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Effect of the Orientation of Combined Dent and Gouge Defects on a Pipeline

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ABSTRACT

As part of recent work on the structural behaviour of API 5L X52 pipelines with combined dent and gouge defects, this paper addresses the effects of the defect orientation and pipe geometry on the strength and failure behaviour of pipelines loaded internally with uniform pressure. The commercial finite element software ANSYS in conjunction with the pipe material data characterized through experimental testing was employed in the investigation. A wide range of geometric parameters and orientation of combined dent and gouge defects was systematically selected and modelled with the pipe within the framework of the adopted numerical tool to analyse the influence of d/t ratio, dent and gouge depth, width and length on the structural response of the loaded pipelines. It was found that pipelines with a small d/t ratio are at greater risk of failure compared to large d/t pipelines. Similarly, in relation to the defect width, the defect length plays a more significant effect on the load-bearing capacity of pipelines.

1. Introduction

Buried or submerged oil and gas pipelines are prone to mechanical damage due to third party interference [1-4]. Reports on pipeline failures show that this form of damage is one of the leading causes of pipeline failure [5-8]. Hence, the structural integrity and management is very crucial [9-13]. A dent containing a gouge (known as a combined defect) in a pipeline is an example of a mechanical damage [5, 9-10], as shown in Figure 1.

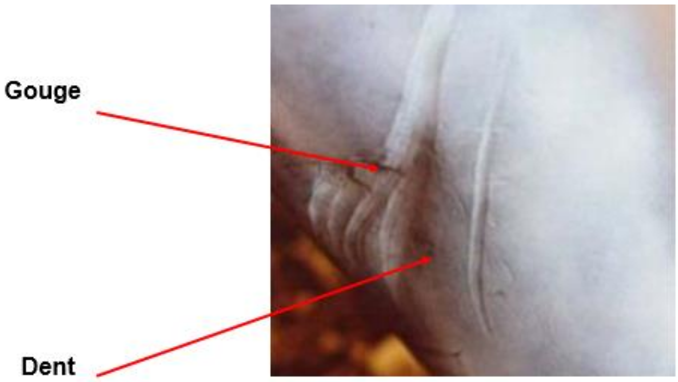

Figure 1: Pictorial presentation of the combined dent and gouge defect [5]

Studies in this field is said to still be at an immature stage because a full understanding of the behaviour of the defect is yet to be known. [8]. This is reflected in the variations in results obtained from the existing failure prediction models such as the Dent Gouge Fracture Model and the Empirical Q-Factor Model, when compared to results of actual experimental burst tests results [14]. Existing research works conclude that the accuracy of failure prediction models will be dependent on a clear understanding of the influence of parameters such as defect geometry, operating conditions, pipe geometry, material properties, indenter shape etc. [15]. Some of the existing research works have focused on performing burst tests using experimental or numerical methods to determine the structural response of combined dent and gouge defected pipelines [17-20]. While this has been adopted, the results obtained can be influenced by other factors apart from the defect itself such as in-situ conditions (buried lines or the support configuration at the test bench). Some results of existing studies have shown that failure occurred at locations outside the defect region [2].This is also coupled with the challenges associated with observing actual events leading to burst at the failure location when experimental testing is deployed. [16[With this observation, assessing the influence of the combined dent and gouge defect using the burst strength approach may not be the most effective way to gain better understanding of the influence of the defect and its parameters on pipeline structural integrity. There is need to adopt a methodology that focuses on the defect area. To this end, the investigation uses finite element method to investigate the triaxial stress distribution in the defect region of the pipeline and evaluate the sensitivity of defect parameters on the severity of the combined defect.

This paper reports some of the results of an ongoing research work at the University of Benin, evaluating the effects of the defect orientation and pipe geometry on the strength and failure behaviour of pipelines loaded internally with uniform pressure.

2. Methodology

The material used for the investigations is the API 5L X52 pipe grade. The material properties employed in this paper are obtained from an experiment, as adopted in [21]. The uniaxial tests performed on the mother pipe and the longitudinal seam weld are reported in Figure 2. The red curve in the plots represents the tensile properties of the mother pipe which is of interest in this investigation. For the material, the yield strength obtained is 435.22 MPa while tensile strength is 548.46 MPa. These were imputed into the finite element model within ANSYS using Equation (1) and (2). The model was developed to simulate a gouged pipe to be impacted by an indenter with dimension: 196mm X84mm X200mm. The outer diameter (OD) of the pipe and wall thickness (wt) are 610 mm and 7.9 mm, respectively. The length of pipe considered was 2500 mm with the defect located at the middle of the pipe. This satisfies the requirement to have the undamaged section of pipe be at least $10\sqrt{r_m t_r}$ from the defect area [23].

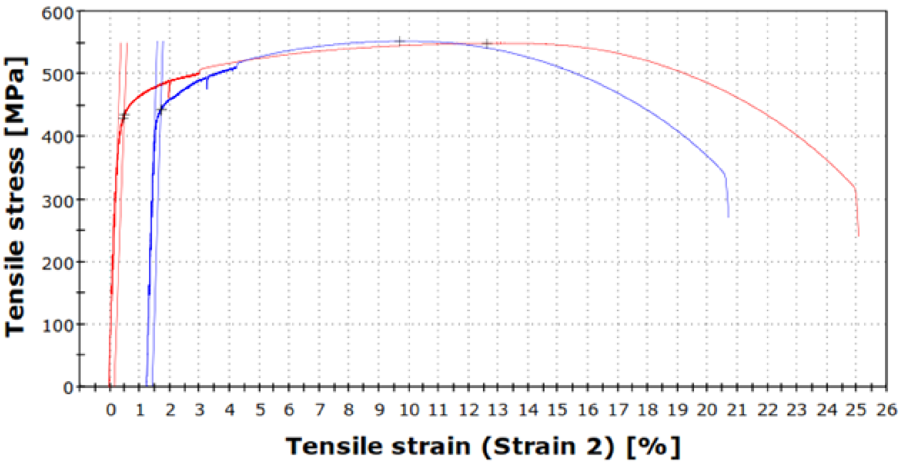

Figure 2: Stress-strain curves for API 5L X52 pipe

The numerical technique used in the numerical tool is the static, nonlinear (material nonlinearity and contact) analysis, employing the Newton-Raphson Method. A typical test set up of a pipe capped at both ends with an indenter positioned above it is shown in Figure 3 [17, 24]. The indenter meets the gouged pipe to create the indentation resulting in the combined dent and gouge defect. It was modelled as a rigid material (elastic) in the investigation. The pipe was anchored at the support locations and restricted from all translational and rotational movements at the anchor points. The defect is introduced at the pipe at the 12 O'clock position simulating a top of pipe defect resulting from contact with an excavator's tooth and an unconstrained dent. The length and width of the gouge were varied in line with the test requirement while other test parameters kept constant. In order to accurately predict the structural response to loading including elastic-plastic behaviour, the engineering stress-strain information obtained from uniaxial tensile test as shown in figure 2 was converted to true stress-strain values using the expressions in equations (1) and (2):

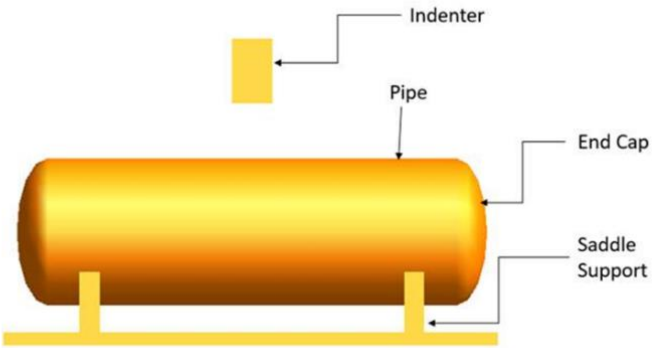

Figure 3: Test set up of Indenter and Pipe

$$S_{true} = S_{eng}(1 + e_{eng}) \tag{1}$$

$$e_{true} = \ln(1 + e_{eng}) - \frac{\delta_{true}}{E} \tag{2}$$

The pipe was modelled using the SOLID187 element, a 3D, 10-node element, while the indenter was modelled using the SOLID 182 element type, 3D, 4 node element. Contact surface was modelled using CON174 while the target surface was modelled using the element type TAR170 [25]. Free meshing was used with convergence obtained to determine optimum element size. To minimize computation time without compromising the integrity of results, the advantage of symmetry was taken (geometry, loading, boundary conditions, and material properties), since the model (including the indenter and support conditions) is symmetrical about the longitudinal axis (y=o), as shown in Figure 4.

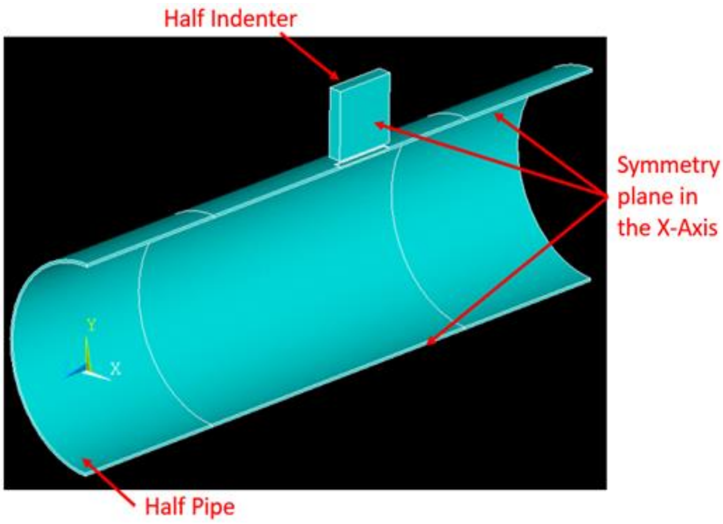

Figure 4: Half pipe model with symmetry planes and support locations

For the investigation performed to determine the influence of pipe geometry (d/t ratio) on the severity of the combined dent and gouge defect, a total of four finite element test models were developed. A range of pipe wall thicknesses were selected for the 24 NPS. The d/t ratios adopted are shown in Table 1.

Table 1: Test Matrix – Influence of d/t ratio

S/N	Specimen No	Outer Diameter (mm)	Wall Thickness (mm)	d/t ratio
1	S40-GD5-DD1-P50	610	7.92	77
2	S41-GD5-DD1-P50	610	10.31	59
3	S42-GD5-DD1-P50	610	14.27	43
4	S45-GD5-DD1-P50	610	17.48	35

To investigate the influence of defect orientation (gouge width and length), a total of 24 finite element models were developed. 12 models for the effect of gouge length and 12 models for the effect of gouge width,
For this study, the gouge depth and width were held constant for each test set while the gouge length varied as presented in Table 2. Following the results obtained from an earlier investigation on the influence of gouge depth which showed the severity increase with increase in gouge depth, it was decided that the most critical depths (i.e. gouge depth at 30%, 40% and 50% wall thickness) is to be considered only for this investigation. [21].

Table 2: Test Matrix – Effect of defect length

Specimen	Dent Depth (%OD)	Gouge Depth (% wt)	Gouge Width (mm)	Gouge Length (mm)
S08.GD3.DD1.P72	3	30	84	196
S60-GD2-DD2-P72	3	30	84	296
S61-GD3-DD2-P72	3	30	84	396
S62-GD4-DD2-P72	3	30	84	496
S09.GD4.DD1.P72	3	40	84	196
S63.GD2.DD1.P72	3	40	84	296
S64.GD2.DD1.P72	3	40	84	396
S65.GD3.DD1.P72	3	40	84	496
S10.GD5.DD1.P72	3	50	84	196
S66.GD4.DD1.P72	3	50	84	296
S67.GD3.DD1.P72	3	50	84	396
S68.GD3.DD1.P72	3	50	84	496

In the case of the investigations on the influence of gouge width, the gouge length and gouge depth were held constant while the width varied as indicated in Table 3

Table 3: Test Matrix – Effect of defect width

Specimen	Dent Depth (%OD)	Gouge Depth (%wt)	Gouge Width (mm)	Gouge Length (mm)
S69-GD1-DD2-P72	3	30	196	84
S70-GD2-DD2-P72	3	30	296	84
S71-GD3-DD2-P72	3	30	396	84
S72-GD4-DD2-P72	3	30	491	84
S73.GD1.DD1.P72	3	40	196	84
S74.GD2.DD1.P72	3	40	296	84
S75.GD3.DD1.P72	3	40	396	84
S76.GD4.DD1.P72	3	40	491	84
S77.GD1.DD1.P72	3	50	196	84
S78.GD2.DD1.P72	3	50	296	84
S79.GD3.DD1.P72	3	50	396	84
S80.GD4.DD1.P72	3	50	491	84

For these investigations, the dent depth and internal pressure were held constant at 3%OD and 0.72Py respectively.

Loading: The load stepping function in ANSYS was used to apply applicable loads. Loading of the structure was applied in 3 stages; (i) internal pressurization to 0.72Py, (ii) bringing the indenter in contact with the gouged region of the pipe and (iii) Unloading the pipeline system by removal of the indenter from contact with the pipe with the internal pressure maintained. The Loads (internal pressure and indentation loads) were applied in small increments of 1/200th. This is to allow for a gradual and uniform distribution of the load.

Failure Criteria: To establish failure criteria, ANSYS uses only the von Mises criteria in which the principal stress components are combined into an equivalent stress. This is as presented in Equation (3).

$$\sigma_{eq} = \frac{1}{2}\sqrt{(\sigma_h - \sigma_r)^2 + (\sigma_h - \sigma_l)^2 + (\sigma_h - \sigma_l)^2} \qquad (3)$$

For the purpose of this work, failure is deemed to have occurred when the equivalent stress exceeds the critical stress which in this case is the ultimate tensile strength of the material.

3. Results and Discussion

The parametric study was performed to determine the influence of defect geometry and defect extent (dent depth and gouge depth) on the severity of the combined dent and gouge defect. The investigations focused on the structural response at the defect area. To perform the investigations, a total of 10 No. test models were developed. The gouge depth varied from 30% up to 50% wall thickness while the internal pressure was held constant at 8.13 MPa (0.72Py). The permanent dent depth was held constant at 3% outer diameter for each of the test sets. Figure 5 presents the results obtained for the influence of pipe geometry while Figures 6 and 7 shows the results obtained for the effect of defect length and defect width respectively.

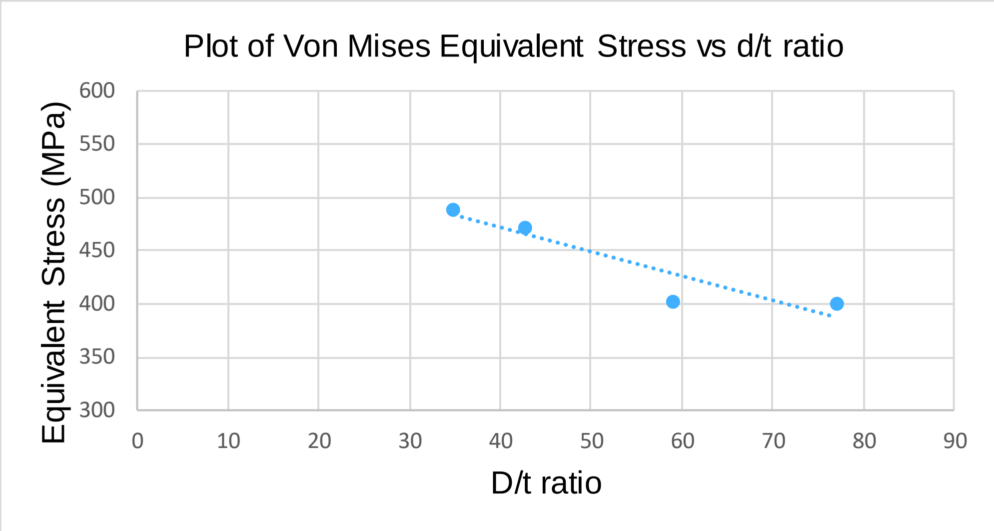

Figure 5: Influence of d/t ratio on stress distribution

Figure 5 shows the results obtained for the influence of pipe geometry. The trend observed in the results indicates a consistent decrease in equivalent stress with decrease in d/t ratio. The results implies that the severity of a defect resulting in a 50% loss of wall thickness is further amplified by the d/t ratio due to the large volume of geometric discontinuity. While it could have been envisaged that the thicker walled pipes should have a better load bearing capacity under constant internal pressure, the volume of metal loss is seen to play a significant role in its structural response to loading. It is seen that the lower d/t ratio results in a sharper defect geometry which in turn results in larger concentration of stress flowlines at the area of geometric discontinuity and as such, greater amplification of the stresses in the defect area.

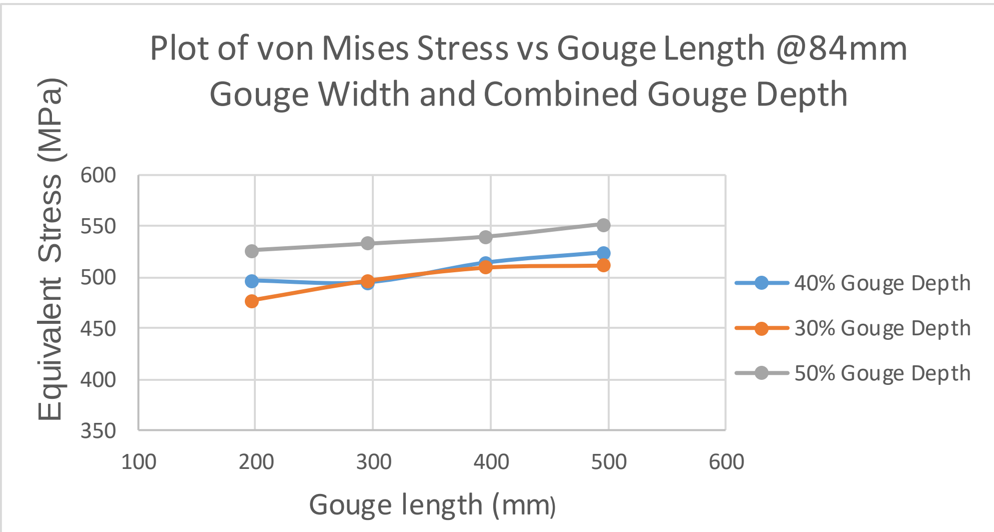

Figure 6: Plot of von Mises Stress vs Gouge Length @84mm Gouge Width and Combined Gouge Depth

Figures 6 show the results obtained for the influence of gouge length. From the results, it is seen that as the gouge length increases, the equivalent stress increases. The increase observed for each variation of defect length (a maximum of approx. 2.29%) is however not significant. This however differs from the results obtained to investigate the influence of gouge width presented in Figure 7. It shows that there is an insignificant deference (a maximum of 0.98%) in the results obtained as the width was varied. Such a variance in results obtained can be attributed to computational errors.

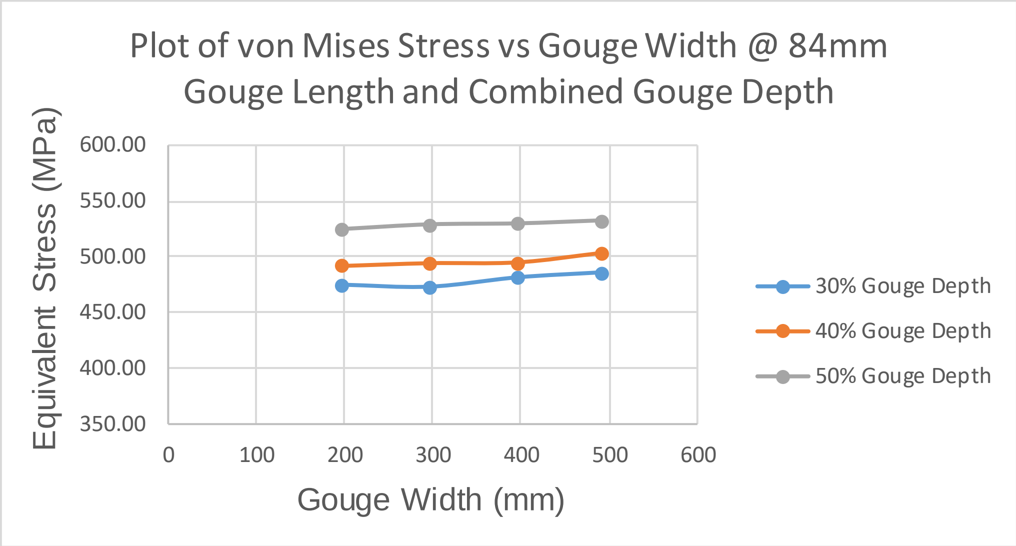

Figure 7: Plot of von Mises Stress vs Gouge Width @ 84mm Gouge Length and Combined Gouge Depth

4. Conclusion

This investigation was carried out to determine the influence of pipe geometry and defect orientation on the structural behaviour of pipelines with the combined dent and gouge defect with focus on the structural response at the defect region. From the results obtained, it is concluded that the d/t ratio influenced the severity of the combined dent and gouge defect, in which, the defect severity increased proportionally with a decrease in d/t ratio (i.e. an increase in the wall thickness at a constant outer diameter). While in defect free pipes, the load bearing capacity of the pipeline increases with a decrease in d/t ratio, it is of a disadvantage when it is subjected to the combined dent and gouge defect. The presence of a geometric discontinuity such as the combined dent and gouge defect reduces the load bearing capacity of the pipeline as the d/t ratio decreases. The parametric studies performed shows that the length component of the combined dent and gouge defect (i.e. metal loss progressively in the axial direction) has a greater influences on the defect severity whereas, the width of the defect (metal loss progressively in the circumferential direction) plays an insignificant role on the severity of the defect as there is no significant increase in equivalent stress induced as the defect width increased. It was also seen that the pipe geometry plays a more significant role when compared with the gouge width and length.

Nomenclature

3D	Three dimensional
D	Outer diameter
E	Young's Modulus
FE	Finite Element
FEA	Finite Element Analysis
OD	Outer Diameter
T	Wall Thickness
P	Internal operating pressure
Py	Yield Pressure
UTS	Ultimate tensile strength
wt	Wall thickness

Wt(%)	Percentage Weight
YS	Yield Strength

Greek letters

S_{eng}	Engineering Stress
S_{true}	True stress
e_{eng}	Engineering Strain
e_{true}	True Strain
σ_h	Hoop Stress
σ_r	Radial Stress
σ_l	Longitudinal stress
σ_{eq}	Equivalent stress
r_m	Mean radius
t_r	Required thickness
3D	Three dimensional
D	Outer diameter
E	Young's Modulus
FE	Finite Element
FEA	Finite Element Analysis
OD	Outer Diameter
T	Wall Thickness
P	Internal operating pressure
Py	Yield Pressure
UTS	Ultimate tensile strength

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