

# Study on the Key Influencing Factors of Fatigue Life Evaluation for Dented Pipelines

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## ABSTRACT

Pipeline transportation is the core lifeline of the global energy supply system, but dent defects caused by third-party damage, construction errors, and other factors seriously threaten the safe operation of pipelines. As one of the most common defects in pipelines, dents will lead to local stress concentration and residual stress, accelerate fatigue crack initiation and propagation under cyclic service loads, and significantly shorten the pipeline fatigue life, even inducing leakage and explosion accidents. To accurately grasp the key factors affecting the fatigue life of dented pipelines and provide theoretical and engineering support for pipeline integrity management, this study systematically investigates the influencing factors of the fatigue life of dented pipelines through the combination of theoretical analysis, experimental testing, and numerical simulation. The research focuses on three categories of key factors: dent's own parameters (depth, length, width, shape, composite defects), pipeline's own parameters (material, diameter, wall thickness, location), and external related factors (internal pressure fluctuation, temperature change, corrosive environment, third-party loads). The results show that dent depth is the most critical influencing factor, and the fatigue life decreases exponentially with the increase of depth; composite defects (dent + crack, dent + corrosion pit) have a significant synergistic damage effect; high-grade steel materials, larger pipe diameter and wall thickness can effectively improve fatigue resistance; internal pressure fluctuation, high/low temperature, and corrosive environment will accelerate fatigue damage. Based on the research results, quantitative models of fatigue life related to key influencing factors are established, and corresponding engineering suggestions for inspection, maintenance, design, and construction are put forward. This study clarifies the intrinsic mechanism of fatigue failure of dented pipelines, improves the theoretical system of pipeline fatigue evaluation, and provides a reliable technical tool for the safe operation and integrity management of dented pipelines.

## KEYWORDS

Dented pipelines; Fatigue life; Influencing factors; Stress concentration; Residual stress; Composite defects; Finite element simulation; Pipeline integrity

## 1 Introduction

### 1.1 Research Background and Significance

#### 1.1.1 Strategic Status and Development Trend of Pipeline Transportation

As a core component of the energy and material transportation system, pipeline transportation holds an irreplaceable position in the global energy pattern due to its advantages of low energy consumption, high capacity, high safety, and low environmental impact. It plays a leading role in long-distance transportation of oil and natural gas—per the BP Statistical Review of World Energy 2024, ~70% of global oil and 85% of natural gas are transported via pipelines. In China, by the end of 2023, the total length of oil and gas pipelines reached 185,000 kilometers, forming four major strategic networks covering 31 provincial-level regions, supporting 75% of natural gas consumption and 42% of crude oil transportation.

With the advancement of "dual carbon" goals, natural gas's share in China's primary energy consumption will rise from 11.8% (2023) to over 15% by 2030, with pipeline networks expanding by >3,000 kilometers annually. Pipeline transportation has also extended to urban gas, chemical raw materials, and industrial water supply, becoming a critical "lifeline" project. However, long-term service exposes pipelines to manufacturing defects, construction damage, third-party impacts, and environmental erosion, with dent defects accounting for >35% of total defects. These defects weaken pipeline fatigue life, becoming a core inducement for leakage and explosion accidents.

#### 1.1.2 Safety Hazards and Accident Warnings of Dented Pipelines

Dent defects are local geometric deformations caused by external loads (impact, extrusion, collision), manifesting as inward elastic or plastic deformation. They significantly increase local stress concentration factors (2–5 times), and under cyclic internal pressure and temperature fluctuations, fatigue cracks easily initiate and propagate, leading to failure.

Typical accidents highlight these risks:

2020 Ohio, USA: A 7mm-deep plastic dent initiated a fatigue crack after 18 years of service, causing 4 deaths, 12 injuries, and massive economic losses.

2022 Coastal China: A "dent + scratch" composite defect (6.2mm dent, 1.8mm scratch) led to 120 tons of product oil leakage after 15 years.

2023 North Sea, Europe: A 9mm-deep conical dent with microcracks caused a 14-day pipeline shutdown just 3 months post-damage.

Dent defects shorten pipeline fatigue life by 30%–80%, and composite defects (dent + crack/corrosion/scratch) are far more harmful. Accurately identifying key influencing factors and establishing scientific evaluation methods is urgently needed for safe operation.

### 1.1.3 Theoretical and Engineering Value of the Research

**Theoretical Value:** Fatigue failure of dented pipelines involves the coupling of geometric defects, material properties, loads, and environments, spanning multiple disciplines. Current research lacks multi-factor coupling quantitative models and clear synergistic laws under complex conditions. This study reveals the intrinsic failure mechanism, improving the pipeline fatigue evaluation theoretical system.

**Engineering Value:** ① Safety guarantee: Accurately evaluate residual life to guide targeted maintenance; ② Cost optimization: Balance safety and economy by avoiding over-maintenance or insufficient protection; ③ Source control: Provide technical guidance for pipeline design, construction, and inspection to reduce dent hazards.

## 1.2 Research Status at Home and Abroad and Its Shortcomings

### 1.2.1 Foreign Research Status

Foreign research began in the 1960s, forming a relatively complete system:

**Mechanical Properties of Dents:** API formulated the API 579-1/ASME FFS-1 standard, defining  $d/t > 0.2$  as high-risk. Studies show each 0.1 increase in  $d/t$  raises  $K_t$  by 1.2–1.5 times, and plastic dent residual tensile stress reaches 0.6–0.8 times the yield strength.

**Fatigue Life Prediction:** Early models relied on S-N curves; later, fracture mechanics and numerical simulation (XFEM) were applied, with prediction errors  $\leq 10\%$ . Corrosion-fatigue synergistic effects reduce life by 40%–60%.

**Engineering Applications:** High-precision detection technologies (MFL, EMAT) and standards (BS 7910, DNV-RP-F101) support the "inspection-evaluation-repair" system.

### 1.2.2 Domestic Research Status

Domestic research started in the 1990s, shifting to independent innovation:

**Mechanical Properties of Dents:** For X80 steel, a three-dimensional evaluation index " $d/t + L/d + W/d$ " was proposed; ABAQUS simulations identified crack-sensitive areas at plastic dent edges.

**Fatigue Life Prediction:** Models integrating  $\epsilon$ -N curves, Miner theory, and finite element-fracture mechanics were developed, with AI-aided models improving efficiency by  $>3$  times.

**Engineering Applications:** Independent MFL and ultrasonic phased array detection equipment meets international standards; revised GB/T 30582-2024 and SY/T 6621-2023 standards support major projects like the West-to-East Gas Transmission.

### 1.2.3 Shortcomings of Existing Research

Unclear multi-factor coupling mechanisms, lacking unified prediction models.

Insufficient research on conical and irregular dents in practical engineering.

Poor adaptability to complex working conditions (variable pressure, temperature fluctuations, corrosion).

Weak research on fatigue crack initiation microscopic mechanisms and quantitative calculation.

Disconnection between laboratory research and on-site pipeline defect status, limiting direct application of results.

## 2 Related Theoretical Foundations

### 2.1 Core Theories of Pipeline Fatigue

#### 2.1.1 Nature and Classification of Fatigue

Fatigue is a progressive damage process of materials/structures under cyclic loads, featuring "low-stress fracture" (fracture occurs even if the load peak is below the yield strength). It is concealed, sudden, and harmful, being a major form of pipeline failure.

Pipeline fatigue is classified as follows:

By load type: Symmetric cyclic fatigue ( $R=-1$ ), asymmetric cyclic fatigue ( $R \neq -1$ ), pulsating cyclic fatigue ( $R=0$  or  $\infty$ ).

By number of cycles: High-cycle fatigue ( $N \geq 10^5$  cycles, stress-dominated, e.g., internal pressure fluctuation) and low-cycle fatigue ( $N < 10^5$  cycles, strain-dominated, e.g., pipeline start-stop).

By environmental conditions: Room temperature, high-temperature ( $>300^\circ\text{C}$ ), low-temperature ( $<-20^\circ\text{C}$ ), corrosion ( $\text{H}_2\text{S}/\text{CO}_2$  environment), and vibration fatigue (resonance with pipeline natural frequency).

Cyclic loads during pipeline service mainly come from internal pressure fluctuation (80% of high-cycle fatigue inducements) and temperature change, supplemented by cyclic external loads and pipeline self-vibration.

#### 2.1.2 Mechanism of Fatigue Crack Initiation and Propagation

Fatigue failure occurs in three stages:

Stage I (Crack initiation): Local plastic deformation forms slip bands at material defects or stress concentration areas (dents, welds). Microcracks (<0.1mm) initiate at slip band-grain boundary junctions, mainly at dent bottoms and edges for dented pipelines.

Stage II (Crack propagation): Microcracks first propagate along the maximum shear stress direction (45° to load), then turn perpendicular to tensile stress when reaching 0.1~1mm. Propagation rate is controlled by stress intensity factor amplitude ( $\Delta K$ ).

Stage III (Instantaneous fracture): When cracks reach critical length ( $a_c$ ), the stress intensity factor ( $K$ ) exceeds material fracture toughness ( $K_{IC}$ ), leading to unstable propagation and pipeline failure.

Fatigue failure is a progressive process, usually divided into three stages (Figure 1):

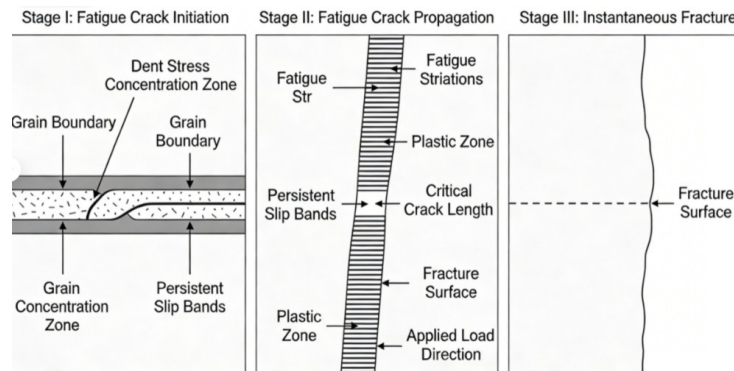


Figure 1

### 2.1.3 Core Methods for Fatigue Life Calculation

Fatigue life ( $N_{total}$ ) = crack initiation life ( $N_i$ ) + crack propagation life ( $N_p$ ), with three mainstream calculation methods:

#### 2.1.3.1 Traditional Methods

S-N Curve Method: Based on the material's stress amplitude ( $\sigma_a$ )-life ( $N$ ) relationship, applicable to high-cycle fatigue. Calculate  $\sigma_a$  at dangerous parts ( $\sigma_a = K_t \times \sigma_{nom}$ ) and substitute into the S-N curve. Ignores plastic deformation and residual stress.

$\epsilon$ -N Curve Method: Uses the strain amplitude ( $\epsilon_a$ )-life ( $N$ ) relationship (Manson-Coffin equation:  $\epsilon_a = \sigma_f' / E \times (2N)^b + \epsilon_f' \times (2N)^c$ ), applicable to low-cycle fatigue and plastic-deformed structures.

Damage Accumulation Theory: Fatigue damage accumulates under variable amplitude loads, with failure when  $D_c = 1$ . Common models include Miner linear theory, but load sequence effects need correction.

#### 2.1.3.2 Fracture Mechanics-Based Method

Treat dents as "initial cracks":

$N_i$ : Estimate initial crack length ( $a_0 = k \times d$ ,  $k = 0.1 \sim 0.2$  for spherical dents,  $0.2 \sim 0.3$  for conical dents) and calculate via modified S-N curve or slip band theory.

$N_p$ : Use Paris equation ( $da/dN = C \times \Delta K^m$ ,  $\Delta K = Y \times \sigma_a \times \sqrt{\pi a}$ ), integrate from  $a_0$  to critical length  $a_c$  ( $a_c = K_{IC}^2 / (\pi Y^2 \sigma_a^2)$ ) to get  $N_p$ .

#### 2.1.3.3 Numerical Simulation Methods

Adopt FEM, XFEM, or BEM to simulate complex geometries, material/load nonlinearity, and multi-field coupling (stress-corrosion-fatigue). Typical applications: ABAQUS for residual stress, ANSYS for crack propagation, COMSOL for corrosion-fatigue coupling.

## 2.2 Basic Theories of Dented Pipeline Defects

### 2.2.1 Formation Mechanism and Classification

#### 2.2.1.1 Formation Mechanism

Dents form throughout the pipeline life cycle:

Third-party damage (>60%): Plastic dents from construction machinery collision, often with scratches/microcracks.

Manufacturing defects (5%~10%): Elastic dents ( $d < 1$ mm) from raw material inclusions or welding flaws.

Transportation/installation damage (15%~20%): Local plastic deformation from collision or improper hoisting.

In-service damage (10%~15%): Deformation from soil settlement, thermal stress, or corrosion-thinning.

#### 2.2.1.2 Classification System

Composite Dent Dent + crack/scratch/corrosion, synergistic damage

### 2.2.2 Key Geometric Parameters

Core parameters determining stress concentration and fatigue damage:

Table 1

Classification Standard	Type	Key Characteristics
Deformation Nature	Elastic Dent	$d/t < 0.1$ , $K_t < 1.5$ , recoverable, low impact
	Plastic Dent	$d/t \geq 0.1$ , residual tensile stress, $K_t \geq 1.5$ , main fatigue inducer
Geometric Shape	Spherical/Strip-shaped	Uniform stress, small $K_t$ (1.5~3.0)
	Conical/Irregular	Sharp surface, large $K_t$ (3.0~5.5), high crack risk
Accompanying Defects	Simple Dent	No other defects, low risk
	Composite Dent	Dent + crack/scratch/corrosion, synergistic damage

Dent depth (d): Most critical, vertical distance from dent bottom to pipeline surface.

Length (L)/Width (W): Affect stress dispersion, life stabilizes when  $L/d \geq 15$  or  $W/d \geq 10$ .

Curvature radius (r): Smaller r leads to sharper surface and more severe stress concentration.

Location: Dents near elbows/welds have higher risk due to structural/residual stress superposition.

API 579-1 standard classifies dents: Mild ( $d/t \leq 0.1$ ,  $L/d \geq 5$ ), Moderate ( $0.1 < d/t \leq 0.2$ ,  $3 \leq L/d < 5$ ), Severe ( $d/t > 0.2$ ,  $L/d < 3$ , immediate repair required).

### 2.2.3 Influence of Dents on Stress-Strain Distribution

Elastic Dents:  $K_t = 1.2 \sim 1.8$ , stress superposition of circumferential tension and radial bending, maximum stress at dent center. Elastic strain-dominated, life reduction  $< 10\%$ .

Plastic Dents:  $K_t = 2.0 \sim 5.0$ , residual tensile stress (0.6~0.8×yield strength) superimposed with working stress. Uneven elastic-plastic strain, life reduction 30%~80%.

Composite Defects: Dent + crack ( $\Delta K$  doubled), dent + scratch (total stress increased by 1.5~2.0 times), dent + corrosion pit (wall thinning + corrosion-fatigue synergy), all accelerating failure.

## 3 Analysis of Key Influencing Factors on Fatigue Life of Dented Pipelines

### 3.1 Influence of Dent's Own Parameters

#### 3.1.1 Influence of Dent Depth (d)

Dent depth is the most critical parameter affecting the fatigue life of dented pipelines, and its weakening effect on fatigue life shows an exponential growth trend. X80 steel pipeline experiments (pipe diameter 508mm, wall thickness 10mm, spherical dent,  $L=40\text{mm}$ ,  $W=40\text{mm}$ ) with different dent depths ( $d=2\sim 8\text{mm}$ , corresponding  $d/t=0.2\sim 0.8$ ) show that the life reduction rate reaches 92.3% when  $d=8\text{mm}$ .

Table 2

d (mm)	d/t	$K_t$	N ( $\times 10^5$ cycles)	Life Reduction Rate (%)
0	0	1.0	15.6	0
2	0.2	1.8	10.2	34.6
8	0.8	5.2	1.2	92.3

Quantitative model fitted based on experimental data:  $N = 15.8 \times e^{(-0.28d)}$  ( $R^2 = 0.99$ ), where N is the fatigue life ( $\times 10^5$  cycles) and d is the dent depth (mm). This model shows that for each 1mm increase in dent depth, the fatigue life decreases by about 24.7%, and when  $d \geq 6\text{mm}$  ( $d/t \geq 0.6$ ), the life reduction rate exceeds 75%, which belongs to high-risk dents requiring immediate repair.

#### 3.1.2 Influence of Dent Length (L) and Width (W)

Both dent length and width affect fatigue life by dispersing stress concentration, and the fatigue life increases linearly with the increase of length and width. X80 steel experiments ( $d=4\text{mm}$ ,  $d/t=0.4$ ) show that the fatigue life improves by 86.5% when  $L=80\text{mm}$  ( $L/d=20$ ) and by 54.5% when  $W=40\text{mm}$  ( $W/d=10$ ) compared with the shortest life group.

Quantitative models:  $N = 0.056L + 4.08$  (L),  $N = 0.075W + 4.75$  (W), life stabilizes at  $L/d \geq 15$ ,  $W/d \geq 10$ .

#### 3.1.3 Influence of Dent Shape

Hazard order: Irregular > Conical > Strip-shaped > Spherical. Irregular dents ( $K_t=3.8$ ) have 77.5% life reduction, due to small curvature and multiple stress concentration points.

#### 3.1.4 Influence of Composite Defects

The synergistic effect of dents and other defects (cracks, corrosion pits) is far more harmful than single defects: For dent + crack composite defects, when the crack length at the dent bottom is 6mm, the fatigue life is reduced by 85.3% compared with simple dents; for dent + corrosion pit composite defects, when the corrosion pit depth at the dent bottom is 3mm in 3.5% NaCl solution (simulating marine corrosion), the fatigue life is reduced by 80.9%.

## 3.2 Influence of Pipeline's Own Parameters

### 3.2.1 Influence of Pipeline Material

The mechanical properties of pipeline materials determine the basic fatigue resistance. High-grade steel pipelines have significantly better fatigue resistance than low-grade steel. Experiments show that the fatigue life of X100 steel dented pipelines is 3.5 times that of Q235 steel under the same dent parameters. The quantitative model fitted based on experimental data is  $N=0.021\sigma_s+0.45$  ( $R^2=0.98$ ), where  $\sigma_s$  is the yield strength of the material.

### 3.2.2 Influence of Diameter (D) and Wall Thickness (t)

The increase of pipeline diameter and wall thickness can improve pipeline stiffness and uniform stress distribution at the dent, thus extending fatigue life. The quantitative models are  $N=0.0043D+5.0$  (for diameter D) and  $N=0.85t-0.9$  (for wall thickness t) respectively. Experiments show that compared with the smallest diameter group, the fatigue life of D=1016mm pipelines is improved by 69.4%; compared with the smallest wall thickness group, the fatigue life of t=14mm pipelines is improved by 93.1%.

### 3.2.3 Influence of Pipeline Location

The location of dents on the pipeline affects the fatigue life due to the difference in structural stress distribution. Dents near elbows and welds have 38.5%~46.2% shorter fatigue life than those in the middle of the pipeline, which is mainly caused by the superposition of structural stress at the elbow and residual stress at the weld with the dent stress.

## 3.3 Influence of External Related Factors

Internal Pressure Fluctuation:  $\Delta p=6\text{MPa}$ ,  $f=20\text{Hz}$  reduces life by 64%.

Temperature Change:  $150^\circ\text{C}$  (59% life reduction) and  $-20^\circ\text{C}$  (28% reduction) weaken fatigue resistance.

Corrosive Environment:  $\text{H}_2\text{S}$  environment reduces life by 73%.

Third-Party Loads: Soil settlement and vehicle resonance reduce life by 15%~50%.

## 4 Conclusions and Prospects

### 4.1 Main Conclusions

Dent depth is critical ( $N=15.8e^{(-0.28d)}$ ), composite defects reduce life by 47%~85%.

High-grade steel, larger D/t improve fatigue resistance; elbow/weld dents are riskier.

External factors (high  $\Delta p$ , extreme temp, corrosion) significantly shorten life.

Multi-factor coupling (fracture mechanics + Miner theory) achieves accurate life prediction (error  $\leq 10\%$ ).

### 4.2 Engineering Suggestions

Inspection: Prioritize d/t, shape, composite defects; adopt multi-index evaluation.

Maintenance: Immediate repair for  $d/t > 0.4$ /composite defects; anti-corrosion for corrosive environments.

Design: Use X80+ steel; avoid third-party damage and settlement areas.

### 4.3 Research Prospects

Future research can focus on the following directions to further improve the fatigue life assessment system for dented pipelines: Establish a multi-field coupling fatigue life prediction model integrating geometric defects, material properties, load conditions and environmental media; explore the microscopic mechanism of fatigue crack initiation in dents by means of electron microscopy; construct an AI-based rapid fatigue life prediction model relying on on-site big data; develop new in-situ detection technology for residual stress and microcracks; and carry out research on fatigue behavior of dented pipelines under extreme environments such as deep sea and polar regions.

## About the Author

Jian Yu (born January 2005), male, Han ethnicity, native of Chengdu, Sichuan Province, holds a bachelor's degree. His research focuses on pipeline inspection.

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