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Review Paper

Standards and methods for dent assessment and failure prediction of pipelines: A critical review

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A B S T R A C T

Dent, a common mechanical damage on pipelines, is associated with a significant local plastic deformation. Dents can cause pipeline failures, especially when they are combined with other types of defects such as gouges, fatigue, corrosion, and cracks. In this work, a systematic review of various assessment methods and standards for pipeline dents, including the combination of a dent with other defects, is conducted. Generally, the methods available today are not sufficiently accurate and reliable to assess pipeline dents, especially the dent-defect combinations. For plain dents on pipelines, both the depth-based criterion and the strain-based criterion are commonly used in engineering. Their main problems include inaccuracy and conservatism. For a dent combined with other defects, the existing assessment techniques are not mature enough to give reliable results. Both experimental testing and numerical modeling through finite element (FE) analysis are capable of investigating the influence of dents and dent-defect combinations on burst failure pressure of the pipelines, although an approximation to the reality is still the main difficulty existing in the experimental testing and FE analysis. Nowadays, relevant studies on assessment techniques for plain dents, a dent with fatigue and a dent with a single gouge have been common in literature. The combinations of a dent with corrosion or cracks have been rarely assessed due to complicated mechanisms involving a multi-physics coupling effect. Development of novel assessment methods by integrating mechanical stress and strain, electrochemical reactions and steel metallurgy will be a key topic to accurately assess the dent-defect combinations for improved pipeline integrity.

1. Introduction

Multiple threats exist to adversely affect the integrity and safety of pipelines in the field. These include corrosion, cracks, mechanical damage, materials and manufacturing anomalies, geohazards and external interference (Revie, 2015). Dent, a common type of mechanical damage introduced during pipeline construction and excavation activities, is defined as a permanent inward plastic deformation on pipe wall. Dents have caused frequent pipeline failures (Hyde et al., 2007; Liu and Francis, 2004; Abdelmoety et al., 2022). It was reported that 50% of pipelines in service contained over 10 dents after excavation and inspection (Dawson et al., 2002). Moreover, 60% of pipeline failure cases were related to dents or dents combined with other types of defects (Tian and Zhang, 2017a). Development of accurate and reliable techniques for dent assessment has been paid extensive attention in pipeline industry.

The commonly used standards and methods for dent assessment and pipeline failure prediction include American Society of Mechanical Engineering (ASME) B31.8, ASME B31G, American Petroleum Institute (API) 579, API 1160, Canadian Standardization Association (CSA) Z662 and UK Onshore Pipeline Association (UKOPA) (Tee and Wordu, 2020; Bernard et al., 2013; Gao and Krishnamurthy, 2015; Dawson et al., 2018). Principally, there are two types of criteria for dent assessment, i.e., the depth-based criterion and the strain-based criterion. The two criteria use a critical depth and a critical maximum strain, respectively, at the center of a dent as indicators to determine the damage associated

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List of nomenclature and variables

3-D	Three-dimensional
ASME	American Society of Mechanical Engineering
API	American Petroleum Institute
BS	British Standard
CFR	Code of federal Regulations
CSA	Canadian Standardization Association
DFDI	Ductile fracture damage index
DNV	Det Norske Veritas
EPRG	European Pipeline Research Group
FAD	Failure assessment diagram
FE	Finite element
HIC	Hydrogen-induced cracking
ILI	In-line inspection
M-E	Mechano-electrochemical
NFAD	Notch-failure assessment diagram
R–O	Ramberg-Osgood
RP	Recommended Practice
SCC	Stress corrosion cracking
SCF	Stress concentration factor
SLD	Strain limit damage
SMYS	Specific minimum yield strength
UKOPA	UK Onshore Pipeline Association
XFEM	Extended finite element method
A	Geometrical coefficient
A_1	Area of metal loss in the longitudinal plane of corroded pipe
A_0	Original area in the longitudinal plane pipe
A_P	Coefficients
b	Bending strain
B	Geometrical exponent
B_P	Coefficient
C_1	Constant
C_2	Elongation rate of pipe steel measured in uniaxial tensile testing
C_P	Coefficient
d	Dent depth
d_c	Corrosion depth
d_g	Maximum depth of the gouge
D	Outer diameter of pipeline
D_{eform}	Damage resulted from deforming
D_{ek}	Damage during the kth load increment
D_{et}	Indicator of the limit state for a structure to carry no further loads
D_i	Internal pipe diameter
e_0	True strain to failure
I	Integral value
K	Fatigue stress concentration factor
K_d	Stress concentration factor associated with the dent
K_r	Toughness ratio
L	The length of dent in axial direction
L_c	Longitudinal length of the corroded area
L_g	The length of the gouge
L_r^P	Load ratio
M	Parameter
m	Membrane strain
N	Estimated fatigue life of the dented pipe in cycles
n	R–O factor
p	Internal pressure
R	Pipe outer radius
R_d	The surface radius of curvature of the dent
R_o	Initial pipe surface radius
R_1	External surface radius of curvature in the transverse plane through the dent
R_2	External surface radius of curvature in the longitudinal plane through the dent
SP	Dent shape parameter
S_F	Burst pressure
S_{flow}	Flow stress
t	Pipe wall thickness
T	Equivalent tensile stress
u	Profile function in longitudinal direction
v	Profile function in circumferential direction
w	Pipe wall deflection in the radial direction
x	Variable
y	Function of the contour of the dented area
z	Length parameter of corrosion defect
α	R–O factor
ε	Strain
ε_1	Bending strain in the circumferential direction
ε_2	Bending strain in the longitudinal direction
ε_3	Membrane strain in the longitudinal direction
ε_d	Critical strain of ductile materials for incipient crack
ε_{pe}	Sum of plastic strain
ε_{eq}	Equivalent strain
ε_i	Equivalent strain on the inside of pipe surface
ε_o	Equivalent strain on the outside of pipe surface
ε_x	Strain in the axial direction
ε_y	Strain in the circumferential direction
ε_z	Strain in the radial direction
σ	Stress
σ_A	Equivalent nominal stress
σ_a	Alternating stress
σ_{eq}	Equivalent stress
σ_{exp}	Experimental stress function
σ_F	Failure stress of the gouged pipeline
σ_{FS}	Fatigue strength
σ_f	Flow stress
σ_m	Average stress
σ_Y	Yield strength of pipe steel
σ_U	Ultimate tensile strength of pipe steel
γ_{xy}	Shear strain
ΔP	Internal pressure variation
$\Delta\varepsilon$	Cyclic strain range
$\Delta\sigma$	Maximum stress
$\Delta\sigma_{nom}$	Nominal stress of an undented pipe with internal pressure

with the dent (Noronha et al., 2010; Wu et al., 2015). Standards based on the critical dent depth have been developed to evaluate dent-induced pipeline damages (Adeeb and Horsley, 2006; Arumugam et al., 2018; Allouti et al., 2012). For the strain-based criterion, formulas are used to calculate the maximum equivalent strain at the dent center based on the dent profile information obtained from in-line inspection (ILI) tools (Gao and Krishnamurthy, 2015; Lukasiewicz et al., 2006). Dents combined with other types of defects, such as gouge, corrosion and cracks, are commonly encountered on pipelines, and tend to fail the pipelines easier (Zhao et al., 2021; Błachut and Iflefel, 2008; Freire et al., 2019). Methods and standards are thus required to estimate threats of the combined defects to the pipelines (Lukasiewicz et al., 2006; Alexander and Brownlee, 2007; Gao et al., 2008).

Experimental testing and numerical modeling have been used to validate and improve the assessment methods and criteria. Typical procedures for both methodologies include denting on a selected pipe segment, removal of the indenter, and application of a load (such as internal pressure) on the dented pipe (Rezaee et al., 2018; P. Zhang et al., 2020; Cunha et al., 2014). When a dent is combined with other types of defects such as gouge, corrosion or cracks, a defect combination is introduced on the pipe surface and then the denting process is conducted. Similar processes are followed in numerical simulation to obtain a model that approximates the experimental condition. It is generally accepted (Choi et al., 2003; Ghaednia et al., 2015a, 2015b) that experimental testing is the best way to generate true results. However, the experiments are usually costly and time-consuming. Modeling by finite element (FE) analysis is a promising alternative (Zhao and Cheng, 2022), while the accuracy and reliability of the model must be verified by testing results.

In this work, a comprehensive review, along with commentary remarks, of various assessment methods and standards was conducted for dent assessment, including a dent combined with other defects, i.e., gouge, corrosion, and cracks. The standards and methods for dent assessment and burst pressure prediction were systematically analyzed. The limitations and problems of the methods were discussed, and modifications and novel methods for improved accuracy and reliability were proposed. Both experimental testing and FE modeling for pipeline dent assessment were considered in the review. Further development and innovation of assessment methods for dents and dent-defect combinations were suggested.

2. Standards and methods for dent assessment on pipelines

2.1. Existing standards for dent assessment

Plain dents, the simplest form of mechanical damage on pipelines, are those with a smooth transition of the curvature from the dent area to pipe body (Allouti et al., 2012). Plain dents induce a significant plastic deformation, but do not reduce failure pressure of the pipelines (Kec and Cerny, 2017). Typical procedures in assessment of a plain dent include (1) ILI data analysis to define geometrical parameters of the dent, such as depth, length and width, (2) calculations of three-dimensional (3-D) strains or dent features such as the critical depth, and (3) prediction of fatigue life of pipelines by applying a failure criterion included in standards (Gao and Krishnamurthy, 2015; Noronha et al., 2010; Okoloekwe et al., 2020).

Although the depth-based criterion for plain dent is generally considered inaccurate, it is convenient to obtain the depth parameter and conduct pipeline failure evaluation (Tian et al., 2020). In contrast, the strain-based criterion is believed more accurate but relies on specific calculation methods. Table 1 lists commonly used standards and methods for assessment of plain dents on pipelines.

where OD is outer pipe diameter, R_o, R_1 and R_2 are initial outer radius of the pipe, outer radius of curvature of the pipe in transverse plane across the dent, and outer radius of curvature of the pipe in longitudinal plane through the dent, respectively, t is pipe wall thickness, L is dent length in longitudinal direction, d is dent depth, ε_1 and ε_2 are bending strains in the circumferential and longitudinal directions, respectively, ε_3 is extensional strain in the longitudinal direction, and ε_i and ε_o are inside and outside equivalent strains, respectively.

During long-term service of dented pipelines in the field, other types of defects can be generated in the dent area (Zhao et al., 2021; Błachut and Iflefel, 2008; He and Zhou, 2021). Fig. 1 shows schematically various types of dent-defect combinations that can be present on pipelines. Compared with plain dents, a dent combined with other defects like gouges, corrosion and crack is much more complicated to evaluate, and is more dangerous to threaten the integrity of the pipelines. It was confirmed that the presence of other defects at the dent area could decrease the pressure-bearing capacity of pipelines (Macdonald et al., 2007; Macdonald and Cosham, 2005; Shaik, 2015). A dent subjected to fatigue or interacting with corrosion or stress corrosion cracking (SCC) is also a big threat to pipeline integrity. The main standards for assessment of combined defects include ASME B31.8, ASME B31G and API 579. The 3-D geometrical parameters of the gouges, corrosion and crack, along with the dent dimension, are required to conduct pipeline failure assessment (Qin and Cheng, 2021). The standards applied on the dent-defect combinations are also listed in Table 1.

2.2. Principles of the standards for pipeline dent assessment

It is seen from Table 1 that, for all the listed standards, the failure criteria for plain dents and dent-defect combinations are similar or identical. Moreover, these standards are not mandatory to follow in engineering. For example, although the ASME B31.8 provides a relatively complete set of evaluation methods, it also states that engineers can select other reasonable methods when assessing a dented pipeline (ASME B31.8, 2020). The same notes are also included in other standards. Obviously, the assessment methods provided in individual standards are not regarded absolutely accurate and reliable by the standard developers.

2.2.1. Plain dents

As stated above, the failure criteria defined in various standards for dent assessment mainly include the depth-based criterion and the strain-based criterion (Adeeb and Horsley, 2006; Wu et al., 2016). The dent depth is a direct geometric parameter to define a plain dent. As a result, the depth-based criterion becomes a convenient and popular method to evaluate dented pipelines for failure prediction (Tian et al., 2020). However, field experiences showed that the dent depth barely affected the pressure-bearing capacity of a dented pipeline when the dent depth exceeded 20% of pipe outer diameter (Tian et al., 2020; Shuai et al., 2018). Even when the dent depth is less than 6% of the pipe outer diameter, the pipeline can still fail due to fatigue (Arumugam et al., 2018). Thus, it is generally believed the depth-based criterion is not sufficiently accurate and reliable for dent assessment on pipelines.

Compared to the depth-based criterion, the strain-based criterion is considered more accurate for failure assessment of pipeline containing plain dents (Wu et al., 2015; Okoloekwe et al., 2020). The strain-based criterion requires input parameters such as the dent length (L) in axial direction, the initial pipe surface radius (R_o), the external surface radius of curvature in the transverse plane (R_1) through the dent, and the external surface radius of curvature in the longitudinal plane (R_2) through the dent, and the dent depth (d). The 3-D strains and equivalent strain are calculated using formulas, i.e., Eqs. (1)-(5), in ASME B31.8, as shown in Table 1. The surface radius of curvature (R_d) can be calculated by:

$$\frac{1}{R_d} = \frac{\frac{d^2y}{dx^2}}{\left[1 + \left(\frac{dy}{dx}\right)^2\right]^{\frac{3}{2}}} \tag{6}$$

where R_d can be either R_1 or R_2, and y is a function of the contour of dented area with the variable x. The profile of the dented area should be measured to determine the function of the geometrical shape and then the radius of curvature by Eq. (6). ILI tools are

Table 1
Standards and methods used for assessment of plain dents and a dent combined with other types of defects on pipelines (Tee and Wordu, 2020; Bernard et al., 2013; Gao and Krishnamurthy, 2015; Dawson et al., 2018).

Standard	Plain dents not requiring repair	Dent with a gouge	Dent with corrosion	Dent with a crack
ASME B31.4	Dent depth <6% OD	Repair	Corrosion defect is accessed by ASME B31.G	Repair
ASME B31.8	Circumferential bending strain $\varepsilon_1 = (1/2)t(1/R_0 - 1/R_1)$ (1) Longitudinal bending strain $\varepsilon_2 = t/(2R_2)$ (2) Longitudinal extensional strain $\varepsilon_3 = (1/2)(d/L)^2$ (3) Equivalent strain on the inside pipe surface $\varepsilon_i = (2/\sqrt{3})[\varepsilon_1^2 + \varepsilon_1(\varepsilon_2+\varepsilon_3) + (\varepsilon_2+\varepsilon_3)^2]^{1/2}$ (4) Equivalent strain on the outside pipe surface $\varepsilon_o = (2/\sqrt{3})[\varepsilon_1^2 - \varepsilon_1(\varepsilon_3-\varepsilon_2) + (\varepsilon_3-\varepsilon_2)^2]^{1/2}$ (5) Maximum equivalent strain <6% Or dent depth <6% OD	Repair	Repair	Repair
CSA Z662	Dent depth <6% OD and length/depth <20 or the maximum equivalent strain <6%	Repair	Accessed by ASME B31.G for corrosion between 10 and 40% of wall thickness	Repair
49CFR 192	Dent depth <6% OD	Repair	6% OD and metal loss per corrosion criterion	Repair
49CFR 195	Dent depth <6% OD	Repair	Repair	Repair
API 1160	Dent depth <6% OD	Repair	Immediate repair, unless engineering evaluation shows not an immediate risk	Repair
UKOPA	Dent depth <7% OD or strain <6%	Repair	Corrosion depth <20% wall thickness	Repair

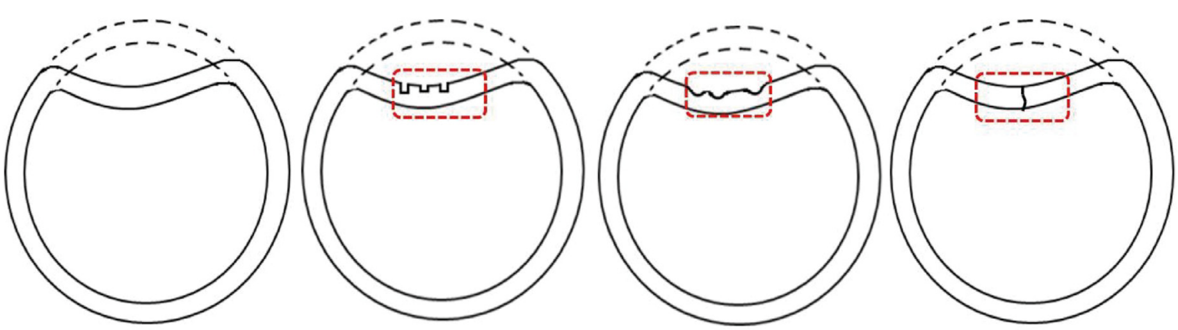

Fig. 1. Schematic diagram illustrating different types of dent-defect combinations that can be present on pipelines.

effective to measure and estimate the profile of the dented area (Xie and Tian, 2018; Coramik and Ege, 2017).

Strains calculated in ASME B31.8 include bending strains in both the circumferential (ε_1) and longitudinal (ε_2) directions, a membrane strain in the longitudinal direction (ε_3), and equivalent strains on the inside (ε_i) and outside (ε_o) of pipe surface. Eqs. (1)-(5) in Table 1 are developed based on a thin plate model (Gao et al., 2008), in which the total strain is divided into axial and circumferential bending strains and membrane strains, respectively. A further assumption is that the circumferential membrane strain is ignored due to a negligible change of transverse girth for the dented pipelines. However, this assumption is questionable. From FE analysis and full-scale tests on dented pipelines, it was found that the maximum circumferential membrane strain was 20% (Md Rafi et al., 2012), which was significant compared to other strains. When the dent is deep, the circumferential membrane strain cannot be ignored. Investigations indicated that the accuracy of the membrane strain formula by ASME B31.8 was poor due to an inadequate analogy to radial strains in a circular plate (Lukasiewicz et al., 2006). Modifications were thus made to overcome the problem for improved accuracy in strain determination.

According to a large deformation thin shell theory, strains of dented pipelines were derived by Lukasiewicz et al. (2006). The equivalent strain was calculated by:

$$\varepsilon_{eq} = \frac{2}{\sqrt{3}}\left[\varepsilon_x^2 + \varepsilon_x\varepsilon_y + \varepsilon_y^2\right]^{\frac{1}{2}} \tag{7}$$

where ε_{eq} is equivalent strain, and ε_x and ε_y are strains in the axial and circumferential directions, respectively, which can be calculated by:

$$\varepsilon_x = \varepsilon_x^m \pm \varepsilon_x^b,\ \varepsilon_y = \varepsilon_y^m \pm \varepsilon_y^b \tag{8}$$

where the superscripts “m” and “b” refer to membrane strain and bending strain, respectively. The sign is positive for the strain of inner pipe surface, and negative for the outer pipe surface. Thus, the equivalent strain should contain membrane strain in the circumferential direction. While there is not a theoretical base for equivalent strain calculations in ASME B31.8, Eq. (7) is derived based on the plastic strain theory with the presupposition that the volume of the material remains constant during deformation (i.e.,

$\varepsilon_x + \varepsilon_y + \varepsilon_z = 0$).

2.2.2. Dent with a gouge

A gouge (or a scratch) is a mechanical damage characterized with steel removal from pipe surface. A high length-to-width ratio and a sharp notch profile are main geometric features of a gouge (Pluvinage et al., 2011). A cold-worked hardened layer will form at the gouge to reduce local ductility (Macdonald and Cosham, 2005). Generally, a gouge can be generated along with a dent, and greatly reduce the pressure-bearing ability of the pipeline (Błachut and Iflefel, 2007, 2008). The combination of a dent and a gouge is not allowed in the standards listed in Table 1. The combined defects should be repaired once detected. In addition, gouges on pipelines are frequently associated with cracks (Ma et al., 2013).

For a dented pipeline accompanied with a gouge, the burst pressure of the pipeline is lower than the pipeline containing the plain dent only or the equivalent gouge in an undented pipeline. For example, Macdonald et al. (2007) found that the burst and fatigue strengths of a pipe containing a dent combined with a gouge were remarkably lower than the strength of the pipe containing an equivalent plain dent. The failure mode during burst testing on a pipe containing the combined defects was rupture associated with a brittle crack propagation (Błachut and Iflefel, 2007). Large tearing through the gouge was found on the dented pipe, where the failed area propagated symmetrically on the dent shoulder. With further microscopic examination and magnetic particles inspection, the hardening effect and microcracks were identified in the dent/gouge area (Zarea et al., 2014). The burst pressure was mainly dependent on the geometrical parameters of the dent and the gouge, such as the dent depth and shape, and the gouge size (Zhao et al., 2021; Tian and Zhang, 2017a). As the depth and length of the gouge increased, the burst pressure of the pipe decreased. A plastic strain was concentrated in the dent area, and the circumferential strain was larger than the axial strain at the dent center. In most studies, the gouge was usually located at the center of the dent area, where the length of the gouge was aligned with the longitudinal or circumferential direction of the pipeline. In general, the location and orientation of a gouge on pipelines are not certain. The relative position of the gouge in the dent area plays an important role in affecting the burst pressure of the dented pipeline (Lancaster and Palmer, 1996). It was found that, when the gouge was located at the dent center and the gouge length was short relative to the dent size, the dent depth did not apparently influence the burst pressure. Where the gouge was on the flank of the dent area, or the gouge was sufficiently long, the burst pressure would reduce remarkably as the dent depth increased.

To date, there has not been a definitive criterion in the standards for assessment of a pipeline containing a combined dent and gouge. For pipelines that contain a longitudinally oriented gouge under static loading, the NG-18 equation is widely used to determine failure stress (σ_F) of the gouged pipelines (Bernard et al., 2013):

$$\sigma_F = 1.15\sigma_Y \left[\frac{1 - \frac{d_g}{t}}{1 - \frac{d_g}{(Mt)}} \right] \tag{9}$$

$$M = \sqrt{1 + 0.26\left(L_g \middle/ \sqrt{Rt}\right)^2} \tag{10}$$

where σ_Y is yield strength of pipe steel, d_g is maximum depth of the gouge, t is pipe wall thickness, L_g is length of the gouge, and R is the pipe outer radius.

In ASME B31G (Bernard et al., 2013), the method for failure stress determination of gouged pipelines is similar:

$$\sigma_F = \frac{\sigma_Y + \sigma_U}{2} \left[\frac{1 - \frac{d_g}{t}}{1 - \frac{d_g}{(Mt)}} \right] \tag{11}$$

$$M = \sqrt{1 + 0.8\left(L_g \middle/ \sqrt{Rt}\right)^2} \tag{12}$$

where σ_U is ultimate tensile strength of pipe steel. The modified ASME B31G equation is also included in ASME B31G with an improved accuracy of the parameter M:

$$\sigma_F = \frac{\sigma_Y + \sigma_U}{2} \left[\frac{1 - \frac{d_g}{t}}{1 - \frac{d_g}{(Mt)}} \right] \tag{13}$$

$$M = \sqrt{1 + 0.314\left(L_g \middle/ \sqrt{Rt}\right)^2 - 0.0084\left(L_g \middle/ \sqrt{Rt}\right)^4} \tag{14}$$

Other standards like DNV RP-101 also have similar equations. These methods attempt to estimate the failure pressure of a pipe containing a gouge, with the assumption that plastic deformation is constrained (Allouti et al., 2014).

2.2.3. Dent with fatigue

Dents on pipelines serve as local stress raisers and strongly affect fatigue failure of the pipelines. The fatigue assessment of dented pipelines by methods given in the standards in Table 1 is basically inadequate. Cyclic loading due to pressure fluctuations of both liquid and gas pipelines remarkably affects the stress and strain at the dent and the fatigue failure of the pipelines. The constraint form of the dent influences the fatigue life. Particularly, a constrained dent is the dent that a re-rounding process does not occur under the internal pressure after denting, where the indenter keeps contacting with the pipeline. Generally, the constrained dent will enable a longer fatigue life than a dent-free pipeline as the indenter supports the pipeline against internal pressure fluctuations (Gao and Krishnamurthy, 2015). For deep constrained dents (e.g., the dent depth exceeds 4% of the pipe outer diameter), the crack location is away from the dent center. For shallow constrained dents, the crack is usually located at the dent center.

The API RP 1183 provides methods for assessment of fatigue life of dented pipelines (API RP 1183, 2020), where three levels of assessment include dent geometry severity ranking (Level 1), dent geometry and load severity ranking (Level 2), and dent fatigue life assessment (Level 3). In Level 1 assessment, the dent geometrical parameters are used to estimate the fatigue life of the dented pipeline by:

$$N = A(SP)^B \tag{15}$$

where N is the estimated fatigue life of the dented pipe in cycles, SP is the dent shape parameter, and A and B are geometrical coefficient and exponent, respectively. Different from Level 1, the historical data of operating pressure and constrained condition of the dent are considered in Level 2. The number of stress cycles can be estimated by Eq. (15) under different pressures. The assessment methods of Levels 1 and 2 are empirical and conservative. The Level 3 assessment based on FE modeling provides a more accurate method, where the crack growth can be simulated by nonlinear numerical analysis.

The method for fatigue assessment on dented pipelines included in API 1156 is based on limited conditions, i.e., the geometrical characteristics and stress concentration level at the dent (Cunha et al., 2014). The formulas used to determine the fatigue life based on S–N curves include:

$$N = 4.424 \times 10^{23} (K \cdot \Delta P)^{-4} \quad (16)$$

$$N = \exp\left(43.944 - 2.971 \cdot \ln\left(K \cdot \frac{\Delta P}{2}\right)\right) \quad (17)$$

where K is the fatigue stress concentration factor and ΔP is the internal pressure variation. In this method, the conversion factor used for calculating the nominal hoop stress range from the internal pressure considers the indenter shape, d/t, i.e., the ratio of the dent depth to pipe wall thickness, for two values only (i.e., 34 and 68) (Alexander, 1999). It is thus unclear how the conversion factor can be computed for other d/t values, especially outside the range of 34 and 68. It was thought that the method was conservative by a factor of two with respect to stress and twenty with respect to cycle number (Alexander, 1999).

In both ASME FFS-1 and API 579-1, the dent fatigue assessment is performed by Level 2 method (Shirband et al., 2020). Based on a semi-empirical S–N model established by European Pipeline Research Group (EPRG), the remaining fatigue life of a pipeline containing unconstrained dents is calculated by:

$$K_d = 1 + 2\sqrt{d^{1.5} \cdot \frac{t}{D}} \quad (18)$$

$$N_c = 5622 \cdot \left(\frac{\sigma_U}{2\sigma_A K_d}\right)^{5.26} \quad (19)$$

where σ_A is the equivalent nominal stress, and K_d is stress concentration factor associated with the dent. It should be noted that a safety factor of 10 is used to ensure a conservative estimation.

2.2.4. Corrosion in dent

Corrosion is one of the primary mechanisms causing pipeline failures (Qin and Cheng, 2021; Leis, 2021; Cosham and Hopkins, 2004; X. Zhang et al., 2021). As the main form of metal loss defect, both uniform corrosion and localized corrosion are commonly present on pipelines. Moreover, pipeline corrosion can happen internally and externally. A big decrease of pipe wall thickness due to corrosion will greatly influence the mechanical performance of pipelines, such as burst pressure, fatigue life and plastic fracture resistance (Shuai et al., 2008). Qin and Cheng (2021) reviewed defect assessment techniques for corroded pipelines. For dented pipelines, corrosion tends to preferentially occur in the dent area due to a high local stress and, sometimes, an aggressive environment generated at the dents (Babbar and Clapham, 2009; Hafez, 2021).

The ASME B31.8 suggests that, for a combined dent with corrosion, the safety assessment should be performed separately. The dent, which is regarded as a plain dent, is assessed by the strain-based criterion, and the corrosion defect is assessed by ASME B31G (Shuai et al., 2017). In standards like CSA Z662 and UKOPA, the depth-base criterion is used for dent assessment. Among various standards, the ASME B31G is most used, where the burst pressure, S_F, is determined by:

$$S_F = S_{flow}\left[\frac{1 - \frac{2}{3}\left(\frac{d_c}{t}\right)}{1 - \frac{\frac{2}{3}\left(\frac{d_c}{t}\right)}{M}}\right] \quad M = \sqrt{1 + 0.8z} \quad (20)$$

where $z = L_c^2/Dt$, L_c is longitudinal length of the corroded area, and d_c is corrosion depth. Eq. (20) is applicable for $z \leq 20$. When $z > 20$, the burst pressure is determined by:

$$S_F = S_{flow}\left(1 - \frac{d_c}{t}\right) \quad (21)$$

The flow stress S_{flow} is set as 1.1 × SMYS (specific minimum yield strength). A modified version of ASME B31G defines that, for $z \leq 50$,

$$\sigma_F = S_{flow}\left[\frac{1 - 0.85\frac{d_c}{t}}{1 - \frac{0.85 d_c}{(Mt)}}\right] \quad M = \sqrt{1 + 0.6275z - 0.003375z^2} \quad (22)$$

For $z > 50$, $M = 0.032\ z + 3.3$. It is noted that the assessment methods listed above is categorized as Level 1, and the profile of the corroded area is treated as parabolic ($z \leq 20$) or rectangular ($z > 20$). In the modified method, the corrosion profile is regarded as a mixed type of geometric shape (Qin and Cheng, 2021). The circumferential geometry of the corrosion area is ignored. In addition to ASME B31G, the standards such as DNV-RP-F101, API 579 and British Standard (BS) 7910 assess corrosion defects in similar formulas with different M factors and flow stresses.

The Level 2 method for assessment of corroded pipelines is provided in ASME B31G using an effective area method (ASME B31G, 2017; Adib-Ramezani et al., 2006). The area of metal loss in the longitudinal plane A_1 and the original area A_0 should be measured to calculate the burst pressure by:

$$S_F = S_{flow}\left[\frac{1 - \frac{A_1}{A_0}}{1 - \frac{\left(\frac{A_1}{A_0}\right)}{M}}\right] \quad (23)$$

The accuracy of the corrosion area is critical to Level 2 assessment.

The Level 3 assessment relies on FE modeling and numerical calculations, and gives more accurate results compared with Level 1 and 2 assessments.

2.2.5. Dent with cracks

Cracks represent the most dangerous feature to pipeline integrity (Okodi et al., 2020). Cracks usually initiate at irregularities such as dents on pipe surface and serve as stress risers, especially at the crack tip. Crack growth due to steel yielding and plastic deformation can be induced by a high stress concentration. For pipelines containing cracks, prediction of the burst pressure depends on geometry of the cracks, such as depth, width and length, as well as the direction of crack propagation. Compared with cracks with other orientations, the longitudinal cracks which are perpendicular to the primary stress (i.e., hoop stress) resulted from internal pressure are generally more dangerous (Okodi, 2021). Pipelines can be failed by either fatigue cracking or SCC (Liu et al., 2011; Okodi et al., 2021; Tang and Cheng, 2011), both of which can initiate at dents. Commonly used standards for crack assessment include API 579 and BS 7910 (Bedairi et al., 2012), where the failure assessment diagram (FAD) is used. There are three levels of assessment. In API 579, Level 1 and Level 2 assessments are applicable for cracks that become arrested and stop growth under given loading conditions and service environments. Critical length and depth of the cracks are considered in Level 1 to estimate severity of the damage. In Level 2, the stress intensity factor is determined for assessment. The crack dimension obtained from ILI data is used in calculations of local stress and then the corresponding stress intensity factor. The FAD is used to determine if the cracks are acceptable. Sometimes, the critical crack length can also be predicted by FAD in Level 2. Fig. 2 shows a typical FAD recommended by API 579, where K_r is toughness ratio and L_r^p is load ratio (API/ASME 579-1/FFS-1, 2016). If a point is on or inside the FAD boundary, the crack size under the given conditions is acceptable.

If a crack is expected to grow, Level 3 assessment should be conducted (API/ASME 579-1/FFS-1, 2016), where true stress-strain results are used in the FAD. It is assumed that the growth of a pre-existing crack is controlled by stress intensity factor at the crack tip. Four types of crack growth mechanisms are assessed for the remaining life prediction, including fatigue cracking, corrosion fatigue cracking, SCC and hydrogen-induced cracking (HIC). The BS 7910 standard also used FAD as the major method for crack assessment with a similar procedure to API 579. A basic difference between API 579 and BS 7910 is the method to determine reference stress and the stress intensity factor (Bedairi et al., 2012).

Dents on a pipeline can be accompanied with cracks, where a high strain is generated during formation of the dent or due to preferential corrosion, mechanical damage or cyclic loading (Ghaednia et al., 2013). Field experiences on dented pipeline showed that cracks could initiate even when the dent was shallow (Arumugam et al., 2018). Although a plain dent contributes little to failure of pipelines, but the cracks initiating in the dent area remarkably degrade the pipeline integrity (Alexander., 1999). It was found (Luo et al., 2020) that penetrating cracks located in the dent center possessed typical fatigue characteristics. In addition, the external coating can be damaged during denting. As a result, a corrosive environment will form, which, combined with the stress concentration at the dent, causes SCC (Mueller et al., 2018). A widely cited concept of the Mechano-electrochemical (M-E) Interaction explains pipeline SCC initiating at dents due to a synergism of local stress or strain and electrochemical corrosion reaction (Xu and Cheng, 2012a, 2012b). When a dent is combined with a gouge, the micro-cracks generated at the base of the gouge can lead to propagating cracks.

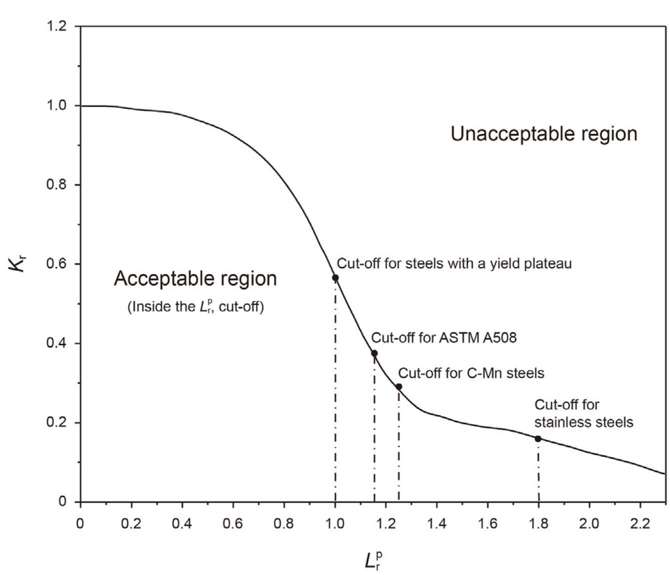

Fig. 2. A typical FAD recommended by API 579 for crack assessment (API/ASME 579-1/FFS-1, 2016).

A combination of dent and cracks is not allowed in most standards. Once one or more cracks are detected at a dent, remediation or replacement will be required. Due to the limited resolution and accuracy of ILI tools, most cracks cannot be easily found until pipeline leaking or other failure modes happen. Standards such as 49 CFR 192 (gas pipelines) and 195 (liquid pipelines) do not include sufficient methods for assessment of the dent-crack combination. For gas pipelines, an immediate repair is recommended. For liquid pipelines, cracks combined with a dent on the upper 2/3 of the pipeline needs to be repaired immediately and otherwise, a service for 60 days is acceptable (Gao and Krishnamurthy, 2015). The ASME B31.8 states that a dented pipeline with cracks less than 12.5% of pipe wall thickness can be removed by grinding (Ghaednia et al., 2015). It was also found (Ghaednia et al., 2014) that the burst pressure of pipelines was rarely affected when the crack depth was small; while when the crack exceeded 40% of the pipe wall thickness, the burst pressure decreased by 55%.

2.3. Commentary remarks on existing standards and the improvements

As seen in Table 1, the present standards for pipeline dent assessment mostly focus on the plain dents. For dents combined with other types of defects, there has been no reliable method available for accurate assessment. Moreover, the existing standards and methods are usually conservative and suffer from certain limitations in dent assessment. A further improvement on dent assessment techniques, especially for dent-defect combinations, is critical to pipeline integrity and safety.

Nowadays, modifications on plain dent assessment have mainly focused on implementation of the strain-based criterion to replace the commonly used depth-based criterion. The depth-based methods are mostly empirical and do not have sufficient theoretical support. Thus, they can only be used as the Level 1 assessment. Instead, more information can be obtained from strain analysis at a dent, such as fatigue life evaluation and cracking prediction (Dawson et al., 2018). There have been three improvements achieved, i.e., methods for strain calculation, estimation of dent profile, and pipeline failure criteria.

The ASME B31.8 introduces the strain-based criterion for dent assessment. However, many problems still exist. First, it is assumed that the maximum bending and membrane strains are located at the center of a dent (Noronha et al., 2010). However, both experimental testing and FE analysis indicated that the maximum strain was not always at the dent center (Md Rafi et al., 2012). As the dent depth increases, the location of the maximum strain moves from the center of the dent to the sides (Shuai et al., 2020). It means that the failure assessment based on strain calculations at the dent apex will give misleading information, especially for deep dents. Second, the formulas in ASME B31.8 are confusing. For example, the formulas for bending and membrane strains are from empirical methods. The FE analyses have shown that the formulas can have predictable erroneous strains (Shahzamanian et al., 2021). Moreover, there is no clear explanation about the origin of the empirical equivalent strain equations (Gao et al., 2008). Third, an important assumption in the standard is that the membrane strains in circumferential and radial directions and the shear strain are negligible (Noronha et al., 2010). Nevertheless, denting is a plastic deformation on pipelines, where the plane strain assumption is not proper. Finally, for unconstrained dents, there will be a re-rounding process after denting, during which the dent depth and strain will decrease. The maximum deformation during the denting cannot be accurately estimated by ASME B31.8 (Zhang et al., 2020). In summary, the strain-based method in ASME B31.8 cannot provide accurate and reliable results for dent assessment and pipeline failure prediction.

By analyzing the problems of strain calculations in ASME B31.8, Lukasiewicz et al. (2006) proposed a more accurate formula based on the theory of large deformation of a cylindrical shell. Using the dent profile data from ILI tools, the bending strains in longitudinal and circumferential directions can be calculated by:

$$\varepsilon_x^b = \frac{t}{2}\frac{\partial^2 w}{\partial x^2},\ \varepsilon_y^b = \frac{t}{2}\frac{\partial^2 w}{\partial y^2} \tag{24}$$

where w is pipe wall deflection in the radial direction. The profile functions in longitudinal and circumferential directions are defined as u and v. The membrane strains ε_x^m and ε_y^m and shear strain γ_{xy} can then be derived by:

$$\varepsilon_x^m = \frac{\partial u}{\partial x} + \frac{1}{2}\left(\frac{\partial w}{\partial x}\right)^2 + \varepsilon_x^o,\ \varepsilon_y^m = \frac{\partial u}{\partial y} + \frac{w}{R} + \frac{1}{2}\left(\frac{\partial w}{\partial y}\right)^2 + \varepsilon_y^o$$

$$\gamma_{yx} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} + \left(\frac{\partial w}{\partial x}\right)\left(\frac{\partial w}{\partial y}\right) \tag{25}$$

The equivalent strains are estimated by Eq. (7). Compared with the method in ASME B31.8, the Lukasiewicz method is more accurate. The ASME B31.8 method underestimates the equivalent strain by a factor of about 2 (Gao et al., 2008). Moreover, the membrane and shear strains cannot always be ignored since they can have similar values to longitudinal strains.

Other methods to calculate strain at dents based on derivation of elasticity mechanics were proposed by Dubyk et al., but with complicated forms (Dubyk and Seliverstova, 2019). The strain evaluation depends on measurements of the dent profile to calculate the parameters like the curvature of the dent area. To approximate the dent profile, the most widely studied method is the B-spline curve method, a piece-wise polynomial interpolation function based on data from ILI or FE analysis (Okoloekwe et al., 2018). A fourth-order B-spline curve was used by Noronha Jr. et al. to approximate the dent profile in longitudinal and circumferential directions (Noronha et al., 2010). It was confirmed that the method could simulate the dent profile at a reasonable accuracy (Zhang and Huang, 2015).

3. Failure criteria for dented pipelines

The critical strain-based criterion in ASME B31.8 standard for pipeline failure prediction is an empirical recommendation. It is assumed that the dented pipeline is safe under cyclic loading when the maximum equivalent strain is smaller than 6% (Rafi, 2011). However, the strain limit of 6% is arbitrarily selected. New failure criteria are thus proposed, as described below.

3.1. Oyane's plastic failure criterion and ductile fracture damage index (DFDI) criterion

Ductile damage resulting from accumulation of plastic deformation is one of the mechanisms for pipelines to initiate cracks and fracture (Alashti et al., 2015). Oyane et al. (1980) considered the cumulative damage generated during plastic deformation, and proposed a plastic failure criterion:

$$I = \frac{1}{C_2}\int_0^{\varepsilon_{eq}} \left|\frac{\sigma_m}{\sigma_{eq}} + C_1\right| d\varepsilon_{eq} \tag{26}$$

where I is an integral value used as the damage indicator, C_1 is a constant and obtained through burst test on a non-indented pipe, C_2 is elongation rate of pipe steel measured in uniaxial tensile testing, σ_m is average stress, and σ_{eq} and ε_{eq} are equivalent stress and strain, respectively. When the indicator I is equal to and exceeds 1, the ductile fracture of the pipe will occur (Wu et al., 2019).

Similarly, the DFDI criterion assumes that the growth of micro-cracks on ductile solids causes the material to fracture (Li and Dang, 2017). The DFDI criterion is expressed as:

$$\mathrm{DFDI} = \int_0^{\varepsilon_{eq}} \frac{d\varepsilon_{eq}}{1.65\varepsilon_d \exp\left(-\frac{3}{2}\frac{\sigma_m}{\sigma_{eq}}\right)} \tag{27}$$

where ε_d is critical strain of ductile materials for incipient crack that is measured by uniaxial tensile testing (Gao et al., 2013; Arumugam et al., 2016). Plastic fracture takes place when the DFDI value is equal to or exceeds 1, as shown in Fig. 3 (Arumugam et al., 2016). Both Oyane's criterion and the DFDI criterion are verified experimentally and numerically to effectively predict cracking of materials including steels (Arumugam et al., 2016, 2018; Wu et al., 2016). The formation of dents on a pipeline is a plastic deformation process, where both criteria are suitable for failure assessment of the pipeline (Li and Dang, 2017).

3.2. Strain limit damage (SLD) criterion

The SLD, as recommended by ASME (Gao and Krishnamurthy, 2015), uses elastic-plastic FE analysis to estimate the accumulated plastic damage on pressure vessels, including pipelines:

$$D_{et} = D_{eform} + \sum_{k=1}^{M} D_{e,k} \le 1 \tag{28}$$

where D_{et} is an indicator of the limit state for a structure such as pipeline to carry no further loads, D_{eform} is the damage resulted from deforming, and $D_{e,k}$ is the damage during the kth load increment, which is associated with the total plastic strain and stress. When D_{et} exceeds 1, the load capacity of the structure reaches its limit. The SLD criterion is based on the minimum reduction area and elongation to failure, while the properties of the material are not required. The stress and strain data used in the criterion is obtained from FE analysis.

3.3. Net section failure criterion and plastic collapse strain criterion

The net section failure criterion is a stress-based criterion, which specifies that the minimum von Mises stress in the dent area should not exceed the flow stress, $\sigma_f = (\sigma_Y + \sigma_U)/2$ (Liu et al., 2017).

The plastic collapse strain criterion is commonly used in pressurized structures like pipelines. The plastic collapse state is defined as the point of intersection on the load-displacement curve between the peak and a line drawn from the origin with a slope twice of the elastic slope (TES) (Zhao et al., 2020). It is effective to use the plastic collapse criterion to assess dented pipelines where a large plastic deformation occurs (Baek et al., 2012).

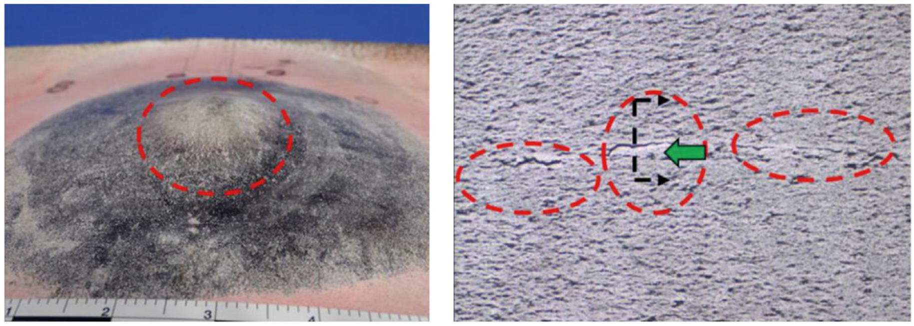

Fig. 3. Experimental validation for a dented pipeline to fracture when the DFDI value exceeds 1 (Arumugam et al., 2016).

3.4. Remaining fatigue life criterion

Methodologies for fatigue life assessment of dented pipelines are summarized and compared in Ref. (Cunha et al., 2014), where EPRG 1995 and EPRG 2000 are thought as the best empirical methods in terms of the quality-of-fit to published full-scale test data (Gao and Krishnamurthy, 2015). Fatigue life of a pipeline containing an unconstrained dent is determined by the cycles of circumferential stress, N, and the stress concentration factor, K:

$$K = 2.871 \cdot \sqrt{d \cdot \frac{t}{D}} \tag{29}$$

$$N = 1000 \cdot \frac{\sigma_U - 50}{2\sigma_{FS} K} \tag{30}$$

where d is dent depth, t is pipe wall thickness, D is pipe outer diameter, and σ_{FS} is fatigue strength.

Stress-life fatigue design equations were used by Petrobras (Cunha et al., 2014) to estimate the fatigue life of dented pipelines, where the stress concentration factor was limited to the linear elastic stage. The fatigue limit of pipeline steels is assumed to be attained at 10^6 cycles.

$$K = A_P + B_P \left(\frac{d}{D}\right)\left(\frac{D}{t}\right)^{1.14} \tag{31}$$

$$N = \left[\frac{\sigma_a}{C_P\left(1 - \left(\frac{\sigma_m}{Su}\right)^2\right)}\right]^{\frac{1}{b}} \tag{32}$$

where A_P, B_P and C_P are coefficients, which depend on dent geometry, pipe dimension and steel properties, respectively, and σ_a and σ_m are alternating stress and mean stress, respectively. Both EPRG methods and the Petrobras model are stress-based.

A strain-based model was proposed for fatigue life assessment of dented pipelines (Gao and Krishnamurthy, 2015):

$$\Delta\varepsilon = 3.5 \frac{\sigma_U}{E} N^{-0.12} + e_0 N^{-0.6} \tag{33}$$

where $\Delta\varepsilon$ is the cyclic strain range, E is elastic modulus, and e_0 is true strain to failure. The cyclic strain range at the dent can be obtained by FE analysis.

3.5. Dent with gouge

Pluvinage et al. (2011) thought that the classical fracture mechanics methods were not appropriate for assessing combined defects, including a dent combined with gouges. Instead, a notch-failure assessment diagram (NFAD) was proposed, where the limit analysis and notch fracture mechanics were believed more reasonable. For the combined dent and gouge, if the dent depth is less than 10% of the pipe outer diameter, it is preferable to use the ductile failure criterion, rather than empirical rules, for failure assessment. Allouti et al. proposed a collapse modified strip-yield model to calculate the circumferential fracture stress of a pipe containing a combined dent and gouge (Allouti et al., 2014).

4. Existing experimental testing for dent assessment of pipelines

Along with numerical modeling, experimental testing is critical to provide direct data and results on dented pipelines.

4.1. Plain dents

Plain dents, as the simplest defect on pipelines, have been extensively investigated experimentally. For pipelines containing plain dents, the main testing includes burst test, strain and stress measurements, bending, and buckling test, as shown in Table 2, where a list of experimental testing on dented pipes and the relevant testing methods are provided.

Burst tests are conducted to determine the internal pressure capacity of a dented pipeline. The general procedure includes selection of a pipe segment, denting, and the burst pressure loading. To perform burst testing, caps are required to install at both ends of the pipe, while the influence of the caps should be eliminated by adjusting the ratio of the pipe length to the outer diameter. Typical experimental set-up for measurements of burst pressure of a dented pipeline is shown in Fig. 4 (a) and 4 (b) (Shuai et al., 2018). Generally, the burst pressure of the dented pipeline is not affected by the plain dent. To obtain the relationship between the indenter displacement (i.e., the dent depth) and the load applied on the pipe, a typical dent depth vs. load curve is obtained. The strain at the dent area varies during denting. Upon removal of the indenter for unconstrained dents, the re-rounding process also changes the strain distribution. A load-deformation curve measured during denting and re-rounding is shown in Fig. 4 (c) (Ghaednia et al., 2014). The strain at the dent during denting and re-rounding cannot be directly measured. Strain gauges placed in the dent area will fail when the indenter loads on them (Md Rafi et al., 2012). Thus, there were work installing strain gauges on the pipe body outside the dent in both circumferential and longitudinal directions to measure strain variations during the denting process (Ghaednia et al., 2014).

The mechanical response of pipe steels at the dent area is affected by shape, depth and length of the dent. For rectangular and spherical dents, a local strain as high as 29.6% could cause pipeline

Table 2
Some experimental testing conducted on dented pipelines and the relevant testing methods.

Method	Specimen	Boundary condition	Indenter	Objective
Baek et al. (2012)	Pipe with semi-spherical caps	Two supports	hemispherical rods	Denting
Allouti et al. (2014)	Pipe with caps	Appropriate constraints	Rigid spherical indenter tooth 40 mm	Burst test of dented pipeline with a gouge
Kec et al. (2017)	High pressure gas pipeline after long term service	\	unknown	Fatigue, burst test
Oshana (2014)	Full-scale pipe with thick end plates	the pipes rested on a rigid table	Spherical; rectangular; dome	Strain distribution
Arumugam et al. (2016)	Full-scale	Wooden saddles as supports with pipe ends reinforced	Spherical	Validation of DFDI criterion
Arumugam et al. (2018)	Full-scale test pipe with hemispherical caps	\	Spherical	Outside cracking of dented pipeline
Shuai et al. (2018)	Full-scale pipe with hemi-spherical caps	Fixed in the bottom	Spherical	Burst pressure
Shuai et al. (2020)	Small diameter API 5L L245 steel pipe without caps	Bottom of the pipeline was welded with channel steel	Spherical	Mechanical behavior under concentrated lateral load
Zhao et al. (2020)	Indentation with no internal pressure so no caps at ends	Bottom of the pipe was fully welded with channel steel axially	Spherical	Strain distribution

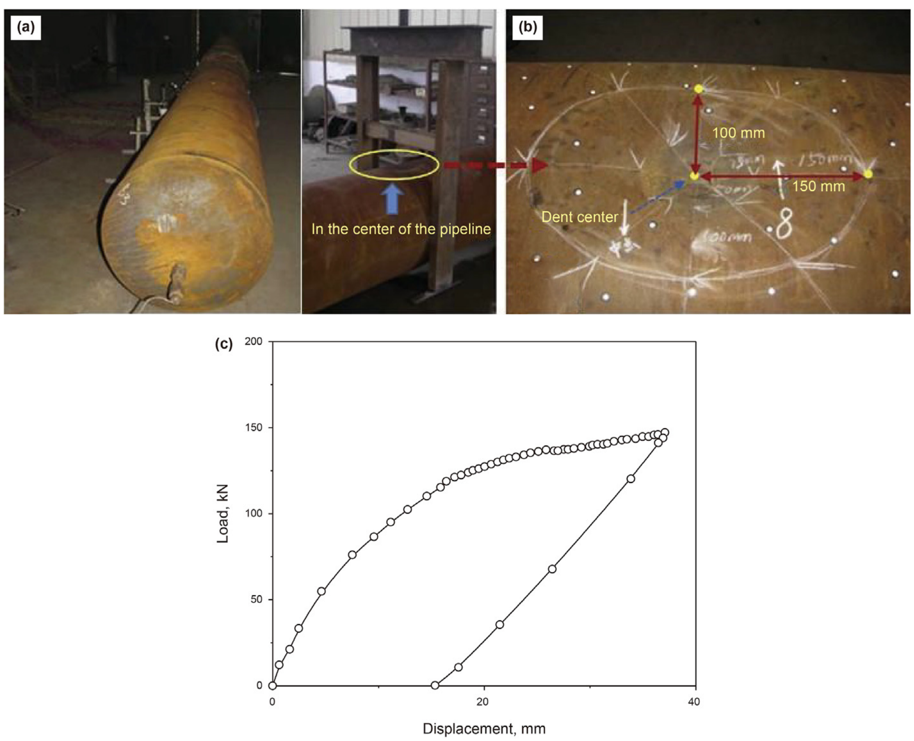

Fig. 4. (a) Experimental setup for measurements of burst pressure of a dented pipeline, (b) the geometrical parameters of the dent (Shuai et al., 2018), and (c) a load-deformation curve during denting and re-rounding of a pipe (Ghaednia et al., 2014).

leak or rupture (Md Rafi et al., 2012). Generally, under identical conditions, a higher strain was detected at a rectangular dent than a canoe shape dent (Oshana Jajo, 2014).

4.2. Dent with fatigue

Pipelines may fail under cyclic stress at a level well below the steel strength (Cunha et al., 2009; Zheng et al., 2005). Table 3 lists experimental tests to measure and validate theoretical models for pipeline fatigue assessment. Typically, the fatigue test procedure for a dented pipeline includes (Bolton et al., 2008; Pinheiro and Pasqualino, 2009):

- The pipe segment was dented by an indenter to a certain depth
- For an unconstrained dent, the indenter was removed to complete the re-rounding process; while for a constrained dent, the indenter remained at the bottom of the dent
- For fatigue testing, a medium, such as water, was pumped into the pipe to induce an internal pressure to reach the maximum pressure (i.e., 80% SMYS) by 10% increment each time
- The internal pressure was then reduced by 10%
- The pressure increasing and decreasing process was repeated until the fatigue failure occurred

The main test results include the load applied during denting,

Table 3
Experimental tests to measure and validate theoretical models for pipeline fatigue assessment.

Method	Specimen	Parameters	Indenter	Procedure	Objective
Bolton et al. (2008)	Full-scale pipe, Small-scale specimen	0.1–0.8 SMYS cyclic load	Spherical	Denting, fatigue	Denting; Fatigue
Cunha et al. (2014)	Small-scale specimen	Failure range: 6000–10^6	Spherical	Denting, fatigue	Stress concentration factor determine
Pinheiro et al. (2019)	Small-scale specimen	Dent depth 5%OD and 10%OD	Spherical	Denting, internal pressure test, fatigue	Fatigue
Tiku et al. (2012)	Full-scale pipe	0.1–0.8 SMYS cyclic load	2:1 ellipsoidal shape	Denting, fatigue	Parameter influence
Pournara et al. (2019)	1 m long X52 6 in diameter seamless pipe	(a)Bending loading until fatigue cracking occurs in the low cycle fatigue range(b)5000 cycles	Wedge-shaped indenter	Two different cyclic loads applied	Fatigue under cyclic bending and pressure
Luo et al. (2020)	A leak dented gas pipeline that has been in service for six years	\	Approximately circular	Multiple methods to examine the pipe	Fatigue failure determination

dent depth, internal pressure, number of cycles, and strain distributions during the test. A general fatigue testing process on dented pipelines is shown in Fig. 5.

Cunha et al. conducted many tests to investigate the fatigue life and stress concentration factor of dented pipes (Cunha et al., 2009). It was found that most of the dented pipes failed (leaked) with a cycle number from 5000 to 10^6 (Cunha et al., 2009; Pinheiro and Pasqualino, 2009). Parametric effects such as pipe steel, pipe geometry, internal pressure, dent shape and dent depth were investigated on dented pipes to determine the fatigue life and failure performance (Tiku et al., 2012). For constrained dented pipes, the fatigue cracks were located on the longitudinal dent shoulder in a circumferential direction. Moreover, fatigue cracks on the inner surface were longer than those on the outer surface. However, for unconstrained dented pipes, cracks were located on the longitudinal dent shoulders in a longitudinal direction and multiple long cracks were found on the outer surface. Even when the dent depth was only 1% of the pipe outer diameter, multiple cracks could be induced in the dent area. Deeper unconstrained dents, as compared with shallower unconstrained dents, would result in a shorter fatigue life (Tiku et al., 2016). In addition to internal pressure fluctuations, cyclic bending loads can also cause fatigue failure of dented pipelines (Pournara et al., 2019), where the bending-induced fatigue cracking happened on the side of the dent.

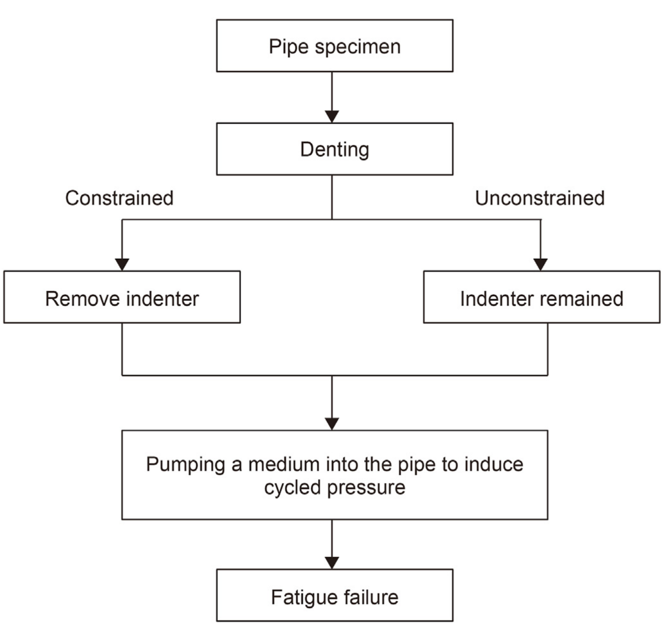

Fig. 5. A chart showing the general fatigue testing process on dented pipelines.

4.3. Dent with gouges

As discussed, a combination of dent with gouges makes pipelines prone to failure (Zarea et al., 2014). Generally, the methods and standards used today are conservative, but acceptable for assessment of pipelines that contain both dent and gouges (Macdonald et al., 2007). There has been limited work investigating the burst pressure of a pipeline containing a combined dent and gouge. Particularly, Zhao et al. (2021) used an X52 steel pipe segment, with caps installed at both ends of the pipe to bear internal pressure. A rigid spherical indenter was used to create a dent, and a gouge was made by electrical discharge machining. The gouge was located at the middle of the pipe and had an axial orientation, as shown in Fig. 6 (Zhao et al., 2021). It was found that the burst pressure of the pipe decreased with increased depth and length of the gouge, as well as the dent depth. When the pipe failed, rupture happened in the defect zone. High-strength pipeline steel such as an X80 steel pipe was also used for testing when a combined dent and gouge was included (Naghipour et al., 2018).

Most lab tests were performed on pipes where a dent was created first and then a gouge was made, where the gouge was located at the center of the dent area with a semi-elliptical notch shape. Loads were then applied on the pipe. The procedure is obviously different from the pipelines in practice. An equipment used by Zarea et al. (2014) created a dent and a gouge at the same time to approximate the reality. It was found that there was a lower burst pressure and a shorter fatigue life for the pipe containing a shallow dent and a shallow gouge with micro-cracks than the pipe with a severe dent and a moderate gouge but without micro-cracks. The results showed that, micro-cracks, if existing, would dominate over the dent and the gouge to determine the pressure capacity and fatigue life of a pipe.

4.4. Corrosion in dent

Corrosion tends to preferentially occur at a dent on pipelines. This is attributed to an enhanced local electrochemical activity. While corroded pipelines have been widely tested and assessed, the corrosion defects are usually made artificially with a regular profile, which is not consistent with real corrosion defects (Bao and Zhou, 2021; Cosham et al., 2007). ILI tools have a limited capacity to

Fig. 6. Experimental testing for indentation of a pipe with a gouge (Zhao et al., 2021).

distinguish corrosion and gouges (Gao and Krishnamurthy, 2015). The two different types of metal loss affect the pipeline integrity at different mechanisms and severities. Compared to the gouge, corrosion is a time dependent process (Cosham and Hopkins, 2004). Even when the metal loss is not remarkable for a corrosion pit at a given instant, the further growth of the pit in corrosive environments can penetrate the pipe wall and cause leaking rapidly. The enhanced corrosion at dents can be explained by the Mechano-Electrochemical Interaction concept developed by Cheng group (Sun and Cheng, 2019a,b, 2020; Xu and Cheng, 2013; Wang et al., 2021; Tang and Cheng, 2009). Basically, the full-scale tests conducted on a pipe with corrosion in dents have been limited.

5. Finite element methods used in dent assessment on pipelines

The FE methods enable development of complicated mechanical and multi-physics field models, which are especially useful for assessment of pipelines containing defects such as dents or a dent combined with other defects.

5.1. Simulation of the denting process

Denting is an elastoplastic deformation process. A typical numerical modeling and analysis follows the steps, as described in Fig. 7 (Shuai et al., 2020; Wu et al., 2019; Li and Dang, 2017; Baek et al., 2012; Zhu and Wang, 2019; Kainat et al., 2019; Pinheiro et al., 2019; Han et al., 2018).

- Denting: An indenter is placed on the pipe surface without force applied between them. A downward displacement load is then applied on the indenter by small increments until a set value of the depth is reached.
- Re-rounding: For an unconstrained dent, when the indenter is removed upward, the dent area will have a re-rounding process. The unconstrained dent has a final depth after a complete rerounding. For a constrained dent, the indenter will be kept at the dent.
- Loading: A static pressure or a cyclic pressure is applied on the interior of the pipe to determine the burst pressure or fatigue life. Other kinds of loads such as bending moment can also be applied.

5.1.1. Material model

As a permanent plastic deformation occurs during denting, modeling of the denting process requires a good alignment with the true stress-strain relationship of the pipe steel. The commonly used elastoplastic material models include plastic hardening model, Ramberg-Osgood (R–O) stress-strain rule, and power-law model (Qin and Cheng, 2021). The true stress-strain data measured by testing are used as input to develop the material model (Luo et al., 2020; Arumugam et al., 2016). The plastic hardening model includes isotropic hardening (Han et al., 2018), kinematic hardening (Li and Dang, 2017; Tiku et al., 2012) and a combination of isotropic and kinematic hardening (Pinheiro et al., 2019). The isotropic hardening model is more frequently used in FE analysis of dented pipelines (Qin and Cheng, 2021):

$$\sigma_{\mathrm{yhard}} = \sigma_{\exp}\left(\varepsilon_{\mathrm{eff}}\right) - \sigma_{\mathrm{Y}} = \sigma\left(\varepsilon_{\mathrm{pe}} + \frac{\sigma_{\mathrm{eq}}}{E}\right) - \sigma_{\mathrm{Y}} \tag{34}$$

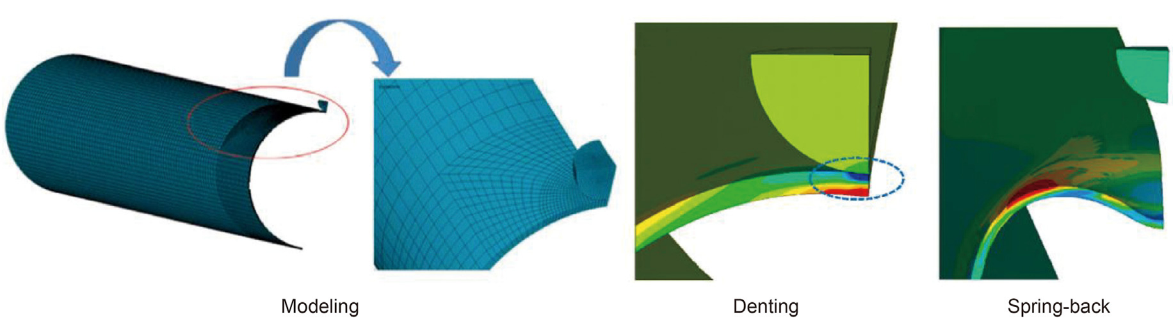

Fig. 7. Schematic diagram showing the steps for FE modeling of a dented pipeline (Shuai et al., 2020).

where σ_{exp} is an experimental stress function derived from the measured engineering stress-strain curve, ε_{eff} is effective strain, ε_{pe} is sum of plastic strain, σ_Y is yield stress, and E is Young's modulus.

The R–O stress-strain rule is also used for FE modeling of dented pipelines by (Bratton et al., 2012):

$$\varepsilon = \frac{\sigma}{E} + \alpha\left(\frac{\sigma}{\sigma_y}\right)^n\left(\frac{\sigma}{E}\right) \tag{35}$$

$$\varepsilon = \frac{\sigma}{E} + 0.079\left(\frac{\sigma}{\sigma_y}\right)^{12.64} \tag{36}$$

where σ is stress, ε is strain, and α and n are R–O factors which are constants for specific materials. For low-grade pipeline steels, Eq. (35) applies, while Eq. (36) is applicable for high-grade steels.

The power-law model uses the true stress-strain relationship as input data:

$$\begin{cases} \sigma = E\varepsilon & \sigma < \sigma_f \\ \sigma = \alpha\varepsilon^n & \sigma \geq \sigma_f \end{cases} \tag{37}$$

5.1.2. Model development

Common numerical models are developed by 3-D solid elements (Kainat et al., 2019; Iflefel et al., 2005), where a quarterly symmetric model is often used to reduce the density of grids and save computational time. The advantages of using solid elements include that they can better approximate a dented pipeline, and that the mechanical parameters in axial, circumferential and radial directions can be conveniently calculated. Shell element is also used for FE analysis (Pournara et al., 2019; Pinheiro et al., 2019; Lockey et al., 2014) and is performed well in nonlinear analysis where large inelastic deformations occur on steel cylinders. To eliminate the effect of the structural edges on modeling, the pipe should be long enough and the ratio of pipe length to pipe outer diameter is more than 3 (Z. Zhang et al., 2020; Shuai et al., 2018). Contact element and target element should be assigned to the indenter surface and the dent area, respectively. The grid density away from the dent area can be sparse, while the density should be increased in the dent area to satisfy the requirement of accuracy.

In experimental testing, caps should be placed at both ends of a pipe to enable the pipe with an internal pressure-bearing capacity. However, the FE modeling can simplify the structure without caps at both ends. Instead, the equivalent tensile stress due to internal pressure is applied on the ends of the pipe. The equivalent stress is calculated by the shell theory (Iflefel et al., 2005):

$$T = \frac{pD_i^2}{D^2 - D_i^2} \tag{38}$$

where T is the equivalent tensile stress and p is internal pressure.

5.1.3. Modeling verification

A comparison between the modeling results and testing data is the most directive method to verify the accuracy of a model. Strain gauges cannot be attached during denting, but other parameters can be used to verify the FE modeling, such as the relationship between reaction force and displacement of the indenter during denting and removing of the indenter (Han et al., 2018; Zhao et al., 2020).

5.2. Burst and fatigue modeling of dented pipelines

Burst and fatigue tests provide direct data to prove the accuracy of the FE model. Due to strict requirements of testing facility and space, as well as a high cost, modeling is regarded as a promising alternative for pipeline failure assessment. Table 4 lists the typical burst and fatigue modeling by FE analysis on dented pipelines.

The main factor affecting the fatigue life of dented pipelines is the stress concentration factor. In FE modeling, the location with the greater stress is identified, and the stress concentration factor (SCF) can be estimated by (Cunha et al., 2009; Turnquist and Smith,2016):

$$\mathrm{SCF} = \frac{\Delta\sigma}{\Delta\sigma_{nom}} \tag{39}$$

where $\Delta\sigma$ is maximum stress and $\Delta\sigma_{nom}$ is nominal stress of an undented pipe with internal pressure. The estimated fatigue life is then calculated. Another fatigue evaluation method is to calculate the maximum stress or strain in the circumferential or longitudinal direction. With a given S–N curve or $\Delta\varepsilon$~N fatigue curve of the steel, the residual cyclic life is determined (Kainat et al., 2019).

5.3. Dent combined with a gouge

Gouge is frequently detected on a dented pipeline. In experimental testing, the gouge defect is machined on a pipe specimen, and an indenter is then applied on the pipe to make a combination of dent with the gouge. Numerical modeling by FE has the similar procedure. To model a gouge on pipe wall, the solid element is selected. The shape of the gouge can be semi-elliptical (Allouti et al., 2014), cylindrical (Zhao et al., 2021), semi-cylindrical (Tian and Zhang, 2017b) or rectangular (Cosham et al., 2007). The stress concentration at the corner of the gouge is usually reduced. Additionally, grids in the defect area should be refined to ensure accuracy. The gouge can be located at the center of the dent, across the dent area or at the side of the dent. After denting, loads like internal pressure or bending moment are applied on the pipe (Tian and Zhang, 2017b; Bao and Zhou,2021).

5.4. Dent combined with corrosion and cracks

The corrosion defect can be numerically modeled as a single pit, a long groove or a large area with various shapes in FE analysis (Shuai et al., 2008). Basic parameters to model a corrosion defect include the corrosion depth, width and length. Rectangular (Choi et al., 2003), spherical, semi-elliptical and long-bunt notch shapes (Ma et al., 2013; Adib-Ramezani et al., 2006) have been chosen to represent the corrosion defect. Solid element is assigned on the model, and grids in the vicinity of the corrosion defect are refined. The pipe wall thickness is reduced at the corrosion defect, which causes a decrease of the burst pressure. Therefore, the burst pressure is the main criterion for assessment of the residual strength of a corroded pipeline. Although there are numerous investigations conducted on assessment of pipelines containing corrosion defect, there has been very limited work about the dent-corrosion combination on pipelines.

Modeling of cracks in pipelines by FE is challenging, while some progresses have been made in the recent years. Bedairi et al. (2012) investigated cracks in corrosion area by modeling the crack tip as a blunt notch with a specific radius of one thousandth of the size of the plastic zone. V-shape notch was used by Ghaednia et al. (2015a, 2015b) to model cracks in pipelines, where the grids in crack area were properly adjusted. Another method to model pipeline cracks is the so-called extended FE method (XFEM) (Okodi, 2021; Z.W.

Table 4
Typical burst and fatigue modeling by FE analysis on dented pipelines.

Method	Pipeline steel	Materials model	Dent	Failure criterion	Dent depth
Allouti et al. (2012)	A37 steel	Isotropic strain hardening	Spherical	Burst pressure	0.1–0.28 OD
Liu et al. (2017)	API X60	Stress-strain relationship	Spherical	Burst failure	0.02–0.2 OD
Shuai et al. (2018)	API 5L X52	R–O model	Spherical	Burst failure	0.09 OD
Cunha et al. (2014)	Low carbon steel	Combined isotropic and kinematic hardening	Spherical and cylindrical	Failures ranging from around 6000 to more than 10^6 cycles	0.02–0.12 OD
Locky et al. (2014)	\	Linear-elastic material curve	\	S–N curve in standard	Less than 0.02 OD
Tiku et al. (2012)	X52	Nonlinear kinematic hardening	Ellipsoidal shape	Fatigue failure	0.01–0.10 OD
Kainat et al. (2019)	API 5L X70	Kinematic hardening	Spherical	S–N curve in a standard	Multiple depth
Pournara et al. (2019)	X52	flow plasticity model	wedge-type	$\Delta\varepsilon \sim N$ fatigue curve	Multiple depth

Note: OD refers to pipe outer diameter.

Zhang et al., 2021). The XFEM is a built-in module in ABAQUS that can simulate structural discontinuities such as cracks and holes. A dented pipe with a crack was modeled by shell and solid elements using the XFEM technique, where the shell element was used to model the pipe body, and the solid element modeled the crack (Okodi, 2021). The shell-solid coupling constraint was utilized to attach the shell elements with the solid elements. A dent can be produced by applying a load on the indenter.

In addition to the pipeline containing a single corrosion or crack, the interaction between corrosion defects can strongly influence the mechanical performance of pipelines. Cheng group investigated the interaction of multiple corrosion defects and its effect on burst pressure of the pipeline. For example, when a critical distance between the defects was reached, the burst pressure of the pipe could be apparently reduced (Sun and Cheng, 2018). The enhancing influence of stress and strain on corrosion was also studied, where a multi-physics field coupling FE model was developed for stress-corrosion of pipelines (Xu and Cheng, 2013, 2017). It was demonstrated that, when a local strain at the corrosion defect reached the plastic stage, the corrosion rate increased remarkably, while the effect of elastic strain was marginal. Further work was also carried out to study the mutual mechano-electrochemical interaction between circumferentially aligned, longitudinally aligned and overlapped corrosion defects, as well as double-ellipsoidal corrosion defect on pipelines (Sun and Cheng, 2019a,b, 2019, 2020; Zhang, Ni and Cheng, 2020).

6. Conclusions

A complete review of various assessment methods and standards, as well as representative experimental testing and numerical modeling, for dented pipelines, including the combination of a dent with other types of defects such as gouges, fatigue, corrosion, and cracks, is conducted in this work. Generally, the dent assessment methods available today are not sufficiently accurate and reliable for pipelines, especially for the pipelines containing dent-defect combinations. A further improvement of the existing assessment techniques and development of new assessment methods are critical to improve pipeline integrity and safety.

For plain dents on pipelines, both the depth-based and the strain-based criteria are commonly used in engineering. The main problems of the two criteria are inaccuracy and conservatism of the assessing results, though these criteria could in some cases lead to nonconservative assessments. The critical depth used in the depth-based criterion and the strain determination method in the strain-based criterion are applicable for dents with a small depth and a low strain level only. Some modified methods such as Lukasiewicz strain formula (Lukasiewicz et al., 2006) have not been widely accepted by industry owing to limited application conditions of the method and the complexity in numerical computations.

For dents combined with other types of defects, the existing assessment techniques are not sufficiently reliable to generate accurate results. The standards have a low tolerance to the presence of the dent-other defect combinations on pipelines. In addition, the assessment methods consider the other types of defects with a regular geometry only, and do not have a sufficient ability to incorporate actual complex shape of the defects with various orientations (such as longitudinally, circumferentially or a cluster of defects) relative to the dent. Thus, the existing methods and standards are insufficient for assessment of dent-defect combinations on the pipelines. Due to the reality that multiple types of defects are usually co-exist with a dent, it is urgent to develop accurate methods for assessment of the dent-defect combinations.

Both experimental testing and numerical modeling through FE analysis can investigate the influence of a dent and dent-defect combinations on burst failure pressure of a pipeline. The experiments and FE analysis consider multiple affecting factors and parameters, such as shapes of the dent and the defect, their geometrical dimensions, orientation of the defect relative to the dent, loading size and stress sources. Generally, similar procedures are employed in different experimental investigations on dented pipelines. Reproduction of the realistic conditions is still the main difficulty in experimental testing and FE analysis.

Nowadays, studies on plain dent, fatigue at a dent, and dent combined with a single gouge have been common in literature. Dent combined with corrosion and cracks has been rarely assessed due to complicated mechanisms involving a multi-physics field coupling effect. Development of novel assessment methods by integrating mechanical stress and strain, electrochemical reactions and steel metallurgy will be a key topic to accurately assess dent-defect combinations (e.g., corrosion in dent, and cracks at dent) for improved pipeline integrity.

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