Fracture Behavior of Circumferentially Surface-Cracked Elbows

October 1993-March 1996

Manuscript Completed: June 1996
Date Published: December 1996

Prepared by
T. Kilinski, R. Mohan, D. Rudland, M. Fleming, R. Olson
P. Scott, F. Brust, N. Ghadiali, G. Wilkowski, A. Hopper

Battelle
305 King Avenue
Columbus, OH 43201

M. E. Mayfield, NRC Project Manager

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER

Prepared for
Division of Engineering Technology
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001
NRC Job Code D2060

NUREG/CR-6444 has been reproduced
from the best available copy.

ABSTRACT

This report presents the results from Task 2 of the Second International Piping Integrity Research Group (IPIRG-2) program. The focus of the Task 2 work was directed towards furthering the understanding of the fracture behavior of long-radius elbows. This was accomplished through a combined analytical and experimental program. J-estimation schemes were developed for both axial and circumferential surface cracks in elbows. Large-scale, quasi-static and dynamic, pipe-system, elbow fracture experiments under combined pressure and bending loads were performed on elbows containing an internal surface crack at the extrados. In conjunction with the elbow experiments, material property data were developed for the A106-90 carbon steel and WP304L stainless steel elbow materials investigated. A comparison of the experimental data with the maximum stress predictions using existing straight pipe fracture prediction analysis methods, and elbow fracture prediction methods developed in this program was performed. This analysis was directed at addressing the concerns regarding the validity of using analysis predictions developed for straight pipe to predict the fracture stresses of cracked elbows. Finally, a simplified fitting flaw acceptance criteria incorporating ASME B₂ stress indices and straight pipe, circumferential-crack analysis was developed.

DISCLAIMER

**Portions of this document may be illegible
in electronic image products. Images are
produced from the best available original
document.**

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

CONTENTS

	<u>Page</u>
EXECUTIVE SUMMARY	xv
ACKNOWLEDGMENTS	xix
NOMENCLATURE	xxi
PREVIOUS REPORTS IN SERIES	xxix
1.0 INTRODUCTION	1-1
1.1 Rationale and Objective for Task 2	1-1
1.2 Technical Approach	1-2
1.3 References	1-3
2.0 COMPILATION AND ASSESSMENT OF EXISTING REFERENCES AND DATA FOR CRACKED FITTINGS	2-1
2.1 Cracked Fitting Literature Survey	2-1
2.2 Fitting Database	2-1
2.3 References	2-5
3.0 IPIRG-2 TASK 2 ELBOW EXPERIMENTS	3-1
3.1 Objective of the Task 2 Elbow Experiments	3-1
3.2 Choice of Crack Orientation	3-1
3.3 Elbow Specimen Design	3-2
3.3.1 Elbow Details	3-2
3.3.2 Crack Geometry Details	3-5
3.4 Material Property Data	3-6
3.4.1 Tensile Properties	3-7
3.4.2 Quasi-Static and Dynamic J-Resistance Tests on Compact Specimens at 288 C (550 F)	3-9
3.4.3 Chemical Analysis	3-11
3.5 The IPIRG-2 Elbow Experimental Facilities	3-14
3.5.1 Pipe-System Experimental Facility	3-14

CONTENTS

	<u>Page</u>
3.5.2 Quasi-Static Elbow Experimental Facility	3-19
3.6 Elbow Experiments	3-19
3.6.1 Test Procedures	3-21
3.6.2 Specimen Preparation	3-21
3.6.3 Test Conditions	3-22
3.6.4 Instrumentation	3-22
3.6.5 Results of IPIRG-2 Elbow Experiments	3-24
3.7 References	3-42
4.0 ANALYSIS OF EXPERIMENTS	4-1
4.1 Fracture Prediction Methodology for Cracked Elbows	4-1
4.1.1 J-Estimation Scheme for Circumferentially Surface-Cracked Elbows	4-2
4.1.2 J-estimation Scheme for Axially Surface-Cracked Elbows	4-5
4.2 Straight-Pipe Fracture Prediction Methods	4-7
4.2.1 Net-Section-Collapse Analysis	4-8
4.2.2 Dimensionless-Plastic-Zone-Parameter (DPZP) Analysis	4-8
4.2.3 SC.TNP Analyses	4-10
4.3 Straight-Pipe Failure Avoidance Criteria	4-12
4.3.1 R6 Revision 3 Option 1 Method	4-12
4.3.2 ASME Appendix C and Appendix H Analyses	4-12
4.4 Material Property Data Used in Fracture Analysis	4-14
4.4.1 Tensile Data	4-14
4.4.2 J-R Data	4-15
4.5 Definition of Crack Size	4-17
4.5.1 ASME Code Definition of Crack Size	4-17
4.5.2 Equivalent Length Definition of Flaw Size	4-19
4.6 Comparisons of Maximum Stress Predictions With Experimental Data	4-19
4.6.1 IPIRG-2 Elbow Data	4-20
4.6.2 η -Factor Analyses of Elbow Experiments	4-27
4.6.3 Through-Wall Elbow Fracture Experiment Analysis	4-29
4.6.4 Summary of Results	4-30

CONTENTS

	<u>Page</u>
4.7 References	4-31
5.0 DEVELOPMENT OF A SIMPLIFIED FAILURE AVOIDANCE ANALYSIS PROCEDURE FOR CRACKS IN FITTINGS	5-1
5.1 Basic Premise of Simplified Analyses	5-1
5.2 Development of Analysis Procedure	5-2
5.2.1 Axial Surface Crack Along Elbow Flank	5-3
5.2.2 Circumferential Surface Crack Centered Along the Extrados of an Elbow	5-10
5.3 Discussion and Further Validation Needs	5-18
5.3.1 Generalized Approaches	5-18
5.3.2 Validation Needs	5-19
5.4 References	5-20
6.0 INTRODUCTION	6-1
6.1 References	6-3
APPENDIX A BIBLIOGRAPHY OF PIPE FITTING FRACTURE PAPERS	A-1
APPENDIX B FITTING DATABASE OF EXPERIMENTS - ELBOWCK	B-1
APPENDIX C FITTING OF DATABASE OF EXPERIMENTS - TEECK	C-1
APPENDIX D DETAILED GEOMETRY OF THE IPIRG PIPE LOOP FACILITY	D-1

CONTENTS

Page

LIST OF FIGURES

3.1 Schematic of elbows and terminology used for IPIRG-2 elbow experiments	3-4
3.2 Pre-test wall thickness measurements for carbon steel and stainless steel elbows taken at the elbow mid-plane	3-4
3.3 Crack geometry orientation for elbow experiments	3-5
3.4 Distribution of J versus position on crack for elbow specimens	3-6
3.5 Ratio of J at 45-degree location to J at the crack centerline versus normalized moment for line-spring and three-dimensional finite element models for circumferential elbow crack	3-7
3.6 Schematic of layout for material characterization specimens	3-8
3.7 Stress-strain curves for carbon steel Elbow IP2-FE17	3-10
3.8 Stress-strain curves for stainless steel Elbow IP2-AE1	3-10
3.9 J-Resistance curves for carbon steel Elbow IP2-FE17	3-12
3.10 J-Resistance curves for stainless steel Elbow IP2-AE1	3-12
3.11 Artist's conception of the IPIRG pipe loop	3-15
3.12 Physical dimensions of pipe-system test facility near the test elbow location	3-16
3.13 Pre-test photograph of sandbags positioned near the pipe system	3-18
3.14 Schematic of test facility for quasi-static elbow experiments	3-20
3.15 Pre-test photograph of quasi-static elbow test facility	3-21
3.16 Scale drawing of crack plane for the stainless steel elbow used in Experiment 2-3 (elbow pipe-system experiment)	3-23
3.17 Layout of external instrumentation for quasi-static elbow experiments	3-25
3.18 Overall schematic for external instrumentation for elbow pipe-system experiments	3-26
3.19 External instrumentation near the test elbow for the elbow pipe-system experiments	3-26
3.20 Location of internal instrumentation for all elbow experiments	3-27

CONTENTS

	<u>Page</u>
3.21 Actuator displacement versus time for carbon steel, pipe-system Experiment 2-1	3-29
3.22 Actuator displacement versus time for stainless steel, pipe-system Experiment 2-3	3-29
3.23 Pipe displacement at the load point and total applied load versus time for carbon steel, quasi-static elbow Experiment 2-2	3-30
3.24 Pipe displacement at the load point and total applied load versus time for the stainless steel, quasi-static elbow Experiment 2-4	3-31
3.25 Moment and internal pipe pressure versus time for carbon steel, elbow pipe-system Experiment 2-1	3-32
3.26 Moment and internal pipe pressure versus time for stainless steel, elbow pipe-system Experiment 2-3	3-32
3.27 Moment and internal pipe pressure versus time for carbon steel, quasi-static elbow Experiment 2-2	3-34
3.28 Moment and internal pipe pressure versus time for stainless steel, quasi-static elbow Experiment 2-4	3-34
3.29 Crack section moment versus centerline crack-mouth-opening displacement for the carbon steel, quasi-static and pipe-system elbow experiments	3-35
3.30 Crack section moment versus crack-mouth-opening displacement near the point of surface-crack penetration for the carbon steel, quasi-static and pipe-system elbow experiments	3-35
3.31 Crack section moment versus centerline crack-mouth-opening displacement for the stainless steel, quasi-static and pipe-system elbow experiments	3-36
3.32 Crack section moment versus crack-mouth-opening displacement near the point of surface-crack penetration for the stainless steel, quasi-static and pipe-system elbow experiments	3-36
3.33 Crack section moment versus total rotation (2ϕ) for the carbon steel, quasi-static and pipe-system elbow experiments	3-37
3.34 Crack section moment versus total rotation (2ϕ) for the stainless steel, quasi-static and pipe-system elbow experiments	3-37
3.35 Overview of fracture surface for Experiment 2-3	3-39
3.36 Close-up photographs of fracture surface for Experiment 2-3, (a) Side A, 45 degrees from the crack centerline, (b) Side B, 45 degrees from the crack centerline	3-40

CONTENTS

	<u>Page</u>
3.37 Post-test fracture surface measurements, (a) a/t ratios for carbon steel elbow experiments (b) a/t ratios for stainless steel elbow experiments	3-41
4.1 Schematic of circumferential crack geometry used for development of an elbow analysis	4-2
4.2 Schematic of axial crack geometry used for development of elbow analysis	4-5
4.3 Fit of DPZP equation through pipe test data	4-9
4.4 R-6 failure assessment diagram	4-13
4.5 Experimental stress-strain results along with the corresponding Ramberg-Osgood representation for the carbon steel elbow material	4-16
4.6 Experimental stress-strain results along with the corresponding Ramberg-Osgood representation for the stainless steel elbow material	4-16
4.7 Experimental J-R data with corresponding extrapolation curve for the carbon steel elbow material	4-18
4.8 Experimental J-R data with corresponding extrapolation curve for the stainless steel elbow material	4-18
4.9 Illustration of ASME Section XI method of defining the crack dimensions for an in-service crack evaluation	4-19
4.10 Schematic of active elbow crack geometry showing ASME designed and equivalent length definition crack shapes	4-20
4.11 Maximum predicted moment versus a/t for carbon steel elbow experiments	4-23
4.12 Maximum predicted moment versus a/t for stainless steel elbow experiments	4-23
4.13 Moment versus J for stainless steel elbow, pipe-system Experiment 2-3 using both straight-pipe and elbow J-estimation schemes	4-27
4.14 Maximum moment data for circumferential through-wall-cracked elbow experiments	4-30
5.1 Comparison of limit-load definitions by design stress and fracture approaches	5-2
5.2 J versus moment calculations for an axial, flank, surface crack (SC.ELB3 analysis) in an elbow and various straight-pipe circumferential crack J-estimation schemes, (a) $R_m/t = 5$, (b) $R_m/t = 10$, (c) $R_m/t = 20$	5-4
5.3 Comparison of J versus moment for circumferential, surface-cracked, straight pipe to moment for axial, flank, surface-cracked elbow at the same J values ($M^{pipe}/M^{elbow} _J$)	5-6

CONTENTS

	<u>Page</u>
5.4 Comparison of ASME elbow stress indices to ratio of moment for circumferential, surface-cracked, straight pipe to moment for axial, flank, surface-cracked elbow at the same J values ($M^{pipe}/M^{elbow} _J$)	5-8
5.5 Comparison of EDF, axial, flank, surface-cracked elbow experiment Y6135 on an aged cast stainless steel elbow to criteria developed in Figure 5.4	5-10
5.6 J versus moment calculations for circumferential, extrados, surface crack (SC.ELB1 and SC.ELB2 analyses) in an elbow and various straight-pipe circumferential crack J-estimation schemes, (a) $R_m/t = 5$, (b) $R_m/t = 10$, (c) $R_m/t = 20$	5-12
5.7 Comparison of J versus moment for circumferential, surface-cracked, straight pipe to moment for, circumferential, extrados, surface-cracked elbow at the same J values ($M^{pipe}/M^{elbow} _J$), (a) Using SC.ELB1 analysis, (b) Using SC.ELB2 analysis	5-14
5.8 Comparison of ASME elbow stress indices to ratio of moment for circumferential, surface-cracked, straight pipe to moment for circumferential, extrados, surface-cracked elbow at the same J values ($M^{pipe}/M^{elbow} _J$), (a) Using SC.ELB1 analysis, (b) Using SC.ELB2 analysis	5-15
5.9 Comparison of IPIRG-2, circumferential, extrados, surface-cracked, experiments on A106-90 and WP304L elbows to criteria developed in Figure 5.8 (SC.ELB1 and SC.ELB2 analyses virtually identical)	5-17
5.10 Comparison of axial-flank and circumferential-extrados surface-cracked elbow failure avoidance criteria	5-19
D.1 Artist's conception of the IPIRG pipe loop test facility	D-1
D.2 Overall dimensions of the IPIRG pipe loop test facility	D-2
D.3 Layout of strain gages for the IPIRG-2 pipe-system experiments	D-3
D.4 String potentiometer locations for the IPIRG-2 pipe-system experiments	D-3
D.5 Elbow girth weld experiment pipe loop geometry	D-4
D.6 North moment cell geometry	D-5
D.7 Leg 3 end cap section	D-5
D.8 South moment cell	D-6
D.9 Leg 3 elbow transition piece	D-6

CONTENTS

	<u>Page</u>
D.10 Leg 4 elbow transition piece	D-7
D.11 East moment cell	D-7
D.12 Leg 4 end cap section	D-8
D.13 Straight pipe wall thickness measurements	D-8
D.14 Elbow wall thickness measurements	D-9
D.15 Test elbow dimension	D-9

LIST OF TABLES

1.1 Experimental test matrix for Task 2 elbow experiments	1-3
2.1 Summary of experiments listed in ELBOWCK database	2-2
2.2 Summary of experiments listed in TEECK database	2-4
3.1 Fabrication procedures for the carbon steel and stainless steel elbows used in the Task 2 elbow experiments	3-3
3.2 Average outside diameter measurements for the elbow test specimens	3-3
3.3 Tensile properties summary	3-9
3.4 C(T) specimen dimensions	3-11
3.5 Fracture toughness summary	3-13
3.6 Chemical analysis for A106 Grade B carbon steel elbow (IP-FE17)	3-13
3.7 Chemical analysis for TP304L stainless steel elbow (IP-AE1)	3-13
3.8 Experimentally measured damping value and natural frequencies associated with the IPIRG-2 pipe loop facility at 288 C(550 F) and 15.5 MPa (2,250 psi) internal pipe pressure	3-19
3.9 Instrumentation used during the IPIRG-2 elbow fracture experiments	3-23
3.10 Key results for the IPIRG-2 elbow experiments	3-28
4.1 Tensile properties of the carbon steel and stainless steel materials used in the analysis of the elbow experiments	4-15

CONTENTS

	<u>Page</u>
4.2 Extrapolated J-R curve constants for the carbon steel and stainless steel elbow materials	4-17
4.3 Fracture ratios for Task 2 elbow experiments	4-22
4.4 Fracture ratios for carbon steel, dynamic, elbow experiment using measured experimental crack length	4-25
4.5 Fracture ratios for stainless steel, dynamic, elbow experiment using measured experimental crack length	4-25
4.6 Fracture ratios for carbon steel, dynamic, elbow experiment using total measured and equivalent crack lengths	4-26
4.7 Fracture ratios for stainless steel, dynamic, elbow experiment using total measured and equivalent crack lengths	4-26
4.8 Comparison of J_i values from η -factor analyses of surface-cracked elbow experiments and J_i values from C(T) specimen tests	4-28
4.9 Fracture ratios for through-wall-cracked elbows	4-31
5.1 Parameters used in analyses of axial, flank, surface-cracked elbows	5-4
5.2 Parameters in EDF axial, flank, surface-cracked, elbow Experiment Y6135	5-9
5.3 Parameters in IPIRG-2 circumferential, extrados, surface-crack, elbow experiments	5-16

EXECUTIVE SUMMARY

This report presents the results from Task 2 of the Second International Piping Integrity Research Group (IPIRG-2) program. The IPIRG-2 program is an international group program managed by the U.S. Nuclear Regulatory Commission (U.S. NRC) and funded by a consortium of organizations from 15 nations. The objective of the IPIRG-2 program was to build on the results of the first IPIRG program (IPIRG-1) and other related programs by extending the state-of-the-art in pipe fracture technology through the development of data needed to verify engineering methods for assessing the integrity of nuclear power plant piping systems that contain cracks.

The majority of piping integrity research to date has focused on critical flaw assessments of straight pipe. As elastic-plastic fracture mechanics and limit-load solutions become more refined, the confidence with which we can predict the fracture behavior of cracked straight pipe increases. Jurisdictional codes have adopted these engineering methods for use on straight pipe, but the applicability of these methods for fitting analyses is still speculative. Due to physical characteristics, such as geometric stiffness and larger wall thickness, pipe fittings are generally considered less critical than straight pipe when assessing the integrity of a complete piping system. However, concerns have arisen regarding the analysis of cracked fittings. Most importantly, the question of whether or not existing techniques developed for straight pipe can be successfully used to estimate the behavior of cracked fittings.

The work in Task 2 of the IPIRG-2 program was directed toward investigating the fracture behavior of elbows. The focus of the work was to develop engineering estimation methods to predict the fracture behavior of surface-cracked elbows, validate these methods with large-diameter elbow fracture experiments, and assess the applicability of using straight pipe analyses for predicting the failure stresses of cracked elbows.

The Task 2 work was divided into four main components. The first objective was to review and compile existing analytical and experimental research data on cracked fittings. By drawing on existing knowledge of elbow fracture, the IPIRG-2 work could be directed toward improving existing elbow fracture studies, and fill gaps in the area of elbow fracture which are important to understanding the behavior of elbows, but were not presently available. As a result of the literature survey, a bibliography of the pertinent analytical and experimental papers on fitting fracture was created. This listing contains 107 references pertaining to the analysis techniques, experimental research, and documented service failures relating to elbows. In conjunction with the literature survey, two fitting databases were prepared from the data found in the literature survey, and collected from IPIRG-2 member and non-member organizations. The elbow database (ELBOWCK) contains the available experimental test conditions, experimental results, and material property data for 76 elbow experiments conducted worldwide. The tee database (TEECK) contains similar data for 18 tee experiments. The information from the literature survey and databases was used to determine the location and orientation of the crack geometry which would be the focus of the Task 2 elbow work.

The next objective was to develop an estimation model for use on surface-cracked elbows. Existing methods developed for use on straight pipe would be studied, and modified to be applicable for the cracked-elbow geometry. The developed model was validated by comparison with finite element solutions. A J-solution was developed which used an engineered form of a finite element line-spring model. This model included combined bending and internal pressure effects. This method was originally

Executive Summary

developed for a straight length of pipe containing a surface crack subjected to bending loads. However, since the element was based on beam theory, it was a logical extension to modify it for elbows using curved beam theory. Three J-estimation schemes were developed as part of this work. Two estimation schemes were developed for the case of a circumferential crack located on the extrados (SC.ELB1 and SC.ELB2). One scheme (SC.ELB3) was developed for the case of an axial crack located along the flank of the elbow.

The third objective of Task 2 was to perform large-scale elbow fracture experiments to help verify the J-estimation schemes, and provide essential data necessary to evaluate the complex response of a cracked elbow subjected to combined inertial and displacement-controlled dynamic loads. Two materials were evaluated: A106-Grade B carbon steel and WP304L stainless steel. Tensile and J-R curve material property data were developed at quasi-static and dynamic loading rates using elbows identical to those tested in the large-scale elbow experiments. In addition to the two dynamic, elbow pipe-system experiments, two quasi-static experiments were performed for comparison. All four experiments were conducted at pressurized water reactor (PWR) conditions (i.e., 15.5 MPa [2,250 psi] internal pressure and 288 C [550 F]). Prior to performing the elbow experiments, modifications to the quasi-static and dynamic pipe testing facilities was required to allow for the testing of an elbow test specimen. For the dynamic test facility, the IPIRG pipe loop was modified by replacing five meters (15 feet) of pipe in the area of the test elbow. This modification included the installation of a third "moment cell" to infer the applied moment at the elbow location. For the quasi-static elbow experiments, a new strongback system was designed and constructed over the existing quasi-static facility. This strongback made use of one of the existing hydraulic rams for the applied load.

The final objective of Task 2 was to address whether existing straight-pipe fracture analyses could be used successfully to predict elbow fracture results. A comparison of the experimental elbow data was made with the maximum stress predictions using various straight-pipe fracture prediction methods, and the elbow prediction methods developed as part of this task. The experimental maximum moments were compared with the predicted maximum moments from the analysis predictions to gauge the accuracy of each method. The effects of input variables such as dynamic or quasi-static material property data, method of defining crack length, and the sensitivity of measured crack depth were studied. Also, initial work was completed for developing a simplified fitting flaw acceptance criteria incorporating the ASME B₂ stress indices and existing straight-pipe circumferential crack estimation techniques.

As a result of completing the four objectives associated with Task 2 of the IPIRG-2 Program, the following conclusions were made:

- (1) The existing database of fitting fracture experiments is somewhat limited. Most data focus on uncracked burst strength of elbows and tees. Some work has been performed on through-wall cracks. Experiments conducted as part of this effort focused on evaluating circumferential cracks located at the elbow extrados. Experimental data on surface-cracked fittings is almost non-existent. The IPIRG-2 elbow fracture experiments are the only circumferential, extrados, surface-cracked data found pertaining to combined pressure and bending loading conditions.
- (2) The use of quasi-static stress-strain properties resulted in the best predictions of the elbow experiments. Therefore, the development and use of dynamic stress-strain data is probably not necessary. The conclusion is consistent with conclusions from the IPIRG-2 Task 1 (on cracks in straight-pipe sections) and Task 3 (on material properties and sensitivity analyses) reports.

- (3) For the carbon steel material evaluated, there was no significant change in toughness for increased strain rates. From other work in the IPIRG-2 program, this is not necessarily true for all carbon steels.
- (4) For the stainless steel material evaluated, there was a significant increase in toughness at increased strain rates. Therefore, quasi-static J-R curves should be used in the analysis of quasi-static experimental data, and dynamic J-R curves should be used for dynamic experiments to make more accurate predictions.
- (5) All the straight pipe analysis techniques underpredicted the experimental moments.
- (6) Fracture ratios (experimental/predicted maximum stresses) were more accurate when the equivalent crack length was used in the analysis predictions. However, in practice, it could be difficult to obtain an accurate profile of the existing crack to make this calculation.
- (7) The fracture ratios (experimental/predicted maximum stresses) for all four elbow experiments, based on the straight-pipe SC.TNP1 J-estimation scheme, are close to but slightly higher than the previously established scatter band of fracture ratios for the SC.TNP1 analysis method when used for straight pipe. This tends to indicate that the straight-pipe SC.TNP1 method is adequate for predicting the load-carrying capacity of circumferential cracks along the extrados of an elbow with an R/t ratio about 6. For higher R/t elbows, the elbow failure loads should be below the straight-pipe results.
- (8) The SC.ELB2 method results in a reasonable underprediction of the experimental moments for these circumferential extrados-type cracks. For both materials, and for all of the crack sizes considered, the difference in predictions between the SC.ELB2 elbow solution and the SC.TNP1 straight-pipe solution is less than 10 percent for the $R_m/t = 6$ elbows examined. This is well within the typical experimental scatter band observed in straight-pipe experiments.
- (9) An assessment of the new elbow J-estimation schemes for the case of an axially oriented elbow flank crack was not done directly (see discussion in Conclusion 11). This was because no axial surface-cracked elbow experiments in the ELBOWCK database had exactly the flaw length used in the J-estimation scheme used.
- (10) For circumferential through-wall cracks, limit-load solutions for straight pipe and elbows both under predict the elbow experimental data for crack lengths larger than 30 percent of the circumference. For cracks less than 30 percent in length, the elbow limit-load solution follows the trend of the experimental data. For the crack lengths studied, the fracture ratios for the elbow limit-load solution ranged between 1.19 and 1.42.
- (11) An effort was undertaken to see if the elbow analyses developed in this report could be simplified to a readily codifiable procedure, and in that same process could also be extended to other crack lengths. The approach undertaken was to see if there was a multiplier that could be used on the circumferential surface-cracked straight-pipe solutions. The simplest and most conservative approach was to estimate the elbow failure loads by using the straight pipe loads divided by the ASME B_2 stress indices for elbows. This was always conservative, but perhaps too conservative for circumferential flaws in elbows or at higher R/t ratios. The second approach was to investigate if a more accurate solution could be used rather than just the B_2 stress indices. A stress multiplier, called the Y-function, was developed from the ratio of the moments in the straight pipe to that in the elbow

Executive Summary

at constant values of J (for the same crack sizes in the pipe and elbow). Comparisons to the IPIRG-2 circumferential extrados experiments and an EDF axial, flank experiment on an aged cast stainless steel elbow were in good agreement with the Υ analysis. This method looks extremely promising, but some further validation is needed before it is ready for code implementation. The Υ -function was found to be valid through the elastic-plastic region and is therefore also valid for limit-load solutions. Finally, from this exercise, it is now seen how Υ -functions could be more easily developed for through-wall cracks in elbows, cracks in tees, or cracks in any other pipe fitting. This could be done without the extensive need of J -estimation scheme developments as was done in this report.

- (12) The experimental data and subsequent analysis predictions were developed for a limited set of material data, and for a specific crack orientation, crack length, and limited a/t ratio. Caution should be used before applying the results and conclusions drawn from this work to a broad generalization regarding the fracture behavior of other geometries. Issues/variables such as material, elbow diameter, crack location, and crack size need to be investigated and may or may not support the findings of this work.

ACKNOWLEDGMENTS

The IPIRG Program was an international group program coordinated by the U.S. Nuclear Regulatory Commission's Electrical, Materials, and Mechanical Engineering Branch of the Office of Nuclear Regulatory Research under Contract No. NRC-04-91-063 to Battelle. Mr. Michael Mayfield was the U.S. NRC program manager. Dr. Allen Hopper was the Battelle program manager.

The members of the IPIRG-2 Program and their representatives to the IPIRG Technical Advisory Group (TAG) were:

Bulgaria

- CUAEP

Mr. Y. Yanev

Canada

- AECB^(*)

Dr. B. Jarman^(**), Mr. J. K. Pereira

- Ontario Hydro

Mr. M. Kozluk

Czech Republic

- NRI

Dr. J. Zdárek, Dr. M. Brumovsky, Dr. P. Kadečka,
Mr. J. Palyza

France

- EDF^(*)

Mr. C. Faigy^(**), Mr. P. Le Delliou

- CEA

Ms. F. Gantenbein, Mr. E. Debec-Mathet

- Framatome

Dr. Ph. Gilles

Hungary

- HAEC

Mr. A. Fehérvári

Italy

- ANPA-DISP^(*)

Dr. C. Maricchiolo^(**)

Japan

- CRIEPI^(*)

Dr. K. Kashima^(**), Mr. N. Miura

Lithuania

- VATESI

Mr. P. Vaisnys

Republic of China

- INER/AEC^(*)

Dr. Li-Fu Lin^(**)

(*) Contractual organization

(**) TAG representative

Acknowledgments

Republic of Korea

- KINS^(*)
- SKKU

Dr. J. B. Lee^(**), Dr. Y. H. Choi
Dr. Y. J. Kim

Slovak Republic

- VUJE
- NRA

Dr. L. Kupca
Dr. J. Misak

Sweden

- SKI^(*)
- SAQ

Dr. G. Hedner^(**)
Dr. B. Brickstad

Switzerland

- KKL^(*)
- HSK

Mr. R. Wanner^(**)
Dr. D. H. Njo

United Kingdom

- Nuclear Electric^(*)

Dr. T. C. Chivers^(**), Dr. J. Darlastan

United States

- U.S. NRC-RES^(*)
- U.S. NRC-NRR^(*)
- EPRI^(*)

Mr. M. Mayfield^(**)
Mr. K. Wichman^(**)
Mr. S. Gosselin^(**), Dr. Y. K. Tang

We would like to express our appreciation for the support and interest of the IPIRG members in this program.

We would like to thank others at Battelle who have helped in these efforts. Technicians who have contributed include: Mr. J. Anthony, Mr. E. Blakesley, Mr. R. Gertler, Mr. P. Held, Mr. P. Mincer, Mr. M. Oliver, Mr. D. Rider, Mr. D. Shoemaker, and Mr. G. Wall. We also would like to recognize Mrs. V. Kreachbaum, Ms. B. Fuller, and Ms. J. Ward for their assistance in preparing this report.

(*) Contractual organization

(**) TAG representative

NOMENCLATURE

1. SYMBOLS

a	Crack depth
A	Area of cross section
A^{uc}	Area of uncracked cross section
a_o	Original crack length
B	Thickness of C(T) specimen
B_2	ASME stress indices for primary bending stresses
B_N	Net thickness of C(T) specimen at sidegrooves
b	Remaining ligament length
C	Closing mode
C_1	Statistically-based parameter from plastic-zone-size screening criteria
C_2	ASME stress indices for primary and secondary bending stresses
C_3	Coefficient in power-law J-R curve equation
c	Distance from neutral bending axis
D_i	Inside pipe diameter
D_m	Mean pipe diameter
D_o	Outside pipe diameter
E	Elastic modulus
E'	$E/(1-\nu^2)$
F_1	Elastic function in GE/EPRI method
F_1^M	Function used in elastic stress intensity factor definition associated with bending
F_1^{pr}	Function used in elastic stress intensity factor definition associated with internal pressure

Nomenclature

$H(a/t)$	Function from SC.ENG1 and SKEWING J-estimation schemes
h	Parameter for ASME B_2 and C_2 stress indices
h_1	Functions in EPRI/GE J-estimation scheme
h_1^M	Coefficient function used in defining the plastic part of crack-driving force associated with bending
h_1^{pr}	Coefficient function used in defining the plastic part of crack-driving force associated with internal pressure
h_1^{elbow}	FEM determined geometric parameters relating moment to J for an elbow
h_1^{pipe}	FEM determined geometric parameters relating moment to J for a straight pipe
I	Area moment of inertia
J	J-integral fracture parameter
$J_{applied}$	Applied J
J_D	Deformation plasticity theory based J
J_e	Elastic component of J
J_p^{elbow}	Plastic part of J due to bending for elbow
J_p^{pipe}	Plastic part of J due to bending for a straight pipe
J_e^{pr+M}	Elastic component of J for axially cracked elbow subjected to pressure and bending moment
J_p^{pr}	Plastic component of J for axially cracked elbow subjected to pressure
J_p^M	Plastic component of J for axially cracked elbow subjected to bending moment
J_i	J at crack initiation
J_{lc}	Plane strain J value at crack initiation
J_M	Modified J
J_p	Plastic component of J
J_R	Crack growth resistance

K_I	Applied linear elastic stress intensity factor
K_I^M	Mode I stress intensity factor for bending moment
K_I^{pr}	Mode I stress intensity factor for internal pressure
K_{Ib}	Stress intensity fracture due to bending stresses
K_{Ic}	Material toughness expressed in terms of K
K_{Im}	Stress intensity factor due to membrane stresses
K_r	Ratio of K_I to $K_{Ic}(a)$ from R6 analysis
ℓ	Total length of axial surface crack
L	Length parameter in SC.TNP and SC.TKP analyses
L_r	Load ratio in R6 analysis
M	Moment
M^{elbow}	Maximum moment for cracked-elbow geometry
M^{pipe}	Maximum moment for a straight-pipe geometry
M_o^{elbow}	Reference moment at a stress of σ_o for elbow geometry
M_o^{pipe}	Reference moment at a stress of σ_o for straight-pipe geometry
m	Exponent in power-law extrapolated J-R curve expression
M_L^c	Net-Section-Collapse moment for a circumferentially surface-cracked pipe used in SC.ENG1 and SKEWING analyses
M_L^d	Net-Section-Collapse moment for an uncracked pipe with a reduced thickness, t_e , used in SC.ENG1 and SKEWING analyses
M_o	Reference moment for a cracked pipe under pure bending
$M_{o(GE)}$	Reference moment of circumferentially cracked pipe used in GE/EPRI method
$M_{o(e)}$	Reference moment for an uncracked elbow
M_o^{NC}	Reference moment for uncracked pipe
$M_{o(NSC)}$	Reference moment using Net-Section-Collapse equations

Nomenclature

M_2	Parameter used in the definition of limit pressure
n	Strain-hardening exponent in Ramberg-Osgood equation
O	Opening mode
P	Applied load
p	Pressure
p_a	Allowable internal pipe pressure
p_o	Limit pressure of straight pipe with axial flaw
P_{NSC}	Net-Section-Collapse predicted failure stress
P_{DPZP}	DPZP predicted failure stress
R_{el}	Elbow radius of curvature
R_i	Inside pipe radius
R_m	Mean pipe radius
R_o	Outside pipe radius
r	Constant having a value of unity and same units as Δa
S_m	ASME code design stress intensity
t	Time, or pipe thickness
t_{pipe}	Actual measured thickness of pipe wall
t_c	Reduced wall thickness representation of cracked section in LBB.ENG2 method
w	Width of C(T) specimen
y	Constant
α	Ramberg-Osgood parameter
Δa	Change in crack length or depth, i.e., crack growth
β	Distance from bottom of pipe to fully plastic neutral axis
ϵ	Strain

ϵ_0	Ramberg-Osgood reference strain
ψ	Elbow angle
Υ_a^c	Elbow function for an axial flank flaw orientation
Υ_c^c	Elbow function for a circumferential extrados flaw orientation
Υ_x^f	Generalized fitting parameter
ν	Poisson's ratio
λ	Elbow parameter
η	Geometric constant used in general analytical procedure where the plastic component of J is calculated using experimental load, displacement, and crack growth data
ϕ	Pipe rotation
σ	Stress
σ_f	Flow stress
σ_0	Ramberg-Osgood reference stress
σ_u	Ultimate stress
σ_y	Yield stress
θ	Half crack angle

2. ACRONYMS AND INITIALISMS

AECB	Atomic Energy Control Board (Canada)
ANPA-DISP	Agenzia Nazionale per la Protezione dell'Ambiente (Italy)
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
CAD	Computer Aided Design
CEA	Commissariat A L'Energie Atomique (France)

Nomenclature

CEGB	Central Electric Generating Board, United Kingdom (now Nuclear Electric)
CMOD	Crack-mouth-opening displacement
CRIEPI	Central Research Institute of Electric Power Industry (Japan)
C(T)	Compact (Tension)
CUAEP	Commercial Use of Atomic Energy for Peaceful Purposes Agency (Bulgaria)
d-c	Direct current
DEGB	Double-ended guillotine break
DPZP	Dimensionless plastic-zone parameter
Dyn	Dynamic
Dyn-Cyc	Dynamic cyclic
EDF	Electricité de France
EDM	Electric-discharge machine
EP	Electric potential
EPRI	Electric Power Research Institute (U.S.)
FAC	Failure assessment curve
GE	General Electric (U.S.)
HAEC	Hungarian Atomic Energy Commission
HSK	Hauptabteilung für die Sicherheit der Kernanlagen (Switzerland)
IP	In-plane
IPIRG	International Piping Integrity Research Group
IPIRG-1	First International Piping Integrity Research Group
IPIRG-2	Second International Piping Integrity Research Group
J-R	J-resistance (curve)
KINS	Korea Institute of Nuclear Safety

KKL	Kernkraftwerk Leibstadt AG (Switzerland)
L-C	Orientation that indicates crack plane is normal to longitudinal axis (L) and crack growth direction is circumferential (C)
L-R	Orientation that indicates crack plane is normal to longitudinal axis (L) and crack growth direction is radial (R)
LVDT	Linear variable differential transformer
MPA	Materialprüfungsanstalt (Germany)
NRA	Nuclear Regulatory Authority (Slovak Republic)
NRC	Nuclear Regulatory Commission (U.S.)
NRC-NRR	Nuclear Regulatory Commission - Office of Nuclear Reactor Regulation (U.S.)
NRC-RES	Nuclear Regulatory Commission - Office of Nuclear Reactor Research (U.S.)
NRI	Nuclear Research Institute (Czech Republic)
NSC	Net-Section Collapse
NTIS	National Technical Information Service Reports
OD	Outside pipe diameter
OP	Out-of-plane
PVP	Pressure Vessel and Piping
PWR	Pressurized Water Reactor
QS	Quasi-static
QS Cyc	Quasi-static cyclic
SC	Surface-crack
SKI	Statens Kärnkraftinspektion (Swedish Nuclear Power Inspectorate)
SKKU	Sung Kyun Kwan University (Korea)
SMiRT	Structural Mechanics in Reactor Technology
TAG	Technical Advisory Group

Nomenclature

TWC	Through-wall crack
U.S.	United States
U.S. NRC	United States Nuclear Regulatory Commission
VATESI	State Nuclear Energy Safety Inspection of the Republic of Lithuania
VUJE	Vyskumny Ustav Jadrovych Elektrarni (Nuclear Power Plant Research Institute of Slovakia)

PREVIOUS REPORTS IN SERIES

Previous Reports from this Program

"Summary of Results from the IPIRG-2 Round-Robin Analyses," NUREG/CR-6337, BMI-2186, February 1996.

"The Effect of Cyclic and Dynamic Loads on Carbon Steel Pipe," NUREG/CR-6438, BMI-2188, February 1996.

"Design of the IPIRG-2 Simulated Seismic Forcing Function," NUREG/CR-6439, BMI-2189, February 1996.

"Deterministic and Probabilistic Evaluations for Uncertainty in Pipe Fracture Parameters in Leak-Before-Break and In-Service Flaw Evaluations," NUREG/CR-6443, BMI-2191, June 1996.

"Development of a J-Estimation Scheme for Internal Circumferential and Axial Surface Cracks in Elbows," NUREG/CR-6445, BMI-2193, June 1996.

Reports from the IPIRG-1 Program

"Evaluation and Refinement of Leak-Rate Estimation Models," NUREG/CR-5128, Revision 1, June 1994.

"Loading Rate Effects on Strength and Fracture Toughness of Pipe Steels Used in Task 1 of the IPIRG Program," Topical Report, NUREG/CR-6098, October 1993.

"Stability of Cracked Pipe Under Inertial Stresses," NUREG/CR-6233, Vol. 1, August 1994.

Previous Related Documents from NRC's Short Cracks in Piping and Piping Welds Program

"Short Cracks in Piping and Piping Welds," First Semiannual Report, NUREG/CR-4599, Vol. 1, No. 1, March 1991.

"Short Cracks in Piping and Piping Welds," Second Semiannual Report, NUREG/CR-4599, Vol. 1, No. 2, April 1992.

"Short Cracks in Piping and Piping Welds," Third Semiannual Report, NUREG/CR-4599, Vol. 2, No. 1, September 1992.

"Short Cracks in Piping and Piping Welds," Fourth Semiannual Report, NUREG/CR-4599, Vol. 2, No. 2, February 1993.

Previous Reports in Series

"Short Cracks in Piping and Piping Welds," Fifth Semiannual Report, NUREG/CR-4599, Vol. 3, No. 1, October 1993.

"Short Cracks in Piping and Piping Welds," Sixth Semiannual Report, NUREG/CR-4599, Vol. 3, No. 2, March 1994.

"Short Cracks in Piping and Piping Welds," Progress Report, NUREG/CR-4599, BMI-2173, Vol. 4, No. 1, April 1995.

"Fracture Behavior of Short Circumferential Short-Surface-Cracked Pipe," NUREG/CR-6298, November 1995.

"Fracture Evaluations of Fusion Line Cracks in Nuclear Pipe Bimetallic Welds," NUREG/CR-6297, April 1995.

"Effect of Dynamic Strain Aging on the Strength and Toughness of Nuclear Ferritic Piping at LWR Temperatures," NUREG/CR-6226, October 1994.

"Effects of Toughness Anisotropy and Combined Loading on Fracture Behavior of Ferritic Nuclear Pipe," NUREG/CR-6299, April 1995.

"Refinement and Evaluation of Crack-Opening Analyses for Circumferential Through-Wall Cracks in Pipes," NUREG/CR-6300, April 1995.

"Probabilistic Pipe Fracture Evaluations for Leak-Rate Detection Applications," NUREG/CR-6004, April 1995.

"Stainless Steel Submerged Arc Weld Fusion Line Toughness," NUREG/CR-6251, April 1995.

"Validity Limits in J-Resistance Curve Determination: Volume 1: An Assessment of the J_M Parameter," NUREG/CR-6264, Volume 1, February 1995.

"Validity Limits in J-Resistance Curve Determinations: Volume 2: A Computational Approach to Ductile Crack Growth Under Large-Scale Yielding Condition," NUREG/CR-6264, Volume 2, February 1995.

Previous Related Documents from NRC's Degraded Piping Program - Phase I Reports

"The Development of a Plan for the Assessment of Degraded Nuclear Piping by Experimentation and Tearing Instability Fracture Mechanics Analysis," NUREG/CR-3142, Vols. 1 and 2, June 1983.

Previous Related Documents from NRC's Degraded Piping Program - Phase II Reports

"Degraded Piping Program - Phase II," Semiannual Report, NUREG/CR-4082, Vol. 1, Oct. 1984.

"Degraded Piping Program - Phase II," Semiannual Report, NUREG/CR-4082, Vol. 2, June 1985.

- "Degraded Piping Program - Phase II," Semiannual Report, NUREG/CR-4082, Vol. 3, March 1986.
- "Degraded Piping Program - Phase II," Semiannual Report, NUREG/CR-4082, Vol. 4, July 1986.
- "Degraded Piping Program - Phase II," Semiannual Report, NUREG/CR-4082, Vol. 5, Dec. 1986.
- "Degraded Piping Program - Phase II," Semiannual Report, NUREG/CR-4082, Vol. 6, April 1988.
- "Degraded Piping Program - Phase II," Semiannual Report, NUREG/CR-4082, Vol. 7, March 1989.
- "Degraded Piping Program - Phase II," Semiannual Report, NUREG/CR-4082, Vol. 8, March 1989.
- "NRC Leak-Before-Break (LBB.NRC) Analysis Method for Circumferentially Through-Wall Cracked Pipes Under Axial Plus Bending Loads," Topical Report, NUREG/CR-4572, March 1986.
- "Elastic-Plastic Finite Element Analysis of Crack Growth in Large Compact Tension and Circumferentially Through-Wall-Cracked Pipe Specimen--Results of the First Battelle/NRC Analysis Round Robin," Topical Report, NUREG/CR-4573, September 1986.
- "An Experimental and Analytical Assessment of Circumferential Through-Wall Cracked Pipes Under Pure Bending," Topical Report, NUREG/CR-4574, June 1986.
- "Predictions of J-R Curves With Large Crack Growth From Small Specimen Data," Topical Report, NUREG/CR-4687, September 1986.
- "An Assessment of Circumferentially Complex-Cracked Pipe Subjected to Bending," Topical Report, NUREG/CR-4687, September 1986.
- "Analysis of Cracks in Stainless Steel TIG Welds," Topical Report, NUREG/CR-4806, November 1986.
- "Approximate Methods for Fracture Analyses of Through-Wall Cracked Pipes," Topical Report, NUREG/CR-4853, January 1987.
- "Assessment of Design Basis for Load-Carrying Capacity of Weld-Overlay Repair," Topical Report, NUREG/CR-4877, February 1987.
- "Analysis of Experiments on Stainless Steel Flux Welds," Topical Report, NUREG/CR-4878, February 1987.
- "Experimental and Analytical Assessment of Circumferentially Surface-Cracked Pipes Under Bending," Topical Report, NUREG/CR-4872, April 1987.

Previous Reports in Series

Other Related Program Reports

“Validation of Analysis Methods for Assessing Flawed Piping Subjected to Dynamic Loading,”
NUREG/CR-6234, August 1994.

1.0 INTRODUCTION

The Second International Piping Integrity Research Group (IPIRG-2) program was an international group program managed by the U.S. Nuclear Regulatory Commission (U.S. NRC) and conducted at Battelle. The overall objective of this program was to continue increasing the understanding of pipe fracture behavior through the development of data needed to verify engineering methods for assessing the integrity of nuclear power plant piping systems that contain cracks. The IPIRG-2 program included five main tasks:

Task 1 - Pipe System Experiments with Cracks in Straight Pipe and Welds

Task 2 - Fracture of Flawed Fittings

Task 3 - Cyclic and Dynamic Load Effects on Fracture Toughness

Task 4 - Resolution of Issues From IPIRG-1 and Related Programs

Task 5 - Information Exchange Seminars and Workshops, and Program Management.

This report presents the work performed in Task 2 (Fracture of Flawed Fittings).

1.1 Rationale and Objective For Task 2

The vast majority of piping integrity research to date has focused on critical flaw assessment methodologies and has addressed the problem in terms of straight pipe only. As elastic-plastic fracture mechanics and limit-load solutions are becoming increasingly more accurate and defined, the confidence with which we can predict the fracture behavior of straight pipe under dynamic loading conditions increases. Jurisdictional codes have adopted these engineering estimation methods for use on straight pipe, but the use of these methods for fitting analysis is still speculative.

Although not a common occurrence in nuclear piping, cracks have been observed in piping fittings. Due to physical characteristics such as increased geometric stiffnesses, larger wall thicknesses, and loading conditions, pipe fittings are generally considered to be less critical than straight pipe when assessing the reliability of a complete piping system. However, questions and concerns have arisen regarding the validity of predicting the fracture behavior of fittings using the analysis procedures developed for straight pipe.

As part of the Second International Piping Integrity Research Group (IPIRG-2) Program, work was directed toward addressing the issue of the fracture of flawed fittings. In general, this research task was developed to investigate the fracture behavior of elbows. More specifically, this work focused on developing engineering estimation methods to predict the behavior of surface-cracked elbows, validating these methods with large-diameter elbow fracture experiments, and assessing the applicability of using existing straight pipe analyses for predicting failure stresses of cracked elbows.

1.2 Technical Approach

To obtain the goal of improving the understanding of subcritical and critical crack growth behavior in cracked elbows under quasi-static and dynamic loading, the work was segmented into four major subtasks: (1) Survey and assessment of cracked fitting data, (2) development of applicable J-estimation schemes for the prediction of cracked elbows, (3) validation of these analysis techniques with full-scale elbow fracture experiments, and (4) determination of the applicability of existing straight pipe solutions for predicting elbow fracture.

The initial focus of this task was to review and compile existing analytical and experimental research data on cracked fittings. In order to better guide the direction of the experimental portion of this task, it was important to evaluate past work performed in this area. By drawing on existing knowledge of elbow fracture, the IPIRG-2 work could be directed toward improving existing elbow fracture studies, and/or fill in gaps in areas of elbow fracture which are important to understanding the behavior of elbows, but were not presently available. A survey was performed to compile the existing analytical and experimental work available in the literature. In conjunction with this, a database was compiled which contains experimental data from the literature and from IPIRG-2 member organizations. The data collected was used to determine the location and orientation of the crack geometry which would give the most benefit, based on service records, existing experimental programs, and concerns of the IPIRG-2 members.

Once the "target" crack geometry was determined, existing J-estimation scheme methods were surveyed and modified for use with cracks in elbows. The literature survey helped indicate which analytical schemes could be modified to be applicable to the cracked-elbow geometry. The developed model was validated by comparison with finite element solutions. One candidate method, developed during the Degraded Piping Program (Ref. 1.1), was an engineered form of a finite element line-spring model extended to include combined bending and internal pressure effects. This method was originally developed for a flat plate or a straight length of pipe containing a surface crack subjected to bending loads. However, since the element was developed using beam theory, it was a logical extension to modify it for elbows using curved beam theory. The focus was to develop a J-solution for the highest crack-driving force location along the crack, which may or may not occur at the mid-plane of the crack.

Four elbow fracture experiments were conducted on elbows having cracks in the region determined from the previous literature and analysis tasks. Two pipe-system experiments and two companion quasi-static elbow fracture experiments provided essential data necessary to evaluate the complex response of cracks in elbows in a pipe system loaded with a combination of inertial and displacement-controlled dynamic loads. The two quasi-static experiments were performed in Battelle's four-point bend pipe test facility. This facility was modified for use with the elbow geometry. The pipe system experiments were conducted in Battelle's dynamic pipe system facility, which was also modified to perform the loading on cracked elbows. Two materials were evaluated, and material properties were developed using elbows identical to those tested in the large-scale experiments. The experimental test matrix is given in Table 1.1.

Table 1.1 Experimental test matrix for Task 2 elbow experiments

Experiment	2-1	2-2	2-3	2-4
Material	Carbon Steel	Carbon Steel	Stainless Steel	Stainless Steel
Loading Type	Pipe System	Quasi-Static	Pipe System	Quasi-Static
O.D.	406 mm (16 inch)	406 mm (16 inch)	406 mm (16 inch)	406 mm (16 inch)
Schedule	100	100	100	100
Test Temperature	288 C (550 F)	288 C (550 F)	288 C (550 F)	288 C (550 F)
Internal Pressure	15.5 MPa (2,250 psi)	15.5 MPa (2,250 psi)	15.5 MPa (2,250 psi)	15.5 MPa (2,250 psi)

1.3 References

- 1.1 Wilkowski, G. M., and others, "Degraded Piping Program - Phase II, "Summary of Technical Results and Their Significance to Leak-Before-Break and In-Service Flaw Acceptance Criteria," March 1984 - January 1989, NUREG/CR-4082, Vol. 8, March 1989.

2.0 COMPILATION AND ASSESSMENT OF EXISTING REFERENCES AND DATA FOR CRACKED FITTINGS

This section describes the efforts to compile a bibliography of published analytical and experimental work regarding cracked fittings. The evaluation of the past work performed on pipe fittings (focusing on elbows) guided the analytical development of J-estimation schemes, and the design of the elbow fracture experiments performed as part of this task. A bibliography was compiled of analytical and experimental work found in the literature. The focus of this literature survey was elbow fracture. However, pertinent papers containing information on other fitting geometries were not discarded in the effort. Two databases were also developed, one for elbow fracture experiments, and one for experiments on tee fittings. The databases were developed to provide a medium for documenting the existing fitting fracture data in one location.

2.1 Cracked Fitting Literature Survey

A literature survey was conducted as part of Task 2 to consolidate into a single document existing references pertaining to cracked fittings. The survey includes 107 references categorized into analytical, experimental, and service information. These references were compiled from technical databases, conference proceedings, and IPIRG-2 member input. The three technical databases searched were Compendex (Engineering Index), National Technical Information Service Reports (NTIS), and Energy Science and Technology (Energy Abstracts). Conference proceedings also contained many of the references used. The International Conference on Pressure Vessel Technology, the Structural Mechanics in Reactor Technology (SMiRT), and the ASME Pressure Vessel and Piping Conference (PVP) were major sources of papers for this bibliography. Appendix A contains the listing of the literature survey.

2.2 Fitting Database

A database of full-scale elbow experiments was developed from the experimental papers obtained in the literature survey, the elbow experiments conducted as part of this IPIRG-2 task, and contributions from other IPIRG-2 member and non-member programs. The format for this database, ELBOWCK, is similar to the circumferentially and axially cracked, pipe fracture databases, CIRCUMCK and AXIALCK, developed as part of the Short Cracks in Piping and Piping Welds Program (Ref. 2.1). This elbow database contains the available experimental test conditions (i.e., elbow sizes, crack sizes, loading conditions, etc.), experimental results (moments at crack initiation and maximum load), and material property data (tensile and fracture toughness data) for 76 elbow experiments conducted worldwide. The database contains experiments on uncracked, surface cracked, and through-wall cracked elbows, at various locations (intrados, extrados, flank), and loading conditions (pressure, bending, or combined). Table 2.1 shows a breakdown of the types of experiments contained in the ELBOWCK database. A second, much smaller database, for tees, was also developed as part of this effort. This tee database, TEECK, shown in Table 2.2, includes 18 tee experiments. Listings for the ELBOWCK database and TEECK database are given in Appendix B and Appendix C, respectively.

Table 2.1 Summary of experiments listed in ELBOWCK database

Crack Type ⁽¹⁾	Orientation	Crack Location ⁽²⁾	Material	Outside Diameter, mm	Type of Bending ⁽³⁾	Pressure	Organization	Number of Tests	Reference Number
Uncracked	n/a	n/a	TP304L	114.3	QS-IP-C	Yes	Westinghouse	1	2.2, 2.3
Uncracked	n/a	n/a	TP316L	114.3	QS-IP-C&O	No	CEA	2	2.4, 2.5
Uncracked	n/a	n/a	A106B	139.2	QS-IP-C&O	No	CEA	4	2.6
Uncracked	n/a	n/a	A234	152.4	None	Yes	GE	1	2.7
Uncracked	n/a	n/a	15MnNi 6 3	489.0	QS-IP-C	No	MPA Stuttgart	1	2.8
Uncracked	n/a	n/a	15MnNi 6 3	489.2	QS-T	No	MPA Stuttgart	1	2.8
Uncracked	n/a	n/a	15MnNi 6 3	472.1	QS-IP-O	No	MPA Stuttgart	1	2.9
Uncracked	n/a	n/a	St. 35.8 I	140.5 to 158.5	QS-IP&OP-C&O	No	MPA Stuttgart	5	2.10
Uncracked	n/a	n/a	X10 CrNiNb 18 9	88.7 to 120	QS-IP&OP-C&O	No	MPA Stuttgart	4	2.10
Uncracked	n/a	n/a	A106B	139.2	QS-IP&OP-C&O	No	CEA	6	2.6
TWC	Circumferential	Extrados	TP316L	114.3	QS-IP-C	No	CEA	4	2.4, 2.5
TWC	Circumferential	Intrados	TP316L	114.3	QS-IP-O	No	CEA	5	2.4, 2.5
TWC	Circumferential	Extrados	TP304L	114.3	QS-IP-C	Yes	Westinghouse	1	2.2, 2.3
TWC	Circumferential	Intrados	TP304L	114.3	QS-IP-C	Yes	Westinghouse	1	2.2, 2.3
TWC	Circumferential	Intrados	X10 CrNiTi 18 9	108.5	QS-IP-C	Yes	MPA Stuttgart	1	2.11
SC	Circumferential	Flank	CF8M	580.0	QS-IP-C	No	EDF	1	2.12
SC	Circumferential	Flank	A234	152.4	None	No	GE	2	2.7
SC	Circumferential	Flank	CF8M	580.0	QS-IP-C	Yes	EDF	1	2.12
SC	Circumferential	Extrados	A106B	406.4	Dyn Cyc-IP-C	Yes	IPIRG-2	2	n/a
SC	Circumferential	Extrados	A106B	406.4	QS-IP	Yes	IPIRG-2	2	n/a
SC	Circumferential	Extrados	WP304L	406.4	Dyn Cyc-IP-C	Yes	IPIRG-2	2	n/a
SC	Circumferential	Extrados	WP304L	406.4	QS-IP	Yes	IPIRG-2	2	n/a
SC	Circumferential	Intrados	X10 CrNiTi 18 9	108.2	QS IP-C	Yes	MPA Stuttgart	1	2.13

Table 2.1 (Cont.) Summary of experiments listed in ELBOWCK database

Crack Type ⁽¹⁾	Orientation	Crack Location ⁽²⁾	Material	Outside Diameter, mm	Type of Bending ⁽³⁾	Pressure	Organization	Number of Tests	Reference Number
SC	Axial	Flank	TP316L	155.0	QS-IP-C	No	CEA	3	2.14
SC	Axial	Flank	CF8M	580.0	QS-IP-C	No	EDF	1	2.12
SC	Axial	Flank	A234	152.4	None	Yes	GE	3	2.7
SC	Axial	Extrados	A234	152.4	None	Yes	GE	3	2.7
SC	Axial	Intrados	17 NnMoV 6 4	168 to 219	None	Yes	MPA Stuttgart	2	2.10
SC	Axial	Flank	CF8M	580	QS-IP-C	Yes	EDF	1	2.12
SC	Axial	Flank	X10 CrNiMoTi 17 12	88.9	QS Cyc-IP	Yes	MPA Stuttgart	1	2.13
SC	Axial	Flank	20 MnMoNi 5 5	870	QS-IP-O	Yes	MPA Stuttgart	4	2.15, 2.16, 2.17
SC	Axial	Flank	20 MnMoNiV	871.2	Dyn Cyc	Yes	MPA Stuttgart	3	2.15, 2.16, 2.17
SC	Axial	Flank	15 NiCuMoNb	452	QS Cyc-IP-O	Yes	MPA Stuttgart	1	2.18
SC	Axial	Flank	20 MnMoNi 5 5	482.5	Dyn-IP-O	Yes	MPA Stuttgart	1	2.19
TWC	Axial	Flank	TP304L	114.3	QS-IP&OP-C&O	Yes	Westinghouse	3	2.2, 2.3
TWC	Axial	Flank	X10 CrNiTi 18 9	108.5	QS Cyc-OP	Yes	MPA Stuttgart	1	2.11
TWC	Axial	Flank	X10 CrNiTi 18 9	108.5	QS Cyc-IP	Yes	MPA Stuttgart	1	2.11
TWC	Helical	Intrados	X10 CrNiTi 18 9	108.5	QS Cyc-IP	Yes	MPA Stuttgart	1	2.11

(1) TWC = Through-wall-crack; SC = surface crack.

(2) The terms elbow "flank" and "crown" are used interchangeably in the literature.

(3) QS = quasi-static, QS Cyc = quasi-static cyclic, Dyn = dynamic, Dyn Cyc = dynamic cyclic. IP = in-plane, OP = out-of-plane. O = opening mode, C = closing mode.

Table 2.2 Summary of experiments listed in TEECK database

Crack Type ⁽¹⁾	Orientation	Crack ⁽²⁾ Location	Material	Outside ⁽²⁾ Diameters, mm	Type of Bending ⁽³⁾	Pressure	Organization	Number of Tests	Reference Number
Uncracked	n/a	n/a	ASTM A234	152.4, 152.4	None	Yes	GE	1	2.7
Uncracked	n/a	n/a	20 MnMoNi 5 5	862, 307	QS-IP-O	Yes	MPA Stuttgart	1	2.15, 2.16, 2.17
Uncracked	n/a	n/a	20 MnMoNi 5 5	862, 307	QS-IP-C	Yes	MPA Stuttgart	1	2.15, 2.16, 2.17
SC	-	J	ASTM A234	152.4, 152.4	None	Yes	GE	3	2.7
SC	-	K	ASTM A234	152.4, 152.4	None	Yes	GE	3	2.7
SC	-	L	ASTM A234	152.4, 152.4	None	Yes	GE	3	2.7
SC	-	K	MnMoNiV	855, 307	QS-IP	Yes	MPA Stuttgart	3	2.15, 2.16, 2.17
SC	-	K	20 MnMoNi 5 5	862, 307	QS-IP	Yes	MPA Stuttgart	1	2.15, 2.16, 2.17
TWC	-	L	08Ch18M12T	560, 273	QS-IP-O	Yes	NRI	1	2.20
TWC	-	L	08Ch18M12T	560, 273	QS-IP-O	No	NRI	1	2.20

(1) TWC = Through-wall crack; SC = Surface crack.

(2) For description of orientation and location of cracks see Appendix C.

(3) QS = quasi-static, Dyn = dynamic.

IP = in plane, OP = out of plane.

O = opening mode, C = closing mode.

2.3 References

- 2.1 Wilkowski, G. M., and others, "Short Cracks in Piping and Piping Welds," Semiannual Report, March 1993 - December 1994," NUREG/CR-4599, Vol. 4, No. 1, April 1995.
- 2.2 Begley, J. A., and Sheinker, A. A., "Crack Propagation Testing for LMFBR Piping - Phase I Final Report," WARD-HT-3045-17, 1976.
- 2.3 Begley, J. A., Wilson, W. K., and Sheinker, A. A., "Crack Propagation Investiagion Related to the Leak-Before-Break Consept for LMFBR Piping," *International Journal of Mechanical Engineering*, pp. 215-224, 1978.
- 2.4 Moulin, D., Touboul, F., Foucher, N., Lebey, J., Acker, D., "Experimental Evaluation of J in Cracked Straight and Curved Pipes Under Bending," 10th SMiRT, Vol. G, pp 323-326, 1989.
- 2.5 Moulin, D., Touboul, F., Foucher, N., Lebey, J., Acker, D., "Crack Initiation and Experimental Determination of J in Bending for Elbows and Pipes of Austenitic Steel," PVP-Vol. 165, pp 89-94, 1989.
- 2.6 Brouard, D., Tremblais, A., Vrillon, B., "In-Plane and Out-of-Plane Bending Tests on Carbon Steel Pipe Bends," 5th SMiRT, Vol. F, 1979.
- 2.7 Vandenberg, S. R., "Reactor Primary Coolant System Rupture Study," General Electric, Quarterly Report No. 20, GEAP-11069, AEC Research and Development Report, April 1970.
- 2.8 Diem, H. K., and others, "Inelastic Analysis of Pipe Bends - Analytical and Experimental Investigation, Load Case, In-Plane Bending, Closing Mode, Load Case Out-of-Plane Loading," Final Report MPA No. 8550 00 000, April 1991.
- 2.9 Diem, H. K., and others, "Inelastic Analysis of Pipe Bends - Analytical and Experimental Investigation, Load Case In-Plane Bending, Opening Mode," Final Report MPA No. 8410 00 000, June 1986.
- 2.10 Diem, H. K., "Untersuchungen zum Geometrieinfluß auf das Verformungs- und Versagensverhalten von Rohrbogen," MPA Stuttgart, 1994.
- 2.11 Diem, H. K., and others, "Failure Behavior of Thick-Walled, Austenitic Pipe Bends Under Cyclic Bending Loading at Constant Internal Pressure," *Nuclear Engineering and Design*, 151, pp 269-289, 1994.
- 2.12 Le Delliou, P., Semete, P., Ignaccolo, S., "Fracture Mechanics Analysis of Cast Duplex Stainless Steel Elbows Containing a Surface Crack," 1996 ASME PVP Conference, *Fatigue and Fracture-1996*, Volume 323, June 1996.

- 2.13 Diem, H.K., et al., "Erzeugung von drei Ermüdungsrissen in Austenitischen Rohrteilen DN 80 für Leckversuche E22," PHDR Report No. 90.068/91, 1991.
- 2.14 Moulin, D., Brochard, J., "Classification of Stress in the Ligament of a Longitudinal Crack in an Ovalizing Elbow," Creep, Fatigue Evaluation, and Leak-Before-Break Assessment, PVP-Vol. 266, pp 147-154, 1993.
- 2.15 Schuler, X., Blind, D., Eiscle, U., Herter, K., Stoppler, W., "Fracture Mechanics Evaluation of Cracked Components with Consideration of Multiaxiality of Stress State," *Nuclear Engineering and Design*, 151, pp 291-305, 1994.
- 2.16 Schuler, X., Blind, D., Eiscle, U., Herter, K., "Extension of Fracture Mechanics Evaluation Methods by Consideration of Multiaxiality of Stress State for Piping Components," *Nuclear Engineering and Design*, 158, pp 227-240, 1995.
- 2.17 Schwartz, Th., Julisch, P., Herter, K., Stopper, W., "Experimental Investigations on the Strength and Fracture Behavior of Degraded Piping Components," SMiRT 12 Conf., Paper F06/1, pp 87-92, 1993.
- 2.18 Diem, H. K., "Investigation on Incipient Cracking, Crack Growth and Leak-Before-Break Behavior of Piping Components Subjected to Constant Internal Pressure on Cyclic Bending Moment," PHDR Report No. 83-92, Kernforschungszentrum Karlsruhe (in German), 1992.
- 2.19 Uhlmann, D., "Investigations on the Influence of Multiple Crack Fields on the Stress Intensity of Pipe Bends Subjected to Constant Internal Pressure and Bending," PHDR Report No. 120-93, Kernforschungszentrum Karlsruhe (in German), 1993.
- 2.20 Carter, A. J., "A Finite Element Analysis of a Cracked T-Joint," Nuclear Electric Report, TEM/REP/0006/94, April 1994.

3.0 IPIRG-2 TASK 2 ELBOW EXPERIMENTS

This section of the report describes the four large-scale pipe experiments performed on 16-inch nominal diameter, Schedule, 100 long-radius elbows. The discussion includes the design of the elbow test specimens, characterization of material properties, a description of the experimental facilities used to conduct the experiments, and the background and experimental results for the two dynamic elbow, pipe-system experiments and the two companion, quasi-static elbow experiments performed under Task 2 of the IPIRG-2 program.

3.1 Objective of the Task 2 Elbow Experiments

Four large-scale elbow fracture experiments were performed to develop experimental data on the fracture behavior of surface-cracked, long-radius elbows subjected to a combination of bending and internal pressure. The data generated from these experiments will serve two major purposes: to aid in the development and verification of elbow fracture analysis schemes developed under this program, and to assess the applicability of using straight pipe analyses to predict elbow fracture stresses. The data generated in this program are unique in that the experiments were performed at PWR conditions, and the elbow specimens were loaded until surface-crack penetration of the elbow wall was achieved. Two of the experiments were performed under quasi-static loading, and two were performed under dynamic loading, combining displacement and inertia forces. In the quasi-static elbow tests, after surface-crack penetration, the test was stopped, the instrumentation was fixed, and then the test was continued as a TWC test.

3.2 Choice of Crack Orientation

Initially, both circumferentially-oriented and axially-oriented cracks were considered. However, assessing the crack location from an experimental viewpoint quickly points out some difficulties with performing axially-cracked elbow experiments. There was some question of whether the existing pipe-system facility could develop the required loads to conduct these types of experiments without damaging the pipe loop. Also, in the event of unstable surface-crack penetration, there was concern about arresting a potential running axial crack and the higher energy release in such an experiment. For the circumferential crack orientation, the existing pipe-system facility had sufficient loading and deflection capabilities to conduct the experiments. The required bending load could be controlled by the original crack geometry (length and depth) to ensure surface-crack penetration. With a circumferential crack, the applied bending load drives the crack growth. This also ensures that the existing instrumentation capabilities would be sufficient to collect data that would be useful input for the analytical model. Design concerns with a circumferential crack orientation included a complete separation of the crack (DEGB), and difficulties introducing an internal machined starter crack due to the geometrical constraints of working inside a curved shell.

From an analytical viewpoint, a circumferential crack orientation facilitated the development of an analytical estimation approach by adapting estimation techniques developed for straight pipe to elbow geometries. A J-estimation scheme was to be developed for axial surface cracks, but little experience existed with this flaw geometry and predicting the resulting through-wall crack instability under dynamic/cyclic loading.

The recommendation of the IPIRG-2 members was to perform this initial investigation using the circumferential crack orientation, located on the elbow extrados, because it had relevance to the concern of the piping industry, and because it would lend itself to the generation of experimental data that would be more easily comparable to existing work with elbow fracture. It was felt that assessing the feasibility of using straight pipe estimation procedures for the analysis of cracked elbows was more important than other possible program objectives. Although it would be possible to develop experimental and analytical approaches for an axial crack in an elbow, the uncertainties would make achieving the overall task objective more difficult.

3.3 Elbow Specimen Design

Four elbow experiments were allocated for the experimental portion of this task. The elbow experiments performed in this task are unique in that there are companion experiments providing both dynamic and quasi-static elbow fracture data for similar crack geometries. It was decided early in the program that more benefit would be obtained from testing two materials with similar crack geometries, as opposed to testing two distinct crack geometries on one material type. The materials chosen to be evaluated were carbon steel and stainless steel. These materials are widely used in the nuclear power industry, and had direct relevance to some of the IPIRG-2 member organizations.

Originally, the proposed work scope called for seam-welded elbows to be used in the experiments. Based on the decision to conduct the elbow experiments with circumferential surface cracks, the potential increased analytical difficulties of dealing with crack growth through a seam weld was considered to be an additional unnecessary complication. Thus, it was decided to use seamless elbows for all of the elbow experiments.

3.3.1 Elbow Details

Test elbows were purchased directly from Custom Alloy Incorporated, a U.S. manufacturer of hot bend formed elbows. The test elbows were manufactured specifically for this test program, using typical manufacturing processes. Three stainless steel elbows were purchased; two test elbows and one elbow for use in developing material property data. All three elbows were manufactured from the same length of 16-inch nominal diameter, Schedule 120, TP304L straight pipe. Because of the high cost of stainless steel elbows, no additional elbows were purchased. A total of eight carbon steel elbows were purchased for this test program. The carbon steel elbows were manufactured from two lengths of 16-inch nominal diameter, Schedule 120, A106 Grade B straight pipe. The two lengths of pipe were from the same lot number and heat treatment to maintain material consistency. One elbow was needed to develop material property data, two elbows were needed for the elbow experiments, two elbows were needed to perform the straight pipe-to-elbow girth weld experiments (Experiments 1-3 and 1-4 from Task 1 of the IPIRG-2 Program), and three elbows were purchased for possible optional tests. The additional cost to purchase the extra elbows was small compared to the cost to develop new material property data if additional work was approved.

The elbows were specified as 16-inch nominal diameter, Schedule 100, seamless, long-radius, 90-degree elbows. All elbows were formed by hot-bending. Details of the fabrication procedures are given in Table 3.1.

Table 3.1 Fabrication procedures for the carbon steel and stainless steel elbows used in the Task 2 elbow experiments

Material	Carbon Steel	Stainless Steel
Initial heat to	980 C (1800 F)	1090 C (2000 F)
Hot bend in closed die	>620 C (1150 F)	>980 C (1800 F)
Fabrication Standard	ASTM A234	ASTM A403
Cooling method	Still air	Still air
Post-forming heat treatment	None	Solution annealing at 1066 C (1950 F) for approx. 1.5 hours w/ water quench

Figure 3.1 shows a schematic of an elbow with nomenclature for describing locations on the elbow. Wall thickness measurements were made for each elbow to determine the manufacturing variability, and to guide the design of the crack geometry. Figure 3.2 shows the wall thickness measurements for the elbows used in the experiments. The measurements were taken using an ultrasonic thickness transducer calibrated by measuring the wall thickness at the end of the elbow and comparing these readings to measurements taken at the same location using a ball micrometer. Some wall thinning occurred in the extrados region of the elbow due to the hot-bending fabrication process. Measurements of the outside diameters of the elbows at the elbow mid-plane show that the fabrication process induced a slight ovalization in the elbow. This initial ovalization was within the allowable guidelines (Ref. 3.1). Table 3.2 gives the average outside diameter measurements for the carbon steel and stainless elbows.

Table 3.2 Average outside diameter measurements for the elbow test specimens

	Carbon Steel	Stainless Steel
Intrados-Extrados	403 mm (15.9 inches)	405 mm (15.9 inches)
Flank-Flank	411 mm (16.2 inches)	410 mm (16.1 inches)

Note: The measurements are taken at the mid-plane of the elbow.

Figure 3.1 Schematic of elbows and terminology used for IPIRG-2 elbow experiments

Figure 3.2 Pre-test wall thickness measurements for carbon steel and stainless steel elbows taken at the elbow mid-plane

3.3.2 Crack Geometry Details

The crack geometry used for all elbow experiments was an internal circumferential surface crack located at the mid-plane of the elbow, centered at the elbow extrados, see Figure 3.3. The cracks were nominally 50 percent of the circumference in length, and were to be machined so that there was a constant remaining ligament (after precracking) over the length of the crack. Since the wall thickness varies over the length of the cracks, this required the crack depth to vary to maintain a constant remaining ligament. Using this crack geometry facilitates analysis by maintaining consistency with the assumptions used in common straight-pipe analyses techniques. However, as will be discussed later in this section, the actual machining of the cracks was difficult, and the resulting crack depth following precracking was somewhat irregular.

Initial analysis of the distribution of the J-integral over the circumference of the elbow helped guide the location for the crack. This analysis was based on three-dimensional models of an uncracked elbow, and a line-spring element cracked elbow model described later in this report. Figure 3.4 shows the calculated J-integral versus angle (degrees from the elbow extrados) for the case of combined pressure and bending. The maximum value of J occurs at approximately ± 45 degrees from the extrados, with a gradual reduction of approximately 38 percent at the extrados. For this reason, the crack was centered on the extrados, and continued for 90 degrees on either side of the center of the flaw. This allows for the possibility of surface-crack penetration occurring at either (or both) of the regions of maximum J and it provides consistency with most of the other IPIRG (Ref. 3.2) and Degraded Piping program surface-crack geometries (Ref. 3.3).

Figure 3.3 Crack geometry orientation for elbow experiments

Figure 3.4 Distribution of J versus position on crack for elbow specimens

Figure 3.5 characterizes the influence of the applied moment on J at the point of maximum J (± 45 degrees) compared with J at the crack centerline (extrados). The analysis shows that as the applied moment increases, there is a decrease in the difference between the J-centerline and J-45 degrees. Therefore, during the experiment, the crack could be expected to initiate and grow through the pipe wall somewhere in the ± 60 degree region about the crack centerline. The occurrence of the largest difference in J at low applied moment levels meant that during fatigue loading to sharpen the crack, there would be a tendency for the crack to preferentially grow at the 45-degree regions, producing an irregular crack depth. The consequences of performing the experiments with a blunt notch front caused more concern than producing a crack of irregular depth. This is because this irregular flaw depth would probably occur in service. Therefore, it was decided to precrack both the carbon steel and stainless steel elbow specimens.

3.4 Material Property Data

The carbon steel specimens tested were fabricated from a 16-inch nominal diameter, Schedule 100, carbon steel, long-radius elbow. The stainless specimens tested were fabricated from a 16-inch nominal diameter, Schedule 100, stainless steel, long-radius elbow. The Battelle pipe identification number was IP2-FE17 for the carbon steel elbow and IP2-AE1 for the stainless steel elbow. Elbows IP2-FE13 through IP2-FE19 and IP2-FE21 were fabricated at the same time from the same heat of A106 Grade B carbon steel pipe as used for IP2-FE17. For the stainless steel elbows, specimens IP2-AE1 through IP2-AE3 were fabricated at the same time from the same heat of TP304L pipe as used for IP2-AE1.

Figure 3.5 Ratio of J at 45-degree location to J at the crack centerline versus normalized moment for line-spring and three-dimensional finite element models for circumferential elbow crack

Figure 3.6 shows the layout of the material property test specimens used to characterize the elbows. Round-bar tensile, high-speed tensile, and compact-tension specimens were machined from material at the elbow mid-plane, on the extrados of the elbow. From the carbon steel elbow, eight Charpy specimens were cut from the centerline-extrados and the centerline-intrados locations to compare impact properties (Charpy specimens are not shown in Figure 3.7). Round-bar tensile and high-speed tensile specimens were also machined from one end of the carbon steel elbow to see if there is a difference in material properties between the elbow mid-plane location and the elbow ends. This was of special concern for the IPIRG-2 Task 1 elbow girth weld experiments.

3.4.1 Tensile Properties

Longitudinal tensile specimens were machined from the elbow extrados. Round-bar tensile specimens with a 6.35 mm (0.25 inch) diameter gage section, oriented such that the tensile axis was parallel to the elbow axis, were used to characterize the quasi-static tensile properties of these materials. An extensometer with a 12.7 mm (0.5 inch) gage length was used to measure axial strain in these quasi-static tests. Flat, pin-loaded tensile specimens with integral flags were used for the dynamic tensile tests. The gage section for the dynamic tensile tests had a width of 6.35 mm (0.25 inch), a thickness of 3.18 mm (0.125 inch), and a gage length of 25.4 mm (1.00 inch). Strain in the gage section of the dynamic tests of the carbon steel elbow was monitored using a high temperature MTS® clip gage. Knife edges were welded to the integral flags to mount the extensometer. The clip gage was also used for the stainless steel specimens. A few of the initial tests used an Optronic® optical extensometer, but this device proved to be

Figure 3.6 Schematic of layout for material characterization specimens

unreliable in these recent tests. In these cases, load-point displacements were used to calculate strains. The temperature during the tensile tests was 288 C (550 F), unless noted.

Table 3.3 is a summary of the tensile properties for the elbow materials. Engineering stress-strain curves for the tensile tests are presented in Figure 3.7 for the carbon steel elbow and Figure 3.8 for the stainless steel elbow. As can be seen in Figures 3.7 and 3.8, the higher strain rate lowered the stress-strain curves for the ferritic material while the higher strain rate had little effect on the stress-strain curves for the stainless steel material. The reduction in ultimate strength for the ferritic materials is typical of the nuclear grade ferritic materials calculated in previous programs and is usually attributed to dynamic strain aging effects (Ref. 3.4).

Table 3.3 Tensile properties summary

Specimen Identification Number	Strain Rate, s ⁻¹	0.2 Percent Offset Yield Strength		Ultimate Tensile Strength		Percent Elongation
		MPa	ksi	MPa	ksi	
IP-FE17-T1	2 x 10 ⁻⁴	208.3	30.21	449.5	65.19	28.3
IP-FE17-T2	2 x 10 ⁻⁴	215.0	31.18	446.4	64.75	29.1
IP-FE17-T3	2 x 10 ⁻⁴	210.4	30.51	452.2	65.58	28.2
IP-FE17-T4	2 x 10 ⁻⁴	203.3	29.49	443.9	64.38	29.5
IP-FE17-HT1	1.0	265.5 ^(a)	38.50	404.0	58.55	30.4
IP-FE17-HT2	1.0	273.7 ^(a)	39.70	412.7	59.86	30.4
IP-FE17-HT3	1.0	248.9	36.10	386.7	56.09	21.9
IP-FE17-HT4	1.0	192.4	27.90	404.0	58.59	25.2
IP2-AE1-T1 ^(b)	2 x 10 ⁻⁴	324.8	47.11	662.3	96.06	75.0
IP2-AE1-T2 ^(b)	2 x 10 ⁻⁴	330.2	47.89	651.1	94.43	73.0
IP2-AE1-T3	2 x 10 ⁻⁴	200.2	29.04	408.0	59.18	47.0
IP2-AE1-T4	2 x 10 ⁻⁴	187.9	27.25	410.6	59.55	46.0
IP2-AE1-HT1	0.80	231.1	33.52	407.3	59.07	52.0
IP2-AE1-HT2	0.80	208.9	30.30	410.7	59.57	50.0
IP2-AE1-HT3	0.85	213.0	30.89	432.1	62.67	50.0

(a) OPTRON® device used. Yield strength was determined using actuator displacement instead of local specimen strain.

(b) The temperature during these tests was 20 C (68 F), all other tests performed at 288 C (550 F).

3.4.2 Quasi-Static and Dynamic J-Resistance Tests on Compact Specimens at 288 C (550 F)

Fracture toughness specimens were of the compact (tension), C(T), design and contained side grooves to a depth of 10-percent per side. They were machined from the pipe thickness without flattening the pipe and were machined in the L-C orientation; that is, the longitudinal direction was the loading direction while the circumferential direction was the crack growth direction. Specimen dimensions are shown in Table 3.4,

Figure 3.7 Stress-strain curves for carbon steel Elbow IP2-FE17

Figure 3.8 Stress-strain curves for stainless steel Elbow IP2-AE1

Table 3.4 C(T) specimen dimensions

Specimen Identification Number	Approximate Time to Initiation, seconds	Specimen Dimensions, mm			
		w	B	B _N	a ₀
IP-FE17-1	0.2	50.82	25.40	20.50	27.73
IP-FE17-2	0.2	50.88	25.40	20.55	27.77
IP-FE17-3	600	50.85	25.43	20.52	27.50
IP-FE17-4	600	50.56	25.40	20.50	27.55
IP-FE17-1	0.2	50.82	25.40	20.50	27.73
IP-FE17-2	0.2	50.88	25.40	20.55	27.77
IP2-AE1-1	600	50.93	25.40	20.30	29.84
IP2-AE1-5	600	50.85	25.40	20.30	29.48

where w, B, B_N, and a₀ denote width, thickness, net thickness at side grooves, and initial crack length, respectively.

The specimens were fatigue precracked according to the specifications in ASTM E1152-87, Standard Test Method for Determining J-R Curves, to produce an initial average crack length of about 0.54W. Both quasi-static and dynamic tests were conducted at 288 C (550 F). Displacement rates in the quasi-static tests were set to cause crack initiation in about 10 minutes. In the dynamic tests, the displacement rates were selected to cause crack initiation in about 0.2 seconds.

The quasi-static specimens were tested in a screw-driven INSTRON[®] machine with a 133.4 kN (30,000 pound) capacity. The dynamic tests were run in a servo-hydraulic MTS[®] test frame with a 89 kN (20,000 pound) capacity. The direct-current electric potential method was used to detect crack initiation and to monitor crack growth during the C(T) tests. The data were recorded using LABTECH Notebook[®] software and included load, ram displacement, load-line displacement, and d-c electric potential.

The procedures used to reduce the C(T) data are described in detail in Reference 3.5. J-Resistance curves are shown in Figure 3.9 for the carbon steel material (IP-FE17), and in Figure 3.10 for the stainless steel material (IP2-AE1). Values of J_i and dJ/da are summarized in Table 3.5. As can be seen in Figures 3.9 and 3.10, the higher loading rate had only a minor effect on the J-R curves for the carbon steel elbows, while the higher loading rate increased the J-R curves for the stainless steel elbows.

3.4.3 Chemical Analysis

A chemical comparison analysis was performed on the two materials to check for conformance with the applicable specification.

Figure 3.9 J-Resistance curves for carbon steel Elbow IP2-FE17

Figure 3.10 J-Resistance curves for stainless steel Elbow IP2-AE1

Table 3.5 Fracture toughness summary

Specimen Identification	Time to Crack Initiation, seconds	J at Initiation		dJ/da ^(a)	
		kN/m	lb/in	MN/m ²	lb/in ²
IP-FE17-1	0.2	373.0	2,130	207.8	30,140
IP-FE17-2	0.2	349.3	1,995	193.8	28,100
IP-FE17-3	600	532.7	3,042	249.9	36,250
IP-FE17-4	600	317.3	1,812	306.6	44,470
IP2-AE1-2	0.2	1,377	7,863	200.0	29,000
IP2-AE1-3	0.2	1,341	7,659	123.0	17,800
IP2-AE1-1	600	1,116	6,347	144.9	21,000
IP2-AE1-5	600	1,062	6065	90.9	13,200

(a) Determined for crack lengths of 0.15 mm to 1.5 mm (0.006 inch to 0.06 inch).

The chemical composition for the carbon steel is shown in Table 3.6 and the chemical composition for the stainless steel is shown in Table 3.7. Both of the materials satisfy the requirement of their specification.

Table 3.6 Chemical analysis for A106 Grade B carbon steel elbow (IP-FE17)

C	Mn	P	S	Si	Ni	Cr	Mo	V	Ca
0.17	0.93	0.017	0.003	0.26	0.015	0.029	0.011	0.000	0.000
Co	Cu	Sn	Al	Zr	Ti	B	Nb	Pb	
0.002	0.010	0.001	0.032	0.000	0.014	0.000	0.028	0.000	

Table 3.7 Chemical analysis for TP304L stainless steel elbow (IP-AE1)

Fe	C	Mn	P	S	Si	Ni	Cr	Mo	V
70.5	0.03	1.90	0.02	0.03	0.32	8.3	18.8	0.19	0.05
Co	Ca	Sn	Al	Zr	Ti	B	Nb	Pb	
0.08	0.0011	0.000	0.04	0.001	0.006	0.0004	0.01	0.000	

3.5 The IPIRG-2 Elbow Experimental Facilities

The IPIRG pipe loop and quasi-static pipe test facility used to perform the elbow experiments were modified from their original straight pipe specimen configurations to perform experiments on these Schedule 100, long-radius elbows. A description of the modifications made to both facilities is given below, along with the implementation of safety devices.

3.5.1 Pipe-System Experimental Facility

The experimental test facility used to conduct the two elbow pipe-system experiments was essentially the same test facility used to conduct the IPIRG-2 pipe-system experiments on straight pipe, except for modifications made near the test elbow to allow for the installation of the required instrumentation.

Figure 3.11 is an artist's conception of the IPIRG-2 pipe-system experimental facility. The test facility is configured as an expansion loop and is fabricated from predominantly 16-inch nominal diameter, Schedule 100 pipe. The straight pipe in the pipe loop is fabricated from ASTM A710, Grade A, Class 3 pipe steel. The five long-radius elbows are 16-inch nominal diameter Schedule 100 elbows. Elbows 1, 2, 3, and 5 are fabricated from WPHY-65 material. The test elbow (Elbow 4) was located as shown in the figure. Figure 3.12 shows the physical dimensions of the pipe system test facility near the Elbow 4 location. To perform the elbow experiments, modifications were made to the pipe sections adjacent to the test elbow: an additional moment cell was added east of the test elbow, and tapered sections were added to accommodate the fact that the test elbow for these experiments was Schedule 100, and not Schedule 160 as was used in the straight-pipe experiments. Appendix D provides the detailed pipe loop dimensions, including wall thickness measurements, for the pipe-system configuration used to perform the elbow experiments.

The boundary conditions for the piping loop are realized by using various specialized pieces of hardware. At the two fixed ends, the pipe loop is welded to a 1,500 pound class weld neck flange, which is bolted to a large steel frame that is buried in a large, heavily reinforced concrete mass. At the actuator location, the pipe loop, which is being forced in the X-direction (see Figure 3.11), is restrained in the vertical direction, and is free to rotate and translate in the other four degrees of freedom. At the two hanger locations near the fixed ends, the pipe is restrained in both the vertical and horizontal directions perpendicular to the pipe axis, but is free to translate and rotate in the other four degrees of freedom. At each of these locations, large spherical bearings allow the pipe to rotate about all three axes and translate in the direction of the pipe axes. At the two vertical supports, the pipe is supported only in the vertical direction. In order to minimize any frictional forces in the X-Y plane at these two locations, the pipe is supported by hydrostatic bearings. Spherical bearings were used in conjunction with the hydrostatic bearings at these two locations to allow the pipe to rotate about each of the three axes.

System loads are applied by a 1.56 MN (350,000 pound), Moog Model 85-454, double-ended piston actuator (equal piston areas for both push and pull) with a 457 mm (18.0 inch) stroke capacity. The actuator is driven by a 7,600 liter per minute (2,000 gpm), Moog Model 79-507, three-stage servo-valve which is supplied with oil at 21 MPa (3,000 psi) by piston-type accumulators with an oil capacity of 760 liters (200 gallons). Nitrogen gas to drive the accumulators is stored in separate pressure vessels.

Figure 3.11 Artist's conception of the IPIRG pipe loop

The pipe loop is connected to an auxiliary expansion tank of 760 liter (200 gallon) capacity, which is filled with air prior to the heat-up. This tank accommodates the expansion of the water as it is heated from ambient temperature to 288 C (550 F). It also provides an accumulator effect for maintaining the pressure at the test conditions. Heat for bringing the pipe loop to test temperature is supplied by heater tapes wrapped continuously around the exterior of the pipe. Water in the pipe loop is circulated by a pump connected to the two fixed ends to provide an even temperature distribution. The pipe loop is completely covered with fiberglass insulation.

Figure 3.12 Physical dimensions of pipe-system test facility near the test elbow location

3.5.1.1 Restraint Systems

In the pipe-system experiments performed with cracks in straight pipe conducted as part of Task 1 of the IPIRG-2 program, a restraint system consisting of a central rod, two baffle plates, and a series of Belleville washers was incorporated into the overall test system design to control the motion of the two halves of the pipe loop in the event a double-ended-guillotine-break (DEGB) occurred (Ref. 3.6). However, because this restraint system relied on a central straight rod to hold the two halves of the pipe loop together, it was not possible to incorporate this device for use in the elbow test specimen due to the curvature of the elbow. Instead, it was decided to limit the amount of subcooled water at the cracked test specimen (i.e., minimize the potential for damaging energy release) by using end caps containing a small hole to restrict the flow of water into the cracked test specimen region. The location of these end caps is shown in Figure 3.12. End caps were welded on both sides of the test specimen 1.83 m (72 inches) from the test elbow to straight pipe girth weld. This length was chosen to minimize the constraint of ovalization at the elbow. Each end cap contained a 19 mm (0.75 inch) diameter hole to allow the circulation of water through pipe loop during heat up.

Another aspect that lessened the probability of a DEGB was that the forcing function used to perform these experiments was shut down as soon as the surface crack penetrated the pipe wall and a specimen pressure drop was detected. Using this procedure, the likelihood of the through-wall crack growing completely around the circumference was judged to be low.

As a backup measure of restraint, a series of 8,800 kg (4,000 pound) bags of sand were placed around critical areas of the pipe loop (Figure 3.13) to absorb the energy of the pipe in the event that a DEGB did occur. The sand bags were stacked in two layers, and placed behind large oak timber barriers. The barriers were placed as close to the pipe loop as possible, without interfering with the pipe motion during the course of the experiment. If a DEGB did occur, the pipe hitting and moving the mass of the sandbags would dissipate energy, thus lessening the overall damage to the pipe loop facility.

3.5.1.2 Uncracked Shakedown Experiment

Prior to conducting any IPIRG-2 pipe-system experiments, an uncracked shakedown experiment was performed to measure the damping and first few natural frequencies of the pipe system. These measurements were conducted with the pipe system prepared to perform the straight-pipe experiments, not the elbow experiments. There were small changes in elbow geometry (the test elbow was Schedule 100 for the elbow experiments and Schedule 160 for the straight-pipe experiments), and with the addition of a third moment cell located east of the elbow specimen, the stiffness was slightly different. It should also be noted that these measurements were performed without the primary internal restraint system in place (the restraint system was not used for the elbow experiments.) The small differences in pipe geometry at the test elbow region should have a negligible effect on the characteristics of the pipe system configuration for the elbow experiments, and the damping and natural frequency data reported are assumed to apply for the elbow configuration.

Figure 3.13 Pre-test photograph of sandbags positioned near the pipe system

The damping and natural frequencies were assessed with the pipe loop at PWR conditions, i.e., 288 C (550 F) and 15.5 MPa (2,250 psi) internal pipe pressure. The procedures for qualifying the damping in the pipe system were the same as used in IPIRG-1 (Ref. 3.2). Table 3.8 gives the measured damping values and first four natural frequencies of the pipe system.

Table 3.8 Experimentally measured damping value and natural frequencies associated with the IPIRG-2 pipe loop facility at 288 C (550 F) and 15.5 MPa (2,250 psi) internal pipe pressure

Damping ⁽¹⁾ , Percent Critical Damping	Natural Frequencies, Hz ⁽²⁾			
	First	Second	Third	Fourth
0.45	4.5	8.5	14.2	18.4

(1) Measured through a system "ring-down" test and analyzed using the log-decrement analysis.

(2) Measured frequency response for an actuator-controlled input displacement using a bandwidth-limited random noise excitation signal with an actuator preload of 31.1 kN (7,000 lbs).

3.5.2 Quasi-Static Elbow Experimental Facility

Two quasi-static elbow experiments were performed to provide data to compare with the pipe-system, dynamic elbow experiments. A strongback facility (Figure 3.14) was designed and constructed to perform the quasi-static experiments on the elbow specimens. This facility was a modification of Battelle's existing large pipe bend facility, and used an existing 2,000 kN (450 kip) hydraulic actuator to apply load to a horizontal length of pipe extending from the elbow specimen. A vertical length of pipe attached to a 1500 pound class weld neck flange fixed the test specimen to the strongback. Both extension pipes were manufactured from 16-inch nominal diameter, Schedule 100, A710 Class 3 pipe. End caps were welded to the extension pipes to limit the volume of pressurized water. The distance from the end caps to the test specimen was at similar distances used in the pipe system experiments to maintain a consistent volume of pressurized water between the two experiments. Figure 3.15 shows a pretest photograph of the quasi-static elbow test facility.

3.6 Elbow Experiments

Four large-scale elbow fracture experiments were performed to develop experimental data on the fracture behavior of surface-cracked, long-radius elbows subjected to a combination of bending and internal pressure. The data generated from these experiments served two major purposes: (1) to aid in the development and verification of elbow fracture behavior estimation schemes, and (2) to assess the applicability of straight pipe analyses for predicting elbow fracture. Two, single-frequency, dynamic, elbow, pipe-system experiments and companion, quasi-static experiments were performed. The elbow materials investigated were the A106 Grade B carbon steel and WP304L stainless steel described earlier.

Note: Moment arm length measured from load point to the intersection of the crack plane and the mean elbow radius of curvature (point M)

Figure 3.14 Schematic of test facility for quasi-static elbow experiments

Figure 3.15 Pre-test photograph of quasi-static elbow test facility

3.6.1 Test Procedures

The IPIRG-2 Task 2 elbow experiments were conducted following the procedures outlined in the Quality Assurance Document IPI2-PP1, Revision 1, "Procedure for Performing Pipe Fracture Experiments Under Combined Inertial and Seismic/Dynamic Displacement Controlled Stresses". This document specified detailed checklist-type procedures for preparing the test specimens (Section 5.0), for setting up the dynamic pipe-system experiments (Section 6.0), for conducting the pipe-system experiments (Section 7.0), for conducting the companion quasi-static bend experiments (Section 8.0), and for documenting the results of the experiments and post-test procedures (Section 9.0).

3.6.2 Specimen Preparation

The four test elbows were manufactured using "typical" hot-bend forming techniques (see Section 3.3) and were purchased as standard hot bent seamless, Schedule 100, long-radius elbows. No special manufacturing procedures were used to fabricate the elbows, and no additional machining was performed on the elbows to alter the wall thickness, or inside and outside diameters. The decision to test "as received" elbows was made in the early phase of the IPIRG-2 Program in order to provide experimental data using actual elbow geometries. Although comparisons of the experimental data would have a higher degree of uncertainty due to the assumptions made in the analysis prediction methods (circular cross section, constant wall thickness, and uniform crack depth), the experimental data generated would reflect a more accurate representation of a typical service crack.

The procedure for machining an internal surface crack located on the extrados of an elbow was a difficult task. In past IPiRG experiments, the cracks were introduced using electric discharge machining (EDM) techniques because of economics and the high quality of the cracks. This technique was also chosen for the elbow specimens. However, due to the out-of-roundness of the elbow, and the variable wall thickness, a slightly different approach was required than was used in the past to machine cracks in straight pipe specimens.

Prior to machining the initial crack geometry, the elbow inside profile and wall thickness were mapped at the crack plane. The variation of the elbow wall thickness over the region of the machined crack is shown in Figure 3.2. These measurements allowed an accurate drawing to be constructed, using computer aided design (CAD) software, of the elbow cross section at the crack plane. Next, the final crack geometry was drawn on the cross-section. This final crack was designed so a constant remaining ligament remained over the entire crack length. To aid in achieving a uniform fatigue precrack over the length of the crack, a scalloped leading edge was incorporated into the machined crack. This technique was used successfully in past pipe programs and was hoped to lessen the chance of obtaining a local dominating region of crack growth. A 2.5 mm (0.01 inch) allowance for fatigue crack growth was incorporated in the design of the EDM probe geometry. Once the crack design was completed, the computer drawing was transferred to a computer-controlled milling machine to fabricate the EDM probes. Three independent fan-shaped probes were used to machine the complete crack. The center probe was a 96-degree probe that contained 12.7 mm (0.5 inch) long scallops. Two independent 43-degree side probes contained scallops except for the final 15 degree region, where no fatigue precrack was expected to occur. The two outer probes overlapped the center probe slightly to provide a smooth transition between the machined crack regions. Figure 3.16 shows a scale drawing of the elbow used in the stainless steel pipe-system experiment (Experiment 2-3). The other elbows tested showed similar variations in geometry.

Although great care was taken to ensure that the reference point of the three probes was identical and at the center of the elbow cross-section, maintaining a precise reference was difficult to achieve, and slight over cuts occurred at the intersection of the EDM probes.

Prior to conducting the experiments, the elbows were loaded with a cyclic bending load (with no internal pressure) to grow and sharpen the machined crack. During this fatigue precracking, the over cut was smoothed out by the advancement of the fatigue precrack. However, the combination of higher J at this location on the elbow and the slightly deeper original crack depth resulted in a test crack with a variable crack depth (a/t) and variable remaining ligament (b/t). The actual crack geometry was measured during post-test fracture analysis, and will be discussed later in this section.

3.6.3 Test Conditions

The test conditions for each of the elbow experiments were representative of pressurized water reactor (PWR) conditions, i.e., 288 C (550 F) and 15.5 MPa (2,250 psi).

3.6.4 Instrumentation

The instrumentation used to collect data during the pipe-system and companion quasi-static elbow experiments is given in Table 3.9. For the most part, the instrumentation used in the elbow experiments is

	Centerline, mm	End A, mm	End B, mm
Wall thickness	29.5	32.7	32.7
Inside radius	173.7	170.7	170.7

Figure 3.16 Scale drawing of crack plane for the stainless steel elbow used in Experiment 2-3 (elbow pipe-system experiment)

Table 3.9 Instrumentation used during the IPIRG-2 elbow fracture experiments

Experiment No.	2-1	2-2	2-3	2-4
Applied Load or Moment	X	X	X	X
Applied Displacements	X	X	X	X
Pipe Displacements	X	X	X	X
Rotation	X	X	X	X
CMOD	X	X	X	X
d-c EP	X	X	X	X
Pipe Pressure	X	X	X	X
Ovalization		X		X
Reaction Force	X		X	
Strain	X	X		

similar to that used in the IPIRG-2 straight-pipe experiments, with the exception that additional string potentiometers were incorporated to measure the elbow displacements during the quasi static experiments, and a third moment cell was added to the pipe-system facility to help in the determination of the moment at the elbow crack location. Figure 3.17 shows the layout for the external instrumentation used during the quasi-static elbow experiments, while Figures 3.18 and 3.19 show the external instrumentation used during the elbow pipe-system experiments.

In conjunction with the external instrumentation, instrumentation was also placed inside the test elbows at the crack location to measure the crack-mouth-opening-displacement and d-c electric potential across the crack. The layout of this instrumentation was the same for all four elbow experiments. Figure 3.20 shows the location of the LVDT's used to measure CMOD, and the d-c electric potential probes, used to detect crack initiation and measure crack growth. Pre-test analysis of the elbow geometry showed that the distribution of J along the crack length was slightly higher at ± 45 degrees from the crack centerline. Therefore, the possibility of multiple initiation sites existed. It was decided to use three LVDT's across the crack in each experiment to ensure that CMOD near the actual point of surface-crack penetration would be recorded. For this same reason, d-c electric potential probes were placed across the ± 45 degree region of the crack in addition to the crack centerline location. These probes were also used during the fatigue precracking of the test specimen to monitor crack initiation and growth.

3.6.5 Results of IPIRG-2 Elbow Experiments

The key results for the two elbow pipe-system experiments and the two companion quasi-static elbow experiments are summarized in Table 3.10. Included in this table are material property data, crack geometry measurements, and moment at crack initiation and maximum moment for each experiment.

3.6.5.1 Loading History

The two dynamic elbow pipe-system experiments, Experiment 2-1 for the carbon steel elbow and Experiment 2-3 for the stainless steel elbow, were performed in the IPIRG pipe loop test facility. The dynamic elbow pipe-system experiments were loaded using a constant-frequency, increasing amplitude, displacement-controlled sinusoidal waveform, similar to that used in the IPIRG-1 and selected IPIRG-2 Task 1 straight-pipe experiments. The forcing function was applied to the pipe system until surface-crack penetration occurred, at which time a Battelle-built programmable attenuator linearly attenuated the forcing function to zero over a four second time period. The attenuator was set up so that once the pressure inside the test specimen dropped below 12.4 MPa (1,800 psi), the forcing function was shut down. Figures 3.21 and 3.22 show the actuator displacement versus time data for Experiment 2-1 and Experiment 2-3 respectively. In Experiment 2-1 (carbon steel), the crack penetrated the surface of the pipe 2.40 seconds into the loading history during the peak portion of the 9th cycle. For Experiment 2-3 (stainless steel), the crack penetrated the surface of the pipe 5.62 seconds into the loading history, during the loading portion of the 22nd cycle. However, the crack only broke through the wall in a local region, and the forcing function continued for another cycle, at which time, the crack broke through along the length of the machined crack, triggering the shutdown sequence of the forcing function.

Figure 3.17 Layout of external instrumentation for quasi-static elbow experiments

Figure 3.18 Overall schematic for external instrumentation for elbow pipe-system experiments

Figure 3.19 External instrumentation near the test elbow for the elbow pipe-system experiments

Figure 3.20 Location of internal instrumentation for all elbow experiments

Table 3.10 Key results for the IPIRG-2 elbow experiments

Experiment No.	2-1	2-2	2-3	2-4
Material	A106 Grade B	A106 Grade B	WP304L	WP304L
Loading Type	Pipe System	Quasi-Static	Pipe System	Quasi-Static
Surface Crack Length/Elbow Circumference	0.49	0.50	0.50	0.50
Average a/t (Crack Depth/Average Wall Thickness)	0.67	0.68	0.63	0.64
Centerline a/t (Crack Depth/Centerline Wall Thickness)	0.60	0.54	0.58	0.53
Maximum a/t (Crack Depth/Local Wall Thickness)	0.84	0.80	0.73	0.77
Location of Maximum a/t (degrees from centerline - Side X)	54 degrees - Side A	55 degrees - Side B	55 degrees - Side A and 70 degrees - Side B	57 degrees - Side A
Moment at Crack Initiation [kN-m (in-kips)]	561.9 to 579.8 (4,973 to 5,132)	593.1 (5,249)	601.1 (5,320)	536.2 (4,745)
Maximum Moment [kN-m (in-kips)]	579.8 (5,132)	607.9 (5,380)	728.5 (6,448)	548.0 (4,850)
Moment at Surface Crack Penetration [kN-m (in-kips)]	446.9 (3,956)	594.3 (5,260)	286.4 (2,535)	504.7 (4,467)

Figure 3.21 Actuator displacement versus time for carbon steel, pipe-system Experiment 2-1

Figure 3.22 Actuator displacement versus time for stainless steel, pipe-system Experiment 2-3

The two companion quasi static experiments, Experiment 2-2 for the carbon steel elbow and Experiment 2-4 for the stainless steel elbow, were performed using the IPIRG-2 elbow bend test facility constructed as part of this experimental task. The loading function for these two experiments was a displacement-controlled, constant-rate ramp waveform. Since the loading rate for these experiments was slow, and the hydraulic actuator was operated in displacement control, there was no need for a programmable signal controller to stop the loading. Once surface-crack penetration occurred, the command signal was manually returned to zero at the servo-hydraulic controller, removing the applied load from the specimen. Figure 3.23 shows the loading history for Experiment 2-2, the carbon steel, quasi-static companion test. This plot shows the pipe displacement at the load point and applied load versus time. A displacement rate of 5.2 mm per minute (0.2 inches per minute) was used for this experiment. Surface-crack penetration occurred at 1,584 seconds after the start of loading, as noted by the sudden drop in applied load. The applied load shown in this figure includes adjustments for the dead weight due to the weight of the pipe and water. Similar data are shown for Experiment 2-4, the stainless steel companion elbow experiment, in Figure 3.24. The same displacement rate was used in both quasi-static experiments. Surface-crack penetration for this experiment occurred at 2,282 seconds after the start of loading.

Figure 3.23 Pipe displacement at the load point and total applied load versus time for the carbon steel, quasi-static elbow Experiment 2-2

Figure 3.24 Pipe displacement at the load point and total applied load versus time for the stainless steel, quasi-static elbow Experiment 2-4

3.6.5.2 Moment and Pressure Data

The moment versus time response for Experiment 2-1 is shown in Figure 3.25. The moment value includes both the applied dynamic moment calculated from the output of three instrumented moment cells located on the straight pipe sections adjacent to the test elbow, and static values inferred from ANSYS® finite element analyses of the piping system. At surface-crack penetration there is a sudden loss of moment carrying capacity of the elbow section. The plot of internal pressure versus time is also shown in Figure 3.25 to further indicate the occurrence of surface-crack penetration. The moment at crack initiation was between 561.9 kN-m (4,973 in-kips) and 579.8 kN-m (5,132 in-kips). This corresponds to an elapsed time of between 1.885 and 2.130 seconds. The ranges given for crack initiation are a result of an uncertainty in estimating the point of crack initiation due to a saturation of the d-c electric potential signal during the initial cycles of the experiment. The maximum moment for this experiment was 579.8 kN-m (5,132 in-kips).

The moment and pressure versus time data for Experiment 2-3 is shown in Figure 3.26. In this figure, the pressure drop occurs on the loading portion of the 22nd cycle. The moment corresponding to crack initiation and maximum moment are 601.1 kN-m (5,320 in-kips) and 728.5 kN-m (6,448 in-kips) respectively. Crack initiation occurred at a time of 3.865 seconds. Maximum moment occurred at a time of 5.150 seconds, on the 20th loading cycle. Following crack penetration, the through-wall crack remained tight, as can be seen in the slow decay of the internal pressure in Figure 3.26. Video cameras monitoring the test section show that steam was venting from two regions approximately 45-60 degrees on either side of the crack centerline. Post-test fracture analysis did show that the crack had propagated along the entire length of the initial machined crack.

Figure 3.25 Moment and internal pipe pressure versus time for carbon steel, elbow pipe-system Experiment 2-1

Figure 3.26 Moment and internal pipe pressure versus time for stainless steel, elbow pipe-system Experiment 2-3

The moment data for the quasi-static experiments are shown in Figures 3.27 and 3.28. The moment values were calculated from the total applied load and the moment arm length from the load point to the crack plane. For the carbon steel elbow, the moment at crack initiation was 593.1 kN-m (5,249 in-kips) and the maximum moment was 607.9 kN-m (5,380 in-kips). For the stainless steel elbow, the moment at crack initiation was 536.2 kN-m (4,745 in-kips) and the maximum moment was 548.0 kN-m (4,850 in-kips).

3.6.5.3 Crack-Mouth-Opening-Displacement Data

Crack-mouth-opening-displacement data were obtained using high temperature/high pressure LVDT's mounted across the crack on the inside pipe surface at three locations; crack centerline, and 45 degrees on either side of the crack centerline. Figure 3.29 shows the crack section moment data versus the CMOD data recorded at the crack centerline for the two carbon steel experiments (Experiment 2-1 and 2-2). The data show similar behavior for the dynamic-cyclic, and the quasi-static-monotonic experiments. This is consistent with the C(T) specimen fracture toughness data shown in Figure 3.9 for this material. The carbon steel showed no significant change in toughness with increasing strain rate. Similar data are shown in Figure 3.30 for the CMOD data taken from the LVDT nearest to the location (Side A or Side B) where surface-crack penetration occurred. There is little difference between these data plots. This suggests that the surface crack was growing in a somewhat uniform manner during both the quasi-static and pipe-system experiments.

The CMOD data for the stainless steel experiments for the crack centerline LVDT, and for the location of surface-crack penetration are shown in Figures 3.31 and 3.32. There is a noticeable difference in CMOD response between the crack centerline and Side B during the final few loading cycles for the pipe-system experiment. This result confirms the visual observation of the crack penetrating the surface on side B one loading cycle prior to the crack centerline. There is also a noticeable increase in moment capacity for the pipe-system experiment. This is also consistent with the results from the C(T) specimen fracture toughness tests for this material (Figure 3.10), where there was an increase in toughness with an increase in strain rate.

3.6.5.4 Rotation Data

Rotation data were obtained by measuring the deflection of the outside surface of the elbow specimen across the crack plane using LVDT's (pipe-system experiments), and string potentiometers and inclinometers (quasi-static experiments). The rotation measurement is total rotation (2ϕ). Although these data are commonly used in the development of analytical pipe fracture predictions, caution should be used when showing elbow test results due to the uncertainties/complications of measuring gross rotation behavior of elbows under bending and pressure loading. The rotation data presented for the quasi-static experiments are calculated from the "horizontal" and "vertical" string potentiometer data (see Figure 3.17). These data were found to most accurately compare with measurements of total rotation taken from photographs made during the tests. Figure 3.33 and Figure 3.34 show the moment verses rotation data for the carbon steel and stainless steel experiments, respectively. Data for both the quasi-static and pipe-system experiments are shown in both of these figures. As can be seen in Figure 3.33, the agreement between the carbon steel, quasi-static moment-rotation curve and the upper envelope of the carbon steel, pipe-system moment-rotation curve is excellent. For the stainless steel elbow experiments, the quasi-static

Figure 3.27 Moment and internal pipe pressure versus time for carbon steel, quasi-static elbow Experiment 2-2

Figure 3.28 Moment and internal pipe pressure versus time for stainless steel, quasi-static elbow Experiment 2-4

Figure 3.29 Crack section moment versus centerline crack-mouth-opening displacement for the carbon steel, quasi-static and pipe-system elbow experiments

Figure 3.30 Crack section moment versus crack-mouth-opening displacement near the point of surface-crack penetration for the carbon steel, quasi-static and pipe-system elbow experiments

Figure 3.31 Crack section moment versus centerline crack-mouth-opening displacement for the stainless steel, quasi-static and pipe-system elbow experiments

Figure 3.32 Crack section moment versus crack-mouth-opening displacement near the point of surface-crack penetration for the stainless steel, quasi-static and pipe-system elbow experiments

Figure 3.33 Crack section moment versus total rotation (2ϕ) for the carbon steel, quasi-static and pipe-system elbow experiments

Figure 3.34 Crack section moment versus total rotation (2ϕ) for the stainless steel, quasi-static and pipe-system elbow experiments

moment-rotation curve is quite a bit less than upper envelope of the moment-rotation curve for the pipe-system experiment, see Figure 3.34. The difference in response between the quasi-static and pipe-system experiments for the two materials is due to the different effect loading rate has on the fracture toughness of the two materials.

3.6.5.5 Fracture Surface Measurements

Figure 3.35 shows an overview photograph of the fracture surface for Experiment 2-3 (stainless steel, pipe-system experiment). From this photograph, the initial machined scalloped crack shape can be seen (scalloped crack) as well as the additional crack growth due to fatigue precracking. The fracture surfaces for the other three elbow experiments show similar shapes, and are not shown here. Figures 3.36a and 3.36b show close-up photographs of the same fracture surface at locations 45 degrees from the crack centerline on Side A and Side B, respectively. The beachmarks from the cyclic crack growth can be seen in both photographs.

Figures 3.37a and 3.37b show plots of the measured initial a/t ratios taken from post-test measurements of the fracture surfaces for the carbon steel and stainless steel elbow experiments, respectively. The plots show the local a/t distribution, calculated by measuring the distance from the inside surface to the edge of the precrack front and dividing this by the local wall thickness measured at this same location, over the length of the machined crack. The variation in initial wall thickness over the crack length are also shown on these plots. These data are given as local measured wall thickness divided by maximum wall thickness (over the crack length).

As was noted earlier, the initial crack geometry for the four experiments could not be maintained at a constant a/t ratio. Therefore, caution should be exercised when making direct comparisons between the measured moment values recorded for the experiments without correcting for the differences in crack depths.

Figure 3.35 Overview of fracture surface for Experiment 2-3

(a) Side A, 45 degrees from the crack centerline

(b) Side B, 45 degrees from the crack centerline

Figure 3.36 Close-up photographs of fracture surface for Experiment 2-3

(a) a/t ratios for carbon steel elbow experiments

(b) a/t ratios for stainless steel elbow experiments

Figure 3.37 Post-test fracture surface measurements

3.7 References

- 3.1 "Chemical Plant and Petroleum Refining Piping," ASME B31.3, 1992.
- 3.2 Scott, P., and others, "The IPIRG-1 Pipe System Fracture Tests: Experimental Results," PVP Vol. 280, pp 135-151, June 1984.
- 3.3 Wilkowski, G. M., and others, "Degraded Piping Program - Phase II, Summary of Technical Results and Their Significance to Leak-Before-Break and In-Service Flaw Acceptance Criteria," March 1984 - January 1989, NUREG/CR-4082, Vol. 8, March 1989.
- 3.4 Marschall, C. W., and others, "Effect of Dynamic Strain Aging on the Strength and Toughness of Nuclear Ferritic Piping at LWR Temperatures," NUREG/CR-6226, July 1994.
- 3.5 Marschall, C. W., and others, "Loading Rate Effects on Strength and Fracture Toughness of Pipe Steels Used in Task 1 of the IPIRG Program," NUREG/CR-6098, BMI-2175, October 1993.
- 3.6 Scott, P., and others, "IPIRG-2 Task 1 Report - Pipe System Experiments with Circumferential Cracks in Straight-Pipe Locations," NUREG/CR-6389, December 1996.

4.0 ANALYSIS OF EXPERIMENTS

The main objectives of Task 2 of this program were to develop engineering estimation methods to predict the behavior of surface-cracked elbows, validate these methods with large-diameter elbow fracture experiments, and assess the applicability of using existing straight-pipe analyses for predicting failure stresses of cracked elbows. In this section, the main focus will be on comparing the experimental elbow data with the maximum stress predictions from various straight-pipe fracture prediction analysis methods, and with the maximum stress predictions from the elbow fracture analysis prediction methods developed as part of Task 2 of this program. In addition, through-wall-cracked elbow experimental data are compared with limit-moment solutions for straight-pipe and elbow geometries.

4.1 Fracture Prediction Methodology for Cracked Elbows

This section describes the development of estimation schemes for circumferentially and axially cracked elbows.

In order to assure the structural integrity of nuclear piping systems, several assessment approaches have been developed as part of the ASME Boiler and Pressure Vessel Code. All of these approaches are strictly applicable to cracked straight-pipe sections. However, service failures do occur in pipe bend or elbow sections of the piping systems. Simple modifications, or extensions, of approaches applicable to cracked straight-pipe sections may be inadequate for pressurized elbows containing cracks. Accordingly, a fracture methodology, based on the spirit of the GE/EPRI estimation scheme (Ref. 4.1), was developed using detailed finite element analyses.

Owing to the large number of finite element calculations needed to develop an estimation scheme, a three-dimensional finite element analysis involving immense computational effort to assure adequate mesh design, enormous computer storage, and significant data reduction, would be a quite formidable task. An attractive alternative, which was used in this work, was the line-spring/shell model, which reduces the three-dimensional surface-crack problem into a more tractable two-dimensional shell problem. This model was proposed by Rice and Levy (Ref. 4.2) for linear-elastic, surface-crack problems and was further extended to account for elastic-plastic deformations by Parks and co-workers (Refs. 4.3-4.5). The line-spring/shell model has been shown to render reasonably accurate predictions of fracture parameters for surface-cracked pipes and elbows in comparison with the full three-dimensional finite element models (Ref. 4.6). The finite element calculations using the line-spring/shell model to develop an estimation scheme for cracked elbows were performed using the finite element software code, ABAQUS® (Ref. 4.7).

A summary of the estimation scheme for circumferentially-cracked and axially-cracked pressurized, long-radius elbows is given below. Additional details can be found in Reference 4.8. In the case of a circumferentially-cracked elbow, the constant-depth crack is located on the inside surface of the elbow at the extrados, with the total crack angle of 180 degrees. A closing in-plane bending moment is applied to the pressurized cracked elbow. A separate estimation scheme for a constant-depth, internal, axial crack having a total length of 30 degrees located at the flanks of the pressurized elbow is also presented in Reference 4.8. The loading for this case is an opening, in-plane, bending moment. Solutions are developed for several radius to wall thickness ratios, as well as crack depth to wall thickness ratios. The

allowable pressure, p_a , in the elbow is calculated using an average value of S_m for various piping materials at an operating temperature of 288 C (550 F). The allowable pressure for straight pipes according to the ASME Section III, Article NB-3640, is given by,

$$p_a = \frac{2S_m t_{\text{pipe}}}{D_o - 2yt_{\text{pipe}}} \quad (4-1)$$

where D_o is the outer diameter of the pipe, t_{pipe} is the actual thickness of the pipe, and the constant y is taken to be 0.4.

4.1.1 J-Estimation Scheme for Circumferentially Surface-Cracked Elbows

A schematic sketch of a circumferentially cracked elbow is shown in Figure 4.1. The crack, located at the extrados, will open with an in-plane closing moment. The equations pertaining to the J-estimation scheme for a circumferentially, surface-cracked elbow are given below. The crack-driving force, J , is decomposed into its elastic and plastic parts. The elastic part of the J is obtained through the knowledge of the stress intensity factor associated with internal pressure, K_I^{pr} , and bending moment, K_I^M . These stress intensity factors are in turn obtained from F_I functions as described below.

$$J = J_e + J_p \quad (4-2)$$

Figure 4.1 Schematic of circumferential crack geometry used for development of an elbow analysis

$$J_e = \frac{(1-\nu^2)}{E} \left[K_I^{pr} + K_I^M \right]^2 \quad (4-3)$$

$$K_I^{pr} = \frac{pR_m}{2t} \sqrt{\pi a} F_I^{pr} \left(y, \lambda, \frac{R_m}{t}, \frac{\theta}{\pi}, \frac{a}{t} \right) \quad (4-4)$$

$$K_I^M = \frac{MR_m}{I} \sqrt{\pi a} F_I^M \left(y, \lambda, \frac{R_m}{t}, \frac{\theta}{\pi}, \frac{a}{t} \right) \quad (4-5)$$

where,

- J_e = elastic component of J-integral
- K_I^{pr} = Mode I stress intensity factor due to internal pressure
- K_I^M = Mode I stress intensity factor due to bending moment
- p = applied pressure
- R_m = mean pipe radius
- F_I^{pr} = function used in elastic stress intensity factor definition associated with internal pressure
- F_I^M = function used in elastic stress intensity factor definition associated with bending moment
- λ = elbow parameter
- a = surface-crack depth
- θ = surface-crack length
- I = moment of inertia
- t = pipe thickness

The plastic part of the crack-driving force is given by,

$$J_p = \alpha \epsilon_o \sigma_y b \left(\frac{R_m}{t\lambda} \right) h_1^M \left[\frac{M}{M_o} \right]^{(n+1)}; b = t - a \quad (4-6)$$

where M_o is a reference moment for a cracked elbow and the coefficient function, h_1 , is given by

$$h_1 \left(\psi, \lambda, \frac{R_m}{t}, \frac{a}{t}, \frac{\theta}{\pi}; n; p \right) \quad (4-7)$$

where ψ is the elbow angle.

Though all relevant dependencies are shown in the h_1 function, it is emphasized that the dependency on y and θ/π are frozen due to the assumptions given earlier and the dependency on the internal pressure, p , is limited as explained earlier. The choice of the reference moment, M_o used in Equation 4-6 is quite

arbitrary. However, h_1^M functions amenable to interpolation are obtained only with a proper choice of M_o . Owing to the fact that no simple expression for the limit moment for a circumferentially cracked elbow is available in the published literature, two different expressions are for M_o , both of which pertain to a straight pipe with an equivalent crack are proposed. The following expressions are used for M_o :

- (i) GE/EPRI approach (used for surface-cracked straight pipes)

$$M_{o(GE)} = M_o^{nc} \frac{A^{nc}}{A} \quad (4-8)$$

where,

A = total area of cross-section

A^{nc} = area of uncracked cross-section

$$M_o^{nc} = 2\sigma_o t (R_o^2 + R_i^2)$$

σ_o = reference stress, typically taken as the yield strength.

- (ii) Net-Section Collapse (NSC) equation (used for surface-cracked straight pipes)

For $\beta < \pi - \theta$

$$M_{o(NSC)} = 2R_m^2 t \sigma_f \left[2\sin\beta - \frac{a}{t} \sin\theta \right] \quad (4-9)$$

$$\beta = \frac{\pi - \theta(a/t)}{2} - \frac{\pi R_i^2 p}{4R_m t \sigma_f} \quad (4-10)$$

For $\beta > \pi - \theta$

$$M_{o(NSC)} = 2R_m^2 t \sigma_f \left[\left(2 - \frac{a}{t}\right) \sin\beta \right] \quad (4-11)$$

$$\beta = \frac{\pi}{2 - a/t} \left[1 - a/t - \frac{R_i^2 p}{2R_m t \sigma_f} \right] \quad (4-12)$$

Where β is the angle from the bottom of the pipe (opposite of the center of the crack) to the fully plastic neutral axis.

The J-estimation scheme for the case when the GE/EPRI approach is used to define M_o is referred to as SC.ELB2. The J-estimation scheme for the case where the NSC approach is used to define M_o is referred to as SC.ELB1.

4.1.2 J-estimation Scheme for Axially Surface-Cracked Elbows

A schematic sketch of an axially surface-cracked elbow is shown in Figure 4-2. Two constant-depth cracks are located at the internal surface of the pipe at each of the flank (crown) locations of the elbow. A 30-degree long crack is assumed at each location. Owing to this geometry, the opening of the cracks will occur when an in-plane opening moment is applied. In the finite element analysis, only one quarter (containing one axial crack) of the cracked elbow is modeled due to symmetry. It is assumed that the total driving force, J , for a pressurized, axially-cracked elbow subjected to bending can be written as the sum of the elastic part due to internal pressure and bending, J_e^{pr+M} , the plastic part due to internal pressure, J_p^{pr} , and the plastic part due to subsequent bending, J_p^M , as given by,

$$J = J_e^{pr+M} + J_p^{pr} + J_p^M \quad (4-13)$$

Figure 4.2 Schematic of axial crack geometry used for development of elbow analysis

where,

$$\begin{aligned} J_e^{pr+M} &= \text{elastic part of } J \text{ associated with combined internal pressure and bending} \\ J_p^{pr} &= \text{plastic part of } J \text{ associated with internal pressure} \\ J_p^M &= \text{plastic part of } J \text{ associated with bending} \end{aligned}$$

with the elastic part given by,

$$J_e^{pr+M} = \frac{[1-\nu^2]}{E} [K_I^{pr} + K_I^M]^2 \quad (4-14)$$

and

$$K_I^{pr} = \frac{pR_m}{t} \sqrt{\pi a} F_I^{pr} \left(\psi, \lambda, \frac{R_m}{t}; \ell, \frac{a}{t} \right) \quad (4-15)$$

$$K_I^M = \frac{MR_m}{I} \sqrt{\pi a} F_I^M \left(\psi, \lambda, \frac{R_m}{t}; \ell, \frac{a}{t} \right) \quad (4-16)$$

where ℓ = total length of axial surface crack.

The plastic part of the crack-driving force due to pressure loading is assumed to be represented by,

$$J_p^{pr} = \alpha \sigma_o \epsilon_o b \lambda h_1^{pr} \left[\frac{p}{p_o} \right]^{n+1}; \quad b = t - a \quad (4-17)$$

where,

$$h_1^{pr} = h_1^{pr} \left(\psi, \lambda, \frac{R_m}{t}; \ell, \frac{a}{t}; n \right) \quad (4-18)$$

where p_o is the limit pressure of a corresponding straight pipe with an equivalent axial crack. The limit pressure, p_o , is calculated using the following expression initially developed at Battelle in the 1960's and is given in Section XI of the ASME Section XI Boiler and Pressure Vessel Code,

$$P_o = \frac{\sigma_o t}{R_m} \frac{[t/a - 1]}{\left[t/a - \frac{1}{M_2} \right]} \quad (4-19)$$

with

$$M_2 = \left[1 + \left(\frac{1.61}{4R_m t} \right) \ell^2 \right]^{0.5} \quad (4-20)$$

where ℓ is the total length of the axial crack. The plastic part of the crack-driving force due to subsequent bending is represented by,

$$J_p^M = \alpha \sigma_o \epsilon_o b \left[\frac{R_m}{t \lambda} \right] h_1^M \left[\frac{M}{M_{o(e)}} \right]^{n+1}; \quad b = t - a \quad (4-21)$$

where

$$h_1^M = h_1^M \left(\psi, \lambda, \frac{R_m}{t}, \frac{\theta}{\pi}, \frac{a}{t}; n; p \right) \quad (4-22)$$

and

$$M_{o(e)} = 0.935 \sigma_o \left(8 R_m^2 t \right) \lambda^{2/3} \quad (4-23)$$

In the above expression, $M_{o(e)}$ defines the limit moment for an uncracked elbow as proposed by Griffiths (Ref. 4.9). The J-estimation scheme developed as part of this effort for axially cracked elbows is referred to as SC.ELB3.

Using the above expressions for the crack-driving force, the F_1 and h_1 functions were determined for axially- and circumferentially-cracked elbows. Additional details are presented in Reference 4.8.

4.2 Straight-Pipe Fracture Prediction Methods

In an effort to evaluate the applicability of straight-pipe analysis techniques for predicting the failure stresses in elbow fracture experiments, the following straight-pipe fracture analysis procedures were considered:

the Net-Section-Collapse (NSC) analysis (Ref. 4.10),

the Dimensionless-Plastic-Zone-Parameter (DPZP) analysis (Ref. 4.11), and

the SC.TNP1 (Ref. 4.12), SC.TNP2 (Ref. 4.13), SC.TKP2 (Ref. 4.13), and SC.ENG2 (Ref. 4.13) J-estimation scheme methods.

4.2.1 Net-Section-Collapse Analysis

The original Net-Section-Collapse (NSC) analysis method was included in this comparative analysis because it is the analysis method which forms the basis for the flaw evaluation procedures in Section XI of the ASME Code, i.e., IWB-3640 and Appendix C for austenitic piping and IWB-3650 and Appendix H for ferritic piping. [Note, Kurihara (Ref. 4.14) modified the basic approach to account for very deep cracks. Comparisons between the Kurihara modified version of the Net-Section-Collapse analysis with the experimental data are not included as part of this analysis.] The original NSC analysis is a simple limit-load analysis and as such assumes maximum moment/stress occurs when the pipe section containing the crack becomes fully plastic, and that there is insignificant crack growth from crack initiation to maximum load. Another major assumption embodied in the Net-Section-Collapse analysis is that the toughness of the material is sufficiently high such that failure is governed by the strength of the material (i.e., the flow stress or collapse stress) and is not sensitive to the toughness of the material. This assumption that the net-section stress reaches a fully-plastic condition is satisfied for smaller diameter pipes and pipes made from high toughness materials, i.e., stainless steel. However, for lower toughness ferritic pipes, especially larger diameter ferritic pipes, this assumption of fully-plastic conditions is not necessarily satisfied. For these larger diameter, lower toughness pipes, contained plasticity conditions often exist, and the resultant failure stresses are typically below those predicted by the Net-Section-Collapse analysis.

4.2.2 Dimensionless-Plastic-Zone-Parameter (DPZP) Analysis

As part of the Degraded Piping program (Ref. 4.15), a semi-empirical analysis method was developed which allows an assessment of whether or not the assumptions in the Net-Section-Collapse analysis, i.e., fully-plastic conditions, are satisfied. This analysis was then extended as part of Reference 4.11 such that the failure stresses for these contained plasticity experiments could be predicted. As part of this analysis method, the ratio of the predicted failure stress to the Net-Section-Collapse predicted failure stress was found to be a function of a Dimensionless-Plastic-Zone Parameter (DPZP). This Dimensionless-Plastic-Zone Parameter is proportional to the toughness of the material and inversely proportional to the pipe diameter and flow stress of the material. Equation 4-24 gives the simplified DPZP where the distance from the neutral axis to the crack tip is the worst case of $D_m/2$.

$$DPZP = 2EJ_I / (\pi^2 D_m \sigma_f^2) \quad (4-24)$$

where,

DPZP = Simplified Dimensionless-Plastic-Zone-Parameter
E = Elastic modulus

- J_i = Value of J at crack initiation from a C(T) specimen test
 D_m = Mean pipe diameter
 σ_f = Flow stress, average of the yield and ultimate strengths.

"Best-fit" curves have been fit to the experimental data relating the ratio of the experimental failure stress-to-the Net-Section-Collapse stress and the simplified Dimensionless-Plastic-Zone-Parameter (DPZP), see Figure 4.3. Separate curve fits were made for surface-cracked and through-wall-cracked pipe experiments, see Equation 4-25.

$$P_{DPZP}/P_{NSC} = \frac{2}{\pi} \text{Arccos}(e^{-C_1[DPZP]}) \quad (4-25)$$

where,

- P_{DPZP} = DPZP predicted failure stress
 P_{NSC} = Net-Section-Collapse predicted failure stress
 C_1 = Empirically derived constant.

Figure 4.3 Fit of DPZP equation through pipe test data

For surface-cracked pipe, the "best-fit" empirically derived constant was found to be 34. For through-wall-cracked pipe, the "best-fit" empirically derived constant, was found to be 18.3.

If the value of J at crack initiation (J_i) from a C(T) specimen test and the flow stress of the material are known, the Dimensionless-Plastic-Zone-Parameter (DPZP) can be calculated. From the flow stress, the Net-Section-Collapse stress can be calculated. The DPZP predicted stress can then be calculated from these quantities using Equation 4-25. This method was found to be very accurate for predicting the maximum experimental stresses, especially for surface-cracked pipe (Ref. 4.13).

4.2.3 SC.TNP Analyses

The SC.TNP analysis for finite length internal circumferential surface cracks was first developed as part of the Degraded Piping program (Ref. 4.12), and is a J -estimation scheme that modifies the GE/EPRI solution for 360-degree cracks. Whereas the Net-Section-Collapse and DPZP analyses required only the flow stress as input for the material's tensile properties, the SC.TNP analysis requires a full stress-strain curve representation through the use of the Ramberg-Osgood relationship. Furthermore, whereas the Net-Section-Collapse analysis was independent of the fracture toughness of the material and the DPZP required only the fracture toughness value at crack initiation (J_i) as input, the SC.TNP analysis method requires the full J -R curve for analysis. As such, the complexity of the SC.TNP analysis method is much more significant than it is for the Net-Section-Collapse or Dimensionless-Plastic-Zone-Parameter analyses. This is evident by the fact that the SC.TNP analysis requires the use of a computer program, NRCPIPES, to complete an analysis of a cracked pipe and the Net-Section-Collapse and DPZP analyses can be carried out routinely without the aid of a computer.

The SC.TNP methodology uses a length parameter, L , which is the distance from the crack plane to the plane for which the stresses in the pipe wall can be assumed to be equal to that in the uncracked pipe. Since a clear definition of this length parameter is elusive, the parameter was initially chosen to be approximately equal to the thickness of the pipe wall (Ref. 4.12). This original definition of L (i.e., $L = t$) was that used in the original version of SC.TNP, i.e., SC.TNP1. As part of the Short Cracks in Piping and Piping Welds program (Ref. 4.13), the effect of changing this length parameter, L , was examined. As part of this effort, it was shown that predictions of J using SC.TNP agreed well with finite element results when L was chosen to be between $2t$ and $3t$ for a strain-hardening exponent (n) value of 3, whereas L needs to be closer to $9t$ for the case of $n = 10$. This finding demonstrated the influence of the strain-hardening level of the material on the choice of L . Based on the dependence of the SC.TNP predictions on the length parameter, L , it appeared that the SC.TNP method could be modified by incorporating the dependence of L on the hardening exponent. For the modified version of SC.TNP, i.e., SC.TNP2, this length parameter is defined as $L = (n-1)t$, where t is the wall thickness of the pipe and n is the strain-hardening exponent of the material.

In Reference 4.13, it was shown that the modified version of SC.TNP, i.e., SC.TNP2, results in more accurate predictions of J when compared with finite element results. However, as part of this same reference, it was shown that the original version of SC.TNP, i.e., SC.TNP1, results in more accurate predictions of the maximum experimental stress when compared with experimental data. This apparent discrepancy has been attributed to the fact that original version of SC.TNP, i.e., SC.TNP1, tends to underpredict the crack-driving force (J) for a given applied bending moment, but that this underprediction is offset by the fact that the crack growth resistance (J_R) for a surface crack growing radially through the

pipe wall is being underpredicted by a J-R curve established from L-C oriented C(T) specimens rather than properly L-R oriented specimens.

For the purpose of completing the analysis of the circumferential surface-cracked elbow experimental data, only SC.TNP1 calculations were performed. In the comparative analysis of the axial and circumferential surface-cracked elbow predictions with the ASME stress indices, both SC.TNP1 and SC.TNP2 evaluations were performed.

4.2.3.1 SC.TKP2 J-Estimation Scheme Method

The SC.TKP2 J-estimation scheme analysis method is similar to the SC.TNP method. The two differences between the two estimation schemes are: (1) the SC.TKP2 method incorporates through-wall stresses in the shell equations, and (2) the definition of the length parameter is taken to be $L = (n+1)/(2n+1)t$. As stated in Reference 4.13, the SC.TKP2 method is more appropriate for longer cracks ($\theta/\pi > 0.25$).

4.2.3.2 SC.ENG2 J-Estimation Scheme Analyses for Surface-Cracked-Pipe

As part of the U.S. NRC's Short Cracks in Piping and Piping Welds program (Ref. 4.13), a new surface-cracked pipe J-estimation scheme was developed. This method predicted the energy release rates for surface-cracked pipes subjected to remote bending loads. This method of analysis involves determining the moment-rotation behavior based on: (1) classical deformation theory of plasticity, (2) a constitutive law characterized by the Ramberg-Osgood model, and (3) an equivalence criterion incorporating a reduced thickness analogy for simulating the system compliance due to the presence of a crack in a pipe. The SC.ENG method is general in the sense that it may be applied in the complete range between elastic and fully plastic conditions. Since it is based on J-tearing theory, it is subject to the usual limitations imposed upon this theory, e.g., proportional loading, etc. It also has the implication that the crack growth must be small, although in practice, J-tearing methodology is used far beyond the limits of its theoretical validity with acceptable results (Ref. 4.16). Anyway, the extent of surface-crack growth in piping is often relatively small.

As indicated in the derivation of the SC.ENG method in Reference 4.13, the evaluation of the plastic component of J (J_p) requires determination of the terms $H(a/t)$ and $dH(a/t)/d(a/t)$. In the equivalence method proposed in Reference 4.13, t_e can be determined by forcing the Net-Section-Collapse moment of the equivalent uncracked pipe to be equal to the Net-Section-Collapse moment of the actual cracked pipe. For an uncracked pipe with reduced thickness, t_e , the Net-Section-Collapse moment, M_L^d , is

$$M_L^d = 4\sigma_f R_m^2 t_e \quad (4-26)$$

where σ_f is the flow or collapse stress of the material and R_m is the mean radius of the pipe. In determining the Net-Section-Collapse moment, M_L^c , for circumferentially surface-cracked pipe, several solutions are available in the literature. In Reference 4.13, two such equations, based on the original Net-Section-Collapse criterion (Ref. 4.10) and the Kurihara modification (Ref. 4.14) to the Net-Section-Collapse criterion, are used to determine $H(a/t)$ and its derivative for the evaluation of J_p . Accordingly, the expressions of J_p based on $H(a/t)$ and $dH(a/t)/d(a/t)$ obtained from the original Net-Section-Collapse

equations and the Kurihara modification to the Net-Section-Collapse equations are referred to as SC.ENG1 and SC.ENG2, respectively. Only the SC.ENG2 analysis method is used in this report.

4.3 Straight-Pipe Failure Avoidance Criteria

The methods described previously Section 4.2 were fracture prediction methodologies typically intended to give accurate predictions of the actual failure stresses. In the following sections, two pipe flaw evaluation methodologies embodied in Section XI of the ASME Code (i.e., IWB-3640 and Appendix C for austenitic piping and IWB-3650 and Appendix H for ferritic piping) and the R6 Revision 3 Option 1 approach are described. These methods are intended to be failure avoidance criteria rather than accurate predictive tools, and, hence, should consistently underpredict the experimental results. Note: to facilitate the comparative analysis between the experimental data and the ASME Section XI procedures, a value of 1.0 has been used throughout for the applied safety factors.

The failure avoidance criteria to which the experimental data were compared include:

- the R6 Revision 3 Option 1 method (Refs. 4.17 and 4.18),
- the ASME Section XI Appendix C criteria for austenitic piping (Refs. 4.19 and 4.20), and
- the ASME Section XI Appendix H criteria for ferritic piping (Refs. 4.21 and 4.22).

4.3.1 R6 Revision 3 Option 1 Method

This approach for evaluating the integrity of cracked structures made of strain-hardening materials was originally developed by the Central Electric Generating Board (CEGB) in the United Kingdom (Refs. 4.17 and 4.18). The basic method involves a diagram of the toughness ratio (K_r) versus the load ratio (L_r) as shown in Figure 4.4. The value of K_r for a cracked structure is the ratio of the linear-elastic stress intensity factors (K_I) to the material toughness (K_{Ic}), or also put in terms of J . The value of L_r is the ratio of the nominal stress in the component to the limit-load strength using the yield stress of the material as the flow stress. If the point (L_r , K_r) falls within the prescribed failure assessment curve, shown in Figure 4.4, then the structure is deemed to be safe. Otherwise, the structure is deemed unsafe.

This method has some inherent safety factors incorporated into the failure assessment curve, (FAC), $K_r = f(L_r)$, and hence, the predicted failure loads should never be higher than the experimental values. The ratio of the distance from the origin to the FAC through the assessment point (L_r , K_r) to the distance from the origin to the assessment point (L_r , K_r) is the margin of safety for the structure. Note, the moment-rotation behavior of the cracked pipe cannot be predicted using this method as is possible using some of the J -estimation scheme analysis methods.

4.3.2 ASME Appendix C and Appendix H Analyses

4.3.2.1 ASME Section XI IWB-3640 and Appendix C Flaw Evaluation Criteria for Austenitic Piping

The technical basis for the ASME Section XI IWB-3640 and Appendix C flaw evaluation criteria for austenitic piping is the Net-Section-Collapse criterion (Ref. 4.10). However, there are two distinct differences between the Appendix C and NSC criteria.

Figure 4.4 R6 failure assessment diagram

1. The flow stress definition in the Appendix C criteria is defined as 3 times the design stress intensity factor (S_m) as defined in Section II Part D of the ASME Code rather than the average of the measured yield and ultimate strengths as used in the NSC analyses discussed above.
2. A Z-factor is introduced in the analyses to account for cracks in lower toughness flux welds in predicting the maximum allowable stresses of these welds.

4.3.2.2 ASME Section XI IWB-3650 and Appendix H Flaw Evaluation Criteria for Ferritic Piping

The ASME Section XI Appendix H flaw evaluation criteria for ferritic piping (Ref. 4.21) is fundamentally different than the Appendix C criteria for austenitic piping in that the Appendix H criteria incorporates a screening criterion to establish the failure mechanism of the cracked pipe (i.e., linear-elastic, elastic-plastic, or limit-load) depending on the strength and fracture toughness of the cracked pipe material. For these lower toughness ferritic pipes and their associated weldments, Appendix H incorporates a stress multiplier (i.e., Z-factor) into the elastic-plastic analysis to account for the crack being in a lower-toughness material. This Z-factor approach is similar to that used for the austenitic criteria in Appendix C for the case of cracks in lower toughness austenitic flux welds, i.e., submerged-arc and shielded-metal-arc welds. As part of previous programs (Refs. 4.13 and 4.23), it has been shown that the elastic-plastic Z-factor solutions for the Appendix H ferritic criteria are much more conservative than the Z-factor solutions embodied in the

Appendix C austenitic criteria. In the past, it has been shown that the calculated fracture ratios (i.e., experimental/predicted maximum stress) for the Appendix C criterion for austenitic piping are on average slightly greater than 1.0 while the calculated fracture ratios for the elastic-plastic criterion embodied in Appendix H for ferritic piping are on average approximately two.

Further details of each of these failure avoidance methods can be found in the appropriate references.

4.4 Material Property Data Used in Fracture Analysis

As part of performing the Task 2 elbow experiments, material property data were developed for the two elbow materials investigated; A106 Grade B carbon steel, and WP304L stainless steel. Details of the material property characterization were discussed in Section 3.4.

Included as part of the investigation into how well the straight-pipe analysis procedures predict the failure stresses of circumferentially cracked elbows, the differences in the predicted stresses based on the use of quasi-static or dynamic material properties were investigated.

This section discusses the material property data used to perform the analysis of the elbow experiments, including details of the Ramberg-Osgood coefficients used in the analyses.

4.4.1 Tensile Data

For the limit-load (i.e., Net-Section-Collapse) or modified limit-load (i.e., Dimensionless-Plastic-Zone-Parameter) analyses, the tensile property required is the flow stress of the material. The flow stress for these analyses has been defined as the average of the yield and ultimate strengths at the test temperature under consideration. For the ASME Section XI Code approaches, i.e., IWB-3640 and Appendix C for austenitic steels and IWB-3650 and Appendix H for ferritic steels, the flow stress has been defined as $3S_m$ and $2.4S_m$, respectively. The stress intensity values, $S_m(\text{code})$, were taken from Section II Part D of the ASME Code.

For the SC.TNP1, SC.TNP2, SC.TKP2, SC.ENG2, and R6 straight-pipe analyses, and the SC.ELB1, SC.ELB2, and SC.ELB3 elbow analyses, the material stress-strain behavior was needed. This stress-strain behavior was modeled using a Ramberg-Osgood relationship, see Equation 4-27.

$$(\epsilon/\epsilon_o) = \sigma/\sigma_o + \alpha(\sigma/\sigma_o)^n \quad (4-27)$$

where,

- σ = Stress
- σ_o = Reference stress
- ϵ = Strain
- ϵ_o = Reference strain
- α = Ramberg-Osgood parameter
- n = Strain-hardening exponent.

The Ramberg-Osgood equation was fit to the stress-strain data in the range of 0.1-percent strain to the strain corresponding to 80 percent of the ultimate strength. The fit of the stress-strain data to the Ramberg-Osgood equation was made using a Battelle-written computer program, ROFIT. Table 4.1 shows the tensile properties of the pipe materials used in the Task 2 elbow experiments. Included in Table 4.1 are the yield strengths, ultimate strengths, and Ramberg-Osgood coefficients (i.e., reference stress, reference strain, α , and n). In addition, Table 4.1 includes the specimen number on which the Ramberg-Osgood coefficients are based. The actual stress-strain data from which the data in Table 4.1 were derived are shown in Figures 3.7 and 3.8 in Section 3.0. The Ramberg-Osgood representations of these stress-strain curves are shown in Figures 4.5 and 4.6. Figure 4.5 shows the comparison of Ramberg-Osgood curve with the carbon steel data, and Figure 4.6 shows the Ramberg-Osgood curve with the stainless steel data.

4.4.2 J-R Data

The J-R curves used in these analyses were based on the deformation theory J-resistance curves, i.e., J_D -R curves. For the surface-cracked pipe experiments, differences in predictions between using modified J_M and deformation theory (J_D) resistance curves are insignificant due to the fact that there is only a small amount of crack growth prior to maximum load.

Table 4.1 Tensile properties of the carbon steel and stainless steel materials used in the analysis of the elbow experiments

Specimen Number	Carbon Steel		Stainless Steel	
	QS	Dyn	Dyn ⁽¹⁾	QS
	FE17-T1	FE17-HT3		AE1-3T
σ_y , MPa	208.3	248.9	200.2	200.2
σ_u , MPa	449.4	386.7	408.0	408.0
σ_o , MPa	208.3	248.9	200.2	200.2
e_o	0.00106	0.001267	0.001096	0.001096
α	3.360	5.001	14.79	14.79
n	4.421	6.239	3.981	3.981

(1) No distinct difference was observed between the dynamic and quasi-static stress-strain experimental tensile results. Therefore, quasi-static results were used in the analysis of the elbow experiments.

In cases where the crack growth of the pipe experiment is larger than the value achieved from the C(T) specimen, the J-R curves would have to be extrapolated. Since only the J_D -R curve was used in these analyses, a power-law extrapolation procedure was used. This procedure is identical to the one found in Reference 4.24. The procedure is as follows:

- The experimental J_D -R curve was used for crack growth up to 30 percent of the original ligament. These data were fit with the following power-law curve

$$J = J_i + C_3(\Delta a/r)^M \quad (4-28)$$

where,

r is a parameter having a value of 1.0 in the same units of Δa , so that C_3 has the same units as J .

Figure 4.5 Experimental stress-strain results along with the corresponding Ramberg-Osgood representation for the carbon steel elbow material

Figure 4.6 Experimental stress-strain results along with the corresponding Ramberg-Osgood representation for the stainless steel elbow material

- In the analysis, the actual J values from the C(T) experiments were used for the crack extension up to 30 percent of the remaining ligament, while the extrapolated values of J were used for the larger crack extensions.

For the analyses of the surface-cracked elbow experiments, the experimental crack growth was within the limits of the C(T) specimen (i.e., Δa did not exceed $0.3 [w-a_0]$). Therefore, the actual J-R curves shown in Figures 3.9 and 3.10 were used as input to NRCPIPES (Windows version 3.0) computer code. As an option, the extrapolated J-R curve constants given in Table 4.2 could be used in the analyses. Figures 4.7 and 4.8 show the J-R representation of the carbon steel and stainless steel materials, respectively. The effect of using quasi-static versus dynamic J-R curve data to predict the results of the dynamic, elbow pipe-system experiments is addressed in Section 4.6.1.2.

4.5 Definition of Crack Size

The definition of crack size used in the analysis may have a substantial effect on the predicted stress results from the straight pipe and elbow analysis procedures investigated. As mentioned previously in Section 3.6, the wall thickness of the elbow specimens varied over the length of the crack, requiring a variable crack depth in order to maintain a consistent a/t ratio over the crack length. Also, the surface cracks for the Task 2 elbow experiments were fatigue precracked to sharpen the machined notch to help eliminate the influence of notch acuity on the test results. The distribution of J along the notch face, caused the fatigue

Table 4.2 Extrapolated J-R curve constants for the carbon steel and stainless steel elbow materials

	Carbon Steel			Stainless Steel	
	QS FE17-3	QS FE17-4	Dyn FE17-1	QS AE1-5	Dyn AE1-2
J_0 , kJ/m ²	533	317	373	1062	1377
C_3	297.7	473.9	314.2	211.1	217.1
m	0.624	0.573	0.676	0.487	0.510

precrack to grow deeper in the region 45 degrees on either side of the crack centerline. This resulted in an irregular crack profile for the four elbow specimens, but was typical of what might actually happen.

The variable a/t ratio caused some concern with the analysis of the elbow experiments. The definition of the crack size used as input for the elbow analysis would have an influence on the potential accuracy of the results. This variability in the analysis predictions was addressed by performing the analyses using two different definitions of crack size, i.e., the definition given in the ASME Code, and a definition of crack geometry using an "equivalent length". These two procedures are described below.

4.5.1 ASME Code Definition of Crack Size

In Section XI of the ASME Code, Figure IWA-3310-1 provides illustrations of crack configurations for determining the crack dimensions "a" (depth) and "l" (length) of surface planar cracks oriented in a plane normal to the pressure retaining surface, see Figure 4.9. As shown in Figure 4.9, and further stated in

Figure 4.7 Experimental J-R data with corresponding extrapolation curve for the carbon steel elbow material

Figure 4.8 Experimental J-R data with corresponding extrapolation curve for the stainless steel elbow material

Figure 4.9 Illustration of ASME Section XI method of defining the crack dimensions for an in-service crack evaluation

IWA-3300 of Section XI, the cracks shall be sized by the bounding rectangle for the purpose of description and dimensioning. The dimensions of a crack shall be determined by the size of a rectangle that fully contains the area of the crack. Therefore, for the elbow experiments conducted in Task 2, the ASME Code definition conservatively assumes that the crack has a uniform depth and that the depth is the depth of the crack at its deepest location and that the crack length is the total crack length. The ASME Code approximation of the crack size can significantly overestimate the severity of the actual crack shape.

4.5.2 Equivalent Length Definition of Crack Size

The equivalent crack length is defined as the total crack area divided by the maximum crack depth. This definition maintains that the crack is of uniform depth, however, the crack depth is now the maximum depth for the entire crack length. To account for the increased depth, the crack length is adjusted to maintain the same crack area as the actual variable crack geometry. Figure 4.10 shows a schematic of the actual crack geometry, the ASME Code definition, and the equivalent length definition of the crack geometry for the elbow specimen for Experiment 2-2.

4.6 Comparisons of Maximum Stress Predictions With Experimental Data

In this section, comparisons of maximum stress predictions from the various straight pipe and elbow fracture prediction analysis methods are made with the IPIRG-2 and some CEA elbow experimental data. To aid in performing the calculations needed for these comparisons, the NRCPIPES (Version 3.0)

Figure 4.10 Schematic of active elbow crack geometry showing ASME designed and equivalent length definition crack shapes

computer code for surface-cracks in straight pipe and the IP2ELBOW (Version 1.0) computer code for surface cracks in elbows were used. The IP2ELBOW code was developed as part of the IPIRG-2 Program, and uses the two estimation methods for circumferential cracks discussed in Section 4.1 for predicting the elbow fracture stresses.

4.6.1 IPIRG-2 Elbow Data

The main objective to be addressed in this section is to evaluate if existing straight-pipe analysis techniques are sufficient for use in predicting the fracture stresses for elbows containing circumferential surface cracks. To accomplish this, the four elbow experiments were analyzed using the straight-pipe fracture prediction analysis methods described in Section 4.2, and the elbow fracture analysis prediction methods developed in this program as described in Section 4.1. The results are shown as fracture ratios (maximum experimental stress divided by the maximum predicted stress). The analysis predictions considered combined pressure and bending loading. The bending stress was calculated from the experimental and predicted moment values using the flexural stress formulation Mc/I , where I equals $0.0491(D_o^4 - D_i^4)$. The membrane stress was calculated using the ASME Section III equation $(PD_o/4t)$. These formulations assume circular cross-sections and a constant wall thickness, neither of which occur in actual elbows. However, these assumptions are used by the analysis predictions. Because the objective was to assess the applicability of straight-pipe analysis techniques, no adjustments were made to the analysis predictions for variations in wall thickness, out-of-roundness, or crack angle. Local crack depth (a) and local wall thickness (t) corresponding to the location of maximum a/t along the crack length were used in the analyses. Quasi-static stress-strain properties were used in the analysis of all experiments. Quasi-static J-R curves were used in the analysis of the quasi-static Experiments 2-2 and 2-4, while dynamic J-R curves were used to analyze the elbow pipe system experiments 2-1 and 2-3. This

combination of material property data has been demonstrated to give the best correlation of fracture ratios for straight-pipe analysis (Ref. 4.25).

The results of these analyses are given in Table 4.3. Comparing these fracture ratios with straight-pipe experiments loaded in combined bending and pressure shows that the elbow data fall within an established scatter band associated with straight-pipe experiments (Ref. 4.13) for the SC.TNP1 and ASME methods. Except for Experiment 2-2, there is also good agreement for the R6 analysis, with the Experiment 2-2 ratio falling slightly above the expected scatter band (mean plus one standard deviation). For the NSC and DPZP analysis, the average fracture ratios for the elbow experiments are 20 and 26 percent, respectively, higher than the corresponding straight-pipe ratios. The reason is not clear as to why the NSC analysis consistently predicts higher stress ratios for the elbow experiments. The reason that the DPZP analysis predicts higher stress ratios than previously observed for the straight-pipe experiments is probably a carry over of the inaccuracy associated with the NSC analysis since the DPZP predictions are based on the NSC predictions.

No adjustments of the straight-pipe predictions were made to account for the off-center crack present in the elbow experiments. In general, the adjustment would lower the predicted moment value, resulting in a greater underprediction of the experimental values. Therefore, better predictions are achieved when no adjustment is made for off-center cracks.

The two elbow estimation procedures show fracture ratios that are, in general, closer to 1.0 than the straight-pipe predictions. The most accurate correlation (closest to 1.0) was found with the SC.ELB1 procedure when applied to the carbon steel elbow data. (The SC.ELB1 method is that method which uses the GE/EPRI method to define the reference moment, M_o .) However, this analysis results in a slight overprediction of the experimental moments. The fracture ratios for the stainless steel elbow data are of similar values with the SC.TNP1 method for straight pipe.

This finding suggests that straight-pipe analyses can be used to predict the behavior of circumferential cracks located in the extrados of a long-radius elbow, at least for the R_m ratios, crack sizes, etc., considered in these experiments. This could be a significant result, since it would imply that certain straight-pipe estimation schemes can be used and maintain the same degree of accuracy as expected with predictions on straight pipe. However, caution should be taken to consider the limited scale for which these comparisons have been made. Variables such as elbow diameter, crack geometry, R/t ratio, and material should be considered before making a broad statement about the suitability of these procedures for the analysis of elbow fracture on a general scale.

4.6.1.1 Sensitivity of Predictions on a/t Ratio

To better understand the trends of the elbow and straight-pipe analysis procedures, the maximum predicted moment values for each method are plotted versus a/t for the carbon steel (Figure 4.11) and the stainless steel (Figure 4.12). For these analyses, the average wall thickness of the elbow at the crack plane, the ASME definition of crack size, and quasi-static stress-strain and J-R curve properties were used as input parameters. The significance of these plots is to show the relative differences in the analysis scheme predictions over a reasonable range of a/t values. Also shown on these plots are the experimental values of maximum moment for the pipe-system and companion quasi-static experiments.

Table 4.3 Fracture ratios for Task 2 elbow experiments

Expt. Number	Material	Loading condition	SC.ELB1 (elbow)	SC.ELB2 (elbow)	NSC (straight)	SC.TNP1 (straight)	DPZP (straight)	R6 (straight)	ASME App. C (straight)	ASME App. H (straight)
2-1	A106-B Carbon Steel	Pipe System	0.94	1.18	1.37	1.23	1.38	1.79	n/a	2.36
2-2	A106-B Carbon Steel	Quasi-static	0.94	1.14	1.33	1.15	1.33	1.92	n/a	2.26
2-3	WP304L Stainless Steel	Pipe System	1.31	1.19	1.37	1.27	1.37	1.57	1.45	n/a
2-4	WP304L Stainless Steel	Quasi-static	1.15	0.99	1.20	1.12	1.21	1.39	1.28	n/a

Comparison of experimental maximum moment with analytical predictions for combined bending and pressure load cases for straight pipe (Ref. 4.13).			NSC (straight)	SC.TNP1 (straight)	DPZP (straight)	R6 (straight)	ASME App. C (straight)	ASME App. H (straight)
Average			0.92	1.10	1.05	1.43	1.16	2.14
Std. Dev.			0.12	0.15	0.13	0.40	0.19	0.29

Figure 4.11 Maximum predicted moment versus a/t for carbon steel elbow experiments

Figure 4.12 Maximum predicted moment versus a/t for stainless steel elbow experiments

For the carbon steel predictions (Figure 4.11), all five fracture prediction methods (SC.ELB1, SC.ELB2, NSC, SC.TNP1, and DPZP) show similar trends for the a/t range of 0.5 to 0.7. For a/t ratios greater than 0.7, the SC.ELB1 method begins to diverge from the other methods, and predicts considerably higher maximum moments. The SC.ELB1 method overpredicts the experimental data by approximately 10 percent, while the other three methods underpredict the experimental results by 10 to 35 percent. The SC.TNP1 method predicts the experimental data reasonably well, considering this is a straight-pipe method. As expected, the failure avoidance criteria (ASME Appendix H and R6) show a significant underprediction with respect to the experimental data.

The predictions for the stainless steel experiments (Figure 4.12) show a more consistent trend for all the prediction methods. Excluding the R6 method, the other estimation schemes slightly underpredict the quasi-static experimental results, the worst prediction still being within 30 percent. All methods drastically underpredict the pipe-system (dynamic) experimental results.

The purpose of these figures is to show, in general, the difference between the elbow fracture prediction methods and the straight-pipe methods. Direct comparisons between the individual methods predicted values, and an assessment of the sensitivity of these predictions to material property and crack size are addressed in the following sections.

4.6.1.2 Sensitivity of Prediction Methods to Material Property Data

Typically, for straight-pipe analysis, it has been found that the most accurate predictions of experimental results are obtained when quasi-static stress-strain properties and quasi-static J-R curves are used in the analysis of quasi-statically loaded pipe experiments, and quasi-static stress-strain properties and dynamic J-R curves are used in the analysis of dynamic experiments (Ref. 4.25).

To determine what effect the choice of material property data has on the predicted results for the elbow and straight-pipe analysis methods, the carbon steel and stainless steel elbow pipe-system experiments were analyzed using various combinations of stress-strain and J-R data. For these analyses, the ASME definition of crack size and the wall thickness corresponding to the local wall thickness at the region of maximum a/t were used. The data are reported as a fracture ratio (experimental/predicted maximum stress). Table 4.4 shows the fracture ratios obtained for the carbon steel, elbow pipe-system experiment when various combinations of quasi-static and dynamic material property data are used in the analyses. What is noticeable in this table is that the results for the J-estimation schemes do not show much variation when using either quasi-static or dynamic J-R curves, combined with quasi-static stress-strain properties. The largest difference occurred with the SC.ELB1 method, for which the results only varied by 3.3 percent. This effect is driven by the fact that there is no noticeable change in toughness with increasing strain rate for the carbon steel elbow material (see "Material Property Analysis" Section 3.4). The NSC method does not consider toughness in the calculation, and therefore, does not show any difference for this comparison. Obviously, when there is more scatter between replicate tests, as is the case for the dynamic tensile specimens, a larger difference will be seen in the predicted results depending on which specimen is used in the analysis.

Table 4.5 shows the fracture ratios for the stainless steel, dynamic, elbow pipe-system experiment. The scatter between tensile specimens were negligible, so comparisons are made between using quasi-static or dynamic J-R curves in the analyses. For this case, the use of dynamic J-R curves more accurately predicts

Table 4.4 Fracture ratios for carbon steel, dynamic, elbow experiment using measured experimental crack length^(a)

Analysis Method	QS Ten1 QS JR1	QS Ten1 QS JR2	QS Ten1 Dyn JR1	Dyn Ten1 Dyn JR1	Dyn Ten2 Dyn JR1
SC.ELB1 (elbow)	0.91	0.92	0.94	1.00	1.03
SC.ELB2 (elbow)	1.16	1.21	1.18	1.18	1.46
NSC (straight)	1.37	1.37	1.37	1.42	1.52
SC.TNP1 (straight)	1.20	1.24	1.23	1.28	1.38
DPZP (straight)	1.38	1.38	1.38	1.43	1.53

(a) Fracture ratio is experimental/predicted maximum stress. "a/t" was maximum for the experiment. "t" was local to maximum value a/t. Measured (experimental) length was 176 degrees.

Table 4.5 Fracture ratios for stainless steel, dynamic, elbow experiment using measured experimental crack length^(a)

Analysis Method	QS Ten1 QS JR1	QS Ten1 Dyn JR1
SC.ELB1 (elbow)	1.36	1.31
SC.ELB2 (elbow)	1.24	1.19
NSC (straight)	1.37	1.37
SC.TNP1 (straight)	1.44	1.27
DPZP (straight)	1.37	1.37

(a) Fracture ratio is experimental/predicted maximum stress. "a/t" was maximum for the experiment. "t" was local to maximum value a/t. Measured (experimental) length was 180 degrees.

experimental data (fracture ratio closer to 1.0). Also, the SC.TNP1 method gives as good a prediction of the experimental data as the two elbow prediction methods.

No cyclic J-R curve data (as in Task 3 of the IPIRG-2 program [Ref. 4.27]) were developed for either of the elbow materials. For the carbon steel pipe system test, the stress ratio (R-ratio) was about +0.05 so it is anticipated that there should not have been significant cyclic degradation of the J-R curve. Also, in Figure 3.29, it can be seen that the cyclic plastic displacement increment (for the 3 cycles prior to maximum load) is about 0.25, which is slightly less severe than uses in most of the past work (Ref. 4.21). Furthermore, in this test it can be seen in Figure 3.29 that there was a slight reduction in maximum moments, with a larger reduction of the crack-mouth-opening displacement, CMOD, at maximum moment (about a 35-percent reduction) which implies a small amount of cyclic degradation for this material.

For the stainless steel elbow test, the stress ratio (R-ratio) was -0.45, with a cyclic plastic displacement increment of about 0.1, see Figure 3.31. For this R-ratio, toughness, and the higher σ_y/σ_u for this stainless steel, the results from Task 3 of the IPIRG program on a similar toughness stainless steel showed no significant detrimental cyclic effects. Figure 3.31 shows that the pipe system moments were higher, and there was no loss in the CMOD. Hence, there was no observable cyclic degradation for this steel, and in fact, the dynamic J-R curve was about 25 percent higher than quasi-static J-R curve, showing some beneficial effect of dynamic/cyclic loading for this particular stainless steel.

4.6.1.3 Sensitivity With Regard to Crack Length

Table 4.6 and Table 4.7 show comparisons of the fracture ratios (experimental/predicted maximum stresses) for the carbon steel and stainless steel, elbow pipe-system experiments for two definitions of crack size; ASME definition, and equivalent crack length. The analyses were performed using the same wall thickness definition used in the previous section. Quasi-static stress-strain and dynamic J-R data were used in this comparison.

The shorter crack length for the "equivalent length" definition resulted in an increase in predicted moment for all the analysis procedures. Since the SC.ELB1 method performed on the carbon steel elbow geometry was the only method to overpredict the experimental moment, it was the only method resulting in a less accurate prediction when the equivalent length crack size was used. For the other methods, the use of the equivalent length brought the predicted moment values closer to the experimental results. However, in actual practice, the use of an equivalent length requires an accurate mapping of the crack depth profile, which may not be available or feasible to achieve.

Table 4.6 Fracture ratios for carbon steel, dynamic, elbow experiment using total measured and equivalent crack lengths^(a)

Analysis Method	Measured Length	Equivalent length
SC.ELB1(elbow)	0.94	0.92
SC.ELB2 (elbow)	1.18	1.05
NSC (straight)	1.37	1.28
SC.TNP1 (straight)	1.23	1.18
DPZP (straight)	1.38	1.28

- (a) Fracture ratio is experimental/predicted maximum stress. "a/t" was maximum for the experiment. "t" was local to maximum value a/t. Measured (experimental) length was 176 degrees. Equivalent length was 167.0 degrees. Quasi-static stress-strain and dynamic J-R curves were used.

Table 4.7 Fracture ratios for stainless steel, dynamic, elbow experiment using total measured and equivalent crack lengths^(a)

Analysis Method	Measured Length	Equivalent Length
SC.ELB1 (elbow)	1.31	1.05
SC.ELB2 (elbow)	1.19	1.10
NSC (straight)	1.37	1.17
SC.TNP1 (straight)	1.27	1.15
DPZP (straight)	1.37	1.17

- (a) Fracture ratio is experimental/predicted maximum stress. "a/t" was maximum for the experiment. "t" was local to maximum value a/t. Measured (experimental) length was 180 degrees. Equivalent length was 147.6 degrees. Quasi-static stress-strain and dynamic J-R curves were used.

4.6.2 η -Factor Analyses of Elbow Experiments

In this section, the results of a series of η -factor calculations for the surface-cracked elbow experiments will be discussed. Since the η -factor solution for a circumferentially surface-cracked elbow does not exist, the η -factor solution for a circumferentially surface-cracked pipe was used. It is believed that the η -factor for a circumferentially cracked elbow may be similar to that of a circumferentially cracked pipe, at least for certain R/t ratios. Figure 4.13 shows the plot of J versus moment for the stainless steel, elbow, pipe-system experiment (Experiment 2-3). In this figure, two analyses were conducted, the straight-pipe analyses SC.TNP1 and the GE/EPRI elbow analyses (SC.ELB1). The differences between the maximum stress predictions are small, indicating that the straight-pipe and elbow η -factor solutions should be similar in this case. The straight-pipe η -factor analysis (Refs. 4.26 and 4.27) is a simple method for estimating the fracture resistance of a pipe material from a pipe test experimental record, used in lieu of three-dimensional finite element analyses. In calculating J using the η -factor analysis, J is separated into its elastic and plastic components.

$$J = J_e + J_p \quad (4-29)$$

where the elastic component of J is

$$J_e = K_I^2/E' \quad (4-30)$$

Figure 4.13 Moment versus J for stainless steel elbow, pipe-system Experiment 2-3 using both straight-pipe and elbow J -estimation schemes

where

$$K_I = K_{Im} + K_{Ib} \quad (4-31)$$

and

$$E' = E/(1 - \nu^2) \quad (4-32)$$

and K_{Im} and K_{Ib} can be calculated using the equations embodied in Paragraph H-4220 of Appendix H to ASME Section XI.

The plastic component of J , J_p , is the energy absorbed during the test, i.e., the area under the plastic portion of the moment-rotation curve, multiplied by a geometric term, i.e., the η -factor.

The J_i values for the various elbow experiments from these η -factor calculations are presented in Table 4.8, along with the J_i values from the C(T) specimen tests. Both quasi-static and dynamic C(T) specimen J_i values are shown in Table 4.8.

Table 4.8 Comparison of J_i values from η -factor analyses of surface-cracked elbow experiments and J_i values from C(T) specimen tests

Experiment Number	$\theta/\pi^{(1)}$	$J_i, \text{kJ/m}^2$		
		Elbow Experiment	Quasi-Static Monotonic C(T) Specimen	Dynamic Monotonic C(T) Specimen
2-1 (Pipe System)	0.46	662	NA ⁽²⁾	361 ⁽³⁾
	0.50	729		
2-2 (Q-S)	0.42	1,085	425 ⁽³⁾	NA
	0.50	1,336		
2-3 (Pipe System)	0.41	559	NA	1,359 ⁽³⁾
	0.50	674		
2-4 (Q-S)	0.40	1,447	1,089 ⁽³⁾	NA
	0.50	1,856		

(1) First number is based on the equivalent crack length and the second on the total crack length.

(2) NA - Not applicable.

(3) Average of two specimens.

In making these calculations, the experimental moment-rotation curves were input into the analyses along with the appropriate elbow and crack dimensions and material property data. The rotations were measured at ± 127 mm (5 inches) from the crack plane in the pipe system experiments, and near the elbow girth

welds in the quasi-static elbow experiments. It was assumed that the plastic rotation component of the total experimental rotation was due solely to the crack, and not to plasticity in the uncracked elbow. For each analyses, nominal diameter and wall thickness measurements were used. The deepest crack depth, as well as the total and equivalent crack lengths were used.

In examining Table 4.8, there does not appear to be a direct correlation between the η -factor J_i values from the elbow experiments and the C(T) specimen J_i values. For the carbon steel experiments (2-1 and 2-2), the trends between the J_i values for the elbow and C(T) experiments are similar. The resistances for the quasi-static monotonic experiments are higher than for the dynamic experiments. However, the magnitudes of the J_i values between the C(T) and elbow experiments are not the same. This difference may be due to the sidegrooving of the C(T) specimens, (which lowers the apparent resistance), anisotropy which is much larger in ferritic than austenitic steels [the C(T) specimen was in the lower toughness L-C orientation, where the elbow surface-crack growth was in the L-R orientation], and any plasticity in the uncracked elbow. The elbow rotations were taken closer together in the pipe system experiment than the quasi-static test, hence the quasi-static test rotations should be larger than the pipe system rotations.

For the stainless steel experiments (2-3 and 2-4), the trends are not similar between the J_i values for the elbow and C(T) experiments. Under dynamic loading, the resistance from the C(T) experiments increased as compared with the resistance under quasi-static loading. However, in the elbow-system test, the resistance calculated for the dynamic experiment was lower than that calculated for the quasi-static, monotonic experiment. The moment-rotation response for the stainless steel experiments is shown in Figure 3.34. This figure suggests that the load-carrying capacity of the elbow was increased under dynamic, cyclic loading as compared to quasi-static monotonic loading. However, as shown in Table 3.10, the moments at crack initiation for the two experiments were similar (601 kN-m for Experiment 2-3 and 536 kN-m for Experiment 2-4); however, the rotations at these moment were extremely different in both the elastic and plastic range, i.e., (approximately 1 degree for Experiment 2-3 and 1.75 degrees for Experiment 2-4). It is this difference in the rotations that is causing the large differences in J . Obviously, the increased rotations observed for Experiment 2-4 are impacting the η -factor solution for straight pipe. This may come from the rotations being measured further apart in the quasi-static test, where plasticity in the elbow can affect the amount of rotation and hence the J values.

Another possible explanation for the discrepancies shown in Table 4.8, could be the effect of cyclic loads. As discussed in Reference 4.28, cyclic loading causes crack tip and void sharpening which increases the crack tip stress intensity and decreases the apparent resistance of nuclear piping steels. As noted earlier, for the R-ratio relative to the toughness of the materials tested, cyclic effects on the J-R curve should be negligible in these experiments.

4.6.3 Through-Wall Elbow Fracture Experiment Analysis

Experiments on through-wall-cracked elbows subjected to in-plane bending have been performed by CEA-CEN Saclay (Ref. 4.29). These data are included in the ELBOWCK elbow database discussed in Section 2.2 and in Appendix B. These experiments were conducted on 4-inch nominal diameter elbows, having a circumferential crack located at the elbow extrados. Maximum moment data were collected for an in-plane bending applied in both the opening and closing modes for crack lengths (θ/π) up to 0.42.

Limit-load solutions for straight pipe (Ref. 4.30) and elbows (Ref. 4.31) are compared against the experimental moments to demonstrate the accuracy of these solutions for predicting the failure stress of through-wall-cracked elbows.

Figure 4.14 shows the data for the through-wall-crack analyses, with the experimental maximum moments. The straight-pipe and elbow predictions give similar predictions for θ/π between 0.3 and 0.5. For shorter crack lengths, the solutions begin to diverge. Table 4.9 gives the results in terms of fracture ratios.

4.6.4 Summary of Results

The primary objective of this section was to address the question as to whether existing analysis methods developed for straight pipe were adequate for the case of a circumferential crack along the extrados of an elbow. The analysis of the IPIRG-2 elbow experiments shows that the J-estimation scheme SC.TNP1

Figure 4.14 Maximum moment data for circumferential through-wall-cracked elbow experiments

Table 4.9 Fracture ratios for through-wall-cracked elbows

θ/π (moment direction)	0.17 (close)	0.25 (close)	0.25 (open)	0.33 (close)	0.33 (open)	0.42 (close)	0.42 (open)
Limit Moment (straight pipe)	0.87	0.99	1.13	1.12	1.18	1.13	1.26
Limit moment (elbow)	1.21	1.23	1.41	1.19	1.25	1.27	1.42

provides results that are slightly greater than the previously established scatter bands of fracture ratios for straight-pipe analysis. Of the two elbow analysis methods, the SC.ELB2 method results in a reasonable underprediction of the experimental moments. However, when considering the trends of the two analyses methods over a/t ratios ranging from 0.50 to 0.85, the difference between the SC.TNP1 and the SC.ELB2 methods is less than 10 percent for both the carbon steel and stainless steel materials considered.

The A106 Grade B carbon steel elbow material showed no significant increase in toughness with increasing strain rates. Therefore, for the carbon steel analysis, either quasi-static or dynamic J-R curves provide acceptable predictions. For the WP304L stainless steel elbow material, there is a significant increase in toughness at increased strain rates. For the analysis of the IPIRG-2 elbow experiments, the most accurate predictions resulted from the use of quasi-static stress-strain properties, combined with the appropriate J-R curve (quasi-static or dynamic).

In all analysis methods considered (for the a/t range of the IPIRG-2 elbow experiments), all methods underpredicted the experimental moments. The use of a crack length calculated from the equivalent length definition increased the accuracy of these methods up to 27 percent.

4.7 References

- 4.1 Kumar, V., German, M. D., Wilkening, W. W., Andrews, W. R., deLorenzi, H. G., and Mowbray, D. F., "Advances in Elastic-Plastic Fracture Analysis," Final Report EPRI NP-3607, August 1984.
- 4.2 Rice, J. R. and Levy, N., "The Part-Through Surface Crack in an Elastic Plate," *Journal of Applied Mechanics*, Vol. 39, pp 185-194, 1972.
- 4.3 Parks, D. M., "The Inelastic Line-Spring: Estimates of Elastic-Plastic Fracture Mechanics Parameters for Surface Cracked Plates and Shells," *Journal of Pressure Vessel Technology*, Vol. 103, pp 246-254, 1981.
- 4.4 Parks, D. M. and White, C. S., "Elastic-Plastic Line-Spring Finite Elements for Surface Cracked Plates and Shells," *Journal of Pressure Vessel Technology*, Vol. 104, pp 287-292, 1982.
- 4.5 Lee, H., and Parks, D. M., "Enhanced Elastic-Plastic Line-Spring Finite Element," *International Journal of Solids and Structures*, Vol. 33, pp 2393-2418, 1995.

- 4.6 Mohan, R., "Application of the Line-Spring/Shell Model to Surface-Cracked Pipes and Elbows," 1996 ASME PVP Conference, *Fatigue and Fracture-1996*, Vol. 324, June 1996.
- 4.7 ABAQUS User's Manual, Hibbitt Karlsson and Sorenson, Providence, R. I., Ver. 5.4, 1995.
- 4.8 Mohan, R., and others, "Development of a J-Estimation Scheme for Internal Circumferential and Axial Surface Cracks in Elbows," NUREG/CR-6445, BMI-2193, June 1996.
- 4.9 Griffiths, J. E., "The Effect of Cracks on the Limit Load of Pipe Bends Under In-Plane Bending," *International Journal of Mechanical Science*, Vol. 21, pp 119-130, 1979.
- 4.10 Kanninen, M. F., and others, "Mechanical Fracture Predictions for Sensitized Stainless Steel Piping with Circumferential Cracks," Final Report, EPRI NP-192, September 1976.
- 4.11 Wilkowski, G. M., and Scott, P. M., "A Statistical Based Circumferentially Cracked Pipe Fracture Mechanics Analysis for Design or Code Implementation," *Nuclear Engineering and Design*, Vol. 111, pp 173-187, 1989.
- 4.12 Scott, P., and Ahmad, J., "Experimental and Analytical Assessment of Circumferentially Surface-Cracked Pipes Under Bending," NUREG/CR-4872, April 1987.
- 4.13 Krishnaswamy, P., and others, "Fracture Behavior of Short Circumferentially Surface-Cracked Pipe," NUREG/CR-6298, November 1995.
- 4.14 Kurihara, R., and others, "Estimation of the Ductile Unstable Fracture of Pipe with a Circumferential Surface Crack Subjected to Bending," *Nuclear Engineering and Design*, Vol. 106, pp 265-273, 1988.
- 4.15 Wilkowski, G. M., and others, "Degraded Piping Program - Phase II, Summary of Technical Results and Their Significance to Leak-Before-Break and In-Service Flaw Acceptance Criteria," March 1984 - January 1989, NUREG/CR-4082, Vol. 8, March 1989.
- 4.16 Kanninen, M., and Popelar, C., *Advanced Fracture Mechanics*, Oxford University Press, New York, 1985.
- 4.17 Milne, I., and others, "Assessment of the Integrity of Structures Containing Defects," CEGB Report R/H/R6 - Revision 3, 1986.
- 4.18 Milne, I., and others, "Background to and Validation of CEGB Report R/H/R6 - Revision 3," January 1987.
- 4.19 ASME Boiler and Pressure Vessel Code, Section XI, Appendix C, 1995 Edition, July 1995.
- 4.20 "Evaluation of Flaws in Austenitic Steel Piping," (Technical basis document for ASME IWB-3640 analysis procedures), prepared by Section XI Task Group for Piping Flaw Evaluation, EPRI Report NB-4690-SR, April 1986.

- 4.21 ASME Boiler and Pressure Vessel Code, Section XI, Appendix H, 1995 Edition, July 1995.
- 4.22 "Evaluation of Flaws in Ferritic Piping," EPRI Report NP-6045, prepared by Novetech Corporation, October 1988.
- 4.23 Scott, P., and others, "The IPIRG-1 Pipe System Fracture Tests: Analytical Results," PVP Vol. 280, pp 153-163, 1994.
- 4.24 Scott, P., and others, "IPIRG-2 Task 1 Report - Pipe System Experiments with Circumferential Cracks in Straight-Pipe Locations," NUREG/CR-6389, December 1996.
- 4.25 Zahoor, A., and Kanninen, M. F., "A Plastic Fracture Mechanics Prediction for Fracture Instability in a Circumferentially Cracked Pipe in Bending - Part I. J-Integral Analysis," *Journal of Pressure Vessel Technology*, Vol. 103, pp 352-358, 1981.
- 4.26 Pan, J., and others, "Application of a Tearing Instability Analysis for Strain-hardening Materials to a Circumferentially Cracked Pipe in Bending," ASTM STP 833, pp 721-748, 1984.
- 4.27 Rudland, D., and others, "The Effects of Cyclic and Dynamic Loading on the Fracture Resistance of Nuclear Piping Steels," NUREG/CR-6440, December 1996.
- 4.28 Moulin, and others, "Experimental Evaluation of J in Cracked Straight and Curved Pipes Under Bending," 10th SMiRT, Vol. G, pp 323-326, 1989.
- 4.29 Kanninen, M. F., and others, "Mechanical Fracture Predictions for Sensitized Stainless Steel Piping with Circumferential Cracks," Final Report, EPRI NP-192, September 1976.
- 4.30 Griffiths, J. E., "The Effect of Cracks on the Limit Load of Pipe Bending Under In-Plane Bending: Experimental Study," *International Journal Mechanical Sciences*, Vol. 21, pp 119-130, 1979.

 

5.0 DEVELOPMENT OF A SIMPLIFIED FAILURE AVOIDANCE ANALYSIS PROCEDURE FOR CRACKS IN FITTINGS

As part of this program, an initial effort to develop a J-estimation scheme for cracks in cracked elbows was undertaken (Ref. 5.1). This involved conducting a large matrix of finite element analyses to develop a J-estimation scheme in the spirit of the GE/EPRI type of J-estimation scheme (Ref. 5.2). Analyses were developed for circumferential surface cracks centered along the extrados of an elbow, and axial surface cracks on the flank (side or crown) of the elbow subjected to pressure and bending. Even though a number of variables were considered (such as crack depth, R_m/t ratios, and strain-hardening exponents), these analyses were limited to one crack length, in-plane bending and long radius 90-degree elbows. There are a significant number of other variables and these make the development of such solutions a seemingly formidable task for all pipe fittings and loading combinations. The lack of such detailed solutions for a wider variety of problems, in combination with the desire to have a codifiable approach, led to the development of a simplified solution that could be used as a failure avoidance criterion. Note the term "failure avoidance criterion" is used since it is recognized that this is not the most accurate solution that could be developed, but it should be conservative considering its developmental assumptions. A more accurate solution that is still simple enough for codification is also presented. It should be emphasized that this is an initial development effort that gives promising results for the cases examined; however, the procedure is not sufficiently validated for codification at this time.

5.1 Basic Premise of Simplified Analyses

The basic concept for developing a fitting failure avoidance analysis procedure involved determining if there was some simple relationship between a pipe fitting failure avoidance criterion and a straight-pipe failure avoidance criterion. For instance, a simple multiplier on the straight-pipe solution might be able to be used for a crack in a fitting of the same physical dimensions. In this context, consideration was given to using either the ASME B_2 or C_2 stress indices as a stress multiplier on the straight-pipe flaw evaluation solutions. The B_2 index is a stress multiplier for bending stresses relative to the bending stress in a straight pipe for limit-load analyses from a design stress viewpoint. (Note that in design stress analyses, limit-load conditions are different than the limit-load conditions for cracked pipe. The design stress limit-load definition usually refers to when a pipe fitting experiences a limited amount of global plastic bending loads or moments. The design stress limit moment corresponds to a moment where an uncracked pipe/fitting test record or nonlinear analysis moment-displacement curve intercepts an elastic slope with twice the actual elastic compliance, see Figure 5.1. The pipe fracture limit load occurs when the maximum load of a cracked structure is reached, and the material is tough enough that there is no crack growth prior to reaching maximum load.)

To check the feasibility of this approach, the IPIRG-2 J-estimation schemes developed for surface cracks in elbows were used. The details of this approach and a separate validation with elbow experimental data are presented below.

Figure 5.1 Comparison of limit-load definitions by design stress and fracture approaches

5.2 Development of Analysis Procedure

Following the desire to develop a simple failure avoidance analysis that could be readily codified, three general steps were used to assess this approach:

- (1) J versus moment curves were generated for the same size crack in both a straight pipe and a comparable fitting. These calculations were done for a stationary crack, i.e., no crack growth was used in the analyses. The calculations were done under combined pressure and bending, with the pressure levels being the same.
- (2) From these calculations, the ratio of the moment for the straight pipe to that for the elbow case at the same value of applied J was determined. A critical aspect was to see if this moment ratio varied much with the applied J level. As will be shown later, this moment ratio was virtually independent of the applied J level for J_{Ic} values of typical nuclear piping steels.
- (3) The moment ratio at constant applied J values was then compared with the ASME stress indices. This was done for pipe and elbows with different R_m/t ratios. The consistency of this comparison determined the applicability of this approach.

Details of the calculations for an axial and circumferential crack in an elbow are given in the following sections, as well as comparisons with some experimental data.

5.2.1 Axial Surface Crack Along Elbow Flank

For this crack geometry case, the elbow axial flank surface-crack solution for combined pressure and bending from Reference 5.1 could be compared with either an axial crack in a straight pipe or a circumferential crack in a straight pipe under pressure and bending. Since there are no solutions for an axial crack in a straight pipe under bending, the case of a circumferential surface crack in a straight pipe under pressure and bending was used.

5.2.1.1 Development of Elbow Axial Flank Surface Crack Crack Failure Avoidance Criterion

For the cracked-elbow J versus moment calculations, the SC.ELB3 analysis method developed during the IPIRG-2 program was used. This analysis is described in detail in Reference 5.1. The straight-pipe analyses used were SC.TNP1, SC.TNP2, SC.TKP2, and SC.ENG2. The SC.TNP1 analysis has been found in Reference 5.3 to give the best agreement between maximum load predictions and experimental data. The SC.TNP2, SC.TKP2, and SC.ENG2 J-estimation schemes were determined to agree better with J values from FEM analyses than the SC.TNP1 analysis, but these three analyses tend to underpredict experimental maximum loads when using L-C oriented C(T) specimen J-R curves. It is believed that the inaccuracy of these three analyses in predicting maximum loads may be due to anisotropy differences between the L-C oriented crack growth and the fact that surface cracks grow in the L-R direction. The L-R direction is typically higher in toughness. Additionally, there is some evidence that the constraint in a C(T) specimen is much higher than for a surface crack in a pipe, hence the apparent toughness for the surface-cracked pipe is higher than from the C(T) specimen. Details of these analyses are given in Reference 5.3. NRCPIPES Code Version 3.0 was used for the straight-pipe analyses, and IP2ELBOW Code Version 1.0 was used for the elbow analyses.

The parameters used to evaluate the applicability of straight-pipe analyses for cracks in elbows are given in Table 5.1. The elbow analyses used 90-degree bends, with a bend radius (R_e) equal to $1.5R_m$ (a long radius elbow). The calculations were done using the A106 Grade B carbon steel elbow stress-strain curve from this program and a non-growing crack for J values up to 2.0 MJ/m^2 ($11,400 \text{ in-lb/in}^2$).

The calculations were done for pressure levels corresponding to a hoop stress of 122.5 MPa (17.77 ksi) which is the S_m value for a number of commonly used stainless and carbon piping steels at 288 C (550 F), Ref. 5.1. This hoop stress corresponds to pressure levels of 20.0 MPa ($2,900 \text{ psi}$), 10.0 MPa ($1,450 \text{ psi}$), and 5.0 MPa (725 ksi) for the R_m/t cases of 5, 10, and 20, respectively. The results of the J versus moment calculations are given in Figures 5.2a, 5.2b, and 5.2c for R_m/t values of 5, 10, and 20, respectively. Note, the J-values had an intercept on the moment axis due to the pressure contribution to J. This J-value was small because it was an elastic contribution, and in some cases is not perceptible in the figures. The SC.TNP1 and SC.TNP2 analyses were used in the following comparisons.

The next step was to construct a plot of the ratio of the moments for the straight pipe to that for the elbow at the same J values, i.e., $(M^{\text{pipe}}/M^{\text{elbow}})|_J$. The variation of this ratio with applied J is illustrated in Figure 5.3. A key aspect of this figure is that after some plasticity occurs, the moment ratio becomes

Table 5.1 Parameters used in analyses of axial, flank, surface-cracked elbows

Variable	SC.ELB3 analysis - Axial surface crack in elbow under pressure and bending	Straight-pipe analyses - Circumferential surface crack under pressure and bending
Diameter, mm (inch)	406.4 (16.0)	406.4 (16.0)
R_m/t	5, 10, 20	5, 10, 20
Crack length, mm (inch)	319 (12.6)	319 (12.6)
Crack length along the elbow bend radius (R_{el}), degrees	30	N. A.
Crack length, percent of circumference	N. A.	0.25
Depth-to-thickness ratio (a/t)	0.5	0.5
Yield and reference stress, $\sigma_y = \sigma_{\infty}$, MPa (ksi)	208.3 (30.21)	208.3 (30.21)
Ultimate strength, MPa (ksi)	449.5 (65.19)	449.5 (65.19)
Strain-hardening exponent (n)	4.421	4.421
α	3.36	3.36
Elastic modulus ^(a) , GPa (ksi)	196.5 (28,500)	196.5 (28,500)

^(a) Reference strain in Ramberg-Osgood analyses is equal to the reference stress divided by the elastic modulus.

(a) $R_m/t = 5$

Figure 5.2 J versus moment calculations for an axial, flank, surface crack (SC.ELB3 analysis) in an elbow and various straight-pipe circumferential crack J-estimation schemes

Figure 5.3 Comparison of J versus moment for circumferential, surface-cracked, straight pipe to moment for axial, flank, surface-cracked elbow at the same J values ($M^{\text{pipe}}/M^{\text{elbow}}|_J$)

constant. This can also be shown mathematically^(*). For instance, the plastic parts of J due to subsequent bending for the straight pipe and the elbow, J^{pipe} and J^{elbow} , are defined in Equations 5-1a and 5-1b.

$$J^{\text{pipe}} = \alpha \sigma_o \epsilon_o b h_1^{\text{pipe}} (M^{\text{pipe}}/M_o^{\text{pipe}})^{n+1} \quad (5-1a)$$

$$J^{\text{elbow}} = \alpha \sigma_o \epsilon_o b [R_m/(\lambda t)] h_1^{\text{elbow}} (M^{\text{elbow}}/M_o^{\text{elbow}})^{n+1} \quad (5-1b)$$

where

- $\alpha, \sigma_o, \epsilon_o, n$ = Ramberg-Osgood parameters
- $h_1^{\text{pipe}}, h_1^{\text{elbow}}$ = FEM determined geometric parameters relating moment to J
- $M_o^{\text{pipe}}, M_o^{\text{elbow}}$ = reference moments at a stress of σ_o
- b = $t-a$
- t = thickness
- λ = an elbow parameter = $R_{el}t/R_m^2$
- R_{el} = bend radius of the elbow
- R_m = mean radius of pipe and elbow

Considering the case where $J^{\text{pipe}} = J^{\text{elbow}}$, for the same material, pipe size, and crack size gives

* Assuming that the plastic part of J due to the subsequent bending dominates the elastic part of J and the plastic part of J due to pure pressure loading.

$$h_1^{\text{pipe}} (M^{\text{pipe}}/M_o^{\text{pipe}})^{n+1} |_J = h_1^{\text{elbow}} [R_m/(\lambda t)] (M^{\text{elbow}}/M_o^{\text{elbow}})^{n+1} |_J \quad (5-2)$$

Rearranging Equation 5-2 gives

$$(M^{\text{pipe}}/M^{\text{elbow}}) |_J = [(h_1^{\text{elbow}}/h_1^{\text{pipe}})^{1/(n+1)} [R_m/(\lambda t)]^{1/(n+1)} (M_o^{\text{pipe}}/M_o^{\text{elbow}})] |_J \quad (5-3)$$

For a given material, pipe, and elbow geometry and similar crack size, the right-hand side of Equation 5-3 is a constant and independent of the J value, and hence $(M^{\text{pipe}}/M^{\text{elbow}}) |_J$ is a constant. This is why the curves in Figure 5.3 are vertical when plasticity dominates the J values.

In the elastic range where the J values are lowest, the $R_m/t = 20$ curve is very different from the other curves. This is caused by poor quality elastic F-functions for the straight-pipe case (Refs. 5.2, 5.4-5.6). Although this is annoying, it has little practical implication in this analysis procedure, since the toughness of typical nuclear piping materials (except some aged cast stainless steels) are outside the range where the elastic F-function is a significant contribution of the total J_{applied} .

Finally, in Figure 5.3 it should be noted that the plastic part of J dominates the moment ratio for J_{applied} values of generally greater than 100 kJ/m^2 (570 in-lb/in^2) which bounds the toughness range of typical nuclear piping material, except perhaps some aged CF8M steels.

The final step was to compare the moment ratios in Figure 5.3 to the stress indices for the elbows. Since the elbow was under bending, the B_2 and C_2 indices were used. The B_2 index is for primary bending stresses to avoid failure by collapse (using the design stress analysis definition of limit load). The C_2 stress index is for primary and secondary bending stresses also to avoid collapse. It should be noted that these stress indices essentially give stress multipliers for the location in the piping product where the stresses are the highest. For the case of an elbow under bending, the stresses are the highest along the flank of the elbow normal to the axial direction, i.e., the crack location for this evaluation. Equations 5-4 and 5-5 give the B_2 and C_2 stress indices, respectively, from Section III, Article NB-3683.7 of the ASME Boiler and Pressure Vessel Code.

$$B_2 = 1.3/h^{2/3}, B_2 \geq 1.0 \quad (5-4)$$

$$C_2 = 1.95/h^{2/3}, C_2 \geq 1.5 \quad (5-5)$$

where

$$h = tR_{\text{el}}/R_m^2 \quad (5-6)$$

These equations assume the elbows have a perfectly circular cross-section, which was a condition in the development of the SC.ELB3 J-estimation scheme.

Figure 5.4 shows a comparison of the $(M^{\text{pipe}}/M^{\text{elbow}}) |_J$ values with the B_2 and C_2 stress indices. Four aspects need to be pointed out from this figure.

- First and most importantly, the linear scatter bands show that the stress indices are greater than $(M^{\text{pipe}}/M^{\text{elbow}}) |_J$ values. Hence, dividing the straight-pipe solution by the stress indices will underpredict the moment-carrying capacity of the cracked elbow at the same J_{applied} value in the straight pipe.

- Secondly, it can be seen that there is a linear trend of the B_2 or C_2 stress indices with $(M^{\text{pipe}}/M^{\text{elbow}})_J$ values, and that using the B_2 indices gives a closer agreement to the 1:1 line.
- Thirdly, for each of the scatter bands, the upper bound occurred when using the SC.TNP1 straight-pipe analyses, and the lower bound comes from the SC.TNP2 straight pipe analyses. Using the SC.TNP1 analysis gives closer agreement to the 1:1 line.
- Finally, the scatter in the moment ratio for J values of 100 to 2,000 kJ/m² (570 to 11,430 in-lb/in²) is reflected by the symbols with the lines between them, or the touching symbols of the same type. For instance, for the case of the R_m/t equal to 5 there is a line between the symbols showing the scatter in the moment ratios, but the symbols are touching for the R_m/t values of 10 and 20. This scatter is affected by the accuracy of the straight-pipe elastic F-function as previously discussed.

The best predictions seem to be for the case of using the SC.TNP1 straight-pipe solution and the B_2 stress indices. A more precise failure criterion would account for the difference between the $(M^{\text{pipe}}/M^{\text{elbow}})_J$ versus B_2 values from the 1:1 line in Figure 5.4.

Figure 5.4 Comparison of ASME elbow stress indices to ratio of moment for circumferential, surface-cracked, straight pipe to moment for axial, flank, surface-cracked elbow at the same J values $(M^{\text{pipe}}/M^{\text{elbow}})_J$

5.2.1.2 Comparison of Elbow Axial Surface Crack Failure Avoidance Criterion with Elbow Axial Surface Crack Experimental Data

To validate the use of this failure avoidance approach, it was desirable to compare this approach with experimental data. There are limited experimental results for axial, flank, surface cracks in elbows where there is good documentation of all the variables in the experiment. An elbow test by Electricité de France (EDF) was well documented (Ref. 5.7), and hence was used in this comparison. The experimental conditions are given in Table 5.2. This was also a long radius elbow (i.e., $R_{el} = 1.5R_m$). Although the strain-hardening exponent (n) is similar to that used in developing Figure 5.4, some key differences between this experiment and the analyses used to develop Figure 5.4 were:

- (1) The crack length was slightly shorter, 26.7 degrees around the circumference versus 30 degrees in the analyses for Figure 5.4,
- (2) The crack depth was much shallower, a/t of 0.24 versus 0.5 for the analyses used to create Figure 5.4, and
- (3) The toughness was 56 kJ/m^2 (320 in-lb/in^2) which is lower than the 100 kJ/m^2 (570 in-lb/in^2) limit used in creating Figure 5.4.

Hence, it was felt that this was a significant test of this failure avoidance criteria.

Table 5.2 Parameters in EDF axial, flank, surface-cracked, elbow Experiment Y6135

Variable	Experimental Data
Diameter, mm (inch)	580 (22.8)
Thickness, mm (inch)	44.0 (1.73)
R_m/t	6.6
Crack length, mm (inch)	210 (8.27)
Crack depth-to-thickness (a/t)	0.26
Yield and reference stress, σ_y, σ_o , MPa (ksi)	321 (46.6)
Ultimate strength, MPa (ksi)	743 (107.8)
Strain-hardening exponent (n)	4.062
α	1.122
Elastic modulus ^(a) , GPa (ksi)	188.8 (27,400)
J_{Ic} , kJ/m^2 (in-lb/in ²)	56 (320)
Internal pressure, MPa (psi)	15.5 (2,250)
Moment at crack initiation, kN-m (in-kips)	2,250 (19,900)

Calculations were made with the SC.TNP1 and SC.TNP2 straight-pipe analysis methods to get the M^{pipe} value at crack initiation, and the experimental moment at crack initiation was used for the M^{elbow} value. The experimental moment ratio values are shown in Figure 5.5 in comparison with the failure avoidance criteria. Considering the differences in material and crack size between the experiment and the case used to develop Figure 5.4, the agreement is remarkably good. This evaluation shows that this methodology is

Figure 5.5 Comparison of EDF, axial, flank, surface-cracked elbow experiment Y6135 on an aged cast stainless steel elbow to criteria developed in Figure 5.4

promising for the case of an axial surface crack in an elbow. Section 5.3 discusses limitations of this methodology.

5.2.2 Circumferential Surface Crack Centered Along the Extrados of an Elbow

In this crack geometry case, the circumferential elbow surface-crack solution for combined pressure and bending was compared with the solution for a circumferential crack in a straight pipe under pressure and bending. The development of the failure avoidance criteria is very similar to the elbow axial surface-crack case. Following this development, the IPIRG-2 elbow test data are compared with this criteria.

5.2.2.1 Development of Elbow Circumferential Extrados Surface Crack Failure Avoidance Criterion

The development of a failure avoidance criterion for a circumferential crack centered along the extrados of an elbow, is parallel to that for the elbow axial crack. Some noteworthy differences are:

- (1) For the circumferential crack in the elbow, the peak J value is at 45 degrees from the center of the crack, whereas for a straight pipe, the peak J value is at the center of the crack. These differences are accounted for in the J-estimation schemes.

- (2) The B_2 and C_2 indices are stress multipliers for the location corresponding to the flank (side or crown) of the elbow. Because the peak driving force for the crack does not occur at this location, it is logical to expect that the stress indices would be less sensitive to the moment ratios at constant J values than were found in the axial, flank, surface-crack case.

For the development of the J versus moment curves, there were two elbow analyses available (SC.ELB1 and SC.ELB2) from Reference 5.1. Both of these analyses were GE/EPRI type fits developed through a matrix of the same finite element solutions, but they have different reference moments and hence different h_1 functions. The SC.ELB1 analysis uses the straight-pipe, circumferential surface-crack, Net-Section-Collapse solution to define the reference moment, and the SC.ENG2 method used the GE/EPRI method to define the reference moment. Differences between the two solutions should only occur for values interpolated between the FEM cases. The SC.ELB1 method was found to give smoother h_1 functions for interpolation purposes in Reference 5.1.

For the circumferential surface crack in the straight-pipe case, the SC.TNP1, SC.TNP2, SC.TKP2 and SC.ENG2 analyses were used. Details of these analyses are given in Reference 5.3. As previously noted, the SC.TNP1 analysis has been found in Reference 5.3 to result in the best agreement in maximum load predictions with experimental data. The SC.TNP2, SC.TKP2 and SC.ENG2 J-estimation schemes agree better with J values from FEM analyses than the SC.TNP1 analysis, but these three analyses tend to underpredict experimental maximum loads when using L-C oriented C(T) specimen J-R curves (perhaps due to anisotropy and constraint effects on toughness). The NRCPIPES code Version 3.0 was used for the straight-pipe analyses, and IP2-ELBOW code Version 1.0 was used for the elbow analyses.

The elbow analyses used 90-degree bends, with a bend radius (R_e) equal to $1.5R_m$ (a long radius elbow). The calculations were done using the A106-90 (Grade B) carbon steel elbow stress-strain curve from this program and a non-growing crack for J values up to 2.0 MJ/m^2 ($11,400 \text{ in-lb/in}^2$). The parameters used in these analyses were the same as in Table 5.2 with the exception that the circumferential crack length was 180 degrees in both the elbow and pipe analyses. This is because the SC.ELB1 and SC.ELB2 analyses were only developed for this crack length.

The calculations were done for the same pressure levels as the axially oriented crack elbow analyses. This corresponded to a hoop stress of 122.5 MPa (17.77 ksi) which is the S_m value for a number of commonly used stainless and carbon piping steels at 288 C (550 F). The results of the J versus moment calculations are given in Figures 5.6a, 5.6b, and 5.6c for R_m/t values of 5, 10, and 20, respectively. Note, the J-value intercept on the moment axis due to the pressure contribution to J was very small because it was elastic, and is not perceptible in these figures. The SC.TNP1 and SC.TNP2 analyses were used in the following comparisons.

The next step was to construct a plot of the ratio of the moments for the straight pipe to elbow at the same J values, i.e., $(M^{\text{pipe}}/M^{\text{elbow}})|_J$. This ratio is illustrated in Figure 5.7a using the SC.ELB1 analysis, and in Figure 5.7b using the SC.ELB2 analysis. As with the elbow axial flank surface-cracked elbow case, this moment ratio reaches a constant value after some plasticity.

A comparison of the moment ratios with the elbow stress indices for J values larger than 100 kJ/m^2 (570 in-lb/in^2) is shown in Figures 5.8a and 5.8b using the SC.ELB1 and SC.ELB2 analyses, respectively. Observations from these figures are:

- The results of the calculations were virtually identical using either the SC.ELB1 or SC.ELB2 solutions. This was because the case used was close to a finite element run used to define the h_1 functions.
- As with the axial elbow crack case, the linear scatter bands show that the stress indices are greater than $(M^{\text{pipe}}/M^{\text{elbow}})_J$ values. Hence, dividing the straight-pipe solution by the elbow stress indices will underpredict the moment-carrying capacity of the cracked elbow, perhaps significantly for the circumferential crack case.
- Secondly, it can be seen that there is a linear trend of the B_2 or C_2 stress indices with $(M^{\text{pipe}}/M^{\text{elbow}})_J$ values, and that again using the B_2 indices gives a closer agreement to the 1:1 line than using the C_2 indices.
- Thirdly, for each of the scatter bands, the upper bound again occurred when using the SC.TNP1 straight-pipe analyses and the lower bound comes from the SC.TNP2 straight-pipe analyses.
- Finally, the range of scatter in the moment ratio for J values of 100 to 2,000 kJ/m² (570 to 11,430 in-lb/in²) is reflected by touching symbols of the same type. There is very little difference between these points for different J values. As noted in the axial flank crack case, this scatter is affected by the accuracy of the straight-pipe elastic F-function.

(a) $R_m/t = 5$

Figure 5.6 J versus moment calculations for circumferential, extrados, surface crack (SC.ELB1 and SC.ELB2 analyses) in an elbow and various straight-pipe circumferential crack J-estimation schemes

(a) Using SC.ELB1 analysis

(b) Using SC.ELB2 analysis

Figure 5.7 Comparison of J versus moment for circumferential, surface-cracked, straight pipe to moment for, circumferential, extrados, surface-cracked elbow at the same J values ($M^{\text{pipe}}/M^{\text{elbow}}|_J$)

DEVELOPMENT OF A SIMPLIFIED FAILURE ANALYSIS PROCEDURE FOR CRACKS IN FITTINGS

(a) Using SC.ELB1 analysis

(b) Using SC.ELB2 analysis

Figure 5.8 Comparison of ASME elbow stress indices to ratio of moment for circumferential, surface-cracked, straight pipe to moment for circumferential, extrados, surface-cracked elbow at the same J values ($M^{\text{pipe}} / M^{\text{elbow}} |_J$)

Based on the analyses shown in Figure 5.8, the best prediction of elbow moment would use the SC.TNP1 straight-pipe solution and the B_2 stress indices. A more precise failure criterion would account for the difference between the $(M^{\text{pipe}}/M^{\text{elbow}})|_1$ versus B_2 values from the 1:1 line in Figures 5.8a and 5.8b. Because the slope of the scatter band is further from the 1:1 line, the circumferential crack case is less sensitive to the stress indices than the axial flank crack case as was anticipated.

As with the axial flank crack case, this result seems to be a promising method for predicting elbow behavior using straight-pipe analyses, but validation with experimental data is required.

5.2.2.2 Comparison of Elbow Circumferential Extrados Surface Crack Failure Avoidance Criterion to Experimental Data

As a first step in validating the use of this failure avoidance approach, a comparison with the IPIRG-2 elbow experimental data discussed earlier in this report was made. The experimental conditions used in the analyses are given in Table 5.3.

Table 5.3 Parameters in IPIRG-2 circumferential, extrados, surface-crack, elbow experiments

Variable	Experimental Values			
IPIRG-2 Experiment Number	2-1	2-2	2-3	2-4
Material	A106 B	A106 B	TP304L	TP304L
Diameter, mm (inch)	409 (16.1)	406 (16.0)	409 (16.1)	406 (16.0)
Thickness, mm (inch)	32.1 (1.263)	32.0 (1.26)	33.2 (1.31)	33.0 (1.30)
R_m/t	5.9	5.8	5.7	5.7
Crack length, mm (inch)	531 (20.9)	537 (21.1)	536 (21.1)	534 (21.0)
Crack depth-to-thickness (a/t)	0.84	0.80	0.73	0.77
Yield and reference stress, $\sigma_y = \sigma_o$, MPa (ksi)	208 (30.2)	208 (30.2)	200 (29.0)	200 (29.0)
Ultimate strength, MPa (ksi)	450 (65.2)	450 (65.2)	408 (59.2)	408 (59.2)
Strain-hardening exponent (n)	4.421	4.421	3.981	3.981
α	3.36	3.36	14.78	14.78
Elastic modulus ^(a) , GPa (ksi)	196.5 (28,500)	196.5 (28,500)	182.7 (26,500)	182.7 (26,500)
J_{IC} , kJ/m ² (in-lb/in ²)	373 (2,130)	402 (2,300)	1,380 (7,860)	1,060 (6,065)
Internal pressure, MPa (psi)	15.5 (2,250)	15.5 (2,250)	15.5 (2,250)	15.5 (2,250)
Moment at crack initiation, kN-m (in-kips)	562 (4,970)	593 (5,250)	601 (5,320)	536 (4,745)

There were four experiments that can be used to help validate the elbow circumferential surface-crack failure avoidance criterion, two on an A106-90 (Grade B) elbow and two on a stainless steel WP304L elbow. The two experiments for each material were the companion quasi-static and pipe system experiments. These experimental conditions were close to the same assumptions used in the analyses used

to develop the "elbow circumferential flaw failure avoidance" curve. The differences between these experiments and the analyses used to develop Figures 5.8a and 5.8b were:

- (1) The crack depths for the experiments were deeper.
- (2) The elbows in the experiments started with some known out-of-roundness. This out-of-roundness was not accounted for in the B_2 value since in reality, this value may not be known. (The EDF cast elbow tests discussed in the axial elbow tests had no significant out-of-roundness.)
- (3) The stainless steel elbow had a much lower strain-hardening exponent than used in creating Figures 5.8a and 5.8b, but the toughness was much higher than the 100 kJ/m^2 (570 kJ/m^2) lower-bound limit. (The carbon steel elbow had the same strain-hardening exponent as used in creating Figures 5.8a and 5.8b, and the toughness was above the 100 kJ/m^2 (570 kJ/m^2) lower-bound limit used in creating Figures 5.8a and 5.8b.)

Calculations were made with the SC.TNP1 and SC.TNP2 straight-pipe analysis methods to get the M^{pipe} values at crack initiation, and the experimental moments at crack initiation were used for the M^{elbow} values. The experimental moment ratio values are shown in Figure 5.9 in comparison with the scatter band from the analyses predictions and the 1:1 failure avoidance criteria. As in the axial elbow crack case, the agreement is remarkably good. However, in this case there is more conservatism if the 1:1 line is assumed in the failure avoidance criterion.

Figure 5.9 Comparison of IPIRG-2, circumferential, extrados, surface-cracked, experiments on A106-90 and WP304L elbows to criteria developed in Figure 5.8 (SC.ELB1 and SC.ELB2 analyses virtually identical)

5.3 Discussion and Further Validation Needs

A simplified failure avoidance criterion for cracks in pipe fittings that uses a straight-pipe fracture analysis and a geometric multiplier was developed and checked against a few elbow fracture experiments. This geometric stress magnification factor type of approach was originally used by Folias (Ref. 5.8) in comparing failure stresses in flat plates with cracks in pipes and spheres.

5.3.1 Generalized Approaches

To use the information in Figures 5.4 and 5.8b in an actual fracture evaluation, two approaches could be followed. The first is the simplest, but perhaps the most conservative. This approach is to simply take the ASME Section III stress indices and use them directly as simple multipliers, i.e.,

$$M^{\text{elbow}} = M^{\text{pipe}}/B_2 \quad (5-7)$$

Because the B_2 indices are closer to the 1:1 moment ratio line than the C_2 indices, more accurate predictions would be made using the B_2 indices.

Alternatively, one could define a new parameter, called Υ_x^f (where f is the type of fitting, and x is for the crack orientation) that curve fits the data in Figure 5.4 and 5.8b. Using this parameter, the elbow moments are

$$M^{\text{elbow}} = M^{\text{pipe}}/\Upsilon_x^f \quad (5-8)$$

For the axial, flank, surface-crack case:

using the SC.TNP1 straight-pipe analysis

$$\Upsilon_a^e = 0.601B_2 + 0.755, \quad (5-9a)$$

using the SC.TNP2 straight-pipe analysis

$$\Upsilon_a^e = 0.462B_2 + 0.618, \quad (5-9b)$$

For the circumferential, extrados, surface-crack case:

using the SC.TNP1 straight-pipe analysis

$$\Upsilon_c^e = 0.465B_2 + 0.136, \quad (5-10a)$$

using the SC.TNP2 straight-pipe analysis

$$\Upsilon_c^e = 0.351B_2 + 0.121. \quad (5-10b)$$

The $\Upsilon_{a,c}^e$ values are shown in Figure 5.10 for both the SC.TNP1 and SC.TNP2 straight-pipe analysis solutions. Generally the experimental results agreed better with the SC.TNP2 $\Upsilon_{a,c}^e$ values, except for the one IPIRG-2 stainless steel circumferential surface-crack elbow Experiment 2-4 which agreed better with the SC.TNP1 Υ_c^e value. Using the SC.TNP1 based $\Upsilon_{a,c}^e$ values would be slightly more conservative than the SC.TNP2 $\Upsilon_{a,c}^e$ values, yet still reasonably accurate.

Finally, an additional value to the Υ_x^f function approach, is that since this approach is best for very high J values, these functions can be used as a stress multiplier in the limit-load solution. Hence, this approach might be of use for blunt flaws in fittings, such as those caused by erosion corrosion.

5.3.2 Validation Needs

In order to further codify this type of flawed fitting failure avoidance criterion, the following should be done. First, although some of the experiments analyzed had materials with different strain-hardening exponents or different crack sizes, additional analyses should be made to check the sensitivity of the Υ_x^f function to these parameters over a wider range. Additional experimental data in the IPIRG-2 ELBOWCK database could be used to assess the accuracy of these functions. The ELBOWCK database contains 76 elbow experiments in a spreadsheet format.

Figure 5.10 Comparison of axial-flank and circumferential-extrados surface-cracked elbow failure avoidance criteria

Secondly, the Υ_x^f functions could be developed for different cracked fitting cases. It may not be necessary to develop a large matrix of finite element solutions to come up with an estimation scheme. Rather, selected finite element runs for cracked fittings could be conducted to establish Υ_x^f functions. Some experimental data for cracks in tees exist in the IPIRG-2 TEECK data base that could be used to assess such an approach or the more conservative approach of using the B_2 indices approach as in Equation 5-6 for tees.

This approach appears to be a promising method as a failure avoidance procedure for cracked fittings. However, to confirm the practicality of the approach, further validation is needed. For example, elbow radius of curvature is a variable that would directly affect the B_2 indices.

5.4 References

- 5.1 Mohan, R., Brust, F. W., Ghadiali, N., and Wilkowski, G. M., "Development of a J-Estimation Scheme for Internal Circumferential and Axial Surface Cracks in Elbows," NUREG/CR-6445, BMI-2193, August 1996.
- 5.2 Kumar, V. and others, "An Engineering Approach for Elastic-Plastic Fracture Analysis," EPRI Report NP-1931, 1981.
- 5.3 Krishnaswamy, P., Scott, P., Mohan, R., Rahman, S., Choi, Y. H., Brust F., Kilinski, T., Ghadiali, N., Marschall, C., and Wilkowski, G., "Fracture Behavior of Circumferential Short-Surface-Cracked Pipe," NUREG/CR-6298, November 1995.
- 5.4 "Evaluation of Flaws in Ferritic Piping," EPRI Report NP-6045, prepared by Novetech Corporation, October 1988.
- 5.5 Zahoor, A., "Ductile Fracture Handbook," EPRI Report NP-6301-D, Volume 2, June 1989.
- 5.6 Kumar, V. and German, M. D., "Elastic-Plastic Fracture Analysis of Through-Wall and Surface Flaws in Cylinders," EPRI Report NP-5596, January 1988.
- 5.7 Le Delliou, P., Semete, P., and Ignaccolo, S., "Fracture Mechanics Analysis of Cast Duplex Stainless Steel Elbows Containing a Surface Crack," 1996 ASME PVP Conference, *Fatigue and Fracture-1996*, Volume 323, June 1996.
- 5.8 Folias, E., S., "An Axial Crack in a Pressurized Cylinder Shell," *International Journal Of Fracture Mechanics*, Vol. 2, No. 1, pp 104-113, 1965.

6.0 CONCLUSIONS

Task 2 of the IPIRG-2 Program was developed to address questions and concerns regarding the fracture of flawed fittings. The main focus of the Task 2 work was directed towards furthering the understanding of the fracture behavior of long-radius elbows. This was accomplished through the development of J-estimation schemes for both axial and circumferential surface cracks in elbows. Intermediate size, quasi-static and dynamic, pipe-system elbow fracture experiments were performed on elbows containing an internal surface crack at the extrados. In conjunction with the elbow experiments, material property data were developed for both elbow materials investigated on A106 Grade B carbon steel and a WP304L stainless steel. A comparison of the experimental data with the maximum stress predictions using various existing straight-pipe fracture prediction analysis methods, and the elbow fracture prediction methods developed in this program was performed. This series of comparisons was directed at addressing the concerns regarding the validity of using analysis predictions developed for straight pipe to predict the fracture stresses of cracked elbows. Finally, an initial study into developing a simplified analysis approach to estimating fitting fracture was attempted. This approach incorporated the ASME stress indices to adjust common straight-pipe prediction solutions for application with cracked elbows.

As a result of the efforts associated with Task 2 of the IPIRG-2 Program, some key observations have been made. These conclusions are discussed below.

- (1) The existing database of fitting fracture experiments is somewhat limited. A majority of the data are focussed on uncracked burst strength of elbows and tees. Limited data are available for both axial and circumferential through-wall cracks. Data are available for axial surface cracked elbows in extrados, intrados, and flank orientations. For the circumferential surface-cracked elbows, data are available for cracks located on the intrados and flank. The IPIRG-2 elbow fracture experiments are the only extrados, surface-cracked data found. The IPIRG elbow data was also the only data pertaining to circumferential, extrados, surface-cracked elbows under combined pressure and bending loading conditions at dynamic loading rates.
- (2) The use of quasi-static, stress-strain properties resulted in the best predictions of the elbow experiments. Therefore, the development and use of dynamic stress-strain data is probably not necessary. This conclusion is consistent with conclusions from the IPIRG Task 1 and Task 3 reports (Refs. 6.1 and 6.2). However, it was noted in these reports that if the crack was small enough, then the uncracked pipe might experience dynamic plastic strains and the dynamic stress-strain properties may then be important.
- (3) For the carbon steel material evaluated, there was no significant increase in toughness for increased strain rates. Therefore, there was no increased benefit in using dynamic J-R curve data for predicting pipe-system experiments on the material tested. Other work in the IPIRG-2 program, however, showed that this would not be true for all carbon steel materials (Ref. 6.2).
- (4) For the stainless steel material evaluated, there was a significant increase in toughness at increased strain rates. Therefore, quasi-static, J-R curves should be used in the analysis of quasi-static experimental data, and dynamic J-R curves should be used for dynamic experiments to make more accurate predictions.

- (5) All the straight-pipe analysis techniques underpredicted the experimental moments for the $R/t = 6$ elbows tested.
- (6) Fracture ratios (experimental/predicted maximum stresses) were more accurate when the equivalent crack length was used in the analysis predictions. However, in practice, it could be difficult to obtain an accurate profile of the existing crack to make this calculation. The ASME definition of crack length size results increased the fracture ratios by an average of seven percent when compared with when the equivalent length was used for the four elbow experiments assessed.
- (7) The fracture ratios (experimental/predicted maximum stresses) for all four elbow experiments, based on the straight-pipe SC.TNP1 method, were slightly above the previously established scatter band of fracture ratios for the SC.TNP1 analysis method when used on straight pipe. This tends to indicate that the straight pipe SC.TNP1 method is adequate for predicting the load-carrying capacity of circumferential cracks along the extrados of an elbow, at least for the R/t ratio, pipe diameter, and crack geometries considered in this effort. For higher R/t ratio elbows, the elbow failure loads are expected to be below the straight-pipe results.
- (8) The SC.ELB2 method results in a reasonable underprediction of the experimental moments for these circumferential extrados-type cracks. For both materials and for all of the crack sizes considered, the difference in predictions between the SC.ELB2 elbow solution and the SC.TNP1 straight pipe solution is less than 10 percent for the $R_w/t=6$ elbow examined. This is well within the typical experimental scatter band observed in straight-pipe experiments.
- (9) An assessment of the new elbow J-estimation schemes for the case of the axially oriented, elbow flank crack was not done directly (see Conclusion 11). This was because no data exist in the ELBOWCK database which had exactly the same flaw length as used in the new elbow J-estimation scheme. Relative comparison between the axial and circumferential cracked elbow analyses, using similar size cracks, showed the crack-driving force (J) was much higher for the axial crack case.
- (10) For circumferential through-wall cracks, limit-load solutions for straight pipe and elbows both underpredict the elbow experimental data for crack lengths larger than 30 percent of the circumference. For cracks less than 30 percent in length, the elbow limit-load solution follows the trend of the experimental data. For the crack length studied, the fracture ratios for the elbow limit-load solution ranged between 1.19 and 1.42.
- (11) An effort was undertaken to see if the elbow analyses developed in this report could be simplified to a readily codifiable procedure, and if that same process could also be extended to other crack lengths. The approach undertaken was to see if there was a multiplier that could be used on the circumferential surface-cracked straight-pipe solutions. The simplest and most conservative approach was to estimate the elbow failure loads by using the straight-pipe loads divided by the ASME B_2 stress indices for elbows. This was always conservative, but perhaps too conservative for circumferential flaws in elbows or at higher R/t ratios. The second approach was to investigate if a more accurate solution could be used rather than just the B_2 stress indices. A stress multiplier, called the Υ -function, was developed from the ratio of the moments in the straight pipe to that in the elbow at constant values of J (for the same crack sizes in the pipe and elbow). Comparisons to the IPIRG-2 circumferential extrados experiments and an EDF axial, flank experiment on an aged cast stainless steel elbow were in good agreement with the Υ analysis. This method looks extremely promising, but

some further validation is needed before it is ready for code implementation. The Υ -function was theoretically found to be valid through the elastic-plastic region especially at high J values, and is therefore also valid for limit-load solutions. Finally, from this exercise, it is now seen how Υ -functions could be more easily developed for through-wall cracks in elbows, cracks in tees, or cracks in any other pipe fitting. This could be done without the extensive need of J -estimation scheme developments as was done in this report.

- (12) The experimental data and subsequent analysis predictions were developed for a limited set of material data, and for a specific crack orientation, crack length, and limited a/t ratio. Caution should be used before applying the results and conclusions drawn from this work to a broad generalization regarding the fracture behavior of other geometries. Issues/variables such as material, elbow diameter, R/t ratio, crack location, and flaw size need to be investigated and may or may not support the findings of this work.

6.1 References

- 6.1 Scott, P., and others, "IPIRG-2 Task 1 Report - Pipe System Experiments with Circumferential Cracks in Straight-Pipe Locations," NUREG/CR-6389, December 1996.
- 6.2 Rudland, D., and others, "The Effects of Cyclic and Dynamic Loading on the Fracture Resistance of Nuclear Piping Steels," NUREG/CR-6440, December 1996.

APPENDIX A

IPIRG-2

Bibliography of Pipe Fitting Fracture Papers

May 13, 1996

APPENDIX A

BIBLIOGRAPHY OF PIPE FITTING FRACTURE PAPERS

Analytical

*Arav, F., "Evaluation of Pipe Bends Having Local Corrugations," *Third International Conference on Pressure Vessel Technology*, Tokyo, Japan (April 1977).

Azzam, T. J., and Scavuzzo, R. J., "Analysis of Ratcheting in Pressurized Pipe Elbows," *Seismic Engineering*, Edited by Ware, and others, pp 107-116, ASME, San Diego (1991).

Basavanhally, N., and Tonet, N., "A Study of Stress Distribution in Elbows Mounted on Stanchions," *Transactions of 7th International SMiRT Conference*, Vol. F, pp 389-394 (1983).

*Begley, J. A., and Sheinker, A. A., "Crack Propagation Testing for LMFBR Piping - Phase I Final Report," Prepared for the U.S. Energy Research and Development Administration, Division of Reactor Research and Development, Westinghouse Electric Corporation, Advanced Reactors Division, Contract No. E(11-1)-3045, Task 6 (1976).

Burst tests on pressurized scale-model and full-scale elbows with axial through-wall-cracks loaded under bending were presented. A good correlation between scale-model and full-scale elbows was obtained. Also discussed were results on fatigue tests of surface (axial) cracked scale-model elbows.

*Begley, J. A., Wilson, W. K., and Sheinker, A. A., "Crack Propagation Investigation Related to the Leak-Before-Break Concept for LMFBR Piping," *Proceedings of Conference on Tolerance of Flaws in Pressurized Components*, Sponsored by Pressure Vessels Section of the Applied Mechanics Group of the Institution of Mechanical Engineers, pp 215-224 (1978).

Burst tests on pressurized scale-model and full-scale elbows with axial through-wall cracks loaded under bending were presented. A good correlation between scale-model and full-scale elbows was obtained. Also discussed were results on fatigue tests of surface (axial) cracked scale-model elbows.

Brosi, S., Wanner, R., Uhlman, D., and Diem, H., "Fracture Mechanics Studies of a Cracked Pipe Bend Under In-Plane Loading," *Transactions of the 10th International SMiRT Conference*, Vol. G, pp 19-24 (1989).

Brust, F. W., Rahman, S., and Ghadiali, N. D., "Elastic-Plastic Analysis of Small Cracks in Tubes," *Journal of Offshore Mechanics and Arctic Engineering*, Vol. 117, pp 57-62 (February 1995).

Bushnell, D., "Elastic-Plastic Bending and Buckling of Pipes and Elbows," *Computers and Structures*, Vol. 13, pp 241-248 (1981).

*Refers to references containing both experimental and analytical results.

Chattopadhyay, J. Dutta, B. K., and Kushwaha, H. S., "Elastoplastic Fracture Mechanics Analysis of Elbows Using Layered Shell Bending Element," *Proceedings of Fatigue and Fracture in Steel and Concrete Structures, ISFF*, New Delhi, India, pp 79-89 (1991).

Doi, H., et al., "Structural Analysis of Elbow with Surface Crack," *Transactions of ASME-PVP Conference*, Nashville, Tennessee, Vol. 195, pp 99-104 (1990).

Results of finite element analysis of elbow axial cracks were presented. Relationship between COD and crack depth were found to agree well with fatigue experiments. J-integral estimates were conducted for part-through cracks.

*Doyen, J. J., and Marini, J., "Propagation of Inadequate Joint Penetration Defects of Welded Elbows," *Transactions of 4th International SMiRT Conference*, Vol. F, F1/3 (August 1977).

*Erdogan, F., "Theoretical and Experimental Study of Fracture in Pipelines Containing Circumferential Flaws," Final Report to Department of Transportation, Report No. DOT-RSPA-DMA-50/83/3 (August 1982).

Erdogan, F., and Delale, F., "Stress Intensity Factors in Pipe Elbows," *Proceedings of Advances in Fracture Research of the 5th International Conference on Fracture*, Cannes, France, Vol. 1, pp 169-176 (1982).

Findlay, G. E., and Spence, J., "The Effects of Flanges on Smooth Pipe Bends in Piping Systems," *Transactions of 2nd International SMiRT Conference*, Vol. 2, Parts E and F, F3/5 (September 1973).

*Gowda, S.P.T.R., Paramasivam, V., and others, "Experimental and Theoretical Investigation of Stresses and Flexibility Coefficients at Pipe Junctions," *Transactions of the 12th International SMiRT Conference*, F02/2, pp 19-24, (1993).

Grebner, H., and Hofler, A., "Analysis of a Pipe Elbow with Longitudinal Through Crack," *Nuclear Engineering and Design*, Vol. 114, pp 147-153 (1989).

Grebner, H., and Hofler, A., "Crack Opening and Leak Rate Evaluation for Piping Components with Through Cracks," *Nuclear Engineering and Design*, Vol. 135, pp 161-170 (1992).

Elasto-plastic FEM analysis of a through-wall axial crack in the crown of an elbow was conducted. The loading was internal pressure. J estimations and crack-opening behavior were studied.

Grebner, H., Holfer, A., and Haber, O., "Elastic Plastic Analysis of a Cracked Piping System," *Transactions of 10th International SMiRT Conference*, Vol. G, pp 317-322 (1989).

*Heald, J.D., "Reactor Primary Coolant System Rupture Study," Quarterly Progress Report No. 16, GEAP-10024, pp 6-21 to 6-54 (June 1969).

Ignaccolo, S., Proix, J., Churier-Bossennec, H., and Faidy, C., "3D Computation of Cracked Piping Components," *Pressure Vessel and Piping*, Vol. 266, pp 137-146, *Creep, Fatigue Evaluation, and Leak-Before Break Assessment*, ASME (1993).

James, L. A., "Estimation of Crack Extension in a Piping Elbow Using Fracture Mechanics Techniques," *J. of Pressure Vessel Technology*, ASME, Paper No. 74-PVP-14, pp 1-6 (1974).

LEFM analysis of cracks in the inside surface of an elbow (circumferential as well as axial) were conducted. The worst locations of cracks were examined in detail.

Jamet, P., Stamm, M., Bhandari, S., Gruter, L., and Green, D., "Comparative Elastic Analyses of a Cracked Elbow," *Proceedings of 1988 ASME Pressure Vessels and Piping Conference*, Pittsburgh, Pennsylvania, pp 55-58 (1988).

Kalnins, A., "Analysis of Curved Thin-Walled Shells of Revolution," *ALAA Journal*, Vol. 6, No. 4, pp 584-588 (April 1968).

Kano, T., Iwata, K., Asakura, J. and Takeda, H., "Stress Distributions of an Elbow with Straight Pipes," *Transactions of 4th International SMiRT Conference*, Vol. F, F1/5 (August 1977).

Kim, Y. J., and Lee, J. S., "An Interaction Analysis of Twin Surface Crack by the Line Spring Model," *Transactions of 10th International SMiRT Conference*, Vol. G, pp 37-42 (1989).

Kobayashi, A. S., and Emery, A. F., "Theoretical Investigation of Pipe Fracture: A Summary," Final Report, Electric Power Research Institute, EPRI-NP-4565 (May 1986).

Kozluk, M., Manning, B. W., Misra, A. S., Lin, T. C., and Vijay, D. K., "Linear-Elastic Solutions for Long Radius Piping Elbows with Curvilinear Through-Wall Cracks," *Transactions of ASME-PVP Conference*, Pittsburgh, Pennsylvania, pp 23-28 (1988).

Results of LEFM of longitudinal through-wall cracks in the crown of an elbow were presented. The ABAQUS computer code was used. COD, crack-face rotations, and J values were calculated. Examination of Modes I, II and III were made. Cases studied were: internal pressure, in-plane moment, and symmetric force for Mode I loading. For antisymmetric force, Mode II loading was evaluated.

*Krishnaswamy, P., Wilkowski, G. M., and Wambaugh, J. O., "Brittle Fracture Initiation of Heavy-Wall Components," NG-18 Report No. 144, Report to American Gas Association (January 1985).

*Kusmaul, K., Diem, H., and Blind, D., "Deformation and Failure Behavior of Elbows - Experimental Results and Analytical Predictions," *Transactions of 1986 ASME-PVP Conference*, Chicago, Illinois (1986).

*Kusmaul, K., Diem, H., and Blind, D., "Investigations of the Plastic Behavior of Pipe Bends," *Transactions of 1987 ASME-PVP Conference*, San Diego, California.

*Kusmaul, K., Diem, H., Rensch, H.J., and Hofmann, H., "Elastic-plastic analysis of a full-size elbow - Experimental and numerical investigations," *Transactions of the 9th International SMiRT Conference*, Vol. F, pp 325-330 (1987).

*Kusssmaul, K., Diem, H., Roos, E., and Uhlmann, D., "Geometry Influence on the Location of Incipient Cracking of Pipe Bends under In-Plane Bending," *Proceedings of 3rd International Conference on Biaxial Multiaxial Fatigue*, Stuttgart (1989).

*Kusssmaul, K., Kerkhof, K., and Herter, K. H., "System Response of Piping Configurations Under Overload Conditions," *Transactions of the 10th International SMiRT Conference*, Vol. F, pp 94-104 (1989).

Kusssmaul, K., Uhlmann, D., Koski, K., and Hunger, H., "Fracture Mechanics Analysis of a Longitudinally Cracked Bend Under Cyclic Loading," *Transactions of the 12th International SMiRT Conference*, Vol. F, pp 177-182 (1993).

Lazzeri, L., "An Elastoplastic Elbow Element: Theory and Applications," *Transactions of the 5th International SMiRT Conference*, Berlin, Germany, Vol. F, F3/6 (1979).

Mackenzie, D., Comlekci, T., and Boyle, J. T., "Comparison of Flexibility and Finite Element Analysis of Example Piping Systems," *Transactions of 11th International SMiRT Conference*, Vol. F, pp 73-78 (1991).

Matsubara, M., "A Parametric Study on J-integral under Pressurized Thermal Shock by Using Statically Indeterminate Fracture Mechanics," *Transactions of 11th International SMiRT Conference*, Vol. G3, pp 153-158 (1991).

*Mayfield, M. E., Forte, T. P., Rodabaugh, E. C., Leis, B. N., and Eiber, R. J., "Cold Leg Integrity Evaluation," NUREG/CR-1319 (January 1980).

de Melo, F. J. M. Q., Oliveira, C. A. M., de Castro, P. M. S. T., and Wittmann, F. H., "Stress Analysis Near a Part-Through Crack in Thin-Walled Pipe Bends Under In-Plane Bending," *Transactions of the 9th International SMiRT Conference*, Lausanne, Switzerland, pp 57-63 (1987).

Michel, B., Voldoire, F., and Wittmann, F. H., "Mechanical Analysis of an Auxiliar Piping Elbow," *Transactions of the 9th International Conference on Structural Mechanics in Reactor Technology*, Lausanne, Switzerland (August 17, 1987).

*Mikkola, T. P. J., Diem, H., Blind, D., and Hunger, H., "Failure Behavior of a Pipe System with a Circumferentially Orientated Flaw - Analytical and Experimental Investigations," *Nuclear Engineering and Design*, Vol. 112, pp 197-210 (1989).

Mueller, K. U., Kiem, H., and Hunger, H., "Investigations on Stressing and Failure of Pipe Bends Under Complex Loading," *Nuclear Engineering and Design*, Vol. 87, pp 269-279 (1985).

Moulin, D., and Brochard, J., "Classification of Stress in the Ligament of a Longitudinal Crack in an Ovalizing Elbow," PVP-Vol. 266, ASME, pp 147-154, (1993).

Ohtsubo, H., and Watanabe, O., "Flexibility and Stress Factors of Pipe Bends--An Analysis by the Finite Ring Method," *ASME Journal of Pressure Vessel Technology*, Vol. 99, pp 281-290 (1977).

- Paramasivam, V., Achyutha, H., Gowda, S. P. T. R., Kakodkar, A., and Kushwaha, H. S., "Stress Analysis of Tee Pipe Junction," *Transactions of 11th International SMiRT Conference*, Vol. F, pp 61-66 (1991).
- Perry, R. F., "Pipe Elbow Stiffness Coefficients Including Shear and Bend Flexibility Factors for Use in Direct Stiffness Codes," *Transactions of 4th International SMiRT Conference*, Vol. F, F1/2 (August 1977).
- Reynolds, M. B., "Reactor Primary Coolant System Rupture Study," Quarterly Progress Report No. 12, GEAP-5637, pp 17-25 (June 1968).
- *Rodabaugh, E. C., and George, H. H., "Effect of Internal Pressure on Flexibility and Stress-Intensification Factors of Curved Pipe or Welding Elbows," *Transactions of ASME*, Vol. 79, pp 937-948 (May 1957).
- *Rodabaugh, E. C., and Moore, S. E., "Evaluation of the Plastic Characteristics of Piping Products in Relation to ASME Code Criteria," NUREG CR-0261, ONRL/Sub-291318 (July 1978).
- Rodabaugh, E. C., Duffy, A. R., and Atterbury, T. J., "The Internal Pressure Capacity of Butt Welding Elbows," Phase Report on NG-18 Research by Battelle Memorial Institute (September 18, 1969).
- Roos, E., Diem, H., Herter, K. H., Stumpfrock, L., "Fracture mechanical assessment of pipes under quasistatic and cyclic loading," *Steel Research*, Issue No. 4, pp 181-187 (1990).
- Roos, E., Katzenmeier, G., Wanner, R., and Mercier, O., "Finite Element Study of an HDR-RPV-Section Including a Nozzle Under Thermal Shock Transient," NEA/CSNI/R(91)14, *Proceedings of a Workshop-The Complementary Roles of Fracture Mechanics and Non-Destructive Examination in the Safety Assessment of Components*, pp 133-146 (October 1988).
- Sanders, Jr., J. L., "Circumferential Through Cracks in Cylindrical Shells Under Tension," *Journal of Applied Mechanics*, Vol. 49, pp 103-107 (March 1982).
- Sanders, Jr., J. L., "Analysis of Circular Cylindrical Shells," *Journal of Applied Mechanics*, Vol. 50, pp 1165-1170 (December 1983).
- Sanders, Jr., J. L., *Fracture Analysis of Cracks in Complete Cylindrical Shells*, Harvard University, Cambridge, Massachusetts, Division of Applied Sciences (December 3, 1984).
- Sanders, Jr., J. L., "Dugdale Model for Circumferential Through Cracks in Pipes Loaded by Bending," *International Journal of Fracture*, Vol. 34, pp 71-81 (1987).
- Sanders, Jr., J. L., "Tearing of Circumferential Cracks in Pipes Loaded by Bending," *International Journal of Fracture*, Vol. 35, pp 283-294 (1987).
- Sauter, A., Turan, K., Kerkhof, K., and Wagemann, G., "Calculational Models for a Cracked Pipe Elbow is a Feedwater Line," *Nuclear Engineering and Design*, (volume and date unknown). [Also presented at the 13th MPA Seminar, Stuttgart (October 8-9, 1987)].

Sauter, A., Turan, K., Kerkhof, K., and Wagemann, G., "Fracture Mechanics Analysis of a Pipe Elbow," *Nuclear Engineering and Design*, Vol. 112, pp 211-220 (1989).

J-evaluation using a line-spring model for longitudinal cracks (inner surface) in elbows was studied using linear line spring as well as 3D elements. Crack configuration was 97.5° on both sides of pipes measured from extrados. Comparison of linear line-spring model and 3D model was found to be good.

*Shimakawa, T., Takahashi, H., Doi, H., Watashi, K., Asada, Y., "Creep-fatigue crack propagation tests and the development of an analytical evaluation method for surface cracked pipe," *Nuclear Engineering and Design*, Vol. 139, pp 283-292, (1993).

Simos, N., Reich, M., Hartzman, M., and Constantino, G. J., "Assessment of Thermal Fatigue Crack Propagation in Safety Injection PWR Lines," *Proceedings of the 1990 Pressure Vessels and Piping Conference*, Nashville, Tennessee, pp 65-72 (1990).

Smith, E., "Effect of Pipe Bends on the Stability of a Circumferential Through-Wall Crack in a Type 304 Stainless Steel Piping System," *Engineering Fracture Mechanics*, Vol. 29, pp 705-712 (1988).

Smith, E., "Effect of Pipe Bends on the Stability of a Circumferential Through-Wall Crack in a Type 304 Stainless Steel Piping System. Exact Theory Accounting for Axial Strains in the Piping Segments," *Engineering Fracture Mechanics*, Vol. 32, pp 739-743 (1989).

Smith, E., "The Instability of a Circumferential Through-Wall Crack in a Bend in a Stainless Steel Piping System: The Effect of Bend Angle on the Instability Criterion," *Transactions of 10th International SMiRT Conference*, Vol. G, pp 353-356 (1989).

Instability of a circumferentially cracked pipe bend was examined. The crack instability criterion was expressed in terms of the material learning modulus, T_{MAT} , and applied tearing modulus, T_{APP} (or equivalent pipe length, L_{eff}). Also, the effects of pipe bend angle were examined.

Smith, E., "Effect of Pipe Bends on the Elastic Flexibility of a Piping System," *International Journal of Pressure Vessels and Piping*, Vol. 45, pp 121-129 (1991).

Sobel, L. H., "In-Plane Bending of Elbows," *Computers and Structures*, Vol. 7, pp 701-715, Pergamon Press (1977).

Spence, J., "The Creep Bending of Short Radius Pipe Bends," *Transactions of 3rd International SMiRT Conference*, Vol. 2, Part F, F6/2 (September 1975).

*Spence, J., and Findlay, G. E., "New Look at Existing Data Holds Out Hope for Those Oval Pipe Bends," *Process Engineering* (December 1972).

Spence, J., and Findlay, G. E., "Limit Loads for Pipe Bends Under In-Plane Bending," *Proceedings of the 2nd International Conference on Pressure Vessel Technology, Part I*, ASME, pp 393-399 (1973).

Srinivas, S., Panesar, J.S., and Aggarwal, M.L., "Stress Intensity Factors for Longitudinal Cracks at Branch Tee Connections in Pipes," *Transactions of the 6th International SMiRT Conference*, Vol. F, page 9 (1988).

Tanigawa, M., Negishi, H., Shimokoshi, M., Kasahara, N., Nagata, T., and Iwata, K., "A Method for Creep-Fatigue Damage Evaluation at Structural Discontinuity Portions 2: Stress Analysis of Y-Junctions," *Transactions of 11th International SMiRT Conference*, Vol. E, pp 155-160 (1991).

Thomas, K., "Design Guidelines for Elbows with Geometric Non-Uniformities," Westinghouse Report, WARD-5D-3045-16 (1978).

Thomas, K., "The Effects of Geometric Non-Uniformities on the Stress in Piping Elbows," Westinghouse Report, WARD-SD-3045-7 (1978).

Thomas, K., "The Effects of Geometric Irregularities on the Design Analysis of Thin-Walled Piping Elbows," *Journal of Pressure Vessels Technology*, ASME, Vol. 102, pp 410-418 (1980).

Effect of geometric irregularities on stress penetrations in thin-walled elbows loaded under internal pressure and in-plane bending were examined.

Thomas, K., "Stiffening Effects on Thin-Walled Piping Elbows of Adjacent Piping and Nozzle Constraints," *Journal of Pressure Vessel Technology*, Vol. 104, pp 180-187 (August 1982).

Thomson, G., Spence, J., "Combined Pressure and In-Plane Bending on Pipe Bends with Flanges," *Transactions of 3rd International SMiRT Conference*, Vol. G, pp 405-412 (1983).

Thomson, G., Spence, J., "Maximum Stresses and Flexibility Factors of Smooth Pipe Bends with Tangent Pipe Terminations Under In-Plane Bending," *Journal of Pressure Vessel Technology*, Vol. 105, pp 329-336, (November 1983).

A theoretical solution for in-plane bending, linear elastic behavior of smooth, circular cross-sectional constant thickness pipe bends with connected tangent pipes of similar section was presented.

Thompson, J. J., "Shell Theory Analysis of Pure in-Plane Bending of a Pipe Bend," *Transactions of 3rd International SMiRT Conference*, Vol. 2, Part F, F6/1 (September 1975).

*Touboul, F., Ben Jdidia, M., and Acker, D., "Design Rules for Piping: Experimental Validation of Flexibility and Elastic Stress Indices for Elbows Under Bending," *Transactions of the 10th International SMiRT Conference*, Vol. F, pp 75-80 (1989).

Uhlmann, D., Diem, H., and Brosi, S., "Fracture Mechanics Study of a Pipe Bend with a Longitudinal Crack Under Static Loading," *Nuclear Engg. and Design*, Vol 119, pp 347-360 (1990).

Vanderglas, M. L., "Experiences Using Three-Dimensional Finite Element Analysis for Leak-Before Break Assessment," *International Journal of Pressure Vessels and Piping*, Vol. 43, pp 241-253 (1990).

Villasor, A. P., "The influence of geometric mismatch on steam generator U-bend stresses," *Transactions of the 9th International SMiRT Conference*, Vol. F, pp 311-318 (1987).

Whatham, J. F., "Results of Pipe Bend Analysis: Parts VI & VII," Australian Atomic Energy Commission (December 1983).

*Wilkowski, G. M., "Summary of the Status of Pipe Fracture Predictions," *Proceedings of the Seminar on Assessment of Fracture Prediction Technology: Piping and Pressure Vessels*, Nashville, Tennessee (June 18, 1990).

Yadav, R. R. S., Mehra, V. K., and Kakodkar, A., "Stress Analysis of Sleeve Repaired Elbow-Elbow Weld Joint," *Transactions of the 8th International SMiRT*, Brussels, Belgium, Vol. F1-F2, pp 275-280 (1985).

Zahoor, A., *A Ductile Fracture Handbook*, Novetech Corporation, Gaithersburg, Maryland, and EPRI, Palo Alto, California, Vol. 3 (1991).

Experimental

Acker, D., Touboul, F., and Brouard, D., "Experimental Analysis of Ratcheting in Elbows," *Transactions of the 11th International SMiRT Conference*, Vol. E, pp 37-42 (1991).

Ageev, V. L., Dranchenko, B. N., Portnov, B. B., and Seleznev, A. V., "Study of Stress Concentration in Tee-Joints for Optimum Design," *Soviet Machining Science*, pp 50-55 (1987).

*Arav, F., "Evaluation of Pipe Bends Having Local Corrugations," *3rd International Conference on Pressure Vessel Technology*, Tokyo, Japan (April 1977).

*Begley, J. A., and Sheinker, A. A., "Crack Propagation Testing for LMFBR Piping - Phase I Final Report," Prepared for the U.S. Energy Research and Development Administration, Division of Reactor Research and Development, Westinghouse Electric Corporation, Advanced Reactors Division, Contract No. E(11-1)-3045, Task 6 (1976).

*Begley, J. A., Wilson, W. K., and Sheinker, A. A., "Crack Propagation Investigation Related to the Leak-Before-Break Concept for LMFBR Piping," *Proceedings of Conference on Tolerance of Flaws in Pressurized Components*, Sponsored by Pressure Vessels Section of the Applied Mechanics Group of the Institution of Mechanical Engineers, pp 215-224 (1978).

Bhandari, S., Fortmann, M., Grueter, L., Heliot, J., Meyer, P., Percie Du Sert, B., Prado, A., and Zeibig, H., "Crack Propagation in a LMFBR Elbow," *Nuclear Engg. and Design*, Vol 91, pp 107-119 (1986).

Results of large-scale elbow testing were presented. The experiments conducted on maximum design stress values demonstrates low crack growth rates under plant conditions. The experiments involved axial surface cracks. Useful information is provided.

Brouard, D., Tremblais, A., and Vrillon, B., "In-Plane and Out-of-Plane Bending Tests on Carbon Steel Pipe Bends," *Transactions of 5th International SMiRT Conference*, Vol. F, F3/2 (August 1979).

Results of bend tests on 106 Grade B carbon steel 90° and 180° elbows were presented. Significant differences between in-plane and out-of-plane bending were observed. Effects of collapse moment on elbow angle were discussed.

Bubenik, T. A., and Rosenfeld, M. J., "Assessing the Strength of Corroded Elbows," NG-18 Report No. 206 (May 1993).

Burns, D. J., "Crack Growth from Defects in Tee Intersections and Nozzles-Development of Ultrasonic Crack Growth Monitors," Final Report, Atomic Energy Control Board, Ottawa, Ontario, Canada, Report No. AECB-1194 (1982).

Diem, H., Blind, D., Katzenmeier, G., Hunger, H. A., "Crack Initiation and Crack Propagation of an Elbow Under in-Plane Bending in High Temperature Water of Elevated Oxygen Content," *Transactions of 10th International SMiRT Conference*, Vol. G, pp 65-76 (1989).

*Doyen, J. J., and Marini, J., "Propagation of Inadequate Joint Penetration Defects of Welded Elbows," *Transactions of 4th International SMiRT Conference*, Vol. F, F1/3 (August 1977).

Dranchenko, B. N., Portnov, B. B., Seleznev, A. V., and Sokolov, A. S., "On the Methodology of Experimental Studies of Tee Junctions in the Context of Nuclear Power Plant Equipment Design," *Thermal Engineering*, Vol. 37, pp 597-601 (1990).

Eiber, R. J., Maxey, W. A., Duffy, A. R., and Atterbury, T. J., "Investigations of the Initiation and Extent of Ductile Pipe Rupture: Task 17," Final Report, BMI-1908, Battelle, Columbus, Ohio (June 1971).

*Erdogan, F., "Theoretical and Experimental Study of Fracture in Pipelines Containing Circumferential Flaws," Final Report to Department of Transportation, Report No. DOT-RSPA-DMA-50/83/3 (August 1982).

Findlay, G. E., and Spence, J., "Bending of Pipe Bends with Elliptic Cross Sections," *Welding Research Council Bulletin*, No. 164 (1971).

*Gowda, S. P. T. R., Paramasivam, V., et al., "Experimental and Theoretical Investigation of Stresses and Flexibility Coefficients at Pipe Junctions," *Transactions of the 12th International SMiRT Conference*, F02/2, pp 19-24, (1993).

Grebennik, V. S., and Antonova, O. B., "Analysis of the Statistical Data of Ultrasonic Operational Quality Control of the Metal of Bent Parts of Pipes," *Soviet Journal of Nondestructive Testing*, Vol. 25, pp 565-571 (April 1990).

Griffiths, J. E., "The Effect of Cracks on the Limit Load of Pipe Bends Under In-Plane Bending: Experimental Study," *Int. J. Mech. Sci.*, Vol. 21, pp 119-130 (1979).

Limit loads for cracked pipe bends were experimentally determined. Effects of crack size and shape (circumference versus axial) were examined.

*Heald, J.D., "Reactor Primary Coolant System Rupture Study," Quarterly Progress Report No. 16, GEAP-10024, pp 6-21 to 6-54 (Jan. - Mar. 1969).

Hilsenkopf, P., Boneh, B., and Sollogoub, P., "Experimental study of behavior of austenitic stainless steel thin-walled elbows - Functional capability," *Transactions of the 9th International SMiRT Conference*, Vol. F, pp 331-338 (1987).

Iwamoto, T., Yamamura, Y., and Hojo, S., "Observations and Analyses at the Bend and Tee Portions of Buried Ductile-Iron Pipelines During Earthquakes," *Proceedings of the 1985 Pressure Vessels and Piping Conference*, New Orleans, Louisiana, pp 69-79 (1985).

Jamet, P., Moulin, D. D., Toubol, F., Lebey, J., Acker, D., "Crack Initiation and Experimental Determination of J in Bending for Elbows and Pipes in Austenitic Steel," *Proceedings of Seminar on Leak-Before-Break: Further Developments in Regulatory Policies and Supporting Research*, Taipei, Taiwan, pp 101-126 (1989).

Joyce, J. A., Hackett, E. M., and Roe, C., "Elastic-Plastic Characterization of a Cast Stainless Steel Pipe Elbow Material," Nuclear Regulatory Commission Report NUREG/CR-5774 (January 1992).

Kirk, C. J., and Kitching, R., "Tests of Fracture to Bends and Equal Tee Pipe Joints," *Proceedings of the Reinforced Plastic Constructed Equipment in the Chemical Process Industry*, Institution of Chemical Engineers, Manchester, England, pp 1-9 (1980).

Flexibility and strength of pipes, bends and equal tee pipe joints were measured for glass reinforced plastic material and compared with predictions of elastic bending theory.

*Krishnaswamy, P., Wilkowski, G. M., and Wambaugh, J. O., "Brittle Fracture Initiation of Heavy-Wall Components," NG-18 Report No. 144, Report to American Gas Association (January 1985).

*Kusmaul, K., Diem, H., and Blind, D., "Deformation and Failure Behavior of Elbows - Experimental Results and Analytical Predictions," *Transactions of 1986 ASME-PVP Conference*, Chicago, Illinois (1986).

Experimental results on deformation behavior of ferritic pipe elbows loaded quasi-statically as well as cyclically under bending are compared with finite-element results. This work points out the role of strain-induced corrosion cracking caused by very low cycle corrosion fatigue.

*Kusmaul, K., Diem, H., and Blind, D., "Investigations of the Plastic Behavior of Pipe Bends," *Transactions of 1987 ASME-PVP Conference*, San Diego, California.

*Kusmaul, K., Diem, H., Rensch, H. J., and Hofmann, H., "Elastic-plastic Analysis of a Full-size Elbow - Experimental and Numerical Investigations," *Transactions of the 9th International SMiRT Conference*, Vol. F, pp 325-330 (1987).

*Kusmaul, K., Diem, H., Roos, E., and Uhlmann, D., "Geometry Influence on the Location of Incipient Cracking of Pipe Bends under In-Plane Bending," *Proceedings of 3rd International Conference on Biaxial Multiaxial Fatigue*, Stuttgart (1989).

Kussmaul, K., Diem, H., Uhlmann, D., and Hunger, H., "Fatigue and Failure Behavior of a Mechanically Loaded Ferritic Pipe Bend in High Temperature Water with Elevated Oxygen Content," *Transactions of 11th International SMiRT Conference*, Vol. F, pp 213-218 (1991).

*Kussmaul, K., Kerkhof, K., and Herter, K. H., "System Response of Piping Configurations Under Overload Conditions," *Transactions of the 10th International SMiRT Conference*, Vol. F, pp 94-104 (1989).

Kussmaul, K., Maile, K., Eckert, W., and Moller, D., "Large Scale Validation Tests of Pressurized Elbows with Additional Bending Moment at 550°C," *Transactions of 11th International SMiRT Conference*, Vol. F, pp 13-18 (1991).

Kussmaul, K., Roos, E., Diem, H., Katzenmeier, G., and Neugrech, G. E., "Fracture Mechanics Assessment of Cracks in the HDR Reactor Pressure Vessel due to Pressurized Thermal Shock Loading," *Transactions of the 11th International SMiRT Conference*, Vol. G, pp 141-152 (1991).

Maeda, N., "Ultrasonic Wave Propagation in a Curved Surface Body," *Proceedings of the 9th International Conference on Nondestructive Evaluation in the Nuclear Industry*, Tokyo, Japan, pp 105-110 (1988).

*Mayfield, M. E., Forte, T. P., Rodabaugh, E. C., Leis, B. N., and Eiber, R. J., "Cold Leg Integrity Evaluation," NUREG/CR-1319 (January 1980).

Mayfield, M. E., Rodabaugh, E. C., and Eiber, R. J., "A Comparison of Fatigue Test Data on Piping with the ASME Code Fatigue Evaluation Procedure," *ASME Pressure Vessels and Piping Conference*, San Francisco, California (1979).

Merz, K. L., and Ibanez, P., "Seismic and Dynamic Reliability of Eroded/Corroded Piping Components," EPRI TR-102066 (May 1993).

Merz, K. L., and Tang, Y. K., "Dynamic Testing of Eroded/Corroded Piping Components," *Seismic Engineering*, American Society of Mechanical Engineers, Pressure Vessel and Piping Division, Vol. 197, pp 195-200, (June 1990).

Meyer, P., Fortmann, M., Bhandari, S., Heliot, J., "Crack Propagation Testing of a LMFBR Elbow at Operating Temperature," *Transactions of the 8th International SMiRT Conference*, Brussels, Belgium, Vol. F1-F2, pp 485-490 (1985).

*Mikkola, T. P. J., Diem, H., Blind, D., and Hunger, H., "Failure Behavior of a Pipe System with a Circumferentially Orientated Flaw - Analytical and Experimental Investigations," *Nuclear Engineering and Design*, Vol. 112, pp 197-210 (1989).

Morton, J., and Ruiz, C., "Through Cracks in Pipes and Pipe Bends," *Proceedings of the 4th International Conference on Pressure Vessel Technology*, Volume 2: Design, Analysis, Components, Fabrication and Inspection, London, England, pp 217-222 (1980).

Moulin, D., Touboul, F., Foucher, N., Lebey, J., and Acker, D., "Crack Initiation and Experimental Determination of J in Bending for Elbows and Pipes of Austenitic Steel," *Proceedings of the 1989 ASME Pressure Vessels and Piping Conference*, Honolulu, Hawaii (July 23-27, 1989).

Experimental investigations of through-wall circumferential flaws in TP316 stainless steel elbows under opening and closing bending modes were conducted. Comparisons were made with flawed straight pipes. The effect of crack length on limit moment was found to be different in tubes and elbows. An experimental method for determining J was outlined.

Moulin, D., Touboul, F., Foucher, N., Lebey, J., and Acker, D., "Experimental Evaluation of J in Cracked Straight and Curved Pipes Under Bending," *10th SMiRT International Conference on Structural Mechanics in Reactor Technology*, Anaheim, California (August 14-18, 1989).

Experimental investigations of through-wall circumferential flaws in TP316 stainless steel elbows under opening and closing bending modes were presented. Comparisons were made with flawed straight pipes. The effect of crack length on limit moment was found to be different in tubes and elbows. An experimental method for determining J was outlined. Predictions of crack initiation and propagation were made.

Moulin, D., Touboul, F., Lebey, J., Acker, D., Foucher, N., "Conditions of Crack Initiation in a Circumferentially Cracked Pipe in Bending; Experimental Determination of J on Elbows and Straight Pipes in Austenitic Steel," *ASME/JSME Pressure Vessel and Piping Conference*, pp 23-27, Honolulu, Hawaii (July 1989).

Müller, K. U., Diem, H., and Hunger, H., "Investigations on Stressing and Failure of Pipe Bends Under Complex Loading," *Nuclear Engg. and Design*, 87, pp 269-279 (1985).

Investigations on stressing and failure of pipe bends under monotonic and fatigue loading were performed for austenitic and ferritic steel bends. It was found that for thin-walled elbows, crack nucleates from the inside in the region of elbow flank (axial), while for thick-walled elbows circumferentially oriented crack will nucleate. Remarks on component safety are made.

Müller, K. U., and Diem, H., "Deformation and Failure Behavior of Elbows," *Transactions of 8th International SMiRT Conference*, Vol. F1 (1985).

Oesterberg, J., "Thermal Fatigue Cracking in T-Fittings of Feed Water Systems. Development of Testing Methods for the Determination in the Depth of Cracks," Swedish Nuclear Power Inspectorate, Stockholm, Sweden, Report No. SKI-B-6-83 (March 1983).

Prost, J. P., Doyen, J. J., Foul, T., and Jakubowicz, H., "Experimental and Elastic-Plastic Numerical Analysis of a PWR Piping Elbow Subjected to Pressure Cycling," *Transactions of 5th International SMiRT Conference*, Vol. F, F3/1 (August 1979).

Prost, J. P., Taupin, Ph., and Delidais, M., "Experimental Study of Austenitic Stainless Steel Pipes and Elbows Under Pressure and Moment Loadings," *Transactions of the 7th International SMiRT Conference*, Vol. G, pp 381-388 (1983).

Rawls, G. B., Wais, E. A., and Rodabaugh, E. C., "Evaluation of the Capacity of Welded Attachments to Elbows as Compared to the Methodology of ASME Code Case N-318," *Proceedings of ASME Pressure Vessel and Piping Conference*, New Orleans, Louisiana (1992).

Reynolds, M. B., "Reactor Primary Coolant System Rupture Study," Quarterly Progress Report No. 19, GEAP-10143, pp 13-16 (Oct. - Dec. 1969).

Reynolds, M. B., "Failure Behavior of Flawed Carbon Steel Pipes and Fittings," Development Report GEAP-10236 (October 1970).

*Rodabaugh, E. C., and George, H. H., "Effect of Internal Pressure on Flexibility and Stress-Intensification Factors of Curved Pipe or Welding Elbows," *Transactions of ASME*, Vol. 79, pp 937-948 (May 1957).

*Rodabaugh, E. C., and Moore, S. E., "Evaluation of the Plastic Characteristics of Piping Products in Relation to ASME Code Criteria," NUREG/CR-0261, ONRL/Sub-291318 (July 1978).

Sakakibara, Y., Imazu, A., Nagata, T., and Okabayashi, K., "Fatigue Crack Propagation from Surface Flaw of Elbows," *Transactions of the 6th International SMiRT Conference*, Vol. E (1981).

*Shimakawa, T., Takahashi, H., Doi, H., Watashi, K., and Asada, Y., "Creep-fatigue crack propagation tests and the development of an analytical evaluation method for surface cracked pipe," *Nuclear Engineering and Design*, Vol. 139, pp 283-292, (1993).

*Spence, J., and Findlay, G. E., "New Look at Existing Data Holds Out Hope for Those Oval Pipe Bends," *Process Engineering*, (December 1972).

Stoppler, W. Schiedermaier, J., Hippelein, K., Sturm, D., and Shen, S., "Crack Behavior of Pipes Under Internal Pressure and Simultaneous External Bending Moment," *Nuclear Engineering and Design*, Vol. 112, pp 172-182 (March 1989).

Touboul, F., "Experimental Analysis of Elbows with Circumferential Defects," *Transactions of the 11th International SMiRT Conference on Structural Mechanics in Reactor Technology*, pp 31-36 (1991).

Touboul, F., and Acker, D., "Excessive Deformation and Failure of Straight Parts and Elbows," *Transactions of the 11th International SMiRT Conference on Structural Mechanics in Reactor Technology*, Vol. E, pp 19-24 (1991).

*Touboul, F., Ben Jdidia, M., and Acker, D., "Design Rules for Piping: Experimental Validation of Flexibility and Elastic Stress Indices for Elbows Under Bending," *Transactions of the 10th International SMiRT Conference*, Vol. F, pp 75-80 (1989).

Touboul, F., Foucher, A., Acker, D., and Nedelec, M., "Experimental Determination of the Cracking Driving Force J for Circumferentially Cracked Piping Elbows," *2nd International Conference on Pipework Engineering and Operation*, London, England (February 21-22, 1989).

Wanner, R., Brosi, S., Diem, H., Uhlamm, D., "Fracture Mechanics Studies of a Cracked Pipe Bend Under In-Plane Loading," *Transactions of the 10th International SMiRT Conference*, pp 19-24 (1989).

*Wilkowski, G. M., "Summary of the Status of Pipe Fracture Predictions," *Proceedings of the Seminar on Assessment of Fracture Prediction Technology: Piping and Pressure Vessels*, Nashville, Tennessee (June 18, 1990).

Zdarek, J., Pecinka, L., Joch, J., Kadecka, P., Palyza, J., Brumovsky, M., and Svoboda, V., "Large Scale Experiments to Support the Application of the LBB Concept to WWER 440 Reactor Piping," *Transactions of the 12th International SMiRT Conference*, pp 381-392 (1993).

"Piping and Fitting Dynamic Reliability Program," EPRI TR-102792-Vol. 1 through Vol. 5 (1995).

Service

Alkire, J. W., Memorandum to J. W. Riley, "Millstone Unit No. 2 Failure Analysis of 8-GBD-033 Pipe Simple - Lab Test No. 12-91-046," Northeast Utilities Document CTS-91-355, Hartford, Connecticut (December 6, 1991).

Bush, S. H., "Failure Mechanisms in Nuclear Power Plant Piping Systems," *Journal of Pressure Vessel Technology*, pp 389-395 (November 1992).

Caskey, G. R., et al., "Leak History, Reactor Primary Coolant Systems," WSRC-RP-89-126, Westinghouse, Savannah River Company, Aiken, South Carolina, (April 21, 1989).

Ehrhart, W.S., "IGSCC Process Water Piping and Flame Washed Areas Ultrasonic Examination," Report EED870032, E. I. du Pont de Nemours & Company, Savannah River Laboratory, Aiken, South Carolina, (January 29, 1987).

Iwamoto, T., Yamamura, Y., and Hojo, S., "Observations and Analyses at the Bend and Tee Portions of Buried Ductile-Iron Pipelines During Earthquakes," *Proceedings of the 1985 Pressure Vessels and Piping Conference*, New Orleans, Louisiana, pp 69-79 (1985).

Quinones, D., "Typical Elbow Flaws in Nuclear Piping," part of a report written for V. K. Tang at EPRI, (May 1992).

"Fatigue Cracking of Splitter Plates in Pipe Elbow," *Welding in the World*, Vol. 23, pp 20-27 (1985).

"High Level Vibration Test of Nuclear Power Piping--Test Procedure and Test Results," *Transactions of the 10th International SMiRT Conference on Structural Mechanics in Reactor Technology*, Vol. K2, pp 745-750, Anaheim, California (August 1989).

"Investigation and Evaluation of Cracking Incidents in Piping and Pressurized Water Reactors," NUREG-0691, U.S. NRC, Washington, D.C. (September 1980).

"Metal Fatigue in Operating Nuclear Power Plants," Report TR-100252, Electric Power Research Institute, Palo Alto, California (April 1992).

"Report to the U. S. Nuclear Regulatory Commission Piping Review Committee, Evaluation of Potential for Pipe Breaks," NUREG-1061, Vol. 3, U.S. NRC, Washington, D. C. (November 1984).

"Safety Injection Pipe Failure," NRC Information Notice 88-01, U.S. NRC, Washington D.C. (January 27, 1988).

"Stress-Corrosion Cracking in Large-Diameter Stainless Steel Recirculation Piping System at BWR Plants," IE Bulletin No. 83-02, U.S. NRC, Washington, D.C., (March 4, 1983).

"Summary of Responses to NRC Bulletin 87-01, Thinning of Pipe Walls in Nuclear Power Plants," NRC Information Notice 88-17, U.S. NRC, Washington, D.C., (April 22, 1988).

"Thinning Found in Unisolable Pipes at Susquehanna-1 Prompts Notice," *Inside NRC* (May 4, 1992).

 

APPENDIX B

IPIRG-2

Fitting Database of Experiments

ELBOWCK

May 13, 1996

**[For more information, please contact R. Mohan
(614) 424-7594 or G. Wilkowski (614) 424-4680]**

Numbering system A.B.C.D.E

A= FLAW ORIENTATION 0 = No crack, 1 = Axial, 2 = Circumferential, 3 = Helical
 B= FLAW GEOMETRY 0 = No crack, 1 = TWC, 2 = SC, 3 = Combined
 C= FLAW LOCATION 0 = No crack, 1 = Introsdos, 2 = Extrados, 3 = Flank, 4 = Crown, 5 = Other
 D= TYPE OF LOADING = 1 {i or o} {c or p} = QS {in-plane or out-of-plane} {closing or opening} bend,
 2 = pressure,
 3 {i or o} = pres. & {i or o} {c or p} bending,
 4 {i or o} = dyn mono {i or o} bend
 5 {i or o} = QS cyclic {in-plane or out-of-plane} bending,
 6 {i or o} = dyn cyc {i or o} bend,
 7 {i or o} = dynamic cyclic {i or o} bend & pressure
 8 {i or o} = pipe system test,
 9 {i or o} = dyn mono bend & pressure
 10 = QS torsion

crack shape of natural
 formed cracks due to cyclic
 loading are described as
 "~- ELLIPTICAL"

maximum moment m
 in some cases momen
 the end of the experim
 (see comments)

E= EXPERIMENT NUMBER

DRB	EXPT	PIPE	MATERIAL	OUTER	ELBOW	TEST	MOMENT	ARM,	PRESSURE,	Δσ,	MAXIMUM	SHAPE	CRACK	CRACK	CRACK	CRACK
Number	ID#	ID#		DIAM.	RADIUS	TEMP.		mm	MPa	mm	a/t	(Rectangular	INITIATION	MAXIMUM	INITIATION	MAXIMUM
				mm	mm	C				(ON O.D.)	%	elliptical, or	LOAD,	LOAD,	MOMENT,	MOMENT,
												circular)	kN	kN	kN - m	kN - m
UNCRACKED ELBOW DATA																
UNCRACKED ELBOW (90 deg) EXPERIMENTS																
Laboratory: Westinghouse Electric Corporation, Advanced Reactors Division																
Program: US ERDA Piping Program																
References: Begley, J. A., and Sheinker, A.A., WARD-HT-3045-17 (1976); Begley et al., I. Mech. E., 215-224 (1978)																
0.0.0.iic.1-1		304 L		114.3	3.81	152.4	RT		1.38							5.265
Laboratory: CEA-CEN Saclay																
Program: US ERDA Piping Program																
References: Moulin et al., 10th SMIRT, Vol. G,323-326 (1989), PVP Conf., Vol. 165, 89-94 (1989)																
0.0.0.iic.1		316 L		114.3	80 S	8.56	152.4		0							20.493
0.0.0.iip.1		316 L		114.3	80 S	8.56	152.4		0							30
Laboratory: CEA-CEN Saclay																
Program: US ERDA Piping Program																
References: Brouard et al., 5th SMIRT, Vol F, F3/2 (1979)																
0.0.0.iic.1		ASTM A106 B		139.2	7.1	190			0							21.04
0.0.0.iic.2		ASTM A106 B		139.2	7.1	190			0							16.56
0.0.0.iip.1		ASTM A106 B		139.2	7.1	190			0							24.8
0.0.0.iip.2		ASTM A106 B		139.2	7.1	190			0							20
Laboratory: General Electric																
Program: Reactor Primary Coolant System Rupture Study																
References: GEAP-11069 AEC Research and Development Report, April 1970																
0.0.0.2.EL-1-8		ASTM A234		152.4	80	11.51	152.4	60								NA
Laboratory: MPA Stuttgart																
Program: IKA																
References: Diem H. K. et al.: Inelastic Analysis of Pipe Bends - Analytical and Experimental Investigations, Load Case: in-plane bending, closing mode, Load Case: out-of-plane loading																
Research Project BMFT-FKZ 1500 705A																
Final Report MPA No. 8550 00 000, 04/1991																
0.0.0.iic.IKA2	IKA2	15 MnNi 6 3		489.0	30.5	900	RT	3870	0							1495
0.0.0.1o.IKA3	IKA3	15 MnNi 6 3		489.2	30.6	900	RT	5686	0							1700
Laboratory: MPA Stuttgart																
Program: IKA																
References: Diem H. K. et al.: Inelastic Analysis of Pipe Bends - Analytical and Experimental Investigations, Load Case: in-plane bending, opening mode																
Research Project BMFT-FKZ 1500 705 9																
Final Report MPA No. 8410 00 000, 06/1986																
0.0.0.iip.IKA1	IKA1	15 MnNi 6 3		472.1	41.7	950	RT	2330	0							3600
Laboratory: MPA Stuttgart																
Program: IKA																
References: Diem H. K.: Untersuchungen zum Geometrieinfluß auf das Verformungs- und Versagensverhalten von Rohrbogen																
Techn.-wiss. Ber. MPA Stuttgart (1994); Heft 94/02 (in German)																
0.0.0.iic.bend 8		St. 35.8 I		141.6	4.9	126	RT	1486	0							6.83
0.0.0.iic.bend 11	bend 11	St. 35.8 I		140.6	4.3	189.6	RT	1475	0							6.7
0.0.0.iic.bend 12	bend 12	St. 35.8 I		141	4	327.9	RT	1513	0							7.26
0.0.0.iic.bend 10	bend 10	X10 CrNiNb 18 9		120	18.3	153	RT	1540	0							40.05
0.0.0.iic.bend 15	bend 15	X10 CrNiNb 18 9		88.7	5.5	115	RT	1510	0							5.31
0.0.0.iip.bend 16	bend 16	X10 CrNiNb 18 9		89.4	5.8	115	RT	1510	0							13.2
0.0.0.iip.bend 18	bend 18	St. 35.8 I		140.5	9.8	192.2	RT	1541	0							53.9
0.0.0.1o.bend 27	bend 27	St. 35.8 II		158.5	10	290	RT	3550	0							50.6
0.0.0.1o.bend 17	bend 17	X10 CrNiNb 18 9		89.2	5.8	115	RT	2117	0							6,752)

DRB Number	EXPT ID#	PIPE ID#	MATERIAL	OUTER DIAM. mm	SCHED.	t, mm	ELBOW RADIUS mm	TEST TEMP, C	MOMENT ARM, mm	PRESSURE, MPa	Da, mm (ON O.D.)	MAXIMUM a/t, %	SHAPE (Rectangular elliptical, or circular)	CRACK INITIATION LOAD, kN	MAXIMUM LOAD, kN	CRACK INITIATION MOMENT, kN - m	MAXIMUM MOMENT, kN - m	BURST PRESSURE, MPa
UNCRACKED ELBOW (180 deg) EXPERIMENTS																		
Laboratory:		CEA-CEN Saclay																
Program:																		
References:		Brouard et al., 5th SMIRT, Vol. F, F3/2 (1979)																
0.0.0.1ic.1			ASTM A106 B	139.2		7.1	190			0	0	0	NA	NA	NA	NA	14.95	
0.0.0.1ic.2			ASTM A106 B	139.2		7.1	190			0	0	0	NA	NA	NA	NA	14.45	
0.0.0.1ip.1			ASTM A106 B	139.2		7.1	190			0	0	0	NA	NA	NA	NA	17.52	
0.0.0.1ip.2			ASTM A106 B	139.2		7.1	190			0	0	0	NA	NA	NA	NA	14.35	
0.0.0.1o.1			ASTM A106 B	139.2		7.1	190			0	0	0	NA	NA	NA	NA	25.15	
0.0.0.1o.2			ASTM A106 B	139.2		7.1	190			0	0	0	NA	NA	NA	NA	18.81	

CIRCUMFERENTIAL THROUGH-WALL-CRACKED ELBOW DATA

CIRCUMFERENTIAL THROUGH-WALL-CRACKED ELBOW (90 deg) EXPERIMENTS UNDER IN-PLANE BENDING

Laboratory:		CEA-CEN Saclay																
Program:																		
References:		Moulin et al., 10th SMIRT, Vol. G, 323-326 (1989), PVP Conf., Vol. 165, 89-94 (1989)																
2.1.2.1ic.1		316 L		114.3	80 S	8.56	152.4			0	59.8	100	NA	NA	NA	NA	20.616	
2.1.2.1ic.2		316 L		114.3	80 S	8.56	152.4			0	89.8	100	NA	NA	NA	18.72	18.72	
2.1.2.1ic.3		316 L		114.3	80 S	8.56	152.4			0	119.7	100	NA	NA	NA	16.841	16.841	
2.1.2.1ic.4		316 L		114.3	80 S	8.56	152.4			0	149.6	100	NA	NA	NA	13.322	13.322	
2.1.1.1ip.1		316 L		114.3	80 S	8.56	152.4			0	29.9	100	NA	NA	NA	NA	18.602	
2.1.1.1ip.2		316 L		114.3	80 S	8.56	152.4			0	59.85	100	NA	NA	NA	26.25	26.25	
2.1.1.1ip.3		316 L		114.3	80 S	8.56	152.4			0	89.75	100	NA	NA	NA	21.394	21.394	
2.1.1.1ip.4		316 L		114.3	80 S	8.56	152.4			0	119.7	100	NA	NA	NA	16.024	16.024	
2.1.1.1ip.5		316 L		114.3	80 S	8.56	152.4			0	149.6	100	NA	NA	NA	11.886	11.886	

CIRCUMFERENTIAL THROUGH-WALL-CRACKED ELBOW EXPERIMENTS (90 deg) UNDER PRESSURE - BURST TEST WITH APPLIED LIMIT MOMENT

Laboratory:		Westinghouse Electric Corporation, Advanced Reactors Division																
Program:		US ERDA Piping Program																
References:		Begley, J. A., and Sheinker, A.A., WARD-HT-3045-17 (1976); Begley et al., I. Mech. E., 215-224 (1978)																
2.1.2.3ic.1-3	I-3	304 L		114.300		3.81	152.4	RT			53.34	NA	NA	NA	NA	NA	4.79	8.6
2.1.1.3ic.1-6	I-6	304 L		114.300		3.81	152.4	RT			53.34	NA	NA	NA	NA	NA	6.1	>14

This data reported the failure pressure as the pressure at which the patch leaked, not the burst pressure of the elbow.

CIRCUMFERENTIAL THROUGH-WALL-CRACKED 600 ELBOW EXPERIMENTS UNDER IN-PLANE BENDING WITH INTERNAL PRESSURE

Laboratory:		MPA Stuttgart																
Program:		MPA/VGB Research Program: Investigation on Ratcheting Deformation of Austenitic Components																
References:		Diem, H.K. et al.: Failure behaviour of thick-walled, austenitic pipe bends under cyclic bending loading at constant internal pressure. Nuclear Engineering and Design, 151, pp. 269-289, 1994																
2.1.1.5L.PBIV	PBIV	X10 CrNiTi 18 9		108.5		12.8	143	RT	670	16	62 on O.D. 9 on I.D.	100	~ ELLIPTICAL					28.5

CIRCUMFERENTIAL THROUGH-WALL-CRACKED 600 ELBOW EXPERIMENTS UNDER OUT-OF-PLANE BENDING WITH INTERNAL PRESSURE

Laboratory:		MPA Stuttgart																
Program:		MPA/VGB Research Program: Investigation on Ratcheting Deformation of Austenitic Components																
References:		Diem, H.K. et al.: Failure behaviour of thick-walled, austenitic pipe bends under cyclic bending loading at constant internal pressure. Nuclear Engineering and Design, 151, pp. 269-289, 1994																
3.1.1(3).5L.PBII	PBII	X10 CrNiTi 18 9		108.5		12.8	143	RT	850	16	50 on O.D. 10 on I.D.	100	~ ELLIPTICAL					32.6

E.	Coefficients																(J=Ji+cΔa ⁿ m)			Upper	Room	Room Temp	COMMENTS
	Yield	Ult.	Percent	Area													Shelf	Temp.	Shear				
	Stren.	Stren.	Elong.	Reduct.	Sig_o	Eps_o	alpha	n	Ji	dJ/Ja	Ji	c	m	Energy,	Area,	Area,							
	MPa	MPa	%	%	MPa				kN/m	kJ/m^2	kN/m			ft-lbs	ft-lbs	percent							

280	410																(with flanges)
280	410																(w/o flanges)
280	410																(with flanges)
280	410																(w/o flanges)
280	410																(with flanges)
280	410																(w/o flanges)

230	517																
230	517																
230	517																
230	517																
230	517																
230	517																
230	517																
230	517																
230	517																

Applied initial pressure of 1.38 MPa
loaded to limit moment under bending
prior to Burst test.
No crack extension under bending.

262	601	54	NA	262	0.00131	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	pipe bend was initially uncracked, cyclic loading up to failure (leakage) given maximum moment is load level at failure given crack length is crack length at failure
-----	-----	----	----	-----	---------	----	----	----	----	----	----	----	----	----	----	----	---

262	601	54	NA	262	0.00131	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	pipe bend was initially uncracked, cyclic loading up to failure (leakage) given maximum moment is load level at failure crack was located between intrados and flank
-----	-----	----	----	-----	---------	----	----	----	----	----	----	----	----	----	----	----	--

Appendix B

MUM ENT, PRESSURE, - m	BURST MPa	Yield Stren. MPa	Ult. Stren. MPa	Percent Elong %	Area Reduct. %	Coefficients				(J=J _i +cΔa ⁿ)			Upper Shelf Energy, ft-lbs	Room Temp. Energy, ft-lbs	Room Temp Shear Area, percent	COMMENTS
						Sig _o MPa	Eps _o	alpha	n	J _i kJ/m	dJ/Ja kJ/m ²	J _i kJ/m	c	m		

100		259.5	662			259.5	0.00148	1.23	3.54	51						
-----	--	-------	-----	--	--	-------	---------	------	------	----	--	--	--	--	--	--

1	40.4															
1	41.95															

Figures show crack location
To view, click on figure and then drag a corner to enlarge

50		321	743			321	0.0017	1.122	4.062	56						
----	--	-----	-----	--	--	-----	--------	-------	-------	----	--	--	--	--	--	--

.8	-	209	450	28.8		209	0.00106	3.36	4.421	373	278	373	297.7	0.624	200	191
.9	-	210	450	28.8		210	0.00127	5.001	4.421	402	278.2	402	473.9	0.573	200	191
.5	-	200	408	74		200	0.00096	3.247	3.981	1380		1380	211.1	0.487		
3	-	200	408	74		200	0.0011	14.79	3.981	1060	117.9	1060	211.1	0.487		

		262	601	54	NA	262	0.00131	NA	NA	NA		NA	NA	NA	NA	NA	pipe bend was cyclically loaded up to failure (leakage) given maximum moment is load level at failure
--	--	-----	-----	----	----	-----	---------	----	----	----	--	----	----	----	----	----	--

5		262	601	54	NA	262	0.00131	NA	NA	NA		NA	NA	NA	NA	NA	pipe bend was initially uncracked, cyclic loading up to failure (leakage) given maximum moment is load level at failure
---	--	-----	-----	----	----	-----	---------	----	----	----	--	----	----	----	----	----	--

5		262	601	54	NA	262	0.00131	NA	NA	NA		NA	NA	NA	NA	NA	pipe bend was initially uncracked, cyclic loading up to failure (leakage) given maximum moment is load level at failure given crack length is crack length at failure crack was located between intrados and flank
---	--	-----	-----	----	----	-----	---------	----	----	----	--	----	----	----	----	----	---

DRB Number	EXPT ID#	PIPE ID#	MATERIAL	OUTER DIAM. mm	SCHED.	t mm	ELBOW RADIUS mm	TEST TEMP. C	MOMENT ARM. mm	PRESSURE MPa	Da mm (ON O.D.)	MAXIMUM a/t %	SHAPE (Rectangular elliptical, or circular)	CRACK INITIATION LOAD kN	MAXIMUM LOAD kN	CRACK INITIATION MOMENT kN-m
CIRCUMFERENTIAL SURFACE-CRACKED ELBOW DATA																
CIRCUMFERENTIAL SURFACE-CRACKED ELBOW EXPERIMENTS (90 deg) UNDER BENDING																
Laboratory:			EDF													
Program:																
References:			Le Belliou, P., Semete, P., Ignaccolo, S., "Fracture Mechancis Analysis of Cast Duplex Stainless Steel Elbows Containing a Surface Crack," PVP Conf.													
2.2.3.1ic.SEM2	Y6142	CF8M		580		44	900	320		0	88	33.4	ELLIPTICAL			2076
CIRCUMFERENTIAL SURFACE-CRACKED ELBOW EXPERIMENTS (90 deg) UNDER BENDING AND PRESSURE																
Laboratory:			General Electric													
Program:			Reactor Primary Coolant System Rupture Study													
References:			GEAP-11069 AEC Research and Development Report, April 1970													
2.2.4.2.EL-1B-8		ASTM A234		152.4	80	11.25	152.4	60	NA		190.5	71.0	RECTANGULAR	NA	NA	NA
2.2.4.2.EL-2B-8		ASTM A234		152.4	80	11.35	152.4	60	NA		271.8	49.0	RECTANGULAR	NA	NA	NA
Laboratory:			EDF													
Program:																
References:			Le Belliou, P., Semete, P., Ignaccolo, S., "Fracture Mechancis Analysis of Cast Duplex Stainless Steel Elbows Containing a Surface Crack," PVP Conf.													
2.2.3.3ic.SEM3-2	Y6135	CF8M		580		44	900	60		15.5	88	33.4	ELLIPTICAL			2480
Laboratory:			Battelle													
Program:			IPIRG 2													
References:			Kilinski, T., and others, "Fracture Behavior of Circumferentially Surface-Cracked Elbows," NUREG/CR-6444, Sept. 1996.													
2.2.2.8i.1.2-1		IP2-FE18 A106B-90		409	100	32.08		288		15.5		83.8				561.9-579.8
2.2.2.1ic.1.2-2		IP2-FE16 A106B-90		406	100	32		288	3200	15.5		80		196.25	201.14	593.1
2.2.2.8i.1.2-3		IP-AE3 WP304L		409	100	33		288		15.5		73.4				601
2.2.2.1ic.1.2-4		IP2-AE2 WP304L		408	100	33		288	3200	15.5		76.7		177.5	181.5	536.2
Laboratory:			MPA Stuttgart													
Program:			HDR Safety Program, Phase III, Test Group E22													
References:			Diem, H.K. et al.: Erzeugung von drei Ermüdungsrissen in austenitischen Rohrteilen DN 80 für Leckversuche E22. PHDR Report No. 90.068/91, Kernforschungszentrum Karlsruhe (in German)													
2.2.1.5i.E22.22	E22.22	X10 CrNiTi 18 9		108.2		12.8	143	RT	395	0.5	56.7	50	RECTANGULAR WITH CIRCULAR ENDS			
CIRCUMFERENTIAL THROUGH-WALL-CRACKED ELBOW EXPERIMENTS (60 deg) UNDER BENDING AND PRESSURE																
Laboratory:			MPA Stuttgart													
Program:			MPA/VGB Research Program: Investigation on Ratcheting Deformation of Austenitic Components													
References:			Diem, H.K. et al.: Failure behaviour of thick-walled, austenitic pipe bends under cyclic bending loading at constant internal pressure. Nuclear Engineering and Design, 151, pp. 269-289, 1994													
2.1.1.5i.PBIV	PBIV	X10 CrNiTi 18 9		108.5		12.8	143	RT	670	16	62 on O.D. 9 on I.D.	100	- ELLIPTICAL			
Laboratory:			MPA Stuttgart													
Program:			MPA/VGB Research Program: Investigation on Ratcheting Deformation of Austenitic Components													
References:			Diem, H.K. et al.: Failure behaviour of thick-walled, austenitic pipe bends under cyclic bending loading at constant internal pressure. Nuclear Engineering and Design, 151, pp. 269-289, 1994													
3.1.1(3).5i.PBII	PBII	X10 CrNiTi 18 9		108.5		12.8	143	RT	850	16	50 on O.D. 10 on I.D.	100	- ELLIPTICAL			

Appendix B

DRB Number	EXPT ID#	PIPE ID#	MATERIAL	OUTER DIAM. mm	SCHED.	t, mm	ELBOW RADIUS mm	TEST TEMP. C	MOMENT ARM. mm	PRESSURE MPa	Da, mm (ON O.D.)	MAXIMUM a/t, %	SHAPE (Rectangular elliptical, or circular)	CRACK INITIATION LOAD, kN	MAXIMUM LOAD, kN	CRACK INITIATION MOMENT, kN-m	MAXIMUM MOMENT, kN-m	BURST PRESSURE MPa
AXIALLY CRACKED ELBOW DATA																		
AXIAL SURFACE-CRACKED ELBOW EXPERIMENTS (90 deg) UNDER IN-PLANE BENDING																		
Laboratory:			CEA-CEN Saclay															
Program:																		
References:			Moulin, D., and Brochard, J., PVP Conference, Denver (1993)															
1.2.4.1ic.1		316 L	155.000	80 S	10.97	228.6			0		19.95	25	RECTANGULAR	NA	NA			
1.2.4.1ic.2		316 L	155.000	80 S	10.97	228.6			0		19.95	50	RECTANGULAR	NA	NA			
1.2.4.1ic.3		316 L	155.000	80 S	10.97	228.6			0		19.95	75	RECTANGULAR	NA	NA			
Laboratory:			EDF															
Program:																		
References:			Le Belliou, P., Semete, P., Ignaccolo, S., "Fracture Mechanics Analysis of Cast Duplex Stainless Steel Elbows Containing a Surface Crack," PVP Conf.															
1.2.3.1ic.SEMI	Y6140	CF8M	580		44	900	320		0		210	23.9	ELLIPTICAL			2246	>2700	
AXIAL SURFACE-CRACKED ELBOW EXPERIMENTS (90 deg) UNDER PRESSURE																		
Laboratory:			General Electric															
Program:			Reactor Primary Coolant System Rupture Study															
References:			GEAP-11069 AEC Research and Development Report, April 1970															
1.2.4.2.EL-1A-8		ASTM A234	152.4	80	12.45	152.4	60	NA			78.74	61	RECTANGULAR	NA	NA	NA	NA	45.2
1.2.4.2.EL-2A-8		ASTM A234	152.4	80	11.76	152.4	60	NA			160.02	70	RECTANGULAR	NA	NA	NA	NA	32.4
1.2.4.2.EL-3A-8		ASTM A234	152.4	80	11.28	152.4	60	NA			157.48	37	RECTANGULAR	NA	NA	NA	NA	44.6
1.2.2.2.EL-1C-8		ASTM A234	152.4	80	11.96	152.4	60	NA			200.66	65	RECTANGULAR	NA	NA	NA	NA	35.9
1.2.2.2.EL-2C-8		ASTM A234	152.4	80	11.3	152.4	60	NA			182.88	37	RECTANGULAR	NA	NA	NA	NA	48.6
1.2.2.2.EL-3C-8		ASTM A234	152.4	80	10.74	152.4	60	NA			124.46	72	RECTANGULAR	NA	NA	NA	NA	32.4
Laboratory:			MPA Stuttgart															
Program:																		
References:			Diem H. K.: Untersuchungen zum Geometrieinfluss auf das Verformungs- und Versagensverhalten von Rohrbogen Techn.-wiss. Ber. MPA Stuttgart (1994); Heft 94/02 (in German)															
1.2.1.2		17 MnMoV 6 4	168.3		8	260	200				180 on I.D.	94						23.6
1.2.1.2		17 MnMoV 6 4	219.1		8	310	200				180 on O.D.	60	RECTANGULAR WITH CIRCULAR ENDS					18
AXIAL SURFACE-CRACKED ELBOW EXPERIMENTS (90 deg) UNDER PRESSURE AND BENDING																		
Laboratory:			EDF															
Program:																		
References:			Le Belliou, P., Semete, P., Ignaccolo, S., "Fracture Mechanics Analysis of Cast Duplex Stainless Steel Elbows Containing a Surface Crack," PVP Conf.															
1.2.3.3ic.SEM3-1	Y6135	CF8M	580		44	900	60		15.5		210	23.9	ELLIPTICAL			2250	>3150	
Laboratory:			MPA Stuttgart															
Program:			HDR Safety Program, Phase III, Test Group E22															
References:			Diem, H. et al.: Erzeugung von drei Ermüdungsrissen in austenitischen Rohrteilen DN 80 für Leckversuche E22, PHDR Report No. 90.068/91, Kernforschungszentrum Karlsruhe (in German)															
1.2.3.5i.E22.21	E22.21	X10 CrNiMoTi 17 12 2	88.9		5.6	115	RT	387	0.2		120 on I.D.	50	RECTANGULAR WITH CIRCULAR ENDS				1.94	
Laboratory:			MPA Stuttgart															
Program:			BV IV (Phenomenological Vessel Burst Tests - Phase IV: T-branches and elbows)															
References:			Schuler, X., D. Blind, U.Eisele, K.-H. Herter, W. Stoppler: Fracture mechanics evaluation of cracked components with consideration of multiaxiality of stress state, Nuclear Engineering and Design, 151, pp. 291-305, 1994 Schuler, X., D. Blind, U.Eisele, K.-H. Herter: Extension of fracture mechanics evaluation methods by consideration of multiaxiality of stress state for piping components, Nuclear Engineering and Design, 158, pp. 227-240, 1995 Schwarz, Th., P. Julisch, K.-H. Herter, W. Stoppler: Experimental investigations on the strength and fracture behaviour of degraded piping components, SMIRT 12 Conf., Paper F06/1, pp. 87-92, 1993.															
1.2.3.3ip.RB1	RB1	20 MnMoNi 5 5	870.8		54.2	1137	RT	3915	15		845 on I.D.	26	RECTANGULAR				5900	
1.2.3.3ip.RB2	RB2	MnMoNiV-special mel	871.2		53.8	1131	266	3915	16.6		845 on I.D.	24	WITH CIRCULAR ENDS				6000	
1.2.3.7i.RB3	RB3	20 MnMoNi 5 5	870.8		54.2	1137	RT	3915	15		845 on I.D.	26	"				6000	
1.2.3.7i.RB4	RB4	MnMoNiV-special mel	871.2		53.8	1131	266	3915	16.6		845 on I.D.	24	"				6000	
1.2.3.3ip.RB5/1	RB5/1	20 MnMoNi 5 5	874		54.6	1130	RT	3915	15.2		845 on I.D.	46	"			4000	8900	
1.2.3.7i.RB5/2	RB5/2	20 MnMoNi 5 5	874		54.6	1130	RT	3915	15.2		845 on I.D.	46	"				8800	
1.2.3.3ip.RB6	RB6	MnMoNiV-special mel	871.3		54.1	1126	266	3915	15.5		845 on I.D.	48	"			1000	5700	
Laboratory:			MPA Stuttgart/HDR Test Facility															
Program:			HDR Safety Program, Phase II, Test Group T20															
References:			Diem, H.K.: Investigations on Incipient Cracking, Crack Growth and Leak-Before Break-Behavior of Piping Components Subjected to Constant Internal Pressure and Cyclic Bending Moment, PHDR Report No. 83-92, Kernforschungszentrum Karlsruhe (in German)															
1.1.3.8ip.RORV(B)	RORV(B)	15 NiCuMoNb 5	452		26	610	240		10.6		400 on O.D. ~ 640 on I.D.	100					1024	
Laboratory:			MPA Stuttgart/HDR Test Facility															
Program:			HDR Safety Program, Phase III, Test Group E21															
References:			Uhlmann, D.: Investigations on the Influence of Multiple Crack Fields on the Stress Intensity of Pipe Bends Subjected to Constant Internal Pressure and Bending, PHDR Report No. 120-93, Kernforschungszentrum Karlsruhe (in German)															
1.1.3.8ip.E21.1	E21.1	20 MnMoNi 5 5	482.5		28.7	686	240		10.6		600 on I.D. 200 on O.D.	82					1348	

Ult. Stren. MPa	Percent Elong. %	Area Reduct. %	Coefficients				(J=J _i +cΔa ⁿ m)				Upper Shelf Energy. ft-lbs	Room Temp. Energy. ft-lbs	Room Temp Shear Area. percent	COMMENTS
			Sig _o MPa	Eps _o	alpha	n	J _i kJ/m	dJ/Ja kJ/m ²	J _i kJ/m	c	m			

664 60
664 60
664 60

670 258 0.00146 0.834 4.054 0.8

Figures show crack locations.
To view, click on the figure and then drag a corner to enlarge.

692 16 62 573 0.00297 NA NA NA NA NA NA NA 60 NA failure in form of break
612 17 47 410 0.00222 NA NA NA NA NA NA NA 36 NA failure in form of break

743 321 0.0017 1.122 4.062 56

530 55 NA 262 0.00131 NA NA NA NA NA NA NA pipe bend was cyclically loaded up to failure (leakage)
given maximum moment is load level at failure

651 23.6 70.6 518 0.0044 1.06 12.64 304.6 722.92 806.7 0.547 195 200 100 flaw: spark erosiv notch (notch tip radius = 0.15 mm)
627 15.9 38.4 444 0.00411 0.48 10.87 34.7 70.227 108.7 0.329 65 24 20 flaw: spark erosiv notch (notch tip radius = 0.15 mm)
651 23.6 70.6 518 0.0044 1.06 12.64 304.6 722.92 806.7 0.547 195 200 100 flaw: spark erosiv notch (notch tip radius = 0.15 mm), loading: swelling bending
627 15.9 38.4 444 0.00411 0.48 10.87 34.7 70.227 108.7 0.329 65 24 20 flaw: spark erosiv notch (notch tip radius = 0.15 mm), loading: swelling bending
651 23.6 70.6 518 0.0044 1.06 12.64 171.3 NA NA NA 195 200 100 flaw: fatigue precr loading: quasistatic failure: no
651 23.6 70.6 518 0.0044 1.06 12.64 171.3 NA NA NA 195 200 100 continuation of test RBS/1 with swelling bending failure: no (max crack growth
698 13 28.4 507 0.00442 0.3 12.63 31.94 69.094 121.8 0.418 62 24 36 flaw: fatigue precr loading: quasistatic failure: leakage

579 22.5 53.5 399 0.00207 NA NA 49 NA NA 100 100 NA pipe bend was initially uncracked, cyclic loading in high temperature water wit
given maximum moment is load level at failure

590 17.5 63 439 0.00231 NA NA 83 NA NA 150 150 NA pipe bend was initially uncracked, cyclic loading in high temperature water wit
given maximum moment is load level at failure (leakage)

K ON MAXIMUM T, MOMENT, BURST n	MAXIMUM kN - m	BURST PRESSURE, MPa	Yield Stren. MPa	Ult. Stren. MPa	Percent Elong. %	Area Reduct. %	Coefficients					(J=Ji+cAa^n*m)					Upper Shelf	Room Temp.	Room Temp	COMMENTS
							Sig_o MPa	Eps_o	alpha	n	Ji kN/m	dJ/Ja kJ/m^2	Ji kN/m	c	m	Energy, ft-lbs	Energy, ft-lbs	Shear Area, percent		
	4.96	11.2	298	564	71	66													Applied initial pressure of 1.38 MPa loaded to limit moment under bending prior to Burst test. No crack extension under bending.	
	4.06	4.86	298	564	71	66														
	6.71	8.96	298	564	71	66														
	32.6		262	601	54	NA	262	0.00131	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	pipe bend was initially uncracked, cyclic loading up to failure (leakage) given maximum moment is load level at failure given crack length is crack length at failure	
	34.8		262	601	54	NA	262	0.00131	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA		
																			pipe bend was initially uncracked, cyclic loading up to failure (leakage) given maximum moment is load level at failure	

DRB Number	EXPT ID#	PIPE ID#	MATERIAL	OUTER DIAM, mm	SCHED.	t, mm	ELBOW RADIUS mm	TEST TEMP, C	MOMENT ARM, mm	PRESSURE, MPa	Da, mm (ON O.D.)	MAXIMUM a/t, %	SHAPE (Rectangular elliptical, or circular)	CRACK INITIATION LOAD, kN	MAXIMUM LOAD, kN	CRACK INITIAL MOMENT, kN-m
AXIAL THROUGH-WALL-CRACKED ELBOW EXPERIMENTS (90 deg) UNDER PRESSURE - BURST TESTS WITH APPLIED LIMIT MOMENT																
Laboratory:			Westinghouse Electric Corporation, Advanced Reactors Division													
Program:			US ERDA Piping Program													
References:			Begley, J. A., and Sheinker, A. A., WARD-HT-3045-17 (1976); Begley et al., I. Mech. E., 215-224 (1978)													
1.1.4.3ic.1-2			304 L	114.300		3.81	152.4	RT			50.8	NA	NA	NA	NA	NA
1.1.4.3ip.1-7			304 L	114.300		3.81	152.4	RT			101.6	NA	NA	NA	NA	NA
1.1.2.3o.1-4			304 L	114.300		3.81	152.4	RT			50.8	NA	NA	NA	NA	NA
AXIAL THROUGH-WALL-CRACKED ELBOW EXPERIMENTS (90 deg) UNDER BENDING AND PRESSURE																
Laboratory:			MPA Stuttgart													
Program:			MPA/VGB Research Program: Investigation on Ratcheting Deformation of Austenitic Components													
References:			Diem, H. K. et al.: Failure behaviour of thick-walled, austenitic pipe bends under cyclic bending loading at constant internal pressure. Nuclear Engineering and Design, 151, pp. 269-289, 1994													
1.1.3(1).5o.PBIII	PBIII		X10 CrNiTi 18 9	108.5		12.8	143	RT	811	16	10 on O.D. 96 on I.D.	100	~ ELLIPTICAL			
Laboratory:			MPA Stuttgart													
Program:			MPA/VGB Research Program: Investigation on Ratcheting Deformation of Austenitic Components													
References:			Diem, H. et al.: Failure behaviour of thick-walled, austenitic pipe bends under cyclic bending loading at constant internal pressure. Nuclear Engineering and Design, 151, pp. 269-289, 1994													
1.1.3.5ip.PBI	PBI		X10 CrNiTi 18 9	108.5		12.8	143	RT	690	16	20 on O.D. 150 on I.D.	100	~ ELLIPTICAL			

APPENDIX C

IPIRG-2

Fitting Database of Experiments

TEECK

May 13, 1996

QUASI-STATIC MATERIAL PROPERTY DATA FOR MATERIAL CONTAINING THE CRACK																				COMMENTS
maximum moment means in some cases moment at the end of the experiment (see comments)			(Typically the tensile data is the average value of multiple specimens while the Ramberg-Osgood coefficients are for a single specimen.)								(Typically the J _i and dJ/da values are the average values from multiple specimens while the extrapolated J-R curve constants are from a single specimen.)									
			Charpy Data																	
			Extrapolated J-R Curve Constants (full size specimens)																	
CRACK RATIO MOMENT, PRESSURE, m.kN	MAXIMUM MOMENT, PRESSURE, m.kN	BURST PRESSURE, MPa	Yield Stren. MPa	Ult. Stren. MPa	Percent Elong. %	Area Reduct. %	Coefficients				(J=J _i +cDa ^m)				Upper Shelf			Room Temp. Energy, ft-lbs	Room Temp. Shear Area, percent	
							Sig_o ksi	Eps_o	alpha	n	J _i kN/m	dJ/da kN/m ²	J _i kN/m	c	m	Energy, ft-lbs	Room Temp. Energy, ft-lbs			
NA	NA	61.2																		
1994 7-240, 1995 Paper F06/1, pp. 87-92.																				
NA	710	NA	501	640	NA	NA	501	0.0044	0.85	13.5	NA	NA	NA	NA	200	200	100	out-of-plane bending moment up to yield (no leakage or brea		
NA	2200	NA	501	640	NA	NA	501	0.0044	0.85	13.5	NA	NA	NA	NA	200	200	100	in-plane bending moment up to limit load (no leakage or brea		
NA	NA	61.2																		
NA	NA	43.6																		
NA	NA	48.1																		
NA	NA	40.2																		
NA	NA	43.4																		
NA	NA	46.2																		
NA	NA	33.6																		
NA	NA	61																		
NA	NA	62																		
994 -240, 1995 Paper F06/1, pp. 87-92.																				
900	2180	NA	470	621	NA	NA	470	0.0043	0.83	11.7	109.8	NA	170.3	225	0.27	79	40	25	no leakage or burst (max. 5 mm stable crack growth)	
NA	2400	NA	501	640	NA	NA	501	0.0044	0.85	13.5	405.3	NA	1160.1	1051	0.5	200	200	100	no leakage or burst (max. 5 mm stable crack growth)	
000	2220	NA	543	715	NA	NA	543	0.0045	0.39	13.4	27.8	NA	59.8	104	0.4	63	30	21	no leakage or burst (max. 5 mm stable crack growth)	
200	1700	NA	670	829	NA	NA	670	0.0524	0.44	15.8	19.1	NA	NA	NA	NA	100	17 (at test temp	11 (at test temp)	no leakage or burst (max. 5 mm stable crack growth)	

A= FLAW ORIENTATION 0 = No crack, 1 = Location J, 2 = Location K, 3 = Location L. See figure to right for locations.

B= FLAW GEOMETRY 0 = No crack, 1 = TWC, 2 = SC, 3 = Combined

C= TYPE OF LOADING = 1 {i or o} {c or p} = QS {in-plane or out-of-plane} {closing or opening} bend,

2 = pressure,

3 {i or o} = pres. & {i or o} {c or p} bending,

4 {i or o} = dyn mono {i or o} bend

5 {i or o} = QS cyclic {in-plane or out-of-plane} bending,

6 {i or o} = dyn cyc {i or o} bend,

7 {i or o} = dynamic cyclic {i or o} bend & pressure

8 {i or o} = pipe system test,

9 {i or o} = dyn mono bend & pressure

10 = QS torsion

D= EXPERIMENT NUMBER

crack shape of natural
 formed cracks due to cyclic
 loading are described as
 "- elliptical"

DRB	EXPT	PIPE	MATERIAL	OUTER	DIAM.	SCHED.	t	MATERIAL	OUTER	DIAM.	SCHED.	t	TEST	MOMENT	ARM,	PRESSURE,	Δa,	MAXIMUM	SHAPE	CRACK	MAXIMUM
Number	ID#	ID#		DIAM.			mm		DIAM.			mm	TEMP,	mm	mm	MPa	(ON O.D.)	a/	(Rectangular	INITIATION	LOAD, M
													C					%	elliptical, or	LOAD, KN	LOAD, KN
																			circular)		

UNCRACKED TEE EXPERIMENTS

Laboratory: General Electric
 Program: The Reactor Primary Coolant System Rupture Study, Contract AT(04-3)-189
 References: GEAP_11069, AEC Research and Development Report, April 1970

0.0.2.T-1-8	ASTM A234	152.4	80	16.64	ASTM A234	152.4	80	16.64	16	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
-------------	-----------	-------	----	-------	-----------	-------	----	-------	----	----	----	----	----	----	----	----	----	----	----	----	----

Laboratory: Staatliche Materialprüfungsanstalt, University of Stuttgart
 Program: Strength and Fracture Behaviour of Branch Connections and Elbows Under Internal Pressure Load and Superimposed External Bending Moment (BV IV)
 References: Schuler, X., D. Blind, U.Eisele, K.-H. Herter, W. Stoppler: Fracture mechanics evaluation of cracked components with consideration of multiaxiality of stress state. Nuclear Engineering and Design, 151, pp. 291-305, 1995.
 Schuler, X., D. Blind, U.Eisele, K.-H. Herter: Extension of fracture mechanics evaluation methods by consideration of multiaxiality of stress state for piping components. Nuclear Engineering and Design, 158, pp. 22-32, 1995.
 Schwarz, Th., K.-H. Herter, P. Julisch, W. Stoppler: Experimental investigations on the strength and fracture behaviour of degraded piping components. Trans. of the 12th Conf. on SMIRT, August 15-20 1993, Vol. F.

0.0.3o.AZ11	20 MnMoNi 5 5	862.6	49.1	20 MnMoNi 5 5	307.6	41.8	20	1440	15	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
0.0.3i.AZ12	20 MnMoNi 5 5	862.6	49.1	20 MnMoNi 5 5	307.6	41.8	20	1440	15	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

SURFACE-CRACKED TEE EXPERIMENTS UNDER PRESSURE

Laboratory: General Electric
 Program: The Reactor Primary Coolant System Rupture Study, Contract AT(04-3)-189
 References: GEAP_11069, AEC Research and Development Report, April 1970

1.2.2.T-1J-8	ASTM A234	152.4	80	16.38	ASTM A234	152.4	80	16.64	16	NA	NA	127	22	RECTANGULAR	NA	NA
1.2.2.T-2J-8	ASTM A234	152.4	80	15.8	ASTM A234	152.4	80	16.64	16	NA	NA	76.2	55	RECTANGULAR	NA	NA
1.2.2.T-3J-8	ASTM A234	152.4	80	16.2	ASTM A234	152.4	80	16.64	16	NA	NA	132.1	55	RECTANGULAR	NA	NA
2.2.2.T-1K-8	ASTM A234	152.4	80	15.54	ASTM A234	152.4	80	16.64	16	NA	NA	43.2	27	RECTANGULAR	NA	NA
2.2.2.T-2K-8	ASTM A234	152.4	80	16.28	ASTM A234	152.4	80	16.64	16	NA	NA	25.4	30	RECTANGULAR	NA	NA
2.2.2.T-3K-8	ASTM A234	152.4	80	14.2	ASTM A234	152.4	80	16.64	16	NA	NA	33	57	RECTANGULAR	NA	NA
3.2.2.T-1L-8	ASTM A234	152.4	80	16.41	ASTM A234	152.4	80	16.64	16	NA	NA	119.4	23	RECTANGULAR	NA	NA
3.2.2.T-2L-8	ASTM A234	152.4	80	16.38	ASTM A234	152.4	80	16.64	16	NA	NA	127	45	RECTANGULAR	NA	NA
3.2.2.T-3L-8	ASTM A234	152.4	80	17.4	ASTM A234	152.4	80	16.64	16	NA	NA	73.7	57	RECTANGULAR	NA	NA

Laboratory: Staatliche Materialprüfungsanstalt, University of Stuttgart
 Program: Strength and Fracture Behaviour of Branch Connections and Elbows Under Internal Pressure Load and Superimposed External Bending Moment (BV IV)
 References: Schuler, X., D. Blind, U.Eisele, K.-H. Herter, W. Stoppler: Fracture mechanics evaluation of cracked components with consideration of multiaxiality of stress state. Nuclear Engineering and Design, 151, pp. 291-305, 1995.
 Schuler, X., D. Blind, U.Eisele, K.-H. Herter: Extension of fracture mechanics evaluation methods by consideration of multiaxiality of stress state for piping components. Nuclear Engineering and Design, 158, pp. 22-32, 1995.
 Schwarz, Th., K.-H. Herter, P. Julisch, W. Stoppler: Experimental investigations on the strength and fracture behaviour of degraded piping components. Trans. of the 12th Conf. on SMIRT, August 15-20 1993, Vol. F.

2.2.3i.AZ2	MnMoNiV-special melt	854.5	45.4	20 MnMoNi 5 5	307.4	41.7	90	1440	15	80	0.25	ELLIPTICAL	NA	NA
2.2.3i.AZ3	20 MnMoNi 5 5	862.8	49.2	20 MnMoNi 5 5	307.6	41.8	20	1440	16	80	0.25	ELLIPTICAL	NA	NA
2.2.3i.AZ4	MnMoNiV-special melt	855.2	45.4	20 MnMoNi 5 5	307	41.5	130	1440	16	78	0.42	~ ELLIPTICAL	NA	NA
2.2.3i.AZ6	MnMoNiV-special melt	855.3	45.4	20 MnMoNi 5 5	307.2	41.5	32	1440	11	84	0.26	~ ELLIPTICAL	NA	NA

APPENDIX D

IPIRG-2

Detailed Geometry of the IPIRG Loop Facility

Figure D.2 Overall dimensions of the IPIRG pipe loop test facility

Figures D.3 and D.4 show the locations for the strain gages and string potentiometers on the pipe loop. The strain gages were used to measure moments, while the string potentiometers were used to determine pipe loop global displacements.

The geometric details of the pipe loop facility used in the two elbow experiments (Experiments 2-1 and 2-3) are shown in Figures D.5 through D.15. Tables D.5 through D.14 document the pipe loop itself, while Table D.15 provides dimensions for the elbow test specimens.

Figure D.3 Layout of strain gages for the IPIRG-2 pipe-system experiments

Figure D.4 String potentiometer locations for the IPIRG-2 pipe-system experiments

Figure D.5 Elbow girth weld experiment pipe loop geometry

Figure D.6 North moment cell geometry **Figure D.7 Leg 3 end cap section**

Figure D.8 South moment cell

Figure D.9 Leg 3 elbow transition piece

Figure D.10 Leg 4 elbow transition piece

Figure D.11 East moment cell

Figure D.12 Leg 4 end cap section

			Wall Thickness, mm											
			Location											
Leg #	Pipe ID # (a)	Pipe Serial #	1	2	3	4	5	6	7	8	9	10	11	Avg
1	IPF5	54475	26.8	25.5	25.6	27.2	27.2	25.5	26.6	25.8	27.5	27.4	27.3	26.6
2	IPF3	(b)	27.1	27.9	28.5	(c)	26.9	(c)	28.6	(c)	(c)	(c)	(c)	27.8
3	IPF5	54473	26.2	25.8	27.0	28.6	26.3	26.6	26.9	26.8	25.9	25.8	26.8	26.6
4	IPF5	54474	28.2	25.9	25.6	27.9	27.2	26.3	25.7	26.6	27.8	27.5	27.9	26.9

(a) IPF3 was procured as part of IPIRG-1; IPF5 was procured as part of IPIRG-2

(b) Unknown, but either 47453, 47454, 47455, or 47456

(c) Not measured

Figure D.13 Straight pipe wall thickness measurements

(a) Elbows 1 and 5 were procured as part of IPIRG-1; Elbows 2, 3, and 4 were procured as part of IPIRG-2
 (b) Not measured

Figure D.14 Elbow wall thickness measurements

(a) Not measured.

Figure D.15 Test elbow dimension

BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

1. REPORT NUMBER
(Assigned by NRC. Add Vol., Supp., Rev.,
and Addendum Numbers, if any.)

NUREG/CR-6444
BMI-2192

2. TITLE AND SUBTITLE

Fracture Behavior of Circumferentially Surface-Cracked Elbows

3. DATE REPORT PUBLISHED

MONTH | YEAR
December | 1996

4. FIN OR GRANT NUMBER

D2060

5. AUTHOR(S)

T. Kilinski, R. Mohan, D. Rudland, M. Fleming, R. Olson,
P. Scott, F. Brust, N. Ghadiali, G. Wilkowski, and
A. Hopper

6. TYPE OF REPORT

Technical

7. PERIOD COVERED (Inclusive Dates)

10/93 - 3/96

8. PERFORMING ORGANIZATION - NAME AND ADDRESS (If NRC, provide Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)

Battelle
505 King Avenue
Columbus, OH 43201-2693

9. SPONSORING ORGANIZATION - NAME AND ADDRESS (If NRC, type "Same as above"; if contractor, provide NRC Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address.)

Division of Engineering Technology
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555-0001

10. SUPPLEMENTARY NOTES

M.E.Mayfield, NRC Project Manager

11. ABSTRACT (200 words or less)

This report presents the results from Task 2 of the Second International Piping Integrity Research Group (IPIRG-2) program. The focus of the Task 2 work was directed towards furthering the understanding of the fracture behavior of long-radius elbows. This was accomplished through a combined analytical and experimental program. J-estimation schemes were developed for both axial and circumferential surface cracks in elbows. Large-scale, quasi-static and dynamic, pipe-system, elbow fracture experiments under combined pressure and bending loads were performed on elbows containing an internal surface crack at the extrados. In conjunction with the elbow experiments, material property data were developed for the A106-90 carbon steel and WP304L stainless steel elbow materials investigated. A comparison of the experimental data with the maximum stress predictions using existing straight pipe fracture prediction analysis methods, and elbow fracture prediction methods developed in this program was performed. This analysis was directed at addressing the concerns regarding the validity of using analysis predictions developed for straight pipe to predict the fracture stresses of cracked elbows. Finally, a simplified fitting flaw acceptance criteria incorporating ASME B₂ stress indices and straight pipe, circumferential-crack analysis was developed.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)

axial crack, carbon steel, circumferential crack, cyclic loading,
dynamic loading, elastic-plastic fracture, elbow, fittings, fracture,
inertial stresses, J-Integral, nuclear pipe, stainless steel,
surface crack, tee, through-wall crack

13. AVAILABILITY STATEMENT

Unlimited

14. SECURITY CLASSIFICATION

(This Page)

Unclassified

(This Report)

Unclassified

15. NUMBER OF PAGES

16. PRICE