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Critical Strain Based Ductile Damage Criterion and its Application to Mechanical Damage in Pipelines

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Abstract

Strain based assessment of mechanical damage in pipelines requires a failure criterion for cracking based on plastic damage. Several criteria have been proposed by industry codes such as B31.8 and in the literature. However, these criteria essentially are based on engineering decisions. In this paper, a plastic damage based criterion that combines material critical strain and triaxiality of stress is used. The theoretical aspect of the criterion, including early work by Hancock and Mackenzie on strain limit (i.e., reference failure strain), ε_f, for ductile failure is discussed. The experimental aspect of material's critical strain and its measurement using uniaxial tensile testing is described. An elastic-plastic finite element analysis is employed to calculate ductile failure damage indicator (DFDI), which can be used to describe the amount of accumulated plastic strain in the damage and its susceptibility to cracking. Its application to assessing mechanical damage in pipelines, including dent with gouge/crack, is presented. Examples are given to illustrate the effectiveness of the criterion for prediction of cracks in dents in pipelines.

Keywords: Mechanical Damage, Dent, Critical strain, Damage Model (DFDI), ASME B31.8

1 Introduction

Strain calculations have been used in the past to estimate the severity of mechanical damage in pipelines. ASME B31.8 2004 established an allowable strain in dents to be 6% [1] based on the experience of the likelihood cracking of cold bend and puncture in dents when material strain exceeds 12% [2]. Numerous studies of failure criteria involving limit states due to crack initiation in the metal forming industry have been conducted in the past [3-14]. However, none of them have been applied to the pipeline industry for integrity management of mechanical damage.

One of the criteria [7, 10,11] that involves critical strain and utilization of damage parameter, i.e., ductile failure damage parameter (DFDI), is adopted by the present study to calculate the amount of plastic damage in pipelines due to mechanical damage, where the critical strain is a material's property defined as the true strain at the onset of incipient crack measured from uni-axial tensile testing, and the DFDI is a damage parameter that is a function of triaxiality of stresses, equivalent strain, and material's critical strain. The onset of incipient crack in a ductile material due to plastic damage is given when DFDI $\geq$1.

In this paper, the theoretical background of plastic damage due to large deformations in ductile materials is presented first. The critical strain and its measurements using uniaxial tensile testing are described. Its application to evaluate mechanical damage including dents in pipelines is then discussed. The finite element simulation of the denting process is then performed to calculate the cumulative plastic damage and presented as "ductile failure damage indicator" (DFDI). The results demonstrate that the DFDI method predicted well for the crack initiation in dent and can be utilized as a severity indicator and failure criterion for dent repair/mitigation. Finally, an approach proposed by Wang et al [18] that combined DFDI and signal recognition from MFL (magnetic flux leakage) in-line-inspection for evaluation of dent with corrosion/cracking/gouge is presented.

2 Background

As early as the 1960's, a damage relevant stress, i.e., critical stress σ_{cr}, was used as the state limit for sheet forming [7], and was later further developed by others [8,9]. These simplified stress criteria have proven to be very restrictive, as well as related to a special forming process [7,8]. Later, researchers tried to correlate plastic damage to the plastic work done during deformation, and proposed critical work, W_c, as a damage relevant term. However, for the same reasons, the concept of W_c may be suspicious, especially when it is applied to significant crack propagation in a tension bar [9].

Large plastic deformation of ductile materials involves initiation, growth and coalescence of microvoids to form cracks, known as "ductile plastic damage", and is the mechanism for ductile cracking, tearing, and rupture of ductile materials. Considerable effort has been made since the mid-1960's [3-6] to establish a frame work (failure criteria, for example) for studying conditions and variables associated with the failures.

In the late 1960's, McClintock [10] and Rice and Tracey [11] established the basic relation between growth of a void and imposed stress and strain from a tri-axial stress field using a micro mechanics approach. Hancock and Mackenzie [6] in the mid-70's followed Rice et al's work, and proposed a reference failure strain, ε_f, i.e., a strain limit for ductile failure:

$$\varepsilon_f = 1.65\varepsilon_o \exp\left(-\frac{3}{2}\frac{\sigma_m}{\sigma_{eq}}\right) \qquad (1)$$

where σ_m = average stress of three principle stresses in a tri-axial stress field, and σ_{eq} = equivalent von Mises stress. The ratio of σ_m/σ_{eq} represents the tri-axiality of the stress field, and ε_o is the critical strain of ductile materials for incipient crack, a material property measured by uniaxial tension testing.

Equation (1) indicates that the strain limit of a structural component, ε_f, is not a constant. It is a function of stress tri-axiality and the material's critical strain. Equation (1) defines a generalized strain limit, i.e., reference failure strain, for large plastic deformations subject to both uni-axial and multi-axial stress states. In the uni-axial tension condition, Equation (1) becomes $\varepsilon_f = \varepsilon_o$ i.e., the reference failure strain in the uni-axial tension is equal to its critical strain of the material. Equation 1 is derived from the concept that ductile failure results from initiation, growth and coalescence of voids on a micro scale, and formation of cracks during large plastic deformation. Given the established strain limit for ductile failure, the degree of plastic damage is defined as:

$$dD_i = \frac{d\varepsilon_{eq}}{\varepsilon_f} \qquad (2)$$

$$D_i = \int_0^{\varepsilon_{eq}} \frac{d\varepsilon_{eq}}{\varepsilon_f} \qquad (3)$$

Equation (2) shows that the plastic damage induced by each increment of the plastic strain, $d\varepsilon_{eq}$, involved in the deformation process is the ratio of the increment to the failure strain. Equation (3) is the integral of Equation (2), i.e., the total plastic damage for entire plastic deformation. D_i is the indicator of cumulative plastic damage during plastic deformation which has a general form of $D_i = D_i(\sigma_m / \sigma_{eq}, \varepsilon_{eq}, \dot{\varepsilon}_{eq})$, where σ_{eq} is the equivalent von Mises stress, and σ_m is the average stress. Its value ranges from 0 (undamaged) to 1 (rupture). By the definition, ductile failure will occur when $D_i \geq 1$, where D_i is the measure, or indicator, of ductile failure damage. A safe DFDI less than one (<1) would be appropriate to prevent failures.

Substituting Hancock et al's failure strain ε_f (Eq. (1)) into Equation (3), gives

$$D_i = \int_0^{\varepsilon_{eq}} \frac{\exp\left(\frac{3}{2}\frac{\sigma_m}{\sigma_{eq}}\right)}{1.65\varepsilon_o} d\varepsilon_{eq} = \frac{1}{1.65\varepsilon_o}\int_0^{\varepsilon_{eq}} \exp\left(\frac{3}{2}\frac{\sigma_m}{\sigma_{eq}}\right) d\varepsilon_{eq} \qquad (4)$$

Equation (4) relates the ductile failure damage indicator D_i, the stress tri-axiality (σ_m/σ_{eq}) and the material's critical failure strain ε_o. Various modifications of the reference failure strain ε_f, which lead to a better agreement with experiments for high stress tri-axialities, are available in the literature [12-14]. .

3 Critical Strain and its measurement

Critical strain is a material property and measured by uni-axial tension testing. The critical strain of a material, ε_o, is defined as the critical point of the true strain at which incipient crack occurs. To measure the critical strain of a material from a uniaxial tension testing, both engineering and true stress vs. strain curves in the necking (non-uniform elongation) regime are required.

For true stress and strain measurement in the necking (non-uniform elongation) regime, a series of images of the necking area needs to be recorded either on a time or displacement basis. The recorded images are used to determine the radius or the cross-section area of the neck for true stress and strain calculation using the following Equation [5] and to establish the relationship between true stress and true strain:

$$\sigma_{true} = \frac{P}{A}, \; \varepsilon_{true} = \varepsilon_o = 2\ln\frac{A_o}{A} = 2\ln\frac{r_o}{r} \qquad (5)$$

where A_o and r_o are the initial cross-section area and radius of the tensile specimen, respectively, and A and r are the smallest cross section area and radius of the neck at the time of the measurement, respectively.

For the onset point at which incipient crack occurs, cracking, it cannot be determined from the true stress and true strain data itself. It is determined from the second sharp knee on the engineering stress-strain curve or load-displacement curve [7], shown in Figure 1(a).

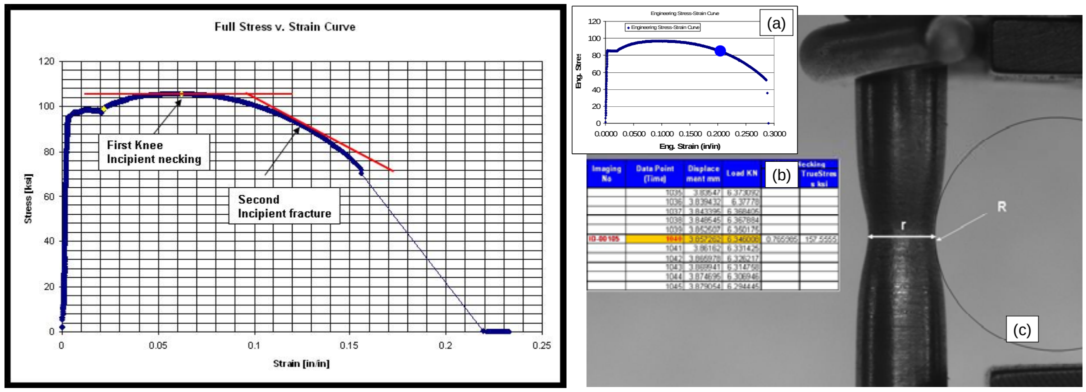


Figure 1: (a) A typical engineering Stress and Strain curve of LXS80, showing the second sharp knee related to the incipient crack (b) Typical image recorded by the video camera on a time-based sampling scheme. The insert shows the respective location of the image on the load-displacement curve

Using the identified onset point of incipient crack and the true strain and true stress curve, the critical strain can be determined by correlating the engineer strain at the onset point of incipient crack to the respective true strain. Efforts were made to develop a time-based switching and data acquisition system. The system consisted of three major components: a closed loop tensile test machine, a high resolution digital video camera, and a synchronized and data acquisition system for simultaneously sampling load-displacement data and image recording. The system provides a signal to trigger the video camera's "shutter" on and off for a given time interval and interfaces between the high resolution digital video camera and the tensile test machine. Each recorded image contains a time code that can be used to match a respective point on the load-displacement curve that was saved at the same time by the data acquisition system of the tensile testing machine. One of the recoded images that correspond to the point of the onset of incipient crack is the one corresponding to the critical strain that can be found from the true stress-strain curve. There is a possibility that no image could be matched with the onset point for critical strain calculation. However, this may be resolved either by interpolating the critical strain values obtained from two adjacent images that are across the onset point, or, more accurately, by establishing an engineering strain and true strain curve around the fracture incipient point and then using the curve-fit equation to calculate critical strain.

3.1 Determination of Crack-incipient from uniaxial tensile test

The information obtained from the synchronized system contains three sets of data: (1) load-displacement data directly obtained from the tensile test machine, (2) the time-based images recorded by the video camera, and (3) the time code for each image and corresponding load and displacement recorded by the synchronized data acquisition board. These three pieces of information were analyzed using the following methods to determine critical strain.

The crack-incipient point is a characteristic point on the load-displacement curve. This point can be diagnosed by a sharp knee in the engineering stress-strain curve or by a second knee in the $d\sigma/d\varepsilon$-ε curve as shown in (a) and (b) of Figure 2, respectively [7].

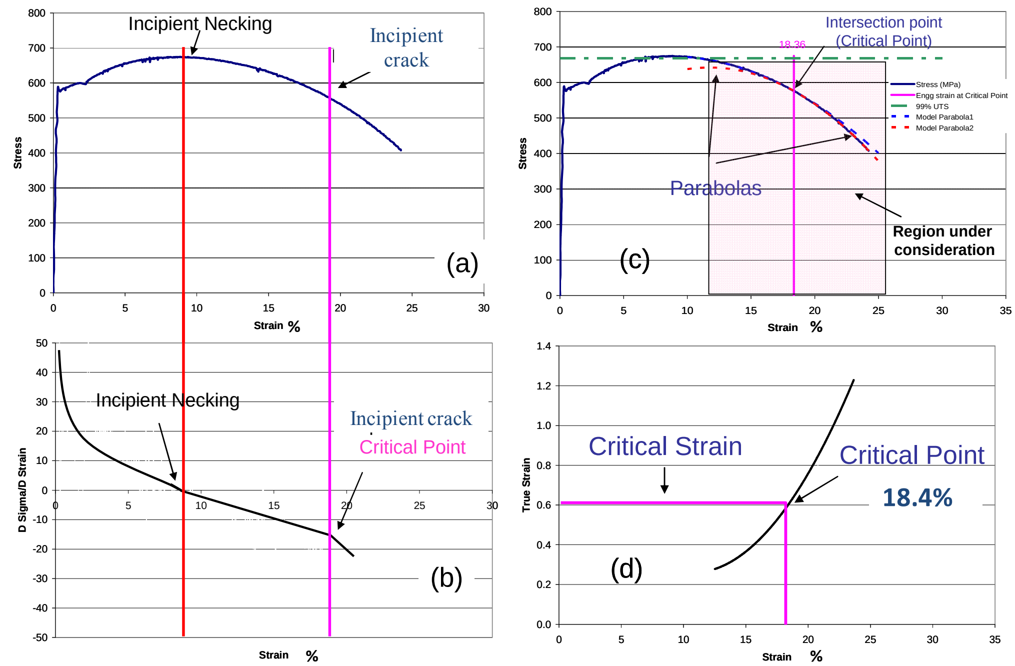


Figure 2: A composite figure showing (a) the engineering stress-strain (σ vs. ε) curve with the incipient necking and crack; (b) dσ/dε vs. ε plot – a knee shaped curve giving the incipient crack point which is the critical point; (c) the intersection of two parabolic curves derived from a mathematical best fit model for determination of critical point; and (d) the relationship between the true strain and engineering strain. The relationship is obtained from the synchronized camera system.

For the sharp knee diagnosis method from the engineering stress-strain curve, two parabolas are used to model the upper and lower portions of the curve [5]. The intersection of the two parabolas is the point that corresponds to the on-set point of incipient crack. For the "second knee" diagnosis method from the dσ/dε-ε curve, two straight lines are used to model the upper and lower portions of the dσ/dε-ε curve. Again the intersection of the two straight lines is the point corresponding to the crack incipient point.

These two diagnostic methods are equally applicable and should yield the same results. However, the data processing showed that because the "second knee" diagnosis method involves a derivative operation of σ with respect to ε from the experimental stress-strain data, which resulted in a large scattered band of the dσ/dε-ε curve, the uncertainty in linear regression for straight line modeling would be large. Therefore, the first method was adopted for the present study. The intersection of the parabolas was found by utilizing the "Method of Least Squares". Once the incipient point is determined, Figure 2(c) it may be used to calculate the critical strain by utilizing the curve fit equation between engineering and true strain, Figure 2(d).

4 Application of DFDI to Mechanical Damage

Dent or indentation in pipe is described as a permanent deformation of the pipe's circular cross section arising from external forces [1]. Depending on the severity of the dent or the amount of plastic deformation, crack(s) may be initiated in the dent. Ductile Failure Damage Indicator

(DFDI) can be utilized as a criterion to gage the severity of plastic damage in dents, and predict its susceptibility to cracking. To evaluate the effectiveness of this model, one case involving 2.7% OD bottom-side rock dent associated with 76% WT metal loss reported by a combo ILI tool (geometry + MFL) is studied. Elastic-plastic finite element modeling incorporating actual measured uni-axial tensile stress-strain curve from pipeline material and calculated critical strain is performed. More case studies involving dents associated with metal loss and plain dents can be found in Reference [21].

The pipe had an OD of 30in, nominal wall thickness of 9.5mm, Grade of X52, constructed in the year 1958 with depth of cover of 90cm, and was operating at 6,895 kPa (77% SMYS). The dent was 2.7% deep with length of 120mm, and width of 97mm, at a clock position of 6:15. Figure 3(a) shows the screenshot of the ILI reported dent deformation profiles in circumferential and axial direction, respectively.

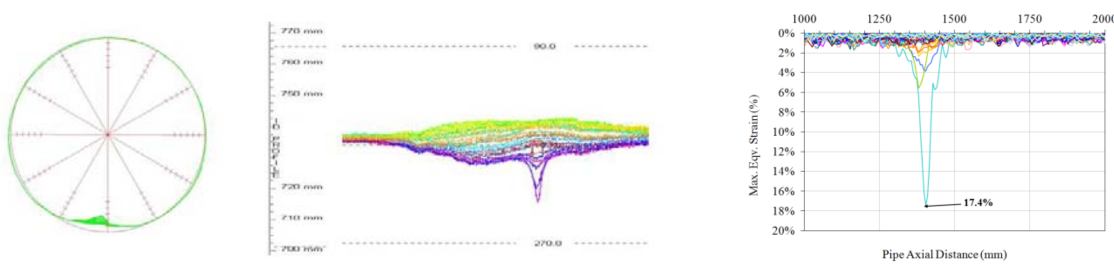
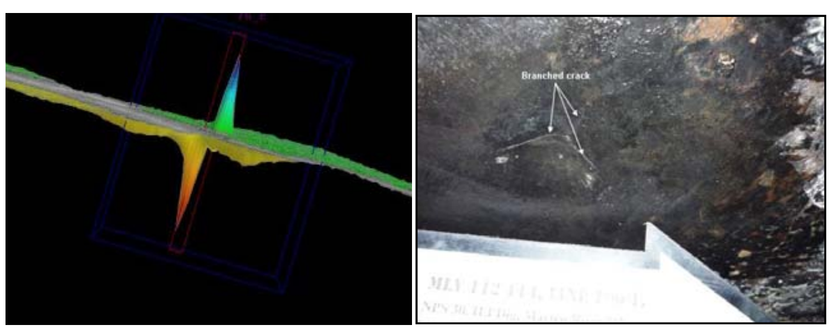


Figure 3: (a) Dent circumferential and axial profile (b) Strain profile using Blade's in-house dent strain software

From Figure 3(a), dent apex seemed sharp, suggesting the possibility of high strain at this location. Strain analyses was performed on this dent utilizing an in-house point-to-point strain analysis tool [17] using the strain equation recommended in the Reference [15, 16]. The calculated maximum equivalent strain (true strain) is 17.4%, which is located at the dent apex.



(a) **(b)**

Figure 4: (a) Equivalent strain distribution plot around and in the dent area, (b) Dent with branched crack in-ditch (OD)

A review of the MFL raw signal showed sharp and strong signal characteristics of magnetic flux leakage, seen in Figure 4(a), suggesting that the reported 76% WT metal loss is more likely cracking or gouging rather than corrosion. The dent was excavated for further investigation. On excavation, it was found to be in contact with a rock. On the removal of the rock, it was found to be associated with three cracks originating near its apex, Figure 4(b). No leak was detected in the field, indicating the cracks were partially through-wall. Since the dent was associated with cracks, the pipe joint was cut out for further investigation. The dent was inspected from inside, which showed branched cracks at the same location as the OD cracks, but in ID surface of the dent apex. A 3D mapping [17] of the cracked dent geometry was conducted using a portable 3D LaserScan system. The axial and circumferential profiles were extracted at the ID surface. The strain analysis was performed using the profiles. The maximum equivalent strain in the dent was found to be 16%, located at its apex.

The measured ILI maximum equivalent internal strain was 17.4%, compared to LaserScan profile internal strain of 16%. The maximum equivalent strain value obtained from LaserScan is comparable to that obtained from ILI; however, this apparent consistency may not be true because the dent profile was significantly changed due to spring back (rebound) when the constraint (rock) of the dent was removed. A comparison of the dent profile before and after excavation is given in Figure 5. The measured dent depth after the rock was removed was ~1.4% OD, which is one half of the ILI-reported depth of 2.7% OD. In order to estimate the change in plastic strain due to rebounding, the high resolution LaserScan ID profile was scaled by a factor of 1.7 to match closely with the ILI data. The calculated maximum equivalent strain after scaling was 32.3%, about twice after rebounding.

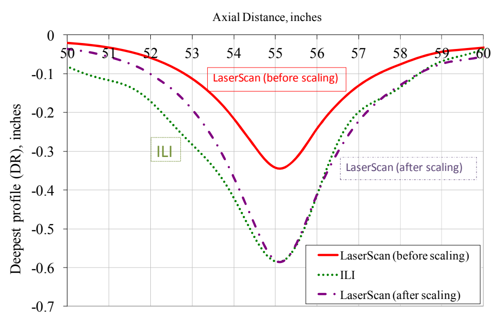
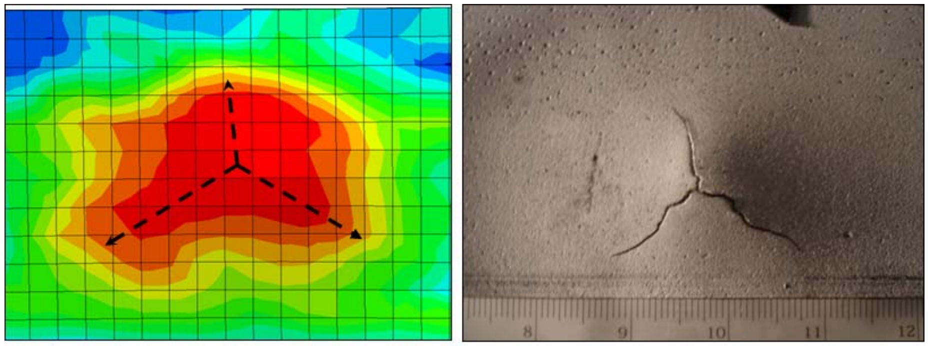


Figure 5: Change in dent ID profile before and after excavation, showing the dent had significantly rebounded.

An elastic-plastic finite element analysis (FEA) was performed using the scaled ID LaserScan profile of the cracked dent. The Critical strain was measured utilizing the procedure in Section 3. The measured value of the material critical strain was 51.2%. The maximum equivalent plastic strain based on FEA in the dent was 35.0%, located at the dent apex. DFDI values were calculated at each of the deformation nodes using the FEA result. The calculated maximum DFDI is 1.1, which is greater than 1.0, indicating that the dent is susceptible to cracking at its internal surface.

Figure 6(a) shows the maximum principal stress contour plot with the probable crack propagation direction, compared with the ID actual crack path, as shown in Figure 6(b). The FEA-predicted crack path is in good agreement with the observed actual crack pattern. FEA also showed a high reaction force associated with the dent, indicating a very high external force might have caused this dent deformation, possibly during construction.



(a) Max principal stress plot with predicted crack path

(b) Actual crack path

Figure 6: Case-1: Color-coded contour plot of maximum principal stress plot (indicated probable crack path) vs. actual crack path (ID)

In summary, this case study showed a failure condition (cracking) of the dent by the plastic damage mode, and demonstrates its effectiveness of capturing critical dents i.e. dents with susceptibility to crack in pipeline which can pose an integrity threat. Inline inspection Magnetic Flux Leakage (MFL) signal data was also utilized as an added dimension in understanding whether the dent is associated with a crack. A combined approach, utilizing the DFDI model and MFL signal recognition to identify dent with corrosion/cracking/gouging is presented in the next section.

3 A combined approach for dent with Corrosion/cracking/gouging evaluation [18]

Current in-line inspection technologies (e.g., caliper/MFL or combo) for mechanical damage assessment can detect dent with metal loss but with limited ability. However, they are incapable of discriminating metal loss from corrosion, gouge and crack. Practical experience showed that, with the assistance of strain based dent analysis and strain limit damage criteria, detailed characterization of MFL signals could effectively facilitate to identify potential risk of dent with cracking and to discriminate between metal loss features of corrosion and cracking/gouging. Therefore, a dent assessment approach which combines the plastic damage model with MFL signal recognition was recently developed by Wang et al and some of the present authors [18]. The strain severity based criterion is used to assess dent susceptibility to cracking regardless if the dent was reported as plain dent or dent with metal loss. Only those dents that meet the strain criterion will be considered as a candidate for investigation of MFL signal characteristics to assure if the dent is associated with cracking/gouging. The flow chart shown in Figure 7 describes the combined approach used for the assessment.

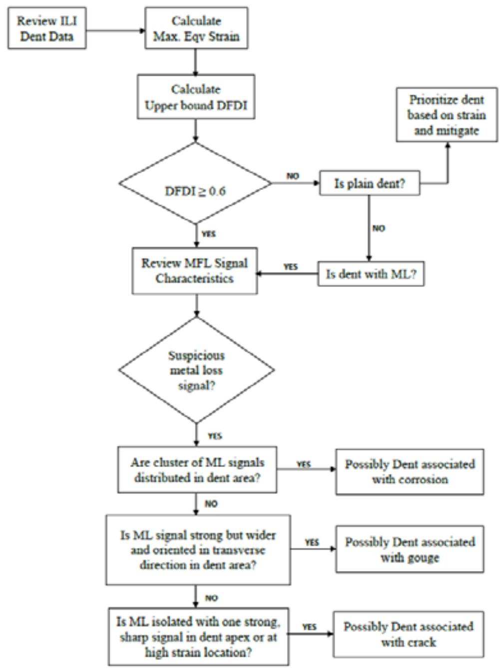


Figure 7: Flow chart – Procedure used in the combined assessment approach.

Using the above described procedure, case studies were performed to quantify the effectiveness of the approach for (1) identifying critical dents that are associated with cracking or gouging; and (2) the ability to discriminate the metal loss features of corrosion vs. cracking/gouging. Assessments were made using two recent in-line inspections which reported 4,823 dents in total. Among them, more than 150 dents were selected for assessment. Eight (8) dents were predicted to contain cracking or gouging. A total of fifteen (15) validation excavations, including the 8 predicted 'dent with crack' and 7 predicted 'dent without crack' were performed. All eight predictions were validated with excavations (true positive). Among them, two (2) were associated with through-wall cracks and were leaking during excavation, and the remaining 6 dents either contain surface cracks or gouges. The other seven (7) excavations showed no cracks or metal loss, i.e. true negative. The combined approach and its impact to integrity management of dents were successfully demonstrated with the case studies. The details of assessment approach, procedure, result and findings can be found in Reference [18] of this paper.

4 Summary

Critical strain based failure criterion, i.e., ductile failure damage indicator DFDI, can be applied to evaluate the severity of mechanical damage in pipelines for predicting susceptibility to cracking. Critical strain can be measured with uni-axial tensile testing and calculated using simplified mathematical model on uni-axial tensile full engineering and true stress-strain data recorded by synchronized data acquisition system. Finite element simulation demonstrated the effectiveness of the DFDI model for predicting cracks in dent. The study further demonstrates that the combined DFDI with MFL signal recognition approach can effectively identify potential risk of dent with cracking and to discriminate metal loss features between corrosion and cracking/ gouging.

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