GJW
FILE
TECH
FRACTURE
MECHANICS

AN EVALUATION OF GIRTH WELD DEFECT ACCEPTANCE CRITERIA

P. D. Hilton
R. A. Mayville

Arthur D. Little, Inc.

Acorn Park

Cambridge, MA 02140

November 1985

Final Report

Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161

prepared for

U.S. DEPARTMENT OF TRANSPORTATION
RESEARCH AND SPECIAL PROJECTS ADMINISTRATION
WASHINGTON, DC

NOTICE

NOTICE

Technical Report Documentation Page

1. Roport No.

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle

AN EVALUATION OF GIRTH WELD DEFECT ACCEPTANCE CRITERIA

5. Roport Date

6. Performing Organization Code

DTS-76

8. Performing Organization Report No.

7. Author's)

P.D. Hilton and R.A. Mayville

9. Performing Organization Name and Address

Arthur D. Little, Inc.
Acorn Park
Cambridge, MA 02140

10. Work Unit No. (TRAIS)

R5547-R5514

11. Contract or Gront No.

DTRS-57-83-C-0078/TTD3

12. Sponsoring Agency Name and Address

U.S. Department of Transportation
Research and Special Projects Administration
Office of Pipeline Safety Regulation
Washington, DC 20590

13. Type of Roport and Period Covered

Final Report
Feb. 1984 - Feb. 1985

14. Sponsoring Agency Code

DMT-30

16. Abstract

This report assesses several proposed girth weld defect acceptance criteria aspresentec in industry report appendices: the British Standards Institution PD 6493 and BS 4515; American Petroleum Institute API 1104; Canadian'Standards Association CSA 2184; and the National Bureau of Standards. While criteria are based on fracture mechanics, their specific defect acceptance procedures are distinct. Assessments were based on identification of in-service loadings to which transmission ,pipelinesare subjected and resulting stresses at girth welds, and application of the proposed standards to hypothetical girth weld defect cases and available full-scale test data on defective girth welds.

Critical assessments are made on each proposed girth weld defect tolerance criteria, considering both range of applicability and level of conservativism. Aspects of the criteria which require alteration are discussed, and improvements are recommended.

17. Key Words

Girth Weld, Defects, Cracks, Acceptance .Standards, COD Design Curve

18. Distribution Statement

DOCUMENT IS AVAILABLE TO THE PUBLIC THROUGH THE NATIONAL TECHNICAL INFORMATION SERVICE, SPRINGFIELD. VIRGINIA 22161

19. Security Classif. (of this report)

Unclassified

20. Security Classil (of this page)

Unclassified

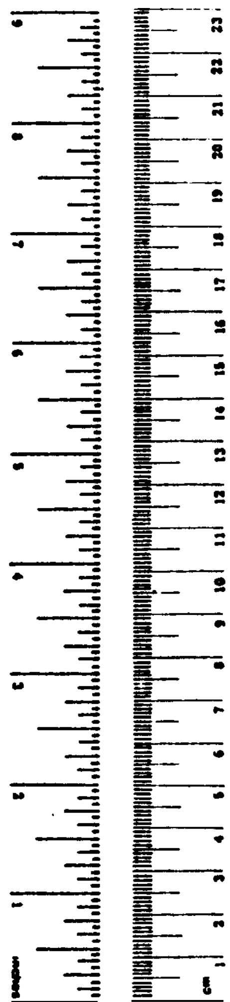
21. No. of Pages

22. Price

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

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



Approximate Conversions from Metric Measures

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

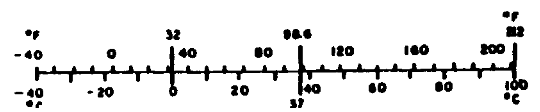


TABLE OF CONTENTS

TABLE OF CONTENTS (cont.)

LIST OF FIGURES

LIST OF FIGURES (continued)

FIGURE Page

LIST OF FIGURES (continued)

FIGURE Page

LIST OF FIGURES (continued)

LIST OF TABLES

LIST OF TABLES (continued)

NOMENCLATURE

a = crack depth for surface defect, half-height for buried defect

$\bar{a}$ = equivalent crack depth or half-height

$2c$ or ℓ = crack length

D = nominal outside pipe diameter

e = strain

e_o = yield strain

E = Young's modulus and longitudinal joint factor for allowable stress

F = multiplication factor on allowable stress for pipe class

K_c = fracture toughness

M = crack geometry correction factor

M_c = empirical factor to account for crack length

P = allowable operating pressure

S or SMYS = specified minimum yield strength

S_B = longitudinal stress due to bending

S_E = longitudinal stress due to thermal contraction

S_L = longitudinal stress due to pressure

t = pipe wall or plate thickness

T = temperature derating factor for allowable stress

δ = crack tip opening displacement (CTOD)

δ_c = CTOD at cleavage fracture without previous stable tearing

= CTOD at initiation of stable tearing

δ_m = CTOD at maximum load without cleavage fracture

δ_u = CTOD at cleavage fracture with previous stable tearing

σ_{axial} = axial stress

σ = stress

σ_f = flow stress

σ_o = yield strength

σ_U = tensile strength

ACKNOWLEDGEMENTS

The authors are grateful for the technical direction provided by Douglas Chisholm of the Research and Special Projects Administration and Oscar Orringer of the Transportation Systems Center. The financial support of the Department of Transportation is also gratefully acknowledged.

EXECUTIVE SUMMARY

This report provides a technical assessment of proposed pipeline girth weld defect tolerance criteria. The Department of Transportation requires that girth welds of pipelines for transport of hazardous materials (oil and gas) be inspected for defects [1]. Inspection is currently performed by radiography. The standard for the U.S. which determines the conditions under which the girth welds must be repaired or replaced is based on the provisions of API 1104 [2], which is incorporated into the code of Federal Regulations (49CFR192 and 49CFR195). This standard is considered to be a workmanship standard, i.e., it enforces that weld quality be maintained. Experience has confirmed that use of the standard results in girth welds which are structurally adequate and safe. On the other hand, a portion of the girth welds which are rejected by the standard are believed to also be structurally sound.

Alternative girth weld defect tolerance criteria based on fracture mechanics technologies have been proposed. The history leading to these proposals involves the Alyeska oil pipeline. During its construction, a large number of girth welds were determined to be in variance with API 1104 subsequent to the completion of a portion of the line. The contractor applied a fracture mechanics based approach to show that the girth weld defects would not reduce the integrity of the pipeline as a basis for requesting a compliance waiver. [3] This led to substantial research [4] to evaluate the waiver requests. The overall conclusion of that research was that fracture mechanics based methodologies for defect tolerance assessment have merit, provided that information on crack depth is available.

The British Welding Institute has been a leader in the area of developing defect tolerance criteria for welds and has proposed the COD (Crack Opening Displacement) Design Curve methodology for setting allowable defect size limits. The British PD 6493 [5] provides detailed methodology for defect tolerance assessment in welds based on the COD Design Curve concept. A proposal has been made to augment the British

These stresses result from axial and bending loads on the pipeline. The axial loads result from a combination of internal pressure and thermal contraction with longitudinal constraint. The bending loads are associated with environmental changes: ground shift, erosion, loss of support, etc. Pipelines are designed for an assumed set of worst loading conditions, and it is these longitudinal stresses which result from the loads that are considered in assessing girth weld performance.

The data that is available on full scale pipe girth weld tests was collected. Approximately twenty-five well documented test results were identified for comparison against performance predictions from the various girth weld defect sizing criteria. The majority of the experimental results were obtained at the University of Waterloo, Canada with a large hydraulic system developed specifically for pipe testing. Results of pipe tests performed at Battelle Memorial Institute and Lehigh University were also used here.

Most of this data is for conditions more severe (larger defect sizes) than are permitted by the proposed defect tolerance standards; thus, comparisons with the data were made by applying the methodologies on which the standards are .based rather than the standards themselves.

We were able to reach a number of conclusions concerning the proposed girth weld defect tolerance criteria which are based on study of the criteria, comparison of the criteria applied to example cases, and comparison of the methodologies which form the bases for the criteria with the available experimental data.

The PD 6493, while not a proposed girth weld defect tolerance assessment criterion, is a detailed methodology for determining allowable defect sizes in weldments. It requires that the user input information on toughness, and either loading or defect size, and it results in corresponding estimates of allowable defect dimensions or applied stresses. The PD 6493 includes elastic crack geometry and residual stress corrections as well as a plastic collapse limit to the COD Design Curve. It results in conservative estimates of allowable strain or allowable defect dimensions for all cases considered. The degree of conservatism is not uniform and in numerous cases appears to be excessive.

The BS 4515 Appendix H is based on PD 6493; however, the applied stress is limited to the yield stress, and the defect (cracks are not permitted) is taken as having a depth of 3 mm (assumed to represent one weld pass). The use of BS 4515 Appendix H results in a required material toughness which depends only on the pipe dimensions and yield strength. For pipelines which meet this requirement, maximum allowable defect length depends on pipe diameter. Application of the methodology on which BS 4515 Appendix H is based resulted in conservative estimates for failure strain in all cases considered. BS 4515 Appendix H can currently be applied without reduction of pipeline integrity or safety, provided there is assurance that the actual defects are limited to 3 mm depth as assumed in the analysis which supports this standard; however, application of this standard also appears to be unduly conservative in many cases.

The CSA 2184 Appendix K is similar to PD 6493 in that it requires user inputs of applied stress and results in ranges of allowable defect dimensions. Application of CSA 2184 Appendix K to the data available in this study resulted in consistently conservative predictions, by at least a factor of two, for allowable strain levels. This standard is unique in that it does not require an absolute minimum toughness, and it does not include a residual stress correction. It is possible that this could lead to less conservative (or nonconservative) predictions for conditions not addressed here which involve lower toughness materials and/or high residual stresses, but this has not been investigated.

The API 1104 Appendix A is different from the other defect tolerance criteria in that it does not explicitly adjust the COD Design Curve to account for crack geometry and that it does not include a plastic collapse limit based on defect size or allowable load level. Comparison of results obtained by application of the methodology on which the standard is based to the available data resulted in a wide

Standard 4515 [6] with Appendix H [7] to include defect tolerance limitations based on PD 6493. The American Petroleum Institute has proposed the addition of Appendix A [8] to API 1104 to set allowable defect size limitations. The Canadian Welding Institute has also proposed an Appendix K [9] to their standard CSA 2184 [10] addressing girth weld defects. API 1104 Appendix A and CSA 2184 Appendix K are also based on the COD Design Curve. Each of the procedures, PD 6493, BS 4515 Appendix H, API 1104 Appendix A, and CSA 2184 Appendix K, are distinct in their detailed requirements. The purpose of the present study is to delineate these differences and to assess the merits of each proposed criterion.

A number of other fracture mechanics based methodologies which are applicable to assessing defects in girth welds have become available over the last decade. These methods are not specifically based on the COD Design Curve. Also, they are not generally in the form of a standard but rather are procedures which require fracture mechanics expertise for implementation. Two alternative methodologies have been included in the scope of this report because they provide guidance and direction in assessing the proposed standards or future standards work. The fitness-for-purpose methods considered in this effort are listed below:

- PD 6493
- BS 4515 Appendix H
- API 1104 Appendix A
- CSA 2184 Appendix K

- National Bureau of Standards (NBS) [11]
- Elastic-Plastic Estimation Procedure [12]

For the purpose of assessing girth weld defect tolerance criteria, the loading conditions to which girth welds are subjected in service have been identified. It is the longitudinal stresses across a girth weld which are of concern as a potential cause of girth weld failure.

range of safety margins on failure strains and nonconservative predictions for allowable strains for some data points associated with relatively long flaws. An earlier study by Wilkowski and Eiber came to a similar conclusion. [13] Comparison of the methodology on which API 1104 Appendix A is based with the other methodologies considered indicates that the lack of uniformity in the safety margin can be reduced and the nonconservative predictions eliminated by including geometry corrections to the COD Design Curve and a plastic collapse based limit on applied stress.

The API 1104 Appendix A requires a minimum toughness (CTOD) of 0.005 in. at 15°C below the lowest operating temperature. This condition was not satisfied by the available experimental data. Thus, no conclusion can be reached about the safety margin that would result from application of the proposed standard to test results involving weldments that meet or exceed the required toughness.

The API 1104 Appendix A requires the applied longitudinal strain magnitude as input and implicitly permits application to applied strain levels beyond yield--a range which is not allowed by the pipeline standard ANSI/ASME B31.8. [14] The higher strain range is apparently permitted in order that the standard may also be used to address installation conditions--a situation not .treated in the present study.

The API 1104 Appendix A explicitly allows cracks and requires the field measurement of defect length and depth dimensions. While nondestructive evaluation was not the focus of the present study, the concern is raised that tools for performing these measurements with appropriate accuracy and confidence may not be available, and therefore, may prevent effective application of this proposed standard.

We recommend that API 1104 Appendix A be altered in two areas prior to usage as a girth weld defect tolerance standard for pipeline service conditions. First, it should be made consistent with the base standard on the topic of allowable longitudinal pipeline stresses, namely, that applied stresses be limited to the specified minimum yield stress.

Second, the standard should be altered (or new data provided) to address the apparent lack of conservatism in its application to the long flaw problem. Possible approaches for altering the standard in this area include, but are not limited to, further restriction on allowable defect length, inclusion of a plastic collapse limit, and/or inclusion of a crack geometry correction to the COD Design Curve. *An* appropriate margin of safety should be demonstrated for the range of defects addressed. The safety factor of 2.0 on applied strain is incorporated into the COD Design Curve and could be utilized in the API 1104 Appendix A.

The NBS procedure is'based on LEFM using the Irwin model for ligament yielding associated with surface cracks and the Dugdale model to account for yielding beyond the crack length. It includes a residual stress correction. Based on an elastic, perfectly plastic material model, it does not allow the applied stress to exceed the material flow stress. No explicit safety margin is built into the NBS procedure.

The failure strain predictions based on the NBS methodology did not correlate closely with the observed failure strains. There appears to be a crack geometry aspect ratio (a/ℓ) influence on the ratio of predicted to measured failure strain. This effect could be the result of constraint influences on critical crack tip opening displacement and/or on the amount of stable tearing which precedes failure. Neither of these influences are accounted for by the NBS model. The NBS methodology follows a procedure developed to determine the conditions for crack growth initiation rather than final failure; however, it is applied in conjunction with crack tip opening displacement data at failure. The ambiguity in the NBS method with respect to crack growth initiation and failure predictions may be a cause for the disparity between its predictions and observations.

The NBS criterion for setting allowable defect sizes is based on a more substantial theoretical foundation than the other approaches which were reviewed here. The NBS methodology involves calculation of the crack tip opening displacement in terms of geometry, material properties, and loading conditions. Conversely, the PD 6493, BS 4515 Appendix H, CSA 2184 Appendix K, and API 1104 Appendix A are each based on the COD Design Curve with various corrections. Our observations indicate that, in spite of this distinction, the NBS methodology does not necessarily produce better estimates of allowable strain level or defect size than the best of the empirical methods. The reason for this may be that where a theoretical model is utilized it is necessary to explicitly account for all the factors which influence failure conditions. In this case these factors include material hardening above yield, stable tearing, and the influence of geometry on apparent material toughness.

We would recommend that research continue in an attempt to develop better theoretical models for the prediction of failure conditions for girth welds containing defects and that the results of the research be made available to aid in improvement of girth weld defect tolerance standards. However, at the present, it appears that such standards should be based on the COD Design Curve with appropriate corrections to account for the various influences discussed above.

1. INTRODUCTION AND BACKGROUND

Gas and oil transmission pipelines are produced by field welding of pipe segments. These field girth welds are inspected and may require repair or replacement based on the inspection findings. This report addresses criteria that may be applied to determine which of the girth weld defects 'found during inspection can be allowed to remain in the pipeline in service. The present girth weld defect tolerance criterion, American Petroleum Institute (API) 1104, is an experience based workmanship standard. It is empirical in nature, historically proven, and set to maintain both safety and high quality workmanship. This standard sets limits on weld defects including inadequate penetration, incomplete fusion, undercuts, and porosity. It does not allow cracks regardless of size and location.

There are perceived to be circumstances in which it may be economically advantageous and functionally safe to leave in defects which violate API 1104. For example, during the construction of the Trans-Alaskan Pipeline System (also known as the Alyeska pipeline), a large diameter pipeline built during the 1970s, defects which violated the criterion were found in girth welds for pipe segments which had been backfilled. The contractor petitioned the Department of Transportation (DOT) requesting waivers from the regulation for these defects. The petition was based on the use of fracture mechanics to determine safe defect sizes.

The American Petroleum Institute has now developed a fracture mechanics based girth weld defect tolerance criterion, API 1104 Appendix A, and has requested DOT to incorporate this criterion in the Code of Federal Regulations. Similar criteria have been proposed in Great Britain and Canada. All are based on the COD Design Curve approach. Alternative fracture mechanics-based approaches for determining safe defect sizes for girth welds in pipelines have been proposed by the National Bureau of Standards (NBS) and Lehigh University.

A number of laboratories have performed test programs to determine the conditions under which girth welds containing defects fail structurally. The data developed in these programs is used here as guidance in assessing the proposed defect tolerance criteria. This report describes our study of fracture mechanics-based girth weld defect tolerance criteria and our recommendations with respect to their applications.

The factors which influence the strength of girth welds containing defects are discussed next. If a pipeline girth weld which contains a defect is loaded until it fails at that defect, the failure may be in the form of material tearing which can result in a leak at the weld or a burst (unstable fracture) of the welded regfon. The defects under consideration are cracks or regions of incomplete welding whose plane is transverse to the pipe axis. These defects may be either surface defects or buried defects. They may increase in size during service as a result of fatigue crack growth. The strength of the girth weld will depend on the size and shape of the defects, i.e., the crack depth, a, and the crack aspect ratio, a/ℓ, shown in Figure 1.1.

For a given defect geometry, the girth weld strength will depend on the toughness of the material adjacent to the defect. The material toughness will be different in the base metal, the heat affected zone, and the weld metal. It will vary with temperature and strain rate. At low temperature the fracture mode will be brittle, while at the higher temperature, it will be ductile. The transition temperature regime separates the brittle (lower shelf) and ductile (upper shelf) fracture behavior. There are various measures of material toughness based on alternative fracture mechanics theories and ranges of application. The primary material toughness measure used for girth weld defect tolerance assessment is the crack tip opening displacement (CTOD). The concept is to measure material toughness, 6, on a standard specimen in the laboratory and to calculate the parameter CTOD for the defect in the girth weld as a function of applied load. In practice most CTOD toughness measurements are performed in accordance with the British Standard BS 5762 which involves use of a three-point bend specimen. By

Pipe Cross Section

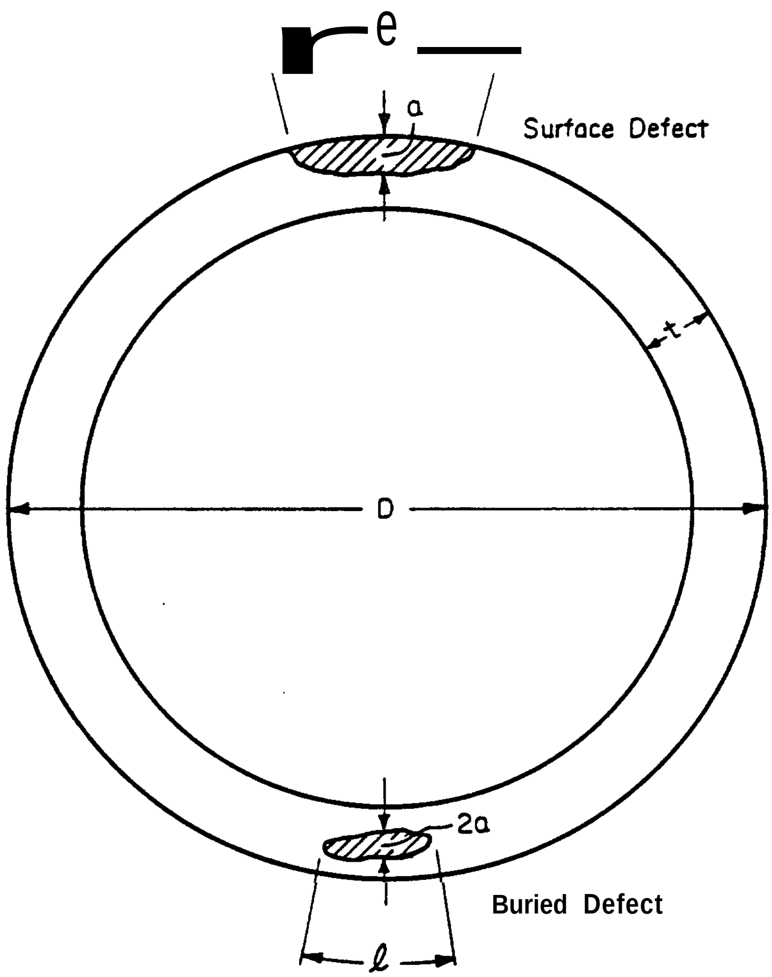


Figure 1.1 Defect and Pipe Geometry

setting the expression for CTOD in terms of applied load equal to the measured toughness, one is able to predict the load carrying capacity of the girth weld which contains the defect.

The material toughness, 6, is actually dependent on the geometry in which it is measured. This geometry dependence is associated with the degree of constraint that the surrounding material imposes on the local crack tip behavior. The BS **5762** three-point bend specimen geometry has been chosen in part because it possesses a high degree of constraint and therefore results in a low measure of fracture toughness, leading to conservative predictions for many applications.

Depending on both the material's ductility and its toughness, failure could occur in the range for which the deformation of the pipe is predominately elastic, or there could be various amounts of plastic yielding (deformation) in the pipe prior to the onset of failure. The amount of plastic deformation which precedes failure influences the type of analysis which is required to determine the crack driving force or applied CTOD. Three distinct regimes exist. In the first, the yielding is localized around the crack front and elastic analyses are applicable. As the loading increases without fracture, the plastic region in the ligament between the crack front and the pipe surface increases and must be accounted for in the analysis. A plastic correction to the elastic result is often used for this purpose. Further loading causes the ligament to yield completely and the plastic zone to extend from the region surrounding the crack and its remaining ligament across the pipe cross section, finally reaching the net section yield or plastic collapse condition for the pipe cross section. In the event that the girth weld can be loaded to the condition of plastic collapse without previously attaining fracture, the pipe will fail by a mode of plastic deformation and stable tearing.

The concept of plastic collapse is associated with an idealization of the material stress-strain behavior called perfect plasticity--that the strain level at yield can increase without any corresponding increase of stress. This idealization ignores material hardening. The behavior of actual structural members in the fully plastic regime is sensitive to material hardening.

Our work refers specifically to defects in welds. Therefore, the material properties to be addressed are those of the weld rather than those of the base metal. If the weld stress-strain behavior is significantly different from that of the base metal, this material inhomogeneity will influence the transfer of stress from the loading point to the defect region and will influence the calculation of the crack driving force.

The process of welding pipelines produces residual stresses in the vicinity of the weld. While these stresses could be removed by post weld heat treatment, it is normal practice to leave in the weld related residual stresses. These stresses can act in concert with the load introduced stresses in driving the crack and need to be accounted for accordingly.

Finally, the geometry of the pipe itself and the type of loadings to which it is subjected will need to be considered in calculations of the crack driving force. In particular, the stresses which influence transverse girth weld defects are axial and related to both axial tensile and bending loads on the pipeline. The increment of load between initial yielding and net section yielding for the cross section is substantially larger for the bending loads case than for the tensile loading case.

In summary, the strength of a girth weld containing a defect is influenced by the crack geometry, by the material properties, and by the sources of crack driving force. In the next section, we identify the loadings to which a pipeline girth weld may be subjected in service and use this information as input for the determination of crack driving forces. The approaches proposed for setting girth weld defect tolerance criteria are reviewed in Section 3. In Section 4, the available laboratory data on performance of girth welds containing defects is reviewed. Section 5 contains the results of calculations performed using the various defect tolerance criteria for cases in which experimental data exists and on the comparison of model predictions with laboratory findings. In Section 6 the proposed defect tolerance criteria are assessed, taking into account both the agreement of the models with observation and with theoretical analyses and the extent to which they can be used effectively by the engineering and design community. Section 7 contains recommendations with respect to the conditions under which proposed criteria should be accepted for field applications and on areas for continued development. This report also includes two appendices. The first provides a detailed description of the API 1104 Appendix A proposed methodology for sizing tolerable defects; the second is an investigation of COD Design Curve geometry correction factors in the presence of plasticity.

2. SERVICE LOADS FOR TRANSMISSION PIPELINES

The fitness-for-purpose criteria for girth weld defects reviewed in this document make different assumptions on the loads to which the girth weld is subjected in service. The BS 4515 Appendix H has been developed using a nominal applied stress equal to the yield stress, a stress concentration factor of 1.3, and a residual stress equal to the yield stress for a total stress of 2.3 times yield. API 1104 Appendix A requires that the user determine and input applied strain. It assumes a 0.2 percent residual strain. In CSA 2184 Appendix K, the user specifies the applied stress and converts it to equivalent strain. Safe assessment according to each criterion requires accurate estimates of load. Therefore, in this section we review the sources of the loads which influence girth weld behavior, their magnitudes, the design standards for setting the loads, and the methodology used by pipeline designers for assigning loads.

The primary service loading on a piping system is due to the internal pressure of the fluid on the pipe walls. This causes a hoop stress and a secondary axial stress, which depends on the axial constraint and on the configuration of the pipeline.. The axial stress is generally less than half of the hoop stress. Typical gas transmission pipelines are designed to be operated such that the nominal hoop stress is approximately 70 percent of yield strength; thus the expected axial stress is less than 35 percent of yield strength. Bending and/or torsional stresses are also produced at bends as a result of hydraulic pressure.

Other sources of service loads which influence girth welds include thermally induced stresses associated with temperature changes of the line, and in-service bending stresses associated with ground movement including settlement, frost heave, washout and earthquakes. Pipelines are also subjected to accidental intrusion loadings on occasion.

A different system of loadings acts on pipelines during installation and prior to testing. These may include large bending loads associated with placing the pipe in the ditch for on-shore service and over the stinger for off-shore installation. Subsequent to installation, pipelines are pressure tested at stress levels which may exceed yield, prior to being put into service. These installation loads may cause residual stresses to remain in the line. However, these loads par se are not addressed in this study.

2.1 Design Codes for Specification of Loads

The Code of Federal Regulations (49CFR192 and 49CFR195) regulates transmission pipeline design, material selection, welding practice, construction, and testing. Maximum allowable operating pressure is set depending on the pipe class. Pipe sections are classified from 1 to 4 with increasing local population density. The factor F, which is applied to limit the operating pressure in conjunction with the pipe class, is given as

class	1	2	3	4
F	0.72	0.6	0.5	0.4

The allowable operating pressure is specified as

$$P = EFT(2St/D)$$

S = specified minimum yield strength *(SMYS)*
t = thickness
D = nominal outside diameter
E = longitudinal joint factor
T = temperature derating factor (only for T > 250°F)

The specified minimum yield stress is measured in the transverse direction on the base metal of the pipe section. The regulations also require the pipeline design to include flexibility so that "bending stresses are minimized."

The ANSI/ASME B31.8 design code "Gas Transmission and Distribution Piping System" also presents loading considerations for pipeline design. Longitudinal stresses due to pressure, S_L, bending stresses due to external loads, S_B, and thermal expansion stresses, S_E, are treated with the following requirements for operating conditions:

$$S_E < 0.72\ S$$

$$S_E + S_L + S_B < S$$

$$S_L + S_B < 0.75\ S$$

Pipeline companies also have proprietary design procedures which treat aspects not considered by the standards. From our limited interviews, we understand that pipeline designers do not normally consider longitudinal stresses in pipelines explicitly but assume that they are below yield. The fact that axial stress due to pressure is usually less than 35 percent of SMYS is considered to provide an adequate safety margin.

2.2 LOAD MAGNITUDES

The Alyeska Pipeline is used here as an example of expected service loading conditions. Load sources included pressure, fluid inertia loading at bends, temperature differential, dead load plus live load, overburden, earthquake (operating and contingency), and differential settlement. Stress analyses were performed for straight and bent pipe under a matrix of loading conditions. The most severe calculated longitudinal stress occurred at a 6" overbend and had magnitude 36.5 ksi for a X-60, 48 inch diameter pipeline, i.e., 61 percent of SMYS. [15]

In service, bending loads on the pipeline associated with earth movement are generally believed to be displacement controlled and therefore relieved by deformation and possible crack growth in the pipeline. These loading conditions differ from load controlled conditions where deformation does not relieve load and pipe fracture behavior is less stable.

2.3 RESIDUAL STRESSES

Residual stresses are induced into pipes during girth welding. These stresses are caused by thermal contraction of the weld metal and adjacent heated base metal during cooling. The residual stress field in a girth weld varies across the pipe thickness and is localized in the region of the weld. No resultant force is created, thus, this stress field is self equilibrating.

The magnitude and distribution of residual stresses depend on the details of the welding process. As a result they are both variable and not well known. In design practice, the residual stress level is often taken to be equal to the material yield strength. This level is the maximum attainable in a material which does not exhibit hardening above yield and is generally believed to be a conservative assumption.

2.4 SUMMARY OF LOADINGS

The implications of the load information developed here on the fitness-for-purpose criteria are as follows:

1. The precise magnitude of axial stress (or strain) in the pipeline is not generally calculated or known by the pipeline designers.

2. Under most circumstances, the nominal longitudinal stress in an on-shore pipeline during service will be less than the yield stress. Exceptions correspond to large earthquakes or major washouts. During installation, however, especially during root bead welding and lineup clamp removal, strains well in excess of yield routinely occurs.

3. The longitudinal stresses are caused by both tensile loads (associated with internal pressure and thermal expansion) and bending loads caused by movement of support.

4. The longitudinal operating stresses are required to be less than the specified minimum yield stress (ANSI/ASME B31.8).

3. APPROACHES FOR SETTING GIRTH WELD DEFECT TOLERANCE CRITERIA

Several methods that can be used for establishing allowable defect sizes in pipeline girth welds have been reviewed in this investigation. Table 3.1 lists these methods. Standards developed specifically for girth weld defect assessment are the American Petroleum Institute's API 1104 Appendix A and Appendix H of the British Standard BS 4515, which is equivalent in scope to API 1104. Canada is also in the process of adding Appendix K to their standard CSA 2184 for the same purpose.

Other methodologies available for the assessment of circumferentially cracked pipe include those developed by the National Bureau of Standards (NBS) with support from the Department of Transportation, and the British document PD 6493. Procedures developed at Lehigh University [16] and at Battelle Memorial Institute [17] were also considered; however, it was decided not to include these in the comparisons presented here because they are not at a state of development similar to the other proposed standards. In addition to these, the EPRI elastic-plastic estimafion procedure was used as a tool in the present in pipelines.

Table 3.1 Methodologies for Assessing Allowable Defect Sizes Considered in this Investigation

API 1104 Appendix A
BS 4515 Appendix H
CSA 2184 Appendix K
NBS Approach
PD 6493
Elastic-Plastic Estimation Procedure (EPRI)

Table 3.2 compares some of the features of the various defect tolerance criteria considered in this study. This is followed by brief descriptions of these criteria. API 1104 Appendix A is described in detail in Appendix A of this report. Before outlining the individual criteria, a description is given of the COD Design Curve, since it is the basis for several of the methods.

3.1 COD DESIGN CURVE

The COD Design Curve is a semi-empirical criterion for determining acceptable defect sizes, allowable loads and minimum toughness. [18] It expresses the CTOD toughness as a function of crack size and applied strain:

$$\delta = 2\pi e_o \bar{a} \cdot \begin{cases} (e/e_o)^2, & e/e_o \leq 0.5 \\ (e/e_o - 0.25); & e/e_o > 0.5 \end{cases} \qquad (3.1)$$

where e is the applied strain, e_o is the yield strain and $\bar{a}$ is the half crack length. Equation 3.1 has a safety factor of 2.0 on CTOD explicitly built into the elastic range ($e/e_o \leq 0.5$) and experience indicates that a similar safety margin exists over the remaining strain range.

For wide center-cracked panels, $\bar{a}$ is equal to one-half the crack length. Otherwise $\bar{a}$ corresponds to the crack depth for surface defects and one-half the crack height for buried defects, both adjusted to account for the effects of crack shape and proximity to the plate surfaces. The adjustment to the actual crack depth or half height, a, is made by finding the equivalent half crack length, $\bar{a}$, which would give the same linear elastic CTOD in a wide center-cracked panel as in the geometry of interest. The curves used are shown in Figure B.2 of this report's Appendix B.

Table 3.2 Comparison of Defect Tolerance Criteria Features

	API 1104 App.A	BS 4515 App.H	CSA 2184 App.K	PD 6493	NBS
Failure Criterion					
fracture	x	x	x	x	x
plastic collapse		x	x	x	x
Fracture Criterion					
COD Design Curve	x	x	x	x	
geometry correction		x	x	x	
residual stress correction	x	x		x	
Other					x
Loadings					
applied stress		x	x	x	x
applied strain	x		x	x	

The definition of applied strain varies from user to user of the COD Design Curve, but in the most conservative form the applied strain includes contributions from the applied external load, residual and thermal strains and strain concentrations. The COD Design Curve is often expressed in terms of stress, in which case e is replaced by σ/E, where σ is stress and E is Young's Modulus.

The CTOD toughness used in the COD Design Curve, equation (3.1), is usually obtained according to the procedures of British Standard BS 5762.[19] This procedure utilizes three-point bend specimens which have a thickness equal to or nearly equal to that found in the structure of interest, in this case, the pipe wall thickness. One can obtain several measures of toughness depending on the material behavior:

δ_i - CTOD at the initiation of stable crack growth,

δ_c - CTOD at unstable fracture or pop-in with no prior stable crack growth,

δ_u - CTOD at unstable fracture or pop-in subsequent to stable crack growth, or

δ_m - CTOD at maximum load for situations where this precedes unstable fracture.

The initiation toughness is the most conservative toughness to use for cases in which fracture in the three-point bend test occurs completely by ductile tearing. However, there is experimental difficulty in determining δ_i, and some investigators have made a strong case for using δ_m in the Design Curve for these situations. [20] Further details on the COD Design Curve can be found in Appendix B of this report.

3.2 SUMMARY OF CRITERIA

3.2.1 PD 6493

The description of the COD Design Curve corresponds closely to its application in the British document PD 6493. [5] The same adjustments are made to account for defect geometry and residual stresses, and consideration is alos given to fatigue crack growth. PD 6493 uses stress in equation 3.1 provided the calculated applied stress, not including residual stress, does not exceed twice the yield stress. Beyond this point, strain must be used. Investigation of failure modes other than fracture is required, including plastic collapse and buckling.

. PD 6493 can be used to assess many types of defects in welded structures and is not restricted to girth welds. It contains a procedure not included in the other girth weld methodologies that employ the COD Design Curve. This procedure is called recategorization and applies to surface and buried defects. It requires that a defect be recategorized as a through defect of the same length if: (1) a through crack of the same length would cause net section yielding of the structure and; (2) the stress in the ligament of the surface or buried defect is equal to the flow stress, $\sigma_f = (\sigma_o + \sigma_u)/2$ where σ_o is the yield strength and σ_u is the tensile strength.

3.2.2 BS 4515 Appendix H

BS 4515 Appendix H is also recently published and based on the COD Design Curve. [7] The defect depth is assumed to be equal to 3.5 mm (0.138in.) which is considered the average depth of a weld pass plus an allowance for fatigue crack growth. No initial cracks are allowed. The maximum allowable defect length depends on the pipe diameter, but for large diameter pipes, D > 900mm (35.4 in.), the defect length cannot exceed 14.5 times the wall thickness. This restriction on crack length is based on an empirical plastic collapse criterion which includes the effect of a 3.5 mm deep crack:

$$\ell \leq 0.016\ Dt$$

where D is pipe diameter and t is wall thickness; all dimensions are in mm. The defect size is adjusted for shape and proximity to the plate surfaces according to the procedure described for the COD Design Curve before substitution in equation 3.1. Stress is used instead of strain and the value is fixed at 2.3 σ_o, which includes the applied stress, equal to the yield stress, σ_o, a stress concentration factor of 1.3 and a residual stress, also equal to σ_o. The standard cannot be used when actual applied stresses are greater than σ_o. The CTOD toughness is determined according to BS 5762 and has a minimum required value of about 0.08 mm (0.003 in.). Figure 3.1 shows an example of the curves used to determine minimum required CTOD for large diameter pipe.

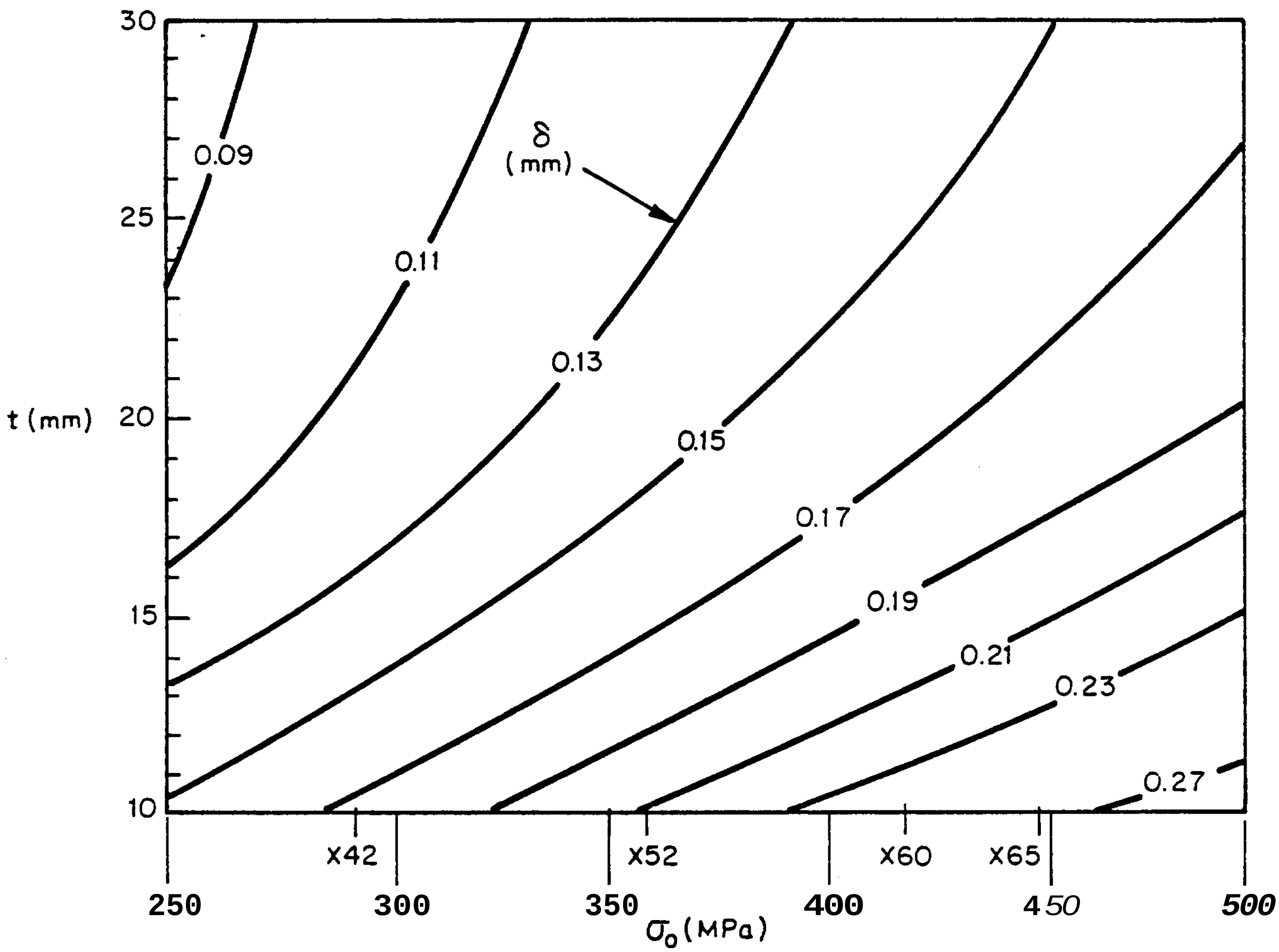


Figure 3.1 Required CTOD Toughness Curves from BS 4515 Appendix H; D > 900 mm

3.2.3 CSA 2184 Appendix K

CSA 2184 Appendix K [9] has been published as a proposed standard. It too is based on the COD Design Curve. Cracks are not allowed. Defect depth is implicitly limited to 50 percent of the wall thickness and further, must be taken equal to the depth of one weld pass if inspection is not used to determine defect depth. The defect depth is adjusted before substitution into equation 3.1 according to the procedure described for the COD Design Curve, except for relatively long defects. For these defects the defect geometry correction curves have been empirically adjusted (see Appendix B). Defect length is limited to 10 percent of the circumference. Additional limits on defect length are also set to avoid plastic collapse. The criterion is shown in Figure 3.2. The applied strain includes contributions from the externally applied load and thermal strain but not residual strain. The CTOD toughness is determined according to BS 5762 and there is no explicit minimum, though an effective minimum would exist in cases for which requirements are placed on Charpy energy.

3.2.4 API 1104 Appendix A

The recently published API 1104 Appendix A [8] uses the COD Design Curve for a fracture mechanics assessment of girth weld defects. The defect depth or half crack height is used directly in equation 3.1; no adjustment is made for defect shape or proximity to the plate surfaces. An adjustment is made to the initial defect size to account for potential fatigue crack growth. The defect length is restricted to 40 percent of the pipe diameter for defects less than or equal to 0.25 times the wall thickness and to four times the wall thickness for defects between 0.25 and 0.50 times the wall thickness. Defects deeper than one-half the wall thickness are not allowed. The applied strain is taken equal to the strain caused by the external load, including thermal strain, plus a residual strain specified as 0.2 percent. The CTOD toughness is determined according to BS 5762 but must be measured at a temperature 15°C below the minimum operating temperature and in any case

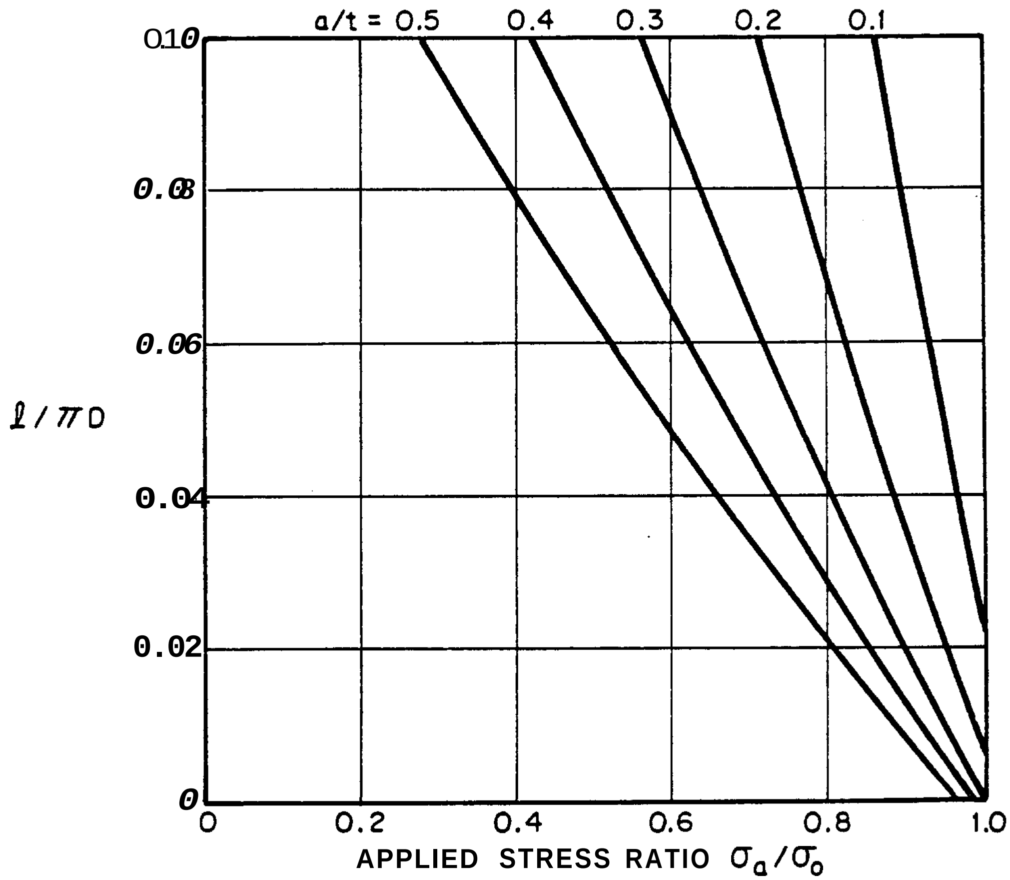


Figure 3.2 Allowable Defect Length from the Collapse Criterion in CSA 2184 Appendix K

must exceed 0.127 mm (0.005 in.). Figure 3.3 shows the curves for allowable defect depth vs applied strain.

3.2.5 NBS Approach

The NBS approach is not based on the COD Design Curve, but it does use CTOD as a fracture criterion. [11, 21] It is a relatively complicated analysis that requires the use of a computer. However, once the conditions and parameters for a particular pipeline installation are known, the program generates a curve of allowable defect depth versus defect length which can be used for acceptance or rejection of all defects.

The NBS approach uses an elastic-perfectly plastic analysis which can be separated into two regimes of elastic-plastic behavior. In the first regime, when plastic deformation is limited to the crack front region, elastic solutions are used with a Dugdale plastically adjusted crack length to calculate CTOD. In the second regime, when the ligament is fully yielded, CTOD is calculated using the Irwin model, by which the surface crack is modeled as a through crack with crack face closure tractions equal in magnitude to the yield stress multiplied by the remaining ligament area. Plastic deformation beyond the crack ends is accounted for by using a Dugdale model of the plastic zone. Nominal stresses greater than σ_f are not allowed since this corresponds to the limit load condition for the elastic-perfectly plastic material. Residual stresses are accounted for by reducing the CTOD toughness by $\sigma_o t/E$. The resulting allowable crack length vs crack depth curves have no explicit safety margin. An example of the output of the NBS program is shown in Figure 3.4.

3.2.6 Elastic-Plastic Estimation Procedure

The elastic-plastic estimation procedure, whose development has in large part been supported by the Electric Power Research Institute (EPRI), can be used in handbook form [12] for a certain class of problems. It enables one to use the J-Integral or CTOD as a measure of

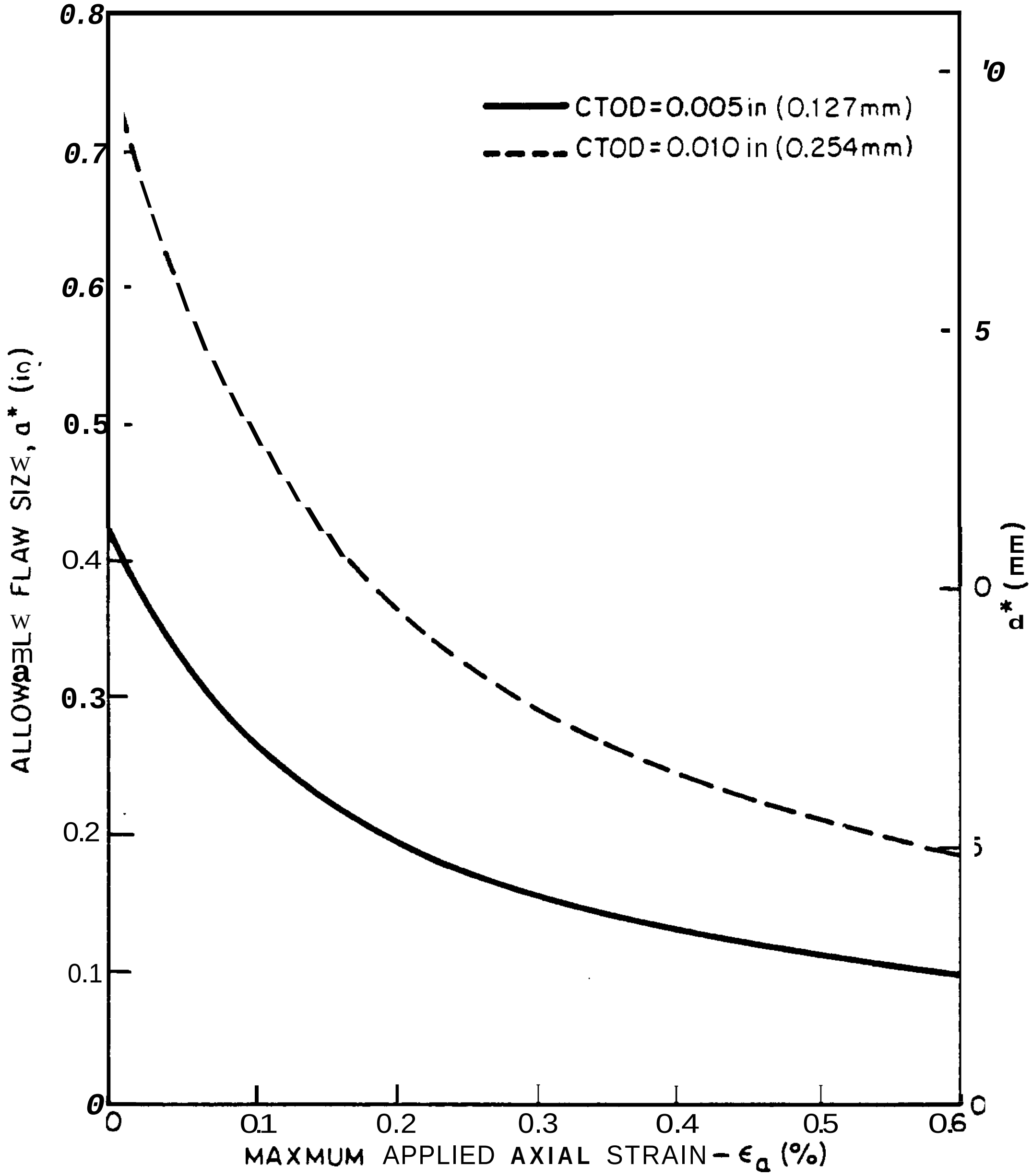


Figure 3.3 Allowable Defect Depth vs Applied Strain from **API** 1104 Appendix A

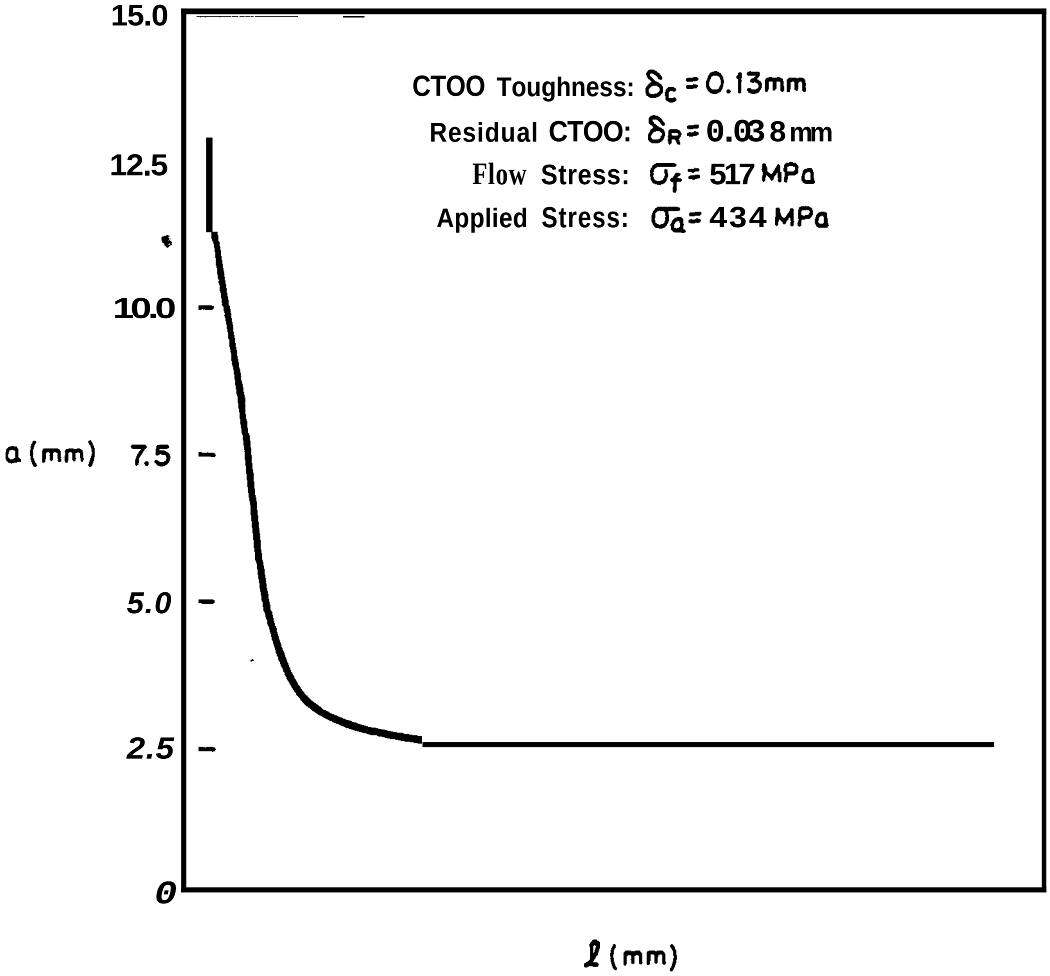


Figure 3.4 An Example of an Allowable Defect Depth vs Defect Length Curve from the NBS Approach

toughness, accounts for strain hardening and allows one to include stable tearing and tearing instability in the analysis. Currently, it is not able to deal with surface or buried defects of the type encountered in pipeline girth welds. There exists a solution for a cylindrical shell containing a part-through circumferential crack which, however, extends around the entire circumference of the shell. Consequently, the elastic-plastic estimation procedure was not considered as a girth weld defect assessment approach but was used to investigate the influence of plasticity on geometry correction factors used with the COD Design Curve; see Appendix B of this report.

3.3 DISCUSSION

As an aid in showing the similarities and differences between the fracture criteria described above, comparisons are presented of CTOD versus applied strain for five crack geometries. The crack geometries, which are listed in Table 3.3 and indicated in Figure 3.5, are representative of dimensions for which certain girth weld defect criteria are applicable. The curves are shown in Figures 3.6 through 3.10 and can be considered as required CTOD toughness vs applied strain, or maximum allowable applied strain vs CTOD toughness for the particular defect geometry. The other parameters used in generating the curves are:

$D = 914$ mm(36 in.),

$t = 11.1$ mm(0.44 in.),

$\sigma_o = 483$ MPa(70 ksi),

$e_o = 0.23$ percent.

These curves were generated by using the corresponding proposed standards. Thus, the curves developed from API 1104 Appendix A were based on Figure 3.3 of this report and include adjustments to the defect depth to account for possible subsequent fatigue crack growth. Similarly, the curves developed from BS 4515 Appendix H were based on Figure 3.1.

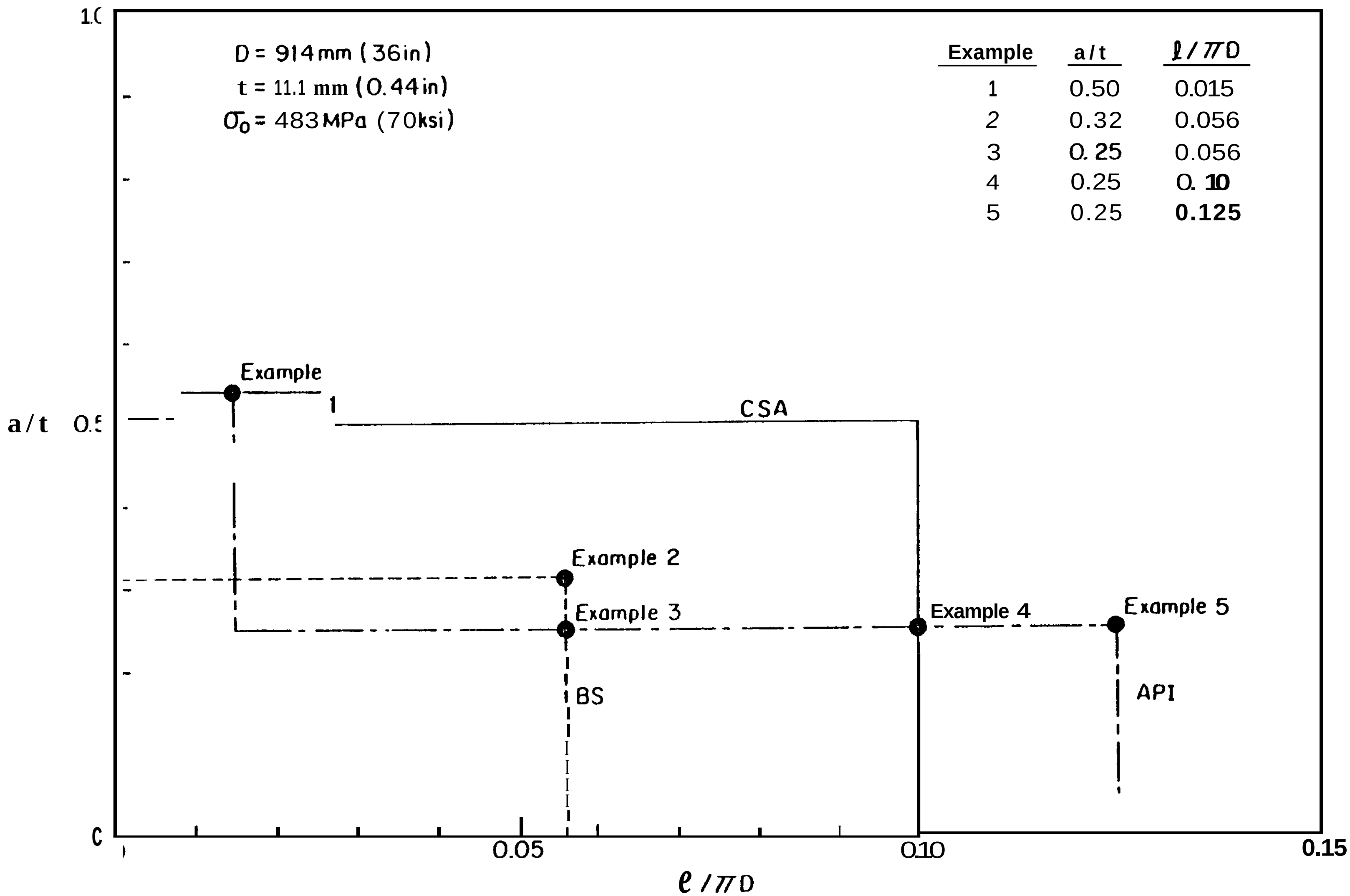


Figure 3.5 Crack Depths and Lengths for Example Calculations

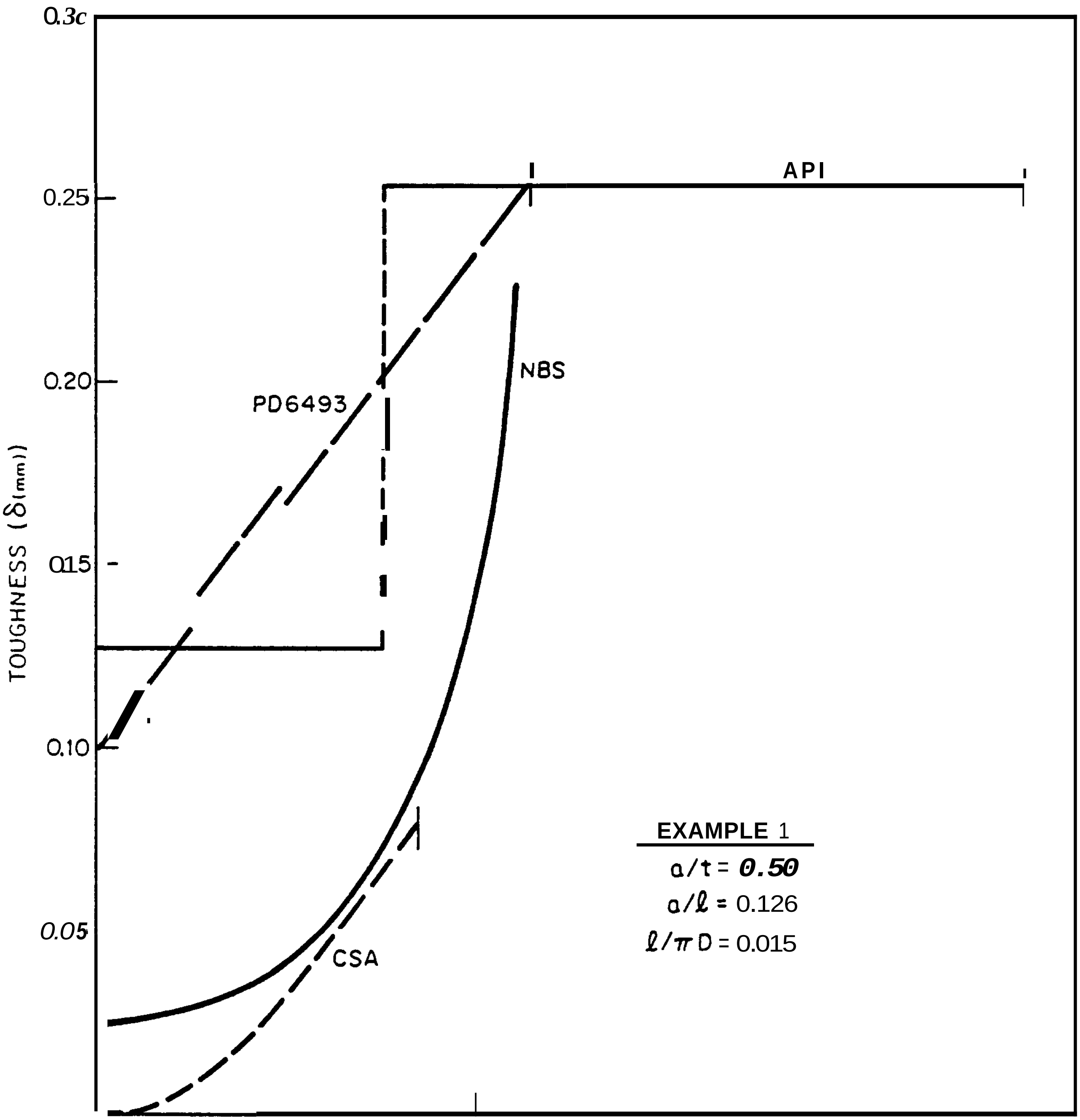


Figure 3.6 Comparison of Required Toughness or Allowable Strain from the Different Defect Assessment Methods: Example 1

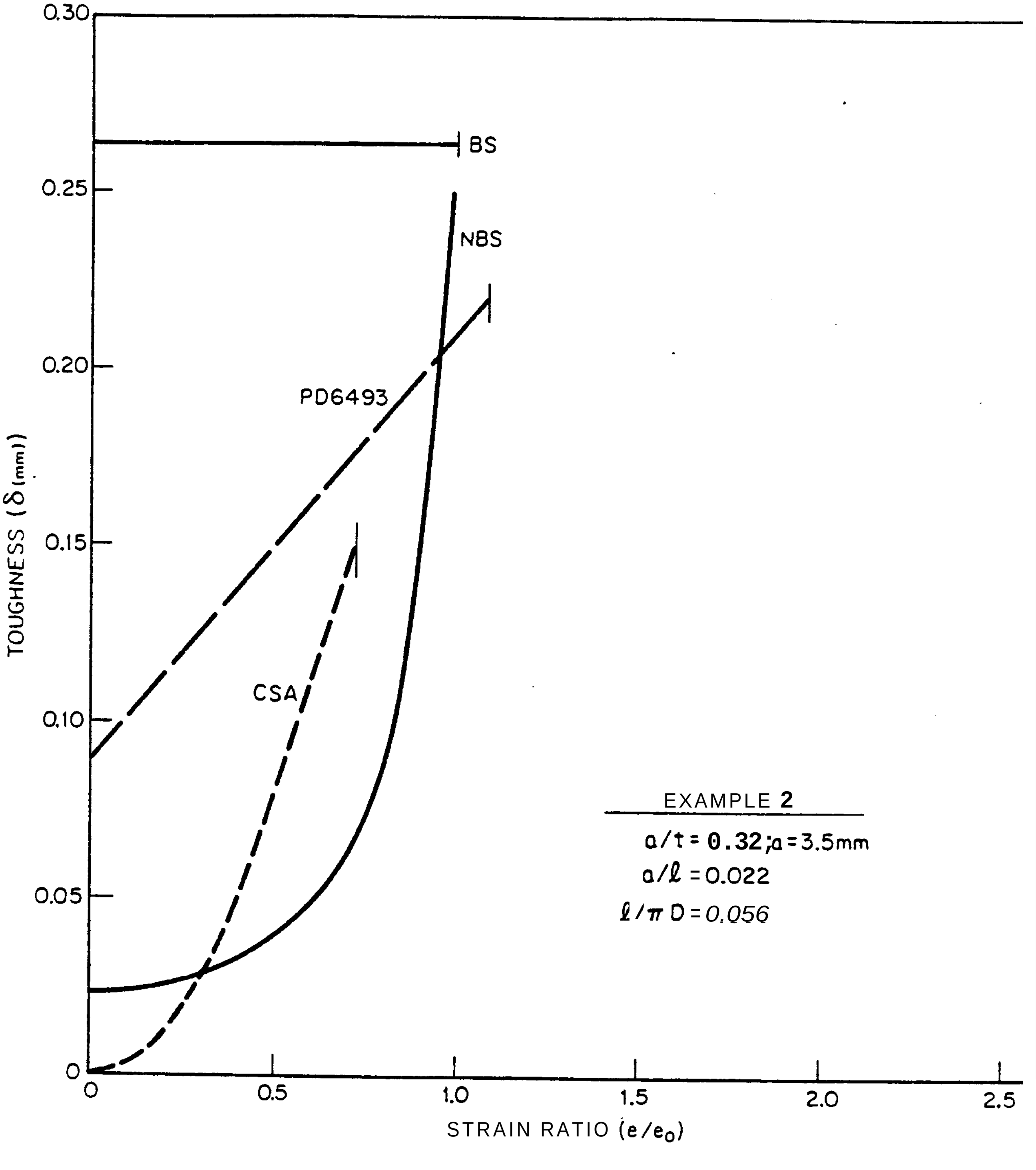


Figure 3.7 Comparison of Required Toughness or Allowable Strain from the Different Defect Assessment Methods: Example 2

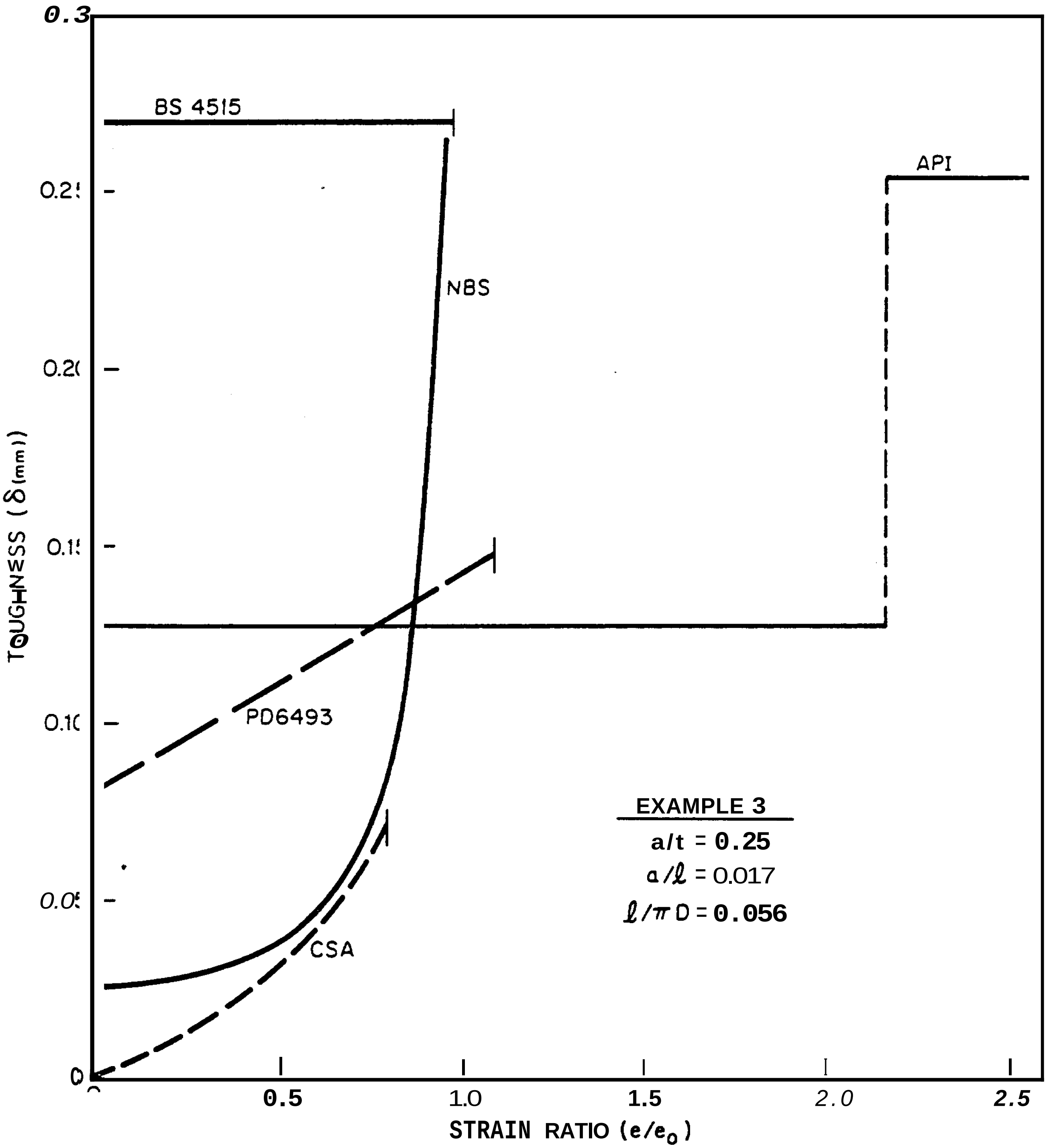


Figure 3.8 Comparison of Required Toughness or Allowable Strain from the Different Defect Assessment Methods: Example 3

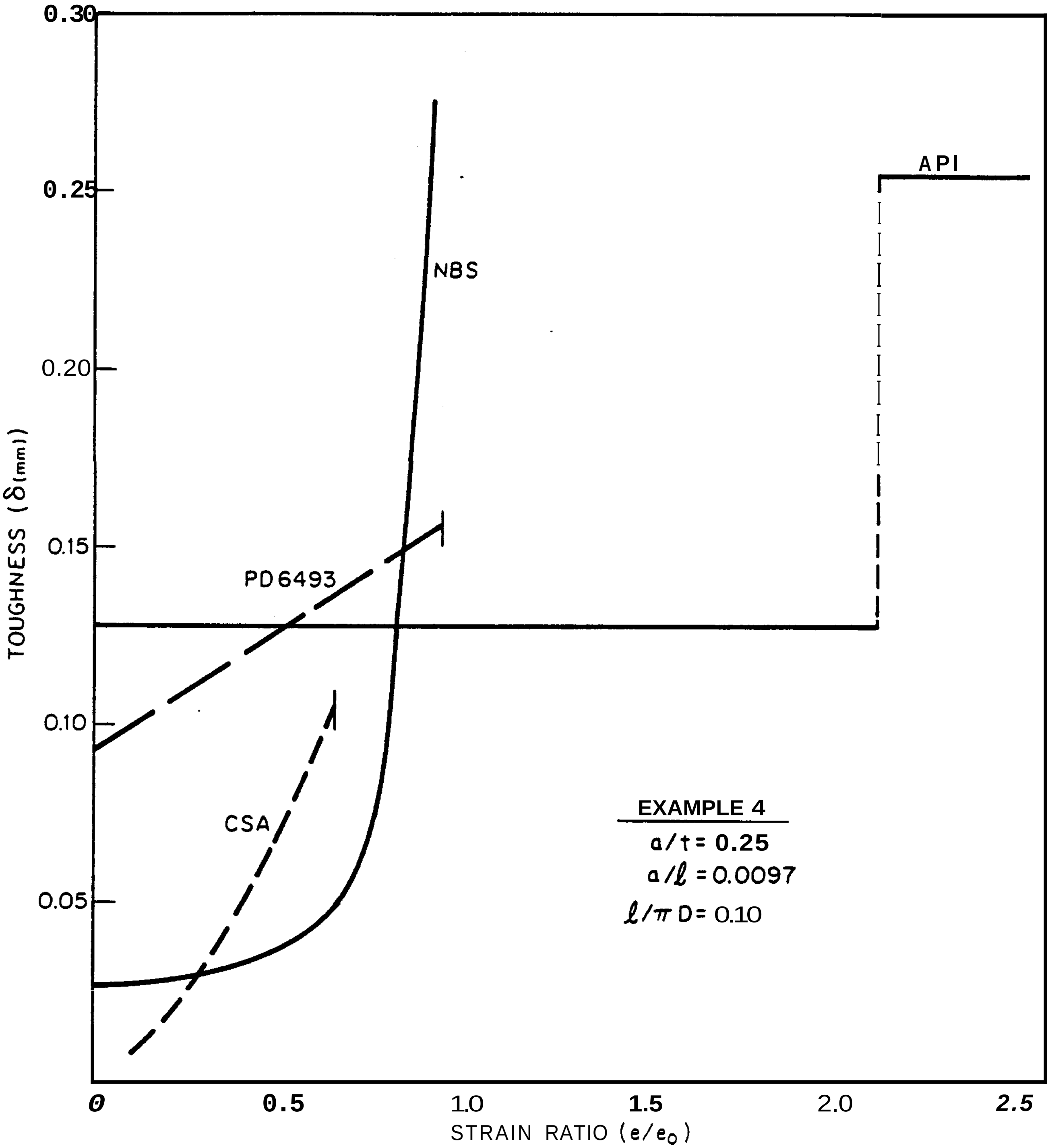


Figure 3.9 Comparison of Required Toughness or Allowable Strain from the Different Defect Assessment Methods: Example 4

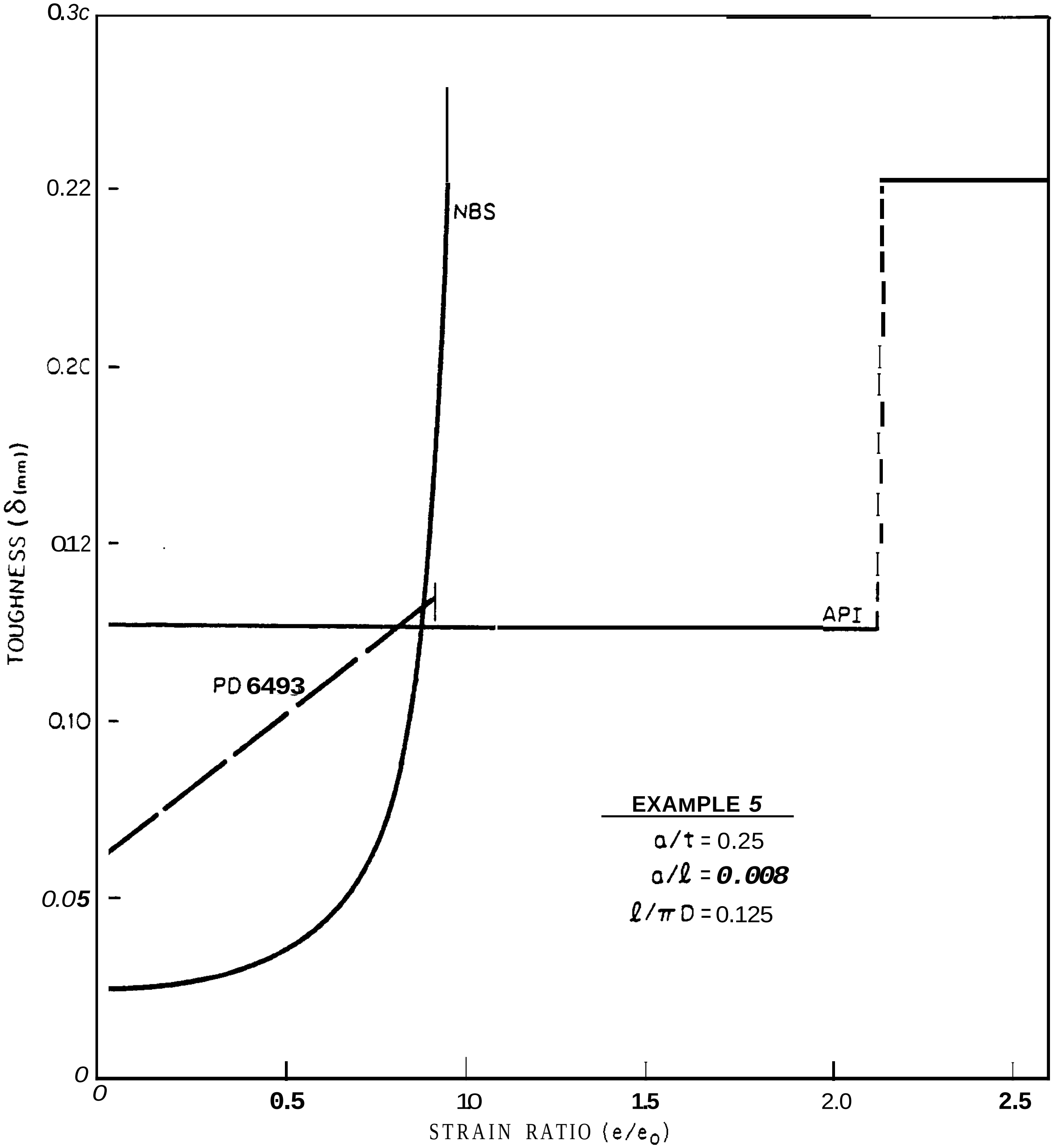


Figure 3.10 Comparison of Required Toughness or Allowable Strain from the Different Defect Assessment Methods: Example 5

Table 3.3 Examples used to Compare Methodologies; D-914 mm (36 in.), t - 11.1 mm (0.44 in.)

Example	a(mm) (in.)	ℓ(mm)(in.)	a/t	a/ℓ	$\ell/\pi D$
1	5.6 [0.22]	44.4 [1.75]	0.50	0.125	0.015
2	3.5 [0.14]	161 [6.34]	0.32	0.022	0.056
3	2.8 [0.11]	161 [6.34]	0.25	0.017	0.056
4	2.8 [0.11]	280 [11.0]	0.25	0.010	0.10
5	2.8 [0.11]	359 [14.1]	0.25	0.008	0.125

The API 1104 Appendix A methodology does not appear for Example 2 because defects longer than 4t are not allowed when $a/t \geq 0.25$; the BS 4515 Appendix H methodology predictions only appear for Examples 2 and 3, since the methodology is not intended for defects deeper than 3.5 mm (0.14 in.) or longer than 14.5t; and the CSA 2184 Appendix K methodology does not appear for Example 5 because defects are restricted to $\ell/\pi D \leq 0.10$. In the application of PD 6493, a criterion is needed for net section yielding or collapse of a pipe containing a circumferential through crack in order to check for recategorization. The criterion $\sigma_f = M_c\sigma$ was used for this purpose [22,23] where

$$M_c = [\,1 + 0.26(\ell/\pi D) + 47(\ell/\pi D)^2 - 59(\ell/\pi D)3]^{1/2}$$

and σ_f = 552 MPa (80 ksi). This value of σ_f was also used in other calculations requiring a flow stress.

Each of these girth weld defect assessment criteria requires that the girth weld toughness be measured (using the BS 5762 methodology) prior to the construction of the pipeline. They further set tighter controls on welding procedure for the purpose of assuring that the girth welds in the line will have toughness levels as represented by the prior

CTOD measurements. The primary reason that the proposed standards require the measuring of toughness and controlling of welding procedures is so that fracture mechanics-based assessments of allowable defect sizes can be performed on these girth welds. A second important advantage of the toughness measurement and weld control requirements is that they result in high and controlled toughness girth welds in the pipeline. The actual level of toughness required is different for each of the standards.

Figures 3.6 through 3.10 illustrate some important differences between the defect assessment methodologies. The API 1104 Appendix A and BS 4515 Appendix H methodologies require a significant minimum toughness even for very small applied strains. The NBS and PD 6493 methodologies include residual stress or strain, thereby also setting minimum toughness levels. In contrast, the CSA 2184 Appendix K technically requires very low toughness for small applied strains. In practice, there is likely to be a minimum placed on Charpy toughness which would effectively result in a minimum CTOD toughness.

Another important difference evident from the figures is the range of strain over which the defects are allowable. PD 6493 and the NBS methodology allow strains only slightly greater than the yield strain. API 1104 Appendix A does not use a net section yield or plastic collapse criterion to limit allowable defect size whereas the other methodologies do.

Figures 3.6 through 3.10 show that the results obtained from PD 6493 depend mainly on defect depth with little dependence on defect length. This lack of sensitivity of results on defect aspect ratio will be discussed further in Chapter 5.

An alternative means of comparing the proposed defect tolerance criteria is shown in Figure 3.11. In this figure the material toughness (6 • 0.13 mm) and applied stress levels ($\sigma/\sigma_o = 0.90$) are assumed to be known and the allowable defect dimensions are determined by the proposed defect tolerance criteria. Curves of this type would be

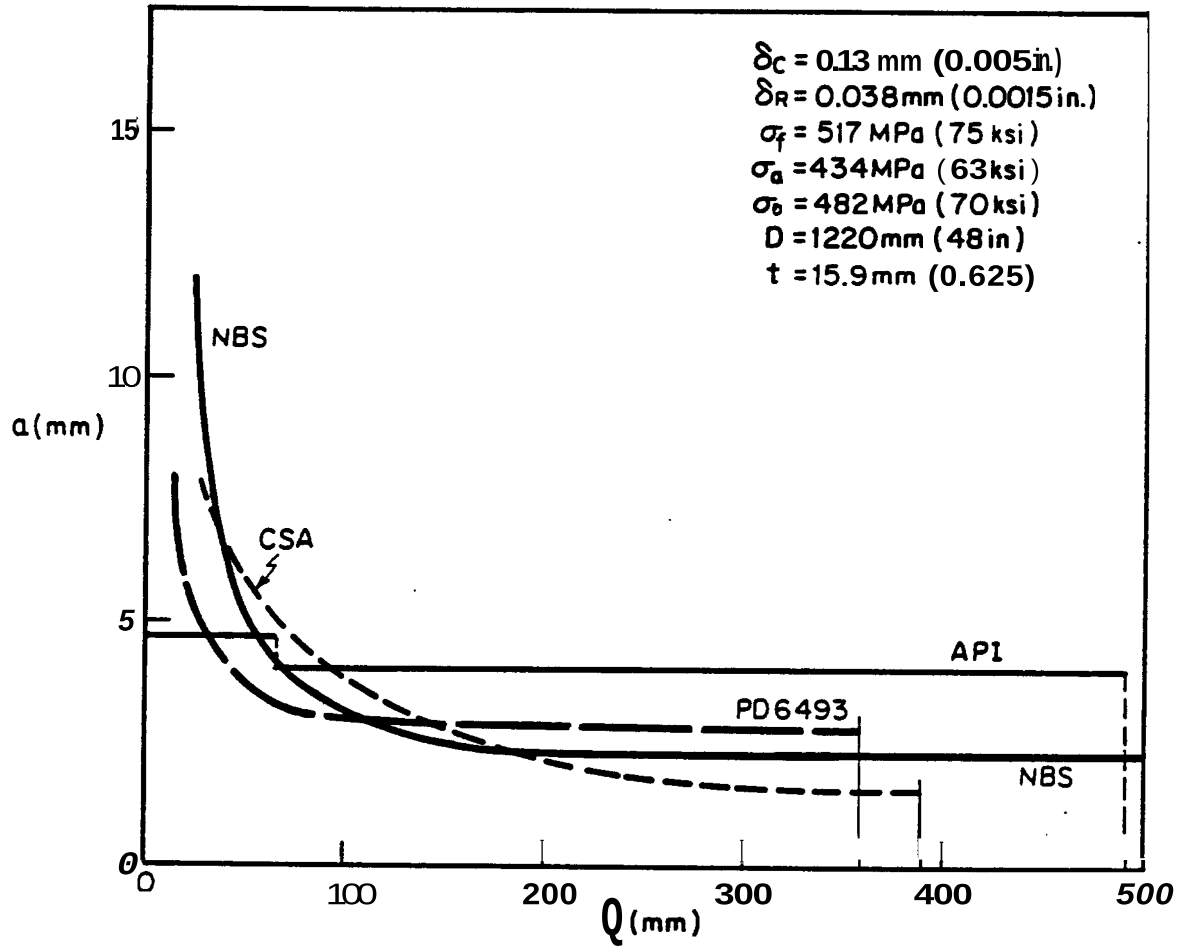


Figure 3.11 Comparison of Allowable Defect Dimensions from the Different Defect Assessment Methods

produced at the time of the pipeline design and used during construction to assess defects which are found. Those defects which are within the allowable range, below the curves, would not need to be repaired while the disallowed defects would require repair. Figure 3.11 shows the range of allowable defects as calculated by the PD 6493, API 1104 Appendix A, CSA 2184 Appendix K, and NBS methods for applied stress equal to 90 percent of yield stress. Note that for this example BS 4515 Appendix H requires a toughness of at least 0.22 mm (0.009 in.) and restricts the defect length to 310 mm. For the CSA 2184 Appendix K, the plastic collapse limitation on flaw size was found to be more severe than that based on the COD Design Curve. The resulting curve reflects this. For this example the API 1104 Appendix A allows deeper defects in the long flaw range than either the PD 6493, the CSA 2184 or the NBS procedure. It is not meaningful to produce a similar graph at higher applied stress or strain levels above yield, because only the API 1104 Appendix A criterion allows defects in that loading regime.

4. TEST DATA FOR FRACTURE OF PIPELINE GIRTH WELDS

Test data were collected on fracture of pipeline girth welds for the purpose of evaluating the different defect assessment procedures described in the previous section. The data considered were from full-scale tests with natural surface or buried defects located in a girth weld and subjected to bending loads. In reviewing the test results described below we recorded, when available, information on pipe geometry, pipe material, including mechanical properties, weld properties, defect geometry, loads, including the accuracy with which they were measured, and general observations made on the pipe fracture process. Some of the data discussed here are not used in our comparison of the different fracture methodologies; they are reported for completeness.

Most of the data reviewed did not include all of the information sought. The primary items required for the assessment of the evaluation procedures are: σ_o, σ_u, the applied strain or stress near the defect at fracture, the material toughness and the defect size. All of the other information is either used to calculate this data or to verify the accuracy of the results. A summary of the data collected is given in Table 4.1.

In 1978, Wilkowski and Eiber [17] published a review of fracture mechanics approaches and experimental data on girth weld defects. They were unable to locate any data on surface or buried defects located in the girth weld of a pipe. However, they were able to report data for circumferential surface defects in the base metal of pipes loaded by internal pressure. This is a biaxial loading situation in which the axial stress is one-half the hoop stress and for which the circumferential crack size must be relatively large before fracture occurs. For example, Eiber et al. [24] tested 610 mm (24 in.) diameter, 17.8 mm (0.7 in.) thick pipes made of A106 Grade B steel loaded by internal pressure. Minimum yield and tensile strengths for this material are σ_o = 241 MPa (35 ksi) and σ_u = 414 MPa (60 ksi). The depth of each defect was 70 percent of the thickness and the length

Table 4.1 Summary of Test Data

Investigator	Material	D(mm)	t(mm)	a/t	$\ell/\pi D$	Loading	No. of Tests
Eiber, et al.	A106	610	17.8	0.70	0.25-0.88	Pressure	5
Glover, et al.	Grade 483	914	10.3	0.17-0.20	0.10	Bending	2*
		914	11.1	0.28-0.91	0.02-0.12	Bending	17
		914	11.7	0.19-0.32	0.04-0.10	Bending	3
		1067	15.0	0.06-0.53	0.004-0.02	Bending	3
Wilkowski & Eiber	X60	762	15.9	0.16-0.78	0.04-0.25	Bending	6
Hopkins, et al.	X60	914	12.7	0.16	0.11	Bending & Pressure	1
Erdogan	X60	508	8.7	0.54-0.77	0.027-0.033	Bending	4

* Buried Defects

varied from 90°-315° of the circumference. The failure (fracture) pressures are shown in Figure 4.1 as a function of flaw length. The tests showed that very long and deep circumferential defects are required to substantially reduce the burst pressure from that of the unflawed pipe. The rise in the curve for large values of $\ell/\pi D$ is attributed [24] to a decrease in the induced bending moment caused by an asymmetrically cracked pipe section.

Since the publication of Wilkowski and Eiber's review paper, additional tests have been performed on pipes containing circumferential cracks or notches. These tests have been done for either the pipeline or nuclear industry.

Wilkowski and Eiber [22] performed room temperature bending tests on pipes to determine fracture conditions in the presence of circumferential weld repair grooves made during the construction of offshore pipeline. Several tests were performed on 4 to 6 inch diameter pipes; only a few full-scale tests were performed. The full-scale pipes had a diameter of 762 mm (30 in.) and a thickness of 15.9 mm (0.625 in.). They were made of X60 steel with σ_o = 410 MPa (59.5) ksi and σ_u = 557 MPa (80.8 ksi). A cellulosic (Ce190) electrode used to make the welds resulted in weld properties: σ_o = 573 MPa (83.1 ksi) and σ_u = 659 MPa (95.5 ksi). No toughness values were given. Three fill-scale tests were performed, each with a different groove geometry which was ground into the weld; the sharpness of the grooves was not specified, but the tip radii were probably on the order of 2.5 - 5 mm (0.1-0.2 in.). Table 4.3 lists the groove geometry as well as other data pertinent to the tests. The pipes were loaded in four-point bending through saddles with moment arms equal to 9 ft and a uniform moment section of 8 ft. Measurements made during the tests included load, crack mouth opening displacement (CMOD), and the strain at the outer' fibers of the pipe, halfway between the weld and the support. No internal pressure was applied. Failure occurred by ductile tearing in all three tests. The fact that the strain for the first test does not increase between crack growth initiation and maximum load, even though

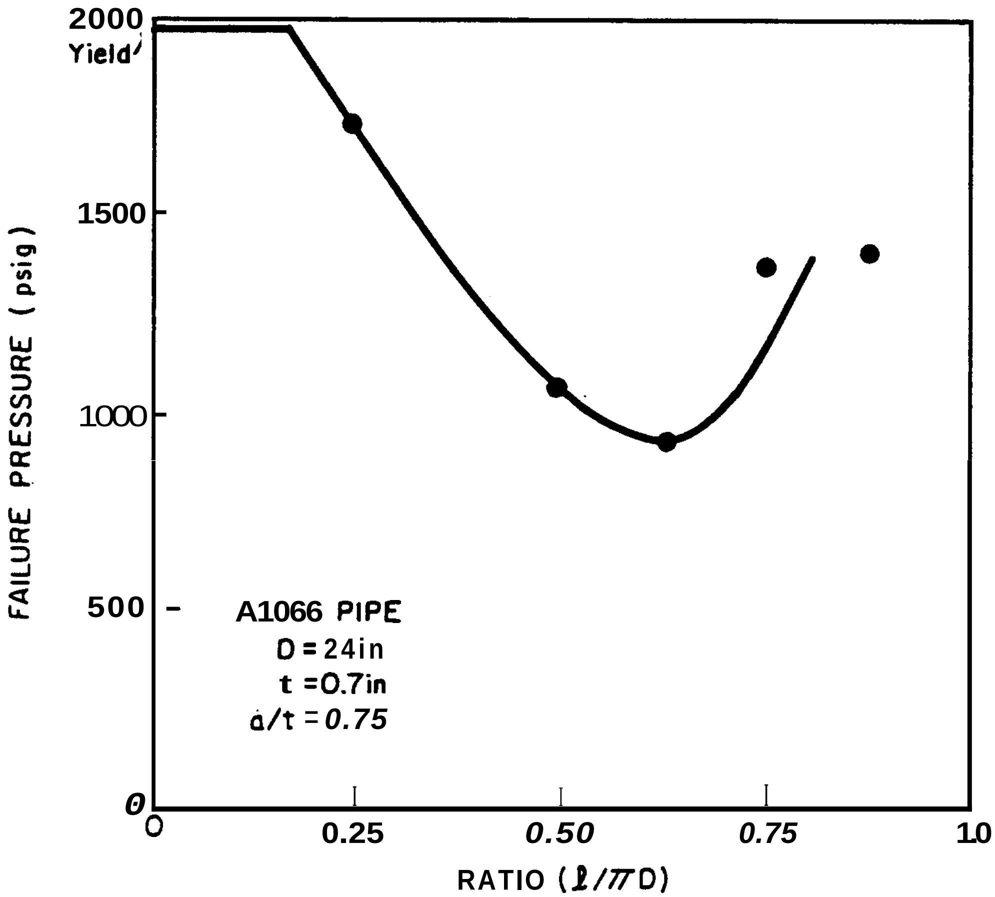


Figure *4.1* Fracture Data for Pipe Loaded by Internal Pressure Containing Circumferential Defects [24]

Table 4.2 Full-scale Bending Tests on Circumferentially Grooved Pipes (Wilkowski and Eiber [22]): D = 762 mm (30 in.), t = 15.9 mm (0.625 in.)

			Initiation			At Maximum Load		
Test	ℓ (mm)	a (mm)	Load (MN)	CMOD (mm)	Strain (%)	Load (MN)	CMOD (mm)	Strain (%)
1	239	12.4	1.73	2.29	0.19	2.18	9.9	0.19
2	239	7.9	2.59	2.29	0.28	2.59	2.29	0.28
3	119	7.9	2.86	2.54	0.31	2.91	7.6	?

the load does, suggests that the nominal loading may not be properly represented by the measured strain.

Wilkowski and Eiber [13] performed three additional full-scale pipe bending tests in an effort to evaluate the proposed API 1104 Appendix A standard. The X60 pipes had a diameter of 762 mm (30 in.) and a thickness of 15.9 mm (0.625 in.). Welds were made with Ce190 electrodes and tests were conducted at -140°F. The tensile properties were: weld metal (-140°F) $\sigma_o = 487$ MPa (70.6 ksi) and $\sigma_u = 637$ MPa (92.4 ksi); (70°F) $\sigma_o = 407$ MPa (59 ksi) and $\sigma_u = 552$ MPa (80 ksi). The critical CTOD values, which were true δ_c values, ranged from 0.051 to 0.14 mm (0.002 to 0.0056 in.). The defects were made by a lack-of-penetration welding procedure that resulted in a sharp crack. Strains were measured 0.61 m (2 ft) on each side of the weld in the 2.4 m (8 ft) gage section of the four-point bend test. The dimensions of the defects and the fracture strains are listed in Table 4.3; failure occurred by cleavage fracture for the first two tests and by buckling for the third test.

Table 4.3 Full-scale Girth Weld Test Data on 762 mm (30 in.) Diameter, 15.9 mm (0.625 in.) Thick X60 Pipes [13]

Test	Defect Size ℓ(mm) x a(mm)	Strain to Fracture percent	Nom. Stress to Fracture (MPa)
1(1)	88.9 x 6.35	0.235	386
2(1)	599 x 3.18	0.173	311
3(2)	88.9 x 2.54	>0.64	-

(1) Failure by cleavage
(2) Failure.by buckling

In 1980 a full-scale testing facility was completed at the University of Waterloo, Canada for the bend testing of large diameter pipe. This has been one of the best sources of data for fracture of circumferential surface defects in pipeline girth welds. The bending loads are applied to the pipe by several hydraulic jacks distributed along the length of the pipe, except near the section that contains the girth weld; this results in a constant bending moment over the cracked section. The results of the tests performed to date have been reported in a number of publications. [25,26,27] The tests have, with few exceptions, been performed on 914 mm (36 in.) diameter, 11.1 mm (0.44 in.) thick pipes made of Grade 483 pipeline steel, a steel with minimum yield strength, σ_o = 483 MPa (70 ksi). Girth welds were produced by shielded metal arc welding (SMAW) with cellulose electrodes which apparently resulted in σ_o = 523 MPa (76 ksi) and σ_o = 628 MPa (91 ksi). Two pipe specimens were made with a gas metal arc welding (GMAW) procedure with σ_o = 689 MPa (100 ksi) and σ_o = 750 MPa (109 ksi). The critical CTOD at the test temperatures ranged from 0.024 to 0.047 mm (0.0009 to 0.0018 in. at -85°C, from 0.089 to 0.16 mm (0.0035 to 0.0063 in.) at -45°C and from 0.10 to 0.18 mm (0.0039 to 0.007 in.) at -5°C, all values for the SMAW. The GMAW girth welded pipes were only tested at -5°C, for which the minimum toughness was also δ = 0.10 mm (0.0039 in.). All of the toughness values at -5°C were apparently maximum load toughnesses as defined by BS 5762.

Three different types of defects were studied: fatigue cracks, laboratory-produced hydrogen cracks and natural cracks which included lack of fusion and hydrogen cracks. All but the natural defects were surface cracks. The defect sizes, which correspond to maximum values, were measured destructively after completion of each test. Several strain gages were applied to each pipe specimen, but the location of the gages from which the readings were taken is not known. A potential drop method was used to establish the initiation of crack growth, values of strain at initiation were reported for some of the tests. The pipe specimens were loaded until failure occurred by fracture or buckling. Most of the specimens failed by ductile tearing. The results of these tests are given in Table 4.4.

Table 4.4 Summary of Full-scale Girth Weld Tests by University of Waterloo and Welding Institute of Canada; 914 mm Diameter, Grade 483 (X70) Line Pipe [25,26,27]

Test	Flaw Type	Temp. (°C)	R x a (mm x mm)	t (mm)	Failure Strain (%)	Initiation Strain (%)	Failure Mode
6		-85	68.6 x 7.8		0.330		C
7		-85	61.0 x 5.3		0.308		C
8		-85	76.4 x 10.1		0.135		C
9	F	-45	81.8 x 8.8	11.1	0.48		DT
10		-85	59.3 x 6.4		0.234		C
11	F	-45	78.9 x 9.3	11.1	0.49		DT
12		-45	63.5 x 6.3		0.500		B
13		-45	62.2 x 6.1		0.357		C
14	F	-5	64.8 x 5.5	11.1	>0.51	0.29	DT
15	F	-5	60.3 x 5.5	11.1	0.47	0.29	DT
16	N,E	-5	300 x 4.1	10.28	>0.78		B
17	N,E	-5	300 x 3.6	10.28	>0.71		B
18	F	-5	265 x 3.3	11.1	0.30	0.24	DT
19	F	-5	278 x 3.2	11.1	0.37	0.24	DT
A1	LC	-5	279 x 3.93	11.1	0.20	0.12	DT
A2	LC	-5	331 x 3.70	11.1	0.20	0.12	DT
A3	LC	-5	75 x 3.50	11.1	0.49	0.20	DT
A4	LC**	-5	315 x 3.7	11.1	0.27	0.195	DT
A5	LC***	-5	282 x 3.1	11.1	0.32	0.134	DT
A6	LC	-5	280 x 2.9	11.72	0.35	0.146	DT
A7	LC	-5	134 x 3.7	11.72	0.31	0.100	DT
A8	LC	-5	116 x 2.2	11.72	0.65	0.24	DT+B
I1*	N	-5	14 x 0.9	15	>0.7		S
I2*	N	-5	38 x 3.0	15	>0.8	0.29	DT+S
I3*	N	-5	70 x 8.0	15	0.62	0.28	DT+B

F = Fatigue Crack
N = Natural Defect from Pipeline
E = Embedded Flaw
LC = Laboratory Crack
DT = Ductile Tearing
S = Test Stopped
B = Buckle
C = Cleavage

* = D=1067 mm (42 in.)
** = Stress relieved
*** = Additional weld adjacent to crack

Hopkins, Jones and Fearnehough [28] report a single full-scale test performed on an X60 pipe with D = 914 mm (36 in.), t = 12.7 mm (0.5 in.) loaded by internal pressure and cyclic bending. The pipe contained a machined semielliptical defect in the girth weld with dimensions, a = 2.0 mm (0.08 in.), ℓ = 305 mm (12 in.). The pipe was pressurized internally to (6.9 MPa (1000 psi)) and subjected to cyclic bending that resulted in an outer fiber stress range of 345 MPa (50 ksi). Evidently, the fixturing was such that the internal pressure did not result in an axial stress because the defect ligament is said to be at the specified minimum yield strength (SMYS) at a bending stress of 50 ksi, and the calculation of ligament stress due only to the bending stress, 50/(1 - 0.16) = 60 ksi (SMYS), is indeed equal to the SMYS. The pipe failed after 1482 cycles at which time the crack had penetrated 89 percent through the pipe wall. The mode of failure is not specified and a lower bound, "pessimistic" CTOD toughness of 0.15 mm (0.006 in.) is reported.

Erdogan [29] performed six large-scale bending tests at room temperature on X60 pipes with D = 508 mm (20 in.) and t = 8.7 mm (0.344 in.). Tensile properties for the base metal were σ_o = 469 MPa (68 ksi) and σ_u = 572 MPa (83 ksi); the pipes did not contain welds. Four of the pipes contained part-through defects which were grown by fatigue; the other two contained through cracks. The dimensions of the defects and the experimentally determined fracture loads for the pipes with part-through defects are given in Table 4.5; P_N corresponds to crack initiation, P_R corresponds to propagation to the back face and P_{max} is the maximum load. The load, P, is equal to one-half of the total applied bending load and the moment arm is equal to 2.2 m (87 in.). Tests were performed under displacement control. Strains and crack mouth opening displacements were measured but only the former are reported. The material toughness is only given in terms of Charpy energy versus temperature.

Table 4.5 Large-Scale Bending Tests on X60 Pipes; D-508 mm (20 in.), t-8.7 mm (0.344 in.) [29] Moment-PxL, L-2.2m (87 in.).

Pipe	a/t	ℓ (mm)	P_N(kN)	P_R(kN)	P_{max}(kN)	e_f(%)
2[(1)]	0.545	42.9	-	-	471	0.270
4	0.727	52.3	387	440	467	0.252
5	0.773	52.3	382	444	473	0.254
6	0.680	50.0	391	449	484	0.257

(1) Pipe failed by inelastic buckling.

The nuclear industry has sponsored experimental projects in which bending tests were performed on pipes containing circumferential part-through notches. [30, 31] The objective of these investigations was to establish if tearing instability and complete rupture of the pipe can occur from a stress corrosion crack. The pipe material studied was 304 stainless steel. This material is very ductile and failure is generally found to be governed by plastic collapse criteria. Most of the data cannot be used to evaluate fracture methodology for gas transmission pipes which are subject to fracture below plastic collapse loads. However, the data could be used to study plastic collapse criteria.

In one project performed for the nuclear industry by Battelle Columbus Laboratories [30], fracture occurred below the theoretical collapse load for a 406 mm (16 in.) diameter, 304SS pipe containing an internal part-through crack. The pipe was tested in four-point bending and the machined defect extended around 50 percent of the circumference and 66 percent through the 26.2 mm (1.03 in.) thickness. The bending moment at crack growth initiation was 9.0×10^5 N-m (8.0×10^6 in-lb) and the maximum bending moment was 1.2×10^6 N-m (10.4×10^6 in-lb). These bending moments are equivalent to nominal outer fiber stresses approximately equal to 310 MPa (45 ksi) and 400 MPa (58 ksi), respectively. The flow stress of the material was about 455 MPa (66 ksi) and the value of J_I at initiation in three-point bend tests was 1050 kJ/m^2 (6000 in-lb/in^2).

Failure analysis reports were also reviewed as part of our search on fracture data for gas transmission pipes containing girth weld defects. [32,33,34] These reports do not include enough data to evaluate the various fitness-for-purpose methodologies. Girth weld fractures are usually attributable to substandard welds and the occurrence of some unusual loading, such as severe soil movement (sagging) [32] or the movement of a heavy vehicle over a nearby bump. [34]