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# Remaining strength assessment of dented pipe based on depth and strain based criteria

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**Abstract.** There are currently two methods which are used in feasibility operation of dented pipeline systems, namely depth based and strain based. In this research, both methods will be compared to determine conservatism degree of each method and as a guideline and considerations in the integrity assessment of pipeline system. The finite element method with including nonlinearities of material properties and dimension will be used as a tool in the analysis. Static indentation was held with using half ball indenter. Variations of applied load are 600 N, 1000 N, 1500 N, 2000 N, and 2500 N. The results of indentation are dent depth ratio ( $d/D$ ) with value 1,93 %, 3,78 %, 5,53 %, 7,08 %, 10,63 %, and plastic strain with value 4,24 %, 5,87 %, 8,36 %, 11,43 %, and 12,93 %, respectively. Based on the Code, depth based criteria use  $d/D < 6$  % and strain ( $\epsilon$ )  $< 6$  % as an acceptance criteria. Based on this research, it can be concluded that strain based method is more conservative rather than depth based method. Then, five model of defected pipe will be simulated in the condition of operation pressure applied to the pipe. Operation pressure was varied with ( $P/P_y$ ) 0.2, 0.4, 0.6, 0.8, and 1. The results show that depth of dent will decrease with variation of strain value.

## 1. Introduction

Piping system as a fluid transportation system plays a very important role in an industry. In the oil and gas industry, piping systems are the most important equipment which became focus and main concern in the design process, installation, operation and maintenance. In the oil and gas industry, losses will be experienced by the company in case of problems in the piping system resulting in cessation of oil or gas transportation. In fact, in a country whose main income comes from the oil and gas industry, problems in pipeline networks may cause a financial deficit for the country. Seeing the importance of the piping system, integrity analysis is needed to ensure sustainability of pipeline operations. Integrity analysis generally refers to predefined and generally accepted Standards, e.g. API 579 / ASME FFS-1 2007, BS 7910, and ASME B31.G. Those standards include integrity analysis for various defect modes of mechanical equipment, including piping systems.

Dent is one of the defects in the pipe material due to applied load, whether static or impact load, resulting in emergence of a local curve or dent, generally inward of the main axis of the pipe. In piping systems, external applied load may be caused by many things, such as due to rock pressure around the pipe, falling objects of pipe material, or other object impacts during pipe installation, maintenance and operation. Dent in the pipe causes the emergence of stresses and residual strain around the pipe material that suffers the defect. Such conditions may lead to decreased fatigue life of the pipeline, increased risk of leakage, and more fatal effects may result in pipeline rupture.

Various previous studies have much to discuss about cases of dent defects, either on the pipe or on the pressure vessel. Theoretically, Ying Wu et al. [1] have formulated an analytical equation for calculating the effect of dent defects on pipe structures in the form of a shell or tube. The equation was derived by considering the effect of operating pressure, either from internal or external pressure. Such research can be useful as a guide in the treatment of piping systems. In 2010, Noronha et al. [2] construct a mathematical formulation to calculate the size of the strain on the dent defect. The



geometry of the dent defect is obtained based on the B-Spline curve which is interpolated from the measurement result using the In-Line Inspection (ILI) instrument. The formulation then was proposed to be used in ASME B.31G Code. If referring to the ASME Code B.31.G-2000 edition [3], the pipe is feasible to operate if depth ratio of defect ( $d$ ) to the outer diameter of the tube ( $D$ ) is small than 6%. The method was finally revised in the 2009 edition by incorporating the latest criteria based on the value of strain occurring around the dent defect area i.e. the pipeline was said to be feasible to operate if the strain value is small than 6%. Ramezani and Neitzert [4] undertook research to develop and understand the geometry and strain distribution characteristics of pipe materials with dent defects. In the study, the analysis was performed using finite element method which was validated with the result of theoretical calculation. The conclusion is that by pressing the larger pipe operation the force required to produce the dent defect is also greater. Likewise, the strain on the pipe increases with increasing depth of dent and internal pressure. Other researchers, Oliveira et.al. [5] use finite element analysis to obtain the value of the stress intensity factor around the dent defect area. The analysis was conducted using two-dimensional model with indenter of cylinder geometry. The stress concentration factor was calculated based on the ratio between the maximum stress and the nominal stress at the center of the dent. It was concluded that the value of stress intensity factor increased with decreasing of indenter diameter. Rachman and Musthafa [6] was generated numerical data of cracked cylindrical structure in order to simplified process of integrity assessment. In their research, failure assessment diagram as an acceptance criteria was constructed based on numerical data an compared to diagram which was available in most commonly used Code or Standard.

Some of the above-mentioned studies are still using two-dimensional models to save computational costs, so that no observation of dent deformities in both longitudinal and circumferential directions is possible. In addition, the variations performed are limited to the size and geometry of the indenter and the depth of the defect, not to the size of the pipe. In this study, pipes and indenters are modeled using three-dimensional elements to obtain a more in-depth analysis of strain, stress, and displacement distributions at each coordinate around the defect area. In addition, investigations were also conducted to look at the behavior of the API 5L-X42 pipeline material when supplied with the induced pressure that caused the dent defect and when the defective pipe was operated with a variety of internal pressures.

## 2. Methodology

Finite element analysis was performed using three-dimensional model of a pipe that a dent deformed on the surface of pipe material. The pipe was modeled intact with a length of 150 mm, a diameter of 40 mm, and a thickness of 1 mm. The determination of the length of the pipe shall be based on the reference to the crack analysis where the ratio of pipe length to defect diameter shall be greater than 10 ( $L/D \geq 10$ ) [7]. In this case, the indenter is a half-sphere with a diameter of 10 mm so that the maximum diameter of the resulting defect is not expected to be much different from indenter's diameter.

The pipe was supported on both free ends by partitioning both ends of the pipe at a width of 10 mm and a holding angle of 90 °. Both free ends of the pipe are held in motion in the x-axis and y-axis direction and to the z-axis rotation ( $U_x = U_y = R_z = 0$ ,  $U_z = R_x = R_y = \text{free}$ ). The emphasis was carried out precisely at the center of the length of the pipe by providing the boundary conditions of free movement of the x-axis indenter, held in the y-axis direction, the z-axis, and all rotational directions ( $U_x = \text{free}$ ,  $U_y = U_z = R_x = R_y = R_z = 0$ ). In finite element analysis three dimensional elements are used with three dimensional brick elements with eight nodal on each element [8]. In order to save computing time and to get more accurate results, meshing strategy was applied by dividing the model into multiple meshing zones. The main zone is the contact area between the indenter and the pipe. In this zone, 3480 elements with size of 0.5 mm were used. For the whole model of pipe and indenter used as many as 5721 elements. The contact line coefficient between the pipe and the indenter is assumed to be 0.3. Interaction and discretization model used are surface to surface with indenter as master surface and the pipe as slave surface.

In finite element analysis, the indenter material is assumed to be very rigid while the pipe material is API 5L-X42 with mechanical properties as given in Table 1. The indenter was assumed as a rigid body to prevent deformation of the indenter at the time of compression and to save computation time. Emphasis will cause plastic deformation of the material, so that the plasticity model of the material must be defined. In this study, elastic-plastic model of material were constructed using the Ramberg-Osgood formula [9]. The relationship between stress and strain on the Ramberg-Osgood formula was given in equation (1). The value of the Ramberg-Osgood constant ( $n$ ) was obtained from calculations using equations (2) and (3). The mechanical properties of the API 5L-X42 pipeline material are taken from the API 5L-2007 Specification for Line Pipe data issued by the API Institute and as shown in Table 1. The pipe specification data obtained then converted to stress-strain curves using non-linear elastic plastic equation that was given by Ramberg-Osgood, the stress-strain curve of the material was showed in Figure 1.

$$\varepsilon = \frac{\sigma}{E} + 0.002 \cdot \left( \frac{\sigma}{\sigma_y} \right)^n \quad (1)$$

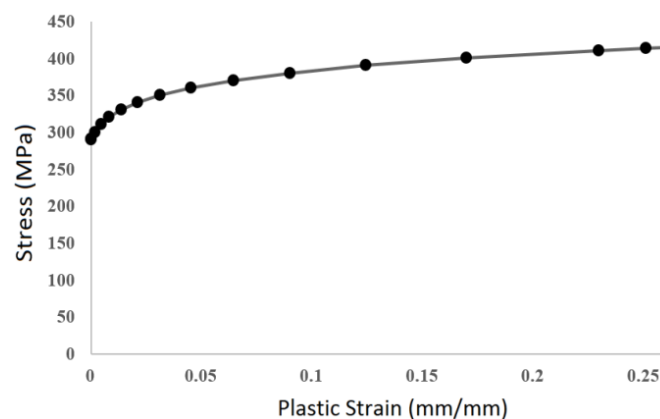
$$n = \frac{\ln(\varepsilon_{us} / 0.2)}{\ln(\sigma_u / \sigma_y)} \quad (2)$$

$$\varepsilon_{us} = 100 \cdot \left( \varepsilon_r - \frac{\sigma_u}{E} \right) \quad (3)$$

**Table 1.** Mechanical properties of API 5L-X42 pipe material. [10]

No	Mechanical properties	Minimum value
1	Yield strength	290 Mpa
2	Tensile strength	415 MPa
3	Strain	26,5 % *
4	Elastic moduli	210 GPa
5	Poisson ratio	0,30

\*based on test specimen with section area equal to 0,44 in<sup>2</sup>



**Figure 1.** Stress-strain curve of API 5L-X42 pipe material which was generated using Ramberg-Osgood equation.

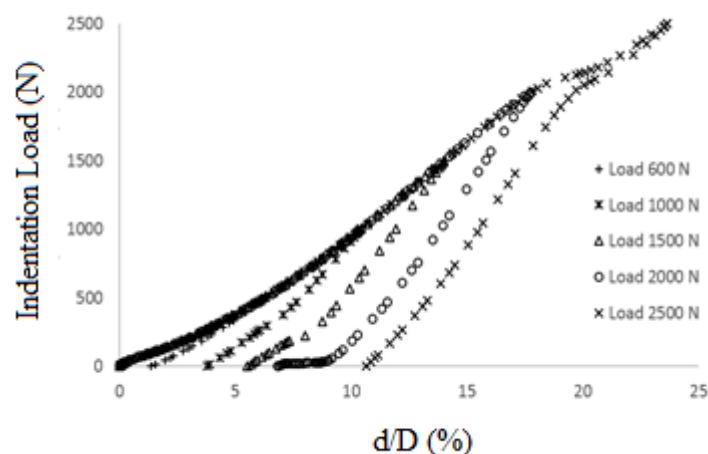
### 3. Results and discussion

The indentation was made on API 5L-X42 pipes using spherical indenters with variations of load are: 600 N, 1000 N, 1500 N, 2000 N, and 2500 N. At pressing, the maximum depth of the dent occurs precisely at the center of the compression by the indenter with the value 2.13 mm, 3.04 mm, 5.6 mm, 7.09 mm, and 9.45 mm, respectively. The final depth of the dent defect was measured under conditions after the compression force was removed by a depth of values of 0.77 mm, 1.51 mm, 2.21 mm, 2.83 mm, and 4.25 mm, respectively.

To facilitate the analysis and ease of use for pipes of different dimensions, the dent depth data is presented in the percentage of depth dent to the outer diameter of the pipe ( $d/D$ ). With an outer diameter of API 5L-X42 pipeline of 40 mm and variations of pressure force of 600 N, 1000 N, 1500 N, 2000 N, and 2500 N, the percentage of dent depth to outer diameter of pipe ( $d/D$ ) 93%, 3.78%, 5.53%, 7.08%, and 10.63% (Table 1). The curve of the relationship between the indentation force ( $F$ ) to the value of the depth ratio of the dent defect ( $d/D$ ) can be seen in Figure 2. Based on the curve, it can be seen that the  $d/D$  value increases when pressurized and decreases as the compression force is slowly lowered. The final depth of the resulting dent defect is then used to analyze the integrity of the pipe when operated with certain internal pressures.

**Table 2.** Variation of indentation load to resulting dent defect with certain depth

No	Load (N)	Maks. dent depth when loading (mm)	Dent depth after unloading (mm)	$d/D$ (%)
1	600	2,13	0,77	1,93
2	1000	3,04	1,51	3,78
3	1500	5,6	2,21	5,53
4	2000	7,09	2,83	7,08
5	2500	9,45	4,25	10,63



**Figure 2.** Loading-unloading curve of indentation load to resulting dent defect.

Besides the depth of the dent, indentation also causes the emergence of stress and residual strain on the pipe material, particularly in the compression area. As the indentation was made by adding the force slowly to its maximum, the maximum stress and strain appeared. Likewise, when the compression force is slowly lowered to 0 N or without pressure force, there will be tension and residual strain on the pipe material. The change in stress and strain values can be seen in Table 3 and Table 4. Distribution of stress on the pipe when it is suppressed with maximum force and when the force of force is removed there is a change in the value of the stress and the displacement from the position of the maximum stress initially concentrated at the center of the dent defect toward the circular direction (circumferential) of the pipe diameter.

**Table 3.** Stress on pipe materials during indentation (loading-unloading).

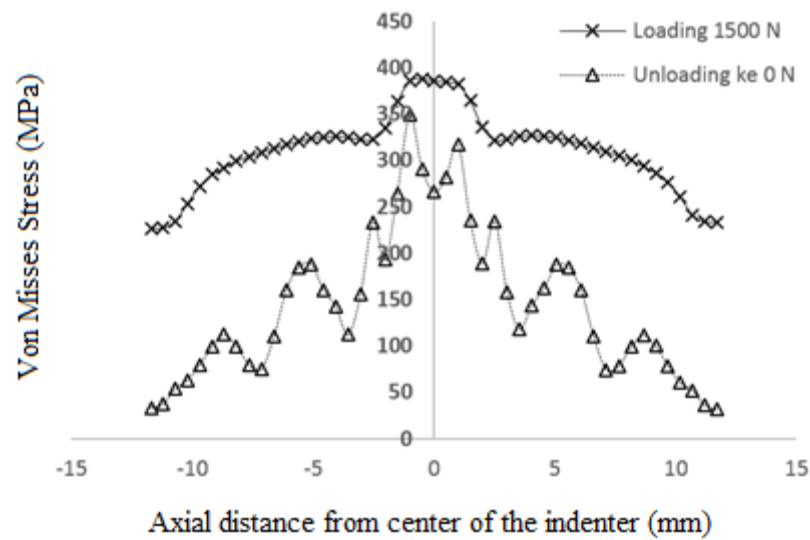
No	Load (N)	d/D (%)	Maximum stress (MPa)	Residual stress (MPa)
1	600	1,93	367,7	309,9
2	1000	3,78	377	322,2
3	1500	5,53	388	348,6
4	2000	7,08	395,6	382,4
5	2500	10,63	400,4	358,6

**Table 4.** Plastic strain on pipe materials during indentation process (loading-unloading).

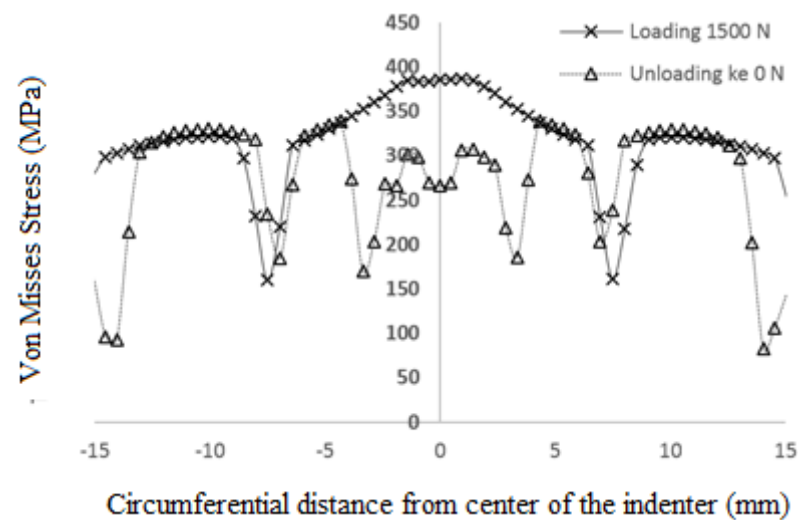
No	Load (N)	d/D(%)	Maximum strain (%)	Residual strain (%)
1	600	1,93	4,24	4,24
2	1000	3,78	5,87	5,88
3	1500	5,53	8,36	8,75
4	2000	7,08	11,43	11.47
5	2500	10,63	12,93	13,56

In a cylindrical structure, for example in a pipe, the greatest stress occurs in the circumferential direction, which is twice the value when compared to the longitudinal direction. In this study, to observe the behavior of changes in the value of stress and strain of the pipe in the longitudinal or circular direction, numerical data was taken in two models, namely the pipe with indentation of 1500 N and 2500 N. In the longitudinal or circular direction, the observations for nodal-nodal distance 15 mm to the right or left from the midpoint of the dent defect. From Figure 3, Figure 4, Figure 5, and Figure 6 it can be concluded that at the time of compression, the maximum stress occurs at the midpoint of the dent defect or the midpoint of the indenter. When the compression force is lowered, there is maximum displacement of the residual stress, the maximum value not at the midpoint of the dent again. This mapping of values and stress positions needs to be done in relation to the analysis of the integrity of the piping system.

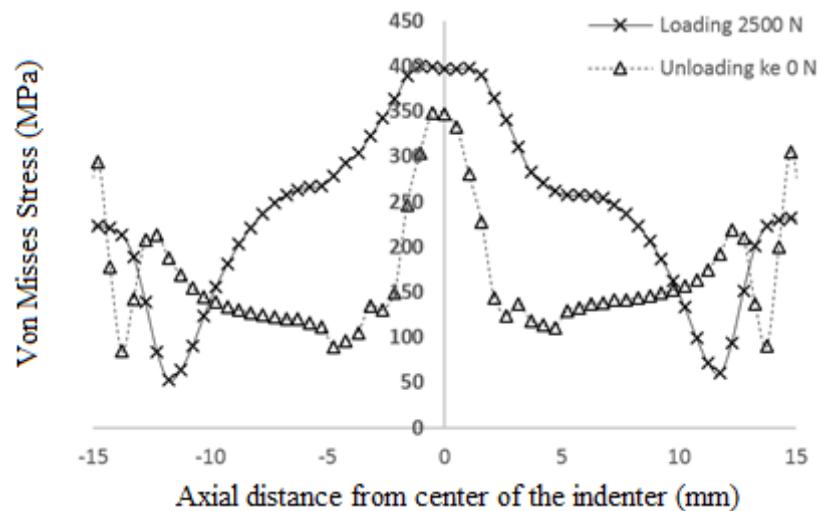
In addition to the above conclusions, from the mapping of the stress values it is seen that in general the value of the circular direction of the circular direction is not much different from the maximum stress when the emphasis is made. A different thing is seen in the longitudinal direction of the stress where the residual stress has a value quite different from the stress when it is suppressed.



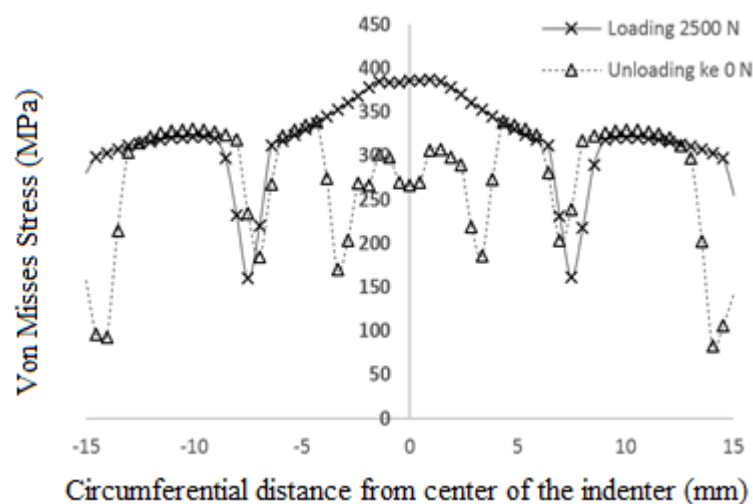
**Figure 3.** Variations of stress along longitudinal axis of dent defect with indentation load 1500 N.



**Figure 4.** Variations of stress along circumferential direction of dent defect with indentation load 1500 N.



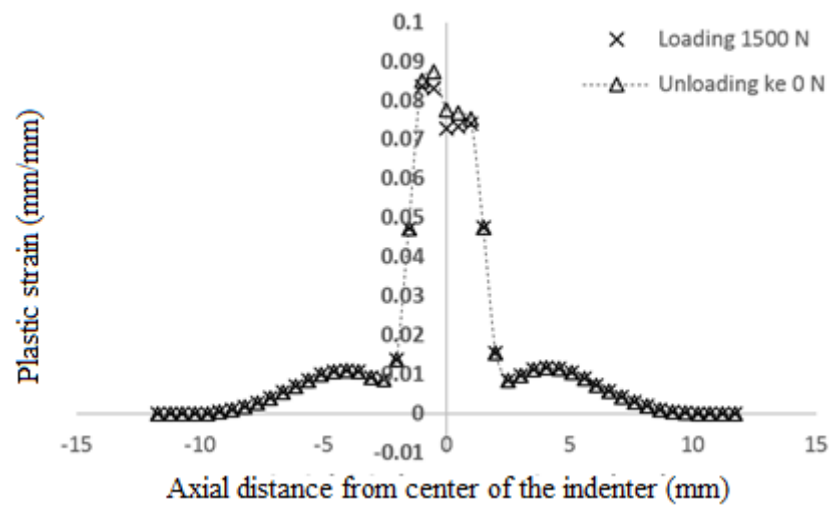
**Figure 5.** Variations of stress along longitudinal axis of dent defect with indentation load 2500 N.



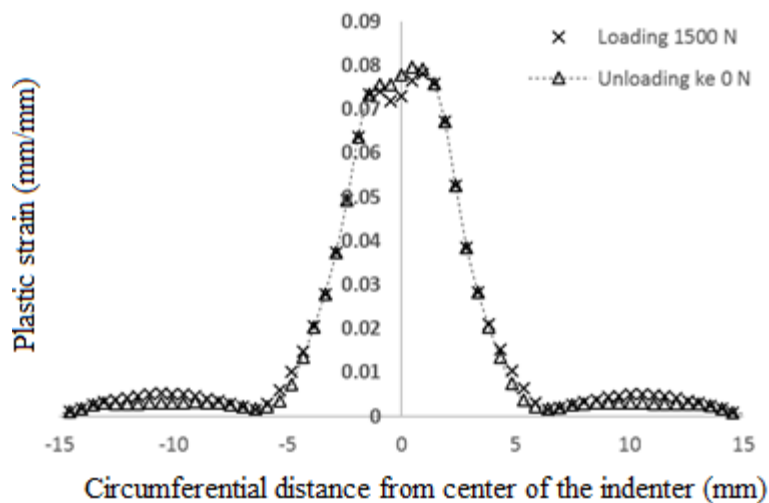
**Figure 6.** Variations of stress along circumferential direction of dent defect with indentation load 2500 N.

The next analysis is the value of the strain that arises when the indentation process. The strain contours in the stress areas generally show no change in position as well as significant strain values when emphasis or when the force of force is removed. The maximum strain value as well as the remaining strain of the elongated or circular direction is in an improper position at the center of the defect, but still in the area of the pipe section subject to the indenter. In Figure 7 to Figure 10 shows the value of strain in a longitudinal or circular direction from the midpoint of the dent.

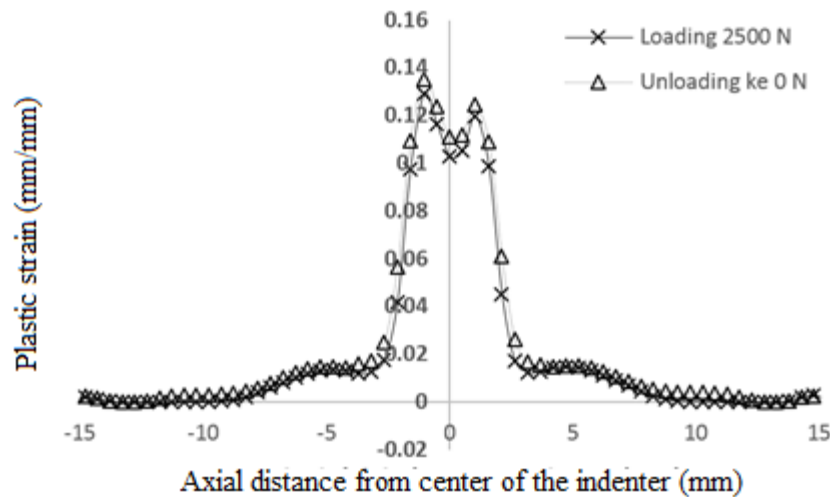




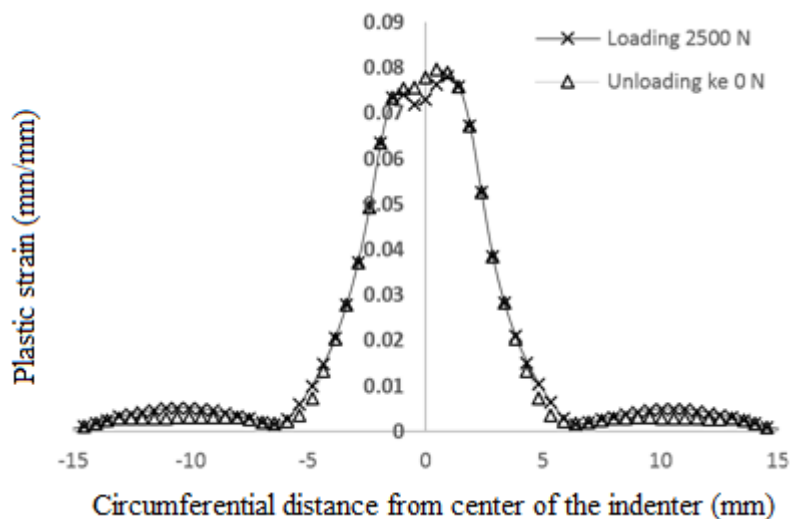
**Figure 7.** Variations of plastic strain along longitudinal axis of dent defect with indentation load 1500 N



**Figure 8.** Variations of plastic strain along circumferential direction of dent defect with indentation load 1500 N.



**Figure 9.** Variations of plastic strain along longitudinal axis of dent defect with indentation load 2500 N.

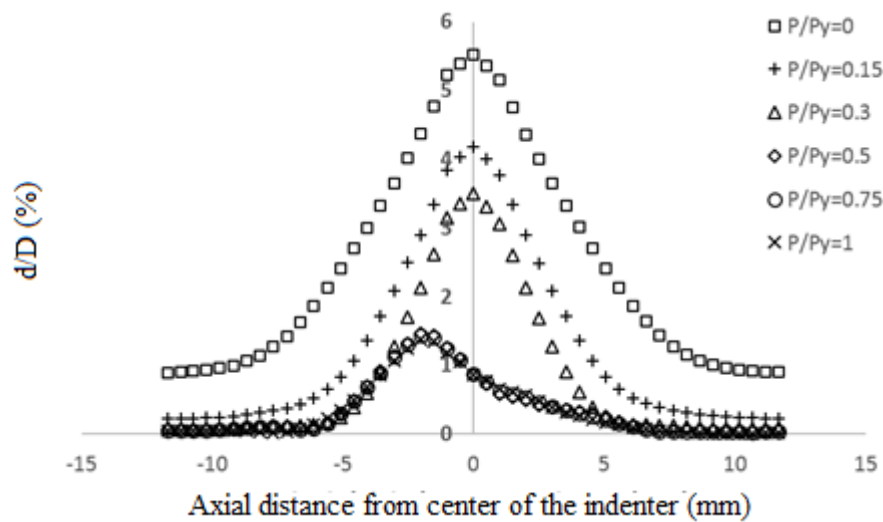


**Figure 10.** Variations of plastic strain along circumferential direction of dent defect with indentation load 2500 N.

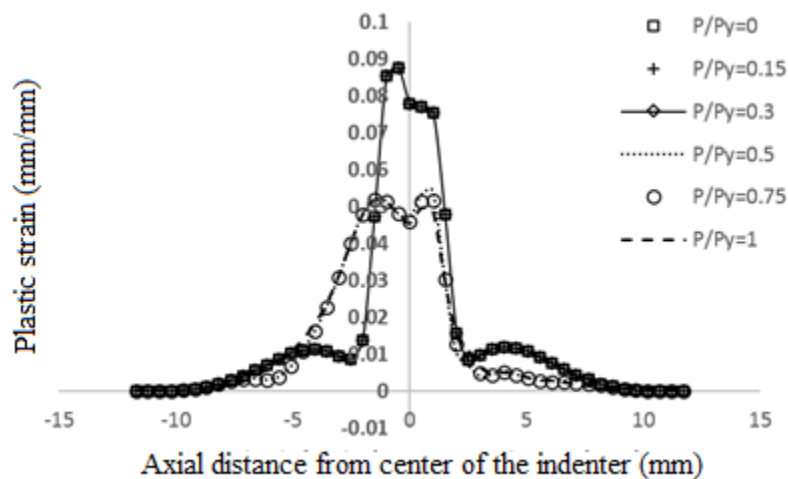
The integrity analysis in this research was conducted on defect pipe that operated with certain operating pressure variation. The selection of operating pressure is carried out with reference to the ratio between actual operating pressures ( $P$ ) to the operating pressure which may cause the tube to undergo plastic deformation ( $P_y$ ).  $P_y$  value is derived from the theoretical equation of the maximum stress on the pipe, as shown in equation (4).

$$P_y = \frac{\sigma_y t}{R} \quad (4)$$

Based on the above equation then obtained  $P_y$  of 15.26 MPa. Furthermore, in the simulation used operating pressure of 2.3 MPa, 4.6 MPa, 7.6 MPa, 11.5 MPa and 15.26 MPa, or in the  $P / P_y$  ratio of 0.15, 0.3, 0.5, 0.75, and 1. When the pipe having a dent defect is operated by providing internal pressure it will change the dimension of the defect. Figure 11 shows that in pipes with  $d / D = 5.53\%$ , an increase in operating pressure causes a decrease in the depth of the dent defect until the  $P / P_y$  value reaches 0.5. Pipe operation may also result in changes in the value of the plastic strain in the dent defect area. Figure 12 shows that for defects with  $d / D = 5.53\%$  there is a decrease in residual strain value if  $P / P_y$  is raised from 0.15 to 0.5.

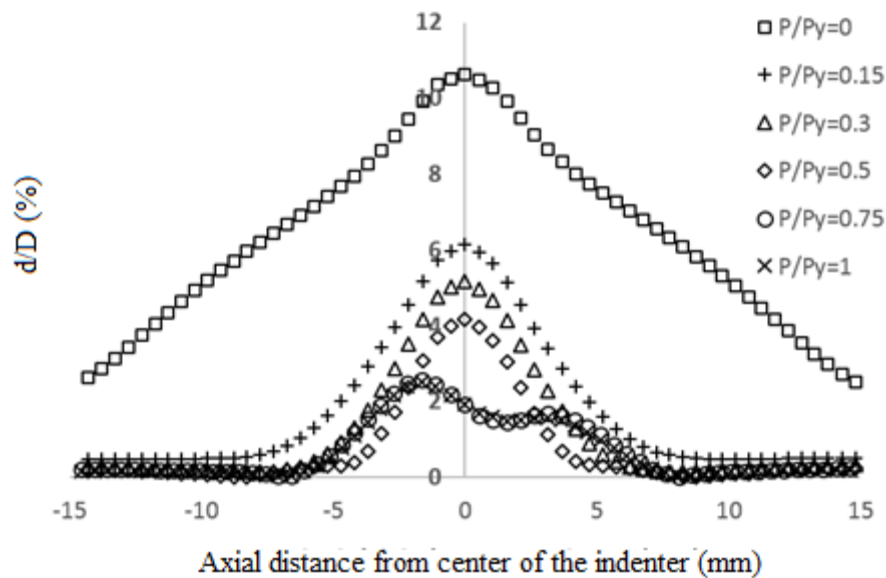


**Figure 11.** Depth of dent defect with  $d/D=5.53\%$  when operated under various internal pressure.

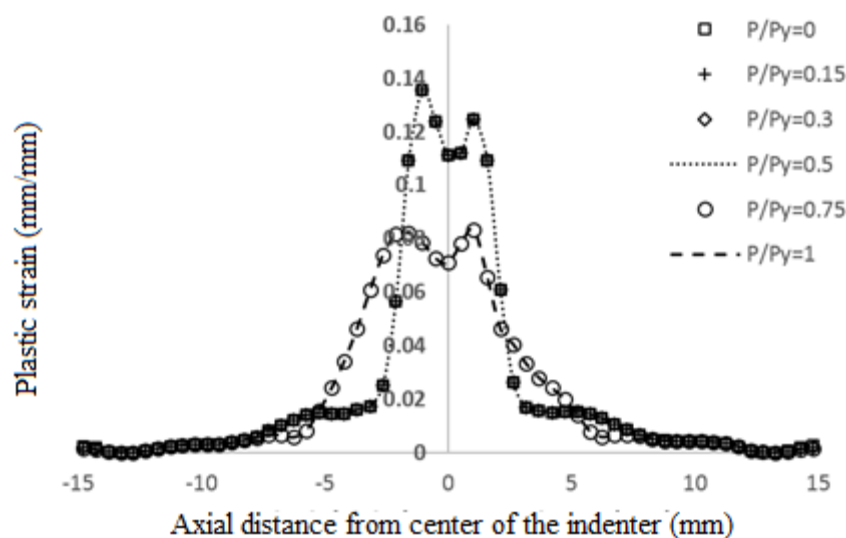


**Figure 12.** Plastic strain distribution of dent defect with  $d/D=5.53\%$  when operated under various internal pressure.

The same phenomenon can also be observed in Figures 13 and 14. In the case of defect with the ratio  $d/D = 10.63\%$  there is a reduction in defect depth until the  $P/P_y$  ratio reaches 0.75. The residual strain value on the pipe decreases in some positions and increases in other positions if the  $P/P_y$  ratio is raised to 0.75.



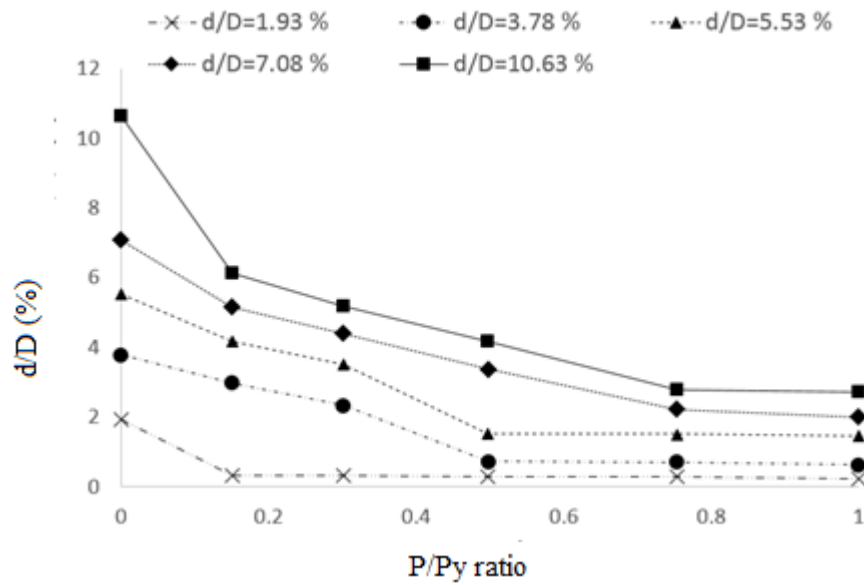
**Figure 13.** Depth of dent defect with  $d/D=10.63\%$  when operated under various internal pressure.



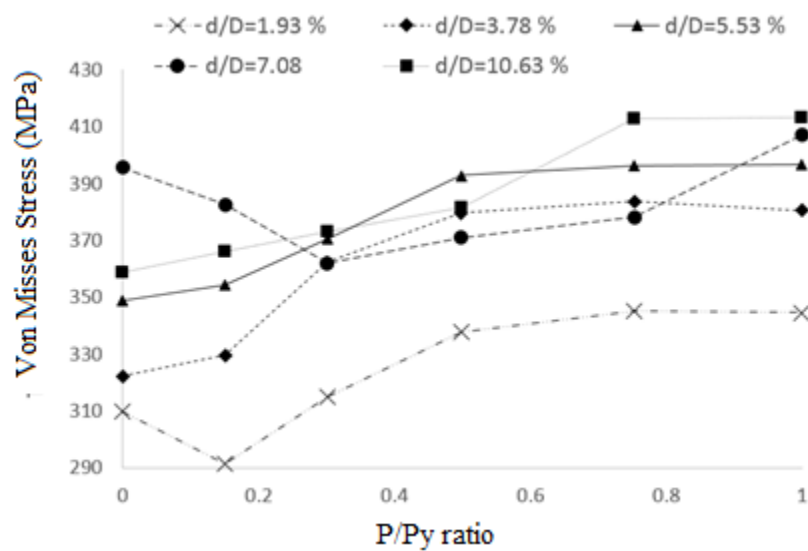
**Figure 14.** Plastic strain distribution of dent defect with  $d/D=10.63\%$  when operated under various internal pressure.

From the simulation performed on 5 models of dent defects with different defect depths, it can be concluded that the pipe has decreased the defect depth due to the increase of operating pressure, in this

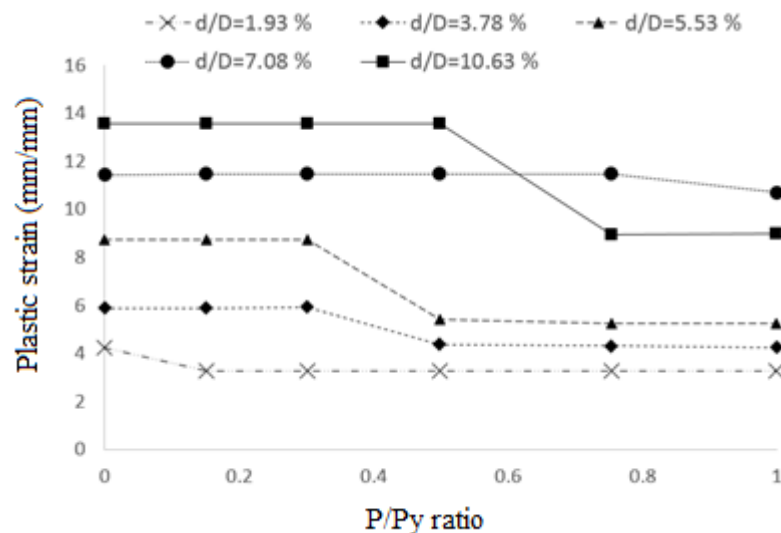
case in the form of  $P/P_y$  ratio (Figure 15). Figure 16 shows that the stress value of the defect increases with the addition of operating pressure, while the residual strain tends to decrease (Figure 18).



**Figure 15.** Effect of increasing internal pressure to depth of dent on pipe material.



**Figure 16.** Effect of increasing internal pressure to stress value on pipe material.



**Figure 17.** Effect of increasing internal pressure to plastic strain on pipe material.

#### 4. Conclusions

Finite element analysis can be used to perform integrity analysis of pipeline systems that experienced a dent defect. There are two criteria which were commonly used in pipeline integrity analysis, namely based on depth based and strain based. The strain values obtained from finite element analysis can be used as acceptance criteria by referring to the existing Code. Some results that can be inferred from the research are:

1. Dent defects that occur due to indentation 2000 N and 2500 N produce dent with  $d/D$  7.08% and 10.63%. Both models are declared FAIL or not feasible to operate if they refer to the depth based criteria.
2. Dent defects that occur due to indentation of 1500 N, 2000 N and 2500 N produce dent with a strain value of 8.36%, 11.43%, and 12.93%. The three pipeline models are declared FAIL or not feasible to operate if referring to strain based criteria.
3. It was concluded that strain based methods are more conservative (easier to assume to fail) than depth based methods.
4. Defective pipes operated by varying internal stresses may cause a decrease in the depth of the defect as well as the strain value.

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