A Comprehensive Framework for Automated Dent Screening and Integrity Assessment Using In-Line Inspection Data and Finite Element Analysis

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Abstract

Pipeline dents are a major threat to the integrity and safety of aging oil and gas transmission systems. While API 1183 provides methodologies for dent assessment, it has several limitations. Traditional strain assessment methods rely heavily on 2D cross-sections, assuming maximum strain or minimum radius of curvature occurs at the dent's apex, and do not distinguish between restrained and un-restrained dents. Furthermore, fatigue evaluation based on regression models often leads to overly conservative and inconsistent outcomes. This paper presents a novel framework to address these limitations and enhance pipeline safety.

The process begins with ILI data collection, followed by an automated Quality Assurance/Quality Control (QA/QC) process utilizing machine learning to resolve data inconsistencies. The framework employs filtering and smoothing techniques to refine the ILI data. Determining the restraint condition is a key step, guiding the appropriate assessment workflow. Un-restrained dent shapes are scaled appropriately to simulate indentation depth which is always greater than ILI reported depth. Strain analysis follows both API 1183 guidelines and recent recommendations published in the PRCI report "Improve Dent/Cracking Assessment Methods, PR-214-203806". Fatigue life is estimated by transforming ILI caliper data into a 3D finite element analysis (FEA) mesh, enabling a rigorous assessment of dent severity.

A critical advancement in this framework is the use of non-linear material properties in the screening level FEA, calibrated to account for residual stresses, to improve stress estimation for restrained dents. By incorporating estimated approximate residual stresses from strain data, the resulting stress values align closely with Level 3 non-linear FEA results, enhancing both accuracy and efficiency in fatigue assessments. Other advancements include the 3D evaluation of dent curvature to identify potential high-strain regions beyond the dent's deepest point, and the integration of IMU data for identifying dents in non-straight pipeline sections.

This paper presents the technical development and real-world applications of the framework, demonstrating its effectiveness in managing pipeline integrity through risk-informed decision making.

Introduction

The management of dents in oil and gas pipelines has been a critical area of research and development for decades due to the potential risks they pose to pipeline integrity. Historically, pipeline regulations and industry practices have relied heavily on prescriptive dent excavation criteria based on depth and interaction with stress risers. These criteria fail to account for the complex behavior of dents, which is influenced by factors like dent shape, formation history, loading conditions (e.g., pressure cycling or hydrotest pressures) etc. As a result, their application often leads

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to inconsistent integrity decisions, with some being overly conservative and others insufficient in identifying injurious dents.

In the early years of pipeline integrity management, dents were assessed visually or through rudimentary depth-based metrics, which were often insufficient to evaluate the dent's present severity or predict the delayed failure mechanisms associated with pressure cycling [1,2]. Over time, the industry transitioned to strain-based assessments, offering a more nuanced understanding of dent severity by evaluating strain concentrations in dented regions. Standards such as ASME B31.8 and CSA Z662 introduced strain thresholds and depth-to-diameter ratios for plain dents, representing a significant advancement in regulatory guidelines [3,4]. However, despite these improvements, dent failures continued to occur, highlighting the inadequacy of these regulations in ensuring long-term pipeline safety.

The availability of commercial finite element analysis (FEA) codes and lower computing costs in the 1990s and early 2000s marked a shift in dent assessment methodologies. FEA enabled detailed modeling of the stress and strain distributions within dented pipeline sections, accounting for factors such as dent shape, indenter interaction, and operational loading conditions. This capability laid the foundation for the development of fitness-for-service (FFS) frameworks, such as API RP 579, which introduced a structured, tiered approach to assess dent severity based on the level of available data and the desired level of conservatism [1,5]. Research programs led by the Pipeline Research Council International (PRCI), such as MD-4-2 and MD-4-9, provided critical experimental data and advanced methodologies for understanding dent behavior, which have significantly influenced modern assessment techniques and standards. More recently, the publication of API RP 1183 has further advanced the field by integrating fatigue-based assessments and shape-based evaluation techniques into a single framework [6]. However, API RP 1183 also has limitations, particularly in its reliance on simplified screening methodologies that often produce inconsistent or overly conservative results when compared to more detailed analyses.

In recent years, significant advancements in in-line inspection (ILI) tools have allowed operators to collect high-resolution data on dent geometry and associated features. This data has enabled shape-based assessments and the integration of modern computational techniques, such as machine learning and automated FEA workflows, into the dent management process [7,8]. Despite these developments, challenges remain in automating data processing, refining fatigue life models, and addressing discrepancies in existing assessment frameworks.

This paper presents a novel framework designed to address these challenges and provide a more robust approach to dent integrity management. The proposed methodology integrates quality assurance/quality control (QA/QC) processes and noise filtering for ILI data, advanced strain-based assessments, and fatigue life estimation using finite element modeling. This framework accommodates both deterministic and probabilistic analyses for a comprehensive assessment of pipeline dents. The key technical aspects of this framework are described within the scope of this

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paper. The effectiveness of the framework is demonstrated through real-world case studies, highlighting its potential to enhance pipeline integrity management while balancing safety and operational efficiency.

Current Challenges in Dent Integrity Assessment

The assessment and management of dents in pipelines face two primary types of challenges: technical limitations and operational challenges. These challenges highlight the complexity of evaluating dents and ensuring pipeline integrity, emphasizing the need for improved methodologies that balance accuracy with practical implementation.

Technical limitations in current dent integrity methodologies have been widely discussed in recent research. PRCI research under MD-5-2 identified inaccuracies in strain prediction models, particularly for unrestrained dents, where re-rounding under pressure alters the strain distribution in ways not accounted for by simplified methods [9]. Additionally, fatigue life prediction models exhibit significant variability due to calibration gaps and the oversimplified treatment of factors such as dent shape and loading history. These limitations reduce the reliability of assessments and undermine the ability to make consistent integrity decisions. API RP 1183 has also been criticized for its reliance on screening tools that are either overly conservative or ineffective. Studies by Leis et al. demonstrated inconsistencies in strain and fatigue life tools within API RP 1183, leading to excessive conservatism in some scenarios while potentially underestimating the severity of dents with complex geometries in others [10]. Follow up research by the same authors highlighted over-reliance on apex-centric assumption (maximum strain always occurs at the apex of the dent), insufficient consideration of complex geometries, inadequacy of the numerical models underlying API 1183 recommendations, etc. [11]. Zhu (2023) highlighted that while API RP 1183 provides a valuable framework, its fatigue life estimations for sharp-curvature dents and interacting features remain inaccurate, necessitating validation through advanced modeling techniques [12]. Furthermore, PRCI research completed within the scope of MD-5-2 outlined significant challenges in consistently classifying dent severity, particularly for asymmetric or multi-peak dents, emphasizing the need for more sophisticated methodologies to address these scenarios [9].

Another significant challenge in dent integrity assessment is the difficulty with effectively incorporating measurement uncertainties. Unlike cracks or corrosion features, which can often be idealized as simplified two-dimensional geometric shapes for assessment, dents present unique complexities. For cracks and corrosion, adding tool tolerance to the measured depth ensures a conservative approach. However, this method does not translate to dents due to the non-linear relationship between dent geometry and strain or stress behaviour. The underlying physics of dent behaviour, including the effects of increased or decreased sharpness on strain and stress estimates, is highly complex and cannot be captured through simple geometric adjustments. Dents defy idealized representations that guarantee consistently conservative results in subsequent analyses. As a result, probabilistic assessment becomes crucial in properly capturing the effect of tool tolerance on dent

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assessment. By considering the full range of possible variations in dent geometry due to measurement uncertainties, probabilistic methods enable a more accurate estimation of the associated strain and stress behaviour. API 1183 does not outline how probabilistic analysis should be performed other than providing few general recommendations. Limited work has been done previously on this topic.

In addition to technical limitations, operational challenges further complicate dent integrity management. Simplified screening tools, while easy to implement, are often overly conservative, leading to unnecessary excavations or repairs that increase costs without improving safety outcomes. On the other hand, advanced methodologies such as shape-based assessments require significant expertise, computational resources, and time, making them impractical for widespread application by operators. Even when these advanced methods are implemented, the incremental improvements in accuracy may not justify the additional effort, especially given the inherent limitations of the underlying models. As a result, operators face a trade-off between using simplistic but incomplete methods and adopting resource-intensive techniques that may not consistently deliver meaningful benefits.

This paper proposes a novel framework to address these challenges, recognizing the distinction between technical and operational limitations. While the framework does not resolve all existing issues, the proposed framework integrates automated processes, improved QA/QC, strain and fatigue assessment methods, and scalable workflows that mitigate many of these problems. The optimized and heavily automated process flow within the framework minimizes manual intervention and maximizes efficiency. Furthermore, its modular design allows for future enhancements as new methodologies and standards are developed. The subsequent sections will explore this framework in detail, demonstrating its potential to improve both accuracy and practicality in dent integrity management.

Overview of the Proposed Framework

The proposed framework is a modular, systematic approach designed to enhance the accuracy, consistency, and practicality of dent integrity assessments. The process begins with the collection and integration of data, including ILI caliper measurements, pipeline attribute details, and Supervisory Control and Data Acquisition (SCADA) pressure data. Optional IMU data adds context by capturing the pipeline's global shape. Automated QA/QC processes refine raw dent profile data by addressing anomalies, correcting errors, and smoothing profiles, ensuring a reliable foundation for subsequent analyses.

Level 2 assessments employ both deterministic and probabilistic methods to evaluate dent severity. These analyses include curvature and restraint condition evaluations, strain demand calculations using analytical equations, and fatigue life estimations via shape-based methods or finite element analysis (FEA). Outputs include strain safety factors, probabilities of exceedance, and both deterministic and probabilistic fatigue life predictions.

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For potentially injurious or complex dents, the framework offers Level 3 detailed FEA, featuring automated mesh generation, iterative indenter modeling, and streamlined workflows for deterministic and probabilistic assessments. These advanced analyses provide detailed insights into critical features, supporting risk-informed integrity decisions. Detailed descriptions of Level 3 methodologies can be found in prior publications [13,14].

The framework's final outputs include comprehensive reports with severity rankings and deterministic and probabilistic results, ensuring actionable insights for integrity management. The following sections detail specific improvements within the framework that address longstanding challenges in dent integrity assessment.

Automated QA/QC of Raw Caliper Dent Profile Data and Filtering Algorithms

High-quality input data is a critical requirement for automating all stages of dent integrity assessment. Unfortunately, the raw ILI caliper dent profile data received from vendors often contains several inconsistencies and inaccuracies that require significant expertise and time to identify and correct. The proposed framework addresses these challenges through a combination of automated QA/QC processes, machine learning models, and advanced filtering techniques, ensuring the data is prepared for reliable downstream analysis.

One common issue is sensor bounce, where caliper sensors register artificially high inward or outward deformations when passing seam or girth welds or due to unknown anomalies. These deformations are physically impossible but, if uncorrected, can result in erroneously high curvature values being flagged during strain calculations and FEA modeling. Filtering algorithms alone cannot resolve these discrepancies because the signal strength from such errors is often very high, necessitating additional diagnostic steps.

Another challenge arises with the identification of dent features reported in the ILI feature listing provided by vendors. These listings include key characteristics like dent depth, relative or absolute axial position, and orientation. However, these reported values can sometimes deviate from the observed dent location in the raw caliper data. For isolated dents, querying based on maximum deformation usually suffices for feature identification. However, when multiple dents are in close proximity within the same pipe joint, misidentifications, particularly for shallower features is a possibility.

Occasionally, channel malfunctions result in artificially sharp or distorted data profiles, which can impact curvature and strain evaluations. Similarly, insufficient correction for ILI tool rotation by vendors may result in unusable shapes, identifiable through visual inspection or roll data from the

IMU tool, if available. These issues highlight the importance of a robust QA/QC process that can detect and correct such anomalies efficiently.

To address these challenges, the QA/QC process employs a k-nearest neighbor (k-NN) machine learning model specifically designed to compare standardized dent feature listings against the raw ILI profile data. This model detects discrepancies in key dent characteristics, including axial location, orientation, and depth, by flagging mismatches between vendor-reported values and ILI profile data. The k-NN model has been calibrated to achieve a recall rate of 100%, prioritizing the detection of all potential discrepancies, even at the expense of precision. This conservative calibration ensures that no critical features are overlooked during the QA/QC process, with an overall model accuracy of approximately 70%. An example of this process is shown in the figure below where the algorithm detects the target dent, identifies the data error due to sensor bounce and corrects the data error automatically.

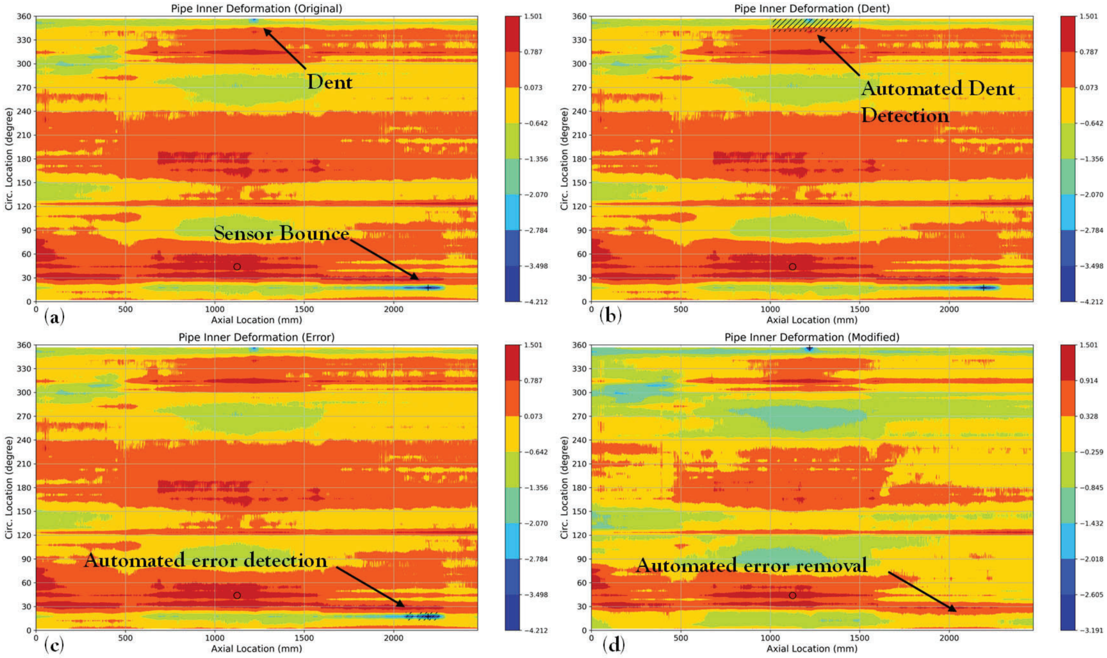

Figure 1. Error in raw caliper data due to sensor bounce detected and corrected using the automated QA/QC algorithm.

Once the QA/QC process is complete, a graphical user interface (GUI) helps with visualizing the results and allows operators to review and manually adjust flagged features as necessary. Following QA/QC, advanced filtering algorithms are applied to remove random and systemic noise from the ILI profile data. Techniques such as Fast Fourier Transform (FFT) and Gaussian filtering smooth the dent profile while preserving critical geometric features, ensuring the data is ready for accurate curvature and strain calculations [15,16]. These filtering techniques, discussed in our prior work, effectively reduce noise while addressing specific data inconsistencies encountered in dent integrity assessments.

Characteristic Length and Area Calculations

Dents require an accurate three-dimensional geometric representation to properly evaluate critical factors such as strain and fatigue life. To support this, API RP 1183 introduces the concept of characteristic lengths and areas, derived from the axial and transverse profile slices of the dent. These profiles, taken through the dent's deepest point, provide a structured two-dimensional representation of the three-dimensional geometry of a dent. Characteristic lengths, such as axial and transverse lengths, are defined based on specific percentages of the dent's maximum depth (e.g., 10%, 50%, 85%). Similarly, characteristic areas quantify the area under the smoothed profiles. These parameters are critical for determining the restraint conditions, strain behavior, and fatigue life of the dent.

The framework ensures precision and consistency in these calculations through an automated algorithm integrated into the overall workflow. This algorithm begins by analyzing the cross-sectional profiles of the dent, identifying reference points such as the apex (deepest point) and locations corresponding to predefined percentages of the maximum depth. Interpolation techniques are employed to ensure that even small geometric nuances are captured accurately. For instance, the axial length is calculated by measuring the distance between the two axial positions where the deformation depth equals a specified percentage of the maximum depth, such as 50%. Transverse lengths are determined circumferentially from the apex using similar criteria.

Characteristic areas are calculated by performing numerical integration under the axial and transverse profiles. These calculations account for sharp curvatures and asymmetries in the dent shape, ensuring accurate representation of the geometry. The process eliminates potential human error and significantly reduces the time required for these computations, allowing for scalable assessments across extensive datasets. Example output from the automated area calculation is shown in figure 2 below.

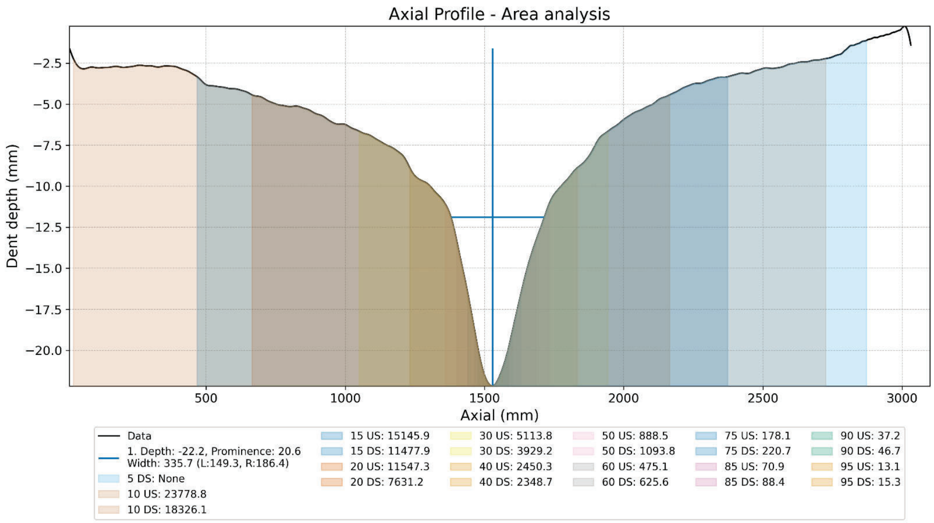

Figure 2. Sample output of characteristic area calculation of the axial profile of a dent.

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The calculated characteristic lengths and areas serve as critical inputs for multiple stages of the assessment process. They are used to compute the restraint parameter, classifying dents as restrained or unrestrained—a key determinant of fatigue life. These parameters also support strain calculations, specifically the membrane strain components, which is essential for evaluating dent severity. Moreover, the shape-based parameters feed directly into fatigue life assessments, ensuring that the dent's true geometry is fully accounted for in subsequent analyses.

Radius of Curvature Calculation and IMU Data Integration

The radius of curvature plays a crucial role in assessing the strain within dented pipeline segments, as it directly influences the estimation of deformation-induced strain. In traditional strain assessments, maximum strain is often assumed to occur at the dent apex, where the deformation depth is greatest. This assumption, while practical for simplified models, fails to capture the true complexity of dent behavior. Advanced techniques, such as full 3D strain contour estimation based on ILI profiles, have been explored in some studies [17,18,19], but the accuracy and applicability of these methods remain uncertain. Furthermore, strain estimation equations in standards such as ASME B31.8 were developed with the dent apex in mind, potentially limiting their reliability when applied to other regions on the dent surface [3]. A reasonable and practical approach involves identifying locations of high curvature outside the dent apex to determine areas of potential high strain, which can then trigger a Level 3 detailed FEA for more precise strain analysis.

In the presented framework, the radius of curvature is calculated in three dimensions using ILI profile data, providing a robust method to identify regions susceptible to high strain. The methodology begins with obtaining discrete data points from ILI measurements representing the axial and circumferential profiles of the dent. These points are parameterized along their cumulative arc length to ensure accurate representation of the dent geometry. Smoothing splines are then fitted to the data to create continuous functions, mitigating the impact of measurement noise and enabling precise curvature computation.

For the axial direction, curvature is determined using derivatives of the fitted spline. The first and second derivatives of the spline are computed, and the signed curvature is calculated using the standard formula for plane curves. The radius of curvature is then obtained as the reciprocal of the computed curvature, providing a measure of bending in the axial profile of the dent. Similarly, for the transverse direction, radial distances from the pipe center to the dent surface are fitted with a smoothing spline, and curvature is calculated based on the Cartesian conversion of radial data. This dual-axis approach enables a comprehensive assessment of curvature across the dent's surface. A sample output from such analysis is shown in figure 3 below for visualization.

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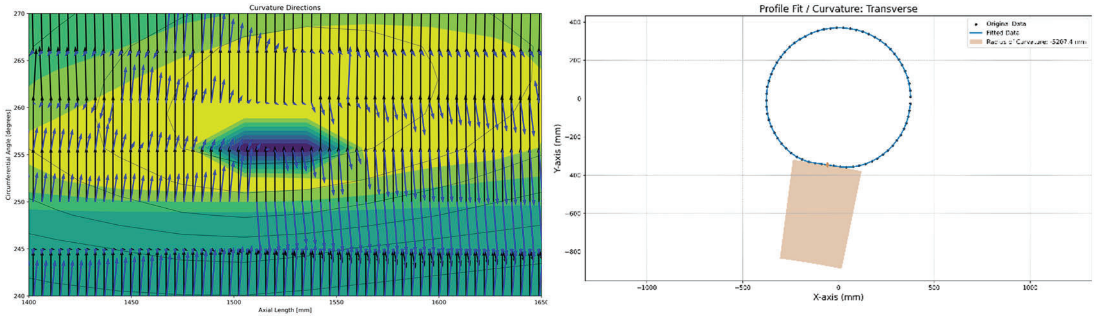

Figure 3. Visual output of radii of curvature analysis.

The quality of the curvature calculations is validated by comparing the original ILI data points with the fitted spline functions. Root-mean-square error metrics are used to quantify the fidelity of the splines, ensuring that the calculated curvatures accurately represent the pipeline's geometry. Regions with small radii of curvature identified through this methodology are flagged as potential high-strain locations. These regions, if located outside the dent apex, indicate that strain assessment based solely on apex parameters may be inadequate. In such cases, the framework triggers a Level 3 detailed FEA to capture the strain behavior with higher fidelity. By integrating these advanced curvature calculations, the framework addresses limitations in traditional practices and enhances the reliability of dent strain assessments.

In addition to radius of curvature calculations, the framework incorporates inertial measurement unit (IMU) data processing and integration to address scenarios where the pipeline deviates from an ideal straight configuration. The caliper ILI tool inherently assumes that the pipeline is straight, leading to inaccuracies when the pipe exhibits out-of-straightness due to features such as field bends, elbows, or ground movement. In such cases, the caliper measurements do not represent the true shape of the dent, resulting in misleading strain and fatigue calculations if the data is used directly.

To address these limitations, the framework includes an automated algorithm that processes IMU data to trace the pipe's center axis over a specified length and estimate the out-of-straightness of the pipeline (figure 4). If the estimated out-of-straightness exceeds a predefined threshold, the framework flags the corresponding segment and notifies the user to perform a Level 3 detailed FEA analysis. This capability ensures that inappropriate screening-level analyses are avoided, enhancing the reliability of integrity assessments for pipelines with geometric deviations.

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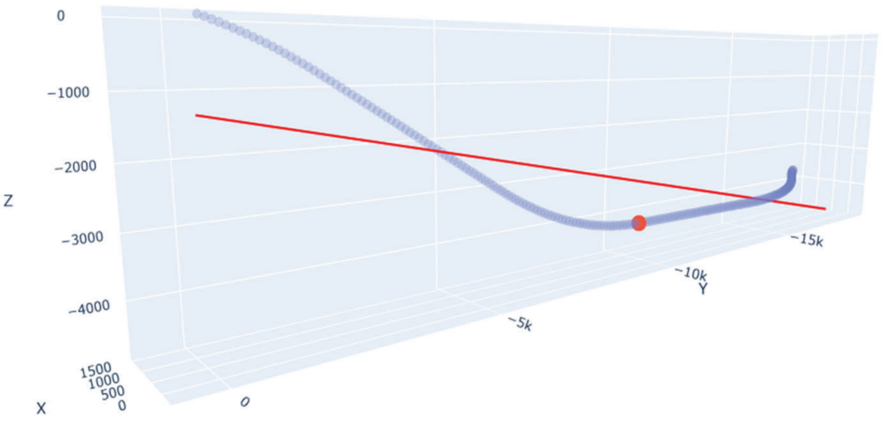

Figure 4. Pipe axis traced from IMU data and determination of out-of-straightness.

Currently, the combination of 3D radius of curvature calculations and IMU data integration within the framework is primarily used to flag scenarios where screening-level analysis is inadequate. However, a natural extension of this work involves integrating IMU-reported pipe curvature with caliper-reported dent geometry to render the true 3D shape of a dent on a curved pipe. This advancement would enable the development of screening-level strain and fatigue assessment methods tailored specifically to non-straight pipeline configurations, significantly improving the applicability and robustness of the framework.

Depth and Shape Scaling

The dent formation process described in API RP 1183 outlines the mechanical stages that a pipeline undergoes when subjected to external forces. Dents form as the result of elastic and plastic deformation, with subsequent changes influenced by the removal of the indenting object and internal pressure cycles. These stages include initial elastic ovalization, plastic deformation as the indenter force increases, and shape adjustments following indenter removal due to elastic spring-back and pressure-driven re-rounding. The final dent geometry is therefore a combination of elastic recovery and residual plastic deformation. For unrestrained dents, this post-indentation re-rounding significantly reduces the apparent depth of the dent, making it critical to adjust the reported depth to better reflect the as-formed geometry for accurate strain and fatigue assessments.

As noted in the 2022 study on the implementation API RP 1183 [14], unrestrained dents reported by in-line inspection (ILI) tools typically represent the dent geometry after re-rounding under pressure. Using these dimensions directly can lead to inaccuracies, particularly in strain assessments, since the plastic strain accumulates significantly toward the end of the indentation process. To address this, depth scaling is employed to approximate the original as-formed dent depth and geometry, thereby improving the accuracy of strain and fatigue life calculations. Current best practices recommend scaling factors to be determined through finite element analysis (FEA) and experimental validation [14].

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To ensure appropriate adjustments to dent profiles, a scaling function is integrated into the analysis framework. This function adjusts the deformation profile systematically while preserving its original shape characteristics. The process begins by centering the deformation profile around its mean, which is achieved by subtracting the average deformation from all data points. This ensures accurate scaling relative to the baseline shape. A scaling factor is then applied, which can be determined adaptively through optimization or directly based on the ratio of the required depth to the current feature depth. Adaptive optimization minimizes errors between the scaled depth and the required depth. In addition to depth scaling, the axial positions of the dent profile are adjusted proportionally while keeping the deepest point fixed. This ensures that the relative distribution of the dent's axial profile remains intact during scaling. Circumferential positions are scaled using a cumulative distribution function (CDF) approach, which adjusts the angle distribution symmetrically around the deepest point and preserves the dent's circumferential characteristics.

The scaled profiles are reconstructed by adding back the mean deformation, resulting in an adjusted profile that reflects the required depth and maintains geometric consistency. A typical output from this reconstruction is illustrated in Figure 5.

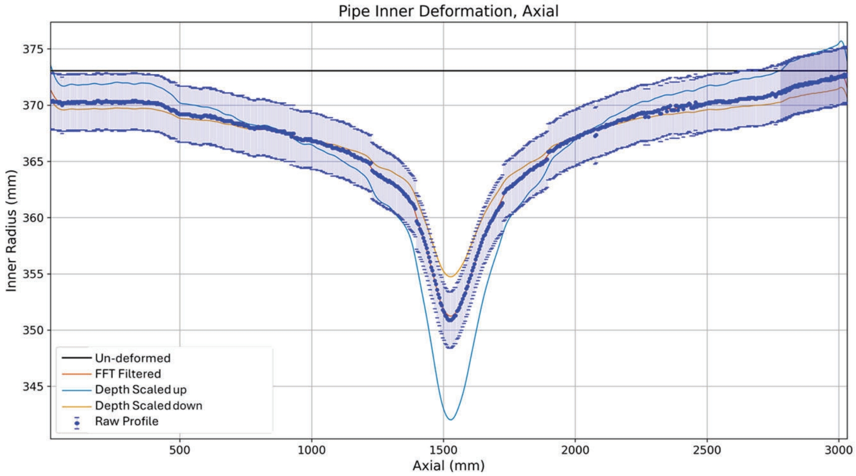

Figure 5. Result of depth and shape scaling shown on the longitudinal cross-section of a dent.

These adjustments enable accurate computation of critical parameters, including the strain components. Additionally, the framework allows for combined depth, axial, and circumferential scaling to simulate variations in dent profiles, supporting probabilistic analyses and optimization of repair strategies. By automating depth and shape scaling, the framework minimizes manual intervention, ensures consistency across assessments, and provides a reliable basis for advanced strain and fatigue calculations. This approach aligns with API RP 1183's emphasis on accurate dent geometry characterization, addressing key limitations in assessing unrestrained dents.

Strain Assessment

Strain in dents provides a quantifiable measure of deformation that is essential for assessing dent severity. Failure mechanisms associated with high strain, such as cracking, underscore the importance of accurate strain assessment in ensuring the safety and reliability of pipelines. Proper strain evaluation allows for the classification of dent severity and the identification of potential areas for immediate intervention.

API RP 1183 provides detailed guidance on strain evaluation in dents, particularly in Section 7.2, which outlines methodologies for estimating strain during indentation. According to API RP 1183, the shape of the dent can infer the dent formation strain, which is crucial for evaluating the potential for crack initiation during indentation. Strain estimation relies on data from in-line inspection (ILI) tools or direct measurement of dent deformation contours. Interpolation or other mathematical techniques can be used to develop surface contour information, which is then used to calculate radii of curvature in longitudinal and circumferential directions. These radii are critical for estimating strain components such as bending strain and membrane strain. The recommended equations for calculating these strain components, based on ASME B31.8 Appendix R, account for bending in both longitudinal and circumferential directions as well as membrane strain in the longitudinal direction [3].

Key strain components include longitudinal bending strain, circumferential bending strain, and longitudinal membrane strain, each calculated using specific geometric parameters such as dent depth, longitudinal length, and radii of curvature in the longitudinal and circumferential directions. Combined strain on the pipe’s inside and outside surfaces is determined by integrating these components. API RP 1183 also highlights advanced techniques, such as finite element analysis (FEA) and the Ductile Failure Damage Indicator (DFDI) [20], and Strain Limit Damage (SLD) [21] for cases requiring detailed material property integration.

A significant aspect of strain assessment is the proper estimation of radii of curvature in the longitudinal and circumferential directions, which directly impacts the accuracy of bending strain calculations. Furthermore, the definition of dent length for longitudinal membrane strain calculation remains ambiguous in current standards, leading to variability in assessment results. This ambiguity stems from the lack of consensus on how and at what depth the dent length should be measured, necessitating a more systematic approach.

Measurement uncertainties further complicate strain assessments. Unlike cracks or corrosion, where assuming greater depths (e.g., reported depth plus tool tolerance) ensures conservatism, such an approach does not work for dents. Accurate strain demand calculations must consider the full three-dimensional shape of the dent, including its sharpness in all directions and variations due to measurement uncertainty. Probabilistic assessments address these challenges by quantifying the distribution of strain demand, enabling operators to estimate the probability of strain demand exceeding strain capacity.

The proposed framework addresses these limitations through innovative methodologies for dent length calculation and uncertainty quantification. Dent length is calculated using an adaptive approach calibrated to Level 3 FEA results. This approach defines dent length as a function of pipe dimensions, dent depth, and restraint conditions. For restrained dents, length is calculated at depths varying between 50% and 95% of the maximum depth, while for unrestrained dents, depths between 75% and 95% are used. For asymmetric dents, the length is conservatively defined as twice the sharper side's length rather than the total length, ensuring robustness in strain calculations [14,16].

The framework also incorporates the improved strain estimation methods described in PRCI's report "Improve Dent/Cracking Assessment Methods" (PR-214-203806) [5]. These modifications address key limitations in ASME B31.8's strain equations by introducing improved axial membrane and circumferential membrane strain formulations. The updated equations provide a more accurate representation of indentation strains, especially for unrestrained dents, and align closely with FEA predictions. Users of the framework have the flexibility to select between these updated methods and traditional approaches or use both for comparative analyses, ensuring adaptability to various operational or regulatory needs.

To address measurement uncertainty, the framework employs a probabilistic Monte Carlo simulation approach. This method generates a million profiles for every dent by incorporating ILI tool tolerances (Figure 6(a)). Simulated profiles are analyzed to produce a strain demand distribution, enabling operators to estimate probabilities of strain demand exceeding strain capacity (Figure 6(b)). This process ensures that both deterministic results (e.g., mean strain demand or 95th percentile strain demand) and probabilistic outputs (probability of strain demand exceeding strain capacity) are available for integrity decision-making.

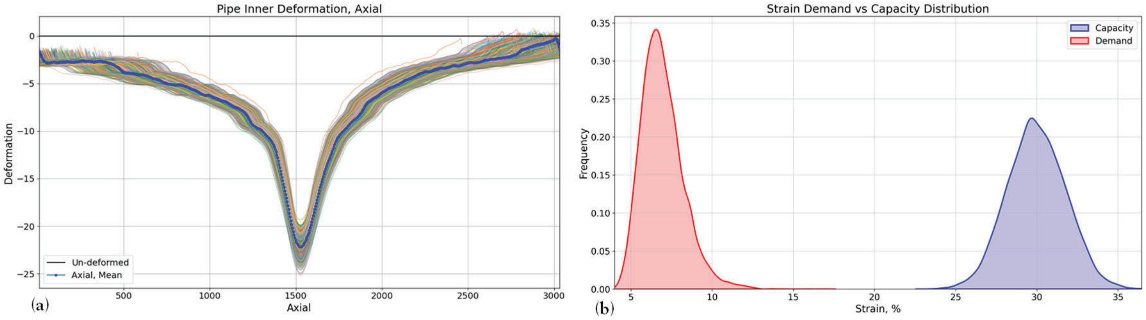

Figure 6. (a) Randomly generated dent profiles using Monte Carlo simulation to model measurement uncertainty, (b) Strain demand and capacity distributions to estimate the probability of exceedance

By integrating advanced methods for strain estimation, improved computational approaches, and probabilistic analyses, the framework significantly enhances the accuracy and reliability of strain assessments. This integration not only addresses existing limitations in industry practices but also

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aligns with the latest research, equipping operators with robust tools to evaluate and mitigate dent-related risks. Representing a substantial improvement over traditional methods, this approach tackles key challenges in strain evaluation while ensuring compliance with evolving industry standards.

Fatigue Assessment

Fatigue assessment is essential for evaluating the long-term integrity of dented pipelines under pressure cycling. The methodologies outlined in API RP 1183 provide a framework, ranging from simplified screening methods to detailed finite element analysis (FEA). These approaches allow for a graduated assessment, balancing conservatism and computational effort based on the complexity of the dent geometry and the availability of data.

The screening-level fatigue assessment methods rely on empirical models and geometric parameters derived from experimental and numerical studies. These methods are particularly effective for simple dent geometries, such as single-peak plain dents, and are commonly used for initial evaluations due to their rapid implementation. Screening-level equations use normalized dent depth, operational pressure ranges, and geometric characteristics to estimate fatigue life. However, these methods are inherently conservative, and their accuracy diminishes for complex dent geometries or interacting features, such as welds or gouges.

Detailed fatigue assessment methods, in contrast, incorporate advanced parameters like stress magnification factors (SMFs) and operational pressure spectra to refine fatigue life predictions. These methods include shape-parameter models and EPRG-based calculations. The application of these methods is often constrained by their limited applicability to certain dent types, as highlighted in API RP 1183. Both screening and detailed methods face limitations in addressing highly irregular dent profiles, making it challenging to ensure reliable predictions across all scenarios.

To overcome these challenges, the framework integrates advanced Finite Element Modeling (FEM) Screening, which has proven to be the most feasible and effective solution for a broad range of dent geometries. Although categorized as a screening method within API 1183, FEM Screening has been significantly enhanced within this framework through methodological innovations, elevating its accuracy to a level comparable to detailed level 3 FEA. This approach allows for a more precise evaluation of stress and fatigue behavior for both restrained and un-restrained dents, where traditional methods often fall short.

The general approach begins with converting the ILI-reported dent profile into a finite element mesh. The QA/QC and filtering modules in earlier stages of the framework ensure that the processed profile data is optimized for meshing. Using 8-node quadrilateral solid elements, the dent geometry is discretized with six elements through the thickness to capture stress responses accurately. A fine mesh zone with a 3-mm resolution encompasses the dented region, transitioning to coarser meshes away from the area to reduce computational demand. The algorithm automatically fits a surface to

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the ILI point cloud, generates a multi-layer solid element mesh by offsetting nodes, and maintains node ordering and connectivity to suit the specific FEA solver. Material properties are assigned based on the restraint condition, and internal pressure is applied to determine the dent's stress response.

Screening level FEA method for un-restrained dents

For un-restrained dents, the FEM Screening approach leverages the understanding that such dents typically experience shakedown to elastic behavior under low cyclic stress ranges. The framework estimates the zero-pressure dent shape by scaling the ILI-reported geometry (previously discussed in the depth and shape scaling section), which corresponds to the pressure at the time of inspection. Linear elastic material properties are then assigned to the modified geometry, and internal pressure is applied in the FEA model to evaluate the stress response. This methodology has demonstrated excellent alignment between screening-level FEA results and detailed Level 3 FEA outputs, ensuring reliable predictions while maintaining computational efficiency. The plot below compares the stress outputs of over 300 unrestrained dents reported by ILI, analysed using screening-level FEA and Level 3 detailed non-linear FEA.

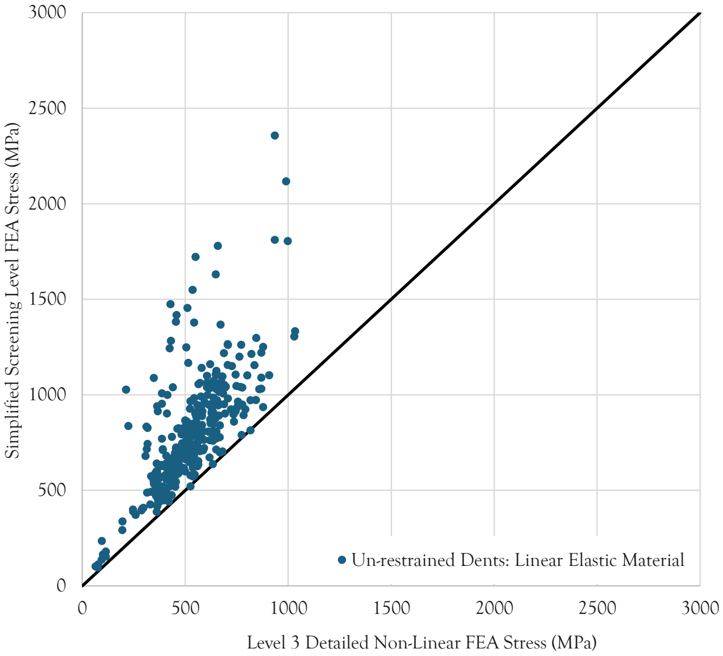

Figure 7. Comparison of FEA stress output of un-restrained dents modelled using the screening level and the level 3 detailed non-linear FEA methods.

Screening level FEA method for restrained dents

Restrained dents exhibit complex stress behaviors influenced by their interaction with external constraints, such as an indenter or surrounding supports. In traditional screening-level FEA, these dents are modeled with linear elastic material properties, leading to highly conservative stress estimates (Figure 11(a)). This conservatism stems from three primary factors: the pronounced

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geometric discontinuity, the assumption of purely elastic behaviour, and the omission of constraints and residual stresses generated during the indentation process. To account for this limitation, the use of non-linear isotropic hardening material in the screening level FEA models for specific applications has been previously explored. This method has proven to be effective in lowering stress values to more realistic ranges that align better with Level 3 FEA stress results. However, this approach still does not account for the accumulation of plastic strain energy and subsequent residual stresses during dent formation and their effect on the stress cycle during the application of pressure cycle, and its conservatism has been observed to be inconsistent.

Incorporating indentation induced plastic strain or residual stresses in a screening level FEA is extremely challenging. To tackle this problem, an innovative approach has been developed that achieves a reasonable alignment between the screening level and detailed level 3 FEA stress results for restrained dents.

The actual stress response of a restrained dent subjected to pressure cycling is dependent on the location and extent of the plastic strain accumulated during the dent formation process. From a detailed level 3 FE analysis, the typical stress strain response at the location of maximum principal stress range of a restrained dent is shown schematically in Figure 8. From this figure, we observe that the stress and strain at the critical location increase during the indentation stage and stabilize at the end. Permanent deformation due to plastic strain accumulation occurred at the end of this step. In the next step, the application of internal pressure introduces additional plastic strain, and the strain and stress increase further. In the last step, the internal pressure is reduced to zero and the stress response becomes elastic. However, the effect of permanent deformation is evident from the stresses going to compression. Subsequent application of pressure load results in linear elastic behavior where the stress cycles between compression and tension.

The solid black line in Figure 8 represents the stress-strain path during the application of indentation load. The area under this curve represents the work done during indentation, or “Indentation Energy”. The dotted line is the stress-strain path during the application of pressure load following indentation. Similarly, the area under this curve is the work done during pressurization, or “Pressurization Energy”. The final state of stress and strain (linear response due to pressure cycling) is dependent on the total work done or the total energy absorbed due to indentation and pressure.

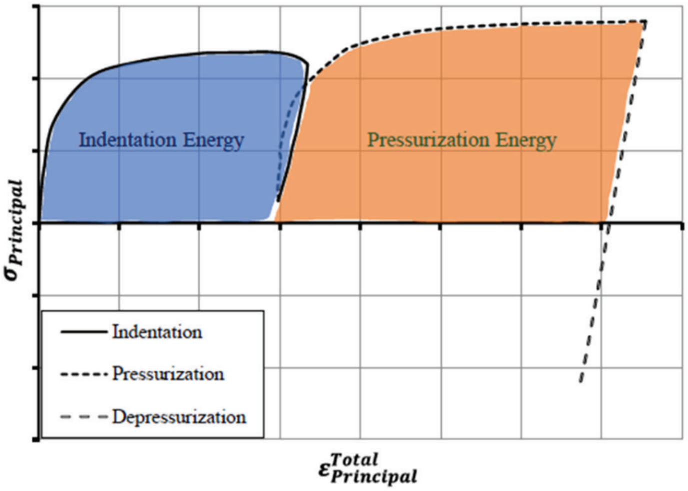

Figure 8. Evolution of stress and strain at the critical location in a dent through its stages of formation and loading (using level 3 detailed FEA with non-linear isotropic hardening material)

It should be noted that the location of maximum stress range in an actual restrained dent is typically at the shoulder, as has been verified by many full-scale tests and NDE reports. The detailed FEA model used in the level 3 analysis can capture this behaviour. The total principal strain shown in Figure 8 comprises of elastic and plastic strain components. The plastic component of the total strain is maximum at the dent apex and reduces towards the dent shoulders. Therefore, the plastic component at the location of maximum stress range is typically significantly lower than the maximum plastic strain at the apex of the dent.

By contrast, the stress-strain response of a restrained dent using non-linear material properties in the screening level FEA model is not capable of capturing the evolution and effects of permanent deformation, as shown schematically in Figure 9 below. Only one load step is used in this approach, where internal pressure is applied to the deformed configuration of the dented pipe model. The stress strain path shown in solid black corresponds to application of pressure load, and the dotted black line corresponds to depressurization. The stress response becomes elastic after the application of maximum operating pressure at a lower strain level compared to detail FEA and does not go into compression due to ignoring the effects of the permanent deformation. The final state of stress and strain (linear response due to pressure cycling) is dependent on the work done or the energy absorbed due to pressurization only. Since the energy required during dent formation process is not captured in this modeling technique, this approach often leads to non-conservative stress results.

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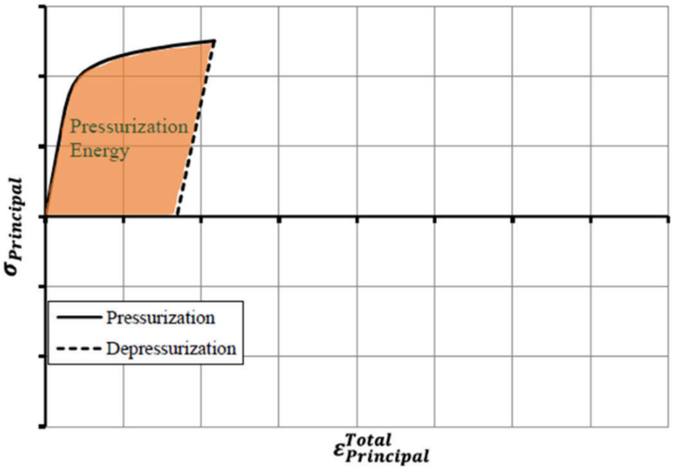

Figure 9. Evolution of stress and strain at the critical location in a restrained dent due to application of pressure load (using screening level FEA non-linear isotropic hardening material)

The only useful information regarding dent formation that can be extracted from the ILI reported shape and measurement is the equivalent plastic strain of the dent using the analytical strain equations as discussed in the strain analysis section. Therefore, the effects of dent formation can be approximately incorporated by estimating the equivalent plastic strain and calculating the energy required to produce that strain value as shown in Figure 10 (Indentation Energy = area under the non-linear stress-strain curve up-to the strain value obtained using dent strain equations).

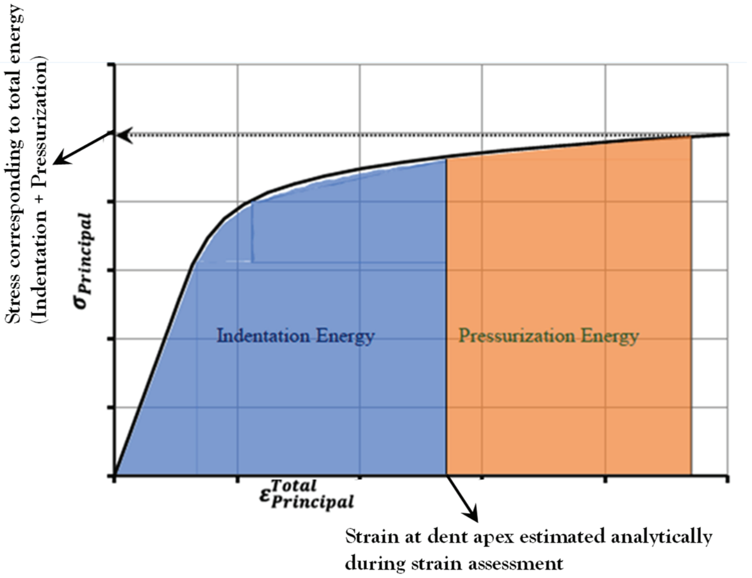

Figure 10. Estimation of stress response considering indentation and pressurization energies in the screening level FEA

This Indentation Energy, when added to the Pressurization Energy estimated from the screening level FEA model (incorporating non-linear isotropic hardening material and only pressure load – Figure 9) is expected to provide a reasonable approximation of the total energy of the dent due to both formation and pressure load. The stress value on the non-linear stress-strain curve corresponding to the estimated total energy is generally a conservative approximation of the stress value of the dent at maximum operating pressure. Using the above-mentioned technique, a good alignment between screening level and detailed level 3 stress results were achieved as shown in Figure 11 (b) below. Close to 200 restrained dents were modelled using screening level FEA and level 3 FEA to validate this methodology.

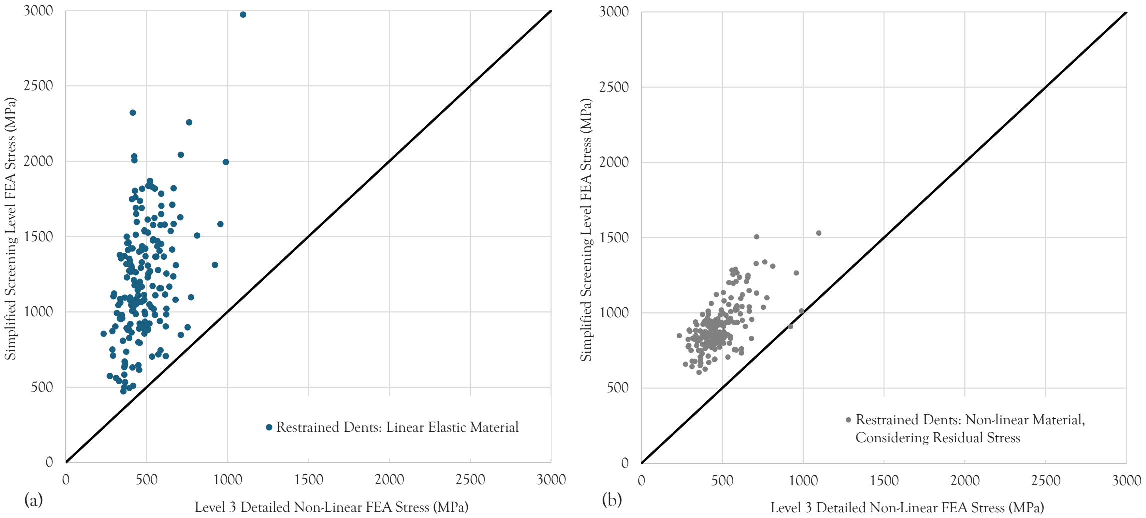

Figure 11. Comparison of FEA stress outputs for restrained dents: (a) screening-level analysis using linear elastic material vs. Level 3 detailed non-linear FEA, and (b) screening-level analysis using non-linear isotropic hardening material vs. Level 3 detailed non-linear FEA.

By incorporating non-linear material properties in the screening-level FEA for restrained dents combined with the effects of indentation strain, the framework significantly reduces the overestimation of stress levels typically associated with linear elastic models (Figure 11 (a)). This approach reduces the conservatism inherent in linear elastic models while maintaining computational efficiency compared to full Level 3 FEA. This balance of accuracy and efficiency makes the approach highly effective for evaluating restrained dents while addressing the limitations of traditional screening methods.

Advanced pressure cycling technique

To further enhance the fatigue assessment module, the framework incorporates an advanced pressure scaling technique outlined in API 1176, offering significant improvements over traditional methods of handling pressure cycling data [22]. SCADA pressure data, a key input for fatigue analysis, is automatically extracted and processed using specialized algorithms. This workflow begins by retrieving high-resolution, time-stamped pressure data from SCADA systems, which is then synchronized with specific pipeline locations using geographic and operational information.

Unlike conventional methods that rely on linearly scaled rainflow data, the framework applies location-specific pressure scaling to account for variations in pipeline conditions, such as elevation changes and station configurations. This ensures that the pressure data used in the analysis reflects the actual pressure loads experienced by each dented location of the pipeline. The scaled pressure data is then subjected to a rainflow counting algorithm, which decomposes the complex pressure histories into discrete cycles, identifying the amplitude and mean pressure of each cycle. This approach provides a more accurate and less conservative representation of pressure cycling conditions compared to traditional scaling techniques.

Implementation of the Framework

Case study 1

Following a Caliper ILI tool run, the ILI vendor identified over 1500 dent features. Among these, 84% of the reported dents were located on the bottom side of the pipeline, and 16% were on the top side. The dent depths varied from a minimum of 0.5% of the outer diameter (OD) to a maximum of 5.1% OD.

Adhering to the framework's general process flow, all necessary data were first collected through an automated data retrieval system and then processed. Probabilistic fatigue assessments to evaluate the likelihood of fatigue damage exceeding critical thresholds before the next scheduled inspection was conducted. The probabilistic assessments results were then integrated with location-specific environmental consequence data to calculate the overall risk associated with each dent feature. Based on the risk rankings, 2% of the dents were flagged for further risk verification out of the total count of reported features.

The risk-based prioritization guided integrity decision-making, with selected features assigned for excavation and remediation, while others were designated for more detailed Level 3 FEA analysis. This comprehensive screening and prioritization process was completed within a month, demonstrating the framework's efficiency in managing complex integrity assessments across large datasets while maintaining rigorous safety and reliability standards.

Case study 2

A second pipeline segment was inspected using an ILI caliper tool as part of a routine integrity assessment program. Upon completion of the full integrity evaluation, a specific dent feature was identified with cracking located at its circumferential shoulder. Investigation revealed that this dent had formed due to the pipe joint settling on a support structure. While the screening framework flagged this feature as injurious, the estimated risk values did not initially indicate its full severity, prompting a root cause analysis to better understand the failure mechanisms.

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During the root cause analysis, advanced techniques for 3D radius of curvature calculations and IMU data integration were employed. These methodologies revealed that the curvatures at the dent's circumferential shoulders were significantly higher than those at the apex, making strain estimates derived from apex-focused screening-level assessments inadequate. Furthermore, IMU data analysis indicated notable out-of-straightness in the pipe segment, suggesting that the caliper data alone did not capture the true dent shape. This discrepancy underscored the limitations of relying solely on caliper-based measurements for strain and fatigue assessments in such cases.

A Level 3 detailed finite element analysis (FEA) was subsequently conducted, incorporating the curved global shape of the pipe joint derived from IMU data. The detailed analysis demonstrated that maximum strain levels were concentrated at the circumferential shoulders of the dent, corroborating the findings from the curvature-based evaluation. Additionally, the stress ranges resulting from pressure cycling closely aligned with the locations of maximum strain, further confirming the criticality of these regions. Figure 12 below shows the stress and strain outputs from level 3 detailed FEA analysis of the feature.

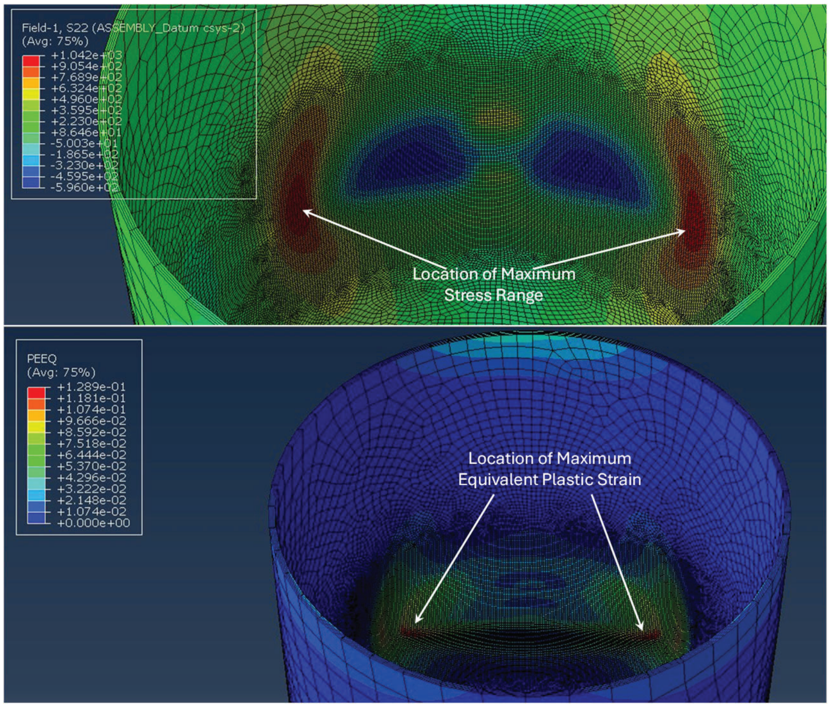

Figure 12. Maximum stress range and equivalent plastic strain locations identified through Level 3 FEA

A strain limit damage analysis performed as part of the detailed assessment revealed a high likelihood of cracking at the circumferential shoulder. This prediction closely matched the actual crack locations observed during excavation and non-destructive examination (NDE). This case study highlights the importance of incorporating advanced analytical techniques such as 3D curvature analysis and IMU data integration to address complex dent features, ensuring a more accurate representation of strain and stress distributions and enhancing the reliability of integrity management decisions.

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Conclusion

This paper has introduced a comprehensive and innovative framework for pipeline dent integrity assessment, addressing critical limitations in existing methodologies. By leveraging advancements in data automation, QA/QC processes, and advanced analysis techniques, the framework integrates deterministic and probabilistic approaches to enhance the accuracy and reliability of dent severity evaluations. Key technical contributions include the integration of advanced strain and fatigue assessment methods, such as the adoption of non-linear material properties and improved pressure scaling techniques, ensuring robust evaluations across a diverse range of dent geometries and operational conditions. Additionally, the incorporation of advanced radius of curvature calculations and IMU data integration enables the identification of high-strain regions beyond the dent apex and addresses scenarios involving non-straight pipeline geometries.

The framework's modular design and automated workflows streamline the assessment process, providing scalable solutions for both routine and complex evaluations. Case studies demonstrate its capability to accurately predict failure-critical conditions and guide risk-informed integrity decisions, underscoring its practical value in real-world pipeline operations. These advancements significantly improve the fidelity of integrity assessments while maintaining computational efficiency, bridging the gap between traditional screening methods and resource-intensive detailed analyses.

Future development opportunities include incorporating the true 3D shape of dents on curved pipe sections by integrating caliper data with IMU-derived pipe axis profiles, conducting parametric studies to determine variable depth scaling of unrestrained dents based on geometry and operating conditions, and improving the incorporation of measurement uncertainties through ongoing PRCI research. These enhancements will enable more accurate strain and fatigue assessments, thereby further extending the framework's applicability and reliability.

In conclusion, the framework represents a transformative advancement in the management of pipeline dents, enhancing both safety and operational efficiency while addressing persistent challenges in the industry. Its adaptability and focus on continuous improvement position it as a valuable tool to ensure the long-term integrity of pipeline infrastructure.

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References

1. API RP 579-1/ASME FFS-1, Fitness-for-Service, American Petroleum Institute, 2007.
2. PR-214-223806-R01, "Guidance for Performing Engineering Critical Assessments for Dents on Natural Gas Pipelines," PRCI, 2023.
3. ASME B31.8, Gas Transmission and Distribution Piping Systems, American Society of Mechanical Engineers, 2020.
4. CSA Z662, Oil and Gas Pipeline Systems, Canadian Standards Association, 2019.
5. PR-214-203806-R01, "Improve Dent/Cracking Assessment Methods," PRCI, 2024.
6. API RP 1183, Assessment of Pipeline Dents, American Petroleum Institute, 2020.
7. Tang, H., Sun, J., & Di Blasi, M. (2022, September). Machine Learning-Based Severity Assessment of Pipeline Dents. In *International Pipeline Conference* (Vol. 86564, p. V001T07A019). American Society of Mechanical Engineers.
8. Dotson, R. L., Ginten, M., Alexander, C., Bedoya, J. J., & Schroeer, K. (2014). Combining high-resolution in-line geometry tools and finite-element analysis to improve dent assessments. *Journal of Pipeline Engineering*, *13*(2).
9. PR-214-203806, "Improve Dent/Cracking Assessment Methods," Pipeline Research Council International, 2024.
10. Leis, B., Eshraghi, A., Dew, B., & Cheng, F. (2023). Dent strain and stress analyses and implications concerning API RP 1183-Part I: Background for dent geometry and strain analyses during contact and re-rounding. *Journal of Pipeline Science and Engineering*, *3*(3), 100143.
11. Leis, B., Eshraghi, A., Dew, B., & Cheng, F. (2024). Dent strain and stress analyses and implications concerning API RP 1183-Part II: Examples of dent geometry and strain analyses during contact and re-rounding. *Journal of Pipeline Science and Engineering*, *4*(1),
12. Zhu, X. K. (2023). A verification study of fatigue-based methods in API RP 1183 for estimating fatigue life of pipeline dents. *International Journal of Pressure Vessels and Piping*, *205*, 104969.
13. Hassanien, S., Kainat, M., Adeeb, S., & Langer, D. (2016, September). On the use of surrogate models in reliability-based analysis of dented pipes. In *International Pipeline Conference* (Vol. 50266, p. V002T07A018). American Society of Mechanical Engineers.
14. Kainat, M., Virk, A., Yoosef-Ghodsi, N., & Bott, S. (2022, September). Implementation of API 1183 Recommended Practice for Reliability-Based Assessment of Dents in Liquid Pipelines. In *International Pipeline Conference* (Vol. 86571, p. V002T03A013). American Society of Mechanical Engineers.

https://doi.org/10.52202/078572-0094

15. Ergezinger, N., Virk, A., Woo, J., Kainat, M., Adeeb, S., "Application of Noise Filtering Techniques for the Quantification of Uncertainty in Dent Strain Calculations," Proceedings of the 13th International Pipeline Conference, IPC2020-9580.
16. Virk, A., Langer, D., Woo, J., Kainat, M., "Improved Semi-Quantitative Reliability-Based Method for Assessment of Pipeline Dents with Stress Risers," Proceedings of the 13th International Pipeline Conference, IPC2020-9472.
17. Okoloekwe, C., Aranas, N., Kainat, M., Langer, D., Hassanien, S., Roger Cheng, J. J., & Adeeb, S. (2018). Improvements to the ASME B31. 8 dent strain equations. *Journal of Pressure Vessel Technology*, *140*(4), 041101.
18. Okoloekwe, C., Kainat, M., Langer, D., Hassanien, S., Roger Cheng, J. J., & Adeeb, S. (2018). Three-Dimensional Strain-Based Model for the Severity Characterization of Dented Pipelines. *Journal of Nondestructive Evaluation, Diagnostics and Prognostics of Engineering Systems*, *1*(3), 031006-031006.
19. Cousart, K., & Holliday, C. (2022, September). A Study on the Conservatism of the Dent Screening Criteria in the Canadian Standards Association (CSA) Z662: 19 Oil and Gas Pipeline Systems Standard. In *International Pipeline Conference* (Vol. 86571, p. V002T03A042). American Society of Mechanical Engineers.
20. Arumugam, U., Gao, M., Krishnamurthy, R., Wang, R., & Kania, R. (2016, September). Study of a plastic strain limit damage criterion for pipeline mechanical damage using FEA and full-scale denting tests. In *International Pipeline Conference* (Vol. 50251, p. V001T03A034). American Society of Mechanical Engineers.
21. American Society of Mechanical Engineers. (2023). *BPVC Section VIII: Rules for construction of pressure vessels, Division 3: Alternative rules for construction of high-pressure vessels*. ASME.
22. American Petroleum Institute, API RP 1176, Recommended Practice for Assessment and Management of Cracking in Pipelines, API, Errata 1, February 2021.