HSE
Health & Safety
Executive

OFFSHORE TECHNOLOGY REPORT - OTO 99 003

Review of Current Practice in Pipeline Defect Assessment - Annex to OTO 99 002

Date of Issue : February 1999

Health & Safety Executive

Review of Current Practice in Pipeline Defect Assessment - Annex to OTO 99 002

Prepared by
Billington Osborne
Moss Engineering Limited
Ledger House
Forest Green Road, Fifield
Maidenhead, Berkshire
SL6 2NR

BOMEL ENGINEERING CONSULTANTS

HEALTH AND SAFETY EXECUTIVE

CONTRACT No MaTSU/8632/1/3175

REVIEW OF CURRENT PRACTICE IN PIPELINE DEFECT ASSESSMENT

ANNEX TO C5980R04.05

CONTENTS

EXECUTIVE SUMMARY

A review of references on pipeline defect assessment, published in the period 1993-1994, has identified new developments which address some of the issues identified in the comprehensive review report (BOMEL, 1993).

The new developments include:

- Additional validation of the PD 6493 : 1991 procedures for assessment of girth weld defects.
- Detailed information on the comprehensive EPRG guidelines for assessment of girth weld defects.
- New experimental and numerical data on the failure characteristics of corrosion defects, and improved guidance on behaviour of closely spaced pits and effects of combined pressure and axial loading.
- Data on stress concentration, due to plain dents in pipelines subjected to cyclic internal pressure, for use in fatigue assessments.

While these new developments provide better conditions for assessment of pipeline defects, they do not change the overall conclusions and recommendations detailed in the comprehensive review report and reiterated in Section 6 of this report.

1. INTRODUCTION

In fulfilment of the requirements of contract MaTSU/8438/3/2930, BOMEL has produced a comprehensive review report (Reference C5980R04.05, Rev A October 1993) on defect assessment methods for pipelines; this relates both to onshore and offshore pipelines. This report is thorough and has been well received by the HSE, MaTSU and members of the pipeline inspectorate.

The report indicated that different methods are available for assessing different categories of defect; some are based on general methodologies whilst others are pipeline specific. The difficulty for those performing or reviewing assessments is to determine whether a method is applicable to specific circumstances and what assumptions or conservatisms are inherent within it, and what is the basis of its validation.

Discussion of the comprehensive review report between BOMEL, HSE and MaTSU resulted in two key points emerging:

- Significant added value could be derived from the work contained within the report if it would be cross-referenced in such a way that:

  (a) pipeline inspectors could provide a rapid response to problems by ensuring that appropriate defect assessment techniques are selected, thus contributing to the continued safe operation of pipelines;

  (b) a rational and consistent base could be provided against which inspectors can assess Safety Case submissions by directing them to the appropriate background information.

- Since the date of completion of the comprehensive review report a number of publications have appeared that may contribute to the state of the art capability in pipeline defect assessment.

In response to this BOMEL produced a proposal (Reference C5980P02.05, Rev A October 1993) for additional work, in which two objectives were set:

1. To prepare a concise User's Guide, summarising the available methods for defect assessment in pipelines which were detailed in the comprehensive review report as cited above.

2. To prepare an annex to the comprehensive review report cited above, detailing the contribution to defect assessment methodology made by key references published since October 1993.

This document represents a final report on the work performed to fulfil the requirements of Objective 2, above.

The scope of work covered by this document is as listed below:

1. Obtain references published since January 1994 and review in detail publications which make a significant contribution to current pipeline defect assessment capabilities.

2. Prepare an Annex to the comprehensive review report.

Although a relatively large number of recently published papers have addressed some issues relevant to pipeline defect assessment (see Section 5 and Appendix A to Warrant Number 1/3175 under Agreement Number MaTSU/8632), only a few of these offer guidance that can be readily used in practice, or provide new significant data. The present report is restricted to reviewing papers that satisfy the latter criteria including detailed reviews in Sections 2 to 4 and short reviews in Section 5. Section 6 reiterates the overall conclusions and recommendations detailed in the comprehensive review report.

2. ASSESSMENT OF GIRTH WELD DEFECTS

2.1 Leggatt and Challenger (1993) - Assessment of Girth Weld Defects using PD 6493 : 1991

The safety and accuracy of some fracture mechanics based fitness-for-purpose analysis methods, with regard to predicting the failure of defective pipelines, was examined in Section 7.6 in the comprehensive review report (BOMEL, 1993). Data from published comparative and validation studies on assessment of pipeline defects in general and girth weld defects in particular, were presented and discussed. The analysis methods examined included: PD 6493 : 1980, PD 6493 : 1991, BS 4515 : 1984, API 1104 : 1983 and CSA Z184 : 1986.

This section reports the findings of a recent study concerning the validity of PD 6493 : 1991 for assessment of girth weld defects. The study, undertaken by Leggatt and Challenger of TWI (1993), is essentially similar to the earlier investigations by Coote et al (1986) and Glover et al (1992). All three studies consider the same Canadian database of full scale pipe bend tests for evaluating the fracture assessment procedures of either PD 6493 : 1980, PD 6493 : 1991, or CSA-Z184 (see Section 7.6 in the comprehensive review report).

Leggatt and Challenger reanalysed the pipe test data in conformity with both Levels 1 and 2 of PD 6493 : 1991. The plastic collapse parameter S_r was evaluated using solutions published by Wilkowski and Eiber (1980), Willoughby (1982), Bergman et al (the Swedish assessment procedure), in addition to the flat plate solution of PD 6493 : 1991. The stress intensity factor solutions of Raju and Newman suggested in PD 6493 : 1991 were used to evaluate the fracture parameter K_r. However, since these appear to be developed for thick walled pipe geometries, a further assessment was made using a stress intensity factor solution suggested by Zahoor (1985) for ratios of pipe radius to pipe wall thickness up to 20.

Results of the analyses, using Raju and Newman solutions with the aforementioned approaches for evaluating plastic collapse, are shown in Figures 2.1 and 2.2. Conclusions from the study are summarised by Leggatt and Challenger as follows:

- PD 6493 : 1991 procedures applied to the pipe bending tests are conservative at both Levels 1 and 2 when the Raju and Newman stress intensity solutions and flat plate net section stress equations as given in PD 6493 : 1991 are used.

- The use of the flat plate net section stress solutions appears to be over-conservative in a number of cases. The net section stress solutions suggested by Willoughby and by Wilkowski and Eiber give significantly improved results but remain conservative.

- The collapse solution proposed in the Swedish assessment procedure does not give consistently conservative results at Level 2 without the use of partial safety factors.

- There is a shortage of stress intensity solutions for this specific geometry. Existing solutions appear mainly to be developed for thick walled pipe geometries. The Raju and Newman stress intensity solution, suggested by PD 6493 : 1991, appears to be satisfactory for the cases considered in this study.

- The assumption of yield magnitude membrane tensile residual stresses may give excessively conservative values of the fracture parameter $\sqrt{\delta_r}$ at deep defects.

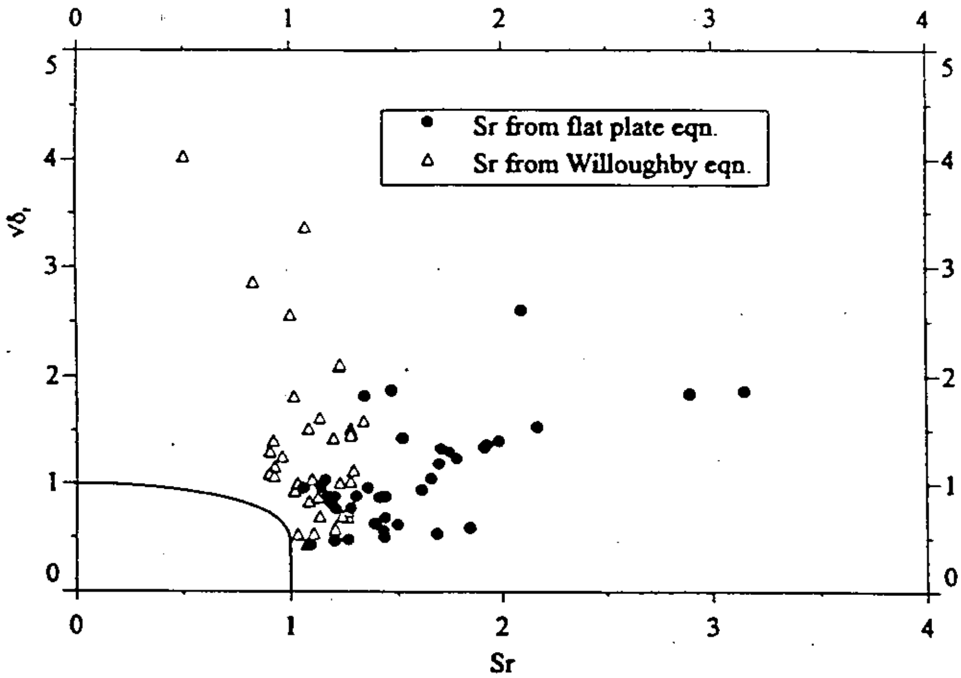

Figure 2.1 Comparison of PD 6493 : 1991 Level 2 failure assessments using solutions for plastic collapse (Leggatt and Challenger, 1993)

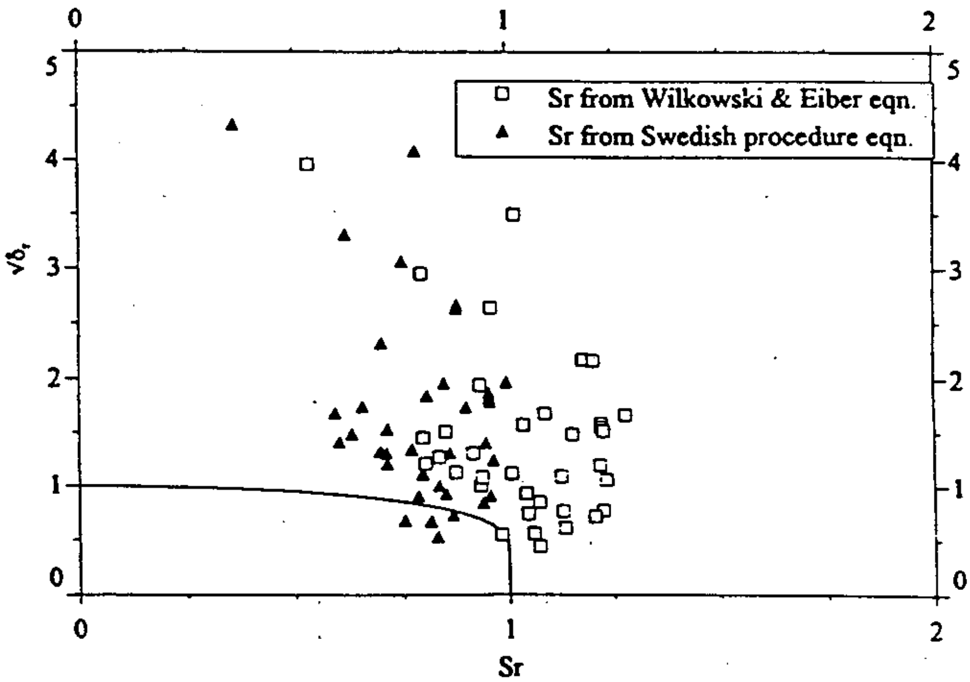

Figure 2.2 Comparison of PD 6493 : 1991 Level 2 failure assessments using solutions for plastic collapse (Leggatt and Challenger, 1993)

2.2 Hopkins and Denys (1993) - EPRG Guidelines

EPRG is a group of European gas companies and pipe manufacturers who have set out to produce new guidelines on assessment of defects in pipeline girth welds. This work was motivated by differences and varying levels in conservatism in the defect acceptance criteria offered by codes such as API 1104, BS 4515 and CSA Z-184. Background work leading to the EPRG guidelines is outlined in the comprehensive review report (C5980R04.05). Hopkins and Denys (1993) describe the new guidelines in detail providing information on their technical derivation and limitations. These are summarised in Tables 2.1 and 2.2 respectively. In addition a simple comparison of acceptance limits for planar defects using the EPRG three tier approach is given in Table 2.3 and Figure 2.3.

The EPRG Girth Weld Defect Guidelines			
	Tier 1	Tier 2	Tier 3
Shape/Profile Defects	BS 4515	BS 4515	BS 4515
Undercut	BS 4515/ API 1104	Wide Plates	Full Scale Tests
Planar Defects	BS 4515/ API 1104	Wide Plates	Full Scale Tests
Non-Planar Defects	BS 4515	BS 4515/ PD 6493	PD 6493 and Full Scale Tests
Interaction Criteria	BS 4515	BS 4515/ PD 6493	PD 6493 and Full Scale Tests
Accumulation Criteria	BS 4515	BS 4515/ PD 6493	PD 6493 and Full Scale Tests
Toughness Requirement (mean/min)	Charpy: 40/30J	Charpy: 40/30J	Charpy: 40/30J Plus CTOD: 0.15/0.10mm

Table 2.1 Summary of the technical basis for the EPRG guidelines (Hopkins and Denys, 1993)

1. 7mm ≤ t ≤ 25.4mm where t is the pipe wall thickness.
2. Average and minimum values for the Charpy V energy of the weld, at the minimum design temperature, are 40J and 30J, respectively.
3. 0.5% yield strength of the weld ≥ 0.5% yield strength of the pipe material.
4. Non-planar defects should not be surface breaking. Surface breaking non-planar defects should be treated as planar defects.
5. Pipelines subjected to onerous fatigue duty, or severe environmental effects may require higher levels of acceptance.
6. Defect depth ≤ 3mm.
7. Actual yield to actual ultimate tensile strength of the pipe material ≤ 0.85.
8. Applied axial stress ≤ 0.5% pipe yield strength.
9. Pipes on either sides of the girth weld are of equal grade, thickness and are subjected to 100% NDT.
10. Minimum yield strength of the pipe material ≤ 483 N/mm^2.
11. Average and minimum values for the CTOD toughness of the weld, at the minimum design temperature, are 0.15mm and 0.1mm, respectively.

- Requirements 1 to 5 apply to Tier 1
- Requirements 1 to 10 apply to Tier 2
- Requirements 1 to 11 apply to Tier 3
- Additional notes regarding some of the above requirements are given in the source reference.

Table 2.2 Conditions for application of the EPRG Guidelines, Hopkins and Denys (1993)

	Individual length	Total length
Tier 1 Workmanship (for lack of fusion defects)	50mm	50mm in 300mm, or 15% (lesser)
Tier 2 Fitness-for-purpose	7*t	7*t in 300mm
Tier 3 Fitness-for-purpose	See Figure below	See Figure below

Table 2.3 Examples of defects limits for planar defects (EPRG)

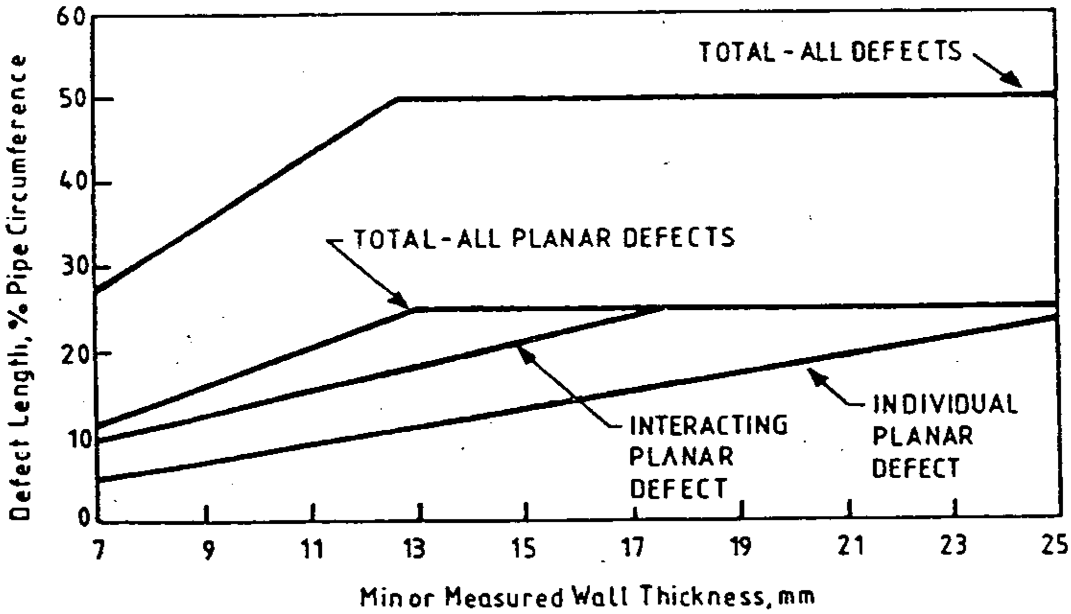

Figure 2.3 Tier 3 Girth weld defect limits

3. ASSESSMENT OF CORROSION DEFECTS

3.1 Chouchaoui and Pick (1993, 1994) - Assessment of Corrosion

Chouchaoui and Pick (1994) propose a three level corrosion assessment procedure intended to provide a framework into which the results of various investigations can be accommodated. The procedure allows increasingly accurate assessment levels for increased knowledge of the corrosion geometry, pipe properties and loading conditions. Level 1, providing the simplest evaluation model, adopts the basic B31G approach and allows three options for the assessment. These incorporate new models designed to reduce the conservatism of the basic B31G procedure. Level 2 is intended to be more accurate and comprehensive than Level 1 but still providing simple assessment procedures. Level 3, intended to provide the most accurate evaluation, requires detailed knowledge of the relevant geometry, material and loading parameters. For this assessment, a three-dimensional, large displacement elastic-plastic finite element analysis is recommended. Guidance on conducting such an analysis is given based on the authors' experience (Chouchaoui and Pick, 1993).

Level 2 is reported to be at an early stage of development and requiring further work before it can be defined clearly. However, the following possible assessment models are discussed:

- Wang (1993): Uses limit load analysis to provide bounds to the burst pressure of corroded pipe.
- Kanninen (1993) and Popelar (1993): Classical shell theory is used to determine the local bending stresses in the region of reduced sections of the pipe wall, simulating corrosion.
- Stephens and Bubenik (1993): Use a modified shell finite element analysis. Results are presented for rectangular regions of uniformly reduced wall thickness.
- Chouchaoui (1993): Proposes using a compensation technique within an elastic finite element analysis to simulate local plasticity and strain hardening in the ligament of corrosion pits.

Within Level 1, three options for the assessment are available. Options 1 and 2 consist of using the basic B31G model, and the associated effective area technique incorporated in the PC based RSTRENG program (Kiefner and Vieth, 1989), respectively. Thus, Option 2 may provide more accurate and less conservative assessments than Option 1. However, in both Options the corrosion geometry is projected onto a longitudinal plane acted upon only by the circumferential stress. This does not allow considerations of the circumferential spacing of corrosion or of longitudinal stresses. In order to improve the assessment for these and other cases further adjustments to the Option 2 RSTRENG technique are proposed within an Option 3, Level 1 assessment.

The recommendations proposed for Option 3 are drawn from a series of burst tests on pipe sections with both service and simulated corrosion and a complementary series of finite element analyses.. The results of these investigations, reported to be in agreement with other published work including studies at Battelle and British Gas are outlined below:

- Circumferential lines of corrosion pits fail at pressure levels within the expected scatter of a single isolated pit and longitudinal lines of pits interact to reduce the burst pressure only when the pits touch. Thus, it is recommended that corroded areas separated by full thickness pipe be treated as independent areas.

- Under normal operating conditions, the circumferential extent of corrosion does not appear to influence the failure process. In agreement with the B31G criterion, it is recommended that corrosion be assessed, considering the depth and longitudinal dimension of the corrosion, through projection of the corroded area into the longitudinal plane.

- Defects longer than 75% of the pipe diameter should be assessed as a defect of that length.

- Shallow corroded areas do not reduce the pipe burst strength if the corrosion is smooth bottomed. It is recommended that corrosion with a depth less than 20% of the wall thickness not be assessed.

- It is recommended that external and internal corrosion be evaluated similarly.

- For the various pipe materials studied by the authors, a flow stress of the actual yield plus 68.95 MPa in an elastic-perfectly plastic material model allowed accurate prediction of the burst pressure. Finite element analysis indicated that such a flow stress remains valid for predictions with higher strength steels. For situations where the actual yield stress is not known, a flow stress of the SMYS plus 68.95 MPa is a conservative representation of material hardening.

- It is recommended that under normal operating conditions, longitudinal stress not be considered in the assessment procedure.

- If corrosion occurs in regions of compressive stress, such as would occur in pipe bending caused by lack of support, a lower burst pressure than predicted by B31G should be considered.

- In cases of high longitudinal stress such as in pipe bending, the circumferential extent of corrosion should be considered.

It is finally noted that Option 3 remains incomplete as various corrosion features have not been addressed and will require further investigation. For example, burst tests of deep pits within larger shallower pits indicate that treatment of such a configuration as a pit in a pipe of reduced wall thickness is overly conservative. In addition the assessment of corrosion at specific features such as welds, bends and dents also requires study.

4. ASSESSMENT OF MECHANICAL DAMAGE DEFECTS

4.1 Fowler (1993) - Fatigue Assessment of Dented Pipelines

Fowler (1993) presents a procedure for assessing the fatigue strength of dented pipelines subjected to cyclic internal pressure loading. The dents considered are restricted to plain dents (without gouges) in the pipe parent metal. The fatigue assessment procedure is based on experimental and analytical (FE based) studies involving pipe sections with diameter to thickness ratios in the range 18 to 50 and dent to diameter ratios up to 11%.

While a survey conducted as a part of the investigations revealed three main types of pipeline plain dents (Figure 4.1), only Type III was considered in the experimental programme. Fowler justifies this choice on the basis that the analytical work indicated that the dent type (I, II or III) and length were not important. In contrast the dent depth and pipe diameter to thickness ratio were of primary importance to the fatigue strength. In addition, the analytical work indicated that stresses for some combinations of thin pipes and deep dents exceed yield, which implies that the ratio of hoop stress range to pressure range ($\Delta\sigma/\Delta p$) may be significantly overestimated if based on elastic analyses. As a result, non linear elastic plastic finite element analyses were undertaken to determine more accurate ($\Delta\sigma/\Delta p$) data and to examine analytically the phenomenon of dent removal due to pressure application. These studies involved determining ($\Delta\sigma/\Delta p$) from small perturbations of pressure about three values of mean internal pressure: 500, 1000 and 1500 psi. The results are given in Tables 4.1 to 4.3 in terms of pipe diameter to thickness ratio and dent depth to diameter ratio. These allow the ($\Delta\sigma/\Delta p$) ratio to be determined and used in S-N type fatigue analyses in conjunction with Miner's rule. Fowler analysed his experimental fatigue results using this approach with the API X' and the Department of Energy B S-N curves, and concluded that while the API S-N curve was excessively conservative, less conservative lower bound predictions to the test data can be obtained using the Department of Energy B S-N curve. He also concluded that based on possible pressure fluctuation data received from a number of operators, plain smooth dents less than 5% of the diameter for pipe with diameter to thickness of less than 30 were not a problem for normal pipeline service.

Contents

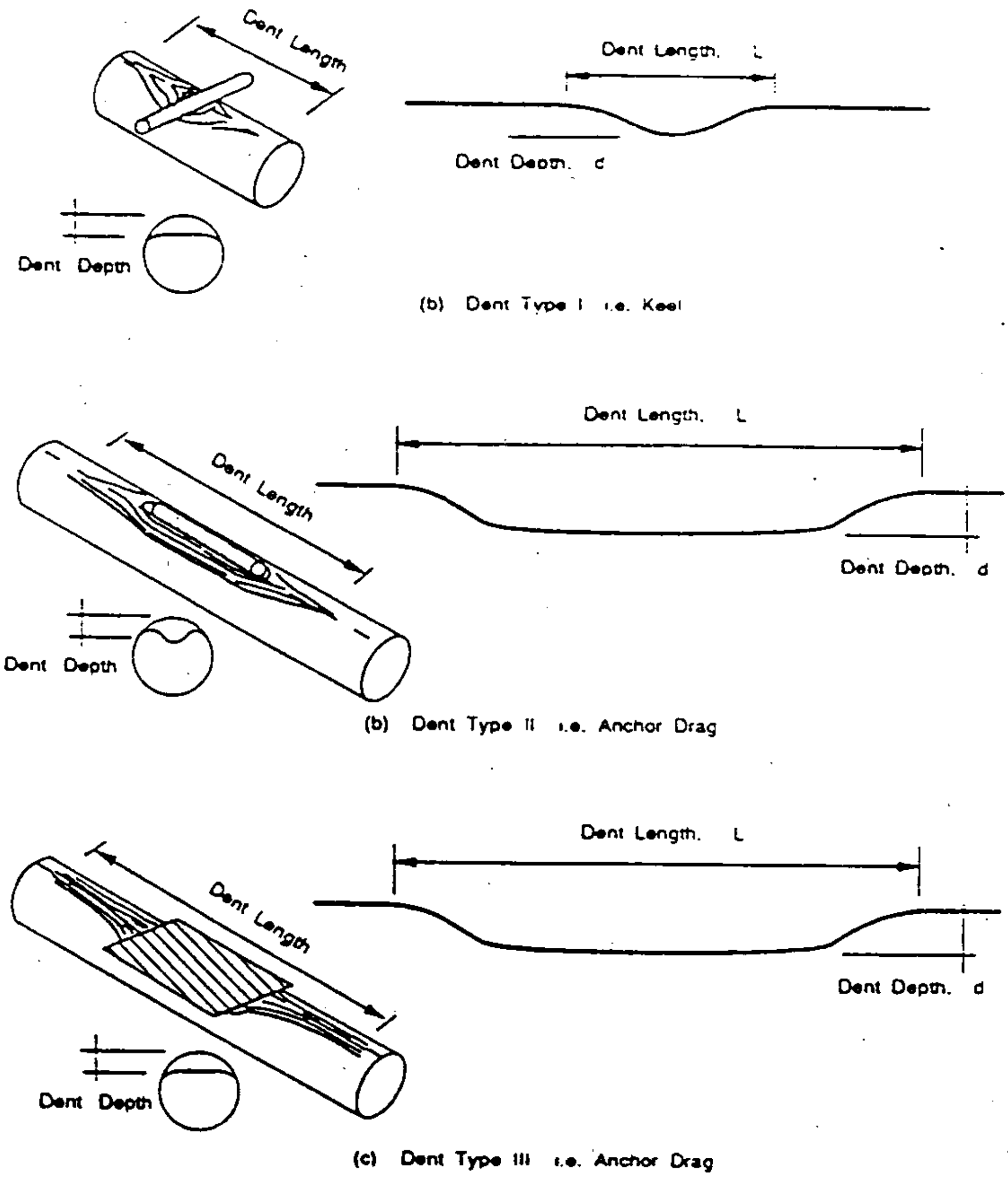

Figure 4.1 Plain dent types (Fowler 1993)

$\frac{\Delta\sigma}{\Delta p}$ for an average operating pressure of 500 psi.

D/t d/D(%)	18	20	25	30	35	40	45	50
1	14.21	13.55	12.53	23.98	35.44	46.90	58.35	69.81
2	20.16	22.09	27.20	37.54	47.88	58.23	68.57	78.91
3	26.10	30.63	41.87	51.10	60.33	69.56	78.78	88.01
4	32.04	39.18	56.55	64.66	72.77	80.88	89.00	97.11
5	37.98	47.72	71.22	78.22	85.21	92.21	99.21	106.2
6	43.93	56.26	85.89	91.77	97.66	103.5	109.4	115.3
7	49.87	64.80	100.6					
8	55.81	73.34	115.2					
9	61.76	81.88	129.9					
10	67.70	90.42	144.6					
11	73.64	98.96	159.3					

$\frac{\Delta\sigma}{\Delta p}$ for an average operating pressure of 1000 psi.

D/t d/D(%)	18	20	25	30	35	40	45	50
1	13.94	13.25	15.00	20.93	29.80	38.68	47.55	56.43
2	19.64	21.18	25.20	32.53	39.87	47.20	54.53	61.87
3	25.35	29.11	38.34	44.14	49.93	55.72	61.51	67.31
4	31.05	37.04	51.49	55.74	59.99	64.24	68.50	72.75
5	36.76	44.97	64.63	67.34	70.05	72.77	75.48	78.19
6	42.46	52.89	77.78	78.95	80.12	81.29	82.46	83.63
7	48.17	60.82	90.92					
8	53.87	68.75	104.1					
9	59.58	76.68	117.2					
10	65.28	84.61	130.4					
11	70.99	92.53	143.5					

$\frac{\Delta\sigma}{\Delta p}$ for an average operating pressure of 1500 psi.

D/t d/D(%)	18	20	25	30	35	40	45	50
1	13.65	13.06	15.00	19.61	27.20	34.79	42.38	49.96
2	19.14	20.39	23.66	39.65	35.63	41.62	47.60	53.58
3	24.63	27.73	35.31	39.69	44.06	48.44	52.82	57.20
4	30.12	35.06	46.95	49.72	52.50	55.27	58.05	60.82
5	35.61	42.39	58.59	59.76	60.93	62.10	63.27	64.44
6	41.11	49.73	70.23	69.79	69.36	68.93	68.50	68.06
7	46.60	57.06	81.87					
8	52.09	64.39	93.51					
9	57.58	71.73	105.1					
10	63.07	79.06	116.8					
11	68.56	86.39	128.4					

Tables 4.1 to 4.3 Results for dent alternating stresses as a function of pipe diameter to thickness ration (D/t) and a final dent depth ratio (d/D) (Fowler 1993)
Top $\Delta\sigma/\Delta p$ for an average operating pressure of 500 psi
Middle $\Delta\sigma/\Delta p$ for an average operating pressure of 1000 psi
Bottom $\Delta\sigma/\Delta p$ for an average operating pressure of 1500 psi

5. SUMMARY OF OTHER RELEVANT REFERENCES

Author(s)	Main topic	Relevant section(s) in comprehensive report	General description of contents
Fowler*	Fatigue of dented pipe	7.4	Describes an S-N based procedure for fatigue assessment of plain dents including stress concentration factors, based on FE analysis, and experimental validation.
Stephens and Bubenik	Corrosion: complex geometry and loading	7.3	Provides background information on aspects of corrosion assessment under internal pressure. Outlines scope of the Battelle work which covers evaluation of corrosion defects, including effects of axial loads and defect interaction. Gives a very brief example on application of the new Battelle guidance for corrosion assessment under internal pressure only.
Bubenik	Corrosion of elbows	7.3	Executive summary indicates that recommendations are given based on B31.G (straight pipes) with modifications to account for differences in the yield and ultimate strengths associated with elbow connections.
Gordon, Wang and Dong	Flaws in Sleeve welds	7.2	Presents results of FE studies to determine stress concentration factors and stress intensity factors for cracks in pipes and/or pipe/sleeve connections. Recommends a fracture assessment procedure considering brittle fracture only but the need to assess for plastic collapse is discussed.
Hopkins and Denys*	Girth welds EPRG	7.2.8 7.2.9	Describes the EPRG guidelines comprehensively.
Kormi and Webb	Bursting of gouged and dented pipe	7.4?	FE modelling of pipe gouging, denting and explosion, including residual stresses due to denting. No experimental validation. No general guidance, only description of numerical techniques.
Jiao	Hydrotesting	2.1, 2.2	Discusses background aspects of: fracture assessment, reliability approach; uncertainty measures (with regard to fracture toughness, flow stress, defect size, wall thickness and internal design pressure), sensitivity studies and effects of hydrotesting.
Barbian and Beller	In-line inspection	5.3.2	General discussion of needs for (and potential uses of) pigs. Description of pipetronix capabilities with regard to detection of metal loss defects and cracks using ultrasonic and eddy current techniques, respectively.
Chouchaoui and Pick*	Interaction of corrosion pits	7.3 7.3.7	Describes results of experimental and finite element studies on burst strength of pipes with multiple corrosion pits.

Contents

Author(s)	Main topic	Relevant section(s) in report	General description of contents
Kanninen, Grigory, Roy, Couque and Smith	Corrosion assessment + combined loading	7.3	Presents a fundamental theoretical model for assessment of corrosion based on elastic shell theory allowing for combined loading including effect of bending and thermal stress. Validation using existing data indicates good agreement with the modified B31G approach for internal pressure loading. Application of the model to typical service conditions suggest that ignoring the effects of combined loading when these arise in service may lead to unacceptably non-conservative predictions.
Hopkins	General defect assessment	5.7	General aspects of defect assessment and development + monitoring priorities.
Stewart, Klever and Ritchie	Burst strength: intact and corroded pipes	2, 7.3	Presents a fundamental theoretical model for prediction of burst pressure of uncorroded and corroded pipes containing long smooth corrosion. Validation of the model against a limited set of burst tests indicates good agreement.
Chouchaoui and Pick*	Corrosion assessment	7.3	Proposes a comprehensive 3 level corrosion assessment procedure.
Fu and Jones	Spiral corrosion	7.3?	Presents an analytical approach to assess spiral corrosion based on derivation of correction factors, allowing for the effects of mixed mode crack loading, and corresponding failure criteria. Validation against limited experimental data indicates good agreement.
Salama	Fatigue-TMCP	7.5	Presents crack growth data in TMCP steels for different crack orientations. These indicate important differences in growth rates as a function of crack orientation, especially near the threshold region. However, such difference become minimal at higher stress ratios. The results also show that crack growth rates in TMCP steel in air are higher than the PD 6493 : 1991 rates for air environment, and lower than the PD 6493 : 1991 rates for marine environment. In addition it is found that the ΔK_{th} equation proposed in PD 6493 : 1991 overestimate the threshold value at low R ratio but is appropriate at high R ratio.
Pisarski, Phaal, Hadley and Francis	Reeling	2, 7.2	Stability of flaws in pipes during reeling and unreeling is assessed using full scale bend tests and PD 6493 : 1991 Level 3.
Leggatt and Challenger*	Weld defect assessment	7.2	Validation of PD 6493 : 1991 for assessment of girth weld defects.

* Reference is reviewed in detail in Sections 2 to 4

Contents

6. CONCLUSIONS AND RECOMMENDATIONS

A review of references on pipeline defect assessment, published in the period 1993-1994, has been conducted. The review has revealed a number of new developments which address some of the outstanding issues identified in the comprehensive review report. However, these new developments do not change significantly the overall conclusions and recommendations detailed in the comprehensive review report.

6.1 Conclusions

The issues covered in the present report include assessment of girth welds, corrosion and dent defects. The main conclusions are as follows:

- A reanalysis of pipe test data, covering defective girth welds has confirmed that the Level 1 and 2 procedures of PD 6493 : 1991 are conservative when used with specific stress intensity factors and plastic collapse solutions. Issues requiring further attention are broadly similar to those identified in the previous studies reported in the comprehensive review report.

- Information on derivation, validation and application of the comprehensive EPRG guidelines for assessing girth weld defects have been outlined. A three tier approach is proposed based on workmanship and fitness for purpose acceptance criteria. Toughness requirements are specified in terms of average and minimum Charpy V energy (40 and 30J respectively) for Tiers 1-3; and average and minimum CTOD toughness (0.15 and 0.1mm respectively) for Tier 3 only.

- New experimental and numerical data on the failure characteristics of corrosion defects including the behaviour of closely spaced corrosion pits and effects of combined loading (internal pressure and axial or bending loads) have been highlighted. In addition a number of approaches to improve corrosion assessment procedures including a three level assessment methodology, which incorporates the basic B31G model alongside more refined techniques have been outlined.

- New experimental and numerical findings concerning effects of plain dents on stress concentration and the associated fatigue life of pipelines subjected to cyclic internal pressure have been described. It is concluded, based on possible pressure fluctuation data, that plain smooth dents, less than 5% of the diameter to pipe with diameter to thickness of less than 30, are not a problem for normal pipeline service.

- Additional references briefly summarised in Section 5 include studies on: corrosion of elbows, spiral corrosion, flaws in sleeve welds and fatigue crack growth in TMCP steels.

6.2 Recommendations to Establish Comprehensive Pipeline Defect Assessment Methodologies

The following work is recommended in order to develop comprehensive pipeline defect assessment methodologies:

Short term objectives:

- Collation and evaluation of all available experimental data on failure of defective pipe sections including: weld, corrosion and mechanical damage defects. The resulting database can then be used in any subsequent validation and/or development of existing or new defect assessment procedures.

- Development of a methodology for the assessment of pipeline weld defects using the failure assessment diagram approach. Such a methodology would allow the defect assessment procedure of Appendix H of BS 4515 : 1984 to be updated and would provide guidance on evaluation of the following parameters:

  - stress intensity factors, especially for thin walled pipe geometries and shallow low aspect ratio defects

  - residual stress models with consideration of effects of installation and hydrotest loads

  - plastic collapse models for evaluation of flawed pipes (eg. local and global collapse concepts and expression for the flow stress)

  - toughness estimation with consideration of specimen geometry and constraint effects.

- Collation and evaluation of data on the effects of dents on burst strength, stress concentration and fatigue, in addition to their interaction with other defects such as corrosion and gouges.

Long term objectives:

- Development of comprehensive methodologies for the assessment of metal loss defects (corrosion, gouges) taking into account the findings of the ongoing British Gas JIP on assessment of corrosion in addition to other relevant investigations and giving guidance on:

  - categorisation of metal loss

  - complex shaped, interacting and long defects

  - defects in high grade, thick walled and low toughness pipes

  - combined axial, bending and internal pressure loading especially at spans

  - defects which intersect or are near weld and heat affected zones

  - stress corrosion cracking.

- Evaluation of the implications of using high strength steel (eg. API X70 and X80), especially in deep water, on current defect assessment techniques of weld and pipe body defects. Topics to be considered include:

  - effects of weld to parent metal yield strength ratio (ie. overmatching or undermatching)

  - effect of yield to ultimate strength ratio and ductility

  - expression for the flow stress and its interaction with plastic collapse models of flawed pipes.

- Evaluation of the implications of using stainless steel on various aspects of pipeline defect assessment.

- Examination of models of hydrodynamic loading at spanning pipelines in shallow and other water depths, and evaluation of the corresponding effects of fatigue, fracture and other modes of failure on allowable spans.

- Derivation of partial safety factors in order to account for inaccuracies in the failure models used in assessment of various types of defects, and uncertainties in the evaluation of variables such as: defect type and geometry, applied stress levels and material toughness and yielding.

7. REFERENCES

1. Barbian A O, Beller M and Garrow W. 'Inspection of offshore pipelines by using in-line inspection tools'. 3rd International Offshore and Polar Engineering Conference, Singapore, 1993.

2. Bergman M, Brickstad B, Dahlberg L, Nilsson F and Sattari-Far I. 'A procedure for safety assessment of components with cracks - Handbook'. The Swedish Plant Inspectorate, SA/FoU - Rapport 91/01.

3. Billington Osborne-Moss Engineering Limited. 'A review of current practice in pipeline defect assessment'. Report to the HSE. BOMEL Document No. C5980R04.05, 1993.

4. British Standards Institution. 'PD 6493 : 1991 Guidance on methods for assessing the acceptability of flaws in fusion welded structures'.

5. Chouchaoui B A. 'Evaluating the remaining strength of corroded pipelines'. PhD Dissertation, Department of Mechanical Engineering, University of Waterloo, Ontario, 1993.

6. Chouchaoui B A and Pick R J. 'Interaction of closely spaced corrosion pits in line pipe'. 12th Offshore Mechanics and Arctic Engineering Conference, Glasgow, 1993.

7. Chouchaoui B A and Pick R J. 'A three level assessment of the residual strength of corroded line pipe'. 13th Offshore Mechanics and Arctic Engineering Conference, Houston, 1994.

8. Fowler J R. 'Criteria for dent acceptability in offshore pipeline'. 25th Offshore Technology Conference, Houston, 1993.

9. Fu B, and Jones D G. 'Failure of spiral corrosion in linepipe'. 13th Offshore Mechanics and Arctic Engineering Conference, Houston, 1994.

10. Gordon J R, Wang V Y and Dong P. 'The development of fitness for purpose flaw acceptance criteria for sleeve connections'. Proceedings of the 8th Symposium on Line Pipe Research, sponsored by PRC/AGA, Texas, 1993.

11. Hopkins P and Denys R. 'The European Pipeline Research Group's guidelines on acceptable girth weld defects in transmission pipelines'. Proceedings of the 8th Symposium on Line Pipe Research, sponsored by PRC/AGA, Texas, 1993.

12. Jiao G. 'Effects of hydrotesting on pipeline design safety'. 3rd International Offshore and Polar Engineering Conference, Singapore, 1993.

13. Kanninen M F. 'An axisymmetric analysis model for corroded pipelines'. 12th Offshore Mechanics and Arctic Engineering Conference, Glasgow, 1993.

14. Kanninen M F, Grigory S C, Roy C, Couque H R and Smith M Q. 'Generalised guidelines for determining the residual strength in service conditions'. International Pipeline Rehabilitation Seminar, Texas, 1993.

15. Kiefner J F and Vieth P H. 'A modified criterion for evaluating the remaining strength of corroded pipe'. Final report on Project PR 3-805, Battelle memorial Institute, Columbus, 1989.

16. Leggatt R H and Challenger N V. 'Investigation of validity of BS PD 6493 : 1991 defect assessment procedures by analysis of full scale pipe bend tests'. Proceedings of the 8th Symposium on Line Pipe Research, sponsored by PRC/AGA, Texas, 1993.

17. Pisarski H G, Phaal R, Hadley I and Francis R. 'Integrity of steel pipe during reeling'. 13th Offshore Mechanics and Arctic Engineering Conference, Houston, 1994.

18. Popelar C H. 'A plane strain analysis model for corroded pipelines'. 12th Offshore Mechanics and Arctic Engineering Conference, Glasgow, 1993.

19. Salama M M. 'Effect of orientation on near-threshold crack growth in TMCP steels'. 13th Offshore Mechanics and Arctic Engineering Conference, Houston, 1994.

20. Stewart G, Klever F J and Ritchie D. 'An analytical model to predict the burst capacity of pipelines'. 13th Offshore Mechanics and Arctic Engineering Conference, Houston, 1994.

21. Wang V S. 'Remaining strength of pipes with axi-symmetric and axially invariant corrosion patterns'. Proceedings of the 8th Symposium on Line Pipe Research, sponsored by PRC/AGA, Texas, 1993.

22. Wilkowski G M and Eiber R J. 'Evaluation of tensile failure of girth weld repair grooves in pipes subjected to offshore laying stresses'. Energy Sources and Technology Conference, New Orleans, 1980.

23. Willoughby A A. 'A survey of plastic collapse solutions used in failure assessment of part wall defects'. The Welding Institute Research Report No 191/1982, September 1982.

24. Zahoor A. 'Closed form expressions for fracture mechanics analysis of cracked pipes'. Journal of Pressure Vessel Technology, Vol 107, May 1985.