Calibration of load and resistance factors for the limit state-based assessment of dent-gouge defects on energy pipelines

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ABSTRACT: A limit state-based fitness-for-service assessment framework for steel oil and gas pipelines containing dent-gouges is developed in the present study. This framework allows pipeline engineers to identify dent-gouges that require rehabilitations with a consistent level of implied failure probability due to the pipe internal pressure. The burst capacity of a dent-gouged pipeline is evaluated using the well-known European Pipeline Research Group model but improved using the Gaussian process regression technique and full-scale burst test data reported in the open literature. The limit state-based assessment is then formulated by assigning resistance factors to the dent depth, gouge depth and Charpy toughness, respectively, to compute the factored burst capacity at the dent-gouge, and by assigning a load factor to the maximum operating pressure of the pipeline. Rehabilitation is initiated if the factored burst capacity at the dent-gouge is less than the factored pressure. The load and resistance factors are calibrated by making the outcomes of the limit state-based assessment consistent with those of the reliability-based assessment corresponding to a pre-defined allowable failure probability for a set of assessment cases. The validity of the calibrated load and resistance factors is demonstrated using a set of assessment cases that are independent of those employed in the calibration. The limit state assessment framework developed in the present study can be applied to other types of flaws on pipeline such as metal-loss defects and surface cracks.

Buried steel oil and gas pipelines is occasionally subjected to mechanical damage due to impact by foreign objects such as excavation equipment and rocks (Lam and Zhou 2016; Tian and Lu 2022). A dent-gouge is a type of mechanical damage that can markedly reduce the pressure containment capacity (i.e. burst capacity) of the affected pipeline (Gao and Krishnamurthy 2010; Cosham and Hopkins 2020). A dent is a smooth change in the curvature of the pipe wall without any reduction in the wall thickness (Roovers et al. 2000). A gouge is a metal-loss defect on the pipeline as a result of the foreign objective in contact with and scraping material out of the pipe external surface (Cosham and Hopkins 2020; Macdonald and Cosham 2005), and a dent-gouge involves a gouge located within a dent, typically at the deepest point of the dent. The high-resolution in-line inspection (ILI) tool is used to detect and size dent-gouges on pipelines (McNealy et al. 2008; Gao and Krishnamurthy 2010). Deterministic fitness-for-service (FFS) assessments of dent-gouged pipelines are commonly carried out based on the ILI data. The burst capacity of the pipeline at the dent-gouge is first evaluated using an appropriate model. The evaluated burst capacity is divided by the nominal operating pressure of the pipeline, i.e. the maximum operating pressure (MOP), to compute the failure pressure ratio (FPR) at the dent-gouge (Al-Amin et al. 2020). If FPR is greater than or equal to a pre-defined safety factor (e.g. 1.25), the dent-gouged pipeline is considered fit for service without rehabilitation; otherwise, the pipe segment is excavated and repaired (or replaced). Deterministic FFS assessments do not take into account the inherent uncertainties associated with the pipe geometric and material properties and measurement errors in the ILI-reported sizes of dent-gouges, and therefore cannot achieve reliability-consistent assessment outcomes, i.e. the failure probability of a dent-gouged pipeline that is deemed fit for service after the assessment is below an allowable failure probability. On the other hand, the limit state-based assessment (LSBA) is a viable option to achieve reliability-consistent outcomes by incorporating appropriately calibrated load and resistance factors in a deterministic assessment format, similar to the load and resistance factors based design approach.

The objective of the present study is to calibrate the load and resistance factors for carrying out LSBA of dent-gouged pipelines such that reliability consistent assessment outcomes are achieved. A burst capacity model for dent-gouges is first selected for the assessment. Key input variables to which PSFs are applied are identified. A novel calibration process is then proposed to evaluate the load and resistance factors based on a large number of analysis cases representative of the real-world FFS assessment. Finally, the validity of the calibrated load and resistance factors is demonstrated through analysis cases independent of those considered in the calibration.

1. CAPACITY MODEL

A bust capacity model adopted by the European Pipeline Research Group (EPRG), also known as the EPRG model, is widely used in the pipeline industry to evaluate the burst capacity of dent-gouged pipelines. He and Zhou (2022) recently proposed an improvement of the EPRG model, referred to as the EPRG-C model, by adding a correction term in the EPRG model and applied the Gaussian process regression (GPR) to quantify the correction term based on full-scale burst tests of dent-gouged pipe specimens collected from the literature. The EPRG-C model is shown to be markedly more accurate than the EPRG model. Therefore, the EPRG-C model is adopted to evaluate the burst capacity of a dent-gouged pipeline. The burst capacity predicted by the EPRG-C model, $P_{EPRG\text{-}C}$, is computed as follows:

$$P_{EPRG-C} = P_{EPRG} + \mu_{c|o} P_0 \tag{1}$$

$$P_{EPRG} = \frac{4 w_t \bar{\sigma}}{\pi D} \cos^{-1}\left[\exp - \left\{113 \frac{1.5\pi E}{\bar{\sigma}^2 A_{23} d_g}\left(Y_1\left(1 - 1.8\frac{1.43H_r}{D}\right) + Y_2\left(5.1\frac{D}{w_t}\frac{1.43H_r}{D}\right)\right)^{-2} \exp\left[\frac{\ln(0.738 C_{v23}) - 1.9}{0.57}\right]\right\}\right] \tag{2}$$

$$\bar{\sigma} = 1.15\sigma_y\left(1 - \frac{d_g}{w_t}\right)\left(1 - \frac{d_g}{M_1 w_t}\right)^{-1} \tag{3}$$

$$M_1 = \sqrt{1 + 0.52\left(\frac{l_g}{\sqrt{D w_t}}\right)^2} \tag{4}$$

$$Y_1 = 1.12 - 0.23\left(\frac{d_g}{w_t}\right) + 10.6\left(\frac{d_g}{w_t}\right)^2 - 21.7\left(\frac{d_g}{w_t}\right)^3 + 30.4\left(\frac{d_g}{w_t}\right)^4 \tag{5}$$

$$Y_2 = 1.12 - 1.39\left(\frac{d_g}{w_t}\right) + 7.32\left(\frac{d_g}{w_t}\right)^2 - 13.1\left(\frac{d_g}{w_t}\right)^3 + 14.0\left(\frac{d_g}{w_t}\right)^4 \tag{6}$$

where P_{EPRG} denotes the burst capacity predicted by the EPRG model; $P_0 = 2w_t\sigma_y/D$; D, w_t and σ_y denote the pipe outside diameter, wall thickness and yield strength, respectively; M_1 is the so-called Folias factor; C_{v23} and A_{23} indicate the upper-shelf impact energy and net cross-sectional area of a 2/3-sized Charpy V-notch (CVN) specimen, respectively; d_g and l_g denote the gouge depth and gouge length (along the wall thickness and pipe axial directions), respectively; H_r is the dent depth under non-zero internal pressure, and $\mu_{c|o}$ is the correction factor obtained using GPR and full-scale burst test data (He and Zhou 2022). The dent depth in the EPRG model corresponds to zero internal pressure, denoted by H_0. An empirical equation is proposed in Roovers et al. (2000) to relate H_0 to H_r, i.e. $H_0 = 1.43H_r$. For in-service pipelines, we assume that the ILI-measured dent depth corresponds to the non-zero internal pressure condition. Therefore, $1.43H_r$ (as opposed to H_0) is employed in Eq. (2). Detailed procedures for evaluating $\mu_{c|o}$ are provided in He and Zhou (2022) and not repeated in this paper for brevity.

2. LSBA OF DENT-GOUGED PIPELINES

2.1. Formulation

LSBA of dent-gouged pipelines is formulated as follows:

$$\begin{cases} P_\phi < \alpha P_c: & Repair \\ P_\phi \geq \alpha P_c: & No\ repair \end{cases} \tag{7}$$

where P_ϕ denotes the factored burst capacity at the dent-gouge, and αP_c denotes the factored internal pressure of the pipeline with α ($\alpha > 1$) and P_c representing the load factor and characteristic value of the internal pressure, respectively. The value of P_ϕ is computed using the EPRG-C model with values of the model input variables (e.g. the pipe diameter and wall thickness, steel yield strength, and dent depth) equal to either the corresponding characteristic values or characteristic values multiplied by the respective resistance factors. The characteristic values of the input variables on both sides of Eq. (7) are defined to be the corresponding nominal values. More specifically, these nominal values include the nominal pipe outside diameter (D_n) and wall thickness (w_{tn}), the specified minimum yield strength (SMYS), 2/3-sized Charpy impact energy obtained from tests (C_{v23n}), ILI-reported dent depth (H_{rn}), gouge-depth (d_{gn}) and gouge length (l_{gn}), and MOP.

We assign a resistance factor ϕ_{cv} ($0 < \phi_{cv} < 1$) to the Charpy impact energy but do not assign a resistance factor to the pipe yield strength. This is because the uncertainty in the latter is much smaller than that in the former (CSA 2019). We further assign a resistance factor ϕ_{Hr} ($\phi_{Hr} > 1$) to the dent depth and a resistance factor ϕ_{dg} ($\phi_{dg} > 1$) to the gouge depth because these two variables have a large impact on the burst capacity of dent-gouged pipeline (He and Zhou 2022). The nominal (i.e. unfactored) values of all the other input variables involved in the EPRG-C model are employed in the computation. It follows that Eq. (7) can be written as

$$\begin{cases} P_\phi < \alpha \text{MOP}: & Repair \\ P_\phi \geq \alpha \text{MOP}: & No\ repair \end{cases} \tag{8}$$

$$P_\phi = P_{EPRG-C}(D_n, w_{tn}, \text{SMYS}, \phi_{cv} C_{v23n}, \phi_{Hr} H_{rn}, \phi_{dg} d_{gn}, l_{gn}) \tag{9}$$

2.2. Calibration of load and resistance factors

The calibration of load and resistance factors for the design code typically involves assuming the factored resistance to equal the factored load effect and then adjusting load and resistance factors to ensure that the computed reliability of a wide range of design cases on average achieve the pre-defined target reliability level (Bartlett et al. 2003). This calibration process is however inapplicable to the limit state-based FFS assessment: while one can always ensure the factored resistance to equal the factored load effect in a design, one cannot ensure the same in the FFS assessment of in-service pipelines because the only decision variable in the assessment is the decision of repair or no repair.

A novel process to calibrate ϕ_{cv}, ϕ_{Hr}, ϕ_{dg} and α is therefore proposed in this study. This process first considers a large set of assessment cases representative of those in practice. The first-order reliability method (FORM) (Melchers 1999; Low and Tang 2007; Zhou et al. 2015) is then employed to evaluate the probabilities of failure (p_f) of the assessment cases. Those assessment cases with the failure probabilities falling within a narrow probability band around the pre-defined allowable failure probability (p_{fa}) are referred to as the critical assessment cases. The values of ϕ_{cv}, ϕ_{Hr}, ϕ_{dg} and α are selected such that outcomes of LSBA of the critical assessment cases are reliability consistent. That is, for a given critical assessment case, $P_\phi \geq \alpha$MOP if $p_f \leq p_{fa}$ (i.e. no repair), and $P_\phi < \alpha$MOP if $p_f > p_{fa}$ (i.e. repair). It is expected that the values of ϕ_{cv}, ϕ_{Hr}, ϕ_{dg} and α will lead to reliability-consistent outcomes of LSBA for non-critical assessment cases, i.e. $P_\phi >> \alpha$MOP if $p_f << p_{fa}$, and $P_\phi << \alpha$MOP if $p_f >> p_{fa}$. The proposed load and resistance factors calibration process is to certain extent the reverse of that typically employed in the design code calibration.

The assessment cases considered in this study have the same D_n = 610 mm and MOP = 8.0 MPa, but different w_{tn} and SMYS. The combinations of w_{tn} and SMYS considered in the analysis are summarized in Table 1. For a given steel grade, four values of C_{v23n} (30, 60, 90 and 120 J) representative of low to high Charpy toughness are assumed. We further consider five values of H_{rn}/D_n: 1.5, 2.0, 2.5, 3.0 and 3.5%; four values of d_{gn}/w_{tn}: 15, 25, 30 and 40%, and three values of l_{gn}: 50, 100 and 200 mm. The combinations of pipe properties and dent-gouge sizes result in a total of 2880 unique assessment cases. It should be emphasized that 414 assessment cases are considered irrelevant to the present study because their burst capacities predicted by the EPRG-C model using nominal values of the input variables are less than or equal to 0.9MOP. Such a low capacity likely leads to immediate failures of the dent-gouge. By eliminating these irrelevant cases, a total of 2466 assessment cases are included in the reliability analysis.

Table 1: Nominal pipe wall thicknesses and yield strengths of assessment cases considered in the calibration

No.	w_{tn} (mm)	SMYS (MPa)
1	6.31	483
2	7.02	483
3	8.42	483
4	10.10	483
5	7.37	414
6	8.19	414
7	9.82	414
8	11.79	414
9	8.52	358
10	9.47	358
11	11.36	358
12	13.63	358

The limit state function, g, for burst of a pipeline at a dent-gouge defect under internal pressure is given by

$$g = \zeta P_{EPRG-C} - P \tag{10}$$

where ζ is the model error associated with the EPRG-C model, and $g \le 0$ implies failure. The FORM is employed to evaluate p_f as

$$p_f = \Phi(-\beta) \tag{11}$$

where β denotes the reliability index obtained from the FORM, and $\Phi(\cdot)$ represents the standard normal distribution.

The probabilistic characteristics of the input variables in the reliability analysis are summarized in Table 2. All random variables are assumed to be mutually independent. The quantities ε_{Hr}, ε_{dg} and ε_{lg} in Table 2 denote the additive measurement errors that are assumed to be associated with the ILI-reported dent depth, gouge depth and gouge length, respectively.

$$H_r = H_{rn} + \varepsilon_{Hr} \tag{12}$$

$$d_g = d_{gn} + \varepsilon_{dg} \tag{13}$$

$$l_g = l_{gn} + \varepsilon_{lg} \tag{14}$$

Table 2: Probabilistic characteristics of input variables in the reliability analysis

Var.	Dist.	Mean/nominal	COV (%)
D	Determ.	1.0	-
w_t	Normal	1.01	1.6 for $w_{tn} \le 8$ mm 1.6 + 0.15(w_{tn} - 8) for 8 < $w_{tn} \le 12$ mm 2.2 for w_{tn} > 12 mm
σ_y	Normal	1.1	3.5
C_{v23}	Lognormal	1.0	$2.23C_{v23n}^{0.46}$ for $C_{v23n} \le 100$ J $4.21C_{v23n}^{0.29}$ for $C_{v23n} > 100$ J
ε_{Hr} (%D_n)	Normal	0	^{a}0.6
ε_{dg} (%w_{tn})	Normal	0	^{a}9.3
ε_{lg} (mm)	Normal	0	^{a}7.8
P	Gumbel	1.03	2.0
ζ	Lognormal	1.01	9.2

a: values are standard deviations

The FORM is employed to evaluate β values for the 2466 analysis cases, of which 634 cases are observed to have β values less than or equal to 1.0 (i.e. $p_f \geq 0.159$). These cases are excluded from further considerations as their failure probabilities are too high to be considered relevant to the present study – such cases likely correspond to immediate failures in practice. The β values for the remaining 1832 assessment cases are depicted in Fig. 1. An allowable failure probability of $p_{fa} = 5 \times 10^{-3}$ or equivalently a target reliability index β_T of 2.57 (represented by the dash line in Fig. 1) is selected for illustrative purpose. Those cases with $\beta = \beta_T \pm 0.2$, i.e. $2.8 \times 10^{-3} \leq p_f \leq 8.9 \times 10^{-3}$ are selected as the critical assessment cases as shown within the gray band in Fig. 1. It follows that 264 critical assessment cases are identified, of which 124 cases have $p_f > p_{fa}$ (i.e. cases needing repair), and 140 cases have $p_f \leq p_{fa}$ (i.e. cases not needing repair).

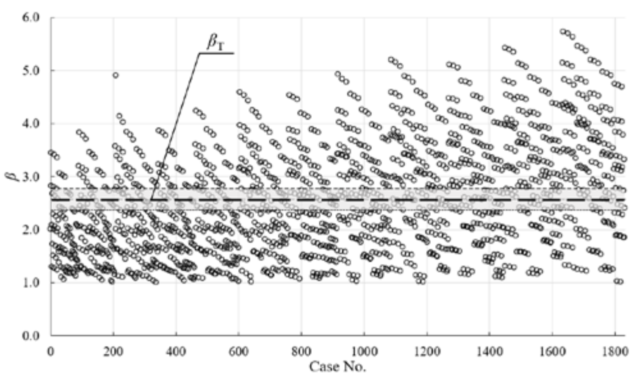

Figure 1: The β values for the 1832 assessment cases and critical assessment cases corresponding to β_T = 2.57

The load and resistance factors should be selected such that the outcomes of LSBA are reliability consistent. In reality, outcomes of LSBA may not be perfectly reliability consistent. It follows from the binary assessment outcomes (i.e. repair and no repair) that a confusion matrix for the outcomes of LSBA can be constructed as depicted in Table 3, where TR, FN, FR and TN denote true repair, false non-repair, false repair and true non-repair, respectively.

Table 3: Confusion matrix for the outcomes of LSBA

Reliability-based assessment outcomes		LSBA outcomes	
		$P_\phi < \alpha$MOP	$P_\phi \geq \alpha$MOP
$p_f > p_{fa}$	Repair	TR	FN
$p_f \leq p_{fa}$	No repair	FR	TN

The adequacy of the calibrated load and resistance factors are quantified by the common performance indices associated with the confusion matrix, i.e. the true repair rate (TRR) or sensitivity, true non-repair rate (TNR) or specificity, and overall accuracy (ACC), which are defined as follows:

$$\mathrm{TRR} = \frac{N_{TR}}{N_{TR}+N_{FN}} \tag{15}$$

$$\mathrm{TNR} = \frac{N_{TN}}{N_{TN}+N_{FR}} \tag{16}$$

$$\mathrm{ACC} = \frac{N_{TR}+N_{TN}}{N_{TR}+N_{FN}+N_{TN}+N_{FR}} \tag{17}$$

where N_{TR}, N_{TN}, N_{FR} and N_{FN} denote the number of critical assessment cases in TR, TN, FR and FN, respectively, corresponding to the load and resistance factors.

We propose to determine the load and resistance factors by the following constrained optimization procedure:

$$\{\phi_{cv}, \phi_{Hr}, \phi_{dg}, \alpha\} = \underset{\phi_{cv}, \phi_{Hr}, \phi_{dg}, \alpha}{\operatorname{argmax}} \ f_o \tag{18}$$

$$s.t.\ 0.6 \leq \phi_{cv} < 1, \phi_{Hr} > 1, \phi_{dg} > 1, 1.1 \leq \alpha \leq 1.5$$

$$f_o = w\mathrm{TRR} + (1-w)\mathrm{TNR} \tag{19}$$

where f_o is the objective function, and w and (1-w) are the relative weights assigned to TRR and TNR in the objective function. The constraints on ϕ_{cv}, and α in Eq. (18) are applied for practicality: ϕ_{cv}, is limited by a lower bound of 0.6 to prevent very low factored toughness value from being used in the EPRG-C model, and the range of α is consistent with typical industry practice in deterministic FFS assessment of dent-gouges.

3. RESULTS

The calibrated values of ϕ_{cv}, ϕ_{Hr}, ϕ_{dg} and α corresponding to w = 0.7 are shown in Table 4. Note that the value of w depends mainly on the pipeline operator's attitude towards FN and FR. A false non-repair can have potentially more serious consequences (e.g. a missed opportunity to prevent failure) than a false repair (e.g. higher maintenance cost). The adequacy of the calibrated load and resistance factors in terms of TRR, TNR and ACC for the 264 critical assessment cases is also summarized in Table 4. The results indicate that LSBA is highly accurate in identifying TR and also reasonably accurate in identifying TN. Figure 2 depicts the outcomes of LSBA for the 264 critical assessment cases.

Table 4: Calibrated load and resistance factors for LSBA of dent-gouged pipelines and performance indices based on 264 critical assessment cases

Calibrated load and resistance factors				Performance indices		
ϕ_{dg}	ϕ_{Hr}	ϕ_{cv}	α	TRR (%)	TNR (%)	ACC (%)
1.21	1.05	0.65	1.33	92.7	83.6	87.9

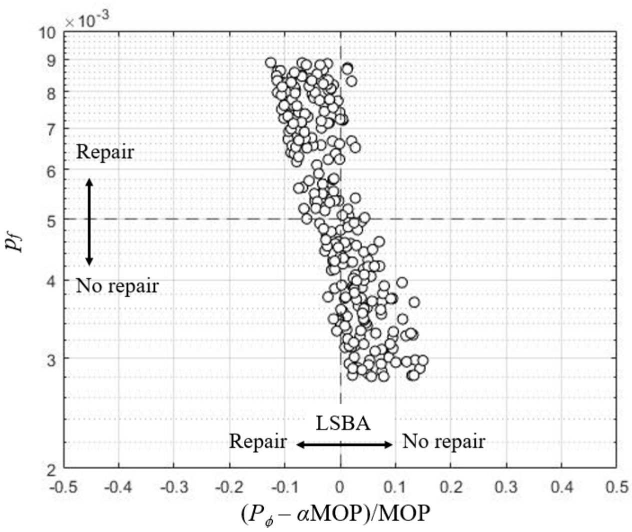

Figure 2: Outcomes of LSBA for the 264 critical assessment cases with ϕ_{dg} = 1.21, ϕ_{Hr} = 1.05, ϕ_{cv} = 0.65, and α = 1.33

The validity of the calibrated load and resistance factors is verified by carrying out LSBA on the 1568 non-critical cases of the 1832 assessment cases described in Section 2.2. Figure 3 depicts p_f versus the corresponding values of (P_ϕ - αMOP)/MOP for these cases. The results in Fig. 2 indicate that LSBA utilizing the calibrated load and resistance factors is highly accurate in identifying both repairs and non-repairs of the 1568 non-critical assessment cases.

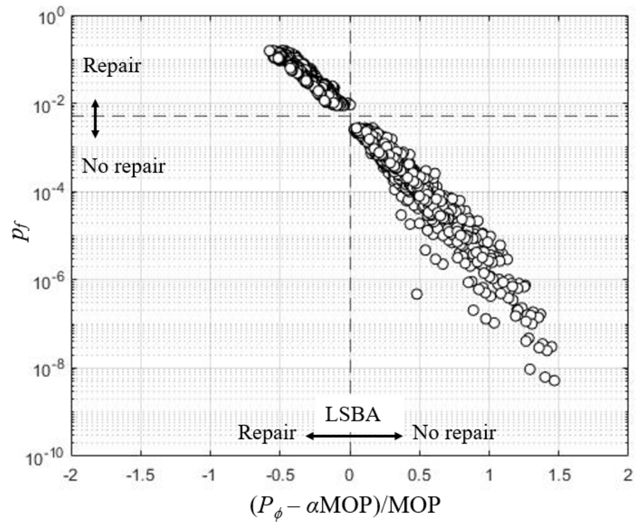

Figure 3: Outcomes of LSBA for the 1568 non-critical assessment cases with ϕ_{dg} = 1.21, ϕ_{Hr} = 1.05, ϕ_{cv} = 0.65, and α = 1.33.

4. CONCLUSIONS

We present a framework for carrying out LSBA of steel oil and gas pipelines containing dent-gouges. LSBA is formulated by computing the factored burst capacity at a dent-gouge using the factored gouge depth ($\phi_{dg}d_{gn}$), dent depth ($\phi_{Hr}H_{rn}$) and Charpy toughness ($\phi_{cv}C_{v23n}$) in the EPRG-C model. If the factored burst capacity is less than the factored pipe internal pressure (αMOP), rehabilitation actions are initiated. The resistance and load factors (i.e. ϕ_{dg}, ϕ_{Hr}, ϕ_{cv} and α) are calibrated for a pre-defined p_{fa} through the use of the confusion matrix associated with the outcomes of LSBA for a set of critical assessmsent cases. The FORM is employed to evaluate the failure probabilities of the assessment cases by taking into account uncertainties involved in the pipe geometric and material properties, sizes of dent-gouges, as well as the model error associated with the EPRG-C model.

The load and resistance factors are calibrated for p_{fa} = 5 $\times 10^{-3}$. The validity of the calibrated load and resistance factors is shown based on assessment cases independent of those considered in the calibration. The proposed LSBA framework and calibration process can be applied to pipelines containing other types of flaws such as metal-loss corrosion and stress corrosion cracking defects.

5. ACKNOWLEDGEMENT

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