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Sensitivity of Defect Geometry in a Combined Dent and Gouge Defected Pipeline

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Abstract

Mechanical damage in pipelines that results from contact with a foreign body has been identified as one of the most common causes of pipe failure. The combined dent and gouge defect is considered a severe form of mechanical damage as it can lead to immediate rupture of the pipeline structure, posing a serious concern to the pipeline operators. Obtaining a clear understanding of this defect type and developing its accurate predictive and assessment models are currently receiving attention from the scientific community, including parts of the ongoing research activities at the University of Benin. The present paper reports the investigation into the influence of the geometry of combined dent and gouge defects on the load-bearing capacity of pipelines through finite element modelling developed with experimentally characterized pipe material data. It has been shown that the combined defects with gouge depth of up to 50% wall thickness do not result in rupture of the pipeline structure. And that, the dent plays a less significant role in the combined dent and gouge defect.

1. Introduction

Pipeline systems are considered critical assets in the transportation of hydrocarbon in both onshore and offshore environments. Considering cost-effectiveness, security and safety, pipeline system are the most preferred means of transporting crude oil, natural gas, multiphase hydrocarbon and other refined products from wellheads or production facilities to sales terminals and final end-users. Although pipelines have generally shown a good safety record over the years, there have been occasional incidents of failure [1-2]. This can be very catastrophic, leading to severe injuries, fatalities, loss of revenue, environmental damage, etc. Failures in pipelines have been attributed to issues such as material degradation (corrosion), mechanical damage resulting from third-party interference, construction issues, operations & maintenance. Mechanical damage is a localized damage to the pipe resulting from contact with a foreign body - third-party interference [3]. It has been identified as one of the major threats to the integrity of pipeline systems and a leading cause of pipeline failure in the United States of America, Canada, Europe and West Africa [4-6]. It can result in distortion of the pipe curvature (dent), scrape off from the pipe wall thickness (gouge) or a combination of both (dent and gouge) which is known as the combined defect. The combined dent and gouge defect has been identified as a severe defect by the ASME codes and pipeline asset owners and operators. This has led to several numerical and analytical studies, focusing on the behaviour of the defect with a view of providing a better understanding of how pipeline structures respond to such defects, and to establish a fitness for service assessment model [7-11].

However, even with the amount of information available from existing research work, a clear understanding of the underlying damage mechanisms and the development of accurate predictive models have not been completely achieved. The existing formula for the assessment of such defect (i.e. empirical Q factor model and the dent gouge fracture model) have their range of applicability limited to certain pipe grades, diameter and wall thickness. One of the limiting factors contributing to the gap in knowledge about the defect is the difficulty in assessing information from the metal loss or defected area during experimental investigations. This is because the gauges (such as strain gauges expected to measure parameters of interest) are damaged at the point of indentation. For this reason, other assessment methodologies (like the finite element method) that allow for the gathering of sensitive information during indentation and around the defected area have been deployed for the investigations. This also provides the flexibility of carrying out parametric studies on various defect geometries as it affects the behaviour of the pipe. This numerical approach using ANSYS coupled with experimental testing for key material properties have been employed in this paper, which reports some preliminary results from an ongoing research programme into the behaviour of pipelines with combined dent and gouge defect at the University of Benin.

2. Methodology

2.1 Material Characterization

Experimental testing was carried out on a sample pipe to obtain its mechanical properties and chemical composition. The following tests were performed as part of material characterization.

Chemical Composition: Chemical analysis was performed on the sample specimens using the spark atomic spectrometry method in accordance with the guidelines of ASTM E415 [12]. Two specimens were tested for chemical composition. Result obtained from the chemical analysis is presented in Table 1 below for the API 5L X52 pipe grade;

Table 1: Chemical Analysis Result

Elements	C	Si	Mn	P	S
- Wt (%)	0.0748	0.2620	1.4100	0.1026	0.0038
	0.1050	0.2650	1.4200	0.0120	0.0034
Elements	Cr	Mo	Ni	Nb	Ti
- Wt (%)	0.0221	0.0045	<0.0015	0.0340	0.0200
	0.0248	0.0048	<0.0015	0.0343	0.0206
Elements	V				
- Wt (%)	0.0028				
	0.0032				

Tensile Testing: This was performed to obtain the uniaxial tensile properties of the line pipe. This is performed in line with the requirements of ASTM E8 [13]. The test sample was obtained from the bare pipe. Dimensions of the test specimen are presented in Figure 1.

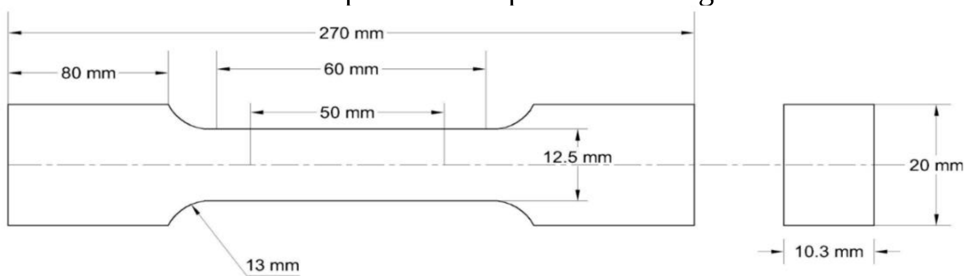


Figure 1: Rectangular tension test specimen

The specimens were subjected to uniaxial tensile load. Figure 2 shows the ruptured specimen attached to the Instron 6000DX tensile testing machine.

Figure 2: Ruptured tensile test Specimen

The Engineering Stress–Strain graph obtained from two of the test specimens is presented in Figure 3. The graph presents the results obtained from the mother pipe is presented in red while that obtained from the weld is presented in blue. The material properties of the mother pipe were used for this investigation as it is predominant.

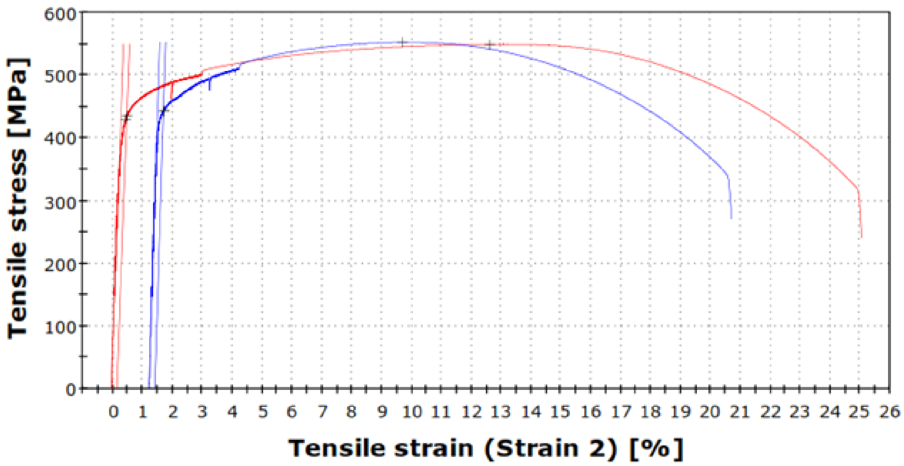


Figure 3: Stress-Strain Graph

From the test results, the YS and UTS obtained are 435.22 MPa and 548.46 MPa respectively. This test also provides details of the elastoplastic behaviour of the material (as shown in Figure 3) which served as an input to the finite element modelling and analysis.

2.2 Finite Element Modelling and Analysis

Finite Element Model: FEA models were developed to simulate the behaviour of the test specimens. The general purpose software ANSYS was developed for investigations. The numerical modelling technique considered static, nonlinear (material nonlinearity, geometry of deformation and contact) finite element analysis using ANSYS.

The pipe OD and wt. used is 24” (610 mm) and 7.9 mm respectively. The length of the pipe is 2500 mm and the defect with a length 196 mm located at the middle of the pipe. This satisfies the requirement to have the undamaged section of pipe be at least 10√rmtr from the defect area [14]. The indenter of dimension 196mm X84mm X200mm simulates a typical excavator tooth. Figure 4 presents a typical test set up of a pipe capped at both ends with an indenter positioned above it which comes in contact with the pipe to create an indentation. This simulates a typical test set up which has been used in several burst test analyses [16-19]. The pipe is anchored at the support locations and restricted from all translational and rotational movements at the anchor points.

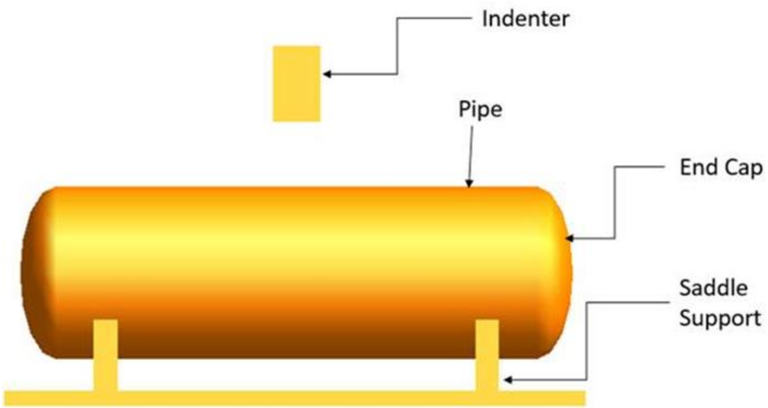


Figure 4: Test set up of Indenter and Pipe

Defect Location & Geometry: The defect is positioned at the center of the pipe at the 12 O'clock position simulating a top of pipe defect resulting from contact with an excavator's tooth. This is typically an unconstrained defect. The length and width of the gouge were kept constant at 196mm x 84mm while the gouge depth and other parameters were varied in line with test requirements.

Material model: During indentation, it is expected that the pipe material will experience stresses beyond yield leading to permanent plastic deformation. To accurately simulate the material response to loading including elastic-plastic (nonlinear) material behaviour, the engineering stress-strain information obtained from uniaxial tensile testing (including detail of the elastic-plastic region) was converted to true stress-strain values using the expressions in Equations (1) and (2).

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

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

The indenter was modelled as a rigid material (elastic). For this analysis, elastic-plastic isotropic hardening material properties were used in ANSYS.

Element Type and Meshing: The pipe was modelled using the SOLID187 element, a higher-order 3D, 10-node element. This element type was selected because of its suitability for integrating nonlinearities (material and geometric) and other true material behaviour needed for the analysis. The indenter was modelled using the SOLID 182 element type. A 3D, 4 node element. Contact and target surfaces were modelled using CON174 and TAR170 respectively [15].

Free meshing was used with convergence obtained to determine optimum element size as seen in Figure 5.

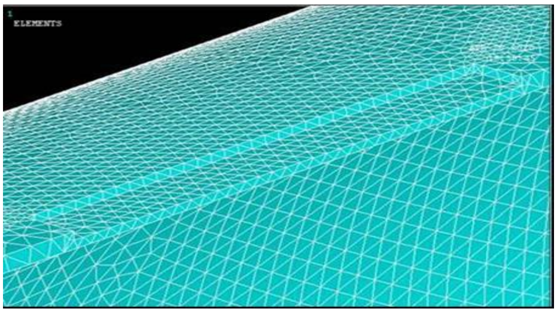
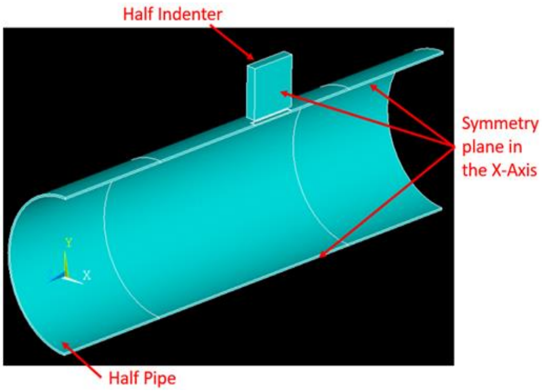
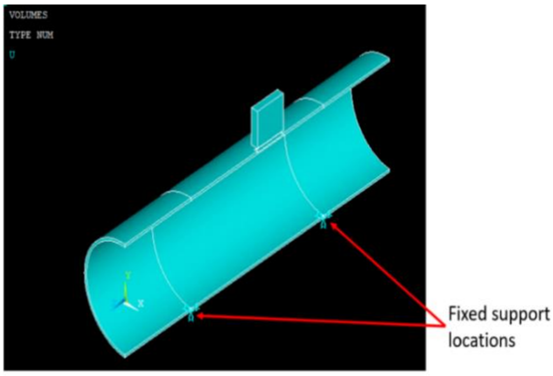


Figure 5: A Close view of the Meshed Structure

Loading and Boundary Conditions: To minimize computation time without compromising the integrity of results, the advantage of symmetry was taken (geometry, loading, boundary conditions, and material properties). The model was considered to be symmetrical about the longitudinal axis. In this case, half of the pipeline test set up and indenter were modelled. See Figure 6 (a). Displacement boundary conditions were also applied to the symmetry planes. The pipe was fully restricted at (zero displacement in all degrees of freedom) at the anchor locations as shown in Figure 6 (b)





(a) Pipe & indenter modelled with symmetry planes (b) Model showing anchor support locations

Figure 6: Half pipe model with symmetry planes and support locations

To perform the investigations, a total of 10 Nos. test models were developed to investigate the influence of gouge depth. The gouge depth varied from 10% up to 50% wall thickness. For this case, the internal pressure was held constant at 0.72Py. Two (2) sets of test models (5 models each) were used in the investigations. The permanent dent depth was held constant at 3% and 6% for each of the test sets while the gouge depth was varied. See Table 2 for the test matrix.

Table 2: Test Matrix – Effect of gouge depth

S/N	**Model Specimens**	**Gouge Depth**	**Dent Depth**	**Internal pressure**	**Dent Length**	**Dent Width**
		(%wt)	(%OD)	(MPa)	(mm)	(mm)
Set 1: (@3% dent depth, 0.72Py) – API 5L X52						
1	S06.GD1.DD1.P72	10	3	8.13	196	84

2	S07.GD2.DD1.P72	20	3	8.13	196	84
3	S08.GD3.DD1.P72	30	3	8.13	196	84
4	S09.GD4.DD1.P72	40	3	8.13	196	84
5	S10.GD5.DD1.P72	50	3	8.13	196	84
Set 2: @6% dent depth, 0.72Py – API 5L X52						
1	S16-GD1-DD2-P72	10	6	8.13	196	84
2	S17-GD2-DD2-P72	20	6	8.13	196	84
3	S18-GD3-DD2-P72	30	6	8.13	196	84
4	S19-GD4-DD2-P72	40	6	8.13	196	84
5	S20-GD5-DD2-P72	50	6	8.13	196	84

To investigate the influence of gouge depth a total of 10 models were also developed. In this case, the gouge depth was held constant while the dent depth varied between 0 to 6% OD. Table 3 presents the text matrix used for the investigations.

Table 3: Test Matrix – Effect of dent depth

S/N	**Specimen**	**Gouge Depth**	**Dent Depth**	**Dent Length**	**Dent Width**	**Internal pressure**
		(%wt)	**(%OD)**	**(mm)**	**(mm)**	**(%Py)**
1	S29.GD3.DD0.P72	30	0		84	
2	S08.GD3.DD1.P72	30	3		84	
3	S18.GD3-DD2-P72	30	6		84	
4	S30.GD4.DD0.P72	40	0		84	
5	S09.GD4.DD1.P72	40	3	196	84	72
6	S19.GD4-DD2-P72	40	6		84	
7	S31.GD5.DD0.P72	50	0		84	
8	S10.GD5.DD1.P72	50	3		84	
9	S20-GD5-DD2-P72	50	6		84	

Using the Load stepping function in ANSYS, loading was performed in 3 stages; (i) Internal pressurization of the pipe (0.50Py or 0.72Py), (ii) bringing the indenter in contact with the gouged region of the pressurized pipe (iii) Unloading the system by removing the indenter contact with the pipe while internal pressure remains the same. Loading was applied in small increments; 1/200th of load to be applied.

Table 1 and 2 presents the test parameters deployed to investigate the influence of gouge depth and dent depth respectively.

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 this investigation, failure is said to have occurred when equivalent stress exceeds the critical stress which in this case is the material ultimate tensile strength.

3. Results and Discussion

3.1 Model Validation

To ascertain the suitability of the finite element model to be used for the analysis, defect-free pipe models were developed and validated against the results obtained using Barlow's expression for hoop stress. It was also decided that a uniaxial field variable (hoop stress) be compared to avoid complexities in results obtained for the triaxial stress state which can be influenced by several other parameters including the support type, location, etc. The objective was to obtain results to be compared with that obtained from analytical results using Barlow's expression presented in Equation (4).

$$P = 2\ x\ UTS\ x\ \frac{t}{D} \qquad (4)$$

For the validation studies, several pipe geometries were considered for the mother pipe of interest. In this case, the nominal wall thickness for the 24" (610 mm) pipe was varied between 7.92mm to 17.48mm. Results obtained are presented in Table 4.

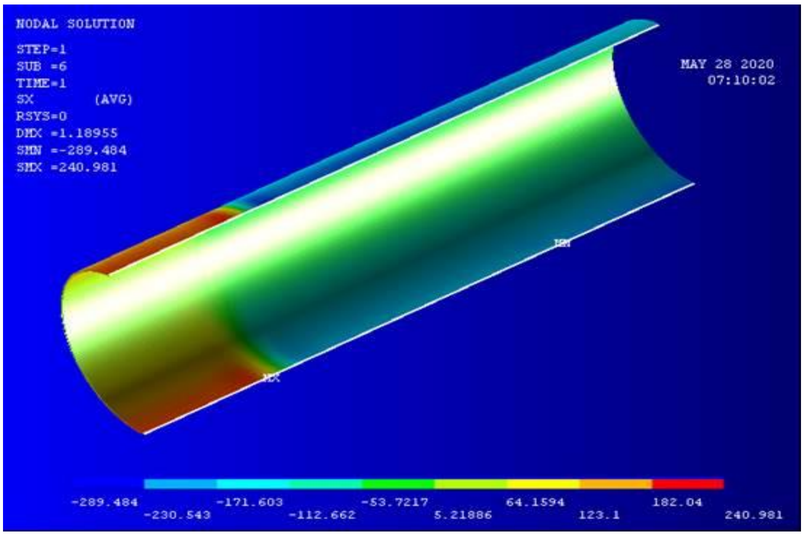


Figure 7: Model output

Table 4: Test Matrix – Finite element model validation results

NPS	Wall Thickness	Hoop Stress (Analytical)	Hoop Stress (FEA)	Deviation
-	mm	MPa	MPa	
24	7.92	217.58	240.98	-10.75
	10.31	167.14	164.66	1.49
	14.27	120.76	120.51	0.21
	17.48	98.58	103.43	-4.92

Results obtained from FEA give a maximum deviation of 10.5% which is considered acceptable and the model deployed for the investigations.

3.2 Parametric Study

A parametric study was performed to determine the influence of defect geometry (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 10% 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% and 6% for each of the test sets. Figure 8 and Figure 9 presents the results obtained for the influence of gouge depth on the severity of the combined dent and gouge defect at 3% dent depth and 6% dent depth respectively.

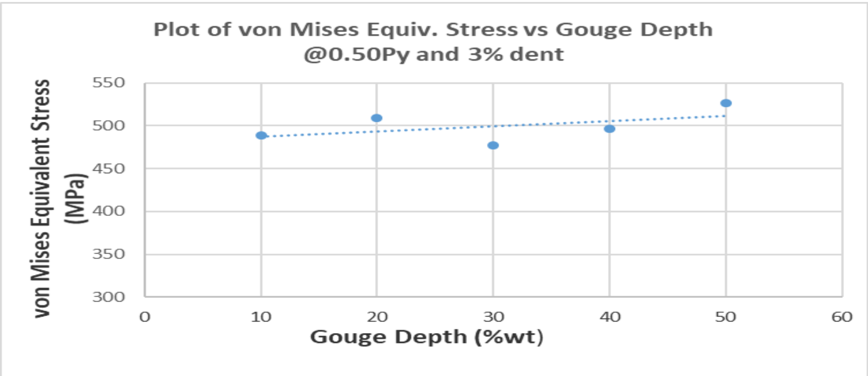


Figure 8: Effect of gouge depth on von Mises Equivalent stress at 3% OD dent

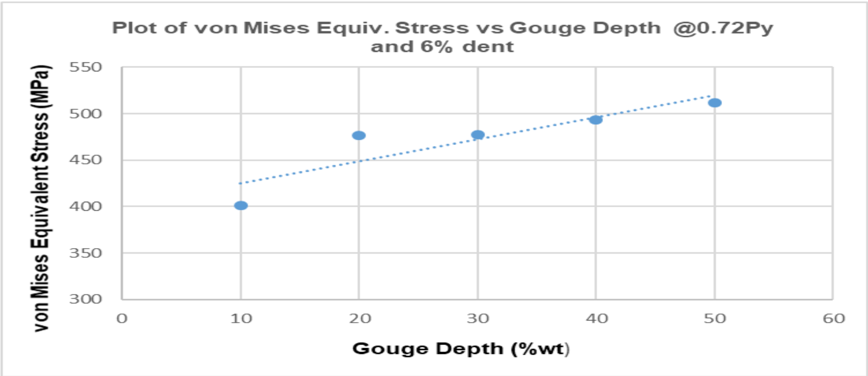


Figure 9: Effect of gouge depth on von Mises Equivalent stress at 6% OD dent

The influence of dent depth was also considered in the investigations to determine its influence on the defect severity. For this investigation, 18 No. test models were developed. For each test case, the gouge depth was held constant with the internal pressure while the dent depth varied between 0% OD, 3% OD and 6% OD. The investigations were performed under two internal operating pressure conditions. A total of 9 test models were developed for each internal pressure considered; 5.65 (0.5Py) and 8.13 MPa (0.72 Py). Following the results obtained from the investigations on the influence of gouge depth which showed the severity of the defect increasing with increase in gouge depth, it was decided that the most severe cases be used for the investigations. In this case, the gouge depth varied between 30%, 40% and 50% wall thickness.

Figures 10 and 11 show the plot of the results for the investigations performed at 0.72Py and 0.5Py respectively.

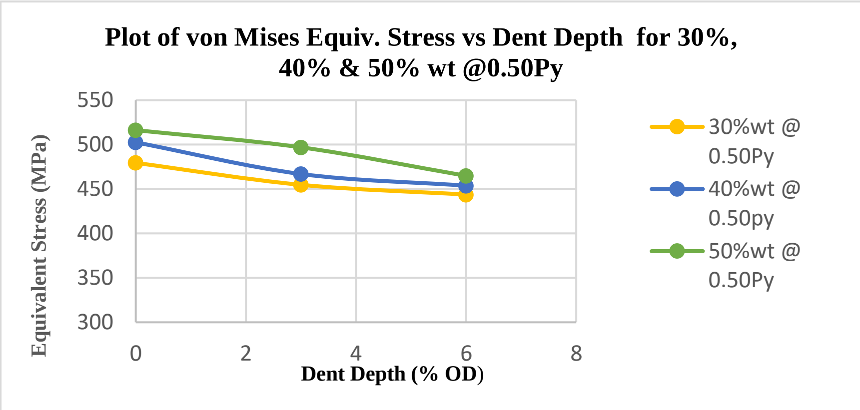


Figure 10: Effect of dent depth on Equivalent Stress at 0.72Py

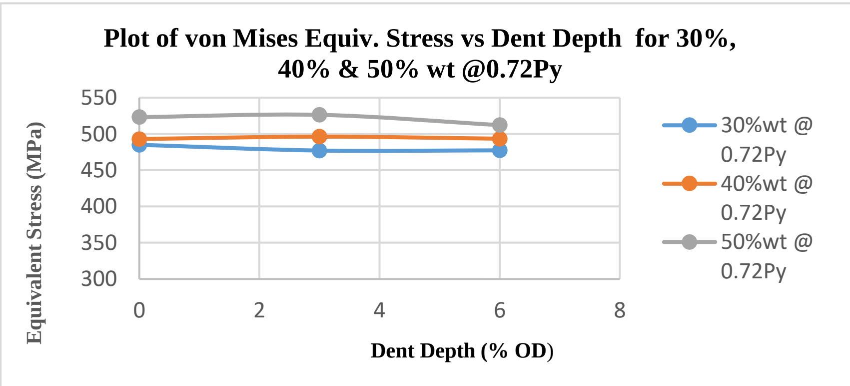


Figure 11: Effect of dent depth on von Mises Stress @ 0.5Py

3.3 Discussion

Figures 8 and 9 show that a reduction in wall thickness negatively impacts the load-bearing capacity of the pipeline. The investigations reveal that as the gouge depth increases, the induced stresses also increase and therefore pose a threat to its integrity. It shows that the induced stress is amplified at the metal loss area. This implies that the amount of metal loss experienced from the mechanical impact is critical to the pipeline's structural integrity and serviceability. This finding aligns with results of existing research works on the influence of gouge depth [19][20].

Furthermore, analysing the trend of the results shown in Figures 8 and 9, it is seen that the equivalent stress exceeds yield strength but at 50% wall thickness, the stresses do exceed the material UTS and as such, the defect does not result in rupture of the pipeline structure.

Figures 10 and 11 also present the results of the investigations performed to determine the influence of gouge depth on the severity of the combined dent and gouge defect. The results show that as the dent depth increases from 0 to 6% of outer diameter, the equivalent stress induced decreases with the most severe condition observed at zero dent depth. The results indicate that indentation which results in permanent plastic deformation does not severely negatively impact the load bearing capacity of the pipeline. This observation implies the plastic deformation resulting from cold working or strain hardening reduces stress amplification and as such plays a less damaging role in the severity of the combined dent and gouge defect.

Comparing the influence of each of the parameters of interest in this investigation, it is seen that the gouge depth plays a more significant role in the severity of the combined dent and gouge defect when compared with the dent depth.

4. Conclusion

The study was undertaken to investigate the influence of defect geometry on the load bearing capacity of pipelines with the combined dent and gouge defect, with a focus on the impact of dent depth and gouge depth on defect severity. The finite element method in which pipe material data obtained from experimental testing were employed in the models, was used in the investigation. The defect area with the pipe was the main reference area, to enhance understanding of how the structure respond to such a defect. The investigation revealed:

1) Stress amplification is observed as expected around the combined dent and gouge defected area, posing a severe threat to the integrity of pipelines.
2) Pipelines with the combined dent and gouge defect with a gouge depth greater than 10% wall thickness and up to 50% wall thickness experience stresses beyond material yield strength but do not lead to rupture at the defect area. In order words, for conditions considered, failure resulting in a leak or rupture will not occur due to this defect.
3) The degree of indentation, leading to work hardening of the pipeline material helps to reduce stress amplification at the defect region. This therefore implies that the indentation improves the structural response of the pipeline with the said defect as far as it does not lead to collapse or an unserviceable system.
4) Parametric study shows that the most critical defect component which determines the severity of the combined dent-gouge defect is the gouge depth. So, assessment and repair methodologies should be focused on methodologies that restore the structural strength of the pipeline with the combined dent and gouge defect.

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

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