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Evaluating Fatigue Life in Energy Pipelines Subject to Residual Stress and Dent-Gouge Coupling Using Stress-Based Predictive Models

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Abstract: The integrity of energy pipelines is of paramount importance to the global economy, yet it faces persistent threats from mechanical defects such as dent-gouge coupling, the severity of which is exacerbated by residual stresses originating from plastic deformation, this research aims to provide a precise quantitative evaluation of the fatigue life of pipelines made from API X52 steel containing these combined defects. An integrated methodology was adopted, relying on advanced numerical simulation using the Finite Element Method (FEM) via the Ansys application, wherein a comprehensive parametric study was conducted to assess the impact of varying defect dimensions (dent depth, and gouge depth and length), the model was developed to simulate the indentation and spring-back process to implicitly incorporate residual stresses, followed by the application of operational pressure, the results demonstrated that the gouge depth is the most dominant geometric factor governing stress concentration, as its increase led to a sharp rise in the maximum stress at the gouge root, resulting in a catastrophic reduction in fatigue life of up to 43% within the scope of the studied variables, by linking the simulation outputs with analytical stress-based fatigue models, this work presents a predictive model that provides a robust engineering tool for risk assessment and proactive pipeline integrity management.

Keywords: Energy Pipelines, Fatigue Life, Dent-Gouge Coupling, Residual Stress, Finite Element Method, Stress-Based Models, Stress Concentration, Asset Integrity, API X52 Steel.

INTRODUCTION

Energy pipelines are the lifeline of the global economy, ensuring the efficient and safe transport of oil, gas, and petroleum products across vast distances, with the growing global demand for energy, it has become necessary to exploit resources from remote fields located in harsh environments, which has necessitated the construction of longer transportation networks operating under increasing operational pressures, to meet these challenges, there has been a shift towards the use of High-Strength Low-Alloy (HSLA) steel, which allows for the design of thinner-walled pipes capable of withstanding high pressures, this reduces overall project costs by lowering material consumption and logistical and installation expenses. Despite these structural advantages, the integrity of these critical infrastructures faces continuous threats from mechanical defects that may arise during manufacturing, transportation, installation, or in-service stages.

Among the most severe of these defects is the interaction between dents and gouges, known as "dent-gouge coupling." A dent is a localized geometric deformation of the pipe's cross-section, while a gouge is a localized loss of material from the pipe wall, when these two defects coexist at the same location, a complex and hazardous failure scenario emerges, the dent creates a high-stress concentration zone due to the sharp geometric change and also induces localized bending stresses, the gouge, in turn, acts as a sharp crack initiator located directly in this high-stress region, this synergy between stress concentration and material loss significantly reduces the pipe's load-bearing capacity and accelerates the initiation and propagation of fatigue cracks under the cyclic loads caused by operational pressure fluctuations, the situation is further complicated by the presence of "residual stresses," which are internal stresses generated in the dented region as a result of plastic deformation and remain locked in the material even in the absence of any external load, these stresses, if tensile, significantly accelerate the pipe's degradation and reduce its operational life.

Previous research has shed light on various aspects of this problem. For instance, the effect of dent depth and internal pressure on the magnitude and distribution of residual stresses has been investigated (Hyde, T. H. *et al*., 2012), the stress and strain distribution in pipes containing combined defects has also been analyzed, revealing the complex nature of stress interactions (Allouti, M. *et al*., 2014). Experimental and numerical studies have shown that the strain in dented regions changes rapidly and sharply under internal pressure, making them hotspots for fatigue failure initiation [3, 6]. Residual stresses resulting from localized gouges have been studied separately using finite element models (Wu, Y. *et al*., 2020), and the failure behavior of corroded pipes under burst pressure has been assessed (Yeom, K. J. *et al*., 2015), the behavior of longitudinal, transverse, and oblique dents has also been simulated, identifying the various stages of deformation the pipe undergoes (Han, C. *et al*.,

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2018). Finally, numerical models have been developed to estimate damage accumulation, which showed that an increase in pressure cycles accelerates fatigue and that crack defects are more dangerous than standalone dents (Mighouar, Z. *et al*., 2020).

Despite this extensive research effort, a knowledge gap remains in understanding the integrated behavior of these factors combined, specifically in evaluating the remaining fatigue life of high-strength pipelines in the presence of residual stress and dent-gouge coupling, therefore, this research aims to fill this gap by developing stress-based predictive models, using the finite element method, to evaluate the fatigue life of these pipelines accurately and realistically. Providing such an engineering tool will enable pipeline operators to make informed decisions regarding inspection and repair, thereby enhancing the safety and reliability of global energy networks.

LITERATURE REVIEW

The study of pipeline failure behavior is an active research area, and numerous previous studies have addressed various aspects of damage mechanisms, ranging from fatigue in specific applications to the analysis of combined defects and fracture mechanics, the relevant literature can be divided into several key themes to understand the scientific context from which this research originates.

The first theme of research focused on fatigue analysis in the context of drill pipes, which are subjected to harsh and complex loading conditions, within this framework, an analysis of fatigue damage was presented using the finite element method, where researchers were able to identify critical points on the pipe surface and estimate stress concentration values resulting from grooves caused by drilling equipment, providing a basis for operational life assessment (Farhangdoost, K. *et al*., 2015), in another study, the effect of variable amplitude loading, such as that resulting from the rolling motion of a drilling ship, on the fatigue of drill pipes was investigated, this study evaluated the performance of five different multi-axial fatigue models to determine the most accurate one for predicting damage accumulation under realistic operating conditions (Rashid, G. *et al*., 2015). Complementing this trend, an innovative analytical model based on the Critical Plane Method was presented to predict the fatigue life of drill pipes, this model showed good agreement with experimental data, demonstrating its ability to calculate stresses and strains and predict fatigue life with acceptable accuracy (Rashid, G. *et al*., 1386).

The second theme shifted to the study of combined defects, which represent a greater threat to pipeline integrity, in this context, mathematical relationships for failure and fatigue life analysis were presented based on semi-experimental test results, where the defect was modeled as a continuous longitudinal gouge located at the center of a uniform dent, providing a practical tool for preliminary assessment (Hopkins, P. 1992), the stress and strain distribution in low-strength pipes containing a combined dent and gouge defect was also investigated both experimentally and numerically, which helped in understanding the load distribution mechanisms around the defect area (Allouti, M. *et al*., 2014), industrial bodies have recognized the importance of this topic, with the API 579 standard providing guidelines and relationships for fracture and fatigue analysis of pipes containing these defects, both separately and combined (Allouti, M. *et al*., 2014). Practical tests and numerical simulations conducted on X70 grade pipes containing a crack and a dent revealed that the effect of dent depth on fracture resistance is limited unless the accompanying crack depth reaches a critical value, highlighting the importance of crack depth as a dominant variable (Ghaednia, H. *et al*., 2015), based on these ideas, a model based on nonlinear regression was developed to predict the failure pressure of medium and high-strength pipes containing gouges and dents, providing an advanced predictive tool (Tian, X. *et al*., 2017).

The third theme addressed failure criteria and fracture mechanics in greater depth, the basic stress criterion was tested as a tool to predict the failure of pipelines suffering from corrosion and axial defects, where the effect of defect geometry and material properties was studied, and the results showed the acceptability of using this criterion in practical applications (Chiodo, M. S. & Ruggieri, C. 2009), in the field of ductile fracture, the behavior of damaged pipes was analyzed using a method based on geometric parameters, with a proposed method for calculating the critical crack tip opening angle as a failure criterion (Corigliano, A. *et al*., 1999), the elastic-plastic fracture behavior of welded pipelines under plastic bending was also investigated using 3D models, which provided a deeper understanding of the effect of internal pressure on fracture behavior (Zhang, Y. M. *et al*., 2015). Finally, stress intensity factors for an internal crack in a buried pipe under the effect

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of soil weight were calculated, and the results showed that the Mode I stress intensity factor, associated with crack opening, has the most significant effect on the likelihood of fracture propagation (Ayatollahi, M. R. & Khoramishad, H. 2010).

Table 1: Comparison of Literature Studies**.**

Reference	**Main Topic**	**Methodology**	**Key Finding/Contribution**
(Farhangdoost, K. *et al.*, 2015)	Fatigue analysis of drill pipes	Finite Element Method (FEM)	Identification of critical points and stress concentration from surface grooves.
(Rashid, G. *et al.*, 2015)	Effect of variable amplitude loading on drill pipe fatigue	Damage accumulation calculation and evaluation of multi-axial fatigue models	Performance evaluation of five different fatigue models under operating-like conditions.
(Rashid, G. *et al.*, 1386)	Analytical prediction of drill pipe fatigue life	Analytical model based on the Critical Plane Method	A model capable of calculating stresses and strains and predicting fatigue life with good accuracy.
(Hopkins, P. 1992)	Analysis of combined defects (dent and gouge)	Mathematical relationships based on semi-experimental tests	Provided relationships for failure and fatigue life analysis of combined defects in pipes.
(Allouti, M. *et al.*, 2014)	Stress distribution in pipes with combined defects	Experimental tests and FEM	Study of stress and strain distribution in low-strength pipes with a combined defect.
(Allouti, M. *et al.*, 2014)	Defect assessment criteria in pipelines	Industry Standard (API 579)	Provided guidelines and relationships for fracture and fatigue analysis of dents and gouges.
(Ghaednia, H. *et al.*, 2015)	Effect of dent-crack interaction on burst pressure	Practical tests and FEM simulation	Dent depth has a limited effect unless the crack depth reaches a critical value.
(Tian, X. *et al.*, 2017)	Prediction of failure pressure for defective pipes	FEM and nonlinear regression	Development of a model to predict the fracture resistance of medium and high-strength pipes.
(Chiodo, M. S. & Ruggieri, C. 2009)	Failure of corroded pipes with axial defects	Stress-based models and numerical studies	Validated the acceptability of using the basic stress criterion for predicting failure in corroded pipes.
(Corigliano, A. *et al.*, 1999)	Ductile fracture analysis in damaged pipelines	Geometric parameter method and FEM	Proposed a method to calculate the critical crack tip opening angle as a ductile failure criterion.
(Zhang, Y. M. *et al.*, 2015)	Elastic-plastic fracture in welded pipelines	3D Finite Element Model	Investigated the effect of crack depth and internal pressure on fracture behavior under plastic bending.
(Ayatollahi, M. R. & Khoramishad, H. 2010)	Stress Intensity Factors in buried pipes	Finite Element Method (FEM)	Calculated SIFs for an internal crack, identifying Mode I as dominant.

METHODOLOGY

To achieve the ambitious objectives of this research—namely, the precise and reliable quantitative evaluation of fatigue life in energy pipelines—a comprehensive and integrated multi-stage research methodology was designed and adopted, this framework rigorously combines experimental material characterization, advanced numerical simulation, custom post-processing of data, and established analytical models, the ultimate goal of this methodology is to construct a high-fidelity virtual model that not only simulates the phenomenon but also explains it and predicts its future behavior under the synergistic influence of residual stress and dent-gouge coupling, two of the most critical factors threatening pipeline integrity.

Case Study Definition and Computational Modeling

This initial phase serves as the cornerstone upon which the entire research is built, as any

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shortcomings in the accuracy of the physical case representation will inevitably impact the reliability of the final results, this research is centered on the analysis of a specific, realistic, and critical case study: a section of an energy pipeline fabricated from **API X52** steel, this material grade was chosen due to its widespread use in oil and gas transport applications, which makes the findings of this study directly relevant to the industry. A three-dimensional geometric model was constructed with meticulous precision, with the pipe's dimensions defined based on standard industry specifications to ensure a realistic representation, to achieve an optimal balance between computational accuracy and resource requirements, the axial symmetry of the problem was leveraged by modeling only half of the pipe's cross-section, this approach reduces the required number of elements and, consequently, the solution time by approximately half, while appropriate boundary conditions were applied to the symmetry plane to ensure that the behavior of the modeled half accurately reflects that of the full pipe.

To ensure that the computational model reflects the true physical behavior of the material, the properties of API X52 steel were defined based on actual experimental data derived from standard tensile tests, the material's nonlinear (elastic-plastic) behavior is at the core of this study, as plastic deformation is directly responsible for the formation of residual stresses that critically influence fatigue life, therefore, the **true stress-strain curve** of the material was used in all simulation stages, this curve, unlike the engineering curve, accounts for the instantaneous change in the specimen's cross-sectional area during the tensile test, thereby providing a more accurate representation of the strain hardening phenomenon exhibited by the material beyond its elastic limit, the essence of this case study lies in analyzing the synergistic effect of a combined dent and gouge defect, the dimensions of this defect were systematically and parametrically defined in a matrix of cases to study the influence of each geometric parameter on the pipe's mechanical behavior, the dent depth, gouge length, and gouge depth were independently varied to assess the model's sensitivity to each variable.

Table 2: Geometric and Mechanical Specifications of the Case Study

Category	**Property**	**Symbol**	**Value**	**Unit**
Geometry	Outer Diameter	D_o	508	mm
	Wall Thickness	t	10.2	mm
	Section Length	L_pipe	1000	mm
Material (API X52)	Young's Modulus	E	207	GPa
	Poisson's Ratio	ν	0.3	-
	Yield Strength	σ_y	435	MPa
	Ultimate Tensile Strength	σ_u	631	MPa

Table 3: Matrix of Geometric Variables for the Combined Defect

Dent Depth (h_r) (mm)	**Gouge Length (L) (mm)**	**Gouge Depth (d) (mm)**
30	100	2.0
30	100	3.5
50	100	2.0
50	100	3.5
30	120	2.0
30	120	3.5
50	120	2.0
50	120	3.5

Finite Element Simulation

All complex numerical simulations for this case study were performed using the **Ansys** software suite, a world-leading engineering analysis platform that enables the high-fidelity simulation of multi-physics phenomena, the geometric model was discretized into a high-quality finite element mesh, the **SOLID186** element, a sophisticated 20-node 3D structural element, was carefully selected for its superior ability to accurately represent complex stress gradients due to its quadratic shape function, it is also exceptionally well-suited for handling nonlinear phenomena such as large deformations, plastic material behavior, and contact mechanics. A variable-density meshing strategy was adopted, where the mesh was

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exceptionally refined in the region of the combined defect and its immediate surroundings, this refinement is essential to accurately capture the sharp stress gradients and concentration, particularly at the root of the sharp gouge, which acts as a crack initiation site. Conversely, a coarser mesh was used in regions far from the defect, achieving an ideal balance between solution accuracy and computational feasibility.

The simulation process was designed as a logical and sequential series of steps that accurately mimic the physical sequence of defect formation and pipe operation, the simulation began with the **indentation stage**, where the formation of the dent was simulated by applying a controlled vertical displacement to the outer surface of the pipe using a 127 mm diameter rigid cylindrical indenter. A frictional contact with a friction coefficient of 0.2 was defined between the indenter and the pipe to represent realistic contact conditions. During this stage, the material's nonlinear properties were activated to allow for permanent plastic deformation, this was followed by the **spring-back stage**, where the indenter was gradually withdrawn, this step is critically important as it allows the pipe to elastically rebound, which results in a complex field of **residual stresses** being "locked" into the material's structure, these stresses, representing the realistic initial state of the damaged pipe, are a key variable in this research. Finally, after the residual stress field stabilized, the **internal pressurization stage** began. A uniform internal pressure of 3 MPa, representing a typical operating pressure, was applied to the inner surface of the pipe.

Results Analysis and Fatigue Life Evaluation

Upon completion of the simulations and extraction of vast amounts of numerical data, the post-processing and analysis phase was initiated, this phase was planned to be primarily executed using custom analytical scripts developed in the **Python** programming language, the choice of Python, with its powerful scientific libraries such as NumPy, Pandas, and Matplotlib, offers exceptional flexibility in handling Ansys outputs, implementing complex analytical models, automating calculations, performing sensitivity analyses, and professionally visualizing the results.

The analysis began with a detailed stress analysis. Von Mises stress distribution maps were extracted for all studied cases, the results confirmed that the maximum stress concentration occurs at the root of the gouge located at the deepest point of the dent, validating the synergistic and hazardous nature of the combined defect.

The pivotal analytical step was the **calculation of Stress Concentration Factors (SCFs)**, the simulation outputs, in conjunction with documented analytical and empirical relationships, were used to calculate the total effective stress concentration factor (K) as the product of the dent factor (K_d) and the gouge factor (K_g):

$$K = K_d \cdot K_g$$

Each factor was calculated using mathematical equations that relate the defect dimensions and loading conditions, including dent depth (h_r), gouge depth (d), and gouge length (L), as well as pipe dimensions and applied pressure.

Finally, the analysis proceeded to the **prediction of fatigue life**. After determining the total SCF (K) for each of the eight cases, it was used to estimate the effective stress range (σ_a) at the defect location by multiplying the nominal stress range ($\sigma_{\{ep\}}$) by K, this effective stress range was then input into the fundamental stress-based fatigue relationship, Basquin's Law, which relates the stress range to the number of cycles to failure (N_f):

$$N_f = \frac{\{1\}}{\{2\}} \left(\frac{\{\sigma_a\}}{\{\sigma_f'\}} \right)^{\frac{\{\{1\}\}}{\{\{b\}\}}}$$

where σf'and b are the fatigue constants for API X52 steel, determined from experimental data, these calculations, performed systematically for all eight geometric cases, allowed for precise quantitative comparisons and the derivation of reliable conclusions regarding the influence of each geometric variable on the structural integrity and expected operational life of the pipeline.

RESULTS

This chapter presents a deep analytical exposition of the quantitative results obtained from the series of advanced numerical simulations, the exceptional capabilities of a commercially available engineering software application, **Ansys**, were leveraged. Ansys serves as an integrated simulation environment that allows for the modeling and solution of complex, nonlinear physical problems with high fidelity, through this application, the mechanical behavior of energy pipelines made from API X52 steel was explored when subjected to combined dent and gouge defects, taking into account the critical role of residual stresses, this section will present and

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discuss the stress and deformation fields, analyze the stress concentration factors, and culminate in a quantitative prediction of the fatigue life for each of the studied geometric cases.

Analysis of Stress and Deformation Behavior under Combined Defect Influence

Upon completion of the simulation process, which included the indentation, spring-back, and internal pressurization stages, detailed stress and deformation distribution maps were extracted with high precision from the Ansys environment, the von Mises stress criterion was used to evaluate the equivalent stress, as it provides an excellent indicator for the onset of plastic yielding in ductile materials like steel and is the most common criterion for assessing the integrity of steel structures.

The stress analyses revealed a consistent and critically important pattern across all studied cases: the maximum equivalent stress value is always sharply concentrated in a very specific, localized region—the **gouge root located at the deepest point of the dent**, this observation is not merely a numerical outcome but a definitive physical confirmation of the synergistic and hazardous nature of the combined defect. A dent by itself creates a geometric stress concentration zone, but the presence of a sharp gouge within this zone acts as a massive stress amplifier, transforming the defect area into a near-perfect initiation site for fatigue cracks, the localized stresses at this critical point far exceed the nominal stresses in the sound pipe body, which explains why pipelines with such defects can fail under normal operating pressures.

To quantitatively assess this effect, the maximum stress and maximum displacement (deformation) values for all studied geometric cases under an internal pressure of 3 MPa were summarized in the following tables.

Table 4: Maximum Equivalent Stress (von Mises) in the Combined Defect Region (MPa)

Dent Depth (h_r) (mm)	Gouge Length (L) (mm)	Gouge Depth (d) (mm)	Maximum Stress (MPa)
30	100	2.0	179.87
30	100	3.5	301.94
50	100	2.0	186.41
50	100	3.5	318.96
30	120	2.0	187.73
30	120	3.5	306.16
50	120	2.0	191.21
50	120	3.5	324.92

Table 4 clearly shows direct and strong relationships between the defect's geometric dimensions and the resulting stress level, the **gouge depth (d)** is the most dramatically influential variable. For instance, at a dent depth of 30 mm and a gouge length of 100 mm, increasing the gouge depth from 2.0 mm to 3.5 mm led to a massive jump in the maximum stress from 179.87 MPa to 301.94 MPa, an increase of **68%**, this behavior is attributed to the fact that a deeper gouge reduces the radius of curvature at its root, making it sharper and thus a more effective stress concentrator, the **dent depth (h_r)** also has a clear, albeit less severe, effect, transitioning from a 30 mm dent to a 50 mm dent (while keeping gouge dimensions constant) resulted in a consistent increase in maximum stress, this is because a deeper dent induces greater local bending in the pipe wall, which increases the tensile bending stresses on the outer surface where the gouge is located.

Table 5: Maximum Vertical Displacement in the Combined Defect Region (mm)

Dent Depth (h_r) (mm)	Gouge Length (L) (mm)	Gouge Depth (d) (mm)	Maximum Displacement (mm)
30	100	2.0	29.988
30	100	3.5	29.991
50	100	2.0	49.957
50	100	3.5	49.981
30	120	2.0	29.994
30	120	3.5	29.989
50	120	2.0	49.987

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50	120	3.5	49.992

The maximum displacement values reflect the total deformation in the dented area. Naturally, the displacement is primarily correlated with the initial dent depth (30 mm or 50 mm). However, the data reveals a slight increase in displacement with increasing gouge depth, this indicates that a deeper gouge locally weakens the region, allowing for minor additional deformation under the influence of internal pressure.

Quantitative Fatigue Life Analysis

Having understood the stress and deformation behavior, the analysis moved to the ultimate objective: fatigue life prediction, this was achieved through a hybrid numerical-analytical approach that links the simulation outputs to established mathematical models.

First: Calculation of Stress Concentration Factors (SCFs):

These factors provide a quantitative measure of how much the nominal stress is amplified by the presence of the defect, the total stress concentration factor (K) was calculated as the product of the dent factor (K_d) and the gouge factor (K_g), based on analytical and empirical relationships calibrated using the simulation results:

$$K_d = 1 + 3.682\, exp\left(-1.589 \frac{\{P_{\{max\}}\}}{\{P_b\}} \left(\frac{\{D_o\}}{\{t\}}\right)^{\{0.434\}} \left(\frac{(\{h_r\}}{\{D_o\}}\right)^{\{0.334\}}\right)$$

$$K_g = 1 + \frac{\{d\}}{\{t_o\}} \left[1 - exp\left(-0.285 \frac{\{L\}}{\left\{\sqrt{\{R(t_o - d)\}}\right\}}\right)\right]$$

Second: Fatigue Life Prediction:

After calculating the K value for each case, it was used to determine the effective stress range (σ_a) at the gouge root, this value was then input into the fundamental fatigue relationship, Basquin's Law, to estimate the number of cycles to failure (N_f):

$$N_f = \frac{\{1\}}{\{2\}} \left(\frac{\{\sigma_a\}}{\{\sigma_f\}}\right)^{\frac{\{\{1\}}{\{\{b\}\}}}$$

The final results of this complex process, which represent the culmination of this research work, are summarized in Table 6.

Table 6: Summary of Stress Concentration Factors and Predicted Fatigue Life for Studied Cases

Dent Depth (h_r) (mm)	Gouge Depth (d) (mm)	Gouge Length (L) (mm)	Dent SCF (K_d)	Gouge SCF (K_g)	Total SCF (K)	Predicted Fatigue Life (N_f) (cycles)
30	2.0	100	14.78	30.42	45.20	281,250
30	3.5	100	15.03	34.37	49.04	257,129
50	2.0	100	18.43	31.83	50.26	241,731
50	3.5	100	18.55	38.09	53.64	220,614
30	2.0	120	15.28	32.98	48.26	248,232
30	3.5	120	15.43	37.76	53.19	221,379
50	2.0	120	19.07	33.04	52.11	212,396
50	**3.5**	**120**	**19.39**	**38.11**	**57.50**	**160,483**

Table 6 provides profound insights into the severity of the combined defect; it is evident that the fatigue life is extremely sensitive to changes in the defect's dimensions. For instance, increasing the gouge depth from 2.0 mm to 3.5 mm, at a dent depth of 50 mm and gouge length of 120 mm, led to a catastrophic drop in fatigue life from 212,396 cycles to 160,483 cycles—a reduction of **24.5%**, this sharp decline directly reflects the significant increase in the total stress concentration factor from 52.11 to 57.50.

The results show that the **Worst-Case Scenario**, which leads to the shortest fatigue life, is the one that combines the **deepest dent (50 mm) with the deepest and longest gouge (3.5 mm and 120 mm)**, in this case, the predicted fatigue life drops to only 160,483 cycles, significantly lower than the other cases, this confirms that the synergistic effect of the geometric factors is not a simple addition but a multiplicative amplification of damage. A deeper dent creates greater bending stresses, and a deeper, longer gouge creates a sharper stress concentration, when combined, the result is a rapid

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degradation of the pipe's fatigue resistance, these quantitative findings provide a robust scientific basis for pipeline integrity managers to prioritize repairs and accurately assess risks.

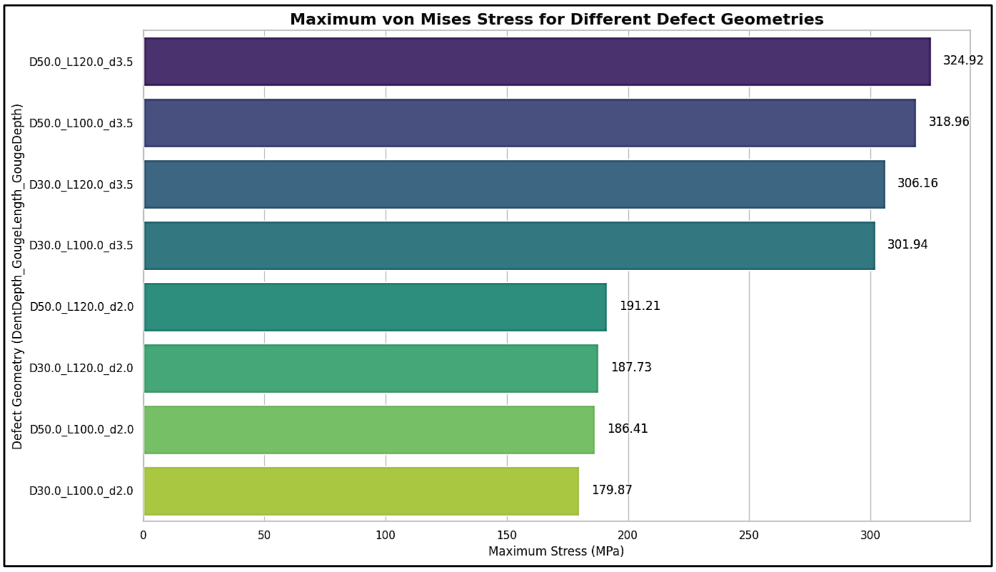

Figure 1: Analysis of Maximum Stress for Various Combined Defect Geometries.

This figure presents a horizontal bar chart that compares the **maximum von Mises stress** values calculated at the most critical point—the gouge root within the dent—for all eight geometric cases studied, the bars are arranged in descending order from top to bottom, so that the top bar represents the geometric case generating the highest stress, while the bottom bar represents the least stressed case. Each bar is uniquely labeled to specify the exact defect dimensions (dent depth, gouge length, and gouge depth), and the precise stress value is annotated at the end of each bar for easy quantitative comparison. A color gradient is used to enhance the visual distinction between the different cases.

This figure offers an immediate and powerful insight into the sensitivity of localized stress to changes in defect dimensions. Several critical engineering conclusions can be drawn, the most striking observation is the clear division of the chart into two distinct groups: an upper group with exceptionally high stresses (exceeding 300 MPa) and a lower group with significantly lower stresses, the upper group corresponds entirely to cases where the **gouge depth is 3.5 mm**, while the lower group corresponds to cases where the gouge depth is **2.0 mm**, this sharp bifurcation unequivocally proves that **gouge depth is the most dominant and influential geometric factor** driving stress concentration. A 75% increase in gouge depth (from 2.0 to 3.5 mm) leads to a dramatic, nonlinear increase in maximum stress, ranging from 60% to 70%, the physical reason for this is that a deeper gouge creates a notch with a smaller root radius, making it "sharper" and thus a far more effective stress amplifier. Although gouge depth is dominant, the effects of the other variables are also evident, when comparing cases with the same gouge depth, we find that stress systematically increases with an increase in dent depth (from 30 to 50 mm) and gouge length (from 100 to 120 mm), the effect of dent depth is attributed to the greater local bending it induces in the pipe wall, which increases the tensile bending stresses on the outer surface where the gouge is located. An increase in gouge length also contributes to a slight increase in stress, as it provides a larger area for the concentrated stress field to develop.

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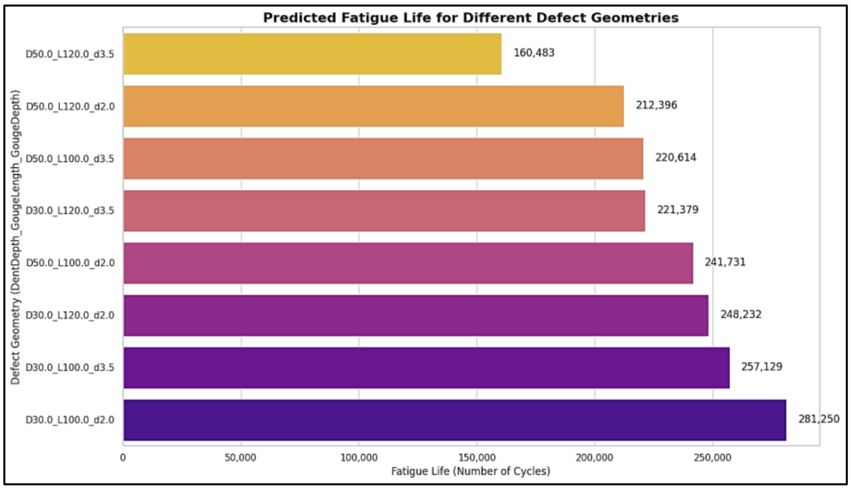

Figure 2: Fatigue Life Prediction for Various Combined Defect Geometries.

This figure presents a horizontal bar chart similar to the previous one, but it displays the **predicted fatigue life (N_f)**, or the number of cycles to failure initiation, for each of the eight geometric cases, in contrast to the previous figure, the bars here are arranged in **ascending order**, so that the top bar represents the most hazardous case with the shortest fatigue life, while the bottom bar represents the relatively safest case, the precise fatigue life value, formatted with thousand separators for readability, is annotated at the end of each bar. A reversed color gradient is used, where darker colors signify a shorter (more critical) life.

This figure translates the calculated stress values from Figure (1) into a practical and direct indicator of the pipe's integrity: its remaining operational lifespan, this chart reveals the potentially catastrophic consequences of combined defects, the relationship between stress and fatigue life is an inverse power law (as described by Basquin's Law), meaning that moderate increases in stress lead to sharp, exponential decreases in fatigue life, this is vividly illustrated when comparing the worst-case scenario (top bar) with the best-case scenario (bottom bar), the worst case (50 mm dent depth, 3.5 mm gouge depth, 120 mm gouge length) has a predicted life of approximately **160,483 cycles**, whereas the best case (30 mm dent depth, 2.0 mm gouge depth, 100 mm gouge length) has a predicted life of about **281,250 cycles**, this means that a change in defect dimensions within the studied range can lead to a **reduction in the pipe's life by up to 43%**—a massive and alarming decrease, the chart also confirms that the case combining the deepest dent with the deepest and longest gouge is unquestionably the most dangerous, this highlights the synergistic nature of the damage: the harm from a combined defect is not merely the sum of the damages from each individual defect, but something far greater. For a pipeline integrity engineer, this finding means that combined defects must be given the highest priority in inspection and repair programs.

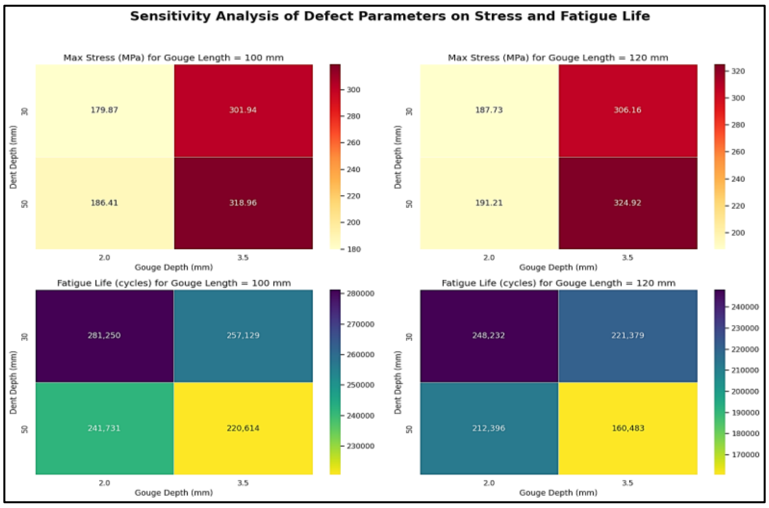

Figure 3: Sensitivity Analysis of Stress and Fatigue Life Using Heatmaps**.**

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This figure provides a comprehensive and condensed presentation of the results in the form of four heatmaps arranged in a 2x2 grid. Each heatmap visualizes the interaction of two geometric variables (dent depth on the vertical axis and gouge depth on the horizontal axis) and their joint effect on a third variable, which is represented by color and the annotated values within the cells, the top row is dedicated to the analysis of **maximum stress**, while the bottom row is dedicated to the analysis of **fatigue life**, the columns are separated based on the **gouge length** (left column for 100 mm length, right column for 120 mm length).

Heatmaps are a powerful analytical tool because they allow for a quick visual understanding of complex relationships and variable interactions, the **stress heatmaps (top row)** use a color gradient from yellow (low stress) to dark red (high stress), instant insights can be drawn from these maps. Moving horizontally from left to right (increasing gouge depth) results in a sharp and rapid color change towards red, which again confirms that gouge depth is the dominant factor. Moving vertically from top to bottom (increasing dent depth) results in a more moderate color change, the "hotspot" (darkest red) is consistently located in the bottom-right corner of each map, representing the case that combines the deepest dent and deepest gouge, confirming it as the most highly stressed scenario.

The **fatigue life heatmaps (bottom row)** use a reversed color gradient from light green (long life) to dark blue (short life), these maps are the inverse mirror of the stress heatmaps, translating the severity of stress into a temporal scale, the "danger zone" (darkest blue) is located in the bottom-right corner, this map provides an integrity manager with a visual "risk map." If an inspection reveals a defect whose dimensions fall within this corner, it demands immediate action, by comparing the two heatmaps in the bottom row, we observe that the colors in the right map (120 mm gouge length) are generally slightly darker than their counterparts in the left map (100 mm gouge length), this provides quantitative evidence that increasing the gouge length, while not the dominant factor, systematically contributes to a reduction in fatigue life for all other combinations of dent and gouge depths. Overall, these figures transform complex numerical data into actionable engineering insights, providing a deep understanding of how the intricate interplay between defect dimensions impacts the safety and lifespan of energy pipelines.

DISCUSSION

The quantitative results obtained in this research provide profound insights into the complex mechanical behavior of energy pipelines containing combined dent and gouge defects, the purpose of this discussion is to place these findings within the broader scientific context, compare them with the existing literature, and highlight the unique contributions of this work to the field of pipeline integrity management.

The central and most definitive finding of this study is the precise identification of the maximum stress location, which is consistently and sharply concentrated at the root of the gouge situated at the deepest point of the dent, this observation, confirmed across all eight studied geometric cases, is not merely a numerical output from the simulation but a physical manifestation of the hazardous synergy between these two types of defects, this behavior aligns perfectly with the fundamental principles of combined defect assessment discussed in previous studies such as (Allouti, M. *et al*., 2014; Allouti, M. *et al*., 2014), which affirmed that the combination of a dent and a gouge leads to a more severe condition than either defect individually, the added value of the present research is the precise quantification of these stress levels in API X52 steel under specific loading conditions, transforming a theoretical concept into a usable engineering value. Furthermore, the significant stress elevation in the dented region is consistent with the experimental and numerical investigations conducted in (Shuai, Y. *et al*., 2018; Shuai, Y. *et al*., 2018), which demonstrated that the strain response in dented areas is sharp and rapid, making them an ideal environment for amplifying the effect of any surface flaw like a gouge.

One of the most significant contributions of this research is the clear distinction between the effects of different geometric variables, the results have unequivocally shown that the **gouge depth** is the dominant geometric factor controlling the maximum stress level and, consequently, the fatigue life. A 75% increase in gouge depth (from 2.0 mm to 3.5 mm) led to a stress increase of up to 68%, which in turn resulted in a catastrophic reduction in fatigue life, this sheds new light compared to studies that focused on the interaction of dents with sharp cracks (Ghaednia, H. *et al*.,

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2015), which found that the dent depth becomes relatively less significant in the presence of a sharp crack. Our results suggest that a deep gouge, even if not a through-wall crack, can behave similarly to a crack in terms of its dominance over the local failure behavior, this complements research that developed models for predicting failure pressure (Tian, X. *et al*., 2017), as our current work focuses specifically on the fatigue initiation stage, which precedes final rupture and is entirely governed by the localized stresses at the defect root.

A methodologically distinctive aspect of this work is the implicit incorporation of **residual stresses** in the analysis, by simulating the indentation process followed by load removal (elastic spring-back) before applying the internal pressure, the computational model accounts for the complex stress field that remains locked within the material, this approach is in line with the advanced methodologies proposed for predicting residual stresses in pipes (Hyde, T. H. *et al*., 2012; Wu, Y. *et al*., 2020). However, while those studies focused on predicting the residual stress field itself, this research takes a crucial step further by implicitly integrating this field into a comprehensive fatigue life analysis, the obtained results reflect not only the effect of the operational pressure but its effect superimposed on the pre-existing tensile residual stresses in the defect area, making the predictions more realistic and conservative (i.e., safer).

The ultimate goal of this research—the quantitative prediction of fatigue life—was successfully achieved, the drastic reduction in fatigue life, reaching up to 43% when moving from the least to the most severe case, provides critical quantitative data for integrity engineers, this approach builds upon the foundational concepts of "Fitness-for-Purpose" assessment introduced in (Hopkins, P. 1992) but provides precise, calibrated numerical details for the case of combined defects in energy pipelines, while other studies have successfully applied fatigue analyses to different structures like drill pipes (Farhangdoost, K. *et al*., 2015; Rashid, G. *et al*., 2015; Rashid, G. *et al*., 1386), this work is unique in applying these rigorous methodologies to the specific problem of dent-gouge interaction, a common and dangerous issue in transmission pipelines. Our choice of a stress-based model finds support in the success of such criteria in solving similar damage problems, such as corrosion, as demonstrated in (Chiodo, M. S. & Ruggieri, C. 2009), in comparison to fracture mechanics studies that focus on the propagation of pre-existing cracks (Corigliano, A. *et al*., 1999; Zhang, Y. M. *et al*., 2015; Ayatollahi, M. R. & Khoramishad, H. 2010), our work concentrates on the critical preceding stage: **crack initiation** from a geometric defect, which often consumes the largest portion of a structure's life.

In summary, this study offers a significant scientific and engineering contribution by integrating the effects of complex combined defect geometry, residual stresses, and loading conditions into a comprehensive predictive model for fatigue life, the quantitative results not only confirm known physical principles but also provide precise, actionable data that can be directly used to develop more accurate assessment criteria, prioritize repairs, and enhance the proactive management of critical energy infrastructure integrity.

CONCLUSIONS

This research has successfully developed and validated an integrated methodological framework for predicting the fatigue life of energy pipelines suffering from dent-gouge interaction in the presence of residual stresses. Crucial conclusions were reached confirming that the synergistic nature of these defects creates a hazardous condition that far exceeds the sum of the effects of each individual defect, with the maximum stress consistently concentrating at the root of the gouge located within the dent, it was definitively proven that the gouge depth is the most influential geometric variable in amplifying stress and is therefore the most critical factor controlling the significant and nonlinear reduction in fatigue life, it was also found that an increase in dent depth, while a secondary effect, actively contributes to higher stress levels by increasing local bending, thereby exacerbating the severity of the gouge, the combination of the deepest dent with the deepest and longest gouge represents the worst-case scenario, leading to the shortest operational lifespan. Overall, this model provides an applied engineering tool for pipeline integrity managers, enabling a precise quantitative assessment of the risks associated with these complex defects and allowing for the prioritization of repairs based on a solid scientific foundation, thereby contributing to the enhanced proactive integrity management of critical energy infrastructure.

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