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An Analytical Strain Analysis Method of Smooth Dented Pipe Based on 3D Scanning

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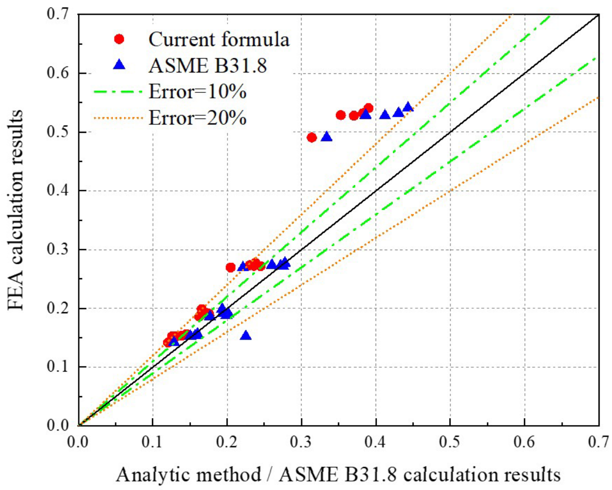
Abstract

An analytical calculation methodology utilizing 3D laser scanning data is presented for the assessment of strain in smoothly dented pipelines, offering enhanced precision. This approach adopts cubic B-spline interpolation to reconstruct a smooth dent surface from preprocessed scanning point cloud data, subsequently organizing these into regular grid node coordinates via data gridding. Displacement and strain at each grid point, resulting from pipeline deformation, are determined by employing thin-shell theory alongside geometric deformation analysis. The accuracy of this method is substantiated through comparisons with results obtained from both the finite element method (FEM) and the ASME B31.8 standard. Additionally, specialized evaluation software for assessing dented pipelines has been developed, leveraging this analytical method. Comparative analysis with the finite element method reveals that the average relative errors for maximum equivalent strain on the pipeline's outer surface are 7.73% and 13.16%, respectively, underscoring the superior accuracy of the proposed method over the ASME B31.8 standard for strain calculations on the outer surface of dented pipelines.

Keywords

3D scanning; smooth dent; dent strain; analytical formula; software

Graphical Abstract



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1 INTRODUCTION

Long-distance pipeline is currently the most widely used oil and gas transportation system. Its advantages of high efficiency, environmental protection, and low cost are irreplaceable by other transportation systems (Janine W, 2019). However, mechanical damage is expected to occur during the pipeline's longterm service due to human or environmental factors. A dent is a typical mechanical damage defect in the pipeline, a permanent inward plastic deformation on the pipe wall (Cosham A and Hopkins P, 2004; Tian X, 2017; Zhu X K, 2023; Huang Y et al., 2023; Wu Y et al., 2023). Studies have shown that there is a close relationship between dent depth and strain, with greater dent depth leading to more significant strain, which directly impacts the pipeline's load-bearing capacity and fatigue life (Chen J et al., 2015; Dou G, et al., 2024). One thousand four hundred ninety dents were detected in a China oil pipeline with a detection mileage of 927.8 km: the maximum dent depth was 9.67% outer diameter (OD). Although a simple smooth dent will not significantly reduce the pipeline's burst strength (Alexander C R, 1997; Alexander C R, 2000; Allouti M, 2012; Song P et al., 2020; Shuai Y et al., 2017), some unconstrained dents are prone to fatigue cracks due to internal pressure fluctuations, significantly impacting the pipeline's fatigue life (Fowler et al., 1994; LI C B et al., 2022). Therefore, dent may become a major danger to the pipeline's future operation. As such, the importance of dents should not be overlooked.

Standards and specifications related to pipeline's smooth dent applicability evaluation mainly include API RP 1160 2019 ' Recommended Practices for Managing the Integrity of Hazardous Liquid Transportation Pipeline Systems ', ASME B31.4 2019 ' Liquid and Mud Pipeline Transportation Systems ', ASME B31.8 2018 ' Gas Transmission and Distribution Pipeline Systems ', SY / T 6996 2014 ' Steel Oil and Gas Pipeline Dent Evaluation Method ', SY / T 6996 2014 ' Steel Oil and Gas Pipeline Dent Evaluation Method ', 49 CFR 195 2017 ' Hazardous Liquid Pipeline Transportation ', 49 CFR 192 2017 ' Natural Gas and Other Gas Pipeline Transportation: Minimum Federal Safety Standards ', CSA Z662 2019 ' Oil and Gas Pipeline Systems ', AS 2885 2012 ' Pipeline Natural Gas and Liquefied Petroleum ', and SY / T 6648 2016 ' Pipeline Integrity Management Specifications.

Most of the above standard specifications are evaluated based on the criteria of dent depth or strain (Kong C J, 2022). Although dent depth can reflect the pipeline's potential danger, many studies have shown that using only depth as an evaluation index cannot accurately reflect the dent's severity (Dawson S J et al., 2006; Md Rafi A N et al., 2012;). The National Energy Board (NEB) of Canada has issued a pipeline safety advisory report. This report specifies that the depth-based dent evaluation criteria fail to detect the risk of pipeline dents on time (Erickson A M, 2010). Compared to dent depth, dent strain is a more accurate indicator of the severity of pipeline deformation. Moreover, criteria based on strain offer a more suitable assessment for high-grade steel pipelines. ASME proposed a strain-based evaluation method for dents based on the study of (Rosenfeld et al., 1998).

The strain of a dented pipeline is divided into three components: circumferential bending, axial bending, and axial film strain; the equivalent strain is calculated using these components. (Lukasiewicz et al.,2006; Czyz J A et al.,2008) introduced circumferential film strain and proposed an alternative method for calculating dent strain by combining mathematical algorithms with finite element modeling. (Gao et al., 2008) compared the analytical results of dent strain between ASME B31.8 and the Lukasiewicz method, improving the ASME B31.8 standard. Researchers mainly investigate the analytical method of dented pipeline strain, focusing on the noise reduction of dented contour data and the selection of interpolation methods. However, there are few studies on the analytical method, with the most widely used analytical method provided in the ASME B31.8 standard (Yang Q and Shuai J,2010; Zhang P et al.,2015; Lei Z Q et al.,2016; Guo J et al.,2018). The equation provided in the ASME B31.8 standard has been revised many times since it was proposed. The latest 2018 version of the equation has greatly improved the accuracy of the calculation results. However, the equation is not derived from rigorous geometric equations, and the accuracy still needs to be considered. Simultaneously, the 2018 ASME B31.8 equation does not provide the selection method of the dent's depth and length required to calculate the axial film strain. The axial film strain equation can only calculate the equivalent strain at the deepest part of the dent. Hence, the equation does not apply to the special dent structure with inconsistent maximum depth and strain position.

An analytical method of smooth dented pipe based on 3D scanning technology is established in this paper. The remainder of the paper is organized as follows. The smoothing method of the 3D laser scanning pipeline dent point cloud model and the reconstruction of a dented surface is introduced in Section 2.1. In Section 2.2, the analytical calculation method of strain suitable for smooth dent is derived based on the reconstructed dent surface. The calculation method of dent strain in 2018 ASME B31.8 is briefly introduced in Section 2.3. In Section 2.4, the finite element model of the dent pipeline is established. In Section 2.5, the Pipeline Dent Assessment (PDA) software is developed according to different dent analysis methods. The accuracy of the finite element model of the dented pipeline is verified in Section 3.1. In Section 3.2, the accuracy of the proposed analytical calculation of dent strain is verified by comparing with ASME B31.8 and the finite element results. The visual interface and case display of the pipeline dent assessment software are introduced in Section 3.3. Finally, the main conclusions of this paper are summarized in Section 4.

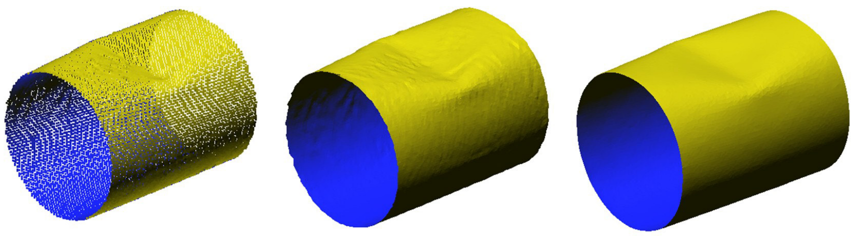
2 Materials and methods

2.1 Dent point cloud model

In recent years, 3D laser scanning technologyhas been used to measure the size of dented pipes (Wang P et al.,2019; Sha S Y et al.,2014). 3D laser scanning is a nondestructive testing technology employing laser lines to capture the three-dimensional shape of physical objects and store and display them digitally. This technology can accurately measure surface defects, metal loss, or geometric deformation of objects. Compared with the traditional grid diameter measurement method and geometric inner detection method, 3D laser scanning technology can collect tens or millions of data points per second due to the extremely high emission laser frequency. Hence, the geometric shape of the dented pipeline can be accurately reconstructed, the accuracy and efficiency of the defect evaluation of the pipeline excavation site can be greatly improved, and the evaluation cost can be reduced. The measurement accuracy reaches to 0.02 mm.

A dented pipe specimen was made according to Rafi's pipeline dent test (Rafi A N et al.,2011). A complete circumferential pipe scanning was performed using a handheld 3D laser scanner (SCANTECH (HANGZHOU) CO., LTD; AXE-B11) to obtain a dented point cloud model. The point cloud data obtained by direct scanning with a handheld 3D laser scanner is relatively scattered. Moreover, there are many small rough features on the pipeline's surface. Therefore, smoothing and regularization preprocessing are required before performing strain calculation.

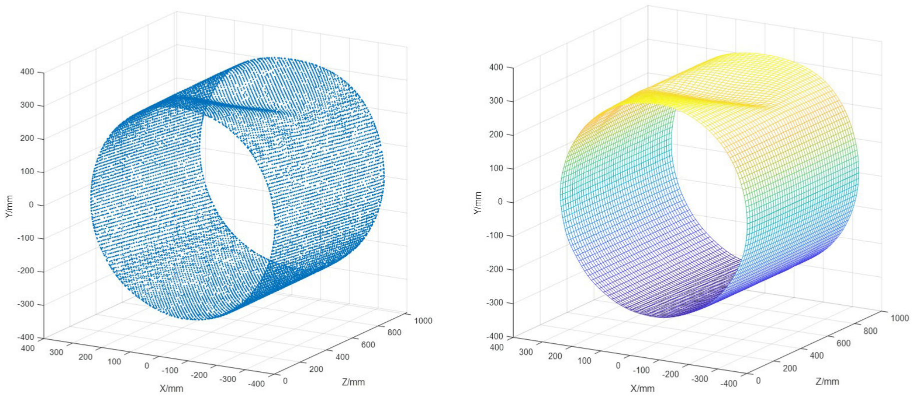
Smoothing preprocessing employs reverse engineering software to remove unnecessary local features in the point cloud model. The pipeline point cloud data are smoothened after cutting off the redundant 'burrs' at both ends of the pipeline dent surface while retaining the main features of the dent surface (Fig. 1).



(a) (b) (c)

Figure 1 From point cloud to smooth dent surface: (a) before processing, (b) triangular patch network fitting results, and (c) after smoothing pretreatment.

An orthogonal coordinate system was established at the location of the maximum dent depth during regularization. The tangent direction of the pipe wall is the X-axis, the normal direction of the pipe wall is the Y-axis, and the axial direction of the pipe wall is the Z-axis. A fitting was performed on the preprocessed point cloud data via cubic B-spline functions to obtain the dent surface. Then, the reconstructed dent surface was uniformly subdivided to form regularly spaced circumferential and axial crosssections, creating a regularized grid (Fig. 2).



(a) (b)

Figure 2 3D laser scanning pipeline dent point cloud model regularization processing: (a) point cloud after pretreatment, and (b) regularized mesh.

2.2 Strain analysis method

2.2.1 Basic assumptions

The pipeline is a typical shell structure. The basic assumptions for the analytical calculation of the strain of the smooth dent pipe are given according to the Kirchhoff-Love assumption (Love A E H et al.,1888):

1. The straight line perpendicular to the middle surface before pipe deformation is still straight after deformation. Moreover, the length is constant, i.e., the pipe's thickness does not change;
2. The pipeline is in a plane stress state, and the stress component perpendicular to the middle plane is much smaller than other stress components. Hence, deformation caused by it is neglected.
3. During pipeline deformation, each point on the middle surface only produces displacement perpendicular to the middle surface. Therefore, the circumferential length of the pipeline is constant before and after deformation.
4. When the dent depth is small, the crosssection circumference of a smooth dent center slightly changes and can be ignored.

2.2.2 Deformation analysis

The cylindrical coordinate system was established with the pipeline's radial, circumferential, and axial directions as the R, ϑ, and Z axes, respectively. The coordinates of the ith node $P_{ext,i}$ (x_{ext}, y_{ext}, z_{ext}, i)(i = 1, 2, ... , n) of dent's outer surface contour obtained by the 3D laser scanning pipeline dent point cloud model were regularized and reconstructed. The coordinates of dent's outer surface (x_{ext}, y_{ext}, z_{ext}, i) (i= 1, 2, ..., n) were converted into cylindrical coordinates (R_{ext}, ϑ_{ext}, Z_{ext}, i) by coordinate transformation. Then, the cylindrical coordinates of the middle and inner surface nodes were calculated. The circumferential displacement, radial displacement, axial displacement, circumferential deflection angle, the deflection angle of the wall thickness direction with respect to the middle surface node, and the deflection angle of the normal direction of the wall thickness in the axial direction are obtained based on the geometric relationship of dent points before and after deformation.

For an arbitrarily chosen node, the deformation of the pipeline in the wall thickness direction is always perpendicular to the outer surface in the circumferential section of the pipeline dent. The middle surface and the inner surface of the pipeline's circumferential cross section (Fig. 3) and the slope of the tangential line at the node $P_{ext,\ i}$, on the circumferential contour of the outer surface of the dent can be obtained according to the geometric relationship of the nodes on the outer surface. The slope of the wall thickness direction (i.e., the t_w direction) k_{tw}:

$$k_{tw} = -\frac{\dfrac{dR_{ext}\left(\theta_{ext}\right)}{dx}\cos\theta_{ext} - R_{ext}\left(\theta_{ext}\right)\sin\theta_{ext}}{\dfrac{dR_{ext}\left(\theta_{ext}\right)}{dx}\sin\theta_{ext} + R_{ext}\left(\theta_{ext}\right)\cos\theta_{ext}} \tag{1}$$

where $R_{ext}(\theta_{ext})$ is the curvature function of the pipeline's outer surface.

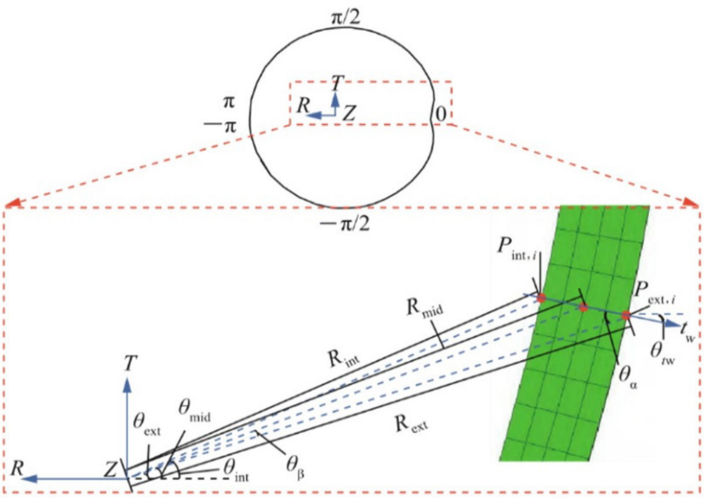


Figure 3. Geometric relationship of dent points on the circumferential crosssection of the pipeline.

Angle ϑ_α between the wall thickness direction and the polar diameter direction at a node $P_{ext,\,i}$, on the outer surface contour can be obtained according to the geometric relationship between the wall thickness direction of the outer surface contour and the polar diameter direction of the outer surface node:

$$\theta_\alpha = \theta_{tw} - \theta_{ext} \tag{2}$$

$$\theta_{tw} = \begin{cases} \arctan k_{tw} - \pi, \theta_{ext} \in [-\pi, 0) \wedge \arctan k_{tw} \geq 0 \\ \arctan k_{tw}, \theta_{ext} \in [-\pi, 0) \wedge \arctan k_{tw} < 0 \\ \arctan k_{tw}, \theta_{ext} \in [0, \pi) \wedge \arctan k_{tw} > 0 \\ \arctan k_{tw} + \pi, \theta_{ext} \in [0, \pi) \wedge \arctan k_{tw} \leq 0 \end{cases} \tag{3}$$

where ϑ_{tw} is the angle of the wall thickness direction in the polar coordinate system, denoted in radians.

Then, in $\triangle ZP_{mid,\,i}P_{ext,\,i}$, the length R_{mid} of the third side $ZP_{mid,\,i}$ and the angle ϑ_β of $\angle P_{mid}ZP_{ext}$ can be obtained according to the cosine theorem. The coordinates of the middle node R_{mid} can be obtained as follows:

$$R_{mid}{}^2 = \left(\frac{t}{2}\right)^2 + R_{ext}{}^2 - R_{ext} t \cos\left(\left|\theta_\alpha\right|\right) \tag{4}$$

$$\theta_{mid} = \begin{cases} \theta_{ext} + \theta_\beta \quad ,\theta_\alpha \leq 0 \\ \theta_{ext} - \theta_\beta \quad ,\theta_\alpha > 0 \end{cases} \tag{5}$$

where t is the wall thickness of the pipe in millimeters.

According to assumption ④, the circumference of the middle surface of the pipeline is constant before and after the deformation. Then, angle ϑ'_{mid} of the middle surface node before deformation can be obtained by calculating the curve arc length in the polar coordinate system:

$$\theta'_{mid} = -\pi + \frac{1}{R'_{mun}} \int_{-\pi}^{i} \sqrt{\left[R_{mid}\left(\theta_{mid}\right)\right]^2 + \left[\frac{dR_{mid}\left(\theta_{mid}\right)}{dx}\right]^2} \partial\theta_{mid}, i \in [-\pi, \pi] \tag{6}$$

where R'_{mid} is the central radius of the original pipe before deformation in millimeters.

The overall position of the point cloud model in the data preprocessing stage has been preliminarily aligned. Therefore, the central axis of the pipeline coincides with the Z axis of the cylindrical coordinate system. However, there is no precise requirement for the polar axis direction. The basic assumption states that the circumferential crosssection circumference of the middle surface of a dented area does not change before and after deformation. Nevertheless, a small error may occur in practice, leading to errors when calculating the circumferential displacement. Therefore, since the polar axis direction is limited, it must point to the deepest part of the dent before using Eq. (6).

The displacement of the mid-plane node can be obtained according to the geometric relationship between the circumferential crosssection dent elements E and E' of the pipeline before and after deformation (Fig. 4):

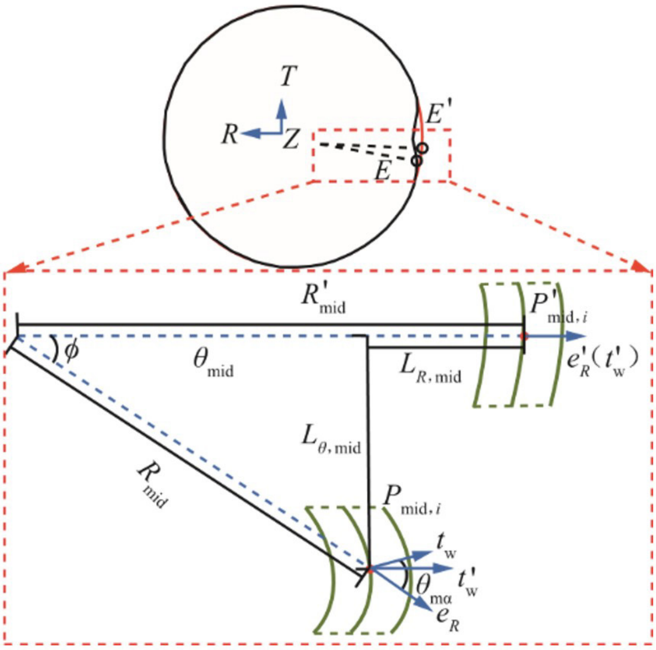


Figure 4. Geometric relation of dent points in circumferential crosssection of the pipeline before and after deformation.

$$L_{\theta,mid} = R_{mid} \sin\phi \tag{7}$$

$$L_{R,mid} = R_{mid} \cos\phi - R'mid \tag{8}$$

$$\phi = \theta_{mid} - \theta'_{mid} \tag{9}$$

where $L_{\vartheta,mid}$ and $L_{R,mid}$ are the middle node's circumferential displacement and radial displacement in millimeters, respectively; ϕ is the circumferential deflection angle of the middle plane node in radians.

$$L_{mid} = L_{\theta,mid} + L_{tw} \sin\theta_{m\alpha} \tag{10}$$

$$L_R = L_{R,\ mid} - L_{tw} + L_{tw} \cos\theta_{m\alpha} \tag{11}$$

$$\theta_{m\alpha} = \theta_{tw} - \theta_{mid} \tag{12}$$

where L_ϑ and L_R are the circumferential and radial displacements of the dent tube surface in millimeters, respectively; L_{tw} is the displacement of the middle node along the normal direction of the wall thickness, $-t/2 \le L_{tw} \le t/2$. The pipe's inner surface is represented by $L_{tw} = -t/2$, and the outer surface of the pipe is represented by $L_{tw} = t/2$. Parameter $\vartheta_{m\alpha}$ is the deflection angle generated by the wall thickness direction t_w around the mid-plane node $P_{mid,i}$ during the circumferential deformation of the wall element.

According to the geometric relationship of the dent points of the axial section of the pipeline before and after deformation (Fig. 5), the axial displacement of the middle surface node can be neglected when the distance between the node and the center of the dent is relatively small. The axial displacement of the inner and outer surface nodes is the distance generated by the deflection of the wall thickness normal direction around the middle surface node (L_z):

$$L_Z = L_{tw} \sin\theta_z \tag{13}$$

$$\theta_Z = \arctan\frac{\partial L_R}{\partial z} \tag{14}$$

where ϑ_Z is the deflection angle of the normal direction of the wall thickness on the axial section of the pipe.

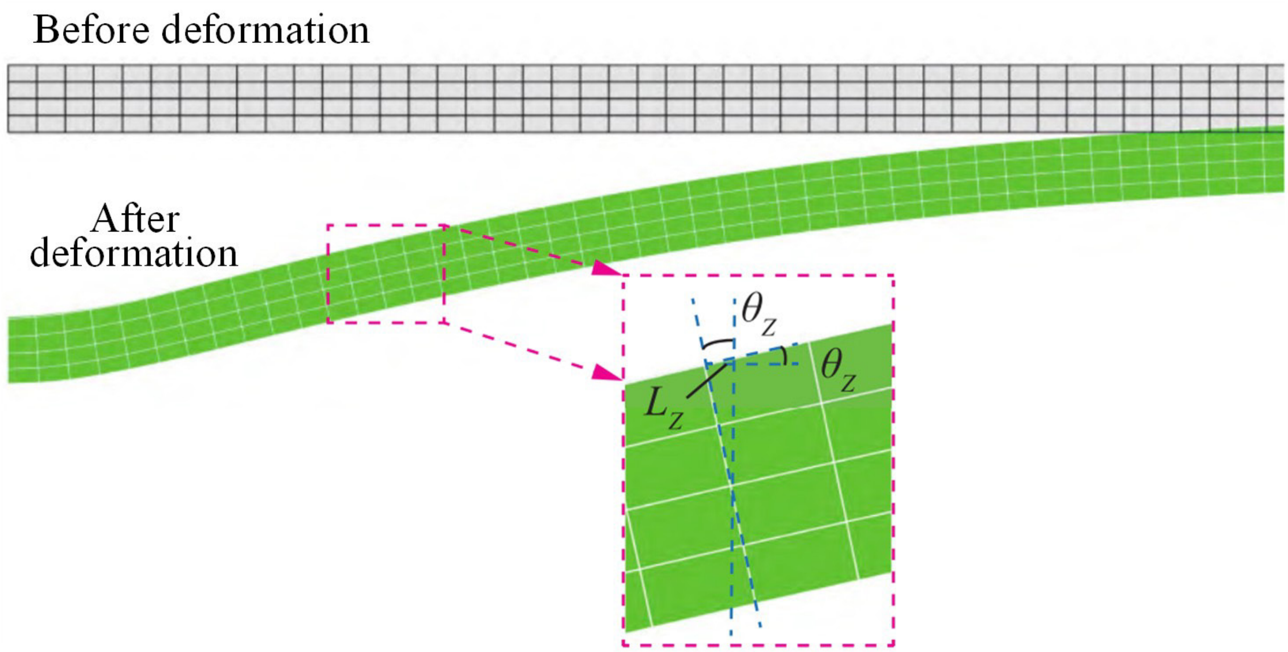


Figure 5. Geometric relation of dent points in the axial section of a pipeline before and after deformation.

2.2.3 Strain analysis

The circumferential membrane expansion during denting is very small; hence, its effect is assumed to be negligible. Therefore, the strain displacement relationship in the polar coordinate system can be calculated as follows:

$$\varepsilon_\theta = \frac{\partial L_\theta}{r\partial\theta} + \frac{L_R}{r} \tag{15}$$

where ε_ϑ is circumferential strain and r is the node radius.

The axial direction of the pipeline in the dent is characterized by obvious elongation. The Green-Lagrangian strain formula can be expressed as follows:

$$\varepsilon_z = \frac{\partial L_R}{\partial Z} + \frac{1}{2}\left[\left(\frac{\partial L_R}{\partial Z}\right)^2 + \left(\frac{\partial L_Z}{\partial Z}\right)^2 + \left(\frac{\partial L_\theta}{\partial Z}\right)^2\right] \tag{16}$$

where ε_Z is the axial strain. Von Mises criterion is used to calculate the equivalent strain, with the three main strain directions being circumferential, axial, and radial:

$$\varepsilon_{eqv} = \frac{1}{1+\mu}\sqrt{\frac{1}{2}\left[\left(\varepsilon_\theta - \varepsilon_Z\right)^2 + \left(\varepsilon_\theta - \varepsilon_R\right)^2 + \left(\varepsilon_R - \varepsilon_Z\right)^2\right]} \tag{17}$$

where ε_{eqv} is the equivalent strain; μ is Poisson's ratio (taken as 0.3); ε_ϑ, ε_Z, and ε_R correspond to the circumferential, axial, and radial strain, respectively. Pipeline denting is a form of plastic deformation. The radial strain of the pipeline is $\varepsilon_R = -(\varepsilon_\theta + \varepsilon_Z)$, and the formula (17) can be obtained based on the incompressible condition of the plastic deformation volume:

$$\varepsilon_{eqv} = \frac{2}{\sqrt{3}}\sqrt{{\varepsilon_\theta}^2 + \varepsilon_\theta \varepsilon_Z + {\varepsilon_Z}^2} \quad (18)$$

2.3 Estimating strain in dents (ASME B31.8-2018)

The calculation method of the dent strain in the ASME B31.8-2018 standard (denoted as ASME B31.8 in following sections) is used to verify the accuracy of the analytical calculation formula of the depression derived in this paper. The calculation method is shown in Fig. 6 (ASME B31 Committee, 2018):

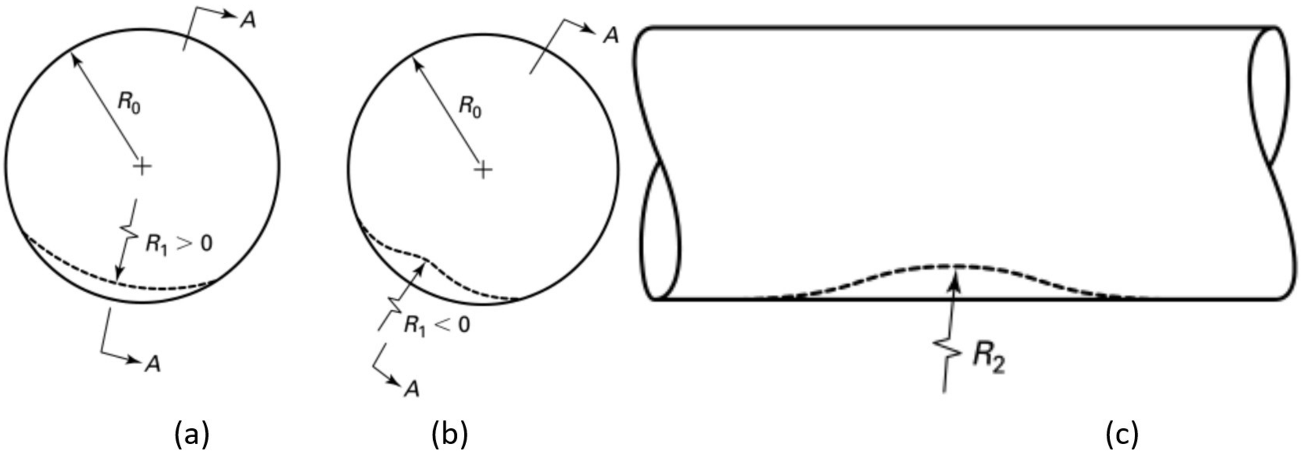


Figure 6. Dent strain estimation (ASME B31 Committee, 2018): (a) non-reentrant, (b) reentrant, and (c) longitudinal profile.

Parameter R_0 is the initial pipe surface radius equal to one-half the nominal pipe OD. The transverse profiles in Fig. 6 show that the indentation may be non-reentrant or reentrant. When the indentation is non-reentrant, the curvature of the pipe surface is in the same direction as the original surface curvature, and R_1 takes a positive value. When the indentation is reentrant, the curvature of the pipe wall is reversed, and *R* takes a negative value. The radius of curvature in a longitudinal plane is determined through the indentation shown as R_2 in Fig .6(c). Other dimensional terms are the wall thickness, *t*, dent depth, *d*, and dent length, *L*. The bending strain in the circumferential direction is calculated as follows:

$$\varepsilon_1 = \left(t/2\right)(1/R_0 - 1/R_1) \quad (19)$$

The term ε_1 is negative at the dent apex, representing compression at the outside pipe surface. In contrast, positive ε_1 represents tension on the inside pipe surface.

The bending strain in the longitudinal direction is calculated as follows:

$$\varepsilon_2 = t/(2R_2) \quad (20)$$

Negative term ε_2 at the dent apex represents compression at the outside pipe surface. In contrast, a positive term ε_2 represents tension on the inside pipe surface.

The extensional strain in the longitudinal direction is calculated as follows:

$$\varepsilon_3 = (1/2)(d/L)^2 \quad (21)$$

The term ε_3 is in tension only. The user is cautioned to avoid overestimating the length dimension, *L*.

The strain at the inside and outside pipe surfaces is calculated as follows:

$$\varepsilon = (2/\sqrt{3})\left[\varepsilon_1^{\ 2} + \varepsilon_1(\varepsilon_2 + \varepsilon_3) + (\varepsilon_2 + \varepsilon_3)^2\right]^{(1/2)} \tag{22}$$

Positive and negative values for ε_1 and ε_2 must be accounted for to determine the combined strain on the inside and outside pipe surfaces.

Compared with the analytical formula in ASME B31.8, the analytical formula of smooth dent established in this paper is derived by more rigorous geometric equations. In addition, a more accurate pipeline dent surface can be obtained by combining it with 3D laser scanning technology, providing a more accurate calculation of pipeline dent strain.

2.4 Finite element model

The finite element method is used to determine the accuracy and error range of the proposed formula by simulating the pipeline dent test. The finite element model of the smooth dented pipeline is established according to the pipeline parameters and loading process adopted by (Rafi A N et al.,2011) in the pipeline dent test. The experimental obtained axial and circumferential strains are compared with the test results to verify the accuracy of the finite element model.

The outer diameter of the pipe is 274 mm, the wall thickness is 8.2 mm, and the length is 100 mm. Pipe ends are sealed with end caps, and the pipe is made of API 5L X52 pipeline steel. The mechanical properties of the pipe in the finite element model are set according to the material's mechanical properties (Table 1 and Fig. 7). The internal pressure of 4.83 MPa was first applied to the pipeline during loading. Then, the depression was applied through an indenter to the pipeline to form a dent. The dent radius of the indenter was 25 mm. After loading and rebounding four times, the remaining dent depths were 3.3% OD, 4.7% OD, 6.2% OD, and 8% OD, respectively.

Table 1 Mechanical parameters of test pipe.

Steel grade	Elastic modulus (GPa)	Poisson ratio	Yield strength (MPa)	Tensile strength (MPa)
X52	200	0.3	410	498

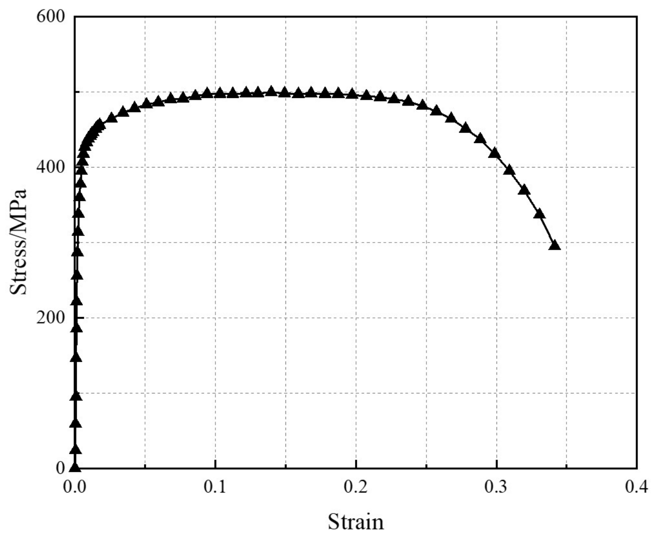


Figure 7. Engineering stress-strain curve used in FEA model.

Nonlinear finite element analysis software ABAQUS was used to establish a dented pipeline model and reproduce the abovementioned test procedure. Due to the model's symmetry, the 1/4 model of the pipeline is established using the 4-node reduced integral shell element (S4R). The spherical indenter model is established using the discrete rigid body. The model size is consistent with the test. The symmetry plane of the pipe adopts symmetrical boundary conditions, the distal section constrains the axial displacement, and the axis of the pipe bottom is clamped. A dense grid of 2 mm × 2 mm is divided in the dent formation area, and the grids in other areas are appropriately sparse, as shown in Fig. 8. The indenter is modeled as a rigid body which ignores any deformation. A reference point is created and coupled with the indenter to apply indentation through the displacement control method. The displacement and reaction force of the reference point are extracted to compare with the experimental data for model validation.

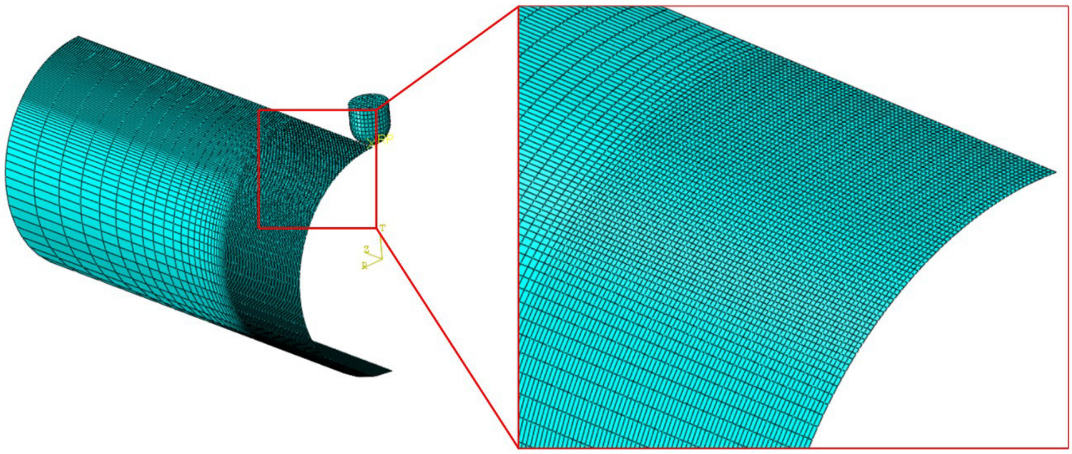


Figure 8. The grid division diagram of the finite element model of a dented pipeline.

2.5 Evaluation software

According to the above study on the analytical method of smooth dent strain calculation, MATLAB's powerful mathematical calculation ability and excellent drawing function are employed in this paper to develop a Pipeline Dent Assessment (PDA) software on the GUI platform (Ozkurt N,2023; Breidt F et al.,2023). Hence, smooth dent strain calculation and result visualization can be achieved (Noor S Z M et al.,2013). More details about the developed PDA software are shown in Section 3.3.

3 RESULTS

3.1 Finite element model validation

The load-displacement curve of the indenter loading process of the simulation results and the axial strain and circumferential strain results of the outer wall of the pipeline dent center were extracted and compared with the test results carried out by (Rafi A N et al.,2011).

Fig. 9 depicts the load-displacement of the indenter during the loading process. Four loading and unloading cycles are performed following the testing procedure accordingly (Rafi A N et al.,2011). Fig. 10 illustrates the distribution of strain in relation to the distance from the center of the dent, extending along both the circumferential and axial directions. Based on the information presented in Figs 9 and 10, we can deduce that the outcomes of the finite element simulations are in good agreement with the experimental results, affirming the validity of the finite element model. Consequently, in the subsequent discussions, the strain data derived from finite element simulations will serve as the benchmark for assessing the precision of the proposed analytical equation and the ASME B31.8 formula.

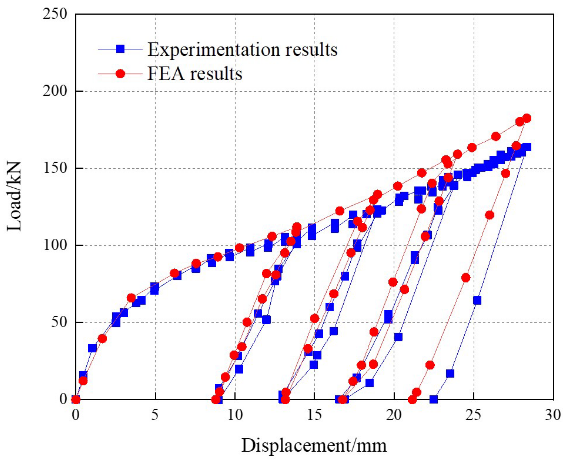
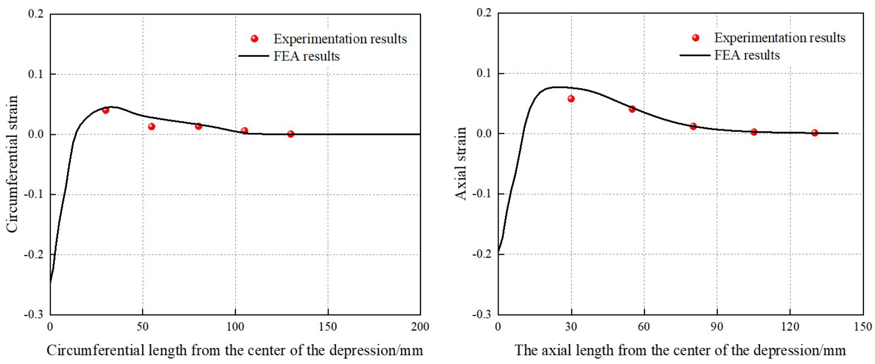


Figure 9. Comparison of load-displacement curves between the FEA and the experiment (Rafi A N et al.,2011).

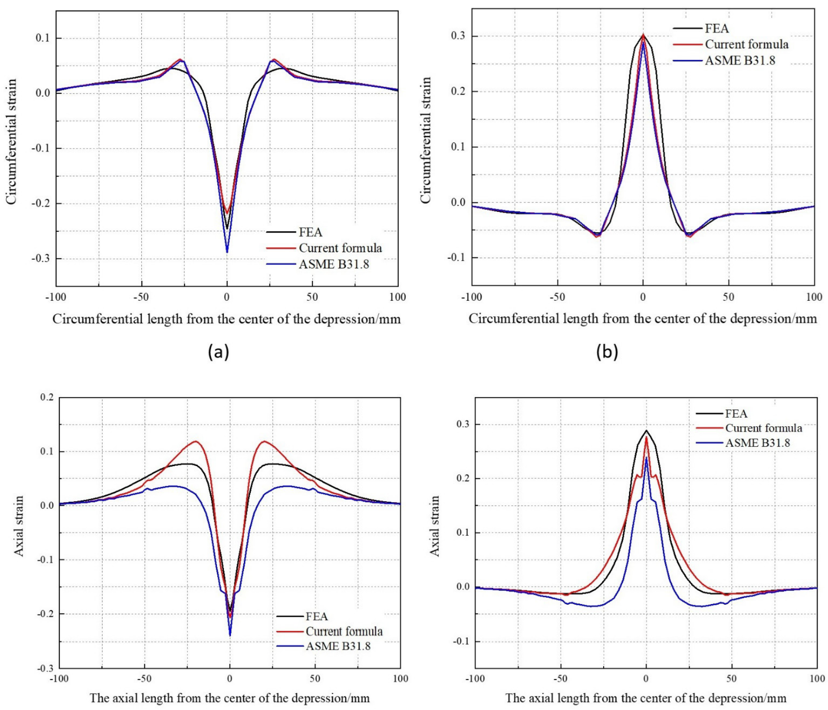


(a) circumferential strain (b) axial strain

Figure 10. Comparison of strain results between the FEA and the experiment (Rafi A N et al.,2011).

3.2 Analytical formula validation

The formula proposed is validated by comparing the strain calculation results with those from the finite element simulation and the results calculated using the ASME B31.8 standard. The geometric data of the dented pipe's outer surface, obtained through 3D laser scanning, is utilized as the input for both the proposed formula (Section 2.2) and the ASME B31.8 formula (Section 2.3). Fig. 11 illustrates the distribution of equivalent strain around the dent along the circumferential and axial directions on both the inner and outer surfaces of the pipe. Given that most dent assessment criteria consider the maximum depth or maximum strain as indicators of a dented pipeline's severity, the maximum equivalent strain at the dent's center is compared across different methods. With the finite element simulation results serving as the benchmark, the relative error of the proposed formula and the ASME B31.8 formula is presented, as indicated in Table 2. The relative errors of the proposed formula are 1.2% and 6.3% for the pipe's outer and inner surfaces at the dent, respectively. The relative errors of the ASME B31.8 formula are 10.5% and 5.7% for the pipe's outer and inner surfaces at the dent, respectively. Based on this data, the proposed formula demonstrates higher accuracy than the ASME B31.8 formula for calculating dent strain on the pipe's outer surface. For the inner surface dent strain calculation, both methods exhibit similar error margins.



(a) (b) (c) (d)

Figure 11. Comparison of dent strain results: (a) circumferential strain on the outer wall, (b) circumferential strain on the inner wall, (c) axial strain on the outer wall, and (d) axial strain on the inner wall.

Table 2. Comparison of maximum equivalent strain results of the pipeline dent obtained via different methods.

Calculation method	Maximum equivalent strain			
	Outer surface	Error/%	Inner surface	Error/%
FEA	0.4296	-	0.6204	-
Current formula	0.4245	1.2	0.5813	6.3
ASME B31.8	0.4746	10.5	0.5853	5.7

The proposed formula has been tested under more working conditions to further study its accuracy. Due to the limitation experimental specimen availability, the finite element mesh node coordinates of the pipeline's outer wall are extracted and used as 3D scanning data for further testing purpose. A X65 pipe with 813 mm diameter and 12.5 mm wall thickness was modeled using finite element method. The radius of the indenter varies from 5% OD to 20% OD in an interval of 5% OD. The dent depth varies from 2% OD to 12% OD in an interval of 2% OD. Thus, a total of 20 groups of testing conditions are obtained by combining different indenter radius and dent depth. The maximum equivalent strain of the inner and outer walls of the dented pipeline are calculated via the proposed formula. The results are compared with the calculation results obtained by the FEA method and the ASME B31.8 standard.

Figure 12 illustrates the maximum equivalent strain results of 20 testing cases on the inner and outer walls of the dented pipeline calculated using different methods. The x-axis represents the values calculated by either the proposed formula or the ASME B31.8 standard, while the y-axis represents the values obtained from the finite element simulation. The diagonal black line indicates where values on the x-axis equal the values on the y-axis. Points lying on this line indicate perfect alignment between the strain values calculated by the formula and the finite element results. The green and red dashed lines represent the 10% and 20% error limits, respectively. As depicted in Figure 12(a), the inner surface strain calculated by the proposed formula consistently exhibits a larger relative error compared to that from the ASME B31.8 formula. For strain values below 0.3, the majority of data from the ASME B31.8 formula fall within the 10% error limit, while the proposed formula data fall between 10% and 20% error. However, for strain values greater than 0.3, the error for both formulas exceed 20%. In contrast, Figure 12(b) illustrates that the proposed formula offers superior accuracy compared to the ASME B31.8 formula for outer surface strain calculation. Regardless of the strain level, the data from the proposed formula remain within the 20% error limit, with some data even exhibiting errors of less than 10%.

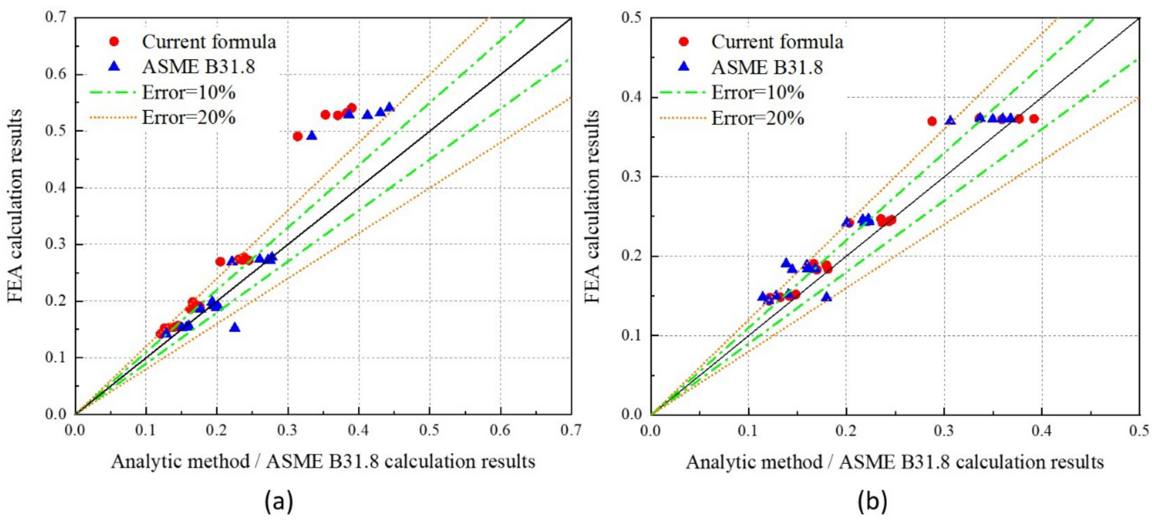


Figure 12. Comparison of the maximum equivalent strain results of the inner and outer wall: (a) inner wall comparison results, and (b) outer wall comparison results.

The average errors from both formulas are presented in Table 3. For the maximum equivalent strain results of the inner wall, the proposed formula and the ASME B31.8 standard exhibit average errors of 17.59% and 11.56%, respectively. Conversely, the average errors for the calculation of outer wall strain are 7.73% and 13.16%, respectively. The formula demonstrates greater accuracy than the ASME B31.8 formula for calculating strain on the outer wall of the dented pipeline. While the calculated strain on the inner wall is less accurate than that obtained using the ASME B31.8 standard, consistent with the observations from Figure 12. This discrepancy could be attributed to the geometric model used in strain calculation, which is based on scanning results of the outer wall of the pipeline. However, the inner wall strain is derived from point cloud data of the outer wall. Hence, the error in the inner wall strain calculation result is relatively large. Additionally, since the formula is derived based on thin-shell theory, the inner wall deformation of the dented pipeline may be relatively large for working conditions with sharp indenters and large dent depths. The change in circumferential circumference of the middle surface before and after deformation must be considered, further distorting the strain calculation results.

Table 3. Comparison of the maximum equivalent strain average error of pipeline dent obtained by different methods.

Calculation method	The average relative error	
	Error/% (Outer wall)	Error/% (Inner wall)
FEA	-	-
Current formula	7.73	17.59
ASME B31.8	13.16	11.56

3.3 Software development result

A Pipeline Dent Assessment (PDA) software was developed on the MATLAB GUI platform based on above analytical method of smooth dent strain calculation. This software can achieve smooth dent strain calculation and results visualization through a simple interactive interface.

3.3.1 Software interface

The interface of the dent strain calculation module is shown in Fig. 13. The user can import the data by opening the point cloud coordinate data file processed by the reverse software. The strain calculation is performed after inputting the pipe diameter, wall thickness, and the number of circumferential and axial points of the regular grid division. Users can freely select between the proposed formula and the ASME B31.8 formula. Once the calculation is completed, the maximum equivalent strain can be output on the interface. The smooth dent can be evaluated according to the critical strain in the ASME B31.8 standard specification or other evaluation criteria. The user can select the point cloud map, the grid map, and the strain components of the inner and outer walls in the drop-down box to visualize the results. Axial and equivalent strain contour maps are not available, since the ASME B31.8 standard can only calculate the axial film strain at the center of the dent.

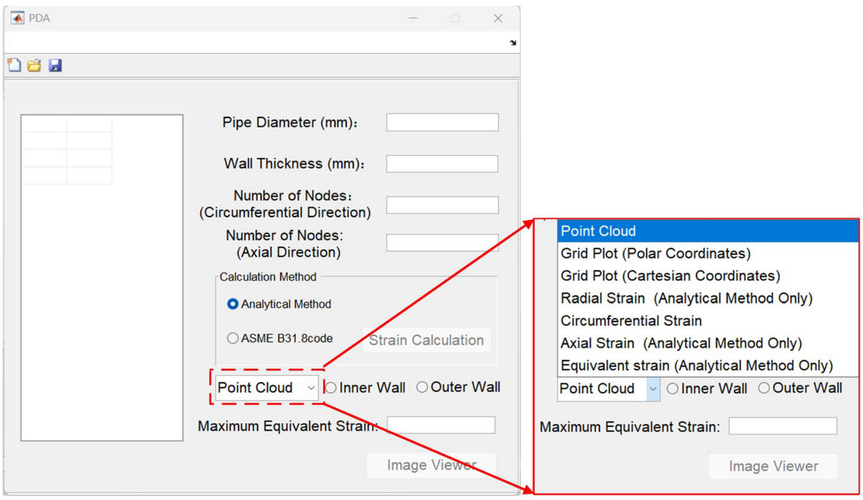


Figure 13. Software Interface of dent strain calculation module.

3.3.2 Case demonstration

The point cloud data of this case come from the grid node coordinates of the finite element analysis model. The modeling calculation is carried out according to the method described in Section 2.4. The specific modeling parameters are shown in Table 4 and Fig. 14. After calculation, the grid node coordinate data are saved as point cloud data.

Table 4. Modeling parameters of the finite element method.

Pipe diameter /mm	Wall thickness /mm	Elastic modulus/GPa	Poisson's ratio	The curvature radius of the indenter	Displacement of indenter
610	6.8	200	0.3	0.12	0.12

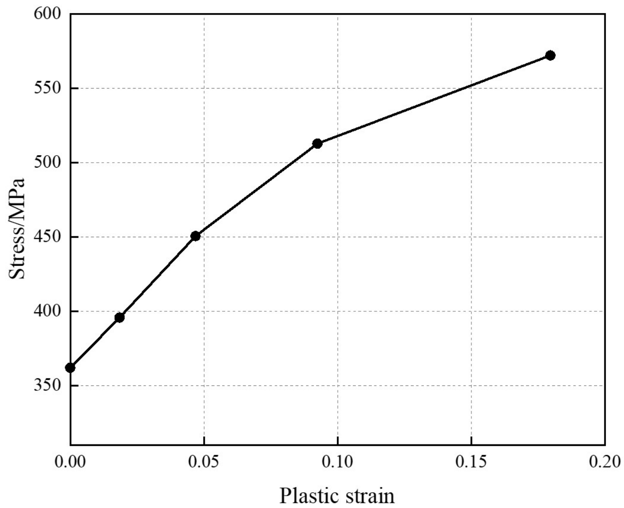


Figure 14. True plastic stress-strain curve.

The specific rectangular coordinates of the point cloud are displayed. The number of point clouds is displayed at the bottom of the table within the point cloud coordinate data file in the interface of the dent strain calculation module. As shown in Fig. 15, the number of point clouds in the demonstration case is 43260. The pipe diameter, wall thickness, and number of circumferential and axial nodes are shown on the right. The proposed formula or ASME B31.8 formula can be selected in the solution method box. Then, the 'strain solution' button needs to be clicked to perform analysis. Once the caluclation is completed, the software will pop the prompt box and display the calculation results in the maximum equivalent strain box. As shown in Fig. 16, the maximum equivalent plastic strain of the finite element calculation of the demonstration case is approximately 16.87%. The result of the proposed formula is 16.418%, and the calculation result of the ASME B31.8 formula is 20.307%. It can be seen that both results exceed the 6% threshold in the ASME B31.8 specification. As such, the demonstrating dented pipe should be repaired.

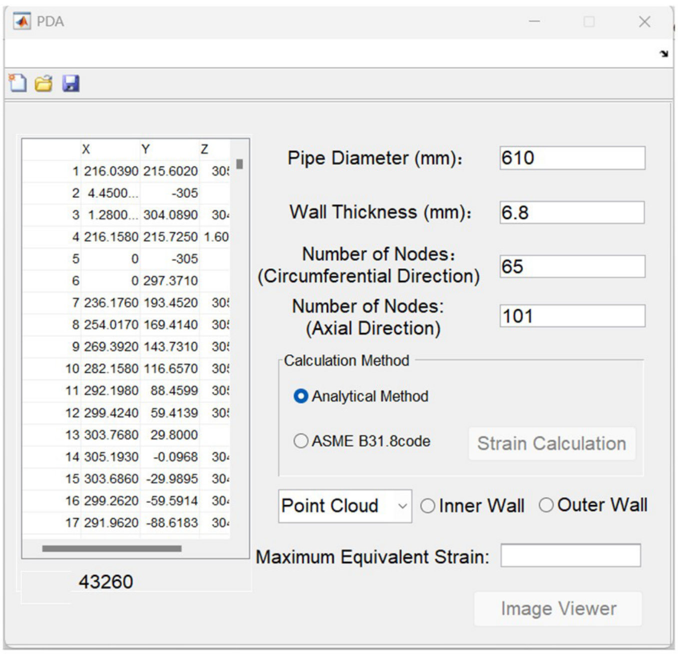


Figure 15. Input interface for dent strain calculation software.

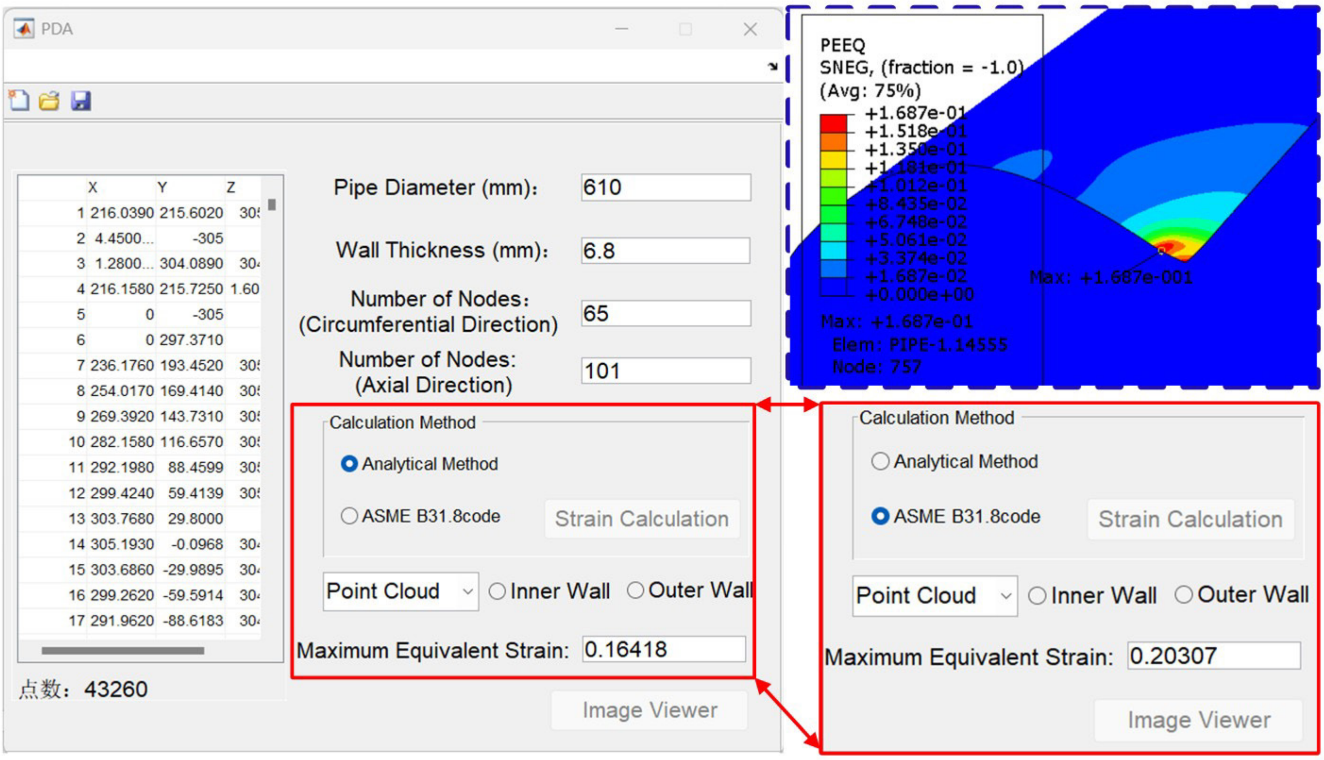


Figure 16. Output interface of dent strain calculation software.

Once the calculation is completed, the point cloud, grid, or strain map can be selected in the drop-down box, and the inner or outer wall is selected. The calculation results can be visually plotted and viewed by clicking the ' image view ' button. Specific calculation results of the strain component or equivalent strain can be obtained by viewing the strain contour map. The circumferential strain component contour map of the outer wall obtained by the analytical and finite element methods are shown in Fig. 17.

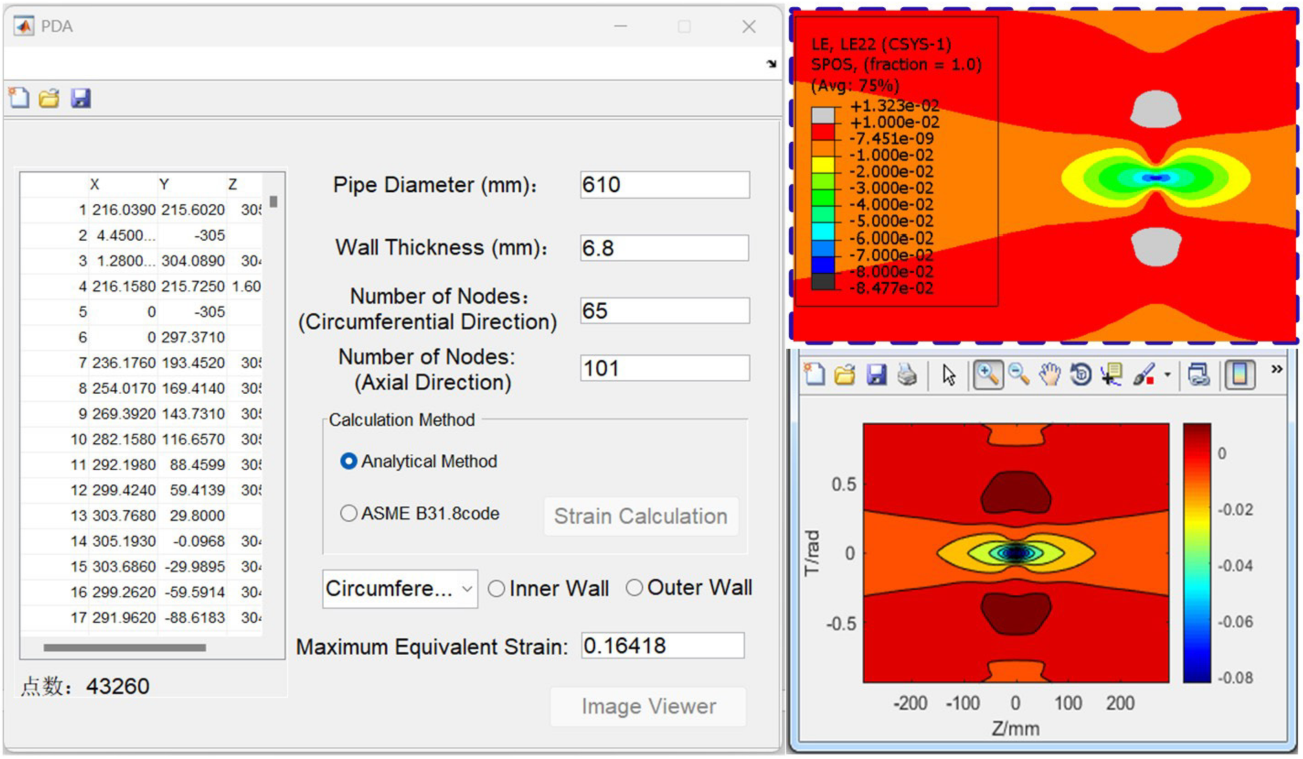


Figure 17. Strain contour plot of the software.

4 CONCLUSION

Dents are critical defects that can compromise the integrity of pipelines, primarily due to the permanent plastic deformation caused by external concentrated loads, which increases the risk of crack initiation. In light of the limitations of current engineering approaches for dent evaluation, this study introduces a new analytical formula to enhance the precision in calculating smooth dent strains. The key findings and contributions of this study are summarized as follows:

1. An analytical approach for calculating the strain in smooth dents on pipelines was formulated. This method leverages geometric analysis of dent deformation and thin-shell theory. To accurately model the dented pipe surface, cubic B-spline interpolation was applied to 3D laser scanning point cloud data, providing a detailed and precise input for the analytical formula.
2. The accuracy and the error margin of the proposed analytical formula were rigorously tested against the finite element method by simulating pipeline dent tests. The comparison indicates that the proposed formula achieves superior accuracy in calculating dent strain on the outer surface of the pipeline when compared with the calculations performed using the ASME B31.8 standard formula.
3. A user-friendly software application was developed on the MATLAB GUI platform, incorporating the new analytical formula for smooth dent strain calculation. This software enhances the flexibility in dent assessment by allowing users to choose between the newly proposed formula and the traditional ASME B31.8 formula for their strain calculations.

These contributions signify a substantial step forward in the field of pipeline integrity management, offering more accurate, reliable, and practical tools for the assessment of dents and their potential impact on pipeline safety.

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Data availability: Research data is available in the body of the article

Editor: Pablo Andrés Muñoz Rojas

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