RAM PIPE REQUAL

Pipeline Requalification Guidelines Project

Report 4

Risk Assessment and Management (RAM) Based Guidelines for Requalification of Marine Pipelines

To

Petroleos Mexicanos (PEMEX)

Instituto Mexicano de Petroleo (IMP)

Minerals Management Service (MMS)

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University of California at Berkeley

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Table of Contents

List of Symbols

Abbreviations

API	- American Petroleum Institute
ASME	- American Society of Mechanical Engineers
ASTM	- American Society of Testing Material
AGA	- American Gas Association
AISC	- American Institute of Steel Construction, Inc.
BSI	- British Standard Institute
DNV	- Det Norske Veritas
IMP	- Instituto Mexicano de Petroleo
ISO	- International Standard Organization
PEMEX	- Petroleos Mexicano
SUPERB	- Submarine Pipeline Probabilistic Based Design Project

ALS	- Accidental Limit States
ASD	- Allowable Stress Design
CTOD	- Critical Tip Opening Displacement
FEA	- Finite Element Analysis
LRFD	- Load Resistance Factor Design
MOP	- Maximum operating pressure
OTC	- Offshore Technology Conference
OP	- Operating Pressure

FS	- Factor of Safety
SMYS	- Specified Minimum Yield Strength of pipe, in psi (N/mm^2)
SMTS	- Specified Minimum Ultimate Tensile Strength of pipe, in psi (N/mm^2)
WSD	- Working stress design
LRFD	- Load Resistance Factor Design
ULS	- Ultimate Limit State
SLS	- Serviceability Limit States
SCF	- Stress Concentration Factor
SNCF	- Strain Concentration Factor
COV	- Coefficient of Variation
X52	- Material grade, yield strength = 52 ksi=358 Mpa
X65	- Material grade, yield strength = 65 ksi=448 Mpa
X52	- Material grade, yield strength = 70 ksi=530 Mpa

Subscripts

0	- mean
d	- design
θ	- circumferential
r	- radial
res	- residual
co	- collapse
u	- ultimate capacity
p	- plastic capacity
g	- global
l	- local
F50	- Median

Superscripts

M	- Moment
P	- Pressure
T	- Tension
C	- Compression

Roman Symbols

General

B_{F50}	- Median bias factor
V	- Coefficient of Variation
γ	- Load Factor
φ	- Resistance Factor
S	- Demand
R	- Capacity
β	- Reliability Index

Design

A	- Cross sectional area of pipe steel, in inches^2 (mm^2)
A_i	- Internal cross sectional area of the pipe, in inches^2 (mm^2)
A_o	- External cross sectional area of the pipe
C_l	-Inelastic local buckling strength in stress units, pond per square inch (N/mm^2)
C_g	- Inelastic global buckling strength in stress units, pond per square inch (N/mm^2)
D	- Outside diameter of pipe (Equation dependent)
D_i	- Inside diameter of pipe, in inches (mm) $= (D-2t)$
D_{max}	- Maximum diameter at any given cross section, in inches (mm)
D_{min}	- Minimum diameter at any given cross section, in inches (mm)
E	- Elastic modulus, in pounds per square inch (N/mm^2)
$g(\delta)$	- Collapse reduction factor
K	- Effective length factor
L	- Pipe length, in inches (mm)
M	- Applied moment, pond-inch (Nmm)
M_p	- Plastic moment capacity, pond-inch (Nmm)

P	- Applied pressure
P_b	- Minimum burst pressure of pipe, in psi (N / mm^2)
P_c	- Collapse pressure of the pipe, in psi (N / mm^2)
P_e	- Elastic collapse pressure of the pipe, in psi (N / mm^2)
P_i	- Internal pressure in the pipe, in psi (N / mm^2)
P_o	- External hydrostatic pressure, in psi (N / mm^2)
P_p	- Buckle propagation pressure, in psi (N / mm^2)
P_y	- Yield pressure at collapse, in psi (N / mm^2)
r	- Radius of gyration
t_{nom}	- Nominal wall thickness of pipe, in inches (mm)
t_{min}	- Minimum measured wall thickness, in inches (mm)
t	- Pipe wall thickness, in inches (mm)
f_0	- The initial ovalization
n	- The strain hardening parameter
S	- The anisotropy parameter
T_a	- Axial tension in the pipe, in pounds (N)
T_{eff}	- Effective tension in pipe, in pounds (N)
T_y	- Yield tension of the pipe, in pounds (N)
T_u	- Tension Load Capacity
δ	- Ovality
δ_c	- the critical CTOD value
ε_0	- the yield strain
a_{max}	- the equivalent through-thickness crack size.
ε_b	- Bending strain in the pipe
ε_{cr}	- Critical strain
ε_{bm}	- The maximum bending strain
σ_a	- The axial stress
σ_h	- Hoop stress
σ_{he}	- Effective hoop stress
σ_{res}	- Residual stress
σ_θ	- Circumferential stress
σ_{xkL}	- The classic local elastic critical stress
σ_u	- ultimate tensile stress
σ_y	- yield stress
σ_0	- flow stress
λ	- Slenderness parameter

Reassessment

A_d	- effective cross sectional area of damaged (dent) section
A_0	- cross-sectional area of undamaged section
d	- damage depth
ΔY	- Primary out-of-straightness of a dented member
ΔY_0	- 0.001L

I_d	- Effective moment of inertia of undamaged cross-section
K_0	- Effective length factor of undamaged member
K	- Effective buckling length factor
λ_d	- Slenderness parameter of a dented member $=(P_{ud} / P_{ed})^{0.5}$
M_u	- Ultimate moment capacity
M_{cr}	- Critical moment capacity (local buckling)
M_{ud}	- Ultimate negative moment capacity of dent section
M_-	- Negative moment of dent section
M_+	- Positive moment of dent section
M^*	- Neutral moment of dent section
P_{crd}	- Critical axial buckling capacity of a dented member ($\Delta / L > 0.001$)
P_{crd0}	- Critical axial buckling capacity of a dented member ($\Delta / L = 0.001$)
P_E	- Euler load of undamaged member
P_{crl}	- Axial local buckling capacity
P_{cr}	- Axial column buckling capacity
P_u	- Axial compression capacity
P_{ud}	- Axial compression capacity of a short dented member

1.0 Introduction

1.1 Objective

The objective of this joint United States - Mexico cooperative project is to develop and verify Risk Assessment and Management (RAM) based criteria and guidelines for **reassessment and requalification** of marine pipelines and risers. The project is identified as the **RAM PIPE REQUAL** project. This project was sponsored by the U. S. Minerals Management Service (MMS), Petroleos Mexicanos (PEMEX), and Instituto Mexicano del Petroleo (IMP).

1.2 Scope

The **RAM PIPE REQUAL** project addressed the following key aspects of criteria for requalification of conventional existing marine pipelines and risers:

- Development of Safety and Serviceability Classifications (SSC) for different types of marine pipelines and risers that reflect the different types of products transported, the volumes transported and their importance to maintenance of productivity, and their potential consequences given loss of containment,
- Definition of target reliabilities for different SSC of marine risers and pipelines,
- Guidelines for assessment of pressure containment given corrosion and local damage including guidelines for evaluation of corrosion of non-piggable pipelines,
- Guidelines for assessment of local, propagating, and global buckling of pipelines given corrosion and local damage,
- Guidelines for assessment of hydrodynamic stability in extreme condition hurricanes, and
- Guidelines for assessment of combined stresses during operations that reflect the effects of pressure testing and limitations in operating pressures.

Important additional parts of this project provided by PEMEX and IMP were:

- Conduct of workshops and meetings in Mexico and the United States to review progress and developments from this project and to exchange technologies regarding the design and requalification of marine pipelines,
- Provision of a scholarships to fund the work of graduate student researchers (GSR) that assisted in performing this project, and
- Provision of technical support, background, and field operations data to advance the objectives of the RAM PIPE REQUAL project.

1.3 Background

During the period 1996 - 1998, PEMEX (Petroleos Mexicanos) and IMP (Instituto Mexicanos del Petroleo) sponsored a project performed by the Marine Technology and Development Group of the University of California at Berkeley to help develop first-generation Reliability Assessment and Management (RAM) based guidelines for design of pipelines and risers in the Bay of Campeche.

These guidelines were based on both Working Stress Design (WSD) and Load and Resistance Factor Design (LRFD) formats. The following guidelines were developed during this project:

- Serviceability and Safety Classifications (SSC) of pipelines and risers,
- Guidelines for analysis of in-place pipeline loadings (demands) and capacities (resistances), and
- Guidelines for analysis of on-bottom stability (hydrodynamic and geotechnical forces),

This work formed an important starting point for this project.

During the first phase of this project, PEMEX and IMP sponsored two international workshops that addressed the issues and challenges associated with development of criteria and guidelines for design and requalification of marine pipelines.

1.4 Approach

Very significant advances have been achieved in the requalification and reassessment of onshore pipelines. A very general strategy for the requalification of marine pipelines has been proposed by DNV and incorporated into the ISO guidelines for reliability-based limit state design of pipelines (Collberg, Cramer, Bjornoyl, 1996; ISO, 1997). This project is founded on these significant advances.

The fundamental approach used in this project is a Risk Assessment and Management (RAM) approach. This approach is founded on two fundamental strategies:

- Assess the risks (likelihoods, consequences) associated with existing pipelines, and
- Manage the risks so as to produce acceptable and desirable quality in the pipeline operations.

It is recognized that some risks are knowable (can be foreseen) and can be managed to produce acceptable performance. Also, it is recognized that some risks are not knowable (can not be foreseen, and that management processes must be put in place to help manage such risks.

Applied to development of criteria for the requalification of pipelines, a RAM approach proceeds through the following steps:

- Based on an assessment of costs and benefits associated with a particular development and generic type of system, and regulatory - legal requirements, national requirements, define the target reliabilities for the system. These target reliabilities should address the four quality attributes of the system including serviceability, safety, durability, and compatibility.
- Characterize the environmental conditions (e.g. hurricane, nominal oceanographic, geologic) and the operating conditions (installation, production, maintenance) that can affect the pipeline during its life.
- Based on the unique characteristics of the pipeline system characterize the 'demands' (imposed loads, induced forces, displacements) associated with the environmental and operating conditions. These demands and the associated conditions should address each of the four quality attributes of interest (serviceability, safety, durability, compatibility).
- Evaluate the variabilities, uncertainties, and 'Biases' (differences between nominal and true values) associated with the demands. This evaluation must be consistent with the variabilities and uncertainties that were included in the decision process that determined the desirable and acceptable 'target' reliabilities for the system (Step #1).

- For the pipeline system define how the elements will be designed according to a proposed engineering process (procedures, analyses, strategies used to determine the structure element sizes), how these elements will be configured into a system, how the system will be constructed, operated, maintained, and decommissioned (including Quality Assurance - QA, and Quality Control - QC processes).
- Evaluate the variabilities, uncertainties, and 'Biases' (ratio of true or actual values to the predicted or nominal values) associated with the capacities of the pipeline elements and the pipeline system for the anticipated environmental and operating conditions, construction, operations, and maintenance activities, and specified QA - QC programs). This evaluation must be consistent with the variabilities and uncertainties that were included in the decision process that determined the desirable and acceptable 'target' reliabilities for the system (Step #1).
- Based on the results from Steps #1, #4, and #6, and for a specified 'design format' (e.g. Working Stress Design - WSD, Load and Resistance Factor Design- LRFD, Limit States Design - LSD), determine the design format factors (e.g. factors-of-safety for WSD, load and resistance factors for LRFD, and design conditions return periods for LSD).

It is important to note that several of these steps are highly interactive. For some systems, the loadings induced in the system are strongly dependent on the details of the design of the system. Thus, there is a potential coupling or interaction between Steps #3, #4, and #5. The assessment of variabilities and uncertainties in Steps #3 and #5 must be closely coordinated with the variabilities and uncertainties that are included in Step #1. The QA - QC processes that are to be used throughout the life-cycle of the system influence the characterizations of variabilities, uncertainties, and Biases in the 'capacities' of the system elements and the system itself. This is particularly true for the proposed IMR (Inspection, Maintenance, Repair) programs that are to be implemented during the system's life cycle. Design criteria, QA - QC, and IMR programs are highly interactive and are very inter-related.

The RAM PIPE REQUAL guidelines are based on the following current criteria and guidelines:

1) American Petroleum Institute (API RP 1111, 1996, 1998),

2) Det Norske Veritas (DNV, 1981, 1996, 1998, 1999),

3) American Gas Association (AGA, 1990, 1993),

4) American Society of Mechanical Engineers (ASME B31),

5) British Standards Institute (BSI 8010, PD 6493), and

6) International Standards Institute (ISO, 1998).

1.5 Guideline Development Premises

The design criteria and guideline formulations developed during this project are conditional on the following key premises:

- The design and reassessment – requalification analytical models used in this project were based in so far as possible on analytical procedures that are founded on fundamental physics, materials, and mechanics theories.
- The design and reassessment – requalification analytical models used in this –project were founded on in so far as possible on analytical procedures that result in un-biased (the analytical

result equals the median – expected true value) assessments of the pipeline demands and capacities.

- Physical test data and verified – calibrated analytical model data were used in so far as possible to characterize the uncertainties and variabilities associated with the pipeline demands and capacities.
- The uncertainties and variabilities associated with the pipeline demands and capacities will be concordant with the uncertainties and variabilities associated with the background used to define the pipeline reliability goals.

1.6 Pipeline Operating Premises

- The pipelines will be operated at a minimum pressure equal to the normal hydrostatic pressure exerted on the pipeline.
- The pipelines will be maintained to minimize corrosion damage through coatings, cathodic protection, use of inhibitors, and dehydration so as to produce moderate corrosion during the life of the pipeline. If more than moderate corrosion is developed, then the reassessment capacity factors are modified to reflect the greater uncertainties and variabilities associated with severe corrosion.
- The pipelines will be operated at a maximum pressure not to exceed the maximum design pressure. If pipelines are reassessed and requalified to a lower pressure than the maximum design pressure, they will be operated at the specified lower maximum operating pressure. Maximum incidental pressures will not exceed 10 % of the specified maximum operating pressures.

1.7 Schedule

This project took two years to complete. The project was initiated in August 1998. The first phase of this project was completed on 1 July, 1999. RAMP PIPE REQUAL Report 1 (Part 1) and Report 2 (Part 2) document results from the first year study. The second phase of this project was initiated in August 1999 and was completed 16 June 2000. Report 3 was issued on 15 December 1999. This report, Report 4, documents the results of Part 4 of this study.

The schedule for each of the project tasks is summarized in Table 1.1.

Table 1.1 - Project Task Schedule

Task	Part 1, Year 1	Part 2, Year 1	Part 3, Year 2	Part 4, Year 2
1 Classifications	--------------X			
2 Buckling	----------------X			
3 Pressure	----------------X			
4 Op. Pressures	----------------X			
5 Pipe Char.		----------------X		
6 Stability		----------------X		
7 Buckling Gl.		----------------X		
8 Press. Gl.		----------------X		
9 Stab. Gl.			----------------X	
10 Requal. Gl.			----------------X	----------------X
11 Workshops.	X X X	X	X	X

1.8 Project Reports

A report will document the developments from each of the four parts or phases of this project. The reports that will be issued at the end of each of the project phases are as follows:

- **Report 1 –** Requalification Process and Objectives, Risk Assessment & Management Background, Pipeline and Riser Classifications and Targets, Templates for Requalification Guidelines, Pipeline Operating Pressures and Capacities (corrosion, denting, gouging – cracking).

- **Report 2 –** Pipeline characteristics, Hydrodynamic Stability, Geotechnical Stability, Guidelines for Assessing Capacities of Defective and Damaged Pipelines.

- **Report 3 –** Guidelines for Assessing Pipeline Stability (Hydrodynamic, Geotechnical), Preliminary Requalification Guidelines.

- **Report 4 –** Guidelines for Requalifying and Reassessing Marine Pipelines. Criteria and guidelines for pipelines subjected to external pressures, bending, tension, and propagating buckling.

2.0 RAM PIPE REQUAL

2.1 Attributes

Practicality is one of the most important attributes of an engineering approach. Industry experience indicates that a practical RAM PIPE REQUAL approach should embody the following attributes:

- **Simplicity** – ease of use and implementation,
- **Versatility** – the ability to handle a wide variety of real problems,
- **Compatibility** – readily integrated into common engineering and operations procedures,
- **Workability** – the information and data required for input is available or economically attainable, and the output is understandable and can be easily communicated,
- **Feasibility** – available engineering, inspection, instrumentation, and maintenance tools and techniques are sufficient for application of the approach, and
- **Consistency** – the approach can produce similar results for similar problems when used by different engineers.

2.2 Strategies

The RAM PIPE REQUAL approach is founded on the following key strategies:

- **Keep pipeline systems in service** by using preventative and remedial IMR (Inspection, Maintenance, Repair) techniques. RAM PIPE attempts to establish and maintain the integrity of a pipeline system at the least possible cost.
- RAM PIPE REQUAL procedures are intended to **lower risks to the minimum that is practically attainable**. Comprehensive solutions may not be possible. Funding and technology limitations may prevent implementation of ideally comprehensive solutions. Practicality implicates an **incremental investment in identifying and remedying pipeline system defects in the order of the hazards they represent**. This is a prioritized approach.
- RAM PIPE REQUAL should be one of **progressive and continued reduction of risks to tolerable levels.** The **investment of resources must be justified by the scope of the benefits achieved.** This is a repetitive, continuing process of improving understanding and practices. This is a process based on economics and benefits.

2.3 Approach

The fundamental steps of the RAM PIPE REQUAL approach are identified in Figure 2.1. The steps can be summarized as follows:

- **Identification** – this selection is based on an assessment of the likelihood of finding significant degradation in the quality (serviceability, safety, durability, compatibility) characteristics of a given pipeline system, and on an evaluation of the consequences that could be associated with the degradation in quality. The selection can be triggered by either a regulatory requirement or

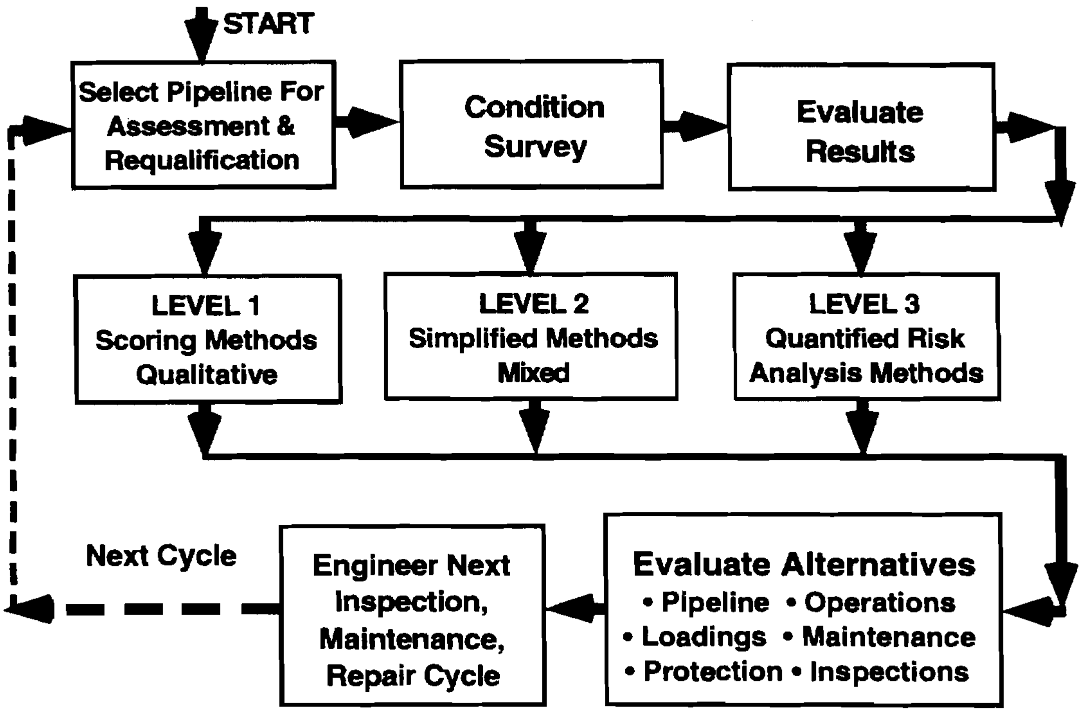

Figure 2.1 – RAM PIPE Approach

by an owner's initiative, following an unusual event, an accident, proposed upgrading of the operations, or a desire to significantly extend the life of the pipeline system beyond that originally intended. ISO (1997) has identified the following triggers for requalification of pipelines: extension of design life, observed damage, changes in operational and environmental conditions, discovery of errors made during design or installation, concerns for the safety of the pipeline for any reason including increased consequences of a possible failure.

- **Condition survey** – this survey includes the formation of or continuance of a databank that contains all pertinent information the design, construction, operation, and maintenance of a pipeline system. Of particular importance are identification and recording of exceptional events or developments during the pipeline system history. Causes of damage or defects can provide important clues in determining what, where, how ,and when to inspect and/or instrument the pipeline system. This step is of critical importance because the RAM PIPE process can only be as effective as the information that is provided for the subsequent evaluations (garbage in, garbage out). Inspections can include external observations (eye, ROV) and measurements (ultrasonic, eddy current, caliper), and internal measurements utilizing in-line instrumentation (smart pigs: magnetic flux, ultrasonic, eddy current, caliper, inertia – geo).
- **Results assessment** – this effort is one of assessing or screening the pipeline system based on the presence or absence of any significant signs of degradation its quality characteristics. The defects can be those of design, construction, operations, or maintenance. If there appear to be no potentially significant defects, the procedure becomes concerned with engineering the next IMR cycle. If there appear to be potentially significant defects, the next step is to determine if mitigation of these defects is warranted. Three levels of assessment of increasing detail and difficulty can be applied: Level 1 – Qualitative (Scoring, Muhlbauer 1992; Kirkwood, Karam 1994), Level 2 – Simplified Qualitative – Quantitative (Bea, 1998), and Level 3 – Quantitative (Quantitative Risk Assessment, QRA, Nessim, Stephens 1995; Bai, Song 1998; Collberg, et al 1996). ISO guidelines (1997) have noted these levels as those of simple calculations, state of

practice methods, and state of art methods, respectively.

The basis for selection of one these levels is one that is intended to allow assessment of the pipeline with the simplest method. The level of assessment is intended to identify pipelines that are clearly fit for purpose as quickly and easily as is possible, and reserve more complex and intense analyses for those pipelines that warrant such evaluations. The engineer is able to choose the method that will facilitate and expedite the requalification process. There are more stringent Fitness for Purpose (FFP) criteria associated with the simpler methods because of the greater uncertainties associated with these methods, and because of the need to minimize the likelihood of 'false positives' (pipelines identified to FFP that are not FFP).

- **Mitigation measures evaluation** – mitigation of defects refers to prioritizing the defects to remedied (first things first), and identifying practical alternative remedial actions. The need for the remedial actions depends on the hazard potential of a given pipeline system, i.e., the likelihood that the pipeline system would not perform adequately during the next RAM PIPE REQUAL cycle. If mitigation appears to be warranted, the next step is to evaluate the alternatives for mitigation.
- **Evaluating alternatives** – mitigation alternatives include those concerning the pipeline itself (patches, replacement of sections), its loadings (cover protection, tie-downs), supports, its operations (pressure de-rating, pressure controls, dehydration) maintenance (cathodic protection, corrosion inhibitors), protective measures (structures, procedures, personnel), and its information (instrumentation, data gathering). Economics based methods (Kulkarni, Conroy 1994; Nessim, Stephens 1995), historic precedents (data on the rates of compromises in pipeline quality), and current standards of practice (pipeline design codes and guidelines, and reassessment outcomes that represent decisions on acceptable pipeline quality) should be used as complimentary methods to evaluate the alternatives and the pipeline FFP. An important alternative is that of improving information and data on the pipeline system (information on the internal characteristics of the pipeline with instrumentation – 'smart pigs' and with sampling, information on the external characteristics of the pipeline using remote sensing methods and on-site inspections).
- **Implementing alternatives** – once the desirable mitigation alternative has been defined, the next step is to engineer that alternative and implement it. The results of this implementation should be incorporated into the pipeline system condition survey – inspection databank. The experiences associated with implementation of a given IMR program provide important feed-back to the RAM PIPE REQUAL process.
- **Engineering the next RAM PIPE REQUAL cycle** – the final step concluding a RAM PIPE REQUAL cycle is that of engineering and implementing the next IMR cycle. The length of the cycle will depend on the anticipated performance of the pipeline system, and the need for and benefits of improving knowledge, information and data on the pipeline condition and performance characteristics.

The ISO guidelines for requalification of pipelines (1997) cite the following essential aspects of an adequate requalifcation procedure – process:

- Account for all the governing factors for the pipeline, with emphasis on the factors initiating the requalification process
- Account for the differences between design of anew pipeline and the reassessment of an existing pipeline
- Apply a decision-theoretic framework and sound engineering judgement

- Utilize an approach in which the requalification process is refined in graduate steps
- Define a simple approach allowing most requalification problems to be solved using conventional methods.

The proposed RAM PIPE REQUAL process, guidelines, and criteria developed during this project are intended to fully satisfy these requirements. A Limit State format will be developed based on Risk Assessment and Management (RAM) background outlined in the next section of this report.

3.0 Pipeline Requalification Formulations & Criteria

The following tables summarize the pipeline requalification guidelines for determination of pipeline strength – capacity characteristics developed during the first phase of this project for in-place operating and accidental conditions. While the tables are not complete at this time, these tables will provide the format that will be used to compile requalification formulations and criteria developed as a result of this project. At this stage, one SSC has been identified for requalification strength criteria. This SSC represents the highest reliability requirements for pipelines and risers for the SSC evaluated during the first phase of this project. The SSC annual Safety Indices are summarized in Table 3.3.

Table 3.1 – Pipeline Capacities

Loading States (1)	**Capacity Analysis Eqn.** (2)	**Data Bases** (3)	**Capacity Analysis Eqn. Median Bias** (4)	**Capacity Analysis Eqn. Coef. Var.** (5)
Single				
Longitudinal • Tension - **Td**	**1**	**1.1**	1.0	0.25
• Compression -**Cd** local - **Cld**	**2**	**1.2**	1.0	0.25
• Compression global - **Cgd**	**3**	**1.3**	1.0	0.25
Transverse • Bending - **Mud**	**4**	**1.4**	1.0	0.25
Pressure • Burst - **Pbd**	**5**	**1.5**	1.2	0.25
• Collapse – **Pcd***	**6**	**1.6**	1.0	0.25
• Propagating–**Pp***	**7**	**1.7**	1.0	0.12
Combined				
T - Mu	**8**	**2.1**	1.0	0.25
T – Pc*	**9**	**2.2**	1.0	0.25
Mu – Pc*	**10**	**2.3**	1.0	0.25
T–Mu-Pc*	**11**	**2.4**	1.0	0.25
C–Mu–Pb	**12**	**2.5**	1.0	0.25
C–Mu-Pc*	**13**	**2.6**	1.0	0.25

*** Accidental Limit State (evaluated with 10-year return period conditions)**

Table 3.2 – Pipeline Loadings & Pressures Biases and Uncertainties

Loading States (1)	In-Place Loading Median Bias B_{F50} (2)	In-Place Loading Annual Coefficient of Variation V_F (3)
Single		
Longitudinal • Tension - **Td**	1.0	0.10
• Compression- **Cd** local - **Cld**	1.0	0.10
• Compression global - **Cgd**	1.0	0.10
Transverse • Bending - **Mud**	1.0	0.10
Pressure • Burst - **Pbd**	1.0	0.10
• Collapse – **Pcd***	0.98	0.02
• Propagating-**Pp***	0.98	0.02
Combined		
T - Mu	1.0	0.10
T – Pc*	0.98	0.02
Mu – Pc*	0.98	0.02
T – Mu – Pc*	0.98	0.02
C– Mu -Pb	1.0	0.10
C– Mu –Pc*	0.98	0.02

*** Accidental Limit State (evaluated with 10-year return period conditions)**

Table 3.3 – Pipeline Design and Reassessment Ultimate Limit State Annual Safety Indices

Loading States (1)	**Annual Safety Index In-Place ULS Pipelines** (2)	**Annual Safety Index In-Place ULS Risers** (3)
Single		
Longitudinal • Tension - **Td**	3.4	3.8
• Compression -**Cd** local - **Cld**	3.4	3.8
• Compression global - **Cgd**	3.4	3.8
Transverse • Bending - **Mud**	3.4	3.8
Pressure • Burst - **Pbd**	3.4	3.8
• Collapse – **Pcd***	1.7	1.7
• Propagating-**Pp***	1.7	1.7
Combined		
T - Mu	3.6	3.8
T – Pc*	2.0	2.0
Mu – Pc*	2.0	2.0
T – Mu – Pc*	2.0	2.0
C – Mu - Pb	3.6	3.6
C – Mu – Pc*	**2.0**	**2.0**

***Accidental Limit State (evaluated with 10-year return period conditions)**

Table 3.4 –In-Place Reassessment Working Stress Factors

[redacted]	Demand/Capacity	Demand & Capacity	In-Place Pipelines	In-Place Risers
	Median Bias	Uncertainty V	ULS - f	ULS - f
Tension	1.00	0.27	0.40	0.36
Compression (local)	1.00	0.27	0.40	0.36
Compression (global)	1.00	0.27	0.40	0.36
Bending	1.00	0.27	0.40	0.36
Burst Pressure (no corrosion)	0.91	0.27	0.44	0.39
Burst Pressure (20 yr corrosion)	0.83	0.27	0.48	0.43
Collapse Pressure (high ovality)*	0.98	0.31	0.60	0.60
Collapse Pressure (low ovality)*	0.98	0.27	0.64	0.64
Propagating Buckling*	0.98	0.12	0.83	0.83
[redacted]				
Tension-Bending-Collapse Pressure*	0.98	0.27	0.64	0.64
Compression-Bending-Collapse Pressure*	0.98	0.27	0.64	0.64
Compression-Bending-Burst Pressure	1.00	0.27	0.40	0.36
*accidental condition with 10-yr demands				

Table 3.5 – In-Place Reassessment Loading Factors

[illegible]	Demand	Demand	In-Place Pipelines	In-Place Risers
	Median Bias	Uncertainty V	LRFD - γ	LRFD - γ
Tension	1.00	0.10	1.29	1.33
Compression (local)	1.00	0.10	1.29	1.33
Compression (global)	1.00	0.10	1.29	1.33
Bending	1.00	0.10	1.29	1.33
Burst Pressure (no corrosion)	1.00	0.10	1.29	1.33
Burst Pressure (20 yr corrosion)	1.00	0.10	1.29	1.33
Collapse Pressure (high ovality)*	0.98	0.02	1.01	1.01
Collapse Pressure (low ovality)*	0.98	0.02	1.01	1.01
Propagating Buckling*	0.98	0.02	1.01	1.01
LRFD Combined In-Place Loadings				
[illegible]				
Tension-Bending-Collapse Pressure*	0.98	0.02	1.01	1.01
Compression-Bending-Collapse Pressure*	0.98	0.02	1.01	1.01
Compression-Bending-Burst Pressure	1.00	0.10	1.29	1.33
*accidental condition with 10-yr demands				

Table 3.6 – In-Place Reassessment Resistance Factors

[redacted]	Capacity Median Bias	Capacity Uncertainty V	Pipelines LRFD - ϕ	Risers LRFD - ϕ
Tension	1.00	0.25	0.53	0.49
Compression (local)	1.00	0.25	0.53	0.49
Compression (global)	1.00	0.25	0.53	0.49
Bending	1.00	0.25	0.53	0.49
Burst Pressure (no corrosion)	1.10	0.25	0.58	0.54
Burst Pressure (20 yr corrosion)	1.20	0.25	0.63	0.59
Collapse Pressure (high ovality)*	1.00	0.25	0.73	0.73
Collapse Pressure (low ovality)*	1.00	0.25	0.73	0.73
Propagating Buckling*	1.00	0.12	0.86	0.86
[redacted]				
Tension-Bending-Collapse Pressure*	1.00	0.25	0.73	0.73
Compression-Bending-Collapse Pressure*	1.00	0.25	0.73	0.73
Compression-Bending-Burst Pressure	1.00	0.25	0.53	0.49
*accidental condition with 10 yr demands				

Table 3.7 –Analysis Equations References

Loading States (1)	Analysis Eqn. (2)	Capacity Analysis Equations References (3)
		Single - Design
Longitudinal • Tension -**T**	1	Andersen, T.L., (1990), API RP 1111 (1997), DNV96 (1996), ISO (1996), Crentsil, et al (1990)
• Compression -**C** 1. local - **Cl**	2	API RP 2A (1993), Tvergaard, V., (1976), Hobbs, R. E., (1984)
• Compression • global - **Cg**	3	API RP 2A (1993), Tvergaard, V., (1976), Hobbs, R. E., (1984)
Transverse • Bending - **Mp**	4	BSI 8010 (1993), DNV 96 (1996), API RP 1111 (1997), Bai, Y. et al (1993), Bai, Y. et al (1997a), Sherman, D.R., (1983), Sherman, D.R., (1984), Kyriakides, S. et al (1987), Gresnigt, A.M., et al (1998)
Pressure • Burst - **Pb**	5	Bea, R. G. (1997), Jiao, et al (1996), Sewart, G., (1994), ANSI/ASME B31G (1991), API RP 1111 (1997), DNV 96 (1996), BSI 8010 (1993)
• Collapse - **Pc**	6	Timoshenko,S.P., (1961), Bai, Y., et al (1997a), Bai, Y., et al (1997b), Bai, Y., et al (1998), Mork, K., (1997), DNV 96 (1996), BSI 8010 (1993), API RP 1111 (1997), ISO (1996), Fowler, J.R., (1990)
		Single - Reassessment
Longitudinal • Tension - **Td**	7	Andersen, T.L., (1990)
•Compression -**Cd** 2. local - **Cld**	8	Loh, J. T., (1993), Ricles, J. M., et al (1992), Taby, J., et al (1980), Smith, C. S., et al (1979)
• Compression • global - **Cgd**	9	Loh, J. T., (1993), Ricles, J. M., et al (1992), Taby, J., et al (1980), Smith, C.S., et al (1979)
Transverse • Bending - **Mpd**	10	Loh, J. T., (1993), Ricles, J. M., et al (1992), Taby, J., et al (1980), Smith, C. S., et al (1979)
Pressure • Burst - **Pbd**	11	Kiefner, J. F., (1974), Kiefner, et al (1989), Chouchaoui et al (1992), Bea, R. G., (1997), Bai, et al (1997c), ASME B31G (1991), Klever, F. J., (1992), Jones, D. G., (1992), Gresnigt, A.M. et al (1996)
• Collapse - **Pcd**	12	Bai, et al (1998)
•Propagating–**Pp***	13	Estefen, et al (1995), Melosh, R. , et al (1976), Palmer, A.C., et al (1979), Kyridkides, et al (1981), Kyriakides, S. et al (1992), Chater, E., (1984), Kyriakides, S. (1991)
		Combined -Design
T - Mp	14	Bai, Y., et al (1993), Bai, Y., et al (1994), Bai, Y., (1997), Mork, K et al (1997), DNV 96 (1996), Yeh, M.K., et al (1986), Yeh, M.K., et al (1988), Murphey, C.E., et al (1984)
T - Pc	15	Kyogoku, T., et al (1981), Tamano, et al (1982)
B - Pc	16	Ju, G. T., et al (1991), Kyriakides, S., et al (1987), Bai, Y., et al (1993), Bai, Y., et al (1994), Bai, Y., et al (1993), Corona, E., et al (1988), DNV96 (1996), BSI 8010 (1993), API RP 1111 (1997), Estefen, S. F. et al (1995)
T – Mp - Pc	17	Li, R., et al (1995), DNV 96 (1996), Bai et al (1993), Bai, Y. et al (1994), Bai, Y. et al (1997), Kyriakides, et al (1989)
C – Mp - Pb	18	DNV 96 (1996), Bruschi, R., et al (1995), Mohareb, M. E. et al (1994)
C – Mp - Pc	19	Kim, H. O., (1992), Bruschi, R., et al (1995), Popv E. P., et al (1974),

Table 3.8 – Capacity Database References

Loading States (1)	Database	Capacity Analysis Equations References (3)
		Single - Design
Longitudinal • Tension -**T**	**1.1**	Fowler, J. R., (1990)
• Compression -**C** 3. local - **Cl**	**1.2**	Ostapenko, A. et al (1979)
• Compression • global - **Cg**	**1.3**	Chen, W.F., et al (1978),
Transverse • Bending - **Mp**	**1.4**	Schilling, G. S. (1965), Jirsa, J. O., et al (1972), Korol, R. M., et al (1979), Sherman, D.R., (1984), Steinmann, S.L., et al (1989), Fowler, J. R., (1990), KyRiakides, S., et al (1985), Johns, T. G., et al (1983)
Pressure • Burst - **Pb**	**1.5**	Sewart, G., et al (1994)
• Collapse - **Pc**	**1.6**	Kyriakides, et al (1984), Kyriakides, et al (1987), Fowler, J. R., (1990), Johns, T. G., et al (1983)
		Single - Reassessment
Longitudinal • Tension - **Td**	**2.1**	Taby, J., et al (1981)
• Compression -**Cd** 4. local - **Cld**	**2.2**	Loh, J.T., (1993), Ricles, J. M., et al (1992), Taby, J., et al (1981)
• Compression • global - **Cgd**	**2.3**	Loh, J.T., (1993), Ricles, J. M., et al (1992), Smith, C.S., et al (1979)
Transverse • Bending - **Mp d**	**2.4**	Loh, J.T., (1993), Ricles, J. M., et al (1992), Taby, J., et al (1981)
Pressure • Burst - **Pbd**	**2.5**	DNV (93-3637)
• Collapse - **Pcd**	**2.6**	
• Propagating–**Pp***	**2.7**	Kyriakides, S., (1984), Estefen S. F., et al (1995), Mesloh, et al (1976)
		Combined -Design
T - Mp	**3.1**	Dyau, J.Y., (1991), Wilhoit, Jr. J.C., et al (1973)
T - Pc	**3.2**	Edwards, S.H., et al (1939), Kyogoku, T., et al (1981), Tamano, T., et al (1982), Kyriakides, S., et al (1987), Fowler, J. R., (1990)
B - Pc	**3.3**	Kyriakides, S., et al (1987), Fowler, J. R., (1990), Winter, P. E., (1985), Johns, T. G., (1983)
T – Mp - Pc	**3.4**	Walker, G.E., et al (1971), Langner, C.G., (1974)
C – Mp - Pb	**3.5**	Walker, G.E., et al (1971), Langner, C.G., (1974)

Table 3.9 – Formulations for Single Loading States

Loading States (1)	Formulation (2)	Formulation Factors (3)
Longitudinal • Tension - **Td**	$Td = 1.1SMYS(A - \Delta)$	
• Compression- **Cd** local - **Cld**	$Cl = 1.1 \bullet SMYS\left(2.0 - 0.28(D/t_{\min})^{1/4}\right) \bullet A \bullet Kd$	Kd = 1 + 3 fd (D / t)
• Compression global - **Cgd**	$Cg = 1.1SMYS\left(1.2 - 0.25\lambda^2\right) \bullet A$ $\lambda = \frac{KL}{\pi r}\left[\frac{SMYS}{E}\right]^{0.5}$	$\frac{P_{crd}}{P_{crdo}} + \frac{P_{crd}\Delta Y}{\left(1 - \frac{P_{crd}}{P_{Ed}}\right)M_{ud}} \leq 1.0$ $\lambda_d = \left(P_{ud}/P_{ed}\right)^{0.5}$ $P_{ud} = P_u\frac{A_d}{A_o} = P_u \exp\left(-0.08\frac{\Delta}{t}\right)$
Transverse • Bending - **Mud**	$\frac{M_d}{M_u} = \exp\left(-0.06\frac{\Delta}{t}\right)$	
Pressure **Burst – Pbd** **Corroded** **Dented** **Gouged** **Dented & Gouged**	$P_{bC} = \frac{2.2 \bullet t \bullet SMTS}{(D-t) \bullet SCFc}$ $Pb_D = \frac{2t\sigma_u}{(D-t) \bullet SCF_D}$ $Pb_G = \frac{2t\sigma_u}{(D-t) \bullet SCF_G}$ $Pb_{DG} = \frac{2t\sigma_u}{(D-t) \bullet SCF_{DG}}$	$SCFc = 1 + 2\ (d/R)^{0.5}$ $SCF_D = 1 + 0.2\ (H/t)^3$ $SCF_G = 1 + 2\ (h/r)^{0.5}$ $SCF_{DG} =$ $[1-d/t-(16H/D)(1-d/t)]^{-1}$
• **Collapse – Pcd** **High Ovality Pipe* (f_{50} = 1 %)** **Low Ovality Pipe* (f_{50} = 0.1 %)**	$P_c = 0.5\left\{P'_{ud} + P_{ed}K_d - \left[\left(P'_{ud} + P_{ed}K_d\right)^2 - 4P'_{ud}P_{ed}K_d\right]^{0.5}\right\}$ $P_c = 0.5\left\{P_{ud} + P_{ed}K_d - \left[\left(P_{ud} + P_{ed}K_d\right)^2 - 4P_{ud}P_{ed}K_d\right]^{0.5}\right\}$	$P'_u = 5.1\frac{\sigma_u t_d}{D_0}$ $P_E = \frac{2E}{1-v^2}\left(\frac{t_d}{D_0}\right)^3$ $K = 1 + 3f\left(\frac{D_0}{t_{nom}}\right)$ $P_{ud} = \frac{2SMTSt_{\min}}{D_0}$
• Propagating-**Pp***	$Pp = 34 \bullet SMYS\left(\frac{t_{nom}}{D_0}\right)^{2.5}$	

*** Accidental Limit State (evaluated with 10-year return period conditions)**

Table 3.10 – Formulations for Combined Loading States

Loading States (1)	Formulation (2)	Formulation Factors (3)
T - Mu	$\left[\left(\frac{M}{Mu}\right)^2+\left(\frac{T}{Tu}\right)^2\right]^{0.5}=1.0$	
T - Pc	$\frac{P}{Pc}+\frac{T}{Tu}=1.0$	
Mu - Pc	$\frac{P}{Pc}+\frac{M}{Mu}=1.0$ *(load controlled)* $\left(\frac{P}{Pc}\right)^2+\left(\frac{M}{Mu}\right)^2=1.0$ *(displacement cont.)*	
T – Mu - Pc	$\left[\left(\frac{M}{M_u}\right)^2+\left(\frac{P}{P_c}\right)^2+\left(\frac{T}{Tu}\right)^2\right]^{0.5}\leq 1$	
C– Mu -Pb	$M_c=M_p f_M$ $M_p=SMYS\bullet D^2t\left(1-0.001\frac{D}{t}\right)$ $\left[\left(\frac{P}{P_{co}}\right)^2+\left(\frac{M}{M_u}\right)^2+\left(\frac{C}{C_g}\right)^2-2\mu\left(\frac{P}{P_{co}}\bullet\frac{M}{M_u}+\frac{M}{M_u}\bullet\frac{C}{C_g}+\frac{P}{P_{co}}\bullet\frac{C}{C_g}\right)\right]^{0.5}\leq 1$	$f_M=k_1\cos\left[\frac{\frac{\pi}{2}\left(k_2-\frac{1}{2}\frac{\sigma_{he}}{SMTS}\right)}{k_1}\right]$ $k_1=\sqrt{1-\frac{3}{4}\left(\frac{\sigma_{he}}{SMTS}\right)^2}$ $k_2=\frac{C}{\pi\bullet SMTS\bullet Dt}$
C– Mu -Pc	$\left(\frac{M}{M_{co}}\right)^2+\left(\frac{P}{P_{co}}\right)^2\leq 1$ $\left[\left(\frac{P}{P_{co}}\right)^2+\left(\frac{M}{M_u}\right)^2+\left(\frac{C}{C_g}\right)^2-2\mu\left(\frac{P}{P_{co}}\bullet\frac{M}{M_u}+\frac{M}{M_u}\bullet\frac{C}{C_g}+\frac{P}{P_{co}}\bullet\frac{C}{C_g}\right)\right]^{0.5}\leq 1$	$M_{co}=M_p\cos\left(\frac{\pi}{2}\frac{T}{T_y}\right)$ $M_p=SMYS\bullet D_0^2t_{nom}\left(1-0.001\frac{D_0}{t_{nom}}\right)$ P_{co} : Timoshenko Ultimate or Elastic equation

Table 3.11 – Formulations for Hydrodynamic Loadings

Formulation (1)	Factors (2)
$F_D = C_D (\rho / 2) D' (Uw + Uc)^2$ $F_L = C_L (\rho / 2) D (Uw + Uc)^2$ $F_I = C_M \rho V' Aw$ $F_T = F_D + F_I$ $Ru \geq F_T \times FS$ $W \geq F_L \times FS$	See Fig. 3.1 $C_D = 1.0$ $C_L = 0.5$ $C_M = 2.5$ $FS = 1.0$
D' = vertical effective (unburied) height of pipe D = pipe diameter V = vertical effective (unburied) volume (per unit length) of pipe Ru = lateral soil – pipeline sliding resistance W = vertical effective weight of pipeline FS = factor of safety for 100-year conditions	Uw = maximum wave velocity normal to pipe axis Uc = maximum current velocity normal to pipe axis Aw = maximum wave acceleration normal to pipe axis

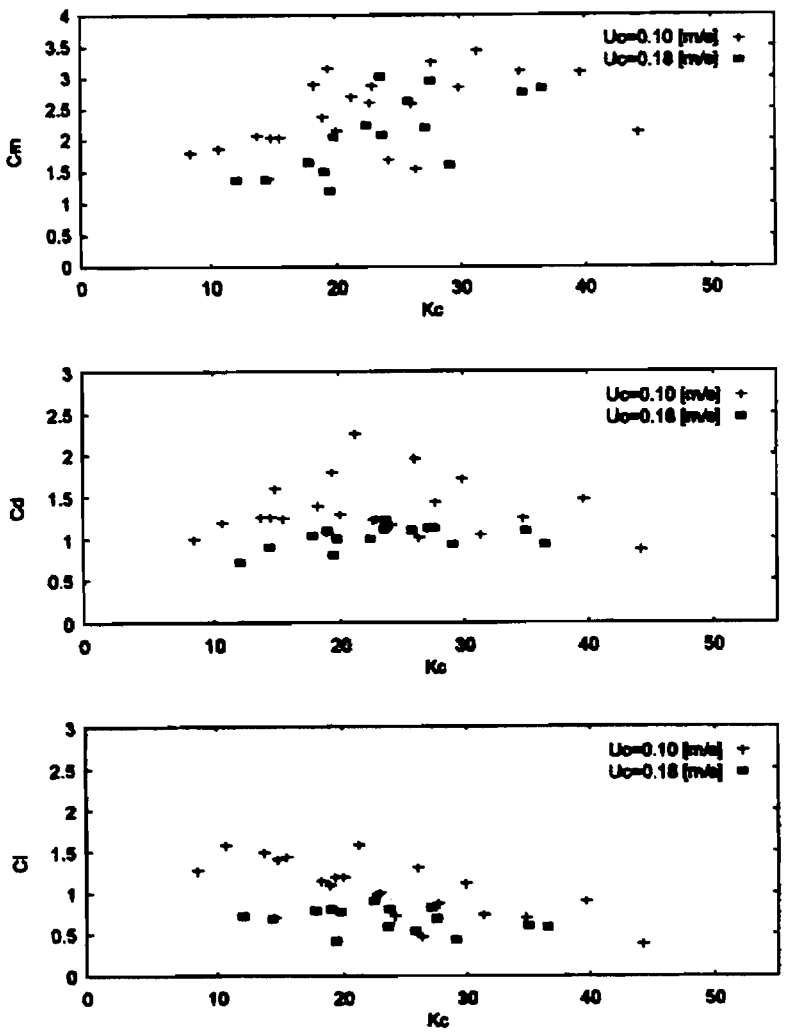

Figure 3.1 – Pipeline hydrodynamic loading coefficients (Neill and Hinwood, 1998)

4.0 Pipeline Capacities

4.1 Buckling and Collapse

Installation is one of the most severe conditions for pipeline design. Buckling and collapse under bending and external pressure is the major failure mode in pipeline installation. Therefore, a comprehensive understanding of this mechanism as well as a rational assessment of the associated uncertainties is essential in the development of the pipeline installation criteria.

Pipe failure under bending basically exhibits two modes: 1) maximum load effect failure (maximum bending moment/strain failure) and, 2) bifurcation failure. The maximum load effect failure is reached when the applied bending load effect exceeds the critical bending strain or bending moment considering the increasing of the circumferential ovalization for increasing load. Bifurcation buckling refers to a change in the deformation pattern and thus also the moment capacity; it is caused by the development of local longitudinal wrinkles in the compressed region of the pipe section.

Bifurcation buckling may occur before the maximum strain is reached for high D/t ratios. For D/t ratios below 35 to 40, the maximum strain is generally reached before bifurcation (Johns, et al 1975). For the pipelines installed in the Bay of Campeche, the relevant D/t ratios are usually below 40, this implies that the maximum load effect failure mode instead of the bifurcation mode is critical for the pipe buckling and collapse.

One of the parameters critical to buckling and collapse is the pipe section imperfection. The increase of ovalization under bending acts as a load-dependent imperfection and may be much larger than the pipe section initial ovality.

At very low D/t ratio, a pipe subjected to bending will collapse due to plastic yielding and the ovalization of the cross-section. At very high D/t ratios, local buckling occurs first. For immediate values D/t ratio (30 to 40), collapse occurs as a combination of ovalization and local buckling. Similarly, for pure external pressure at low D/t, collapse is initiated through yielding, where at high D/t it is initiated through buckling. For D/t ratio between 10 and 40, the failure mode of pipe under combined bending and external pressure is a combination of ovalization, yielding and local buckling.

The objective of this section is to review the buckling/collapse capacity models as well as their uncertainty measures. The following main items are considered:

- Collapse under pure external pressure,
- Buckling under pure bending,
- Buckling/collapse under combined bending and pressure,
- Buckling/collapse under tension and bending, and
- Buckling/collapse under tension, bending, and external pressure.

4.1.1 Review of Design Criteria.

Pure hydrostatic collapse in the elastic or plastic mode may occur due to external pressure alone. The primary variables affecting pipe collapse are the pipe outside diameter, the nominal wall thickness, the initial ovality, the yield stress, and the shape of the stress strain curve as well as anisotropy and residual stress. Residual stresses are particularly important for seamless, UO, UOE manufactured pipe (Gresnight, Foeken, Chen, 2000). The residual stresses act to reduce the collapse pressures. It is important to note that these residual stresses can be relieved with heat-treating the manufactured pipe sections.

By assuming that the pipe has an initial ovality with symmetric cosine shape, Timoshenko derived equations for the hoop compressive force and hoop bending moment (Timoshenko and Gere, 1961). Substituting the force and moment into the initial yielding condition and full yield condition of the rectangle (a unit length along the pipe axial axis), the well known Timoshenko equation and the BSI equation originally by Haagsma and Schaap (1981) are obtained, respectively.

The P_c required to cause buckling/collapse when the external pressure is acting alone, can be obtained from Timoshenko equation:

$$(P_c - P_E)(P_c - P_y) = P_c P_E \frac{3 f_0 D_0}{t_{nom}} \tag{4-1}$$

where:

P_c = collapse (external) pressure

$$P_y = 2 \bullet \sigma_y \bullet \left(\frac{t_{nom}}{D_0} \right)$$

$$P_E = \frac{2E}{1-\nu^2} \left(\frac{t_{nom}}{D_0} \right)^3$$

σ_y = Yield stress

$$f_0 = \frac{D_{max} - D_{min}}{D_{max} + D_{min}}$$

D_0 = Outside diameter

D_{max} = Maximum diameter

D_{min} = Minimum diameter

The initial ovalization, f_0, is defined as the ovalization before applying bending and external pressure.

Solving P_c from the Timoshenko equation, one may obtain that

$$\frac{P_c}{P_E} = 0.5 \left\{ 1 + \frac{3 f_0 D_0}{t} + \frac{P_y}{P_E} - \sqrt{\left(1 + \frac{3 f_0 D_0}{t} + \frac{P_y}{P_E} \right)^2 - 4 \frac{P_y}{P_E}} \right\} \tag{4-2}$$

The collapse pressure for pipes under pure external pressure may also be obtained using BSI 8010 equation:

$$\left(\frac{P_c}{P_E}-1\right)\left(\left(\frac{P_c}{P_y}\right)^2-1\right)=2\left(\frac{P_c}{P_y}\right)f_0\left(\frac{D_0}{t_{nom}}\right) \tag{4-3}$$

where:

$$f_0=\max\left(\frac{D_{max}-D_{min}}{D_{max}+D_{min}}\quad , \quad 2.5\%\right)$$

P_c = Collapse (external) pressure

$$P_y=2\bullet\sigma_y\bullet\left(\frac{t_{nom}}{D_0}\right)$$

$$P_E=\frac{2E}{1-\nu^2}\left(\frac{t_{nom}}{D_0}\right)^3$$

σ_y = Yield stress

D_0 = Outside diameter

D_{max} = Maximum diameter

D_{min} = Minimum diameter

The DNV 96 pipeline design guidelines adopted the BSI 8010 equation in pipeline external pressure criteria. The third equation for collapse pressure is Shell's formula (Murphey and Langner, 1985). This formulation has been used in the API RP 1111.

The API RP 1111 guidelines recommend that submarine pipelines may be subjected to conditions where the external pressure exceeds the internal pressure during construction and operation. The collapse pressure of the pipe must exceed the net external pressure everywhere along the pipeline as:

$$(P_o-P_i)\le f_oP_c \tag{4-4}$$

where:

f_o = collapse factor

= 0.7 for seamless or ERW pipe

= 0.6 for cold expanded pipe such as DSAW pipe.

P_c = Collapse pressure of the pipe, in psi (N/mm^2)

The API equation can be approximated as:

$$P_c=\frac{P_yP_e}{\sqrt{P_y^2+P_e^2}} \tag{4-5}$$

$$P_e=2E\frac{\left(\frac{t}{D}\right)^3}{(1-\nu^2)} \tag{4-6}$$

where:

E = Modulus of elasticity, in psi (N/mm^2)

P_e = Elastic collapse pressure of the pipe, in psi (N/mm^2)

P_y = Yield pressure at collapse, in psi (N/mm^2)

ν = Poisson's ratio (0.3 for steel)

During the RAM PIPE Phase 1 project, a modified Timoshenko equation was developed as:

$$P_c = 0.5\left\{P_u^{'} + P_e K - \left[\left(P_u^{'} + P_e K\right)^2 - 4P_u^{'} P_e K\right]^{0.5}\right\} \tag{4-7}$$

where:

$$P_u^{'} = 5.1\frac{\sigma_u t}{D} = \text{ultimate collapse pressure, in psi } (\mathrm{N/mm^2})$$

$$P_E = \frac{2E}{1-\nu^2}\left(\frac{t_{nom}}{D_0}\right)^3 = \text{Elastic collapse pressure, in psi } (\mathrm{N/mm^2})$$

$$K = 1 + 3f\left(\frac{D}{t}\right) = \text{Imperfection factor}$$

$$f_0 = \frac{D_{max} - D_{min}}{D_{max} + D_{min}}$$

D_0 = Outside diameter

D_{max} = Maximum diameter

D_{min} = Minimum diameter

Figure 4-1 illustrates the comparison between different equations. Initial ovality has significant influence on collapse pressure (Figure 4-1). Bai et al (1993) compared Timoshenko's equation with the BSI formula.

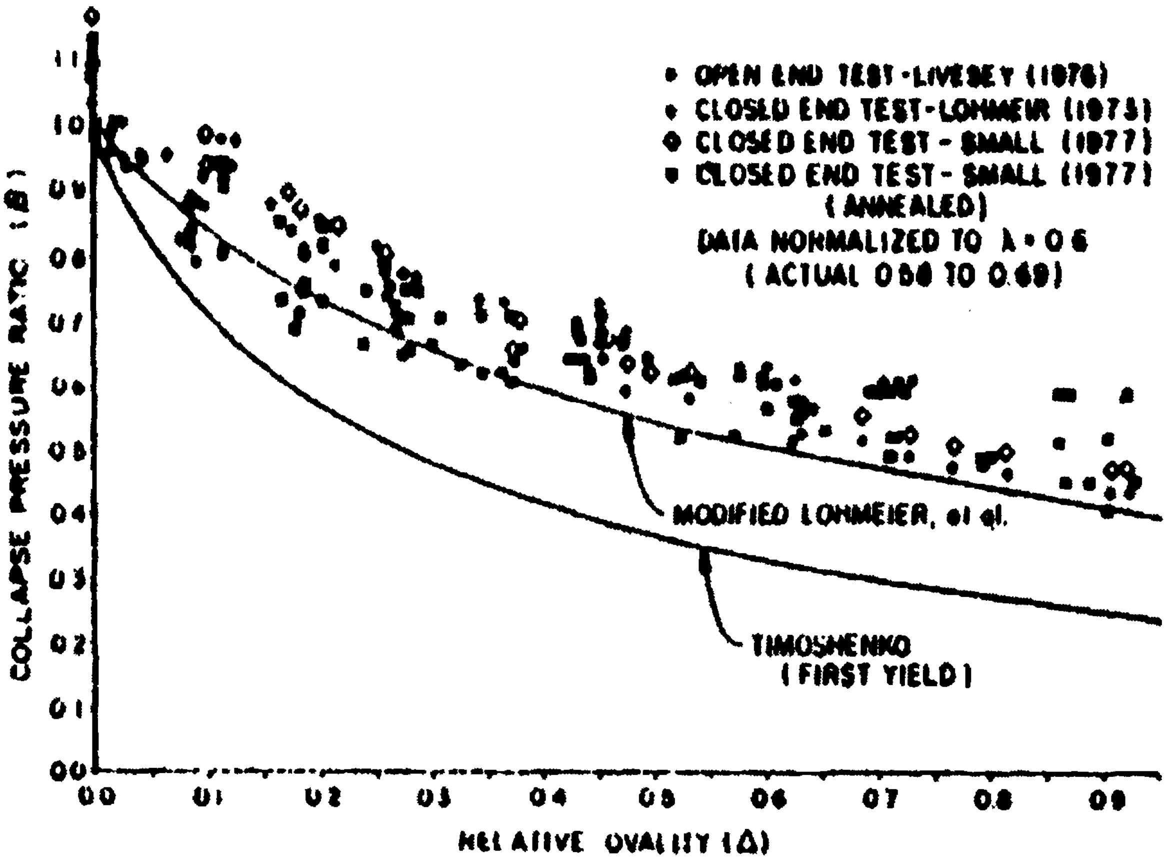

Figure 4-1. Illustration of the Ovality on Collapse Pressure

When comparing initial ovality dependency of predicted collapse pressure for different equations, it has been found that:

- Timoshenko's equation is too sensitive to initial ovality
- Shell formula is insensitive to initial ovality
- BSI formula gives reasonable sensitivity to initial ovality

This study indicates that the modified Timoshenko is the best alternative if the initial ovality is small. However, the BSI equation will be the best for initial ovality is large and for pipe under combined loads.

4.1.2 Review of Test Data

Casing Tubes. Historically, most of the collapse test data found in the literature on long thick wall cylinders subjected to lateral or hydrostatic pressure comes from the well casing industry. API compiled an extensive set of data on casing before early 1980's. This database included 2,700 tests (not all collapsed) reported by manufacturers and contained actual yield strengths and dimensions for each specimen. However, quantities that correlate with a reduction in collapse pressure, such as ovality, shape of stress-strain curve or residual stresses were not included.

The API casing data were grouped by diameter, weight, grade, and type of test. The test types were either long ($L/D \geq 7$) or short ($L/D \leq 2$), in which L and D were the length and diameter of the specimen. The long tests were sometimes open ended, and sometimes closed ended tests. The short tests were always open ended with a special flexible seal to allow the short test to behave like a wide ring.

The casing collapse failure investigation indicated that the casing was made of slack quenched material and contained excessive residual stresses. It was concluded that the fabrication process associated with high residual stresses lowered the collapse strength of Casing (Mehdizadeh, 1976).

Mehdizadeh et al also indicated that different aspects of the API casing data. The Mehdizadeh's data showed that the collapse pressure was influenced by L/D for ratios less than 4. The increase in pressure capacities reached in some cases values beyond 10%. The study also revealed that collapse tests in which the hydrostatic pressure acted axially on the full cross sectional area of the specimen (closed-end samples) gave higher values for collapse pressure than open end tests. Regression analysis of the data indicated that collapse pressures from short open-end tests, L/D up to three, are about 25% greater than those obtained by long closed end tests. Collapse data from long open end and long closed end were similar.

The Mehdizadeh's research also addressed the importance of residual stresses. Two manufacturing operations, quenching and straightening, are mainly responsible for introducing residual stresses in casings. Magnitude and distribution of these residual stresses are influenced by both casing geometry (D/t) and material yield stress. Collapse pressure of fully quenched casings were 10 to 40% higher than those of slack quenched casings, depending on the slack quenching severity. Inner surface compressive residual stress of 20 to 30 ksi magnitude due to rotary straightening found in most casings reduced their collapse strength by 10-40%. However, it is important to outline that the initial ovality in casing is generally small.

The collapse of seamless steel tubes for well casings have been experimentally studied in relation to material yield stress, diameter to thickness ratio, initial ovality and non-uniformity of wall thickness (eccentricity) by Nishioka et al (1976). The effect of eccentricity on the collapse pressure was reported as relatively small for the range of values obtained in the test program. Initial ovality had significant high influence on the collapse pressure. The main problem of this set of data is associated with the small length to diameter ratio of the tested tubes, which was of the order of 2. As this ratio could cause a substantial increase of collapse pressure compared with long tubes.

Pipelines. Emphasis was given to the experimental data of the pipeline strength research. Kyriakides and Yeh conducted the experimental tests for the small diameter seamless tubes in 1980s. Fowler and Stress Engineering Services tested the actual pipes obtained from different fabrication procedures.

Kyriakides and Yeh performed 33 tests on steel tubes with diameters ranging between 1.0 and 1.5 in and lengths between 20 and 30 diameters. Commercially available drawn stainless steel 304 tubes were used in the experiments. The specimens were sealed at both ends and placed in a specially designed 10000 psi capacity pressure test facility. The maximum pressure recorded for each test was taken to represent the collapse pressure. Prior to tests, respective initial ovailities were measured. Typically the diameter variation around the circumference was measured at six to eight stations along the tube length. Variation of wall thickness around the circumference at the two ends was also measured. A longitudinal tensile coupon of width 0.25 in (6 mm) was machined out of each tube used to generate the tested specimens. Each experimental stress-strain curve was fitted with a three parameter Ramberg-Osgood expression. The yield stress as defined by the 0.2% strain offset and 0.5% strain offset were measured.

Fowler performed collapse tests under external pressure for 16 pipes with 16 in diameter. Seamless and Double Submerged Arc Welded (DSAW) tubes were tested. Length to diameter ratio (L/D) was 6.89. For each type of tube, which generates the tested specimens, the following material testing was conducted: chemical analysis, longitudinal and circumferential tensile tests, and residual stress determined by the split ring method. Thickness variation and initial ovality was measured for each specimen prior to the collapse test. Ovalities were calculated based on the diameter difference between a 0-180 degree and a 90-270 degree line and also based on diameter difference between a 45-225 degree line and a 135-315 degree line. The reported ovality is the greater of the two. The tests were performed in a vessel with 30 in outside diameter and 2 in wall thickness. The specimens with both ends sealed were contained entirely within the test vessel. The vessel was pressurized up to the specimen catastrophic failure. For each specimen the maximum recorded pressure was assumed as respective collapse pressure. For DSAW tubes the obtained collapse pressures presented considerable scatter.

SUPERB. The SUPERB project screened and collected the test data. The following assumptions are used to evaluate the collapse prediction:

- Small diameter tests are deemed unfit and are discarded
- The initial ovality is not to be taken less than 0.25% in the test data
- The compressive SMYS in the hoop direction is reduced due to the Baushinger effect for UOE/UO pipes, down to 0.85/0.93 SMYS respectively.

A total of 39 test results for large diameter pipes (both UOE/UO and seamless pipes and mainly for $D/t < 25$) were collected in the SUPERB project.

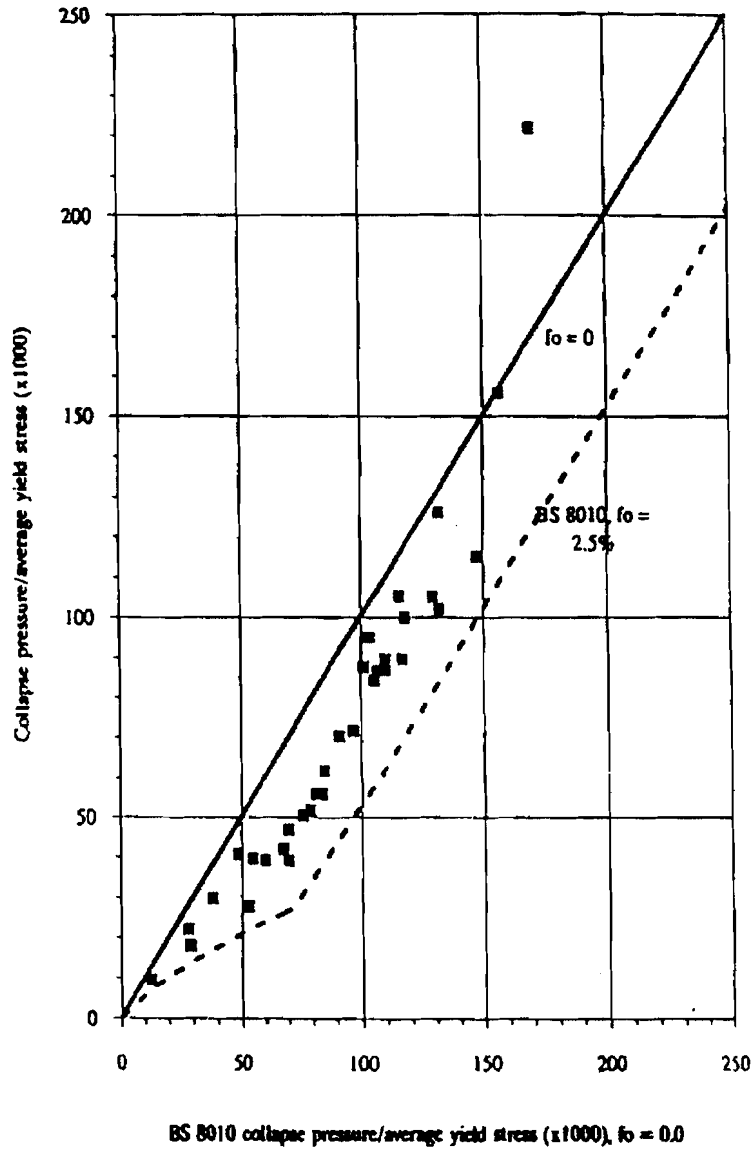

Figure 4-2. Test Data and BSI Predictions for Pipe Under External Pressure

4.1.3 Uncertainty Measures

The SUPERB database specified the mean bias and uncertainty associated with the BSI equation as 1.0 and 11%, respectively. Figure 4-2 illustrates the test data and BSI predictions.

As discussed earlier, initial ovality plays an important role in collapse pressure. Therefore, RAM PIPE project first studied the uncertainty associated with the initial ovality (Figure 4-3). The median Bias and COV of the Bias of the initial ovality of seamless pipe are 0.1 and 89 %, respectively.

Figure 4-4 illustrates the uncertainty analysis of the API RP 1111 collapse equation. The median Bias and COV of the Bias are 1.1 and 15%, respectively. Figure 4-5 illustrates the uncertainty analysis of the modified Timoshenko's equation. The median bias and COV of the Bias are 1.0 and 12.4%, respectively.

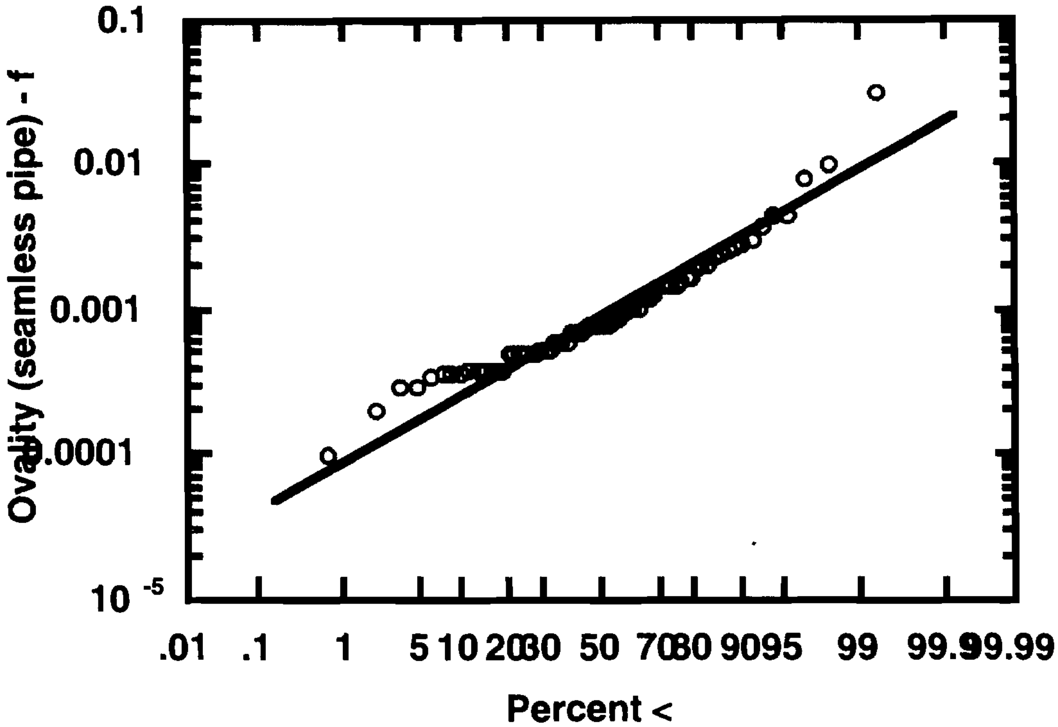

Figure 4-3. Uncertainty of the Initial Ovality

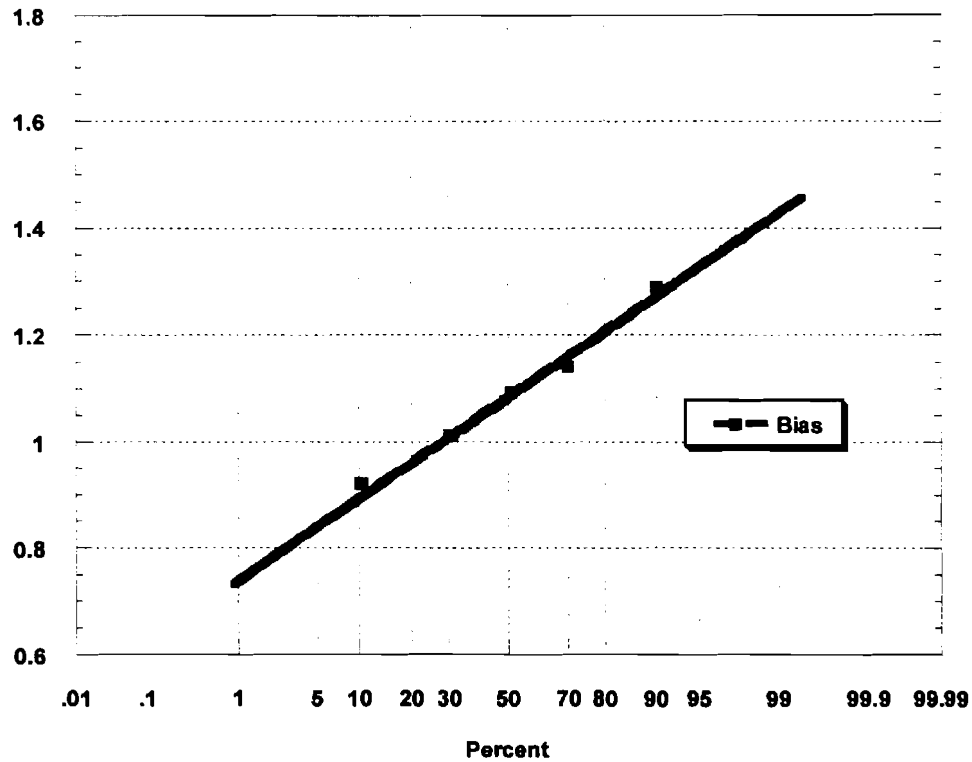

Figure 4-4. Ratio Between the Measured Collapse Pressure and API RP 1111 Based Predicted Collapse Pressure

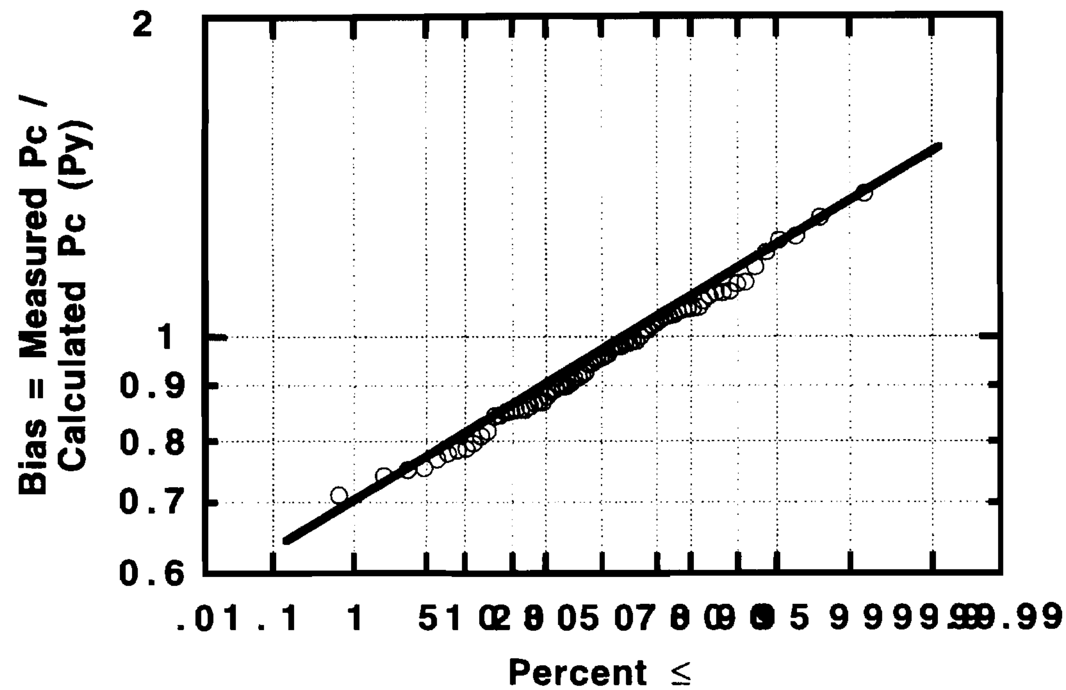

Figure 4-5. Ratio between Measured Collapse Pressure and Modified Timoshenko Based Predicted Collapse Pressure

4.1.4 Development of the RAM PIPE Equations

Fabricated Pipe Data Analysis. The collapse pressure failure mode represents the condition when the pipeline external pressure exceeds the internal pressure at the point of failure. The net collapse pressure (internal minus external pressures) will be indicated as Pc. During the pipeline installation, the pipeline will be installed with the internal pressure equal to atmospheric. Thus, the effective pressure will be the combination of the external hydrostatic and hydrodynamic pressures.

Two different sets of pipeline test data were assembled during this project. The first database was founded on eleven tests on fabricated pipelines: rolled plates welded longitudinally and circumferentially. The second database was founded on seamless pipelines. This section addresses the evaluation of the first database on fabricated pipelines.

The fundamental analytical expression used for evaluation of measured pipeline net collapse pressure was:

$$P_c = 0.5\left\{P_u^{'} + P_e K - \left[\left(P_u^{'} + P_e K\right)^2 - 4P_u^{'} P_e K\right]^{0.5}\right\} \qquad (4\text{-}8)$$

where:

$$P_u^{'} = 2\frac{\sigma_u t}{D} = \text{ultimate collapse pressure, in psi } (\mathrm{N/mm^2})$$

$$P_E = \frac{2E}{1-v^2}\left(\frac{t_{nom}}{D_0}\right)^3 = \text{Elastic collapse pressure, in psi } (\mathrm{N/mm^2})$$

$$K = 1 + 3f\left(\frac{D}{t}\right) = \text{imperfection factor}$$

$$f_0 = \frac{D_{max} - D_{min}}{D_{max} + D_{min}}$$

D_0 = Outside diameter

D_{max} = Maximum diameter

D_{min} = Minimum diameter

This equation is identified as the 'Timoshenko Ultimate' formulation.

A second formulation was used as follows:

$$P_c = 0.5\left\{P_y + P_eK - \left[\left(P_y + P_eK\right)^2 - 4P_yP_eK\right]^{0.5}\right\} \qquad (4\text{-}9)$$

This is the traditional 'Timoshenko Elastic' formulation. The terms in these expressions are as follows:

$$P_y = 2\frac{\sigma_y t}{D} = \text{Yield collapse pressure, in psi } (N/mm^2)$$

$$P_E = \frac{2E}{1 - \nu^2}\left(\frac{t_{nom}}{D_0}\right)^3 = \text{Elastic collapse pressure, in psi } (N/mm^2)$$

$$K = 1 + 3f\left(\frac{D}{t}\right) = \text{Imperfection factor}$$

$$f_0 = \frac{D_{max} - D_{min}}{D_{max} + D_{min}}$$

D_0 = Outside diameter

D_{max} = Maximum diameter

D_{min} = Minimum diameter

The 'Timoshenko Ultimate' formulation was based on an expression for Pu that represents a modification of the traditional yield pressure at collapse, Py. This modification takes account of the additional pressure required to form two plastic hinge lines in the wall of the pipeline.

In general terms, pipelines that have D/t greater than about 25 will be controlled by the elastic buckling pressure, Pe. Pipelines that have D/t less than about 25 will be controlled by the yield or ultimate collapse pressures, Py or Pu.

Figure 3.6 summarizes results of analysis of this database. Figure 4.6 shows the test buckling or collapse pressure, the elastic collapse pressure (Pe), and the Timoshenko Elastic formulation (noted as Timoshenko Reduced Pressure) as a function of the pipeline D/t ratio. For the D/t's greater than about 30, the Timoshenko Elastic formulation results in a dramatic under-prediction of the test collapse pressures. The elastic collapse pressure without any modification for ovality does a better job of matching the test data. But, the test data specimens have ovality and it would not be reasonable to use the elastic collapse pressure as a design formulation.

Figure 4.7 summarizes a statistical analysis of these results. The Timoshenko Elastic formulation has a median Bias (measured pressure / predicted pressure) of 1.6 and has a coefficient of variation of V = 35 %. The elastic collapse pressure formulation has a median Bias of 1.0 and a coefficient of variation of V = 30 %

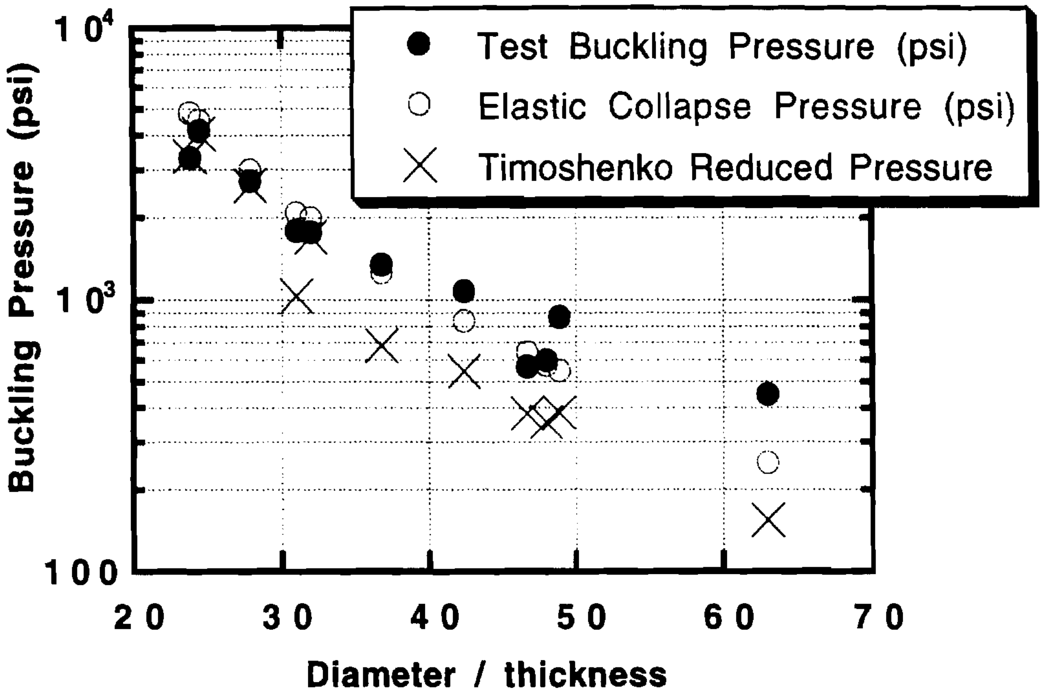

Figure 4-6. Comparison of collapse pressure test data with Timoshenko Elastic and elastic collapse pressure formulations

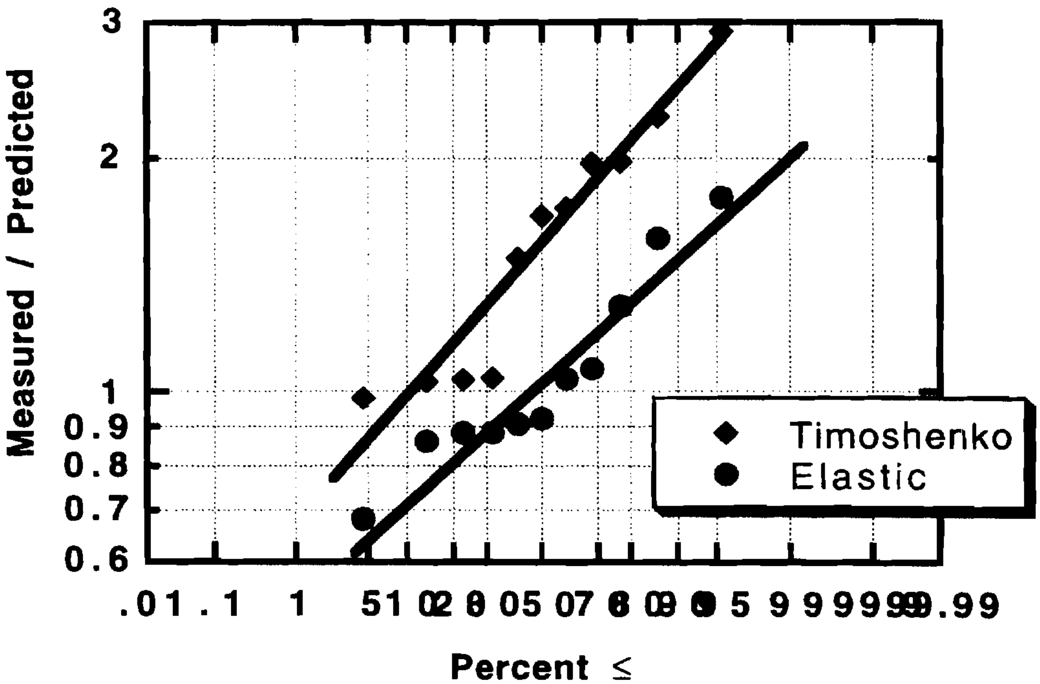

Figure 4-7 Statistical analysis of bias in collapse pressure prediction formulations

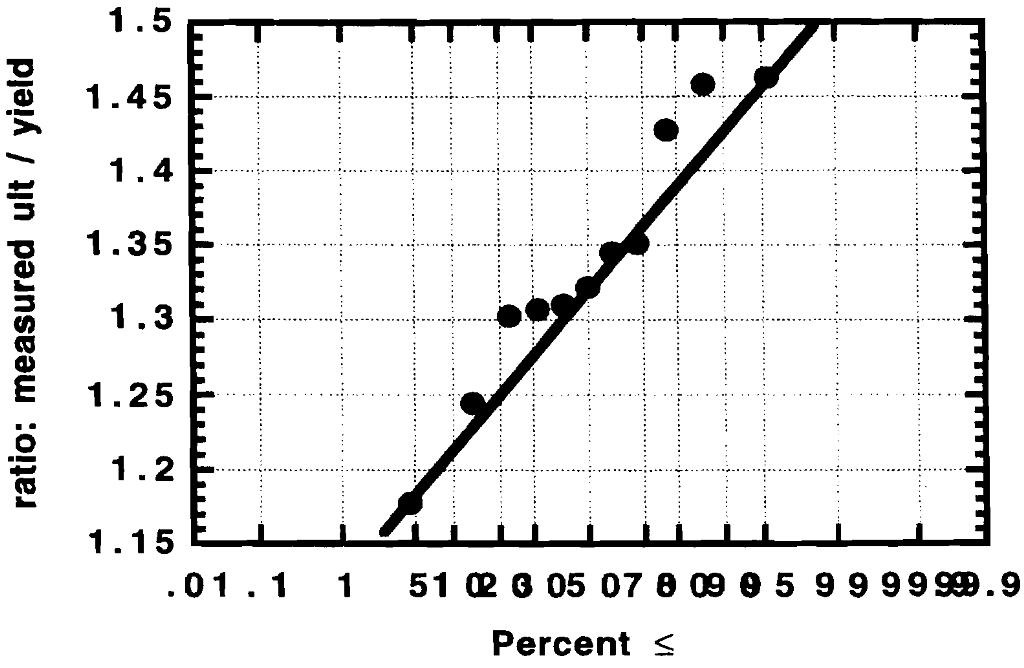

Figure 4-8 Statistical analysis of ratio of ultimate tensile strength (transverse) to yield strength

Figure 4.8 summarizes results from an analysis of the test specimen's measured ultimate tensile strength (transverse) to measured yield strength (transverse) ratios. The median value of this ratio is 1.3. The coefficient of variation of the ratio is V = 6.4 %.

These results were used to re-evaluate the test data based on the formulation identified as Timoshenko Ultimate. A statistical analysis of the results is summarized in Figure 4.9. The median bias in the traditional elastic formulation has been reduced to 1.25 and the Bias has a coefficient of variation of V = 36 %.

Figure 4.9 summarizes the preceding developments. The statistical analysis of the Bias in the prediction analytical models are shown and include the Timoshenko Ultimate, elastic collapse pressure, Timoshenko Elastic, and API 1111 (1998) formulations. The API 1111 formulation has about the same bias and uncertainty as the Timoshenko Ultimate formulation.

In an attempt to develop an un-biased formulation, the Timoshenko Elastic formulation was extended to a 4-hinge model (ratio of 4 hinge to 2 hinge model capacities = 1.7) in which:

$$P_u = 5.1\frac{\sigma_u t}{D} \tag{4.10}$$

was used in the 'Timoshenko Ultimate' formulation. The results are summarized in Figure 4.10. The median Bias is now 1.0 and the COV of the bias is V = 31 %.

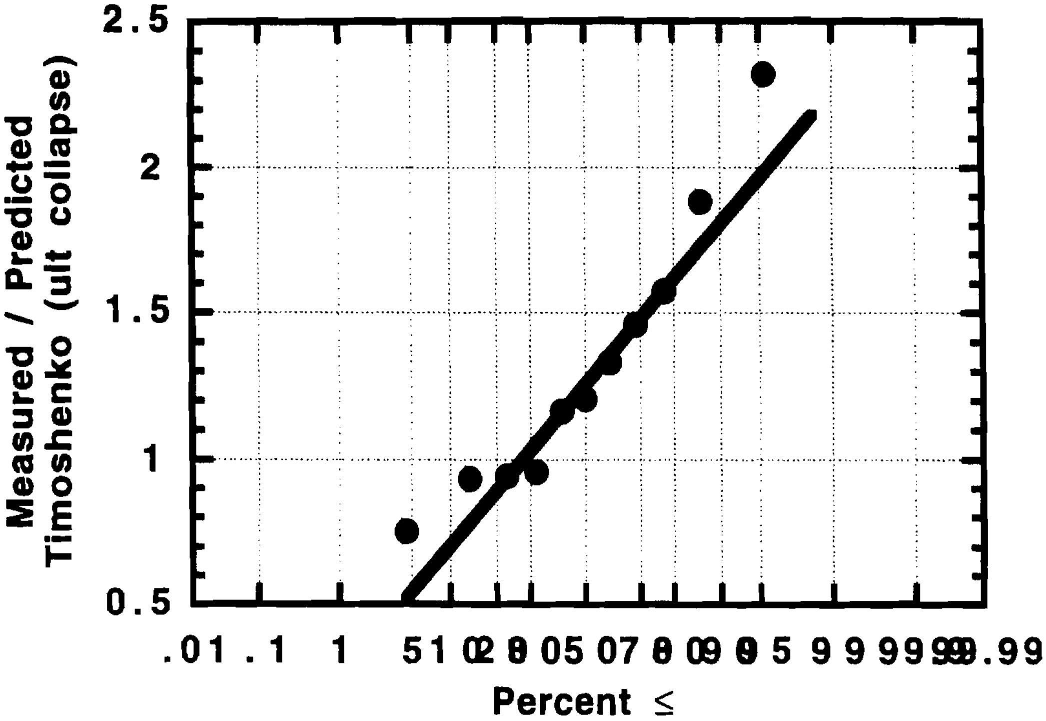

Figure 4-9 Statistical analysis of collapse pressure prediction Bias based on Timoshenko Ultimate formulation

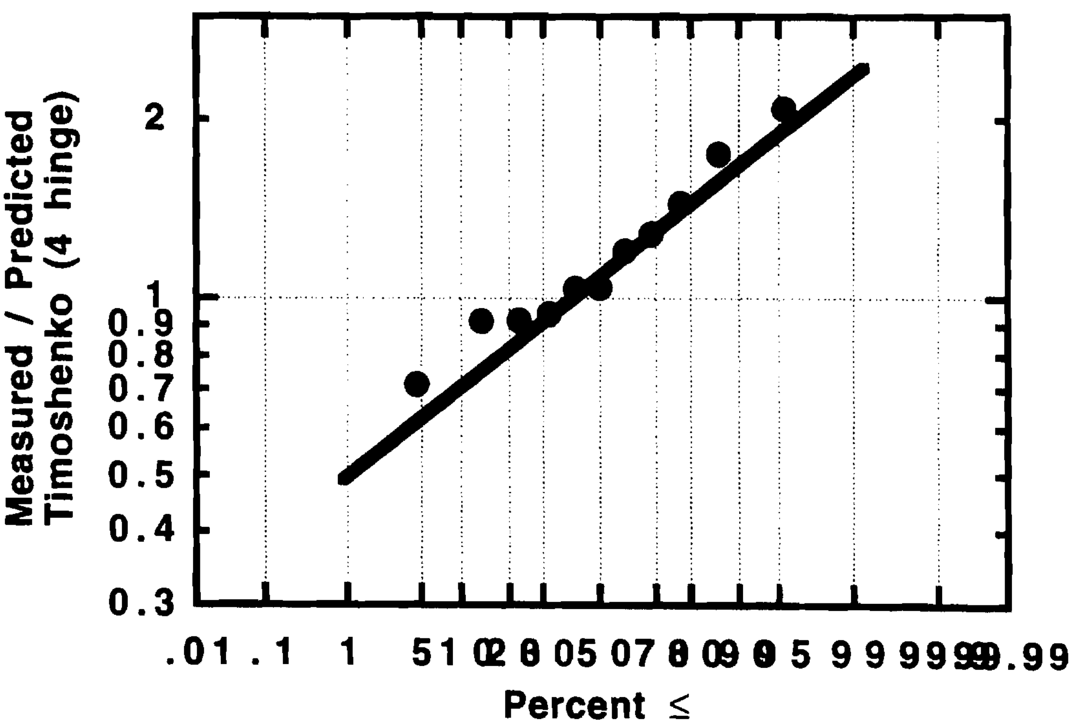

Figure 4-10 Statistical analysis of bias in 4-hinge Timoshenko Ultimate formulation

Seamless Pipe Data Analysis. A database of 74 tests on seamless pipeline test specimens was assembled during this project. This database is summarized in Bea, et al (1998).

In this case, the analyses were initially performed using the 4-hinge Timoshenko Ultimate formulation. The formulation substantially over-predicted the collapse pressures. The analyses were then performed using the Timoshenko Elastic formulation. The results are summarized in Figure 3.11. The median bias is B_{50} = 1.0 and the Coefficient of Variation of the Bias is V_B = 12.4 %.

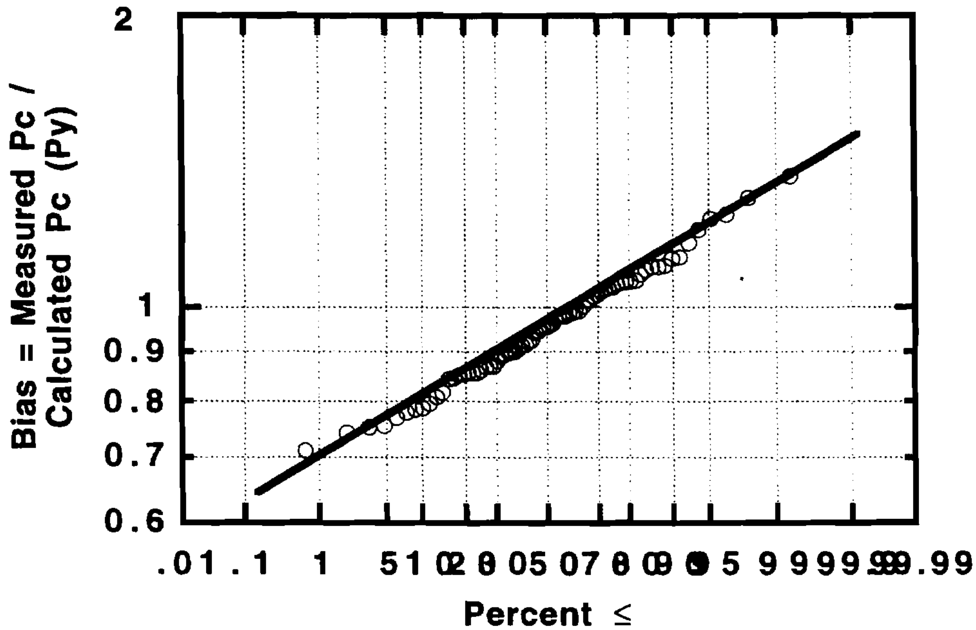

Figure 4-11. Bias in Timoshenko Elastic formulation based on results from seamless pipe tests

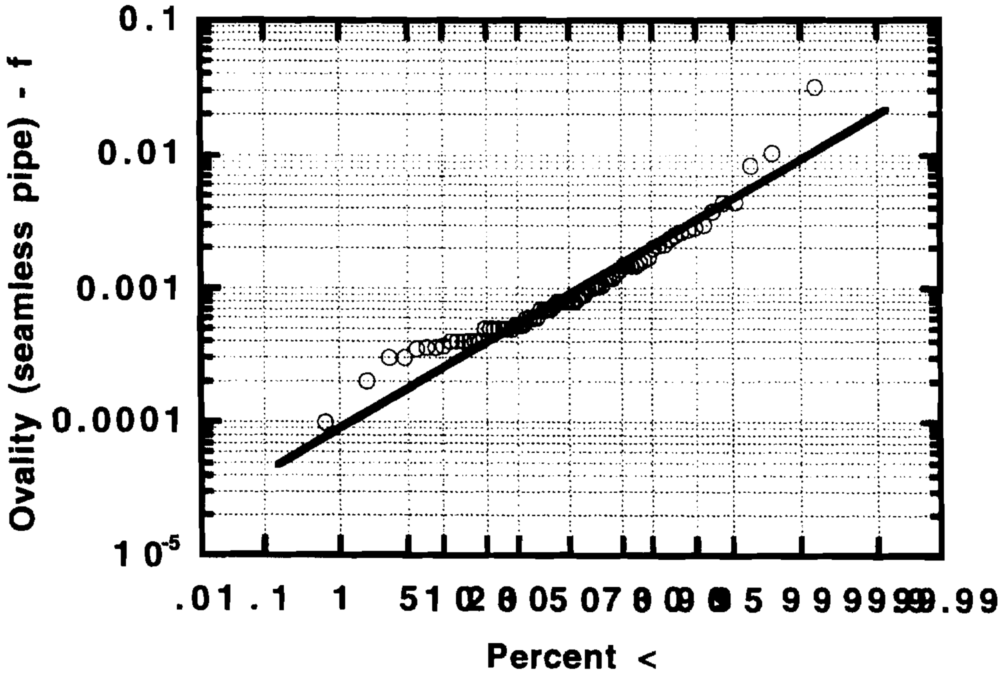

Figure 4-12. Measured ovalities of seamless pipeline test specimens

In an attempt to explain the reason for the differences between the results based on fabricated pipelines and those from seamless pipelines, the ovality of the seamless pipeline test specimens were evaluated. The results are summarized in Figure 3.12. The median ovality is f_{50} = 0.1 % and the ovality of the test specimens has a Coefficient of Variation of V_f = 90 %. These results compare with a median ovality of f_{50} = 1 % for the fabricated pipelines, a factor of 10 larger than for the seamless pipelines. The fabricated pipeline specimens had a Coefficient of Variation of the ovality of V_f = 55 %; somewhat less than for the seamless pipeline specimens.

As mentioned earlier, it should be recognized that the residual stresses manufactured into seamless pipe also have a deleterious effect on the collapse pressures. Gresnigt, et al. (2000) performed tests on three 20-inch diameter UOE manufactured pipes and one seamless pipe. The D/t ratios were 45, 27, 22, and 29. Analysis of the test results using the BS 8010 formulation indicated biases of 0.91, 1.09, 0.78, and 0.65 with the lower biases associated with the smaller D/t ratios. The highest bias was associated with the seamless pipe (no Bauschinger effect). Note the tendency for the BS 8010 analytical model to over-predict the collapse pressures.

The Timoshenko Elastic formulation results in an unbiased formulation of the collapse pressures for the seamless pipelines that have very low ovality. The Timoshenko Ultimate 4-hinge formulation results in an unbiased formulation of the collapse pressures for fabricated pipelines that have very high ovality. The quality assurance and control used in manufacture of the pipeline has an important influence on the pipeline ovality and hence on the appropriate design formulation. This project will be founded on both of the formulations. The design formulation will depend on whether the pipeline is fabricated and has a median ovality of 1 % or is seamless and has a median ovality of 0.1 %.

Gresnigt, et al. (2000) reported on development of a database that included 103 collapse pressure test specimens. The D/t range was 15 to 50. The ovalities were all les than 1 %. Three data subsets were analyzed: 1) all 103 tests analyzed using the tension yield stress, 2) only UOE pipe analyzed using the compression yield stress, and 3) all 103 tests analyzed using compression yield stress for UOE pipe and in other cases the tension yield stress. Their tests on the UOE pipe indicated ratios of longitudinal tensile yield stress to compression yield stress of 0.99, 0.96, 0.94, and 0.89. The ratios of longitudinal to circumferential yield stress were 1.12, 1.23, 1.04, and 0.97. The analyses included the API, Murphey, Langner, De Winter, Timoshenko, and BS 8010 analytical models. Table 4.1 summarizes the results. The BS 8010 model generally had the lowest mean bias and bias COV.

Table 4.1 – Bias statistics for various prediction methods for collapse pressures

Analytial Method	Database 1		Database 2		Database 2	
	Mean bias	Bias COV	Mean bias	Bias COV	Mean Bias	Bias COV
API	1.06	0.148	1.17	0.082	1.05	0.140
Murphey	1.04	0.138	1.14	0.088	1.03	0.130
Langner	1.02	0.167	1.12	0.091	1.04	0.159
De Winter	1.24	0.156	1.39	0.125	1.23	0.152
Timoshenko	1.06	0.140	1.12	0.1329	1.05	0.134
BS 8010	1.08	0.129	1.14	0.121	1.07	0.122

Simulated Pipe Test Data Analysis. A database of 44 simulated 'tests' on collapse pressures of X-52 and X-77 pipe were provided by Igland (1997). This database included only those simulations that did not include residual stresses. The simulations that included residual stresses produced results that were 'unusual' when compared with physical test data. In addition, three of the simulations (No. 55 – 58) did not produce results that were in agreement the same simulations performed earlier; these three simulations were ignored. A summary of the entire collapse pressure simulation database is included in Bea, et al (1998).

Figure 4.13 summarizes results from the statistical analysis of the simulated test data Bias. The Timoshenko Elastic model was used to calculate the collapse pressures. Four ovalities were used in the calcuations: f = measured, f = 0.001 (e.g. high quality seamless pipe), f = 0.01 (low quality fabricated pipe), and f = 0.005.

The formulation based on f = 0.005 produced a median Bias B_{50} = 1.0 and a coefficient of variation of the bias of V_B = 4.0 %.

The formulation based on the measured ovalities and the specified minimum yield strengths times 1.1 produced a median Bias of B_{50} = 0.96 and Coefficient of Variation of the Bias of V_B = 4.1 %. The formulation based on the measured ovalities and the simulation model yield strengths produced a median Bias of B_{50} = 0.90 and Coefficient of Variation of the Bias of V_B = 8.7 %.

If one used the seamless pipeline test data, a median bias of B_{50} = 1.0 and Coefficient of Variation of the Bias of 12.4 %. The simulation data analyzed in the same way as the test data developed a median bias of B_{50} = 0.90 and Coefficient of Variation of the Bias of 8.7 %. The simulation median bias would have to be multiplied by a median Bias correction factor of 1.11. The simulation test data bias Coefficient of Variation would have to have an additional Coefficient of Variation of 8.8 % added to it in quadrature.

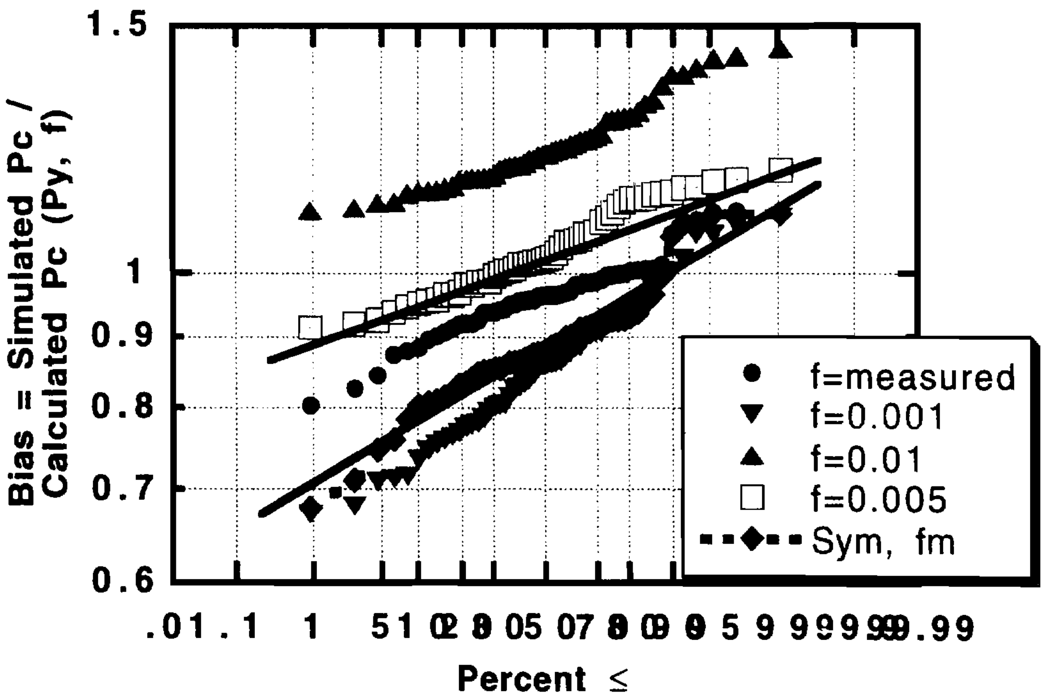

Figure 4-13 Bias from Simulated Test Data for Various Ovalities

4.2 Pure Bending - Buckling

4.2.1 General

Figure 4.14 illustrates the typical behavior of a pure bending load applied to pipe as described by Murphey and Langner (Murphey, et al 1985). As bending moment is applied to the pipe, curvature is induced. The moment-strain relationship is initially linear. As the bending moment is increased, the outermost fibers of the pipe begin to reach the proportional limit stress (point A), plastic deformation initiates and the moment-strain relationship becomes increasingly nonlinear and ovalization of the pipe occurs. Although permanent curvatures are induced, the geometry remains stable due to strain hardening of the material.

Beyond yield level strains, ovalization of the pipe wall increases rapidly, further reducing the slope of the moment strain diagram. Eventually the slope becomes zero and the maximum moment is achieved when ovalization effects overcome strain hardening and buckling is imminent. At the point of maximum moment the pipe has no more reserve stiffness to resist buckling. If the applied loads are not reduced at this point, severe deformation occurs. In a displacement controlled condition, buckling initiates and the pipe deforms to the imposed displacement. In a load controlled condition, failure occurs.

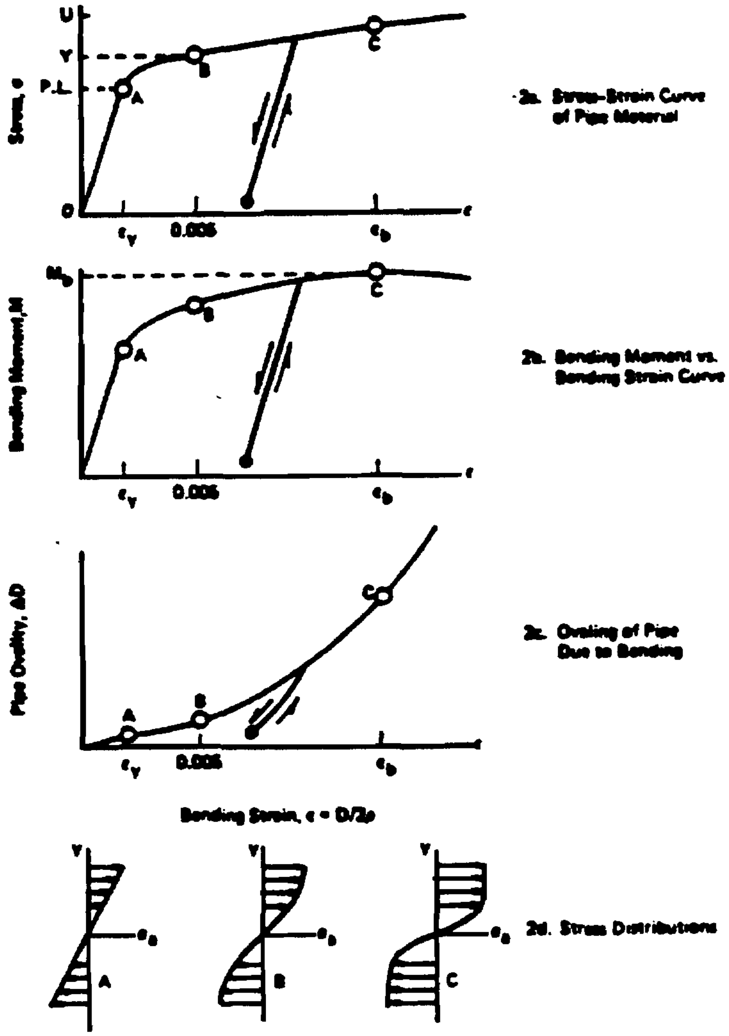

Figure 4-14. Mechanical behavior of Pipe in Pure Bending

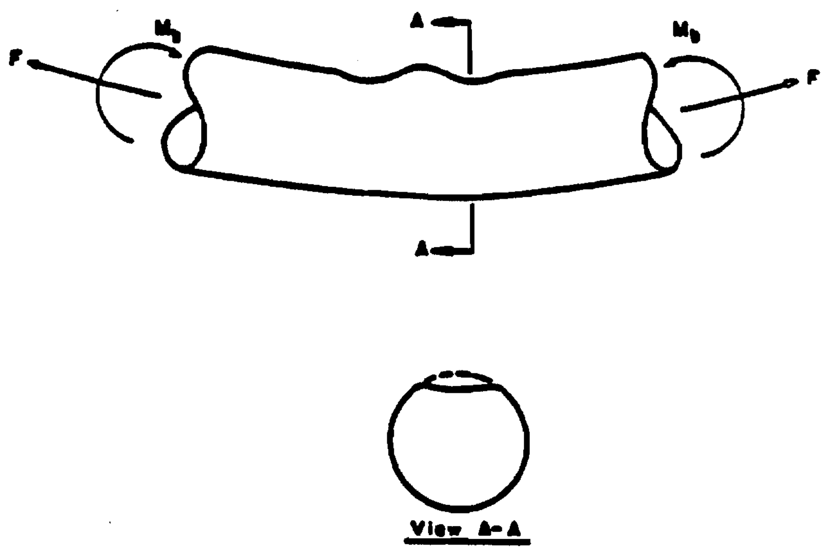

Figure 4-15. Exaggerated View of Small Amplitude Buckle in Thin Wall Pipe

The bending strains and curvatures at the point of maximum moment are defined as the critical buckling strains and curvatures. For thin wall pipe (high D/t ratio) a small amplitude wave or wrinkle may become visible (Figure 3.15) prior to achieving the maximum moment capacity of the pipe. The pipe bending behavior remains stable, however, until the maximum moment is reached.

The diagram in Figure 4.14 is representative of behavior for unpressurized pipe with D/t less than approximately 35. For higher D/t's (i.e., thinner wall pipe), a point of instability and inward buckle may occur before the point of zero slope on the moment curvature diagram. Figure 4.16 compares examples of moment bending strain diagrams for three D/t ratios.

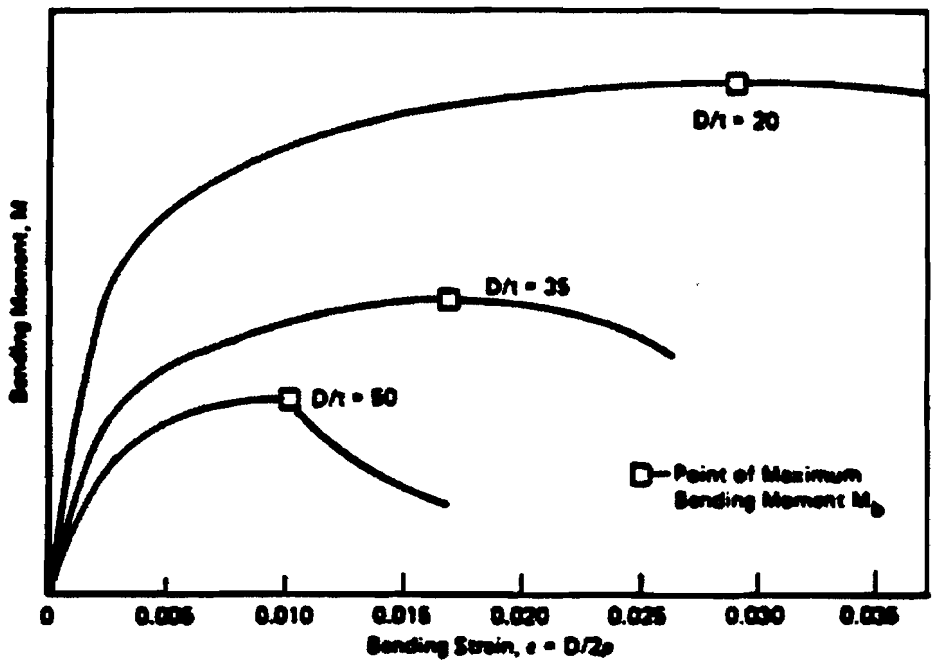

Figure 4-16. Typical Moment versus Strain Curves for Constant Diameter and Yield Stress But Variable Wall Thickness

4.2.2 Review of Design Criteria

Bending Strain Capacity. A critical strain equation for pipes under pure bending is provided by BSI 8010 where

$$\varepsilon_{bc} = 15 \bullet \left(\frac{t_{nom}}{D_0}\right)^2 \tag{4.11}$$

where:

t_{nom} =Wall thickness
D =Outside diameter

The DNV 96 pipeline design guidelines assumes that critical bending strain is a linear function of t_{nom}/D. The API RP 1111 pipeline design guidelines states that $\varepsilon_{bc}$is a linear function of $t_{nom}/2D$.

Bai et al (1994) developed that the critical bending strain corresponding to the maximum moment capacity point is:

$$\varepsilon_{bc} = 0.6275 \bullet f_1(n) \bullet f_2(n) \bullet \left(\frac{t_{nom}}{D}\right) \tag{4.12}$$

where $f_1(n)$ is a function of hardening parameter n in the Ramberg-Osgood Equation:

$$f_1(n) = 0.5 + \frac{8.79}{n} - \frac{21.128}{n^2} \tag{4.13}$$

and where $f_1(S)$ is a function of yield anisotropy parameter S that is yield stress in the hoop direction divided by yield stress in the longitudinal direction:

$$f_2(S) = -0.185 + 1.19S \tag{4.14}$$

Bai's equations for critical bending strain have been developed based on extensive finite element simulation using ABAQUS where the accuracy of the equations were validated using a large amount of experimental data. In other words, the parameter equations were based on experiments with functions defined from analytical and numerical studies. Because the strain hardening parameter n and anisotropy S are available, it is easy to apply the equations in pipeline design.

The BSI 8010 equations assume that critical strain is proportional to $(t_{nom}/D)^2$be not based on analytical considerations. It is based on the experimental test data where some tests were not conducted for pipeline material. Therefore, the BSI equations obtained from fitting curve to experimental results are not strictly applicable to pipelines since material properties significantly affect the critical strain. In some cases, the critical strain obtained from experiments corresponds to the ultimate moment point and in other cases to the local buckling point. It is difficult to define the local buckling point since a sudden reduction of load-carrying capacity is not obvious for thick walled tube. In addition, because of the large and localized strain, the measurement of critical strain is not accurate. This is why the BSI equation overestimates critical bending strain of pipes of small t_{nom}/D.

Bending Moment Capacity. In terms of stress based criteria, SUPERB and DNV 96 recommend that the bending moment capacity is

$$M_u = M_p = \pi D_0^2 t_{nom} \sigma_y \tag{4.15}$$

where:

σ_y - yield stress

D_0 - Mean pipe diameter

t_{nom} - Pipe wall thickness

The RAM PIPE project proposed the following three equations for the pure bending capacity:

$$M_u = \pi D_0^2 t_{nom} \sigma_y \left(1 - 0.001 \frac{D_0}{t_{nom}}\right) \tag{4.16}$$

where:

σ_y - yield stress

D_0 - Mean pipe diameter

t_{nom} - Pipe wall thickness

or

$$M_u = \pi D_0^2 t_{nom} \sigma_y \left(1 - 0.002 \frac{D_0}{t_{nom}}\right) \tag{4.17}$$

where:

σ_y - yield stress

D_0 - Mean pipe diameter

t_{nom} - Pipe wall thickness

or

$$M_u = 1.13 M_p \exp(-X) \tag{4.18}$$

$$M_p = (D_0 - t_{nom})^2 t_{nom} \sigma_y$$

$$X = \frac{\sigma_y D_0}{E t_{nom}}$$

where:

σ_y - yield stress

D_0 - Mean pipe diameter

t_{nom} - Pipe wall thickness

4.2.3 Review of Test Data

The amount of test data for tubes under pure longitudinal bending, are relatively restricted. Sherman (1976, 1984) presents a review of tests on fabricated pipes with geometrical and material characteristics of cylindrical members in offshore structures. Attempts have been made to establish bending limit state criteria based on the full capacity of the tubular cross section. Schilling's tests (Schilling, 1965) derived the following parameter α that characterizes the plastic moment:

$$\alpha = \frac{E/\sigma_y}{D/t} \tag{4.19}$$

where:

E - the elastic modulus
D - diameter
T - pipe wall thickness
σ_y - Yield stress

Schilling (1965) indicated a lower limit of 8.8 for the parameter α.

Uncertainties about the extrapolation of the tubular test results to long pipes, as far as the plastic moment capacity is concerned, led to the testing programs of large-scale pipe beams (Jirsa, et al 1972, Sherman, et al 1976, and Korol, 1979). The results indicated that some tubular sections with α greater than 8.8 did not achieve the plastic moment which implied that the limit for a compact section, was higher than anticipated up to this time, generating an inelastic local buckling criteria for longitudinal bending that is different from axial compression.
Jirsa et al (1972) reported six tests of pipe under pure bending, with diameter varying from 10 to 20 in and D/t from 30 to 78.

Sherman (1976) presented experimental tests data of the tubes under pure bending. The tubes are with outside diameter of 10.75 in and D/t ratios from 18 to 102. Sherman (1976) concluded that the members with D/t of 35 or less can develop a fully plastic moment and sustain sufficient rotation to fully redistribute the moments in fixed end beams. This conclusion was demonstrated for pipe spans up to 22 diameters. In addition, Sherman (1976) concluded that tubes made by Electric Resistance Welded (ERW) could not develop the full plastic moment at as large a D/t as that proposed by Schilling (1965).

Korol (1979) performed a series of nine tests on single span circular hollow tubular beams with D/t ratios from 28.9 to 80.0. Korol (1979) concluded that the buckling strain was found to be inversely proportional to yield stress rose to an exponent factor between 0.5 and 1.0 for ductile materials that possess an essentially bilinear stress-strain curve and a small degree of strain hardening. This exponent factor tends to be 1.0 for elastic-perfectly plastic materials. For a high tangent modulus and small D/t pipe, it tends towards zero.

The Sherman (1986) reviewed six experimental research programs that contain test on cylinders with unstiffened constant-moment regions. A total of 53 tests were included in the review. The test specimens were hot-formed seamless pipe; electric resistance welded tubes and fabricated pipes. The diameters ranged from 4 to 60 inches. However, in most cases the diameters were between 10 and 24 inches.

Two tests of the test series conducted by Sternmann et al (1989) for beam columns were included in the tests database development. These tests were for tubulars with nominal D/t ratio of 42, the outside diameter of 6.625 in and L/D of 24.9 and 17.3. These models were made from X-42 steel ERW pipe.

In addition, tests conducted by Kyriakides, et al (1987), Fowler, et al (1990) and Battelle (1983) for the longitudinal bending alone of the combined loading tests program were included in the database.

4.2.4 Uncertainty Measures

Bending Strain Capacity. The critical bending strain ε_{bc} can be determined based on the following equations:

$$\varepsilon_{bc} = 15 \bullet \left(\frac{t_{nom}}{D_0}\right)^2 \quad \text{(BSI 8010)} \tag{4.20}$$

$$\varepsilon_{bc} = \left(\frac{t_{nom}}{D_0} - 0.01\right) \quad \text{(DNV 96) for } 15 < D/t < 45$$

$$\varepsilon_{bc} = 21\left(\frac{t_{nom}}{D_0}\right)^2 \quad \text{(DNV 98)}$$

$$\varepsilon_{bc} = \frac{t_{nom}}{2D_0} \quad \text{(API RP 1111)}$$

where:

t_{nom} =wall thickness
D =Outside diameter

The median Bias and COV of the Bias of the nominal wall thickness is 1.0 and 2%, respectively. The median Bias and COV of the Bias of the pipe outside diameter is 1.0 and 0.16%. Therefore, the median Bias and COV are 1.0 and 4%, respectively.

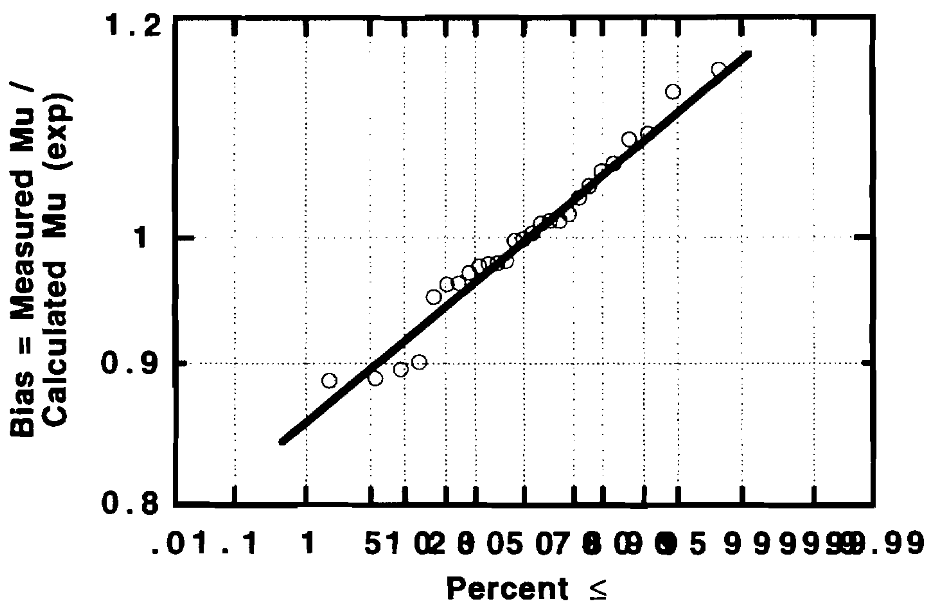

Figure 4-17 The Bias Evaluation for Equation 3.16

Bending Moment Capacity. Figure 3.17 illustrates the uncertainty analysis of Equation 4.16 based on the test data. The median Bias and COV of the Bias are 1.0 and 10.8%, respectively. Figure 4.18 illustrates the uncertainty analysis of Equation 4.18 based on the test data. The median Bias and COV of the Bias are 1.0 and 10.9%, respectively.

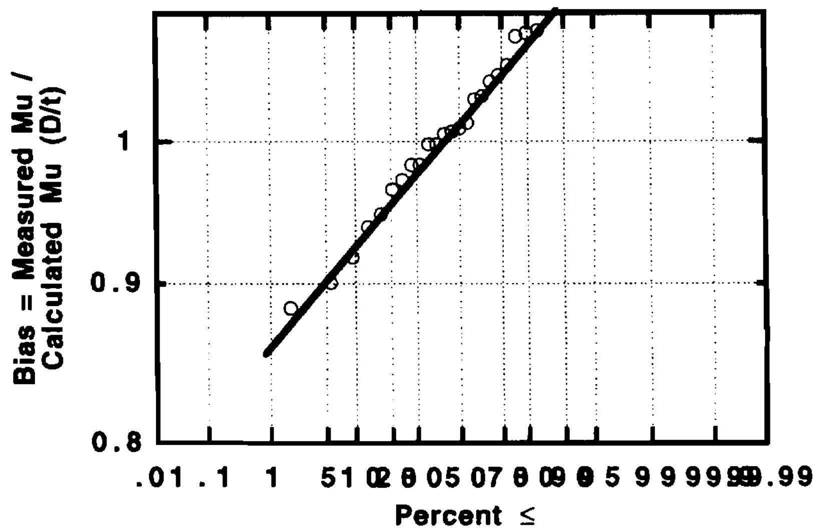

Figure 4-18. Bias Evaluation for Equation 3.18

4.2.5 Development of the RAM PIPE Equation

Bending Strain Capacity. Theoretical, the critical bending strains for deformation controlled situations and load controlled situations correspond to the local buckling point and the maximum moment point, respectively. For typical pipeline materials, local buckling occurs after the maximum moment point for diameter to thickness ratio D/t larger than 35. Since the allowable strain is higher for D/t far less 30, our main interest is to accurately calculate the critical strain for D/t between 30 and 35. Within this region, the critical strains due to local buckling and maximum moment due not deviate significantly.

Given the available data, it is recommended that API RP 1111 critical bending strain equation be used as the RAM PIPE equation. It is expressed as:

$$\varepsilon_{bc} = \frac{t_{nom}}{2D_0} \text{ (API RP 1111)} \tag{4.21}$$

where

t_{nom} =wall thickness
D =Outside diameter

The median Bias and COV of the Bias of the nominal wall thickness are 1.0 and 2%, respectively, for API pipelines. The median Bias and COV of the Bias of the pipe outside diameter are 1.0 and 0.16% for API pipelines, respectively. Therefore, the median Bias and COV of the Bias are 1.0 and 4% for API RP 1111 equation, respectively.

Bending Moment Capacity. Two design formulations were studied to evaluate the ultimate moment capacity of pipelines. The first was:

$$M_u = 1.13 M_p \exp(-X) \tag{4.22}$$

$$M_p = (D_0 - t_{nom})^2 t_{nom} \sigma_y$$

$$X = \frac{\sigma_y D_0}{E t_{nom}}$$

where:

σ_y - Yield stress

D_0 - Mean pipe diameter

t_{nom} - Pipe wall thickness

The second was:

$$M_u = 1.1\pi D_0^2 t_{nom} \sigma_y \left(1 - 0.001\frac{D_0}{t_{nom}}\right) \tag{4.16}$$

where:

σ_y - Yield stress

D_0 - Mean pipe diameter

t_{nom} - Pipe wall thickness

Figure 4.19 summarizes the test data and the calculated ultimate bending moments based on the first formulation. There is substantial scatter in the test data. The analytical model does a good job of predicting the mean values.

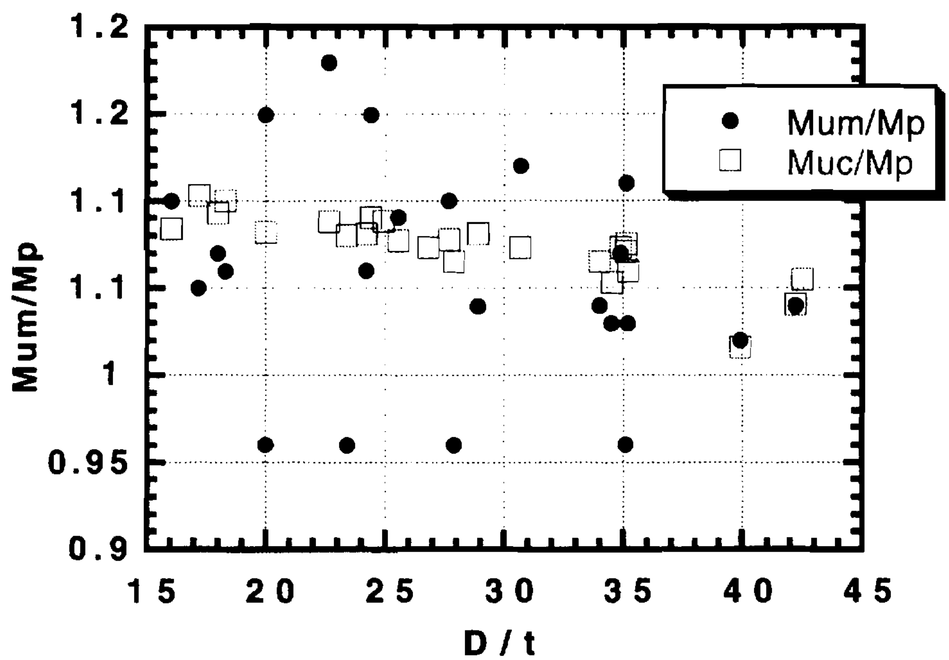

Figure 4-19. Measured and Calculated Ultimate Bending Moment (Mum, Muc) Based on First Formulation

Figures 4.20 and 4.21 summarize the biases developed by both of the analytical models. Both models develop median Biases of B_{50} = 1.0 and COVs of the Biases of V_B = 10.8 %. Figure 3.22 summarizes results of the analyses of the simulated test data. The first model develops an unbiased estimate of the simulated test data. The median Bias is B_{50} = 1.0 and COV of the Bias is V_B = 9.0 %.

Results from the analyses based on the simulated test data are about the same as those based on the physical test data.

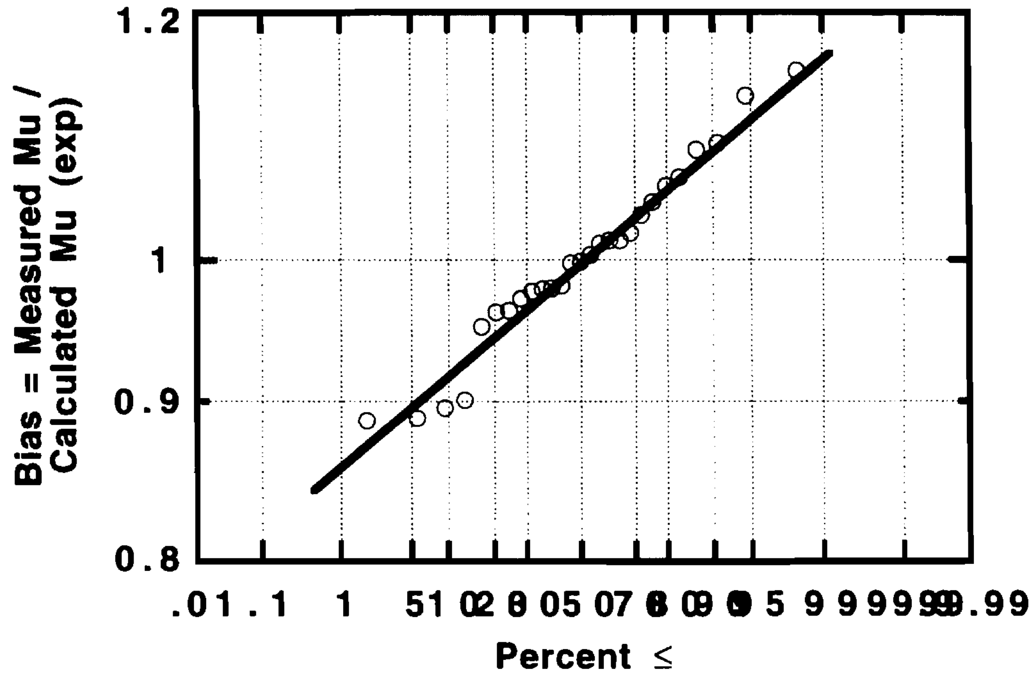

Figure 4-20. Bias in Calculated Ultimate Bending Moments (First Formulation)

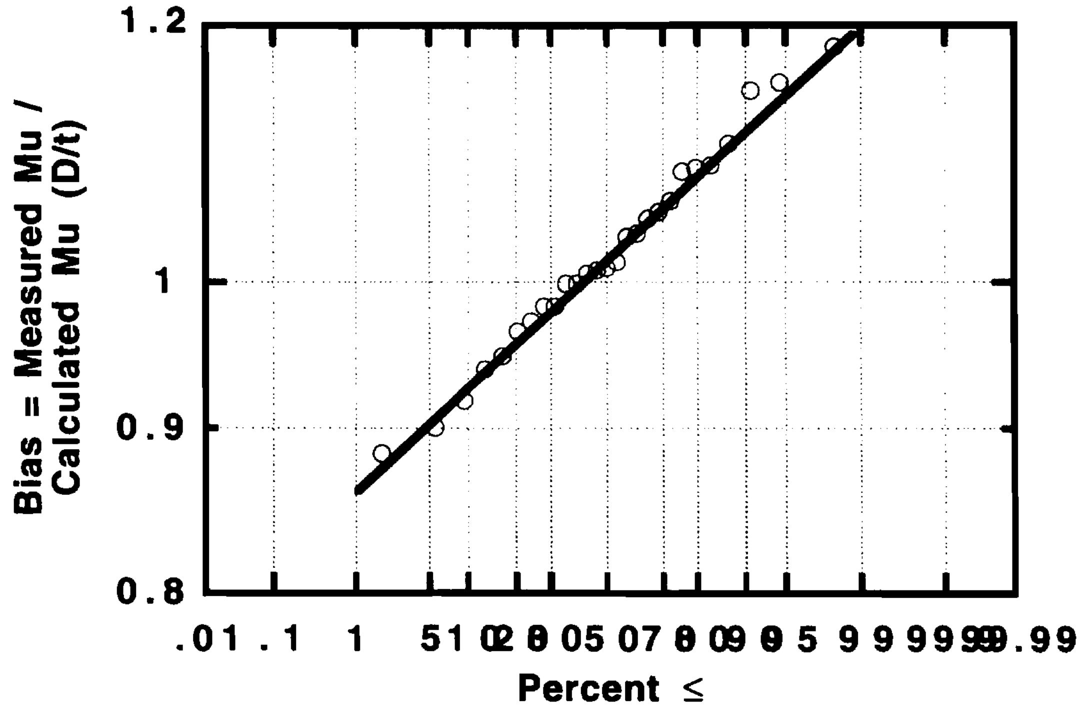

Figure 4-21. Bias in Calculated Ultimate Bending Moments (Second Formulation)

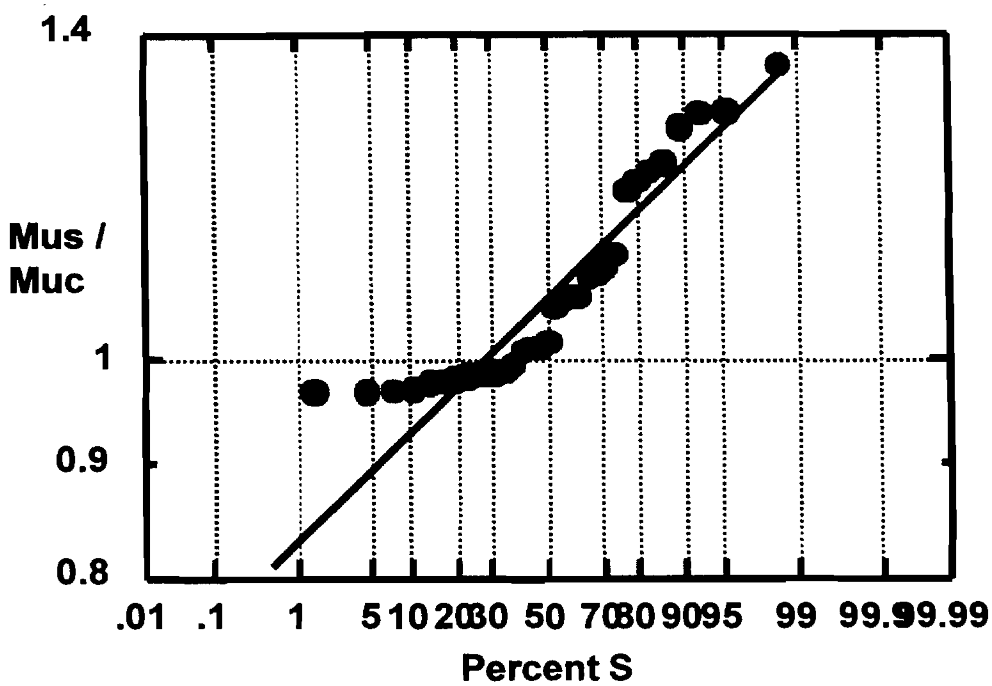

Figure 4-22. Bias in calculated ultimate bending moments (first formulation) based on simulated test data

4.3 Combined Collapse Pressure and Bending - Local Buckling

4.3.1 Review of Design Criteria

Local buckling/collapse may occur due to excessive combined bending and external pressure. At very low values of D/t, a pipe subjected to pure bending will collapse due to plastic yielding and ovalization of cross-section. At very high values of D/t, local buckling occurs first. For intermediate values of D/t, collapse occurs as a combination of ovalization and local buckling. Similarly, for pure external pressure at low D/t it is initiated through elastic buckling. For D/t values between 10 and 40, the failure mode of pipes under combined bending and external pressure is a combination of ovalization, yielding and local buckling.

For local buckling/collapse of pipes, an important characteristic is the moment-curvature relationship. A typical example of a moment-curvature relationship is illustrated in Figure 4.23. Different significant points can be identified in Figure 4.23:

- Elastic limit
- Onset of buckling
- Limit point
- Soften region

The onset of buckling is the point where the collapse mode initiates. Zhou and Murray (1993) developed a procedure to identify the onset of buckling point. The definition of the soften region is very important in displacement controlled conditions. The reason is associated with the prediction of pipe carry capacity with high deformations. Moreover, the prediction of the deformation pattern (the collapse mode) and its amplitude is important as well as the prediction of the moment curvature relation.

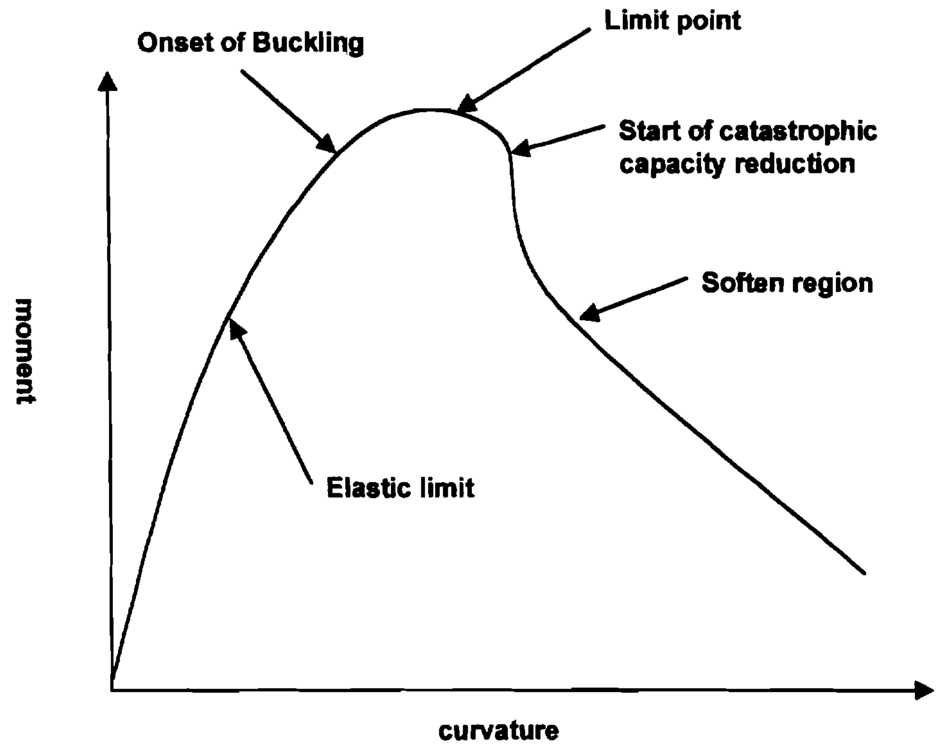

Figure 4-23. Typical Bending Moment Vs Curvature Behavior

Figure 4-23 shows that the use of the elastic limit as design criteria is conservative, because a pipeline section can be strained well beyond the elastic range. Therefore, the design criteria should be based on stress/strain levels reached at a significant point; For example, 1) bending moment or, 2) onset of buckling or, 3) average curvature in buckling segment or 4) at the limit point axial compressive stress or maximum axial compressive strain.

For local buckling, the moment curvature curve for a pipe is independent of whether the applied load is load controlled or displacement controlled. However, it is also important to define whether the pipeline is under load controlled or displacement controlled. The reason is the consequence of exceeding the limit point of the moment curvature curve, which is considered critical for a load, controlled conditions but not for a displacement controlled conditions. For load-controlled condition, catastrophically collapse will occur. For displacement-controlled conditions, the pipe will continue deforming into the plastic region without losing its capacity.

In the most critical conditions, when there is a complete shut down and, hence no internal pressure, there is a need to consider buckling and collapse under combined external pressure and bending. However, the design criteria should specify the displacement-controlled conditions or load-controlled conditions.

Buckling Strain Capacity. The interaction between bending and external pressure has been addressed as:

$$\left(\frac{\varepsilon_b}{\varepsilon_{bc}}\right)^a + \frac{P}{P_c} = 1 \qquad (4.22)$$

where:

ε_b = the applied bending strain

P = The applied external pressure

P_c = The critical pressure for pipe under pure external pressure

ε_{bc} = The critical bending strain under pure bending, and

a=1.0 according to Murphey and Langner and API

a=0.6 according to Bai et al (1994)

a=0.8 according to DNV 96

API RP 1111 recommended that the combined bending strain and external pressure should satisfy:

$$\frac{\varepsilon}{\varepsilon_b} + \frac{(P_o - P_i)}{P_c} = g(\delta) \tag{4.23}$$

where:

ε = bending strain in the pipe

$\varepsilon_b = \dfrac{t}{2D}$ = Buckling strain under pure bending

$g(\delta) = (1 + 20\delta)^{-1}$ = Collapse reduction factor

$\delta = \dfrac{D_{max} - D_{min}}{D_{mx} + D_{min}}$ = Ovality

D_{max} = Maximum diameter at any given cross section, in inches (mm)

D_{min} = Minimum diameter at any given cross section, in inches (mm)

Buckling Capacity. The design criteria can be simplified as:

$$\left(\frac{M}{M_p}\right)^{\alpha} + \left(\frac{p}{p_c}\right)^{\beta} = 1 \tag{4.24}$$

For BSI 8010 pipeline design guidelines, the α, β, and M_p are defined as:

$$M_p = \left(1 - 00024\left(\frac{D}{t}\right)\right)\sigma_y D_0 t^2{}_{nom} \tag{4.25}$$

$$\alpha = 1 + 300\left(\frac{t}{D}\right) \tag{4.26}$$

$$\beta = 1 \tag{4.27}$$

For the DNV 96 pipeline design guidelines, the α, β and M_p are defined as:

$$M_p = \sigma_y D_0 t^2{}_{nom} \tag{4.28}$$

$$\alpha = 2,\ \beta = 2 \tag{4.29}$$

Based on extensive finite element analyses, Bai, et al (1993) indicated that the buckling check equation should be defined as:

$$M_p = \sigma_y D_0 t^2{}_{nom} \tag{4.30}$$

$$\alpha = 1.9,\ \beta = 1.9 \tag{4.31}$$

4.3.2 Review of Test Data

SUPERB PROJECT. The SUPERB database consists of a total of:

- 38 tests with collapse pressure (only test results with steel material quality above X52),
- 47 tests with limiting bending moment and applied external pressure, and
- 63 test results with limiting moment.

RAM PIPE PROJECT. Experimental data for tubes under external pressure and longitudinal bending are mainly from research on submarine pipelines. During the last two decades, experimental research has been conducted by the University of Texas, MaTS, Battelle Laboratories and Shell Development Company. More recently, Stress Engineering Services performed a series of tests on large pipes. The test data are summarized in Bea, et al (1998).

Kyriakides et al (1987) investigated the collapse of relatively thick walled pipes under combined external pressure and longitudinal bending. The experiments involved testing of drawn tubes stainless steel 304, with D/t=17.3, 18.2, 24.5 and 34.7, nominal diameters of 1.25 and 1.375 in and L/D ratios between 18 and 24. Material and geometric properties of each tested specimen were recorded prior to testing. Pressure-curvature interaction envelopes have been developed for two different load paths including external pressure followed by longitudinal bending, and longitudinal bending followed by external pressure. Kyriakides et al (1987) concluded that the most severe condition is represented by external pressure followed by longitudinal bending. It was also concluded from the tests that the presence of initial ovality combined with inelastic effects led to limit load instabilities for the tubes tested. The collapse mechanism under combined external pressure and longitudinal bending was dependent on the load path, as discussed early. For high values of pressure, collapse followed the attainment of the limit moment. For lower values of pressure, bending beyond the limit moment was possible. For tested pipes, the collapse pressure at a given curvature for the pressure-bending loading path was significantly lower than that for the bending-pressure path (Figure 4.24).

Fowler (1990) conducted combined pressure and bending tests on pipes with nominal outside diameter of 6.625 in and L/D=8.0. Initial ovalities were determined as described previously for external pressure loading. The specimens were contained with the loading rms producing bending entirely within the vessel, which has a design pressure capacity of 6000 psi. Two strain gages were installed on either side of the specimens prior to testing. The measured bending strains on the two sides of the pipes were averaged to determine the respective. Six pipes were tested with pressure applied first followed by bending up to collapse and another six pipes with bending first and then pressure up to collapse. For the criteria development, only the former load path was considered. In addition to the measured collapse pressures, strains at failure were also measured. For the sake of presentation of the results in the report, the buckling strains were transformed to the corresponding curvatures by the following expression:

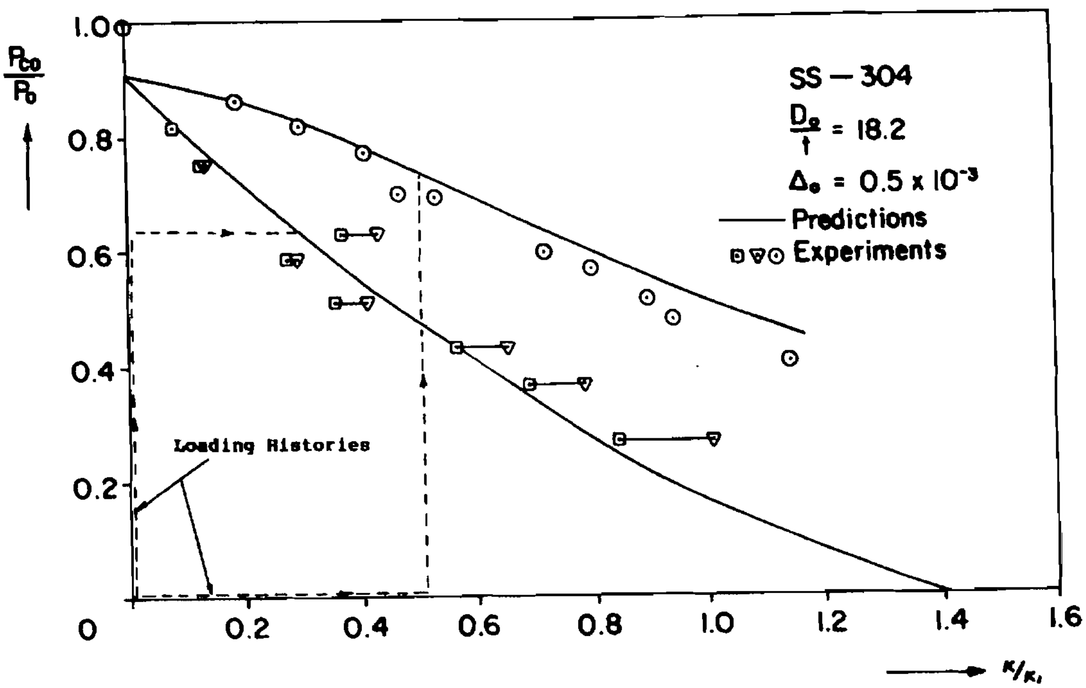

Figure 4-24 The Effects of the Load Path on the Collapse Load

$$k = \frac{\varepsilon}{D/2} \tag{4.32}$$

where:

k - buckling curvature
ε - buckling strain
D - outside diameter

The MaTs research program was conducted for twelve pipes, with D/t between 23 and 32, nominal diameters of 4 and 6.625 in, respective L/D=7.8 and 10.1, and steel grade X-42. Initial ovality and wall thickness variation have been measured for each specimen prior to testing. The pipes with end caps were installed completely inside the pressure vessel.

Different load paths were considered in the MaTS experimental program. In seven tests, external pressure was first applied, followed by longitudinal bending. In five tests, bending was followed by pressure. The load path effects on the collapse results have been confirmed in these tests too. Pressure followed by bending led to the lowest collapse pressure. The tests also indicated that the pipes did not bend uniformly along their length, but that local concentration of curvature occurs. The curvature at collapse was obtained by three different approaches; average from deflection, inclinometers and curvimeters, with different values for each specimen. Curvatures obtained from average deflection were judged more reliable and therefore selected for the uncertainty analysis.

Battelle (1979) conducted an experimental research program aiming at deepwater submarine pipelines. Tests for combined external pressure with longitudinal bending were reported by Johns and McConnell (1983). A total of 45 specimens with nominal D/t ratios of 16, 20, 30 and 40 were machined and smoothed to final diameter. Nominal outside diameters were between 1.316 and 1.428

in. The specimens were made from DOM 1020 steel with yield stresses from 42 to 80 ksi. The range of diameters taken at various angles around the specimens and at various points along the axis of the specimen varied within 0.0005 in which correspond to very small initial ovalities of less than 0.04%.

The Battelle specimens were subjected to bending moments through the use of four point bending fixtures. Pressure was applied to the end capped specimens by placing the bending fixtures in a pressure vessel. The pressure at collapse for varying degrees of bending was then determined. Two different load paths have been used, pressure followed by bending and bending followed by pressure. The tests data was presented in terms of pressure, bending moment and longitudinal strain at collapse for each test specimen.

4.3.3 Uncertainty Measures

Buckling Strain Capacity. The uncertainty analysis of the BSI 8010 equation, DNV 96 equation, and Bai et al equation was performed as part of this study. Figure 4.25 summarizes the uncertainty analysis results. Bias 1 is the uncertainty analysis of the Bai et al (1993) equation. Bias 2 is the uncertainty analysis of the BSI 8010 equation. Bias 3 is the uncertainty analysis of the DNV 96 equation. The median Bias and COV of the Bias of the Bai et al (1993) Equation are 1.1 and 14.3%, respectively. The bias and COV of the BSI 8010 equation are 1.0 and 13.7%. The bias and COV of the DNV are 1.02 and 13.7%.

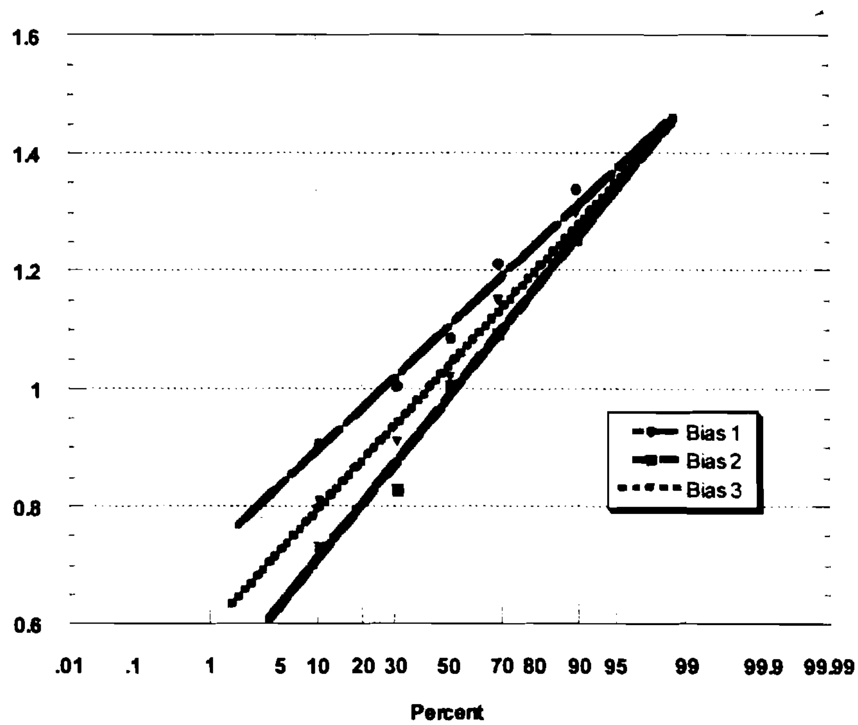

Figure 4-25. RAM PIPE Buckling Strain Capacity Uncertainty Analysis

Buckling Capacity. The SUPERB model is expressed as:

$$X_{\lim} = \left(\frac{M}{M_p}\right)^{\alpha} + \left(\frac{P}{P_c}\right)^{\beta} \tag{4.33}$$

where:

$X_{\lim}$ is the model uncertainty for combined capacity

M is the applied moment,
M_p is the moment capacity,
P is the applied pressure, and
P_c is the external pressure capacity.

In SUPERB test data, sets of (M/M_p) and (P/P_c) at failure were recorded. Hence, for given exponents α and β, the value X_{lim} will indicate failure. It is clear that if exponents are changed so will properties of X_{lim}. The SUPERB project investigated a series of α and β that will provided the most stable and consistent probabilistic description of X_{lim} in terms of mean value (preferably close to 1.0), COV (as close as possible). A number of technical models including α as a function of (D/t) and $\beta = 1.0$ in compliance with different design standards has been analyzed, see Table 4-2.

Table 4-2 Combined Loading Buckling Criteria Models

Model No.	α	β
1	2	2
2-4	3,4,5	1
5-7	$1+n(t/D)$, n=300, 100, 50	1

Based on the probabilistic assessment of the model performance, the two most promising models in SUPERB project were further examined further and shown in Table 4.3. The median Bias and COV of the Bias are (1.0, 13-17%) and (1.0, 14-18%) for Models 1 and 2, respectively.

Table 4.3 The Uncertainty Model of the SUPERB Model

Model	α	β	X_{lim}
1	2	2	LN(1.0, 0.13-0.17)
2	3	1	LN(1.0, 0.14-0.18)

4.3.4 Development of the RAM PIPE Equation

Figure 4.26 summarizes the laboratory test data (37 tests) for pipelines with diameter to thickness ratios in the range of 18 to 35 subjected to external pressure combined with longitudinal bending. There is a linear decrease in the external pressure capacity with the applied bending.

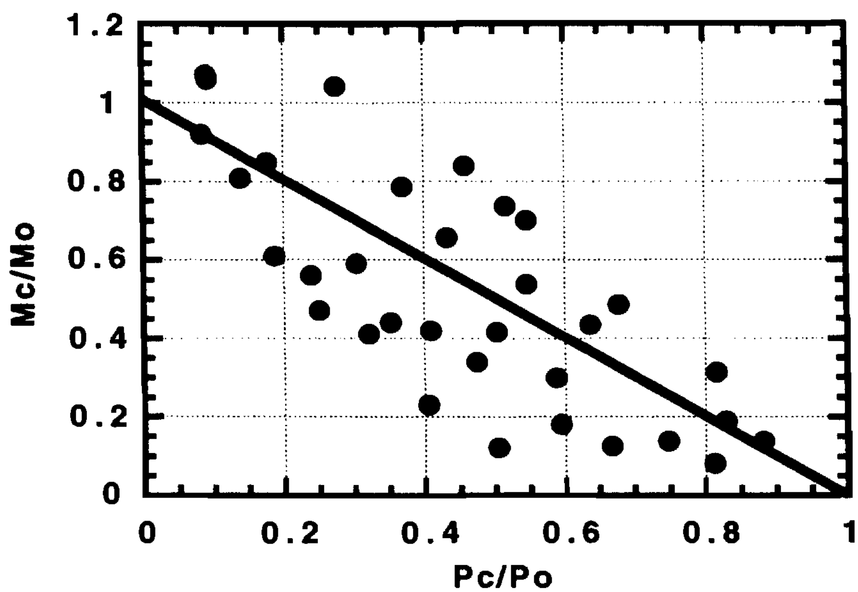

Figure 4-26. Variation of External Collapse Pressure with Applied Bending Moment Based on Laboratory Test Data

Buckling Capacity. Given the discussion of the design criteria, test data, and uncertainty model, it appears that DNV 96 or BSI 8010 equations are the appropriate design equations of the buckling capacity for combined pressure and bending. However, the DNV 96 equation should be modified to include D/t ratio for high D/t ratio thin pipes that are typical in the Bay of Campeche. Therefore, the proposed RAM PIPE design equation is modified as:

$$\left(\frac{M}{M_p}\right)^{\alpha} + \left(\frac{p}{p_{cr}}\right)^{\beta} = 1 \tag{4.34}$$

where $\alpha = 2$, $\beta = 2$, and

$$M_p = \left(1 - 0.001\frac{D}{t}\right)\sigma_y D_0 t^2{}_{nom}$$

The median Bias and COV of the proposed RAM PIPE Equation (4.34) are 1.02 and 14.7%. One should note that proposed RAM PIPE equation is only valid for the load controlled conditions.

Buckling Strain Capacity. The bending – collapse pressure interaction formulation used is:

$$\frac{\varepsilon}{\varepsilon_{bc}} + \frac{p}{p_{cr}} = 1 \tag{4.35}$$

An analysis of the bias associated with this formulation and with two other formulations that utilize an exponent on the bending strain ratio is also shown in figure 3.27. The median bias associated with the linear formulation is $B_{50} = 1.0$ and the Coefficient of Variation of the Bias is $V_B = 19.0$ %.

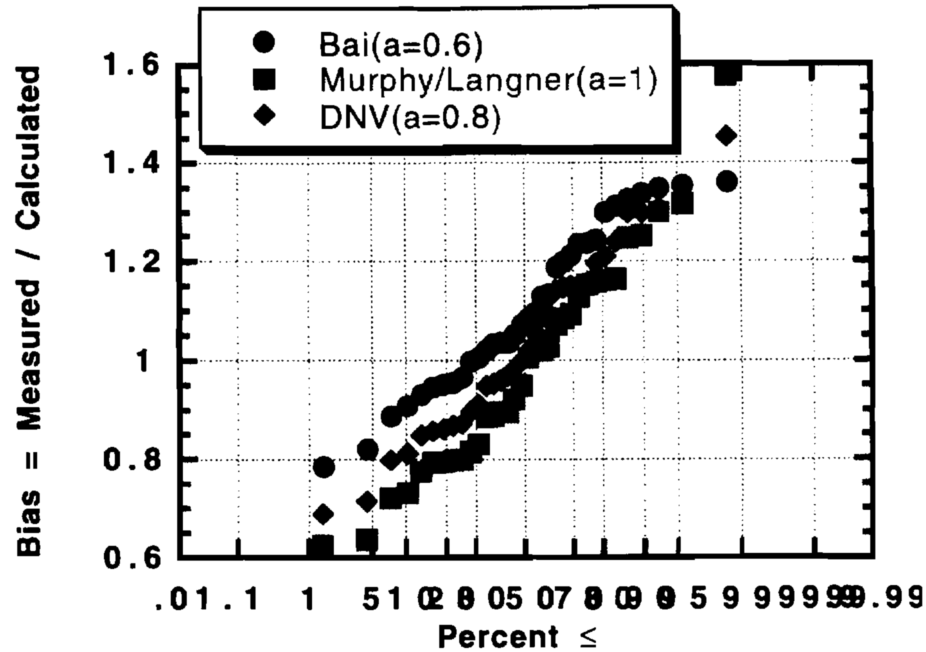

Figure 4-27. Bias in Interaction Formulations with Different Moment Ratio Exponents (a = α)

4.4 Tension and Bending

4.4.1 Review of Design Criteria

Buckling/Collapse Capacity. Pipe under combined tension and bending is not addressed in the API RP 1111. However, DNV 96 specifies that the pipe capacity under combined tension and bending is

$$M_{P,F} = M_P \cos\left(\frac{\pi}{2}\frac{F}{F_P}\right) \tag{4.36}$$

The cosine term provides the reduction in the limit bending moment capacity due to axial force where:

$M_p = \mathrm{SMYS} D_0^2 t_{nom}$ is the plastic moment capacity, and

$F_p = \pi \mathrm{SMYS} D_0 t_{nom}$ is the plastic axial force capacity.

Mork, K. J. et al (1997) addressed that the following restrictions be applied for the DNV 96:

- The equation should not be used for high D/t ratios >50,
- The moment capacity should account for large residual ovalities.

Bai et al (1993) developed the interaction equation between bending and tension based on the parametric Finite Element Analysis (FEA) studies. The interactions are approximated as:

$$\left(\frac{M}{M_u}\right) + \left(\frac{T}{T_u}\right)^{2.4} = 1 \tag{4.37}$$

where:

$$M_u = \pi SMYS\left(1-0.001\frac{D_0}{t}\right)D_0^2 t_{nom}$$

$$T_u = \frac{1}{2}T_0\left[1+\frac{(0.002n)^{-\frac{1}{n}}}{\exp\left(\frac{1}{n}\right)}\right]$$

$$T_0 = \pi SMYSD_0 t_{nom}$$

RAM PIPE developed a tension-bending interaction equation based on the Von Mises criteria (Bea, et al 1998):

$$\left[\left(\frac{M}{M_u}\right)^2+\left(\frac{T}{T_u}\right)^2\right]^{0.5}=1 \tag{4.38}$$

where:

M_u is the moment capacity determined by RAM PIPE design equation, and
T_u is the axial force capacity determined by RAM PIPE design equation.

Buckling/Collapse Strain Capacity. One should note that equations (4.36), (4.37) and (4.38) are all for load controlled design conditions. For the displacement controlled design conditions, the interaction between axial strain and bending strain is complex when axial strain exists. Here the axial strain is defined as axial strain at the neutral axis and the bending strain is the strain linear from the neutral axis based on the beam theory.

Igland (1997) developed the design format between bending and tension under displacement-controlled condition based on a conservation assumption, assuming a linear interaction between axial and bending strain. The equation is expressed as:

$$\frac{\varepsilon}{\varepsilon_c^{MT}} \le 1 \tag{4.39}$$

Where a linear interaction between axial strain and bending strain is assumed. ε_c^{MT} is bending strain when tensile load is applied together, given as:

$$\frac{\varepsilon_c^{MT}}{\varepsilon_{co}} = 1+1.43\left(\frac{T}{T_u}\right)^{2.4} \tag{4.40}$$

where:

$$\varepsilon_{co} = 0.005+13\left(\frac{t}{D}\right)^2$$

4.4.2 Review of Test Data

RAM PIPE investigated the existing experimental data. However, there appears to exist only a limit amount of experimental work on axial tension combined with longitudinal bending for tubulars can be found in literature. Dyau et al (1991) reported tests using tubes with a nominal D/t =24 and 35. The loading condition was the bending of the tubes over a stiff, curved surface, in the presence of axial tension. This simulates the condition of a pipe that is bent over a reel. Dyau et al (1991) also conducted the analytical investigation for a condition that simulates the combined loading of a suspended length of pipe loaded primarily by gravity load. It was concluded that this loading condition has small effect on the ovalization of the cross section of the tube. It was also concluded that ovalization induced by combined bending and tension depended on the load path and tub geometry and material properties.

Wilhoit Jr. et al (1973) performed tests of welded steel MT-1010/1020 tubes in combined bending and tension. The specimens' D/t ratios are between 36 and 83. Their L/D ratios and nominal outside diameters are 8.25 and 20 in. For each D/t, one specimen was tested under pure bending. The other two initially loaded to prescribed axial load (25% or 50% of the axial load capacity) were tested under pressure. Based on the results, it was concluded that the curvature at which buckling occurs in the plastic range under axial tension decreases with D/t up to a point, but increase with the axial tension.

Although Dyau et al (1991) and Wilhoit Jr. et al (1973) conducted the experimental tests of tubes under combined bending and tension. However, some data such as pipe material properties are missing in the literature describing the experimental tests. Therefore, these data are not included the development of the uncertainty model.

4.4.3 Uncertainty Measures

The SUPERB Project concluded that the median Bias and COV of the Bias of the DNV 96 equation were 1.0 and 7% -9%, respectively.

The RAM PIPE Project used the numerical data to develop the uncertainty model. The median Bias and COV of the Bias of the RAM PIPE equation (3.38) are 1.00 and 6%, respectively. Figure 4.28 illustrates the uncertainty analysis results.

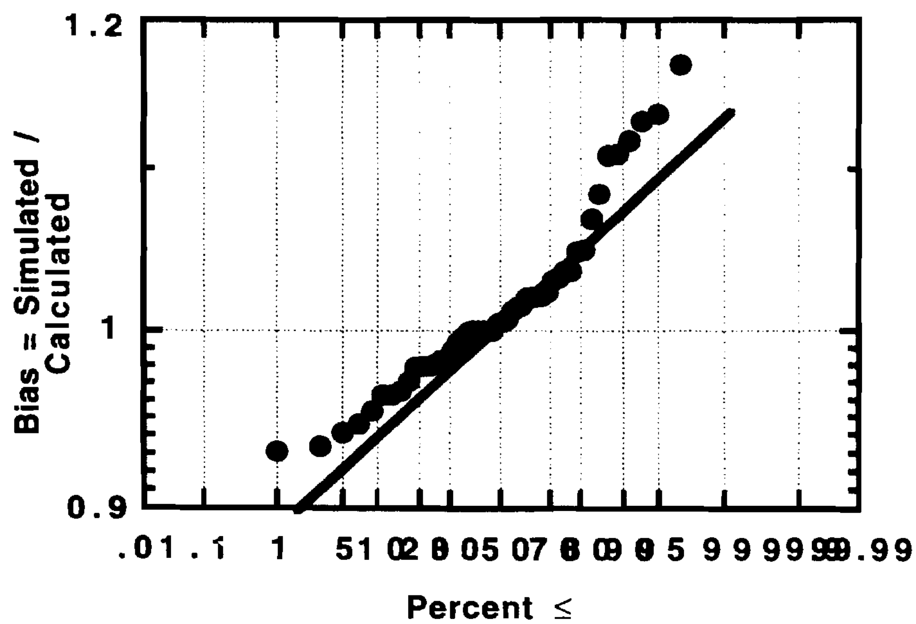

Figure 4-28. Characterization of Bias associated with Von Mises Interaction Formulation

4.4.4 Development of the RAM PIPE Equations

Buckling/Collapse Capacity. Figure 4.29 summarizes the simulation data that is available on combined tensile and moment loadings. The data are summarized as the ratio of the moment capacity determined by the simulation model divided by the plastic moment capacity (Ms/Mo) versus the ratio of the tensile loading imposed on the simulation model divided by the yield tensile loading (Ts/To). The data are for a range of diameter to thickness ratio of D/t = 15 to 25, X52 material characteristics, and ovalities of 0.15 %. The data indicate a linear decrease in moment capacity with the imposed tensile loading.

A tension – moment interaction based on a Von Mises yield formulation was chosen based on its ability to produce an unbiased estimate of the interactions with the lowest coefficient of variation of the interactions (Bea, et al, 1998):

$$\left[\left(\frac{M}{M_u}\right)^2+\left(\frac{T}{T_u}\right)^2\right]^{0.5}=1 \tag{4.39}$$

where:

M_u is the moment capacity determined by RAM PIPE design equation, and
T_u is the axial force capacity determined by RAM PIPE design equation.

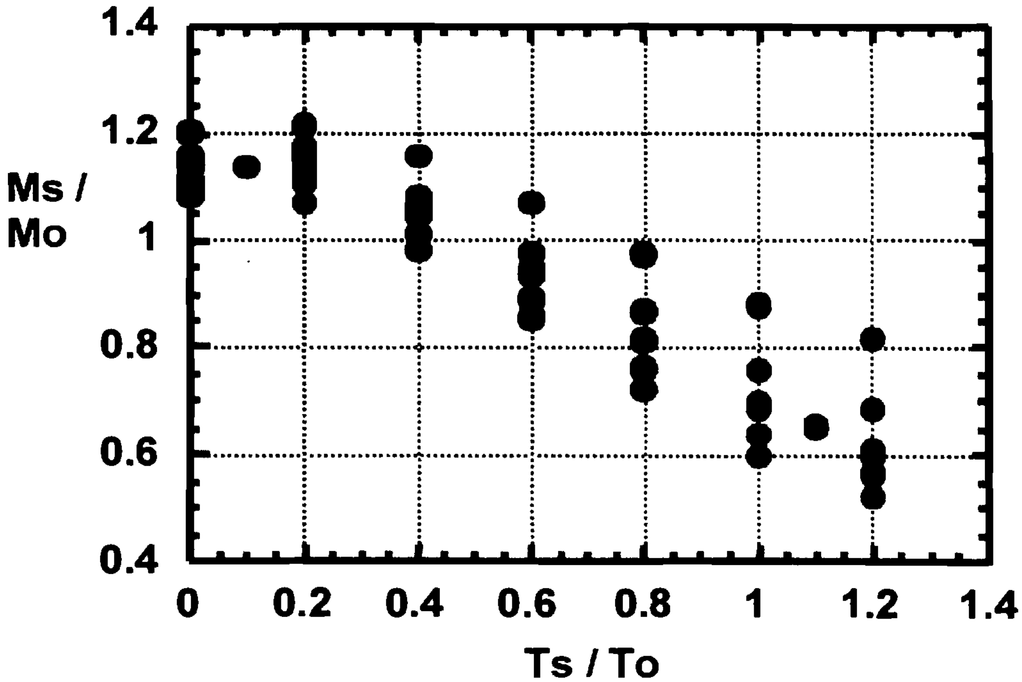

Figure 4-29. Moment Capacity Influenced by Tensile Loadings

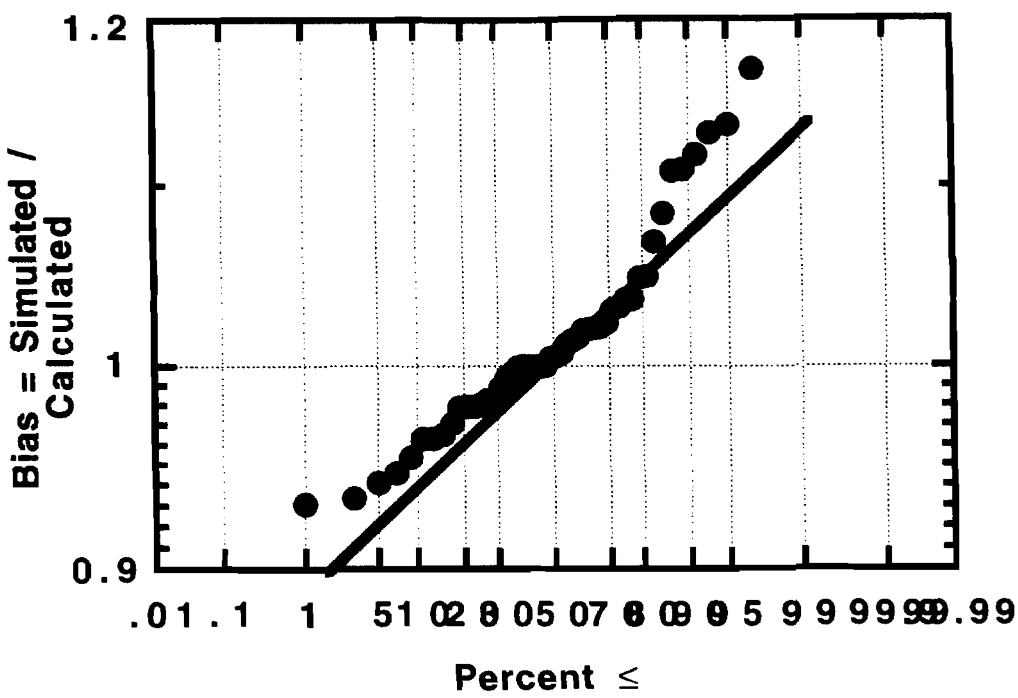

Figure 4-30. Characterization of Bias Associated with Von Mises Interaction Formulation

The simulation data was used to evaluate the bias and uncertainty associated with this interaction formulation. The results are summarized in Figure 4.10. A median Bias of B_{50} = 1.0 and Coefficient of Variation of the Bias of V_B = 6.0 % were determined.

Given the review of the design criteria, discussion of the test data, and development of the uncertainty model, it is suggested that RAM PIPE design equation based on Von Mises criteria be the design equation for pipes under combined tension and bending. The median Bias and COV of the Bias of the RAM PIPE equation are 1.0 and 6%, respectively.

Buckling/Collapse Strain Capacity. The interaction between axial strain and bending strain is complex when axial strain exists. Here the axial strain is defined as axial strain at the neutral axis and the bending strain is the strain linear from the neutral axis based on the beam theory. No specific strain criteria were developed for API RP 1111, DNV 96, and BSI 8010. Reliable physical test data is limited. Given this background, the RAM PIPE has not developed any specific equations for buckling/collapse strain capacity under combined tension and bending.

4.5 External Pressure and Axial Tension

4.5.1 Review of the Design Criteria

Collapse of tubes under combined tension and pressure loads is one of the most critical conditions for the design of deepwater casing. The tension load is due to the weight of the casing strings. API Bul. 3C5 formula was the most widely applied collapse formula. They were developed by curve fitting of the experimental data, and thus are actually four formulas (Yield Strength Collapse, Plastic Collapse, Transition Collapse, and Elastic Collapse) with constants and interface points which depend on D/t and yield strength. Their strength is their wide use and large data base they are based on, and their weakness is the fact that they do not offer any means to account for manufacturing variables such as ovality, residual stresses, etc., and are relatively hard to use.

In this section, the collapse prediction of pipe under combined pressure and tension is treated as a two-part process. The first part is to predict is to predict collapse pressures as a function of material strength, manufacturing variables, and dimensions in the absence of tension load. The second part is to extend the prediction to accommodate external tension loads.

The first part, collapse due to external pressure only, was discussed in early section. API RP 1111/Shell Formula, Timoshenko Formula, BSI8010/DNV96 Formula, and Modified Timoshenko Formula were discussed in detail. It is recommended that modified Timoshenko formula and BSI8010/DNV 96 formula be the proposed RAM PIPE design equations to determine the external pressure.

Most researchers have used the Von Mises combined stress theory to adjust the predicted collapse pressure for external tension. As noted in Figure 3.31, this approach seems to work well for the data developed by Fowler (1990). In the Von Mises theory of combined stresses, failure occurs when the Von Mises equivalent stress equals to the yield strength. The equivalent stress σ_e is obtained from the hoop stress σ_h and axial stress σ_a as follows:

$$\sigma_e^2 = \sigma_a^2 + \sigma_h^2 + \sigma_h\sigma_a \tag{4.40}$$

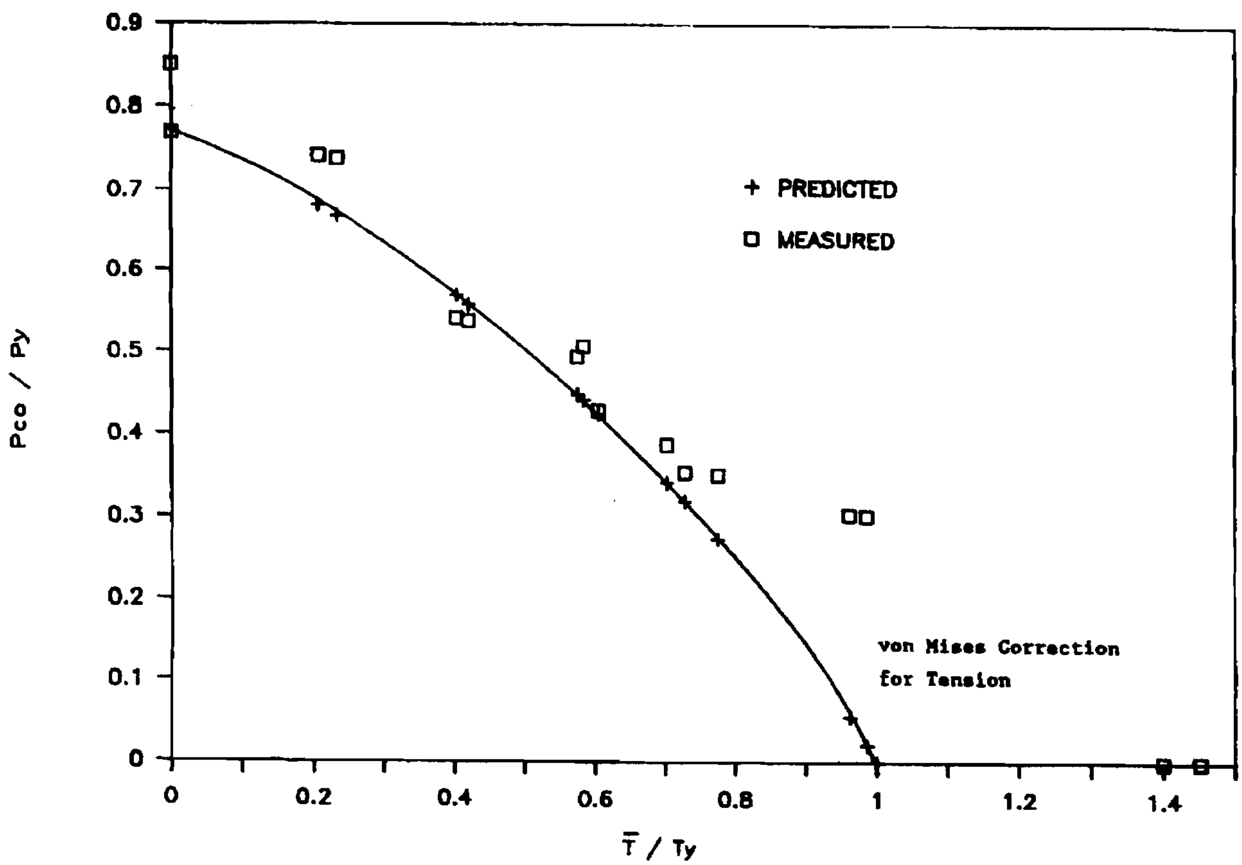

Figure 4-31. Fowler's Tension and Pressure Test Data

To accommodate the Von Mises theory into the collapse formulas that do not include tension, the equation (4.40) is solved for the hoop stress and the hoop yield used for the collapse formulas is adjusted accordingly as

$$\frac{Y_h'}{Y_h} = -0.5\frac{\sigma_a}{\sigma_y} + \left(1 - \frac{3}{4}\left(\frac{\sigma_a}{\sigma_y}\right)^2\right)^{\frac{1}{2}} \tag{4.41}$$

where Y_h' is the adjusted yield stress used for collapse formula.

For cases where the calculated collapse formula does not depend on the yield stress, as in the elastic collapse formula, the collapse pressure is simply adjusted by the same equation (4.41).

Given the Von Mises combined stress theory to reduce the hoop yield stress, the effect of axial tension can be taken into account. However, we need know if it is possible to account for the effect of tension load by using Hill yield conditions for materials with anisotropic yield properties.

Bai et al (1997) used the Hill yield conditions for tubes with anisotropic yield properties:

$$\sigma_0^2 = \sigma_{0x}^2 - \left(1 + \frac{1}{S_\theta^2} - \frac{1}{S_r^2}\right)\sigma_{0x}\sigma_{0\theta} + \frac{\sigma_{0\theta}^2}{S_\theta^2} \tag{4.42}$$

where $S_\theta = \sigma_{0\theta} / \sigma_{0x}$ and $S_r = \sigma_{0r} / \sigma_{0x}$ are the parameters describing the anisotrophy. For a given axial stress σ_{0x} (tension load), the circumferential yield stress can be obtained by solving Equation (4.42) with respect to $\sigma_{0\theta}$. Substituting the obtained circumferential yield stress into for instance the BSI8010/DNV 96 collapse formula, tension-pressure collapse envelopes can be evaluated.

RAM PIPE analyzed the existing test data that is discussed later. A simplified pressure-tension interaction was developed as (Bea, et al 1998):

$$\left(\frac{P}{P_{co}}\right) + \left(\frac{T}{T_u}\right) = 1 \tag{4.43}$$

where P_{co} is the collapse external pressure determined by the proposed RAM PIPE criteria, and T_u is the axial load capacity determined by the proposed RAM PIPE criteria.

4.5.2 Review of Test Data

Most of the experimental data for tubes under external pressure combined with axial tension is originated from research on well casings. The experimental programs (Edwards, et al 1939, Kyogoku, et al 1981, Tamano, et al 1982) should be especially addressed. In addition, Kyriakides et al (1987) and Fowler, et al (1990) conducted the experimental programs aiming at submarine pipes under external pressure and axial tension.

Edwards, et al (1939) discussed more than 200 tests subjected to external pressure and axial tension. The specimens had nominal outside diameter of 2 in, D/t between 11 and 22, and L/D = 15.5. The tube selected for the tests was seamless steel, with yield stress from 30 to 80 ksi. The specimens were grouped according to the steel grade and D/t ratio. For one set of experiments, tested in 1938, the longitudinal yield stress was determined for each group by testing representative strips cut from tubes, and assuming as equal to the stress required to produce a total elongation of 0.5%. For the

"1939 set" stress-strain curve were prepared and slit-ring tests performed to evaluate residual stress. Simple open-end collapse strengths were determined for each group with no longitudinal load. For the combined loading tests, the desired tension load was applied first and held constant, while the pressure in the vessel was gradually raised until the specimen either collapsed or stretched. When the specimen had stretched 0.5% of its effective length, the conditions were recorded as "stretch failure". The test results showed that all cases of combined loads resulted in a low collapse strength than that obtained from the isolated external pressure mode. This reduction of collapse strength was more pronounced for thick-wall low strength specimens than that of thin wall high strength specimens.

Kyogoku, et al (1981) conducted experimental tests of full size commercial casings of 40 feet length produced by seamless mill. Hardness tests within wall thickness and slitting tests were carried out to check the presence of residual stresses. The experiments were conducted mainly using no cold rotary straightened casings, because this production technique is commonly applied to obtain high collapse strength casings. Specimens with D/t of 16.2, 20.4, 24.4, and L/D greater than 8, nominal outside diameters between 9.625 and 13.375 in and yield stresses from 89 to 125 ksi.

Prior to testing, Kyogoku, et al measured the outside diameters by using an ovality gage and well thickness by ultrasonic thickness meter. Collapse tests with axial tension were performed for each group. In the test under combined loading, an axial tension load was first applied and held constant while the external pressure was raised up to the collapse. The results confirmed that axial tension stress has no effect on collapse strength for elastic case. If the axial stress increases to the extent of the biaxial yield ranging defined by the Henckey-Von Mises maximum strain energy of distortion, the collapse strength is reduced depending on the axial tension stress. In the plastic collapse range, experimental values were in good agreement with the formula proposed by API Bul. 5C3 (1989).

Tamano, et al (1982) conducted collapse tests of commercial casings under external pressure and axial tension. Specimens had D/t between 12 and 16, L/D = 6.75, nominal outside diameter of 7 in and yield stresses from 63.7 to 133.4 ksi. Outside diameter and wall thickness were measured at every cross section spaced by one diameter length and at position of every 45 degree in each cross section by calliper and ultrasonic thickness-gage respectively. Residual stresses at the inside surface were determined by the slit-ring tests. Two loading paths were used to perform the experiments, axial load in proportion to external pressure and axial load followed by external pressure. API Bul. 5C3 formula was found to be too conservative for estimating the collapse resistance of commercial casings with geometrical and material characteristics of the test specimens. It was confirmed that in the range of elastic collapse the axial tension stress has small effect on the collapse pressure.
Kyriakides, et al (1987) conducted small diameter tubes tests. The tubes were of 304 stainless steel material, with D/t between 10 and 40, and L/D of 20. The thickness and diameter were measured at 5 to 10 sections along the specimen length prior to testing. For each tube from which specimens had been generated, stress-strain curves were obtained from axial tensile coupons. It was observed that for cold drawn tubes the anisotropy could be significant.

Two different loading paths were used in the Kyriakides, et al (1987) test, with the specimen either loaded by a given axial tension load followed by external pressure up to the collapse or by a certain external pressure and then axial tension. Collapse was characterized by a sudden drop of the pressure inside the test vessel. For the load path axial tension followed by external pressure, 45 specimens were tested. It was observed that for most of the specimens the collapse pattern appeared close to the maximum initial ovality section. Specimens of lower D/t values, tested under very high axial tensile loads, did not fail due to the experimental apparatus capability. The loads in these cases correspond to the highest at which the axial elongation reached the apparatus maximum possible value. Tests of a set of 7 tubes under load path external pressure followed by axial tension were carried out to investigate the effects of the load path on the interaction curve. It was concluded that this effect was not significant.

Fowler (1990) conducted experimental tests of 18 large-scale seamless pipes. With D/t ratios were between 22 and 26, L/D=17.43, and nominal outside diameter of 15 in, under combined external pressure and axial tension. Initial ovalities and thickness variation were measured prior to testing. Loading conditions represented by external pressure acting alone (3 tests), axial tension acting alone (3 tests), external pressure followed by axial tension (6 tests) and axial tension followed by external pressure (6 tests) were simulated. The specimens were assembled in the tests vessel and this vessel placed in an external load frame. End caps welded to the specimens and extended beyond the vessel were gripped to apply tension. Collapse results were presented in terms of maximum applied pressure and axial tension load for the combined loading conditions.

Due to the lack of information of casing related experimental program, only the data from pipeline experimental program have been used in the uncertainty model development.

4.5.3 Review of the Uncertainty Measures

Figure 4.32 summarizes the uncertainty analysis of the RAM PIPE equation. The median Bias and COV of the Bias of the RAM PIPE equation are 1.0 and 8.4%, respectively.

4.5.4 Development of the RAM PIPE Equation

Figure 4.33 summarizes the laboratory test data (57 tests) on combined tension and external collapse pressure capacities of pipelines. These test specimens were all seamless pipe that diameter to thickness ratios of D/t = 13 to 38. There is a linear decrease in the external collapse pressure with an increase in the tension exerted on the pipeline. The relationship between collapse pressure and tension loading can be expressed approximately as:

$$\frac{P}{P_c} = 1 - \nu \frac{T}{T_u} \tag{4.44}$$

Figure 4.34 summarizes the simulation data (34 simulations) on combined tension and external collapse pressure capacities of pipelines. These simulation specimens were all based on X52 pipe steel characteristics with ovalities of 0.15%. The relationship between collapse pressure and tension loading is identical with that indicated by the laboratory test data.

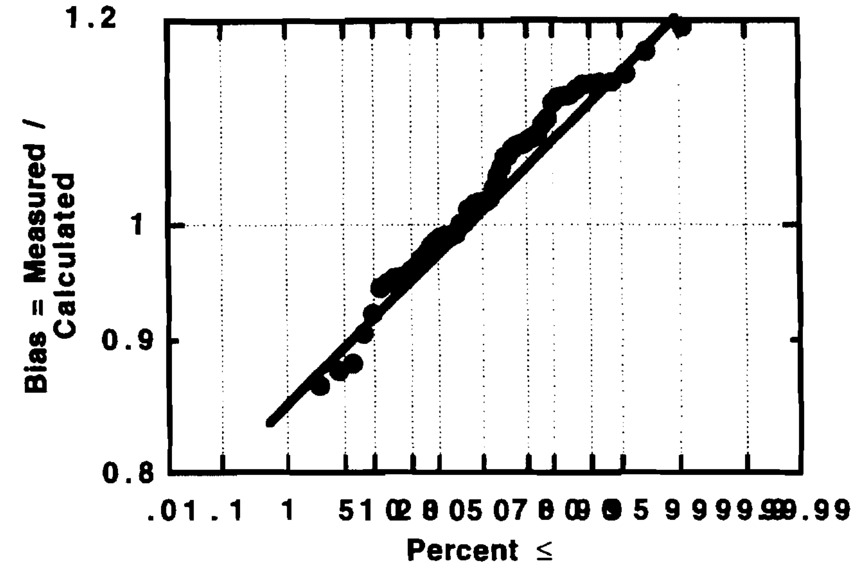

Figure 4-32. Uncertainty Evaluation for the Combined Pressure-Tension Loading

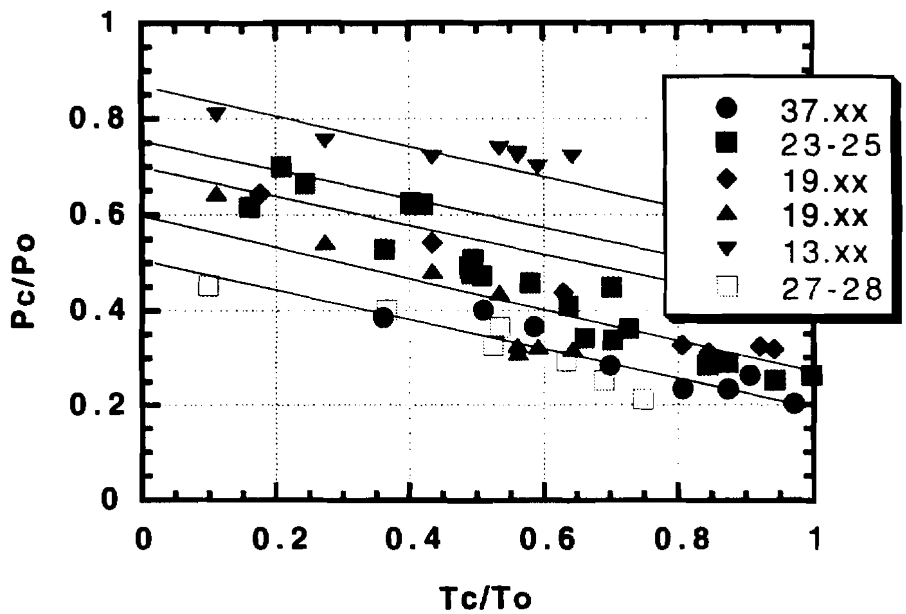

Figure 4-33. Variation of Collapse Pressure with Tension from Laboratory Test Data

The tension – collapse pressure interaction was based on:

$$\frac{P}{P_c} + \frac{T}{T_u} = 1 \tag{4.45}$$

The results of analysis of the laboratory test data to determine the bias and uncertainty associated with this interaction formulation are summarized in Figure 4.35. The median Bias is $B_{50} = 1.0$. The Coefficient of Variation of the Bias is $V_B = 8.4$ %.

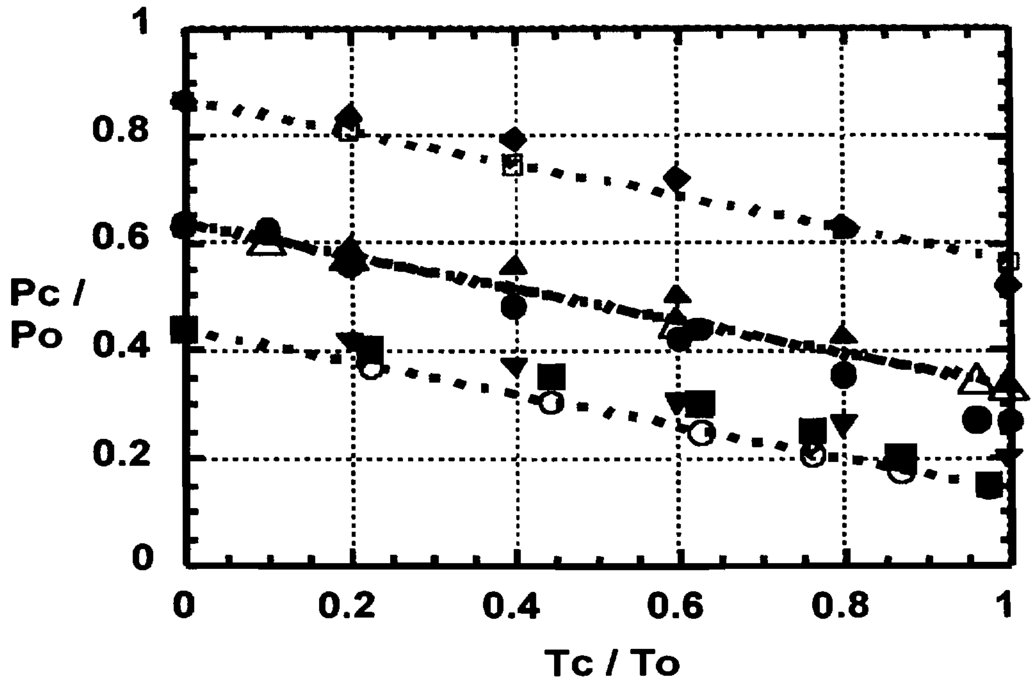

Figure 4-34. Variation of Collapse Pressure with Tension from Simulation Data

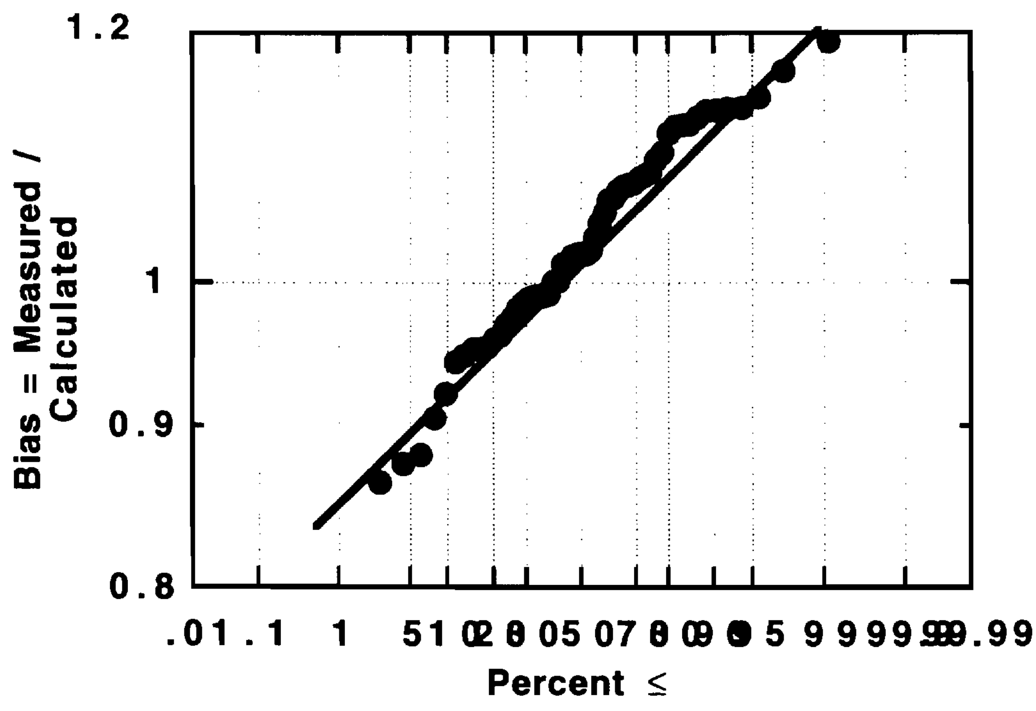

Figure 4-35. Bias Based on Laboratory Test Data and Linear Interaction Formulation

4.6 Tension, Bending, and Pressure

4.6.1 Review of Design Criteria

As discussed earlier, the physical mechanism and failure modes of the pipe under load controlled conditions is different from that under displacement controlled conditions. Therefore, the design equations for the pipe under combined tension, bending and pressure should consider:

- Load controlled conditions, and
- Displacement controlled conditions

For design engineers, SUPERB/DNV 96 made following recommendations:

- A load displacement controlled design check is fundamental and constitutes a sufficient design check in all conditions.
- A displacement controlled design check is recommended only in a true displacement controlled conditions.

Buckling/Collapse Capacity. SUPERB/DNV 96's design criteria for load controlled conditions is expressed as:

$$\left(\frac{M}{M_{P,T}}\right)^2 + \left(\frac{P}{P_{co}}\right)^2 \le 1 \tag{4.46}$$

where P_{co} is the collapse pressure determined by BSI8010 equation (Haagsma and Schaap equation) and:

$$M_{P,T} = M_P \cos\left(\frac{\pi}{2}\frac{N}{N_P}\right) \text{ and } N_P = \pi \bullet \mathrm{SMYS} \bullet D^2 t \tag{4.47}$$

BSI 8010 recommended that the design equation be:

$$\left(\frac{M}{M_{co}} + \frac{T}{T_{co}}\right)^{1+300\frac{t}{D}} + \frac{P}{P_{co}} = 1 \tag{4.48}$$

where $M_{co} = M_0\left(1 - 0.0024\frac{D}{t}\right)$, P_{co} is determined by the BSI 8010 external pressure collapse equation (Haagsma and Schaap equation) and T_{co} is defined as yield tension.

Bai et al (1993, 1994) developed the design equation for combined tension, bending and pressure as:

$$\left(\frac{M}{M_{co}^{**}}\right) + \left(\frac{T}{T_{co}^{**}}\right)^a = 1 \tag{4.49}$$

where $a = 2.4 - 2.5\left(\frac{P_{co}}{P_{co}^{*}}\right) + 1.5\left(\frac{P_{co}}{P_{co}^{*}}\right)^2$

and M_{co}^{**} and T_{co}^{**} denote collapse moment and tension under coupled load after external pressure P_{co} is first applied, respectively. T_{co}^{**} denotes collapse tension load when pressure load P_{co} has been applied together, due to a combination of Hill yield function and Timoshenko equation. M_{co}^{**} is obtained by:

$$\left(\frac{M}{M_{co}}\right)^{1.9} + \left(\frac{P}{P_{co}}\right)^{1.9} = 1 \tag{4.50}$$

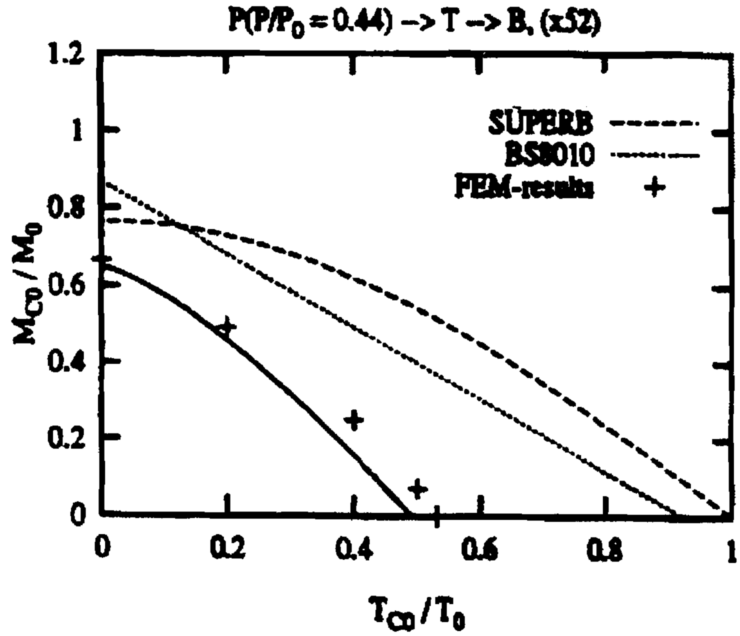

Figure 4-36 Comparison between the SUPERB/DNV96 Code and Experimental / Numerical Data

Igland (1997) compares the BSI 8010 and SUPERB/DNV96 equation. Figures 4.36 illustrate his comparisons. He concluded that SUPERB/DNV 96 was appropriate only in the moment and pressure dominant situations where the tension is moderate while the BSI 8010 was conservative with respect to bending capacity except for extreme pressure dominate condition.

Li, et al (1993) developed the buckling formulation for load-controlled conditions:

$$\left(\frac{M}{M_{CR}}\right)^{3} + \left(\frac{P}{P_{co}}\right) = 1 \tag{4.51}$$

where:

M = The bending moment of the pipe
M_{CR} = The critical bending moment in the pipe under tension and bending only
P = External pressure
P_{CO} = pipe collapse pressure under the external pressure only

The M_{CR} is determined as:

$$M_{CR} = \left[\cos\theta^{*} + (\pi/4)\frac{\Delta\sigma}{1+\sin\theta^{*}}\right] \bullet M_{P} \tag{4.52}$$

where:

$$\Delta\sigma = \frac{\sigma_{max}}{\sigma_y} - 1$$

$$\sigma_{max} = \sigma \text{ at } \varepsilon = 0.6\frac{t}{D}$$

or $\sigma_{max} = \sigma_u$ with the condition, whichever is less applies,

σ_u = ultimate strength of pipe material.

For standard line pipe, this is defined in API RP 5L

D = Pipe diameter

t = Pipe wall thickness

σ_y = yield stress

θ^* = angular parameter shown in Figure 4.37.

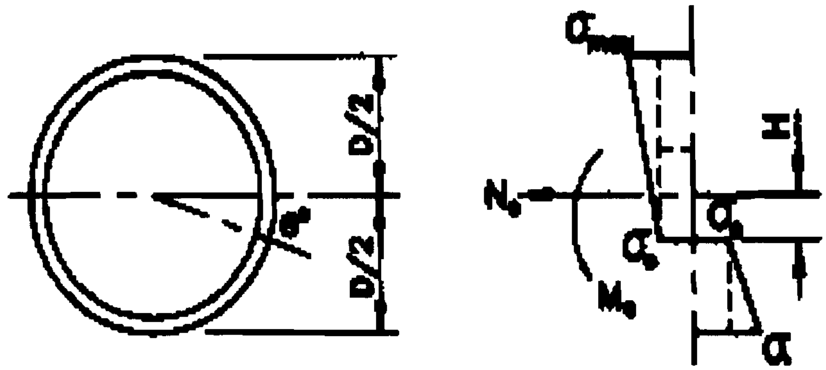

Figure 4-37 The Definition of Angular Parameter

$$\frac{N_c}{N_p} = \frac{2\theta^*}{\pi} + \left[\frac{\sin\theta^*}{1+\sin\theta^*}\right] \bullet \Delta\sigma$$

Where, N_c = axial tension

N_p = full plastic tension

$= \sigma_y \bullet \pi \bullet D \bullet t$

N_c is positive when it is in tension.

P_c is the collapse pressure of pipe with initial geometric ovalization and is determined by the Timoshenko equation as:

$$P_c^2 - \left\{2\sigma_0^H\left(\frac{t}{D}\right) + \left[1 + 1.5f_0\left(\frac{D}{t}\right)\right]P_b\right\}P_c + 2\sigma_0^H\left(\frac{t}{D}\right) \bullet P_b = 0 \qquad (4.53)$$

where:

$$P_b = \frac{2E}{(1-\upsilon^2)}\left(\frac{t}{D}\right)^3$$

$$f_0 = \frac{D_{max} - D_{min}}{D_{nom}}$$

σ_0^H = is determined by the Von Mises Equation:

$$(\sigma_0^H)^2 - \sigma_0^H\sigma_L + \sigma_L^2 = \sigma_y^2$$

$$\sigma_L = \frac{N_c}{\pi D t}$$

Li et al 's equation is calibrated with the experimental data for combined bending and pressure. Figure 3.38 illustrates the calibration.

The RAM PIPE project developed the design equation based on the detailed analysis of the test data and the Von Mises failure criterion. The equation is expressed as:

$$\left[\left(\frac{M}{M_{co}}\right)^2 + \left(\frac{P}{P_{co}}\right)^2 + \left(\frac{T}{T_{co}}\right)^2\right]^{0.5} = 1.0 \tag{4.54}$$

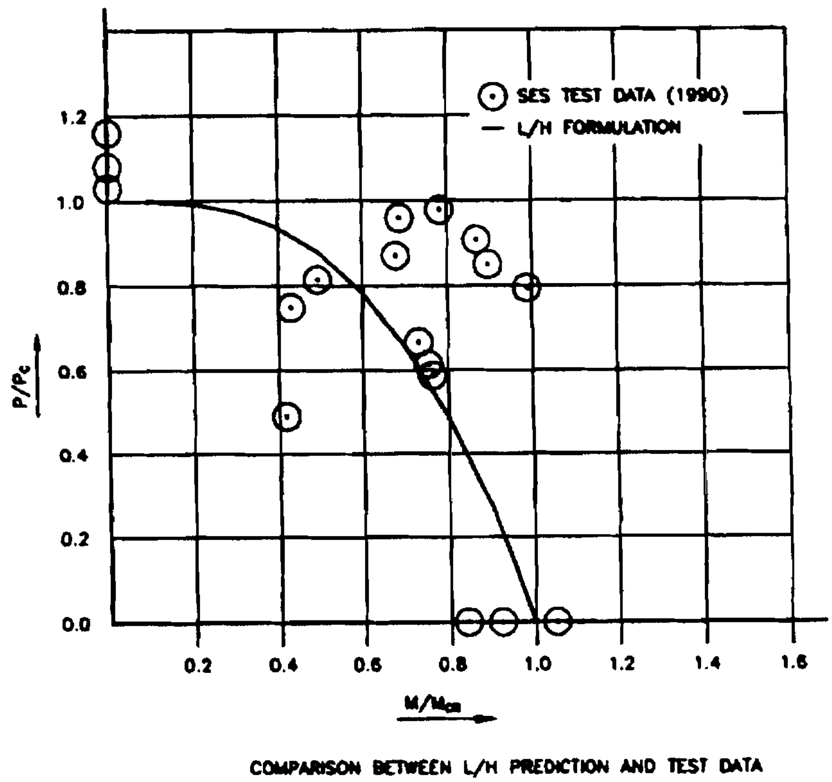

Figure 4-38. Comparison of Li's Equation and Experimental Test Data

Buckling/Collapse Strain Capacity. The strain based pressure-tension-bending interaction is not available in the design codes. However, several interactions between pressure and bending are available.

Igland R. T., (1997) proposed an interaction equation for pressure-tension-bending strain as:

$$\frac{P}{P_{CO}} + \left(\frac{\varepsilon}{\varepsilon_{co}^{MT}}\right)^{0.6-0.25\frac{T}{T_{co}}} = 1 \tag{4.55}$$

where a linear interaction between axial strain and bending strain is assumed and ε_{co}^{MT} is bending strain when tensile load is applied together, given as:

$$\frac{\varepsilon_{co}^{MT}}{\varepsilon_{co}} = 1 + 1.43\left(\frac{T}{T_{co}}\right)^{2.4} \tag{4.56}$$

where ε_{co} is the bending strain under pure bending.

4.6.2 Review of Test Data

No specific test data were identified during the RAM PIPE project. However, an extensive numerical data was used in the RAM PIPE project. The numerical data was developed by a systematic parametric study using the finite element modeling. The finite element model was validated and calibrated by the test data of the pipe under bending and tension, bending and pressure (Figure 4-39).

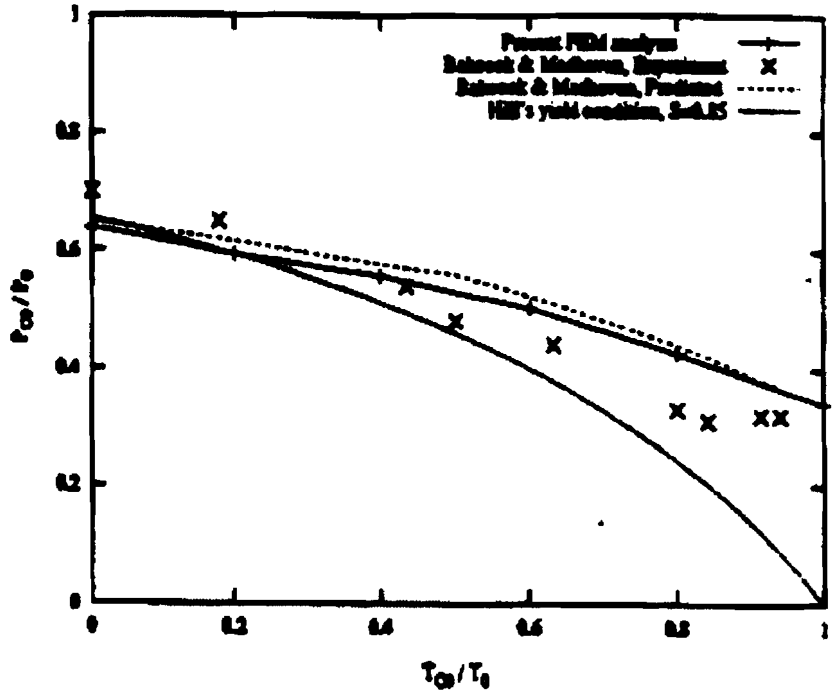

Figure 4-39 Illustration of the Calibration between the FEA Data and Experimental Test Data

It is noted that the numerical data is limited to the following ranges: Mean diameter $D_0 = 8$ in; tube length = infinite; Young's modulus $E = 2.9x10^4$; Poison's ratio $\nu = 0.3$; Diameter to thickness ratio $10 < D_0 / t < 40$; The ratio between the yield parameter and Young's modulus $0.001 < \sigma_y / E < 0.003$; The strain-hardening parameter $5 < n < 25$; The yield anisotropy parameter $0.8 < S < 1.2$; Initial imperfection parameter $0.0015 < \delta_0 < 0.005$; The residual stress parameter $-0.4 < \sigma_r / \sigma_y < 0.4$.

4.6.3 Uncertainty Measures

Buckling/Collapse Capacity. RAM PIPE used the numerical data to develop the uncertainty model. Figure 3.40 illustrates the uncertainty analysis results. The median Bias and COV of the Bias are 1.0 and 6.8%, respectively. Other data or information could not be located during the RAM PIPE project.

Buckling/Collapse Strain Capacity. The buckling/collapse strain capacity equation is not available as well as the uncertainty measures in the existing international design standards. The RAM PIPE Phase 1 and Phase 2 project did not develop any stain capacity equations for the combined axial, bending, and pressure loading. However, Igland's equation may be used as an alternative check.

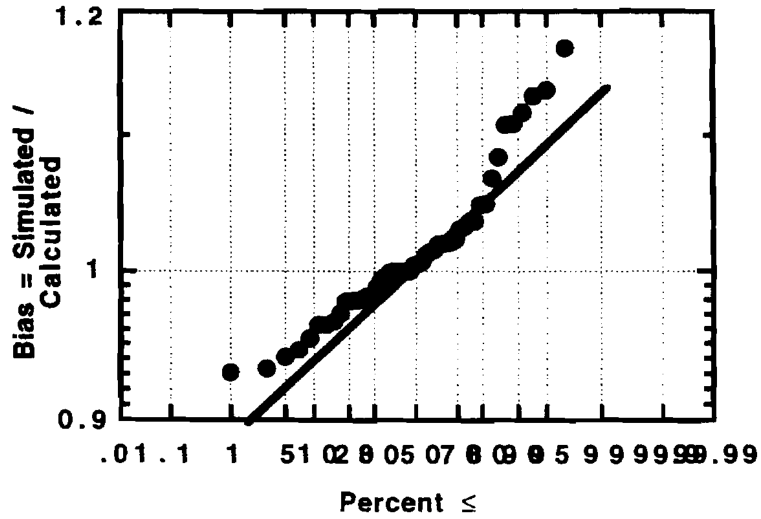

Figure 4-40 The Characterization of Bias associated with Von Mises Interaction Formulation

4.6.4 Development of the RAM PIPE Equations

Figure 4.41 summarizes the interaction of pipeline tension, bending, and collapse pressure based on the simulation data (127 simulations). The simulations covered a diameter to thickness range of D/t = 15 to 35, ovalities of 0.5 % to 0.35 %, X52, X60, and X77 pipe steel characteristics, and a range of residual and circumferential stress characteristics

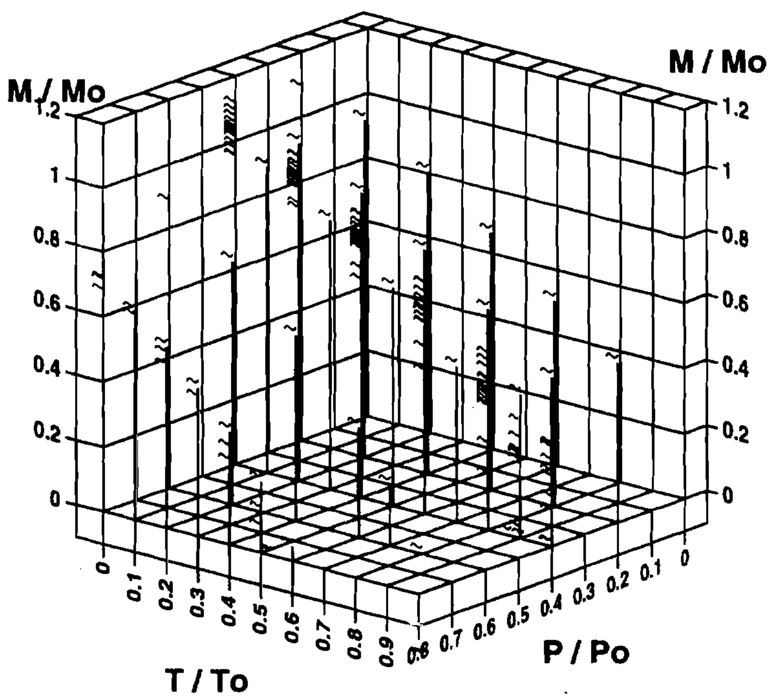

Figure 4-41 Tension, moment, collapse pressure interactions based on simulation data

The interaction formulation that gave the least Bias and least uncertainties associated with the bias was a formulation based on the Von Mises yield criterion:

$$\left[\left(\frac{M}{M_{co}}\right)^2 + \left(\frac{P}{P_{co}}\right)^2 + \left(\frac{T}{T_{co}}\right)^2\right]^{0.5} = 1.0 \tag{4.57}$$

Figure 4.42 summarizes the analysis of the Bias based on the simulation data. The median Bias is B_{50} = 1.0 and the COV of the Bias is V_B = 6.8 %, respectively

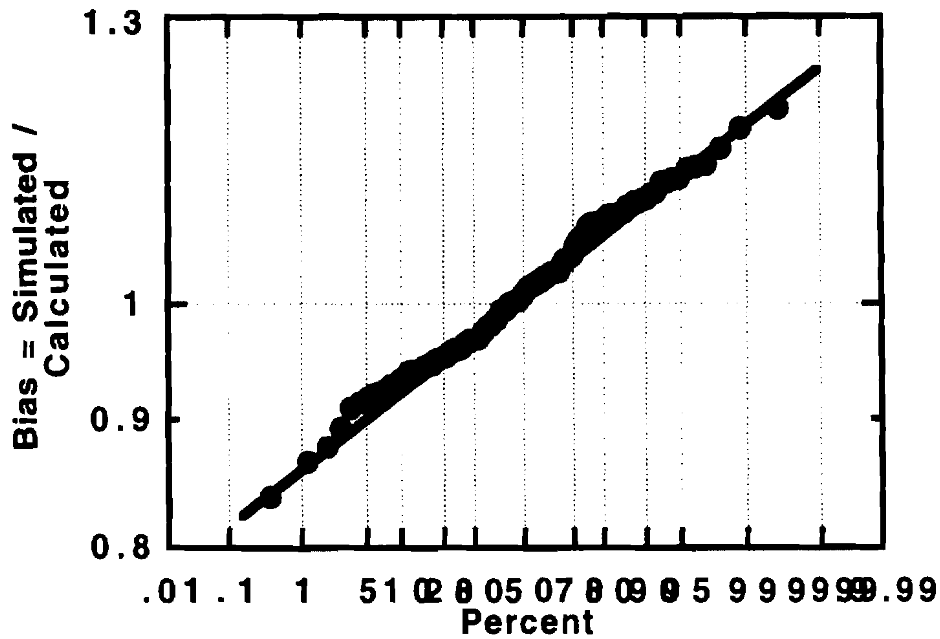

Figure 4-42 Distribution of Bias for Von Mises Interaction Formulation

4.7 Buckling Propagation

As discussed previously, for the range of material and geometric parameters of interest, buckling/collapse results in catastrophic failure of the pipelines. Consequently, the buckling/collapse pressure can be significantly reduced if the geometric integrity of the pipeline is altered. For example, a dent or geometric imperfection induced in a pipe under external pressure can result in local collapse at a pressure much lower than the ones calculated from the expressions mentioned early. Clearly, such a collapse would be at first local in nature. In the early 1970's, it was discovered that such a local collapse could initiate a more global instability where, driven by the external pressure, the buckled (collapsed) section spreads (propagates) along the long pipe, often at high velocity, and flattens it. The buckles stops only if it encounters a physical obstacle that resists the flattening or when it reaches an area of low pressure where propagation cannot be sustained. The phenomenon is known as a propagating buckle (Figure 3.43).

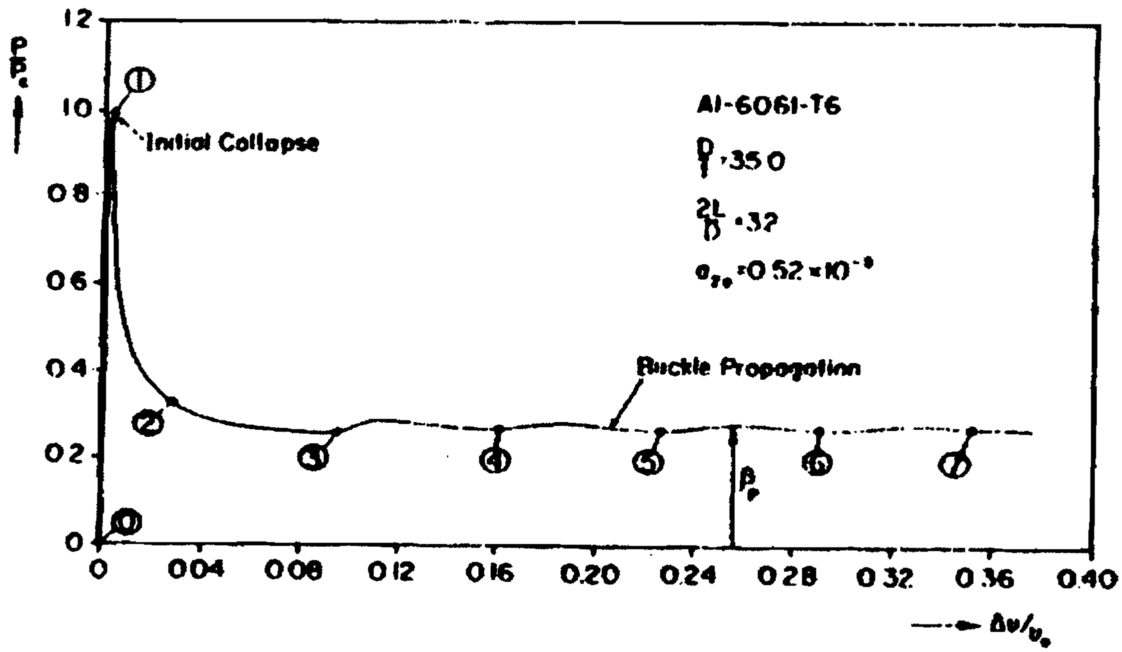

Figure 4-43 Numerical Simulation of the Buckling Propagation Process

4.7.1 Review of Design Equations/Criteria

The commonly used design equations are:

$$\frac{P_p}{\sigma_y} = 6\left[\frac{2t}{D}\right]^{2.5} \quad \text{Melosh et al. (1976)}$$

$$\frac{P_p}{\sigma_y} = \left(10.7 + 0.54\frac{E'}{\sigma_y}\right)\left[\frac{t}{D}\right]^{2.25} \quad \text{Kyriakides, et al (1981)}$$

$$\frac{P_p}{\sigma_y} = 24\left[\frac{t}{D}\right]^{2.4} + 48000\left[\frac{t}{D}\right]^{6} \quad \text{Langner, et al (1984)} \tag{4.58}$$

Estefen, et al (1996) presented a statistical analysis about the empirical design equations based on their test data. The analysis data are shown in Figures 4.44-4.46.

The buckling propagation in DNV 96 is expressed as:

$$\frac{P_p}{\sigma_y} = 26\left(\frac{t}{D}\right)^{2.5} \tag{4.59}$$

API RP 1111 expresses the buckling propagation criteria as:

$$\frac{P_p}{\sigma_y} = 24\left[\frac{t}{D}\right]^{2.4} \tag{4.60}$$

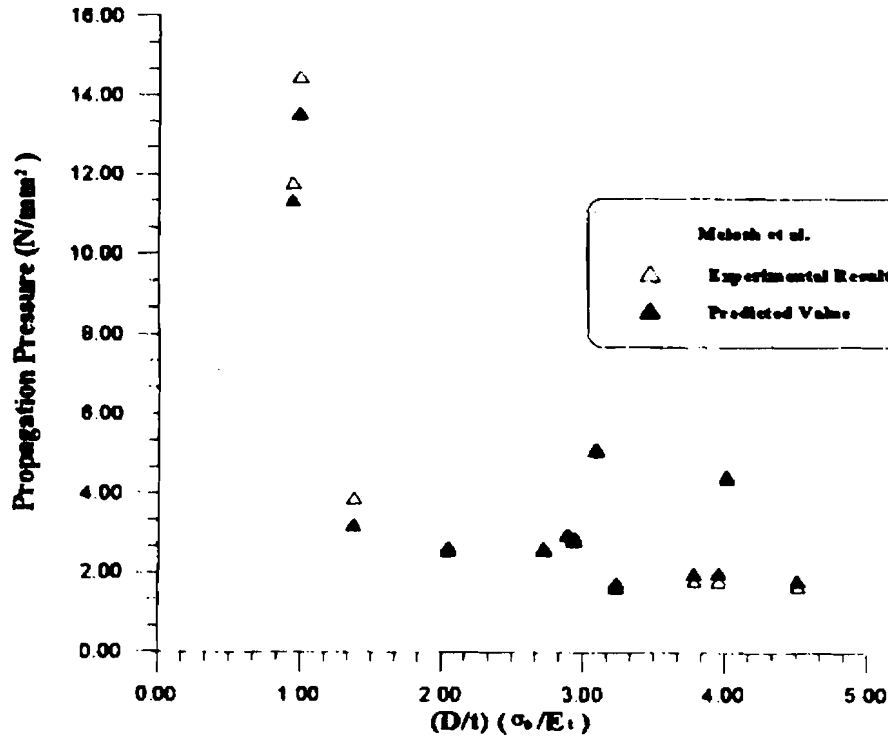

Figure 4-44. Correlation Between Experimental and Predicted Values From Melosh et al. For Propagation Pressure

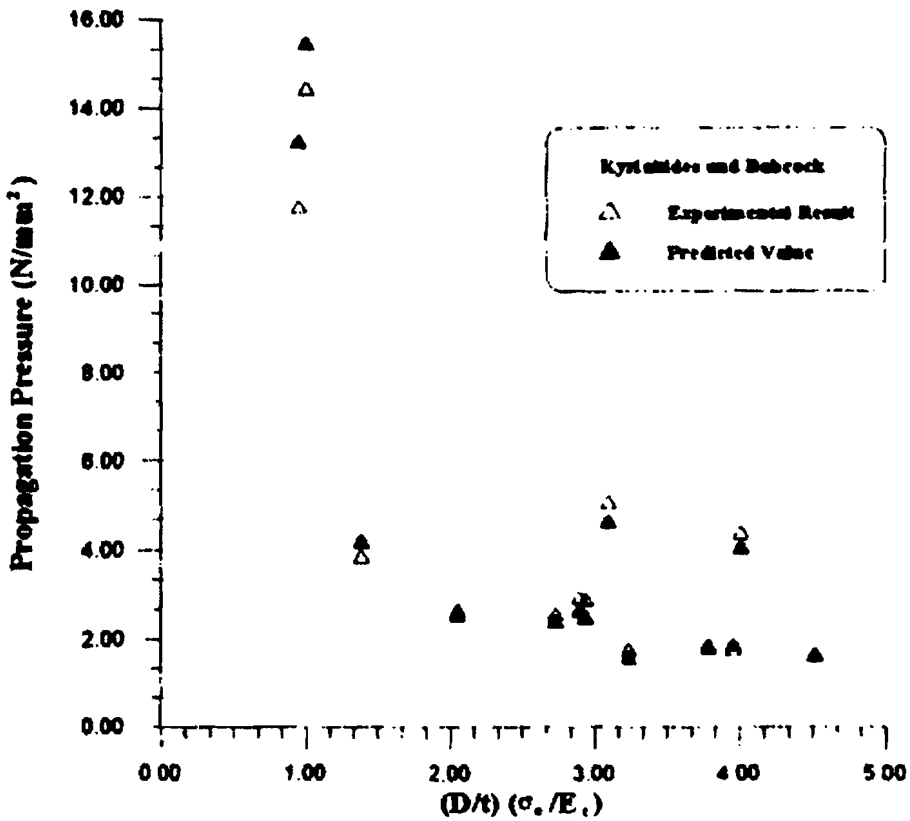

Figure 4-45. Correlation Between Experimental and Predicted Values from Kyriakids and Babcock for Propagation Pressure

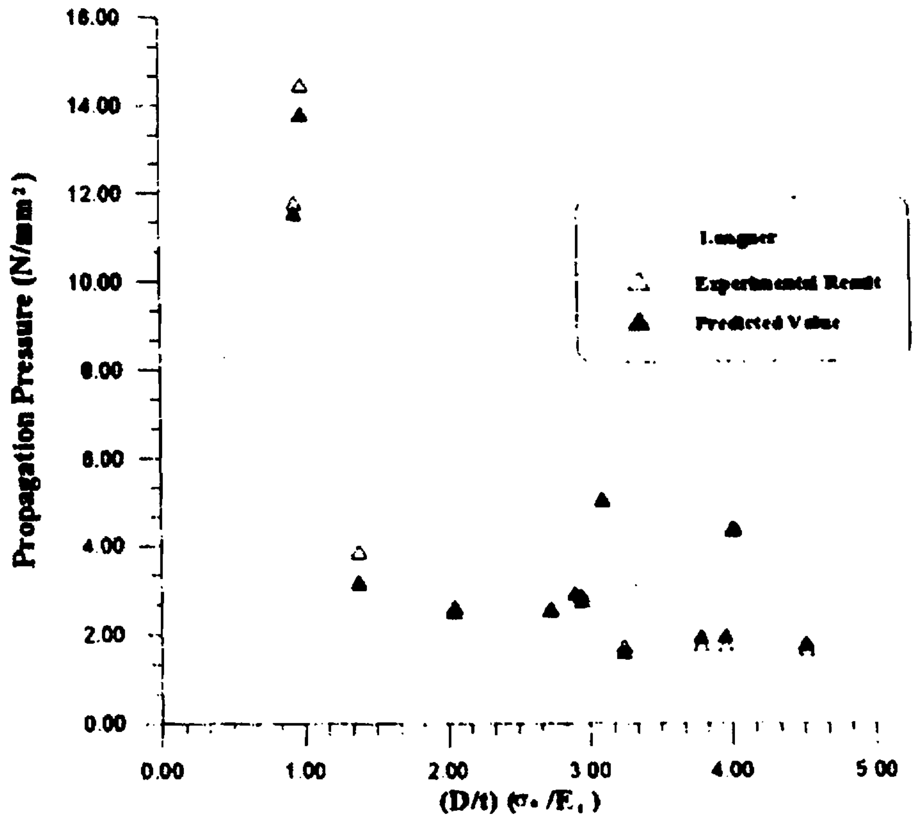

Figure 4-46. Correlation Between Experimental and Predicted Values From Langner for Propagation Pressure

Recently, Hoo Fatt, et al (1998, 2000) have addressed the problem of propagating buckling of pipelines analytically. Using the principle of virtual work, the plastic work dissipated in a cylinder was calculated from a ring collapse mechanism that was used to represent a cross-section of the cylinder subjected to buckle propagation. The plastic work dissipated was due to circumferential bending at four plastic hinges at quarter points of the ring (longitudinal stretching was ignored). The propagation pressure was found to be:

$$\frac{P_p}{\sigma_o} = \pi\left[\frac{t}{D}\right]^2$$

where σ_o is the flow stress. This analytically derived formulation indicates buckling propagation pressures that are somewhat lower than those that have been based on laboratory test results. However, if the effects of the longitudinal stretching and the difference between the yield stress and flow stress are recognized, then the formulation develops propagating buckling pressures that are comparable with those based on laboratory test results.

An interesting part of this development regards the analytical studies of the effects of corrosion on the buckling propagation pressures (Hoo Fatt, Xue, 2000). The results indicate that for corrosion that extends around half of the pipe circumference, that the buckling propagation pressure is reduced in proportion to the reduced wall thickness (tc/t).

4.7.2 Development of the RAM PIPE Equations

Figure 4.47 summarizes the test data utilized by Mesloh, et al (1976). and from the study by Kyriakides and Yeh (1985) to verify their analytical models to determine propagation pressures:

$$\frac{P_p}{\sigma_y} = 34\left(\frac{t}{D}\right)^{2.5} \quad \text{(Mesloh, et al 1976)}$$

$$\frac{P_p}{\sigma_y} = 35.5\left(\frac{t}{D}\right)^{2.5} \text{(Kyriakides, Yeh 1985)} \tag{4.61}$$

Test data on propagation pressures for aluminum and steel tubes also has been provided by Estefen et al (1996). These data are summarized in Bea, et al (1998).

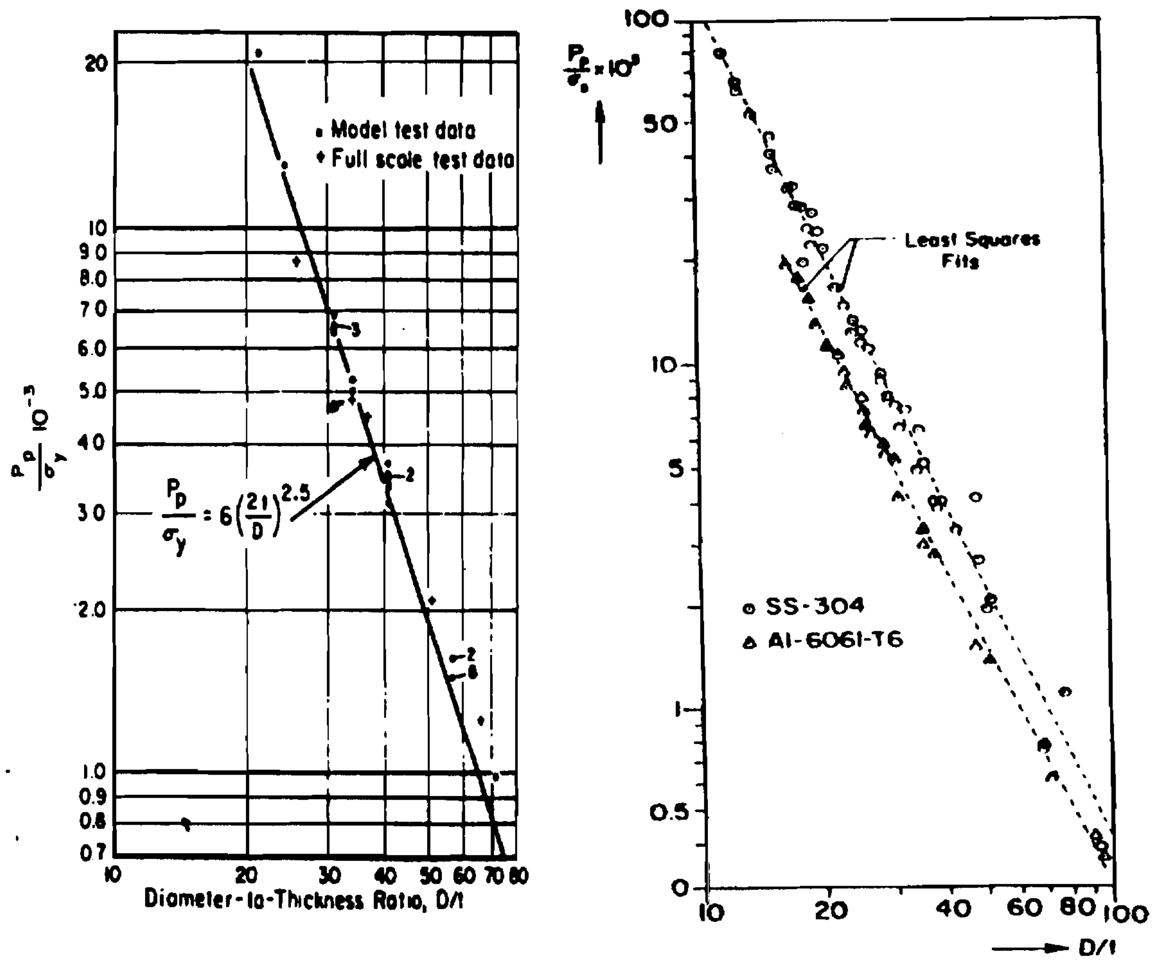

Figure 4-47. Propagation pressure test data compared with analytical models (Mesloh, et al left, Kyriakides and Yeh right)

4.7.3 Uncertainty Measures

Figure 4.48 shows a comparison of this test data with the analytical model proposed by Mesloh, et al (1976). Excellent agreement is indicated for this range of diameter to thickness ratios.

Results from a statistical analysis of the data shown in Figure 4.48 are summarized in Figure 4.49. Bias is defined as the experimental propagation pressure divided by the analytical propagation pressure from the Mesloh, et al (1976) analytical model. The median Bias is indicated to be $B_{50} = 1.0$ and the coefficient of variation of the Bias is indicated to be $V_B = 7.8$ %.

Available data on only steel pipes (Shell Pipeline, 1974) having sizes approximating those of prototype pipelines were assembled and the Bias determined in the same manner (Bea, et al 1998). The results are summarized in Figure 3.50. The median Bias is indicated to be $B_{50} = 1.05$ and the coefficient of variation of the Bias is indicated to be $V_B = 8.8$ %.

In these developments, the Mesloh, et al (1976) formulation will be used as the reference design and reassessment analysis model. The experimental results indicate that this model has a median Bias $B_{50} = 1.05$ and a coefficient of variation of the Bias $V_B = 8$ %.

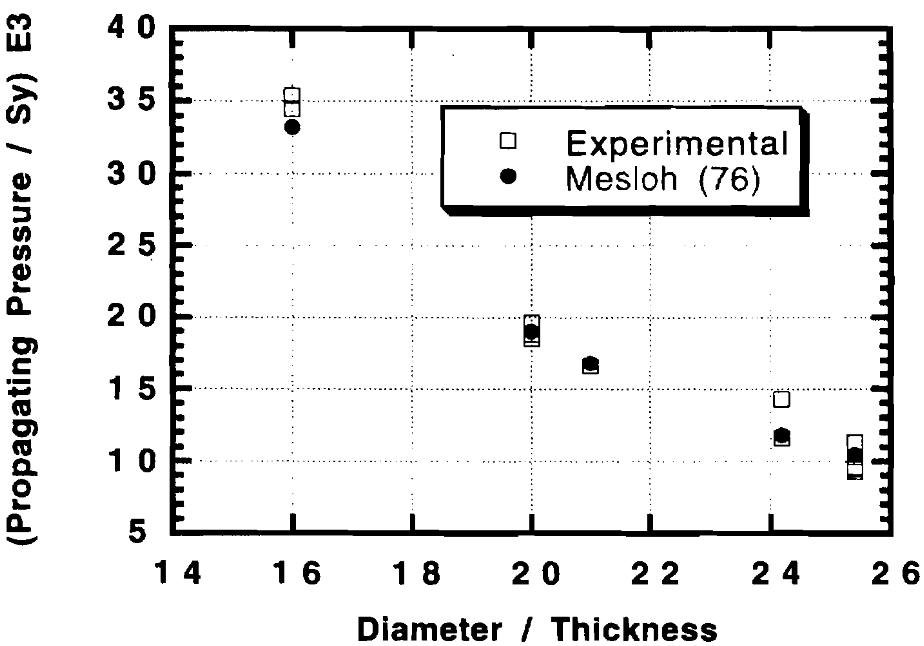

Figure 4-48. Experimental data on propagating pressures compared with Mesloh, et al (1976) analytical model

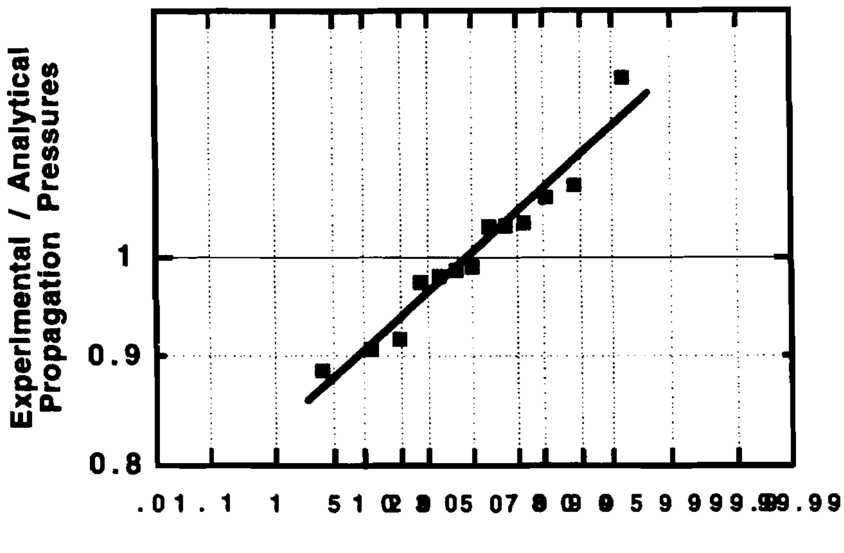

Figure 4-49. Bias in predicted propagation pressures based on Estefen, et al (1996) test data

The experimental Bias characteristics could be validated by considering the basic pipe characteristics:

$$B_{50} = B_{Syn}\left(\frac{B_t}{B_D}\right)^{2.5} \tag{4.62}$$

$$B_{50} = 1.1\left(\frac{1.0}{1.0}\right)^{2.5} = 1.1$$

$$V_B^2 = V_{Sy}^2 + \left(2.5V_{t/D}\right)^2$$

$$V_B = \sqrt{0.05^2 + (2.5 \cdot 0.02)^2} = 0.07$$

These results are very close to those based on the experimental results.

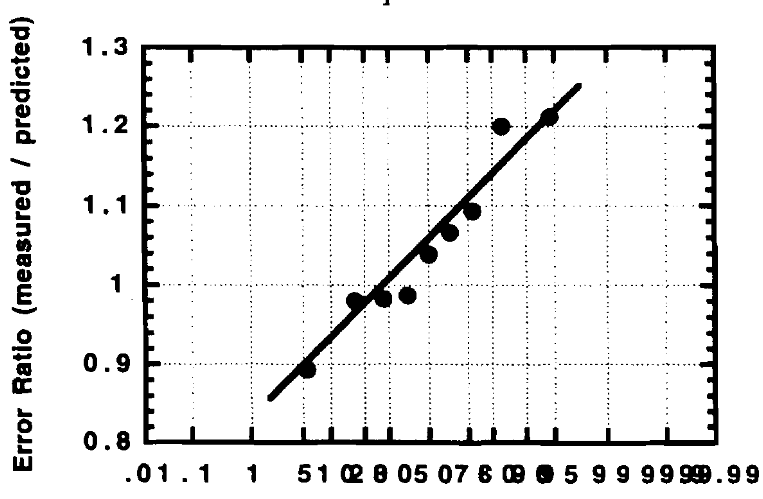

Figure 4-50. Bias in Predicted Propagation Pressures Based on Mesloh, et al (1976) and Shell Pipeline (1974) Test Data

4.7.4 RAM Pipe Equations

The design and reassessment formulation will be expressed as:

$$\frac{P_p}{SMYS} = B_{Sy} 34 \left(\frac{t}{D} \right)^{2.5} \tag{4.63}$$

Where SYMS is the specified minimum yield strength, and B_{Sy} is the median Bias introduced by using the specified minimum yield strength and the Mesloh, et al formulation. Based on the API specification based data cited earlier (B_{Sy} = 1.1 x 1.05 = 1.16), the design and reassessment analysis propagating pressure formula becomes:

$$\frac{P_p}{SMYS} = B_{Sy} 39 \left(\frac{t}{D} \right)^{2.5} \tag{4.64}$$

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