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THE EFFECT OF DENT UNDER FATIGUE LOADING IN PRESSURIZED PIPELINE: A REVIEW

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Abstract—*Pipeline integrity is the cornerstone of many industrial and engineering systems. This paper provides a review of all aspects related to pipeline integrity. Assessment of the fatigue strength and burst strength of steel pipeline is essential consideration in the components which are subjected to cyclic loads in service. This paper also presents a fatigue life assessment review of failure of steel pipeline. Failure or deterioration of pipelines takes place by corrosion and fatigue, which later leads to rupture. Stress-life, strain-life, and linear elastic fracture mechanics crack propagation method has shown to be well accepted as a benchmark model of fatigue assessment. It shows that choosing an appropriate and accurate method is important; particularly for quantifying the extent to which the fatigue life is reduced. Good predictions subsequently offer successful designs of pipelines and therefore, any unwanted damage can then be avoided.*

Index Terms—Pipeline integrity, dent in pipes, fatigue strength, Stress-life, strain-life, cyclic load

1 INTRODUCTION

Oil and gas pipelines are often subject to outside force that causes geometric damages distortions, like dents, smooth localized buckles and wrinkles. The supply of energy has too often been disrupted by local pipeline leaks due to the damages. Historically, mechanical damage is the single largest cause of failures on pipelines [1]. It deforms the shape of the pipe, scrapes away metal and coating, and changes the mechanical properties of the pipe near the damage. Dents in pipelines are a common result of third-party damage or backfill loads over hard spots beneath the pipeline. They induce high localized stresses and have been the cause of a significant number of pipeline failures [2]. Thus, to ensure a safe pipeline operation, it is necessary to make a consistent assessment of the existing dents. A dent causes a local stress and strain concentration and a local reduction in the pipe diameter. The dent depth is the most significant factor affecting the burst strength and the fatigue strength of a plain dent. The stress and strain distribution in a dent does depend on the length and width of the dent. Dents in a pipeline can also present operational problems even though they may not be significant in a structural sense [3]. Consequently, any dent remaining in a pipeline should be checked to ensure that it does not significantly reduce flow rates or obstruct the passage of standard or intelligent pigs. Few papers have been published previously to investigate the effect of dents on pipeline integrity. Orynyak and Shlapak [4] determined the ultimate load of ductile fracture for defects such as dents in pipelines. They proposed a theoretical model of the ultimate plastic state of a pipe with a dent infinite in longitudinal direction. Liu and Francis [5] developed a quasi-static analysis for in-service pressurized pipelines subjected to an external impact.

Based on the assumed simple rigid, perfectly plasticdeformationmodel, a simple relationship was obtained between the external denting force and the maximum dent depth.

Iflefel et al. [6] conducted a FE numerical study of the capacity of a dented pipe to withstand combined pressure and moment loading. The strength of the dented pipe was first assessed under pure bending, applied in such a way that the dent was either on the tension side or the compression side. The strength of the dented pipe was then assessed under internal pressure loading. Finally, the behavior of the dented pipe under combined bending and pressure loading was assessed and interaction diagrams prepared. Hyde et al. [7],[8] determined the elastic-plastic force deflection analysis of unpressurized pipes with long axial and long offset indentations and unsymmetrical support conditions. Solutions from an analytical method were compared to the corresponding finite element solutions and experimental test results. The analytical method was based on a simple energy-based approach developed to predict the initial gradients of the force-deflection curves and the limit loads of the indented rings using linear beam bending theory and upper bound theories. Błachut and Iflefel [9] discussed the numerical results obtained for pipes subjected to transverse denting by a rigid indenter. They introduced axial cracks and gouges of different sizes to the pipe's outer surface. Damaged pipes were then subjected to denting and results, including denting forces, distortion of the cross-sectional area and limit loads were compared with the corresponding results obtained for non-dented and non-gouged geometries as well as with non-dented but gouged cases. Noronha et al. [10] presented a critical review of the equations for estimating strains presented in Appendix R of the ASME B31.8 Code [11]. They also presented a procedure based on B-spline curves that interpolates dent geometry from data measured by in-line inspection tools and evaluates strain components. Baek et al. [12] evaluated the plastic collapse behavior and bending moment of dented pipes containing several dent dimensions using finite element and experimental analyses. However,

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these papers did not study the effect of dent depth and internal pressure during indentation on the strain distributions of a pressurized pipe. In order to handle the complexities associated with dents, an elastic-plastic finite element simulation of a pressurized dented pipe is conducted and the formation of the dent and strain distribution around the dent location is investigated. The FE model is compared with the results of theoretical model presented in ASME B31.8 Code [11].

The stress and strain distribution in a dent does dependon the length and width of the dent. The maximum stressand strain in a long dent occurs at the base of thedent, whereas in a short dent it occurs on the flanks of thedent [3],[9]. The maximum stress in a long dent is greaterthan that in a short dent of the same depth [3],[4],[9]. In long dents, fatigue cracking is longitudinally orientated and usually occurs in the center ofthe dent (but often slightly displaced to one end), whereasin short dents, fatigue cracking usually occurs around theflanks of the dent [6],[10],[11].Dents caused by external interference (unconstrained dents) are typically confined to the top half of a pipeline. Rockdents (constrained dents) are found at the bottom of apipeline. The mostlikely failure mode of a constrained dent isby puncture, but only if the indenter (e.g. a rock) is sufficientlyhard and sharp, and the bearing load is high. Dents may beassociated with coating damage, and hence may be sites forthe initiation of corrosion or environmental cracking.Whether a pipe is gouged during indentation depends onmany factors, including the trajectory of the indentation, thefrictional resistance between the surface of the pipe and theindenter, the shape and sharpness of the indenter, the pipegeometry, the material properties and the internal pressure.A sharp indenter is more likely to cut into the pipe wallwhen the pipe is pressurized [12].

Experimentally it has beenobserved that coated and lubricated pipe surfaces sustain lessdamage than do dry, bare pipe surfaces [12]. In dynamicimpact experiments, it has been observed that a widerdamaging tool produced relatively more indentation and lessgouging than a similarly blunt, but narrower, tool [12].The European Pipeline Research Group (EPRG) haspublished guidelines for the assessment of mechanicaldamage. The American Petroleum Institute hasstudied the significance of constrained dents in a pipeline[11]. The Gas Research Institute has conducted a study ofresearch and operating experience of mechanical damage,and has developed guidance for inclusion in the ASMEB31.8 code for gas transmission pipelines [11]..The significance of dents in pipelines can be summarized as follows:

- Plain dents do not significantly reduce the burst strength of the pipe.
- The fatigue life of pipe containing a plain dent is less than the fatigue life of plain circular pipe.
- Constrained plain dents do not significantly reduce the burst strength of the pipe.
- The fatigue life of a constrained plain dent is longer than that of a plain unconstrained dent of the same depth.
- Kinked dents have very low burst pressures.
- The burst strength and fatigue life of a dented weld, or of a dent containing a defect such as a gouge, can be significantly lower than that of an equivalent plain dent.

2 PIPELINE DENT

A dent in a pipeline is a permanent plastic deformation of the circular cross-section of the pipe. A dent is a gross distortion of the pipe cross-section. Dent depth is defined as the maximum reduction in the diameter of the pipe compared to the original diameter (i.e. the nominal diameter less the minimum diameter) (see Fig.1).

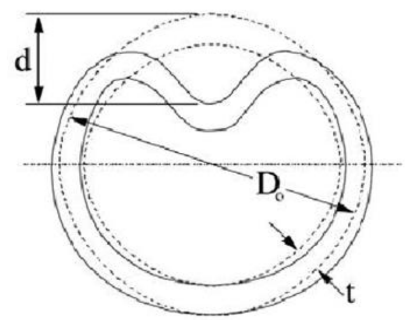

Figure 1Dent Geometry

This definition of dent depth includes both the local indentation and any divergence from the nominal circular cross-section (i.e. outof-roundness or ovality). The following terminology is used here:

- **Smooth dent** a dent which causes a smooth change in the curvature of the pipe wall.
- **Kinked dent** a dent which causes an abrupt change in the curvature of the pipe wall (radius of curvature (in any direction) of the sharpest part of the dent is less than five times the wall thickness).
- **Plain dent** a smooth dent that contains no wall thicknessreductions (such as a gouge or a crack) or otherdefects or imperfections (such as a girth or seamweld).
- **Unconstrained dent** a dent that is free to rebound elastically (spring back) when the indenter is removed, andis free to reround as the internal pressure changes.
- **Constrained dent** a dent that is not free to rebound orreround, because the indenter is not removed (arock dent is an example of a constrained dent).
- **Gouge** is a surface damage caused by contact with a foreignobject that has removed material from the pipe,resulting in a metal loss defect. The depth of agouge is equal to the depth of the metal loss plusthe depth of any cracking at the base of the gouge.

3 DENT WITH OTHER DEFECT

A dent could be associated with other defects that are typically found in pipelines, including pipe body manufacturing defects, corrosion and environmental cracking. There is no research reported in the literature that describes experimental studies of the behavior of a smooth dent containing a defect other than a single gouge (such as corrosion, a weld defect or another gouge). The only exception is a small number of tests of dents containing blunt grooves or slots, or dents containing notches that have subsequently been ground smooth [3],[4],[8],[10],[16].There are nomethods for assessing defects which cannot be readily classified as part-wall defects. It may bereasonable to assume that a defect in a smooth dent which can be characterized as a part-wall defect can be assessed as though that defect was a gouge, but there is limited experimentalvalidation of such an approach.

Table 1 Review of published literatures on investigation of pressurized piping structures.

Sr. No.	Scholar	Material	Structural type	Constant loading	Cyclic loading	Control mode
1	Fujiwaka et al.	Carbon steel: SA106 Gr A	Straight pipe	Internal Pressure	Static displacement;	Displacement control
		Stainless steel: SA312TP304	Elbow pipe/Tee	Internal Pressure	cyclic loading	Displacement control
2	Gau	Carbon steel	Straight pipe	Internal Pressure	cyclic bending load	Displacement-controlled
3	Moreton et al.	Mild steel	Straight pipe	Internal Pressure	Fully reversed cyclic bending moments	Load control
		Stainless steel	Elbow pipe	Internal Pressure	Fully reversed cyclic bending moments	Load control
4	Corona and Kyriakides	Aluminum	Straight pipe	Internal Pressure	Cyclic bending load	Load control
5	Kulkarni et al.	SA333 Gr.6 carbon steel	Straight pipe	Internal Pressure	Cyclic bending load	Load control
		SS304 stainless steel.	Elbow pipe	Internal Pressure	Cyclic bending load	Load control
6	Chen et al.	Low carbon steel	Straight pipe	Internal Pressure	Reversed bending load	Load control
7	Rahmanet al.	Alloy steel 4130	Straight pipe	Internal Pressure	Cyclic rotation	Rotation control
8	Yoshida et al.	Carbon steel	Straight pipe	Internal Pressure	Cyclic axial load	Load control
9	Guionnet et al.	Austenitic stainless	Tubular specimen	Tensile stress	Tensile stress	Load control
		steel (17-12SPH)	Tubular specimen	Tensile stress	Cyclic torsional loading	Load control
10	Rider et al.	304S11 stainless steel En6	Thin-walled cylinders	Internal Pressure	Cyclic tensile loading	Load control
11	Ichihashi	Stainless steel	Piping component	Internal Pressure	Quasi-static cyclic loading	Under sinusoidal
		Low carbon steel	Piping component	Internal Pressure	Dynamic cyclic loading	deflection control
12	Igari etal.	316FR	Straight pipe	Internal Pressure	Cyclic moment loading	Displacement control
13	Acker et al.	Non indicated	Elbow pipe	Internal Pressure	In-plane bending	Displacement control
14	Guionnet	Austenitic stainless steel	Tube	Tensile stress	Cyclic torsional loading	Load control

4 OVERVIEW OF FATIGUE LIFE ASSESSMENT

Fatigue is related to localize permanent structural damage, occurring in a material associated with fluctuating stress. Normally, high-cycle fatigue (HCF) and low-cycle fatigue (LCF) are described as above 10^4 cycles and below 10^3, respectively. For ocean based structures, the actions that produce higher magnitude variable loadings include waves, combination waves, and other variables i.e., ocean currents and equipment induced variable loads. A review by Luo et al. [15] also pointed outthat damage due to fatigue was primarily induced by stress, plastic strains, and dissipated hysteresis energy. An incipient crack, crack propagation, and catastrophic overload rupture, features signs of fatigue failures on structural materials. Strains may culminate in cracks or complete fractures after a number of cycles [2]. In the case of offshore pipelines, mechanical damage, such as fatigue [12], corrosion [24], dents [25] and gouges [26], depress their service life. Chronological failure begins with mechanical defects, which promotes the local stress concentration that leads to local stress exceeding yield strength, and finally degrades the load capacity. Moreover, defects might reduce fatigue resistance and permit premature fatigue failure. Hence, when considering the safety aspects of structural materials, the characteristic of fatigue is necessary to establish. This was done by comparing the predicted fatigue strength of materials against the established fatigue behavior. A number of approaches can be adopted for fatigue life assessment and according to a guide published by the American Bureau of Shipping (ABS) [27]; fatigue assessment can be obtained through the direct calculation of expected fatigue life or fatigue damage evaluation. The stress-life method (S–N), the local strain method, (ε–N) and linear elastic fracture mechanics (LEFM) crack propagation, have become the most classical methods for fatigue life assessment [28]. The characterization of fatigue properties can be attained through S–N, ε–N, and *da/dn*–Δ*K*curves. The concept of the S–N curve was put forward by August Wöhler in the 1860s [29], while the notion of ε–N was pioneered by Louis Coffin and Stanford Manson [14],[17] and Paul Paris popularized the rule of *da/dn*–Δ*K*[26],[30].

HCF was normally carried out to present a safe-life (i.e., stress-based) curve; where plastic deformation does not play a major role [31]. It shows that operating stresses are well below the elastic limit [28]. A set of samples was tested to failure at various stress ranges. The Basquin empirical equation was widely used for the stress-life curve [32], as shown in Eq. bellow;

$$\sigma_a = \sigma_f(2N_f)^b$$

Whereσ_a is the stress amplitude, $\sigma_f$is the fatigue strength coefficient, N_f is the number of cycles to complete failure, and b isthe Basquin exponent. It was noted that the resulting plot depends highly on the test variables (i.e., load ratio $\sigma_{min}/\sigma_{max}$, material, and sample geometry). For mean stress to also be considered in the fatigue life evaluation, it requires a set of number of curves, arranged for different mean stress values. It widely acknowledged that mean stress strongly correlates withfatigue life; both in high and low cycle fatigue. However, the stress-life relationship is more appropriate for high cycle fatigue, in which the operating stresses are below the elastic limit [28]. Alhussein et al. [33] performed experimental works onAPI 5L X52 pipeline steel. The simultaneous influence of sandblasting and hydrogen on the lifetime notched pipe was discovered through a 3-point bending test. Fatigue properties of pipeline steels were obtained using the established Wöhlercurve. In other situations, a rotating bending fatigue test of X70 pipeline steels was demonstrated on smooth and notchedspecimens to evaluate the effect of treatment on fatigue strength [34]. Results were evaluated using the

Basquinfunction through least square and the coefficients of the regression curves fitted technique.As the demand for new designs has increased tremendously, a number of researches have proposed different empiricalrelationships dealing with the mean stress effect on material strength under uniaxial fatigue loadings. Earlier works by railroad and bridge engineers induced the brilliant idea of defining a safe operating region for static and dynamic loads. Parallelto the main concern of safe life operating, the first diagram was constructed and plotted as σ_{max}vsσ_{min} or σ_{range}vsσ_{min} andwas used up to the 1900s [35]. Currently, the most referenced and simplest curve is a constant life diagram N.I.I. Mansor et al.[52].

The life diagram considers the mean stress to represent the safe life under constant amplitudeloading. Other empirical approaches that offered great attention to the mean stress effect on the fatigue life evaluationinclude the Goodman, the Gerber, or the Soderberg relations, and the Smith and Haigh diagram [13],[36].In the case of local yielding taking place, the strain-based approach proves to be a comprehensive method for estimatingthe fatigue life for both low and high cycles. The strain-life curve for crack initiation (as represented by the Coffin–Mansonrelationship) is given in the form of Eq.

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon_f\,(2N)^c$$

As mentioned previously, fatigue damage also corresponds to evaluating lifetime prediction. The linear cumulative damage (known as the Palmgren–Miner rule) is used to calculate fatigue damage, due to variable amplitude loadings [40]. Thisconcept was based on individual damages being summed, in order to establish a fatigue life component. Karunananda et al.[41] indicated that an interesting feature of this rule is a simple life calculation that is reliable when a detailed loading history is unknown. The formula can be expressed as follows:

$$D_i = \sum_{i=1}^{n} \frac{N_i}{N_{fi}}$$

Where, $N_i$is the number of cycle, $N_{fi}$is the number of cycles to failure, and D_i is the damage parameter. Other models werealso invented using the Palmgren–Miner rule. The paper written by Jinescu [13] contains a review of cumulative fatiguedamage and life evaluation. For instance; available models include the modified Palmgren–Miner rule, the Marko-Starkerrelation, and the Morrow approach. Jinescu [13] also proposed a model for cumulative fatigue damage evaluation basedon an energy concept. The approach method is capable of unifying the damage caused by different types of loads e.g., thermalcycling, fatigue, and creep [13].On the basis of fracture mechanic-based approaches, a linear elastic stress intensity factor (K), elastic–plastic (which isdefined by the J-integral and critical Crack-Tip Opening Displacement (CTOD)), was adopted. These methods are normallyprovided for service assessments of pipeline cracks. Under constant amplitude loading, Fatigue Crack Growth Rate's (FCGRs)behavior of metals and alloys are often formulated using a power law expression (known as the Paris equation). The benchmark empirical model is given by Eq,

$$\frac{da}{dn} = C(\Delta K)^m$$

WhereC is a constant, m is the slope on the log–log scale, and ΔK is the stress intensity range. The resulting log–log plots ofda/dn–ΔK show a typical sigmoidal shape, which is classified into three phases. Phases of stage I, II, and III are separated following the sequences of crack initiation, crack propagation, and rapid crack growth, just prior to final failure. It was notedthat a significant portion of fatigue life is occupied in stage II (also known as crack growth). Many previous studies havefocused on this phase because the large-scale plastic zone near the crack tip offers substantial conditions of long distancesteady state crack propagation for pipeline steels [42]. Crack growth rate was estimated at approximately 108–106 m/cycle[43]; which corresponds to the small cracks having a length of approximately 10–50 lm [44]. Therefore, the fatigue lifeassessment through crack growth prediction is acceptable; considering that the crack growth life was almost comparablewith the fatigue life itself [44]. Dmytrakh et al. [45] studied an FCG on low alloyed pipeline steel under hydrogenating conditions. The empirical relationship was derived for fracture risk assessment of defect pipelines. Combination parameters,such as local hydrogen concentration near the crack tip and hydrogen concentration in the bulk of the metal were consideredto model the da/dn–ΔKcurve.In other work, by Jiang and Chen [26], fatigue crack propagation of X70 pipeline steel significantly depended on the ΔKvalue. It was found that mechanical damage and synthetic soil solution enhanced the fatigue crack propagation rate andlowered the threshold stress intensity factor range. Marvasti and Peers [46] highlighted the low loading frequency effectof fatigue crack growth behavior on X52 and X80 pipeline steels. A low cyclic loading frequency is always directed by N.I.I. Mansor et al.[52] pipelines used for high pressure oil and gas transmission. A linear relationship was observed in which lower frequencyyields lowered the crack growth rate.A successful design is relatively close to the success of product life prediction. Hence, the requirement for design lifetimecan be achieved for safe-life, fail-safe, and damage-tolerant approaches. Obtaining an accurate life prediction relies criticallyon the handling of experiment data analysis. A correct method allows quantifying the range to which the fatigue lives arereduced. In conjunction with an appropriate design, any unwanted premature failures are possible to be discarded.

5 BURST STRENGTH OF PLAIN DENTS

Plain dents do not significantly reduce the burst strength of the pipe, unless they are very deep. This observation is based on several studies of the significance of plain dents; the results of the full scale burst tests confirm the high burst strength of plain dents[9],[11],[20],[21]. The results of over 75 burst tests of unconstrained plain dents have been published (dating from 1958 to 2000), but failure in the dented area only occurred in four tests (the remainder of the tests were terminated prior to failure) Note that in all of the full scale tests on plain dents, the dent depths were measured at zero pressure after spring back.

On pressurization the dent attempts to move outward,allowing the pipe to regain its original circular shape. The large stresses and strains introduced by the dent are accommodated by the ductility of the pipe. Deep dents tend to fail either because they are unable to reround or because of wall thinning in the dented area (in tests, outward bulging has been observed in dented areas that have rerounded [21]). The limited number of burst tests on constrained dents indicates that they have burst strength at least that of an equivalent unconstrained dent, unless the indenter is sharp [11].There are no published analytical methods for assessing the burst strength of a plain dent; rather, the results of full scale tests have been used to derive empirical limits for the acceptability of plain dents. Based on a review of available burst test data, British Gas stated that a plain dent of less than 8 percent of the pipe diameter (and possibly up to 24 percent) has little effect on the burst strength of pipe [20],[30]. The EPRG recommendations for the assessment of mechanical damage state that plain dents of less than 7 percent of the pipe diameter, measured at pressure, are acceptable provided they are not subjected to internal pressure fluctuations [13]. Analysis of more recent test data suggests 10 percent (including a factor of safety on the dent depth). There are currently research efforts to develop limits for plain dents based on strain [14].

6 CONCLUSION

Underground pressurized gas pipes can suffer damage dueto earth movement, corrosion, fatigue, or indentations causedby contact with mechanical diggers. This review aims to refine the methodology to assess the fatigue life of dented steel pipelines based on the current high cycle fatigue theory. Corrosion and fatigue correspond to a deterioration process associated with significant uncertainties that lead to lowering the integrity of pipelines. With a need to minimize failures, material and design modifications and an assessment of lifetime service conditions are essential. With this in mind, many methods have addressed accessing fatigue life performance. These include an empirical model using a safe-life approach (i.e., S–N, e–N curve) and a fracture mechanics method via a $da/dN - \Delta K$ curve. Even though bulks of comprehensive studies have been employed on combatting corrosion, failures concerning of steel pipelines continue to occur. It is ratified that response of corrosion depends on various uncertainty parameters. Thereforea robust method is adopted to reduce likelihood of pipeline failures. As corrosion cannot be stopped, the assessment of corroded pipelines is crucial; because failure at any point along the length of the pipeline may lead to serious financial loses. Knowledge of possible consequences of pipeline failure must be improved so that the failure risk can be reduced. Thus, it is important to ensure a robust system and safety is in place. Indeed, safely managing pipeline systems relies on durability design approaches, reliability, and a satisfactory model. Motivated by this, more simulation and experimental evidences are needed to improve corrosion assisted cracking events particularly in the state of variable mechanical loading.

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REFERENCES

[1] Z. Jiao, J.Shuai,"Integrity assessment of pipeline with dents", Journal of Southwest Petroleum University 33 (4), pp. 157-164,2011

[2] Q.Yang, J.Shuai, "Engineering evaluation method for dented pipeline". ActaPetroleiSinica31 (4), pp. 649-653, 2010

[3] K.A.Macdonald, A. Cosham,"Best practice for the assessment of defects in pipelines - Gouges and dents",Engineering Failure Analysis12 (5), pp. 720-745, 2005

[4]I.V.Orynyak andL.S.Shlapak, "Estimation of ultimate pressure for a pipe with a dent". ProblemyProchnosti(5), pp. 101-110, 2001

[5] J.H. Liu and A.Francis, "Theoretical analysis of local indentation on pressured pipes".International Journal of Pressure Vessels and Piping,81 (12), pp. 931-939, 2004

[6] I.B.Iflefel, D.G. Moffat andJ.Mistry, "The interaction of pressure and bending on a dented pipe".International Journal of Pressure Vessels and Piping 82 (10), pp. 761-769,2005

[7] T.H.Hyde, R.Luo. And A.A.Becker, "Elastic-plastic response of unpressurised pipes subjected to axially-long radial indentation". International Journal of Mechanical Sciences 47 (12), pp. 1949-1971,2005

[8] T.H.Hyde, R.Luo. And A.A.Becker,"Elastic-plastic analysis of offset indentations on unpressurised pipes".International Journal of Solids and Structures 44 (2), pp. 399-418, 2007

[9] J. Błachut and I.B. Iflefel, "Analysis of pipes containing plain and gouged dents". Strain 47, pp. 34-51,2011

[10] D.B. Noronha, Martins, B.P. Jacob andE.de Souza, "Procedures for the strain based assessment of pipeline dents".International Journal of Pressure Vessels and Piping 87 (5), pp. 254- 265,2010

[11] ASME B31.8 (2007) gas transmission and distribution piping systems.

[12] J.H.Baek,Y.P. Kim, and W.S. Koo, "Load bearing capacity of API X65 pipe with dent defect under internal pressure and in-plane bending".Materials Science and Engineering 540, pp. 70-82,2012

[13] VV.Jinescu,"Critical energy approach for the fatigue life calculation under blocks with different normal stresses amplitudes". Int J MechSci;67:78–88, 2013

[14] Y.C.Lin,C. Xiao-Min, L.Zheng-Hua, and J. Chen,"Investigation of uniaxial low-cycle fatigue failure behavior of hot rolled AZ91 magnesium alloy". Int J Fatigue ;48:122–132, 2013

[15] Y.R.Luo, C.X.Huang, Y.Guo and Q.Y. Wang,"Energy-based prediction of low cycle fatigue life of high strength tructural steel". J Iron Steel Res Int; 19:47–53,2012

[16]A.G.Gavras, D.A.Lados and J.KDonald."A unified method of design

for fatigue crack growth resistance in structural materials". Int J Fatigue; 47:58–70, 2013

[17] E.Castillo, A. Fernández-Canteli, P. Hernán and López-Aenlle."A general regression model for statistical analysis of strain-life fatigue data". Mater Lett; 62:3639–42, 2008

[18] G. Qian and N. Markus,"Probabilistic fracture assessment of piping systems based on FITNET FFS procedure".NuclEng Des; 241:714–22, 2011

[19] H. L. Zheng,X.Zhai, C. Shu-Ping and R. Liang,"A method of probabilistic analysis for steel pipeline with correlated corrosion defects". CorrosSci;51:3050–6,2009

[20] P.G.Fazzini, J.L. Otegui, "Experimental determination of stress corrosion crack rates and service lives in a buried ERW pipeline". Int J Press Vessels Pip; 84:739–48, 2007

[21] K.A. Macdonald, A. Cosham, C.R. Alexander and P. Hopkins, "Assessing mechanical damage in offshore pipelines –Two case studies", Engineering Failure Analysis 14; 1667–1679, 2007

[22] M. Allouti, C. Schmitt, G. Pluvinage, J. Gilgertand S. Hariri, "Study of the influence of dent depth on the critical pressure of pipeline", Engineering Failure Analysis 21; 40–51, 2012

[23] MaziarRamezani and Thomas Neitzert, "Strain Based Evaluation of Dents in Pressurized Pipes", World Academy of Science, Engineering and Technology Vol: 7; 06-21, 2013

[24] T. Breton, Sanchez-Gheno, JL Alamilla and J. Alvarez-Ramirez,"Identification of failure type in corroded pipelines: a Bayesian probabilistic approach". J Hazard Mater; 179:628–634, 2010

[25] B. Pinheiro, IPPasqualino,"Fatigue analysis of damaged steel pipelines under cyclic internal pressure". Int J Fatigue; 31:962–973,2009

[26] Y. Jiang, M. Chen,"Researches on the fatigue crack propagation of pipeline steel". Energy Proc; 14: 524–528, 2012

[27] American Bureau of Shipping,"Guide for the fatigue assessment of offshore structures", Houston; 2003.

[28] K. Hariharan, RV Prakash, MP Sathya,"Weighted error criterion to evaluate strain-fatigue life prediction methods". Int J Fatigue;33:727–734.

[29] S. Hai-Jun, G. Wan-Lin, M. Jun-Feng, Z.Bao-Tian,"Relations between the S–N, e–N and da/dN– DK curves of materials". Open MechEng;3:35–42, 2009

[30]Y. Li, H. Wang and D. Gong,"The interrelation of the parameters in the Paris equation of fatigue crack growth."EngFractMech; 96:500–509,2006

[31] A. Niesłony and M. Böhm,"Mean stress effect correction using stress ratio S–N curves".Int J Fatigue; 52:49–56, 2013

[32] A. Niesłony, K. Andrzej, D. Chalid and K. Heinz,"A study of compatibility between two classical fatigue curve models based on some selected structural materials". Int J Fatigue; 39:88–94, 2012

[33] A. Alhussein, J. Capelle, J. Gilgert and Z. Azari,"Influence of sandblasting and hydrogen on tensile and fatigue properties of pipeline API 5L X52 steel". Int J Hydrogen Energy;36:2291–2301, 2011

[34] K. Miková, S.Bagherifard and O. Bokuvka, "Fatigue behavior of X70 microalloyed steel after severe shot peening".Int J Fatigue 2013;55:33–42.

[35] GP.Sendeckyj,"Constant life diagrams – a historical review". Int J Fatigue;23:347–353, 2001

[36] J. Polák, J. Man, M. Petrenec, T. Tobiáš,"Fatigue behavior of ferritic–pearlitic–bainitic steel in loading with positive mean stress". Int J Fatigue;39:103–108, 2012

[37] A. Ince, G. Glinka,"A modification of Morrow and Smith–Watson–Topper mean stress correction models". Fatigue FractEng Mater Struct;34:854–867, 2007

[38] NA Al-Asady, S. Abdullah, AK Ariffin, SM Beden and RRRahman,"FEA based durability using strain-life models for different medium carbon steel as fabrication materials for an automotive component". Int J Mech Mater Eng; 4:141–146, 2009

[39] J. Szusta andA. Seweryn,"Low-cycle fatigue model of damage accumulation – the strain approach". EngFractMech;77:1604–1616, 2012

[40] NZ Chen, G. Wang and CG Soares,"Palmgren–Miner's rule and fracture mechanics-based inspection planning".EngFractMech; 78:3166–3182, 2011

[41] K. Karunananda, M. Ohga, S.Siriwardane."Effect of high amplitude loading on fatigue life prediction of steel bridges".ProcEng;14:521–528, 2008

[42] JQ Wang and J. Shuai, "Measurement and analysis of crack tip opening angle in pipeline steels",EngFractMech; 79:36–49, 2012

[43] CARP Baptista, AML Adib, MAS Torres, and VA Pastoukhov. "Describing fatigue crack growth and load ratio effects in Al 2524 T3 alloy with an enhancedexponential model".Mech Mater; 51:66–73, 2012

[44] M Kamaya, M Kawakubo, "Strain-based modeling of fatigue crack growth – an experimental approach for stainless steel". Int J Fatigue; 44:131–40,2012

[45] IMDmytrakh, OD Smiyan, AM Syrotyuk andOL Bilyy."Relationship between fatigue crack growth behavior and local hydrogen concentration near cracktip in pipeline steel."Int J Fatigue; 50:26–32,2013

[46] MH Marvasti, W. Chen and RL Eadie,"Fatigue of steel in air at low cyclic loading frequency".Scr Mater; 64:552–555, 2011

[47] B. Pinheiro, J. Lesage andPasqualino,"X-ray diffraction study of microstructural changes during fatigue damage initiation insteel pipes". Mater SciEng; 532:158–166,2012

[48] J.H. Liu, A. Francis, "Theoretical analysis of local indentation on pressured pipes", International Journal of Pressure Vessels and Piping 81; 931–939, 2004

[49] H. Arabzadeh, M.Zeinoddini, "A closed-form solution for lateral indentation of pressurized pipes resting on a flexible bed", International JournalofMechanicalScience75; 189–199,2013

[50] Andrew Palmer, Martin Touhey, Si Holder , Murray Anderson and Stephen Booth, "Full-scale impact tests on pipelines", International Journal of Impact Engineering 32; 1267–1283, 2006

[51] Andrew Cosham and Phil Hopkins, "The effect of dents in pipelines—guidance in the pipeline defect assessment manual", International Journal of Pressure Vessels and Piping 81; 127–139, 2004

[52] N.I.I. Mansor, S. Abdullah, A.K. Ariffin, and J. Syarif, "A review of the fatigue failure mechanism of metallic materials under a corroded environment", Engineering Failure Analysis 42; 353–365, 2014