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Factors Influencing the Severity of The Combined Dent and Gouge Defect – A Comparative Analysis

E. Anuge[a] and N. Enoma[a]

[a]Mechanical Engineering Department, University of Benin Nigeria
Correspondence: anugeemmanueloz@gmail.com, n.enoma@uniben.edu

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ABSTRACT

In the USA, Europe, Canada and West Africa, mechanical damage due to third-party interference has been identified to be a leading cause of pipeline failures. This type of damage results in either a dent, a gouge or a combination of both, known as the combined dent and gouge defect. 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. The severity of the defect has led to the ASME B31.8 design code prescribing a complete cutout and replacement of the defective section. This paper presents the sensitivity of the combined dent and gouge defect on an API 5L X52 pipe grade to critical parameters such as the defect size, orientation, d/t ratio and pipe geometry. Numerical investigations were performed to ascertain the influence of each of these parameters on the severity of the combined dent and gouge defect. The results from the investigation present a qualitative ranking of the defect parameters considered with the view of providing operators and pipeline asset owners a criticality ranking for the defects to aid repairs of defected structures in a manner that ensures the safe operation of their pipeline.

1. Introduction

Pipeline are critical assets to the oil and gas value chain. They have been used to transport liquid and gaseous hydrocarbon, water, slurries from source to destination for centuries. Over the years, they have been considered the most preferred means of transportation because of their cost effectiveness (compared to other means of transportation like road, rail, sea, and air), documented safety records and reliability in terms of security of supply. While pipelines have been adjudged to have good safe records, pipelines do occasionally fail. [1-2] Statistical reports reveal that mechanical damage due to third-party interference is a leading cause of pipeline failure. The PHMSA reports that it is the second largest cause of pipeline failure (second to corrosion) in the United States of America. The EGIG reports it as the largest cause of pipeline failure in Europe. In Canada, the Energy Research Conservation Board (ERCB) reports that Mechanical damage is the largest cause of pipeline failures. In Nigeria, it is recorded to be the second largest cause of pipeline failure. [4-6]. Mechanical damage due to third-party interference is defined as “Localized damage to the pipe resulting from contact with a foreign body” [3]. A severe form of mechanical damage is a combination of a dent and a gouge in a single defect known as a combined defect. It mostly occurs when excavation equipment impacts a buried pipe. See Figure 1.

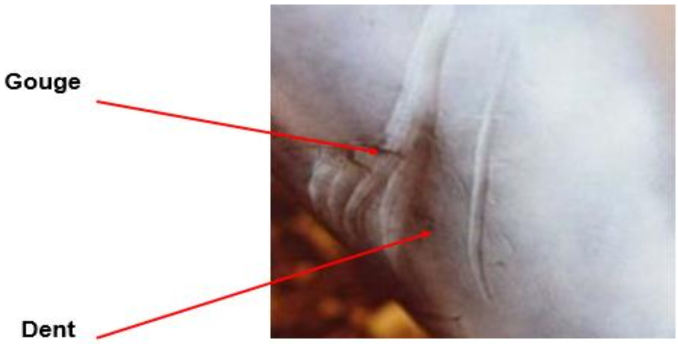


Figure 1. Pictorial presentation of the combined dent & gouge defect [3]

The combined dent and gouge defect has been identified as a severe defect by the ASME codes and by pipeline asset owners and operators as it poses a threat to the reliability and safe operation of the pipeline asset. The severity of this form of defect has led to several studies focused on the behaviour of the defect behaviour with a view of providing a better understanding of how pipeline structures respond to it and also, to establish a less conservative fitness for service assessment model [7-11]. However, even with this 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 achieved.

The existing models for the assessment of the said 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. Also, they have been adjudged to be overly conservative when used to predict failure pressure with a large degree of scatter when compared with experimental burst test results, implying that the current models do not sufficiently describe the structural response of pipelines to the defect. [21-22]

The gaps in the understanding of the structural response of pipelines with the combined defect have led to the prescription of the ASME codes setting criteria for assessment and limited beyond which, the defect area is to be cut out and replaced as a complete cylinder (including ref section). This has however been adjudged to be overly conservative. Earlier research works conclude that the key to a better understanding of the long-term integrity of pipelines with the combined dent and gouge defect is dependent on a clear understanding of the influence of each of the following parameters; Pipeline material properties, Defect geometry, Pipe geometry, Indenter shape, Operation pressure history at and following impact, etc. on the structural integrity of pipelines with the said defect [3][6]. Numerical method (Finite Element Analysis is deployed for the investigations as it allows for the flexibility of varying a single parameter while others are held constant as part of a parametric study to ascertain the influence of each parameter on defect severity. Also, with the method, the problem of damaged strain gauges during indentation is eliminated and as such, sensitive data at the defect location can be obtained. This research is part of an ongoing study at the University of Benin to investigate the influence of some physical parameters on the severity of the combined dent and gouge defect on an API 5L X52 pipe grade. The objective of this work is to perform a comparative analysis of some critical factors influencing the severity of the combined dent and gouge defect. The works consider the impact of gouge depth, gouge length, gouge width, dent depth, internal operating pressure and d/t ratio.

2. Methodology

The research method adopted was done in two stages. The first stage was performing experimental testing to aid material characterization. This included chemical composition analysis of the pipe specimens using the Spark Atomic Emission Spectrometry method in line with ASTM E 415, uniaxial tensile test by the requirements of ASTM A370 and ASTM E8, Charpy test using the Losenhausenwerk-Pendulum Impact tester by ASTM E23, and hardness test using Vickers testing machine in line with the requirements of ASTM E92. The material properties obtained will serve as input to the 3D finite element simulations developed using ANSYS 19.2. The Second stage of the analysis involved performing numerical investigations using the finite element simulation tool (ANSYS) to investigate the influence of each parameter of interest on the defect severity.

2.1. Material Properties

Tensile properties: Figure 2 shows typical dimensions of the test specimens deployed for tensile testing of the API 5L X52 pipe grade. Figure 3 presents the Engineering stress-strain curves of two specimens tested. The tensile properties obtained from specimen 1(presented in red on the graph) are used for the investigations with a yield strength of 435.22 MPa and an ultimate tensile strength is 548.46 MPa.

Using the expressions in Equations 1 and 2, the engineering stress-strain data were converted to the true stress-strain values to be deployed in the FE tool.

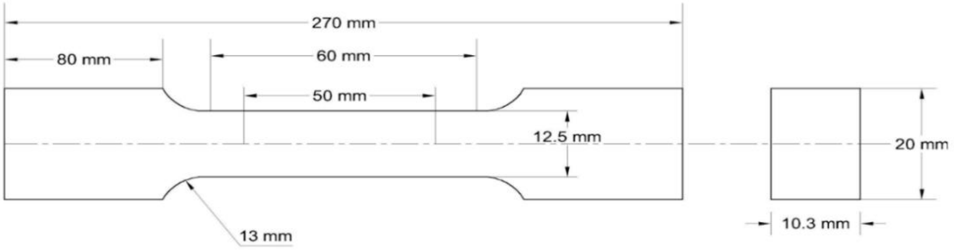


Figure 2. Uniaxial tensile test specimen

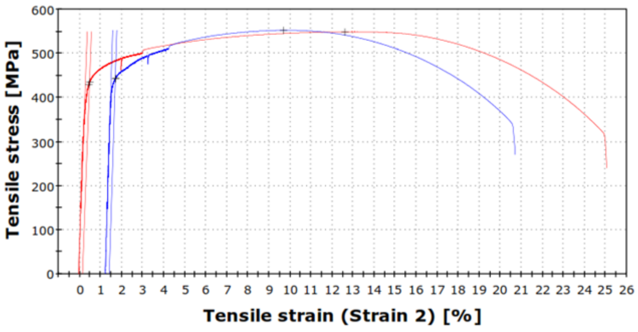


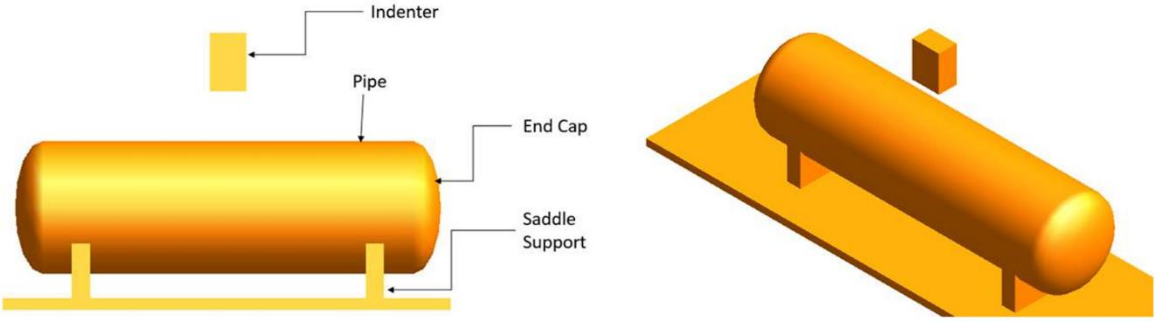
Figure 3. Engineering stress-strain curves for API 5L X52

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

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

2.2 Finite Element Modeling and Analysis

2.2.2 Finite Element Model: 3D Finite Element Model of a pipe with a gouge modelled as a rectangular (representing metal loss from impact from a typical excavator tooth) was generated using solid 3D elements replicating the test set up presented in Figure 4. The indenter was also generated using solid elements. Boundary conditions replicating the test set up and symmetry were applied.



Test set up view - Elevation

Test set up view - Isometric

Figure 4. 3D view of test set up

Appropriate mesh density was adopted from a preliminary study of mesh convergence. Using contact analysis, the indenter was made to contact the pipe model to simulate indentation at the gouged region while the pipeline was under internal pressure. Elastic-plastic analysis was performed to determine the stress distribution for a defect free pipe. The results were compared with analytical results obtained from Barlow’s expressions as recommended by the ASME codes (ASME B31.8, 2014; ASME B31.4, 2012). The results presented in Figure 5 shows a good correlation.

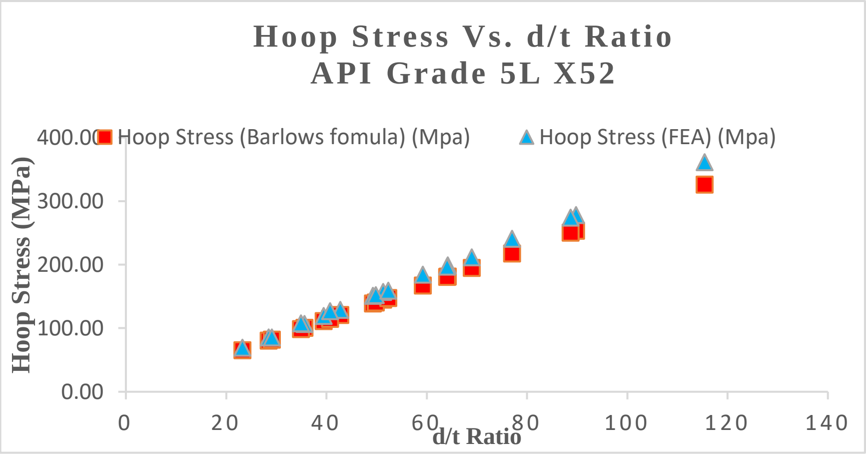


Figure 5. Comparison: ASMEs Barlow's Formula vs FEA for defect free pipes

Following the model validation, a parametric study was performed to investigate the influence of defect geometry, pipe geometry and internal operating pressure on the structural behaviour of in-service pipelines. This sensitivity analysis aided the assessment of the effect of each of the aforementioned parameters on the severity of the combined dent and gouge defect and the performance of a comparative analysis to ascertain the most critical defect parameters

2.3. Parametric Studies

2.3.1 Effect of Combined Dent and Gouge Defect on Pipeline Structural Integrity

To enhance this investigation, a series of finite element models were developed to investigate the influence of varying parameters on the stress distribution at the defected area of the pipeline structure. The parameters varied includes gouge depth, dent depth, Internal operating pressure, pipe geometry (d/t ratio), gouge length and gouge width.

2.3.2. Tests on the effect of Gouge Depth

The influence of gouge depth on stress distributions around the defect area was investigated using 2 sets of test samples. The first set of test specimens had the gouge depth varied from 10% wall thickness up to 50% wall thickness with 10% increase in gouge depth at every interval. The permanent dent depth was held 3%. The second set of test samples maintained the same variations in gouge depth but with a permanent dent depth of 6%. For both test sets, the internal pressure was held constant at 8.13 MPa (0.72Py).

Tests on the effect of Dent Depth. For this investigation, 6 sets of test samples were used with gouge depth varying between 30%, 40% and 50% of pipe wall thickness at 0.50Py and 0.72Py. The decision to use the varying gouge depths considered was because they had been established to be the most severe cases during the investigation of the influence of gouge depth. A total of 18 tests models were developed, nine (9) test models for each operating pressure. For each test set, the internal pressure was held constant at 5.65 MPa (0.5Py) and 8.13 MPa (0.72Py) respectively.

2.4 Tests on the effect of Internal pressure

For this analysis, 2 sets of test specimens were used. For each set, internal pressure was varied for 0.2Py, 0.3Py, 0.4Py, 0.5Py, 0.6Py and 0.72Py. For each case, the gouge depth was held constant at 30% of pipe wall thickness for test sample set 1 and 50% of pipe wall thickness for test sample set 2. The dent depth was held constant at 6% of outer diameter for both test sets used in the investigation. The maximum internal pressure considered was held at 0.72Py and this is the maximum allowable operating pressure recommended by the ASME B31.4 and ASME B31.8 design codes.

2.5 Tests on the effect of Pipe Geometry

For this investigation, the influence of d/t (diameter to thickness ratio) was investigated.
For this analysis, five different pipe wall thicknesses were considered for the 24 inches diameter

pipe. This gave a d/t ratio of 32, 35, 43, 59 and 77 for the respective wall thicknesses. Gouge depth and dent depth held constant at a 50% wall thickness and 3% outer diameter respectively, while Internal pressure was held constant at 0.5Py (5.65 MPa).

2.6 Tests on the effect of Defect Length

For this investigation, the gouge length was randomly selected to vary between 196mm to 596 mm while the gouge width, dent depth, and internal pressure was kept constant at 94mm, 3% outer diameter and 0.72Py(8.13MPa) respectively. The investigations were performed for three sets of varying gouge depth (i.e., 30%, 40% and 50% of pipe wall thickness).

2.7 Effect of Defect Width

For this investigation, the dent depth and internal pressure were kept constant at 3% outer diameter and 0.72 Py respectively. The gouge depth was also held constant for each test set. The gouge depths were held at 30% wall thickness, 40% wall thickness and 50% wall thickness for the varying dimensions of defect width. The gouge width was randomly selected to vary between 196mm to 596 mm while the length was held constant at 84mm.

3. Results and Discussions

3.1 Parametric Study

A validated FEA model from an earlier study was used to perform the parametric studies. The parametric study was performed to determine the influence of defect geometry, pipe geometry and internal operating pressure on the severity of the combined dent and gouge defect. The investigations focused on the structural response at the defect area.

3.2 Results on the influence of Gouge depth

Figure 6 presents the results obtained for the influence of gouge depth.

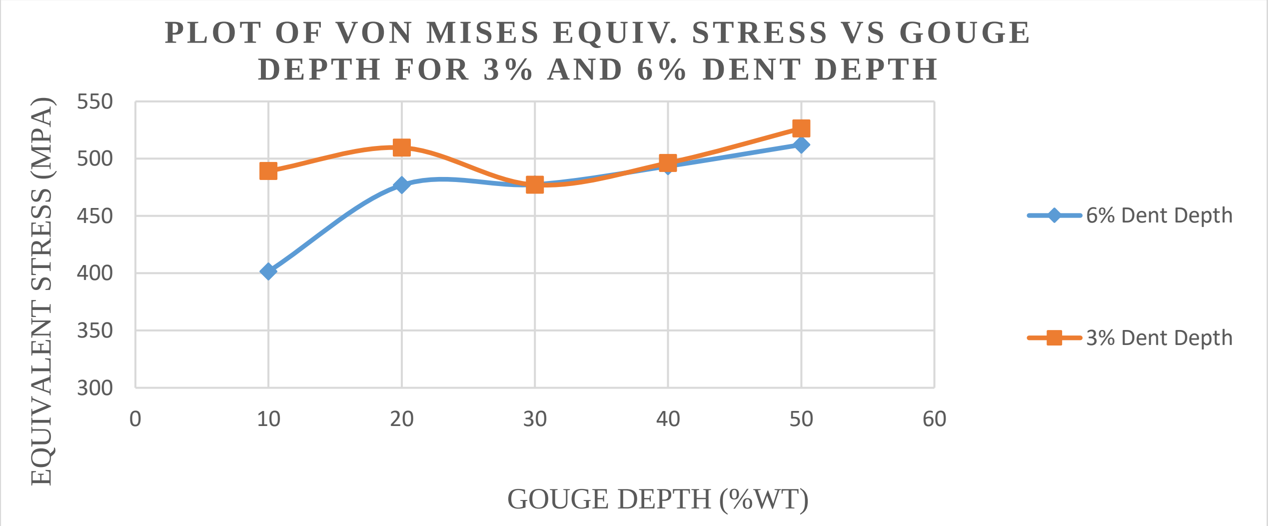


Figure 6: Comparison: Combined plot showing effect of gouge depth

From the results presented in Figures 6, it is observed that there is a consistent increase in equivalent stress as the gouge depth increases from 10% to 50% of pipe wall thickness.
From the results obtained at a constant dent depth of 3% outer diameter, it is seen that the induced equivalent stress increases from 489.29 MPa at 10% gouge depth to 526.37 MPa at 50% gouge depth, a percentage increase of 7.04%. It is also observed that the induced equivalent stress changes at an average of 3.92% for every change in gouge depth considered. It is however also observed that as the gouge depth increased from 20% to 30% in wall thickness, there was a deviation from the results trend where a decrease in equivalent stress was observed. It is also seen from the results that the induced equivalent stress at the minimum gouge depth considered (10% pipe wall thickness) exceeds the material yield strength but is below the ultimate tensile strength.

The results presented in Figure 4.4, which also shows the outcome of the influence of gouge depth when the dent depth is held at 6% outer diameter also shows a consistent trend of an increase in equivalent stress as the gouge depth increases. The most significant change in equivalent stress occurs when the gouge depth increases from 10% wall thickness to 20% wall thickness, an increase of 15.78% after which the increase in equivalent stress increases averagely at a rate of 3.46%. The change in equivalent stress from minimum gouge depth (401.6MPa) to the maximum gouge depth (512.21MPa) results in an increase of 21.59%. It is also seen from the results that at 10% gouge depth, the equivalent stress does not exceed the material yield strength. However, as the gouge depth exceeds 10%, and up to 50% of the pipe wall thickness (limit considered in this work), the equivalent stress exceeds material yield strength but is below the ultimate tensile strength. This implies that while the induced equivalent stress falls within a range not acceptable by the design codes (i.e. equivalent stress shall not be greater than 90% of yield strength), it does not result in leak or rupture of the pipeline structure. It was also observed that the stresses induced on the pipeline was lesser for the 6% dent depth when compared to the 3% dent depth.

From the results obtained, it is seen that the combined dent and gouge defect negatively affects the load bearing capacity of the pipeline structure and is a severe threat to pipeline structural integrity. Analysing the trend observed in the results, it is observed that the load bearing capacity of the structure (pressure containment) decreases as the gouge depth increases, implying that the amount of metal loss experienced from the mechanical impact is critical to the pipeline structural integrity. It is also observed that a loss in wall thickness of up to 50% does not result in failure at the defect area. The fact that the equivalent stresses induced does not exceed the material ultimate tensile strength indicates that rupture does not occur under static loading at the defect area. These findings agree with previous studies performed by Zarea et al. [24].

3.3 Results on the influence of Dent depth

Figures 7 and 8 presents the results obtained for the influence of dent depth.

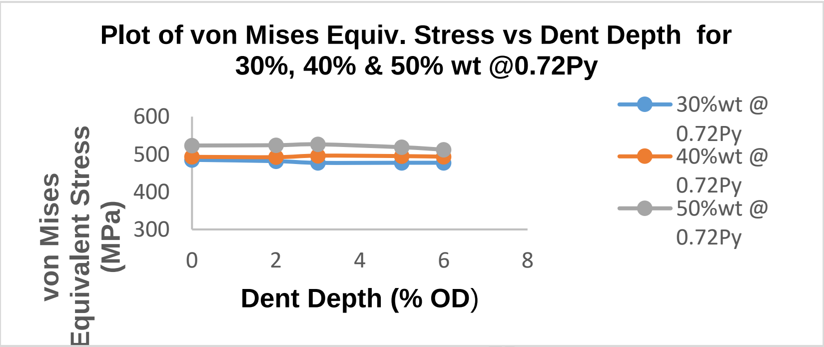


Figure 7. Plot of Equiv. Stress vs Dent Depth for 30%, 40% and 50% gouge depth at 0.72Py

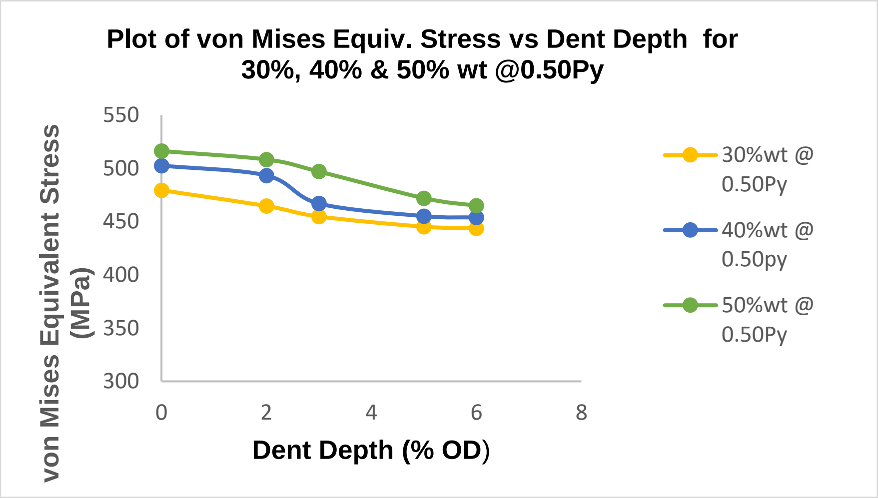


Figure 8. Plot of Equiv. Stress vs Dent Depth for 30%, 40% and 50% gouge depth at 0.50Py

From Figure 7, which presents the results of the investigations performed at a constant operating pressure of 0.72Py, the results show that at zero indentation, (i.e. gouging without permanent indentation), the pipeline structure experience the maximum induced equivalent stress for all cases considered. As the indentation progressed from 0 to 6% OD, the induced equivalent stress reduced consistently. This was consistent for all the gouge depths considered. It was also observed from the results that at 30% gouge depth, the induced stress reduced from 485.07MPa to 477.42MPa, at 1.58%. However, at 40% gouge depth, the induced stress varied upwards to a maximum of 496.27 MPA and then a decline in induced stress experienced at 50% gouge depth wherein the induced stress reduced consistently from 523.2 MPa to 512.21 MPa, a percentage decrease of 2.10%. Also, in all cases considered under the test set, it was observed that the induced equivalent stress was above the material yield but below the ultimate tensile stress.

Also, from the results presented in Figure 8 which shows the results obtained while holding the internal operating pressure at 0.5Py, it is observed that when the gouge depth was held at 30% wall thickness, the induced stress reduced from a maximum of 479.44 MPa at 0% dent to a minimum of 443.76MPa at 6% gouge depth, a percentage decrease of 7.44%. When the dent depth was varied while holding gouge depth at 40%, the results show that the maximum induced equivalent stress was obtained at 0% dent depth (502.55 MPa) while the minimum was obtained at 6% dent depth (453.83 MPa), a percentage decrease of 9.69%. Also, the results obtained while varying the dent depth with the gouge depth held constant at 50% wall thickness shows the maximum stress induced at 0% dent depth (516.25 MPa) and the minimum obtained at 6% dent depth (464.88MPa).

The results presented in Figure 4.5 and 4.6 establishes a consistent trend of a decrease in stress amplification as the dent depth increases. It indicates that indentation, which results in permanent plastic deformation impacts the load bearing capacity. It is seen that the degree of plastic deformation due to indentation load, which results in cold working or strain hardening of the material, reduces the rate of stress amplification in the defect area by reducing the effect of the gouge. It is seen from the results of all the test cases considered in this investigation that the induced stress does not exceed the pipe material's ultimate tensile strength, and as such, rupture does not occur when a pipeline with the simulated defect parameters is subjected to internal pressure loading. The analysis of these findings aligns with works earlier performed, wherein they observed an increase in load bearing capacity as dent depth in the combined dent and gouge defect increased [2][18][25].

3.4 Results on the influence of Internal Pressure

Figure 9 presents the results obtained for the influence of internal pressure.

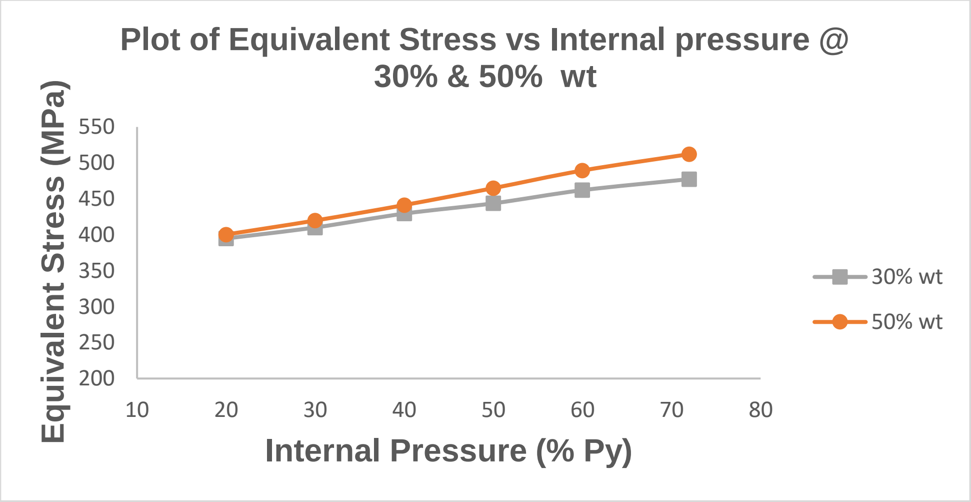


Figure 9: Effect of Internal pressure on Equivalent stress (gouge depth of 30% & 50% wt)

From Figure 9, it is observed that there is a consistent increase in induced equivalent stress as the internal pressure increased. At the minimum internal pressure considered and up to 40%Py, the equivalent stress does not exceed the material yield strength. This applies to both cases considered wherein the gouge depths were held at 30% pipe wall thickness and 50% pipe wall thickness. This implies that at gouge depth of 50%, the pipeline can remain in service subject to the internal operating pressure not resulting in stresses greater that 40% of material yield (i.e. 0.4Py). At 50% and beyond within the pressure range considered for this investigation, the induced equivalent stress exceeds the material's yield strength but is however below the ultimate tensile strength. This implies that while the stresses are above the recommendations of the design codes (i.e. equivalent stress should not exceed 90% of the materials yield strength), it does not lead to rupture of the pipeline structure. Summarily, the level of stresses induced on a pipeline structure is a function of the loads and in this case, the internal pressure it is subjected to.

3.5 Influence of Pipe Geometry Results

Figure 10 presents the results obtained for the influence of d/t ratio on defect severity.

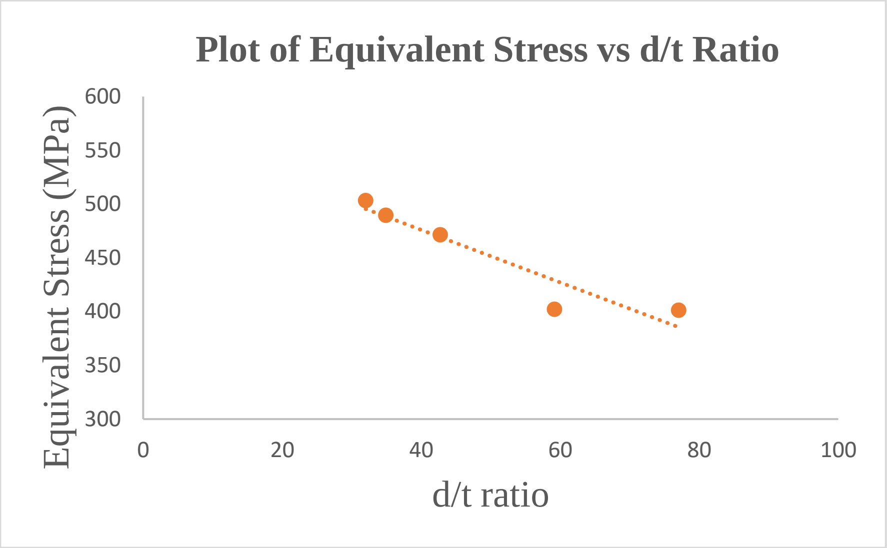


Figure 10. Effect of d/t ratio on Equivalent stress

The results obtained as shown in the plots suggests that the d/t ratio has an impact on the load bearing capacity of pipelines with the combined dent and gouge defect. From analysing the results trend, it is observed that there is a consistent decrease in equivalent stress as d/t ratio increases. As the d/t ratio decreased, implying an increase in pipe wall thickness for the constant outer diameter (OD) considered, the induced equivalent stress increased. Figure 10 shows that the maximum equivalent stress occurred at a wall thickness of 19.05mm, a d/t ratio of 32.

The minimum stress amplification occurred when the wall thickness was set at 7.92mm, a d/t ratio of 77. The greatest change in the equivalent stress occurred when the d/t ratio varied from 59 to 43 and this can be attributed to the fact that it accounts the largest change in wall thickness for the range considered. These observations and findings deviate from the works performed by (Zhao, et al.) who investigated the influence of d/t ratio on the burst strength and found it to increase with increase in d/t ratio [11].

The maximum stress amplification observed at d/t ratio of 32 can be attributed to the fact that the volume of metal loss for the thicker walled pipes (lower d/t ratio) is larger and results in a sharper defect geometry and geometric discontinuity when compared with those produced by the pipes with higher d/t ratio under constant operating conditions hence, the higher stress amplification. This would also suggest that for a d/t ratio less than 59, there is a risk of amplification of stresses beyond the material yield and as such greater severity when compared to that of pipelines with d/t ratio above 59. This makes d/t ratio a critical parameter to be considered when performing engineering critical assessment of pipelines subjected to the combined dent and gouge defect.

3.6 Effect of Defect Length Results

Figure 11 presents the results obtained for the influence of gouge length on defect severity.

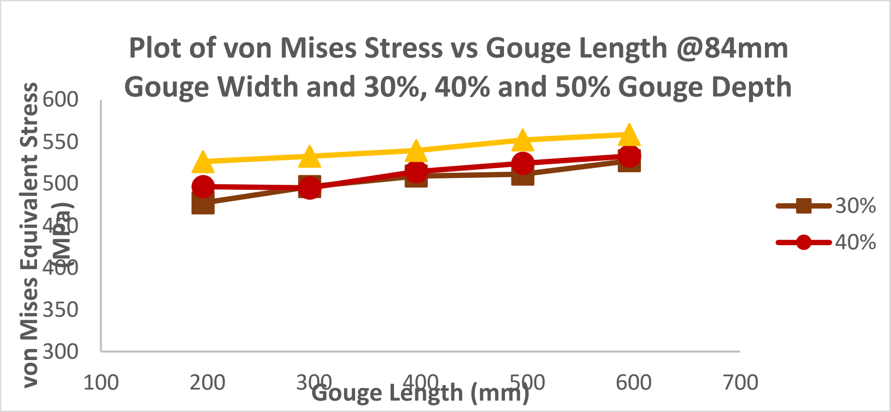


Figure 11: Plot of Equivalent Stress vs Gouge Length at 84mm Gouge Width and Combined Gouge Depth

The results show that the gouge length has an impact on the load-bearing capacity of a pipeline with the combined dent and gouge defect. It shows that there is a small but consistent increase in the induced equivalent stress as the gouge length increases from 196mm to 596mm. The findings from this investigation align with the work performed by (Zhao, et al.) wherein they also found that the defect length in the combined dent and gouge defect impacts negatively, the integrity of the pipeline structure [11].

A maximum increase of 2.24% in equivalent stress is observed per unit change in defect length and this occurs at the most severe case of metal loss in terms of depth (i.e. at 50% of pipe wall thickness) and a change in length of between 396mm to 496mm. It is also important to note that when the gouge length was extended from the minimum length (196mm) to the maximum length considered (596mm), at a less severe gouge depth of 30% pipe wall thickness, the induced equivalent stress was below the ultimate tensile strength as it grew from 477.14MPa to 527.23MPa, a percentage increase of 9.50%. At 40% gouge depth, the equivalent stress increased from 496.67MPa at a minimum length of 196mm to 532.96 MPa at the maximum length, a percentage increase of 6.81%. At 50% gouge depth, the equivalent stress increased from 526.37MPa at the minimum length to 558.67MPa at the maximum length, resulting in a percentage increase of 5.78%.

From these observations, it is seen that there is a consistent decrease in the impact of the gouge length with an increase in gouge depth suggesting that the gouge length begins to have a lesser impact on the defect severity as depth increases.

From these findings, it can be deduced that the influence of the gouge length, while having a deleterious impact on the integrity of pipeline structures, is not as significant when compared with the metal loss in terms of gouge depth. It also suggests that at a certain gouge depth, the impact of the length and other defect parameters becomes insignificant.

3.7 Effect of Defect Width Results

Figure 12 presents the results obtained for the influence of gouge width on defect severity

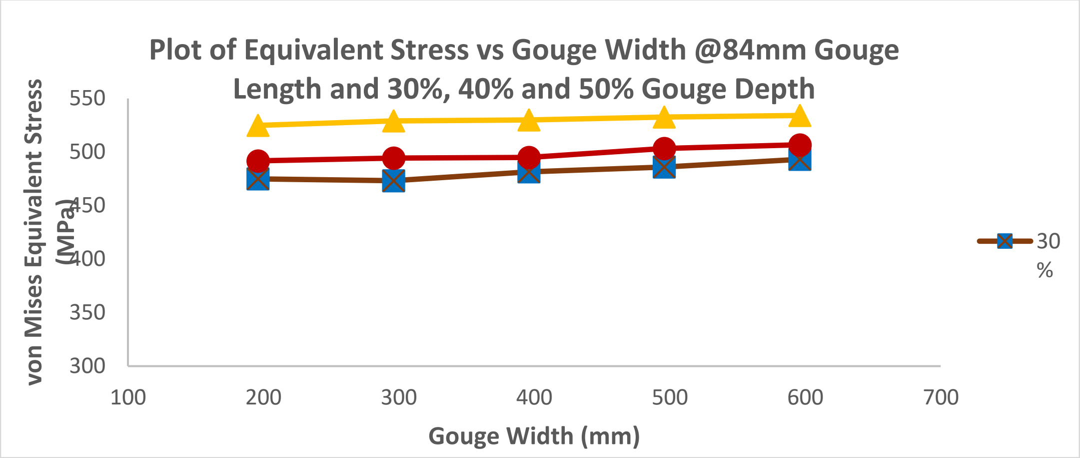


Figure 12. Plot of von Mises Stress vs Gouge Width at 84mm, Gouge Length and Combined Gouge Depth

The results show that the defect width does result in very minimal amplification of stress at the defect area. The increase in equivalent stress was consistent for the investigations at 30%, 40% and 50% gouge depth with a variance only observed at 30% gouge depth and at a gouge width of 296mm. This is seen to have resulted in a decrease in equivalent stress from 475.04MPa to 473.22MPa (0.04% decrease), a variance which is not significant. From analyzing the results trend, it is also seen that there is consistent amplification of stress even though very minimal. The results also show that from the minimum to maximum defect width considered, the equivalent stress induced does not exceed 2.4%, which occurs at 40% loss in wall thickness.

The results also reveal that, at 50% wall thickness, the effect of the defect width diminishes with the resultant percentage increase in induced stress from minimum to maximum range, considered equal to 1.5% as compared to the percentage variance of 2.3% and 2.4%, for the investigations performed at 30% and 40% wall thickness respectively. This implies that as this gouge depth increases, the influence of the gouge width becomes insignificant. The results therefore indicate that the defect width has very little influence on the severity of the combined dent and gouge defect.

Comparing the influence of each of the parameters considered for the investigations; dent depth, gouge depth, gouge length, gouge width, internal operating pressure conditions, and pipe geometry, it is seen that the degree of metal loss (in terms of gouge depth) most severely influences the load bearing capacity of pipelines with the combined defect. The degree of metal loss influences the impact of other parameters. The indentation (permanent deformation) which results in work hardening of the material, helps to reduce the stress amplification effect at the defect area under, due to material cold working resulting from the indentation process. With the observations and findings from the results presented, it can be adjudged that defect assessment and repair methodologies for pipelines with the combined dent and gouge defect should focus on an approach that restores pipeline structural integrity by compensating for metal loss

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 the following conclusions are reached:

1) Pipelines with the combined dent and gouge defect with a gouge depth up to 50% wall thickness can result in stresses beyond material yield strength but do not lead to rupture at the defect area. In order words, for the conditions considered, failure resulting in a leak or rupture will not occur due to this defect under normal operating conditions.
2) The other hand, the degree of indentation, leading to work hardening of the pipeline material helps to reduce stress amplification at the defect region. The length component of the combined dent and gouge defect has a greater influence on the defect severity when compared to the width with the defect later having the least impact on defect severity.
3) The influence of d/t ratio on the severity of the combined dent and gouge defect is only next to that of the influence of gouge depth. Assessment methodologies for performing fitness for service should take into consideration, the influence of this parameter.
4) The internal operating pressure conditions influences the ultimate structural response of pipelines to the said defect. Its impact can be immediately mitigated if the internal operating pressure is reduced to 40% of the design pressure. At this point, the induced equivalent stress is below yield and code compliant.
5) The most critical defect component that controls the severity of the combined dent and gouge defect is the gouge depth. It is concluded that assessment and repair methodologies should be focused on methods that restore the structural strength (i.e. by pipe wall reinforcement) of the pipeline with the combined dent and gouge defect. Specifically, Type A and Type B sleeves which are full encirclement and load bearing can be used to repair defects with gouge depth up to 50% wall thickness and dent depth of up to 6% outer diameter. In addition, the current prescription of the ASME design codes in Section 434.5 for ASME B31.4 and Section 851.4 for ASME B31.8, which currently recommends the need to cut out and replace the affected pipe segment is seen as overly conservative [7-8].

Nomenclature

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

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