DENT AND GOUGE DEFECTS ASSESSMENT: A CASE STUDY OF GAS PIPELINE

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ABSTRACT

This work present case study of engineering integrity assessment of 24inches diameter gas pipeline belonging to Nigeria Gas Company(NGC) that had mechanical damage. The assessment was conducted following detection of plain dent at 7km point and dent-gouge at 22km point with in-line inspection run of geometric and magnetic flux leakage tools as prescribed by American Petroleum Institutes (AP1) 579 code and standard. Result of Level 1 dent assessment showed maximum allowable working pressure (4MPa) was less than maximum operating pressure (6.5MPa) of the pipeline. While Level 2 assessment estimated permissible number of pressure cyclic as 188 cycles. Additionally, Level 1 assessment of the dent containing gouge revealed ratio of gouge depth to wall thickness (0.15) and dent depth to component diameter (0.0362) intercepted in unacceptable region. Further analysis with Level 2 indicated remaining strength factor (0.527) was not greater than or equal to allowable remaining strength factor (0.9). The pipeline failed Level 1 and Level 2 acceptance criteria for both the plain dent and dent-gouge interaction and therefore required immediate mitigative action.

Keywords: Acceptance criteria, dent, gouge, MAWP, RSF.

INTRODUCTION

Mechanical damage is one of the major anomalies that pipeline companies are confronted with and is most often introduced during construction or operation. The mechanical damage usually involves plain dents, dents and gouges. A dent is defined as permanent deformation of pipe cross sectional area as a result of external force. But plain dent is classified as dents that contain no localized defects such as weld, corrosion or gouge (Cosham and Hopkins, 2003). Whereas, gouge is mechanically induced metal loss which may lead to localized and elongated cavities or grooves (POF, 2005). Dents and gouges have been reported as one of the major causes of pipeline failure in the world (Bolt and Owen, 1997). Safe operating pressure and remaining fatigue life of pipelines with mechanical damage are difficult to analyze and the presence of dents and gouges raise pipeline stress level around the edges of defects leading to increasing sensitivity of both fatigue and static loading and eventual failure of pipelines (Tindall et al, 2009). The presence of dent and gouge defects result in plastic strain, plastic flow, wall thinning, crack initiation, ductile tearing and dent movement (Leis et al, 2000). The present aim of the article is to carry out deterministic evaluation of dent and gouge defects under cyclic pressure. The outcome of the findings would help to ascertain whether the defects could lead to potential failure or within acceptable envelop and then make informed decisions to repair, derate or do nothing.

ASME B31.8 (2004) proposed dents assessment based on strain acceptance criterion with the assumption that strains act in the pipe longitudinal and circumferential directions which are categorized into bending and membrane components. Kietner et al (1973) and Shannon

(1974) introduced theoretical concept for predicting failure stress of ductile pipeline with gouges in axial orientation under internal pressure. While computation of the failure stress prediction for ductile pipeline with circumferentially oriented gouges was proposed by Kastner et al (1981). Wang and Smith (1982) and Eliber et al (1981) investigated dents effect on line pipe with plain dent and without dent by conducting full scale fatigue tests and the result of the tests showed decreased in fatigue life compared to line pipe without dent. (Hopkins et al, 1989; Fowler et al, 1994) further studied impact of dents and gouges on transmission pipelines including cyclic pressure effect. The study revealed pipelines with only dent had fatigue life in the order of 10^5 cycles while the fatigue life was further reduced to 10^3 with combination of dent and gouge presence which showed the presence of gouges adversely affected fatigue life of pipelines. Longitudinally orientated dent-gouge empirical fracture model had been developed to enable failure stress prediction of dent-gouge defect (Hopkins, 1992). Bianca and Pasqualino (2009) conducted experimental and numerical fatigue analysis to assess dented pipelines under cyclic internal pressure and found the region of dents plastically deformed with initial cycles and further deformed elastically with increasing cycles. It was concluded that dent with gouge or close to weld impact significantly on the failure pressure and fatigue life of pipelines because of increased stress concentrations with gouge presence. However, dent without the presence of gouge, weld and crack have been reported to be very less severe under static pressure and less significant impact on the failure pressure even up to 24% of pipe outer diameter (Lancaster and Palmer, 1996).

MATERIAL AND METHOD

Case Study

A case study of dents and gouge assessment on 24inches diameter Escravos to Warri gas pipeline belonging to Nigeria Gas Company (NGC), a subsidiary of Nigeria National Petroleum Corporation (NNPC) was carried out. In-line inspections were performed using combination of magnetic flux leakage and geometric inspection tools as prescribed by API (2013) and POF (2005) standards. The tools identified and located dent at 7km point and dent containing gouge at 22km point on the pipeline under cyclic pressure. The pipeline data and measured defects dimension are provided in Table 1 and Table 2 respectively.

Table 1: Pipeline data

Pipeline material grade	X60
Outside diameter	609.6mm
Measured wall thickness	12.7mm
Ultimate tensile strength	517MPa
Allowable stress	172.7MPa
Yield strength	413.7MPa
Maximum operating pressure	6.5MPa
Minimum operating pressure	1.5MPa
Maximum operating temperature	60^0C
Minimum operating temperature	0^0C
Future corrosion allowance	1mm
Weld joint factor	0.85
Impact energy	50 joules (2/3 of size) at -20^0C
Modulus of elasticity	208000MPa

Table 2: Defect dimensions

Damage type	Dent depth	Dent radius	Distance to discontinuity	Distance to nearest weld	Gouge depth
Dent at 7km	35mm	65mm	750mm	120mm	-
Dent in gouge at 22km	31.5mm	60mm	600mm	250mm	1.75mm

Dent Assessment

Fitness for service assessment of the dent located at 7km log distance from Warri axis was performed according to American Petroleum Institute (API) 579 standard. Starting with Level 1, maximum allowable working pressure of the circumferential stress $(MAWP^c)$ was determined with the following formula:

$$MAWP^c = \frac{2SE(t_c - MA)}{D_o - 2Y_{B31}(t_c - MA)}$$

(1)

where, E =weld joint factor, S =material allowable stress, MA =mechnanical allowance for thread or groove depth is 0, D_o =outside pipe diameter, Y_{B31} =ASME B31 piping code coefficient factor for ductile metal is 0.4, FCA =future corrosion allowance, t_{rd} =measured wall thickness at a time of assessment and the wall thickness used in dent assessment, t_c is defined as:

$$t_c = t_{rd} - FCA$$

(2)

$$= 12.7 - 1 = 11.7mm$$

$$MAWP^c = \frac{2 * 172.7 * 0.85\{11.7 - 0\}}{\{609.6 - 2 * 0.4\ [11.7 - 0]\}} = 5.72MPa$$

Next step was to check if the maximum operating pressure (P_{max}) of the pipeline is greater than or equal to 70% of the calculated MAWP:

$$P_{max} \geq 70\%\ MAWP^c$$

(3)

$$6.5MPa \geq \{(70\% * 5.72) = 4MPa\}$$

Some necessary checks such as pipe dent depth under pressurized condition(d_r) to diameter ratio, minimum required distance to structural discontinuities(L_{msd}) and minimum required distance to the weld (L_w) were verified with equations (5), (6) and (7) respectively.

$$d_r = 0.7d_o$$

(4)

where, d_o = dent depth at zero pressure

$$d_r = 0.7 * 35 = 24.5mm$$

$$d_r \leq 0.07D_o$$

(5)

$$24.5mm \leq \{(0.07 * 609.6) = 42.67\}$$

$$L_{msd} \geq 1.8\sqrt{D_o t_c}$$
(6)

$$750mm \geq \{(1.8 * \sqrt{609.6 * 11.7}) = 152mm\}$$

$$L_w \geq max[2t_c, \quad 25mm]$$
(7)

$$120 \geq max\{[2 * 11.7, \ 25mm] = 25mm\}$$

Next was Level 2 assessment beginning with computation of cyclic circumferential membrane stress amplitude (σ_a) and adjusted cyclic circumferential membrane stress amplitude (σ_A) using equation (8) and (10) respectively:

$$\sigma_a = \sigma^c_{m,max} - \sigma^c_{m,min}/2$$
(8)

where, $\sigma^c_{m,max}$ and $\sigma^c_{m,min}$ are maximum and minimum circumferential stress, and σ^c_m is circumferential stress expressed as:

$$\sigma^c_m = \frac{P}{E}\left[\frac{D_o}{2(t_c - MA)} - Y_{YB31}\right]$$
(9)

$$\sigma^c_{m,min} = \frac{1.5}{0.85}\left[\frac{609.6}{2(11.7-0)} - 0.4\right] = 45.26MPa$$

$$\sigma^c_{m,max} = \frac{6.5}{0.85}\left[\frac{609.6}{2(11.7-0)} - 0.4\right] = 196.16MPa$$

$$\sigma_a = \frac{196.16-45.26}{2} = 75.45MPa$$

$$\sigma_A = \sigma_a\left[1 - \left\{\frac{\sigma^c_{m,max} - \sigma_a}{\sigma_{uts}}\right\}^2\right]^{-1}$$
(10)

$$= 75.45\left[1 - \left\{\frac{196.16-75.45}{517}\right\}^2\right]^{-1} = 79.76MPa$$

Next step was computation of stress concentration factor, k_d because of stress distribution at the edge of the dent is defined as:

$$k_d = 1 + C_s\sqrt{\frac{t_c}{D_o}}[d_o * C_{ul}]^{3/2}$$
(11)

where, C_s = fatigue assessment of dent factor= 1 and C_{ul} =conversion factor= 1

$$k_d = 1 + 1\sqrt{\frac{11.7}{609.6}}[35 * 1]^{3/2} = 3.99$$

Finally, empirical model based on $S - N$, modified for stress concentration due to dent was employed to calculate fatigue life of the dent or maximum allowable number of cycles (N) with equation (12):

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$$N = 562.2\left[\frac{\sigma_{uts}}{2\sigma_A k_d k_g}\right]^{5.26}$$
(12)

where, k_g =gouge stress concentration factor= 1

$$N = 562.2\left[\frac{517}{2*79.76*3.99*1}\right]^{5.26} = 188 \text{ cycles}$$

Dent with Gouge Assessment

Fitness for service assessment of dent with gouge interaction located at 22km section of the 24inches diameter gas pipeline from Warri axis was evaluated using API 579 code and standard based on the parameters presented in Table 1 and Table 2. In this case, the calculated values of t_c and $MAWP^c$ from equation (1) and (2) are the same for both dent and dent containing gouge. Hence, a follow up step are computation of dent in gouge depth under pressure and minimum required wall thickness, t_{mm} using equation (4) and (13) respectively:

$$d_r = 0.7 * 31.5 = 22.05mm$$

$$t_{mm} = t_{rd} - d_g$$
(13)

where, d_g =gouge depth

$$t_{mm} = 12.7 - 1.75 = 10.95mm$$

Furthermore, acceptance criteria check of dent in gouge under pressure, distance to structural discontinuities and distance to weld were verified with equation (5 – 7) and minimum required wall thickness with equation (14):

$$d_r \leq \{0.07 * 609.6\}$$

$$\therefore 22.05mm \leq \{42.67mm\}$$

$$L_{msd} \geq \{1.8 * \sqrt{609.6 * 11.7} =\}$$

$$\therefore 600mm \geq \{152mm\}$$

$$L_w \geq max\{2 * 11.7, \quad 25mm\}$$

$$\therefore 250 \geq max[23.4mm, \quad 25mm]$$

$$t_{mm} - FCA \geq 2.5mm$$
(14)

$$\therefore 9.5mm \geq 2.5mm$$

Continuing with the Level 1 assessment criteria, maximum circumferential stress to yield strength ratio, gouge depth to wall thickness ratio and dent depth to component diameter ratio were computed as follow:

$$\frac{\sigma^c_{m,max}}{\sigma_y} = \frac{196.16}{413.7} = 0.474$$
(15)

$$\frac{d_g}{t_c} = \frac{1.75}{11.7} = 0.15$$
(16)

$$\frac{d_r}{D_o} = \frac{22.05}{609.6} = 0.0362$$

(17)

Level 2 assessment was performed using semi-empirical fracture model developed by British Gas (Hopkins, 1992; Hopkins et al, 1989) and later adopted by API 579:

$$RSF = \frac{2}{\pi} Arccos\left[exp^{-}\left\{\left(113\frac{1.5\pi E}{\bar{\sigma}^2 A_{cvn} d_g}\right)\left[Y_1\left(1-\frac{1.8d_o}{D_o}\right)+ Y_2\left(\frac{10.2d_o}{2t_c}\right)\right]^{-2} exp\left[\frac{In(0.738C_v)-k_1}{k_2}\right]\right\}\right] * \left[1-\frac{d_g}{t_c}\right]$$

(18)

where, RSF =remaining strength factor, A_{cvn} =area of charpy specimen fracture surface, $\bar{\sigma}$ =flow stress, C_v =charpy impact energy, E =eleastic modulus, k_1 and k_2 are non-regression parameters given as 1.9 and 0.57 respectively. Equation (18) was further simplified into equations (19 – 25) to ease computation:

$$RSF = \frac{2}{\pi} Arccos[exp^{-}\{Z_1 * Z_2 * Z_3\}] * \left[1-\frac{d_g}{t_c}\right]$$

(19)

$$Z_1 = 113\frac{1.5\pi E}{\bar{\sigma}^2 A_{cvn} d_g}$$

(20)

$$\bar{\sigma} = 1.15\sigma_y\left[1-\frac{d_g}{t_c}\right]$$

(21)

$$= 1.15 * 413.7\left[1-\frac{1.75}{11.7}\right] = 404.39MPa$$

$$Z_1 = \frac{1.5*3.14*208000*113}{404.39^2*56.32*1.73} = 6.87$$

$$Y_1 = 1.12 - 0.23\left(\frac{d_g}{t_c}\right) + 10.6\left(\frac{d_g}{t_c}\right)^2 - 21.7\left(\frac{d_g}{t_c}\right)^3 + 30.4\left(\frac{d_g}{t_c}\right)^4$$

(22)

$$= 1.12 - 0.23\left(\frac{1.75}{11.7}\right) + 10.6\left(\frac{1.75}{11.7}\right)^2 - 21.7\left(\frac{1.75}{11.7}\right)^3 + 30.4\left(\frac{1.75}{11.7}\right)^4$$

$$= 1.269$$

$$Y_2 = 1.12 - 1.39\left(\frac{d_g}{t_c}\right) + 7.32\left(\frac{d_g}{t_c}\right)^2 - 13.1\left(\frac{d_g}{t_c}\right)^3 + 14.0\left(\frac{d_g}{t_c}\right)^4$$

(23)

$$= 1.12 - 1.39\left(\frac{1.75}{11.7}\right) + 7.32\left(\frac{1.75}{11.7}\right)^2 - 13.1\left(\frac{1.75}{11.7}\right)^3 + 14.0\left(\frac{1.75}{11.7}\right)^4$$

$$= 1.039$$

$$Z_2 = \left[Y_1\left(1-\frac{1.8d_o}{D_o}\right) + Y_2\left(\frac{10.2d_o}{2t_c}\right)\right]^{-2}$$

(24)

$$= \left[1.269\left(1-\frac{1.8*31.5}{609.6}\right) + 1.039\left(\frac{10.2*31.5}{2*11.7}\right)\right]^{-2}$$

$$= 0.0042$$

$$Z_3 = exp\left[\frac{In(0.738C_v) - k_1}{k_2}\right]$$

(25)

$$= exp\left[\frac{In(0.738 * 50) - 1.9}{0.57}\right] = 20$$

From equation (18), the remaining strength factor was computed:

$$RSF = \frac{2}{\pi} * Arccos[exp^{-}\{6.87 * 0.0042 * 20\}] * [0.85]$$

$$= 0.527$$

Acceptance criteria for Level 2 assessment for dent containing gouge is finally checked by comparing computed remaining strength factor (RSF) with allowable remaining strength factor(RSF_a) of 0.9 as follow:

$$RSF \geq RSF_a$$

(26)

$$0.527 \geq 0.9$$

Equation (27) was used to reestablish new maximum allowable working pressure $(MAWP_r)$ the pipeline could hold since Level 2 was unsatisfactory:

$$MAWP_r = MAWP^c\left(\frac{RSF}{RSF_a}\right)$$

(27)

$$=5.72\left(\frac{0.527}{0.9}\right) = 3.35MPa$$

RESULTS AND DISCUSSION

Dent defect acceptance criteria for Level 1 and Level 2 analysis are presented in Table 3. Preliminary assessment checks on dent depth under pressurized condition (d_r), minimum require distance to structural discontinuities (L_{msd}) and minimum distance to weld (L_w) were found to be within acceptable criteria. However, the computed maximum allowable working pressure (4MPa) of the circumferential stress was less than maximum operating pressure (6.5MPa) of the 24 inches diameter gas pipeline. Comparative analysis showed the pipeline may potentially fail at the dented region if operated above the computed allowable pressure. So, the Level 1 assessment criteria was therefore not satisfactory because the computed maximum allowable working pressure was less than the current maximum operating pressure of the pipeline under internal cyclic pressure. According to Gheorghe and Lucian (2011) presence of dent and gouge anomalies could significantly reduce loading capacity of pipelines and lead to catastrophic failure if mitigative measures are not taken. Level 2 of the dent assessment was then initiated to compute remaining fatigue life or allowable cycles. Permissible number of cycles based on 35mm dent depth anomaly and fluctuation pressure between 1.5MPa and 6.5MPa was computed as 188cycles and therefore negatively impacted. The analysis agrees with previous work that pipeline with dent undergoing cyclic internal pressure significantly reduce fatigue life (Alexander, 2009; Eliber et al, 1981).

Plot of gouge depth to wall thickness ratio against dent depth to component diameter ratio (Fig 1) was used to check Level 1 acceptance criteria for dent and gouge anomalies interaction. The plot showed computed gouge depth to wall thickness ratio (0.15) and dent depth to component ratio (0.0362) intercepted outside the unacceptable region and defined graph boundary. This implied Level I acceptance criteria for engineering critical assessment of the dent and gouge defects interaction was not passed and therefore required next Level of analysis. Level 2 assessment result of the dent and gouge anomalies as shown in Table 4 used remaining strength factor (RSF) which is a quantitative analysis for evaluating acceptance of damage. The Level 2 analysis showed computed remaining strength factor (0.527) was not greater than or equal to allowable remaining strength factor (0.9) indicating violation of the acceptance criteria with mathematical expression as $RSF \geq RSF_a$. Therefore, the Level 2 assessment was not passed. Additionally, remaining fatigue life could not be computed because there is not available analytical or empirical method for predicting fatigue life of dent and gouge interaction anomalies. However, full scale tests showed fatigue life of pipeline would be reduced from order of 105 cycles to 103 when dent contain gouge defect and therefore more deleterious (Lancaster and Palmer, 1996; Fowler et al, 1994). Hence, immediate remediation was to derate the pipeline current maximum operating pressure (6.5MPa) to 3.35MPa using equation (27) and then plan for temporary or permanent repair of the defective segments.

Table 3: Dent assessment check

Parameters		Level 1 assessment	Level 2 Assessment
P_{max}	6.5MPa	$P_{max} \geq 70\% MAWP^c$	188cycles
d_r	24.5mm	$d_r \leq 0.07D_o$	
L_{msd}	750mm	$L_{msd} \geq 1.8\sqrt{D_o t_c}$	
L_w	120mm	$L_w \geq max[2t_c, 25mm]$	
$MAWP^c$	4MPa	-	-

Table 4: Dent and gouge assessment check

Parameters		Level 2 assessment
RSF_a	0.9	$RSF \geq RSF_a$
RSF	0.527	
$MAWP_r$	3.35MPa	Recommended MAWP

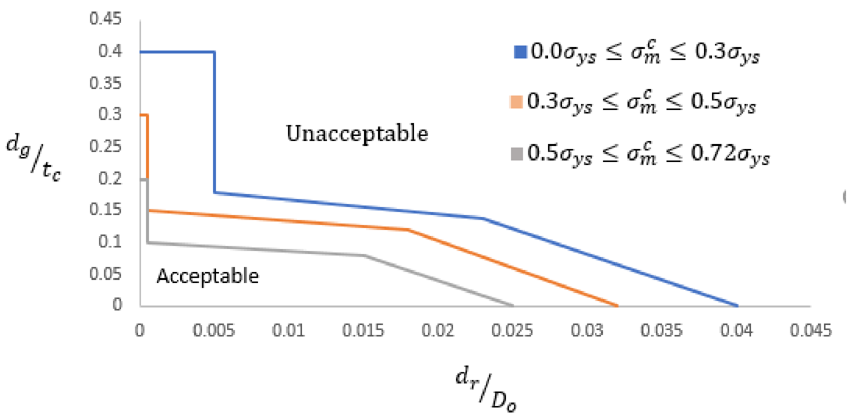

Figure 1: Level 1 Dent – gouge acceptance criteria (AP1, 2009)

CONCLUSIONS

This paper has evaluated integrity of 24inches diameter gas pipeline with dent and dent-gouge interaction defects. The dent assessment failed acceptance criteria for Level 1 and

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consequently impacted on the pipeline loading capacity and remaining cycles. Similarly, the dent-gouge interaction failed both Level 1 and Level 2 acceptance criteria for integrity assessment check. The integrity evaluation of the pipeline defects indicated high severity and potential risk of in service failure with attendant consequence. Therefore, pipeline is not fit to continue in operation based on the maximum operating pressure (6.5MPa) until is rerated to 3.35MPa or sectional replacement at the 7km and 22km points with dent and combination of dent-gouge defects respectively. Systematic fitness for service evaluation, employed in the case study was useful in quantifying the detected mechanical damage and taking informed decision of pipeline defects that required urgent attention or continual monitoring to ensure safe operation.

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