

Review

State of the Art of Fracture Assessment Method on High-Strength Oil and Gas Pipeline Girth Weld

Xiaoben Liu ^{1,*} , Dong Zhang ¹, Jiaqing Zhang ¹, Qingshan Feng ², Zhongjia An ¹ and Hong Zhang ¹

¹ National Engineering Research Center for Pipeline Safety, MOE Key Laboratory of Petroleum Engineering, Beijing Key Laboratory of Urban Oil and Gas Distribution Technology, China University of Petroleum-Beijing, Beijing 102249, China

² China oil & Gas Piping Network Corporation, Beijing 100013, China

* Correspondence: xiaobenliu@cup.edu.cn

Abstract

High-strength oil and gas pipeline girth welds exhibit significant material and geometric discontinuities with high susceptibility to defects, making them a critical weak link in oil and gas pipelines. Researching the fracture assessment technology pipeline's girth welds is essential for enhancing the pipeline's inherent safety and protection levels. Key issues and research progress related to fracture assessment technology are systematically addressed from the perspectives of pipeline fracture behavior and fracture assessment methods in this paper. The core focus of fracture behavior research is determining the crack driving force at the girth weld and the material's fracture toughness. Fracture assessment methods include failure assessment diagrams and limited tensile strain capacity models. The development of single-parameter and multi-parameter fracture mechanics theories in establishing the relationship between in-plane and out-of-plane constraints and material fracture toughness is reviewed. Four commonly used methods for calculating crack driving forces in pipelines are presented. Moreover, the usage scenarios of various failure assessment diagrams in pipeline fracture assessment are analyzed. A comparison of the parameter ranges and applicability of commonly used international tensile strain capacity models is also provided. The paper highlights existing issues in current research on the fracture assessment of high-strength pipelines and outlines directions for further study. Lastly, this paper aims to provide theoretical and technical support for improving the inherent safety level of high-strength pipeline girth welds.

Keywords: high-strength pipeline; fracture toughness; crack driving force; failure assessment diagram; strain capacity



Academic Editor: Qingbang Meng

Received: 12 November 2025

Revised: 7 December 2025

Accepted: 12 December 2025

Published: 17 December 2025

Citation: Liu, X.; Zhang, D.; Zhang, J.; Feng, Q.; An, Z.; Zhang, H. State of the Art of Fracture Assessment Method on High-Strength Oil and Gas Pipeline Girth Weld. *Processes* **2025**, *13*, 4071. <https://doi.org/10.3390/pr13124071>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Material girth welds of oil and gas pipelines vary significantly, encompassing the base material, heat-affected zone, and weld metal, all exhibiting distinct characteristics. Specifically, the softening of the heat-affected zone and the low strength of the weld metal can lead to stress and strain concentration at the girth weld location under load. Additionally, as the strength of the base material increases, a high match with the weld metal is more difficult, often resulting in low-match situations in engineering practice. Moreover, variations in wall thickness and misalignment introduce structural discontinuities in the girth weld. Various unavoidable defects during welding, such as cracks, lack of penetration, lack of fusion, and undercutting, exacerbate deformation at the girth weld location, leading

to fracture failure and making the girth weld the weakest link in buried pipelines [1]. Among these, planar, surface-breaking defects are generally recognized to have the most detrimental influence on both static strength and fatigue life, while volumetric flaws are less critical in terms of ultimate strength but may still reduce fatigue performance when clustered or located near the surface [2]. Field inspection of such defects mainly relies on radiographic testing for volumetric flaws and conventional ultrasonic testing for planar flaws, whereas advanced techniques such as phased-array UT and TOFD have been increasingly adopted to improve detection reliability and sizing accuracy [3]. In addition, at the intersection of longitudinal and circumferential welds, repeated welding thermal cycles can further intensify HAZ softening and local multiaxial constraint, making these regions particularly susceptible to crack initiation and propagation. This highlights the critical importance of understanding the fracture behavior of high-strength girth welds and their surrounding zones.

Several major international accidents caused by the fracture of girth welds in high-strength pipelines occurred recently. In 2010, a natural gas pipeline operated by Pacific Gas and Electric Company in the United States experienced a rupture in its girth weld due to pressurization, resulting in the deaths of eight people. In 2017, a rupture in the girth weld of the Guizhou Qinglong natural gas pipeline, caused by ground movement, led to a fire explosion that resulted in 43 casualties and significant economic losses. In 2018, the Guizhou Qinglong natural gas pipeline suffered another girth weld failure, causing 24 casualties. Similar girth-weld rupture incidents have also been reported in overseas pipelines. In December 2022 the Keystone crude oil pipeline in Kansas, USA, ruptured at a pipe-to-fitting girth weld due to bending stresses and a fabrication flaw, leading to a spill of about 14,000 barrels of oil; failure analysis identified a progressive fatigue crack initiating in the girth weld as the root cause. These incidents represent a significant threat to public safety and property, presenting serious challenges to the inherent safety of girth welds in pipelines. As a response, numerous pipeline companies have initiated investigations and remediation efforts regarding the hazards associated with girth welds, with one important focus being the fracture assessment of these welds. However, the existing assessment methods are characterized by many shortcomings, making it difficult to ensure the inherent safety of the pipelines [4,5].

The fracture behavior of girth welds in pipelines is influenced by many factors. Currently, the mechanisms by which materials, defects, and loads affect the limit state of weld cracking are not fully understood [6]. The existing fracture assessment methods for girth welds are characterized by shortcomings, such as unclear fracture criteria and inaccurate evaluation methods. Hence, ensuring the inherent safety of pipelines is relatively difficult. As vital underground lifelines, high-strength pipelines transport oil and gas resources. Therefore, researching girth welds' fracture behavior and assessment techniques is crucial for enhancing these pipelines' inherent safety and protection levels.

In summary, the core content of the research on the fracture behavior of high-strength pipes is to determine the crack driving force of the girth weld and the fracture toughness of the material. Two fracture evaluation methods, a failure assessment diagram, and a strain capacity model, are developed based on research on crack driving force and fracture toughness. Therefore, this paper discusses the relevant international research progress from material fracture toughness, pipeline crack driving force, and pipeline girth weld fracture evaluation method. Furthermore, the paper discusses the existing problems in the research and the direction of future investigations to provide theoretical and technical support for improving the intrinsic safety level of high-strength pipeline girth welds. Although several review papers have reported progress in pipeline fracture mechanics, existing surveys generally focus on single aspects—such as CTOD testing, constraint theory, or tensile

strain capacity—and often lack an integrated analysis that links weld heterogeneity, crack-driving-force models, failure assessment diagrams, and strain-based design. Moreover, most published reviews do not incorporate the latest full-scale and curved-wide-plate data from recent years, nor do they compare the applicability limits of commonly used international strain capacity models.

The novelty of this paper lies in providing a comprehensive, global synthesis of recent research on the fracture behavior and assessment of high-strength pipeline girth welds. Unlike previous reviews that focus on isolated aspects such as fracture toughness testing, crack driving force analysis, or strain capacity models, this paper systematically integrates (i) the latest developments in single-parameter and multi-parameter fracture mechanics theory, (ii) updated methods for calculating crack driving forces under realistic loading conditions, and (iii) an international comparison of the applicability and parameter ranges of widely used tensile strain capacity models. By consolidating full-scale tests, wide-plate results, constraint-based theories, and engineering assessment methods, the paper highlights the limitations of existing studies and proposes forward-looking research directions. This provides a unified technical framework and offers theoretical and practical support for enhancing the inherent safety of high-strength pipeline girth welds.

2. Material Fracture Toughness

Fracture toughness is influenced by the material properties and the constraint state at the crack tip within the structure. Factors affecting crack tip constraint include the geometric dimensions of the specimen or structure, the geometric dimensions of the crack, and the loading type. Therefore, accurately describing the fracture toughness of engineering structures is relatively complex. The industry generally uses fracture toughness measured from small laboratory specimens to represent the fracture toughness of actual engineering structures. In the pipeline industry, the testing objects for material fracture toughness at different scales mainly include full-size pipeline specimens, wide plate specimens, single-edge notched tensile specimens, single-edge notched bend specimens, and compact tensile specimens. Due to the differences in constraint states, using laboratory specimen test results to characterize the fracture toughness of pipelines requires a clear understanding of the relationship between crack tip constraint and fracture toughness. Research on material fracture toughness and behavior has gradually led to the forming single-parameter and multi-parameter fracture mechanics theories.

2.1. Single-Parameter Fracture Mechanics

Griffith was the first to propose a crack instability propagation criterion based on the energy release rate. Subsequently, Irwin introduced the methods of elastic mechanics for analyzing the stress and strain fields at the crack tip. The authors proposed that the stress and strain fields at the crack tip are controlled by the stress intensity factor K . The calculation method for the crack-tip stress and strain fields within the elastic range was also provided. The stress field is calculated as follows:

$$\sigma_{ij} = \frac{K}{\sqrt{2\pi r}} f_{ij}(\theta) \quad (1)$$

where σ_{ij} ($i, j = 1, 2, 3$) represents the stress components, and r and θ are the polar coordinates of the point near the crack tip, with $f_{ij}(\theta)$ representing a function of the polar angle θ . Traditional strength criteria based on stress cannot measure material failure due to a singularity at the crack tip ($r = 0$). However, the stress intensity factor is a finite quantity that characterizes the intensity of the crack tip stress field. Therefore, Irwin established a fracture criterion based on the stress intensity factor. It is worth noting that the stress

intensity factor can still be used to measure the intensity of the crack tip stress field even when the plastic zone at the crack tip is very small compared to the geometric dimensions of the structure (i.e., small-scale yielding). Williams [7] proposed the general form of the crack tip stress field for type I cracks:

$$\sigma_{ij} = A_{ij}(\theta)r^{-1/2} + B_{ij}(\theta) + C_{ij}(\theta)r^{1/2} + \dots \quad (2)$$

where A_{ij} , B_{ij} , and C_{ij} are functions of the crack tip angle θ . The first term represents the stress singularity term, which is the general form of Equation (1). The first term in the above equation governs the intensity of the crack tip field near the crack surface (as r approaches 0).

In Equation (2), the ellipsis (“...”) denotes the higher-order terms in the Williams eigenfunction expansion of the crack-tip stress field, including additional terms of orders r^1 , $r^{3/2}$, r^2 , and so on, which are generally negligible compared with the leading singular term $r^{-1/2}$.

Rice [8] et al. proposed the J -integral for elastoplastic fracture problems, an elastoplastic fracture parameter based on energy considerations. The J -integral is widely applied due to its clear theoretical and physical significance of the J -integral and path-independence properties. Hutchinson [9] and Rice and Rosengren [10] further derived the method for calculating the stress and strain fields at the crack tip for hardening materials under elastoplastic conditions, dominated by the J -integral, as shown in Equation (3). It is worth mentioning that introducing the HRR solution laid the theoretical foundation for elastoplastic fracture mechanics.

$$\sigma_{ij} = \sigma_y \left(\frac{J}{\alpha \sigma_y \varepsilon_y I_n r} \right)^{\frac{1}{n+1}} \tilde{\sigma}_{ij}(\theta) \quad (3)$$

where $\tilde{\sigma}_{ij}(\theta)$ represents the angular stress function, σ_y is the material's yield strength, α is the material hardening shift coefficient, n is the hardening exponent, ε_y is the strain corresponding to the yield stress, and I_n is a constant related to the hardening exponent n .

In 1965, Wells [11] proposed the crack tip opening displacement (CTOD) as an elastoplastic fracture parameter through extensive experimental research. The author developed a fracture failure criterion based on CTOD. Shih et al. [12] discovered a quantitative relationship between the J -integral and CTOD, which is related to the material properties. The general form of this quantitative relationship is given in Equation (4):

$$\text{CTOD} = d(\alpha \varepsilon_y, n) \frac{J}{\sigma_y} \quad (4)$$

where d is a function related to α , ε_y , and n . The HRR field and the J -integral criterion only apply under small-scale yielding conditions, and the HRR field is valid only under high-constraint conditions. Therefore, the stress intensity factor K or the J -integral can be used as a single parameter to describe the stress and strain fields at the crack tip. When the crack tip constraint is lower, the crack tip field deviates from the HRR field. Consequently, a single parameter cannot accurately quantify the crack tip field. In other words, single parameters K , J , or CTOD cannot accurately represent the material's toughness level, necessitating the development of multi-parameter fracture mechanics theories.

Although the classical single-parameter quantities K , J and CTOD were originally formulated in the 1960s, they have been continuously refined and widely applied in modern pipeline integrity assessments. Recent studies have focused on improving fracture toughness testing and evaluation procedures under realistic, low-constraint conditions. For example, Kang et al. [13] reviewed recent developments in low-constraint fracture

toughness testing for pipelines based on SENT specimens and J/CTOD parameters, while Li et al. [14] and Gong et al. [15] proposed constraint-modified J–R curves and strain-based assessment approaches for X80 pipeline girth welds. In the Chinese literature, Wu [16] and Ren et al. further developed low-constraint fracture toughness testing methods and applied CTOD- or J-based toughness to high-grade pipeline girth welds. Building on these foundations, very recent works from 2024–2025 have extended single-parameter testing to a wider range of steels, weld configurations and constraint levels: Agbo et al. [17] performed systematic CT/SENB/SENT testing on X52 pipe steel to examine toughness transferability under different constraint conditions; Liu et al. [18] quantified the fracture toughness distribution of X80 pipeline girth welds using fractal analysis of fracture surfaces within a J-based framework; Hu et al. [19] investigated the strain-fracture behaviour of X80 welded joints with non-sharp notches at the weld root and proposed an equivalent-crack description still based on J–CTOD relations; and Tian et al. [20] calibrated an improved plasticity factor for J-integral evaluation from SE(T) specimens for high-grade pipeline girth welds. These recent advances demonstrate that single-parameter fracture mechanics models remain an active research topic and provide an essential basis for the multi-parameter fracture mechanics theories discussed in the next subsection.

2.2. Two-Parameter Fracture Mechanics

Single-parameter fracture mechanics assume similarity in the stress and strain fields at the crack tips of different structures, using a single parameter to describe the crack tip fields of all structures. This fundamental assumption holds under small-scale yielding conditions. However, the differences in crack tip fields between structures become significant under large-scale yielding, making single-parameter fracture mechanics inaccurate. Therefore, after introducing single-parameter fracture mechanics, researchers gradually focused on two-parameter fracture mechanics theories that describe the crack tip fields and the constraint levels of different structures. In this approach, fracture parameters such as K , J , or CTOD are used to describe crack tip deformation. In contrast, an additional parameter is introduced to reflect the differences in crack tip constraint among different structures.

Betegon and Hancock [21] used the boundary layer method to analyze and calculate the crack tip fields under elastoplastic fracture conditions. The authors retained the first two terms of Williams' multi-term expansion, as shown in Equation (5):

$$\sigma_{ij} = \frac{K}{\sqrt{2\pi r}} f_{ij}(\theta) + T \delta_{1i} \delta_{1j} \quad (5)$$

where δ_{ij} is the Kronecker delta, and T represents the tensile stress parallel to the crack plane, commonly called T -stress. Betegon's and others' research demonstrated that T -stress affects the crack tip field. When the T -stress in a structure is positive, the crack tip field tends to approach the high-constraint HRR solution, indicating that the crack tip is in a high-constraint state. Consequently, the stress intensity factor K can be used to measure the intensity of the crack tip field. However, when the T -stress is negative, the crack tip stress is significantly lower than the HRR solution, meaning the constraint at the crack tip is lower than that of the HRR solution. In this case, the dominance of K is lost, and K and T -stress are required to describe the fracture behavior of the crack tip. Therefore, Betegon et al. proposed the K - T two-parameter fracture mechanics theory. Although T -stress is an elastic parameter, it can still effectively describe the constraint state of the crack tip even under large-scale yielding conditions. Subsequently, Al-Ani and Hancock [22] developed the J - T two-parameter fracture mechanics theory. The authors investigated the relationship between the fracture toughness of different constraint specimens and the crack growth resistance.

The HRR solution retains the first term of Williams' asymptotic solution. A higher-order asymptotic solution for the first three terms of the crack tip field in type I fracture problems was proposed through the theoretical analysis [23,24], as shown in Equation (6):

$$\frac{\sigma_{ij}}{\sigma_y} = A_1 \left[\left(\frac{r}{L_1} \right)^{s_1} \tilde{\sigma}_{ij}^{(1)}(\theta) + A_2 \left(\frac{r}{L_1} \right)^{s_2} \tilde{\sigma}_{ij}^{(2)}(\theta) + A_2^2 \left(\frac{r}{L_1} \right)^{s_3} \tilde{\sigma}_{ij}^{(3)}(\theta) \right] \quad (6)$$

where s_k is the stress exponent related to the hardening coefficient n ($s_1 < s_2 < s_3 = 2s_2 - s_1$), $\tilde{\sigma}_{ij}^{(k)}(\theta)$ ($k = 1, 2, 3$) represents the angular stress function, and L_1 is the dimensional analysis parameter. Parameters A_1 and s_1 are related to the HRR field and the J -integral and are defined as

$$A_1 = \left(\frac{J}{\alpha \sigma_y \varepsilon_y I_n l_1} \right)^{-s_1} \quad (7)$$

$$s_1 = -\frac{1}{n+1} \quad (8)$$

Equation (6) uses the J -integral with parameter A_2 to describe the crack tip field under elastoplastic conditions; thus, it is called the J - A_2 theory. After introducing the J - A_2 method, Yang et al. [25] employed theoretical analysis and numerical simulations to discover that the parameter A_2 at the crack tip remains constant under large-scale yielding conditions. This finding indicates that the J - A_2 method is suitable for characterizing the effect of constraint conditions on fracture toughness and applies to the crack growth resistance curves of materials under different constraints. Zhu and Leis [26] used the J - A_2 method to investigate pipeline crack applicability assessment by adjusting the J - R resistance curve measured from high-constraint specimens.

A comparative analysis was conducted using the boundary layer model, and Williams' higher-order asymptotic analytical solution was compared with that of the HRR fields. Consequently, a new constraint parameter, Q , was introduced to characterize the deviation between the crack tip field and the reference field caused by structural geometry, load characteristics, and defect geometry. Hence, the J - Q theory was proposed [27–29] where the parameter Q is defined as

$$Q = \frac{\sigma_{\theta\theta} - \sigma_{\theta\theta}^{SSY}}{\sigma_y} \quad (9)$$

where $\sigma_{\theta\theta}$ represents the crack tip opening stress, and $\sigma_{\theta\theta}^{SSY}$ is the opening stress of the reference field under high constraint and small-scale yielding conditions (typically the HRR field). O'Dowd employed the finite element analysis to demonstrate that the J - Q theory is valid within the range of $J/\sigma_0 < r < 5 \times J/\sigma_0$. The author recommended using the parameter Q , calculated at $\theta = 0$ and $r = 2 \times J/\sigma_0$, to quantitatively characterize the constraint state of a structure or specimen. However, in subsequent research, O'Dowd and Shih (1992) [30] found that the crack tip field gradually deviates from the finite element solution for three-point bending specimens under large-scale yielding conditions. Moreover, parameter Q is significantly affected by the distance from the crack tip. Thus, the J - Q theory cannot accurately describe the crack tip field under these conditions. Similar conclusions were reached by Neimitz et al. [31] and Cravero and Ruggieri [32]. The authors also found that the parameter Q strongly correlates with the distance from the crack tip under large-scale yielding conditions.

It is important to note that the K - T , J - A_2 , and J - Q theories are all based on the assumptions of plane stress or plane strain conditions. These theories can only represent the influence of in-plane constraints on material fracture behavior. A numerical simulation analysis of the crack tip field of three-dimensional structures was conducted. Moreover,

the constraint parameter T_z was introduced to describe the effect of out-of-plane constraint on the crack tip stress field [33–35]. Parameter T_z is defined as

$$T_z = \frac{\sigma_{zz}}{\nu(\sigma_{xx} + \sigma_{yy})} \quad (10)$$

where ν represents Poisson's ratio, and σ_{xx} , σ_{yy} , and σ_{zz} represent the normal stresses in different directions at the crack tip. Guo used the J - T_z theory and analytical methods to calculate the crack tip field. The author demonstrated the effectiveness of the J - T_z method in describing out-of-plane constraints by comparing it with finite element results. In fracture problems in real structures, crack tip behavior is influenced by both in-plane and out-of-plane constraints. The J - Q , K - T , J - A_2 , and J - T_z theories alone cannot simultaneously account for the effects of both in-plane and out-of-plane constraints on crack tip behavior in structures [36–40]. Therefore, a three-parameter fracture mechanics theory based on two-parameter fracture mechanics must be developed.

2.3. Three-Parameter Fracture Mechanics

The three-parameter fracture mechanics theory describes the influence of in-plane and out-of-plane constraints on the crack tip field in solid structures. The out-of-plane constraint factor T_z was introduced into the linear elastic K - T two-parameter theory. Hence, the K - T - T_z three-parameter fracture mechanics theory was established. An analytical solution for the crack tip field was provided in three-dimensional solid structures under linear elastic conditions, laying the theoretical foundation for three-parameter fracture mechanics [41,42]. In the context of elastic–plastic fracture problems, Zhao [43] developed the J - Q - T_z three-parameter theory based on the J - Q and J - T_z theories. Zhao [43] proposed approximate solutions for the crack tip field under elastic–plastic conditions by combining the finite element analysis and theoretical derivations for different types of cracks. However, since calculating constraint parameters Q , T , and T_z is complex and these parameters interact, their application in fracture assessments of engineering structures presents several challenges. Consequently, recent research efforts have proposed using a single parameter to describe in-plane and out-of-plane constraints on crack tip behavior.

Clausmeyer et al. [44] proposed using stress triaxiality at the crack tip to represent in-plane and out-of-plane constraints. The authors suggested using the ratio of the plastic zone area at the crack tip in the structure to that in a high-constrained fracture toughness specimen as a unified constraint parameter [45,46]. Further research found that the sensitivity of stress triaxiality to in-plane and out-of-plane constraints varies [47–49]. Compared to stress triaxiality, the ratio of plastic zone areas can improve the relationship between different constraint states and fracture toughness J_{IC} . A significant plastic deformation often occurs at the crack tip during fracture due to the high level of fracture toughness in ductile metallic materials. The method that uses the area A_p enclosed by different equivalent plastic strain contours at the crack tip was proposed based on Mostafavi et al.'s method [50,51]. Moreover, the constraint parameter A_p was employed to compare the plastic zone area in a high-constrained specimen. They established the relationship between the J -integral and A_p under different in-plane and out-of-plane constraint conditions using finite element methods. Zhen et al. [52] also adopted A_p to establish a unified correlation between the crack tip opening angle and A_p for pipeline steels under different constraint states.

2.4. Comparison and Analysis

In summary, fracture mechanics theory has proposed fracture parameters such as the stress intensity factor K , J -integral, and CTOD to measure the stress and strain fields at the crack tip. T -stress, Q parameter, and A_2 parameter were introduced for the in-

plane constraint to characterize the effect of constraint on the crack tip field. In contrast, parameter T_z was introduced for out-of-plane constraint, forming dual-parameter fracture mechanics theories such as $K-T$, $J-T$, $J-Q$, $J-T_z$, and $J-T_z$. The constraint state at the crack tip in engineering structures often combines in-plane and out-of-plane constraints. Therefore, researchers have developed three-parameter theories, such as $K-T-T_z$ and $J-Q-T_z$, based on dual-parameter fracture mechanics theories to represent the coupling effect of in-plane and out-of-plane constraints on the fracture toughness of materials. Researchers have recently proposed parameters that can unify the description of in-plane and out-of-plane constraints, including stress triaxiality and plastic zone area at the crack tip. The researchers used these parameters to establish the relationship between crack tip constraint and material fracture toughness for different structures. However, current research on the relationship between crack tip constraint and fracture toughness in elastic–plastic fracture problems mainly focuses on the J -integral. In contrast, the pipeline industry generally uses CTOD as the fracture parameter.

Additionally, most studies on the constraint–fracture toughness relationship are focused on homogeneous materials. However, strength matching of the weld cannot be ignored for pipeline girth welds. Nevertheless, there is a lack of relevant studies on the relationship between crack tip constraint and fracture toughness in pipeline girth welds. Therefore, studies on the variation in fracture toughness CTOD of pipeline girth welds must be conducted under in-plane and out-of-plane constraints. In addition, their coupling effect should be investigated. These investigations would clarify accurate methods for characterizing crack tip constraint in girth welds and establish a unified correlation between fracture toughness CTOD and in-plane/out-of-plane constraints for pipeline girth welds. As a result, the pipeline industry could be guided to accurately characterize the actual toughness level of girth welds using high-constraint fracture toughness specimens. In addition, several recent studies have further clarified the role of weld strength mismatch and local heterogeneity in high-strength pipeline girth welds. Feng et al. [53] provided a comprehensive review of strength mismatch effects in modern high-grade pipeline girth welds and highlighted their implications for strain-based design and integrity management. Li et al. [2] conducted a detailed failure analysis of a cracked gas transmission pipeline girth weld, combining metallographic examination and finite element analysis to show how fabrication defects and local toughness loss can jointly trigger fracture under service loading. Zhang et al. [54] experimentally investigated inhomogeneous strain behavior across high-strength pipeline girth welds using cross-weld tensile tests and digital image correlation, demonstrating that local strain localization in softened zones can severely reduce the effective tensile strain capacity. These recent findings further support the need to explicitly account for weld strength mismatch and microstructural heterogeneity when characterizing fracture toughness and strain capacity of girth welds.

3. Pipeline Crack Driving Force

Various calculation methods can be employed to determine the pipeline crack driving force. The method, reference stress method, reference strain method, and semi-empirical formulas are typical representatives. These methods are fundamentally based on specific crack driving force calculation formulas, with the unknown parameters typically obtained through nonlinear fitting of numerical simulation results.

3.1. The EPRI

In 1981, the Electric Power Research Institute (EPRI) proposed a calculation method to obtain the crack driving force via J integral for plate cracks. According to the extensive

finite element simulations, the EPRI assumed that the material's constitutive relationship follows the Ramberg–Osgood model [55]:

$$J = J_e + J_p \quad (11)$$

where J_e is the elastic component of the J -integral, and J_p is the plastic component. These components can be calculated via Equations (12) and (13), respectively:

$$J_e = \sigma_0 \varepsilon_0 t_1 h_1 (n = 1) \left(\frac{P}{P_L} \right)^2 \quad (12)$$

where t_1 is the length of the crack ligament; h_1 is a dimensionless factor related to the crack size, structural geometry, and hardening coefficient; P is the load applied to the cracked structure, and P_L is the ultimate load of the cracked structure.

$$J_p = \alpha \sigma_0 \varepsilon_0 t_1 h_1 (n) \left(\frac{P}{P_L} \right)^{n+1} \quad (13)$$

The EPRI formulation for calculating the J -integral introduces the structural limit load into the crack driving force equation. Based on extensive finite element simulations, Kumar and Germán [56] provided tabulated values for h_1 in reference manuals. The authors provided a crucial foundation for the engineering calculation methods of pipeline crack driving forces. EPRI's elastoplastic J -integral estimation method only applies to simple cracked plate structures. Nevertheless, its concepts and formula structure have significantly influenced the development of engineering calculation methods for crack-driving forces in more complex structures.

Many researchers have conducted extensive studies on the limit load calculation methods for cracked pipelines to obtain the limit load of structures for the EPRI crack driving force calculation method. Three-dimensional nonlinear finite element analysis was utilized to investigate the quantitative relationships between the limit load of pipelines with surface cracks and parameters such as crack size, pipe dimensions, and material characteristics under internal pressure, tension, and bending loads [57]. The authors proposed an improved limit load calculation method based on net section yielding conditions. Paredes and Ruggieri [58] developed an improved J -integral and CTOD calculation method for cracks in weld seams in cracked pipelines under pure bending loads. The authors replaced the material parameters in the original EPRI method with weld material characteristics by incorporating the strength mismatch coefficient into h_1 . Moreover, they quantitatively discussed the variations in h_1 corresponding to J -integral and CTOD with influencing parameters through static crack analysis. Lei and Ainsworth [59] equated the dissimilar stress–strain relationships of weld metal and base material to a homogeneous material. The authors integrated the equivalent stress–strain relationship and the limit load of strength-mismatched structures into the EPRI calculation method. Lastly, they provided a method for calculating the equivalent stress–strain relationship using the limit load, establishing a crack driving force calculation method for cracked weld structures.

$$\sigma_{eq}^{Mism}(\varepsilon_p) = \left[\frac{P_L^{Mism} - P_L^b}{P_L^w - P_L^b} \right] \sigma_w(\varepsilon_p) + \left[\frac{P_L^w - P_L^{Mism}}{P_L^w - P_L^b} \right] \sigma_b(\varepsilon_p) \quad (14)$$

These studies have significantly enhanced the applicability of the EPRI method when addressing complex weld structures. To further address the complex loading conditions encountered in actual pipeline operation—namely the coupled effects of internal pressure and large axial plastic strain—recent research has achieved new methodological advances.

Through dimensionless analysis and extensive finite element computations, Zhao et al. [60] overcame the difficulty in determining ultimate loads inherent in traditional methods. They directly established an explicit formula for the strain-type J-integral applicable to circumferential cracks on the inner surface of pipelines. This formula incorporates axial strain, the ratio of circumferential stress to yield strength, crack size, and material hardening index as input parameters, enabling rapid assessment of crack driving forces under the combined action of internal pressure and axial displacement. Although this work effectively addresses complexity under coupled loading conditions, the geometric intricacy of the crack itself remains a critical challenge. Conventional approaches prove difficult to apply directly to such geometrically complex defects subjected to bending moments. Park et al. [61] proposed an innovative engineering solution based on the principle of energy equivalence: conceptually replacing the cracked pipe section with an equivalent thinned crack-free section, thereby transforming the problem into a simplified crack-free beam analysis. This approach derives a closed-form solution for the elastic–plastic J-integral, balancing accuracy with computational efficiency. It proves particularly suitable for probabilistic fracture mechanics assessments requiring extensive iterations. This advancement significantly extends the application scope of EPRI-type engineering methods, demonstrating their adaptability to handling extreme geometric complexities beyond the reach of conventional defect models.

3.2. Reference Stress Method

The EPRI crack driving force calculation method requires the material's stress–strain relationship to adhere to the Ramberg–Osgood constitutive model. Therefore, Ainsworth [62] proposed the reference stress method (Equation (15)). This method introduces reference stress to reduce the reliance of the EPRI method on the material constitutive model. Simultaneously, the influence of material hardening characteristics on the plastic components of J-integral and CTOD is minimized.

$$\sigma_{ref} = \sigma_0 \frac{P}{P_L} \quad (15)$$

Equation (16) can be obtained by combining Equations (12), (13) and (15):

$$J_p = J_e \frac{h_1(n)}{h_1(n=1)} \left(\frac{E\varepsilon_{ref}}{\sigma_{ref}} - 1 \right) \quad (16)$$

Ainsworth proposed a crack-driving force calculation method that reduces the sensitivity of the dimensionless factor to the hardening coefficient by selecting an appropriate limit load (P_L). The authors developed a more generalized form of the calculation method by introducing a plasticity correction term, expanding the applicability of the EPRI method:

$$f(L_r) = \sqrt{\frac{J_e}{J}} = \left(\frac{E\varepsilon_{ref}}{L_r\sigma_0} + \frac{L_r^3\sigma_0}{2E\varepsilon_{ref}} \right)^{-0.5} \quad (17)$$

Kim and Budden [63] introduced a correction factor based on the reference stress method to improve the accuracy of J-integral and CTOD calculations by proposing a modified method for limit load calculations under tensile and bending conditions. Based on Kim's work, Tkaczyk et al. [64] developed a correction factor for limiting loads in pipes with surface cracks subjected to bending loads. The authors incorporated crack length, depth, and material hardening characteristics into the factor, enhancing the precision of the reference stress method for calculating crack driving force. Jia et al. [65] proposed an improved Kastner solution that considers hoop stress to address the limitations of the

reference stress method under biaxial loads and expand its applicability. Li et al. [66] also introduced an improved reference stress method by assuming the corrected limit load calculation formula, as shown in Equation (18). The authors investigated the impact of crack size, diameter-to-thickness ratio, and material hardening characteristics on the correction factor λ by utilizing the semi-empirical J -integral calculation model proposed by Nourpanah and Taheri [67]. Hence, they provided a calculation method for λ and proposed a method for calculating the crack driving force J -integral using the reference stress method:

$$P = 2\pi r t \sigma_0 \lambda \quad (18)$$

In recent research over the past two years, Takanashi et al. [68] directly applied this method to assess crack propagation in nuclear power pipelines under ultra-low-cycle fatigue. Experimental results indicate that while the method's predicted lifetimes tend to be non-conservative (by approximately 33% on average), its simplicity requiring no complex finite element analysis demonstrates significant value for rapid engineering evaluations. Concurrently, Tanaka et al. [69] conducted a systematic three-dimensional elastoplastic finite element benchmark analysis, providing high-precision J -integral comparison data for the reference stress method. They systematically evaluated the accuracy and deviation of simplified formulas in standards such as BS7910 and R6 under various hardening models and crack geometries. This provided direct data support for key parameter corrections and formula optimisation, driving the method towards higher precision.

3.3. Reference Strain Method

Using stress-based methods to calculate the crack driving force in structures may no longer be accurate due to the potential for small stress variations to cause significant strain changes under large-scale yielding conditions. Therefore, based on the reference stress method, Linkens et al. developed a method for calculating the crack driving force J -integral based on reference strain under large-scale yielding conditions:

$$J = 2F^2 \pi a \sigma_{ref} \epsilon_{ref} \quad (19)$$

where F is a coefficient related to the calculated stress intensity factor. The reference strain method proposed by Linkens et al. only applies to cases with small crack sizes. This method represents the reference strain through the nominal strain experienced by the structure and determines the reference stress value at that strain using the material's stress-strain curve. Budden [70] improved the reference strain method by proposing a model for calculating the crack driving force based on reference strain:

$$J = \begin{cases} J_e \left[\frac{D_r \sigma_0}{\sigma_{ref}} + \frac{\sigma_{ref}^3}{2D_r \sigma_0^3} \right] & D_r \leq 1 \\ J_e \frac{2E\epsilon_{ref}}{\sigma_{ref}} & D_r > 1 \end{cases} \quad (20)$$

where D_r is a strain-based plastic instability factor, defined as $\epsilon_{ref}/\epsilon_0$. The reference strain method proposed by Budden suggests using the far-end nominal axial strain to replace the reference strain. However, Jia et al. found that directly substituting the far-end nominal strain for the reference strain could lead to insufficient conservatism in the results when the crack is large, or the diameter-to-thickness ratio is small. Therefore, Jia et al. [71] quantitatively explored the relationship between reference strain and nominal strain under different crack sizes and material yield-strength ratios, improving the calculation of crack driving force in pipelines based on reference strain.

The accuracy of the reference strain method fundamentally relies upon the precise characterization of the material stress–strain relationship. Traditional constitutive models perform well in describing quasi-static, monotonic loading behavior, yet their descriptive capabilities face challenges when addressing complex loading conditions involving dynamic loading, high strain rates, or materials exhibiting non-monotonic deformation behavior. Zhao, Petrov, and Volko [72] proposed an incremental relaxation plasticity model based on the structure-time approach and the concept of nurturing time. By introducing a time-dependent dynamic stress intensity and employing an incrementally updated stress predictor, this model can uniformly describe strain rate effects, non-monotonic yield drop phenomena, and complex work hardening responses without relying on explicit strain rate terms. Experimental validation on materials including 6082-T6 aluminum alloy, API 5L X70 steel, and Ti-6Al-4V titanium alloy demonstrates that this model outperforms traditional empirical models such as Johnson–Cook across a wide strain rate range, particularly in capturing dynamic yield peaks and subsequent flow behavior.

3.4. Semi-Empirical Formula Method

Establishing a finite element analysis model for crack driving force related to the research object and investigating the influence of various parameters on crack driving force through finite element calculations, along with fitting a semi-empirical formula based on the analysis results, has become an important method for researching complex pipeline girth weld crack driving force models in recent years. Jayadevan et al. [73] analyzed the variation in CTOD and loading strain under combined tensile and internal pressure. The authors found a linear relationship between CTOD and far-end axial strain under large conditions. Moreover, they established a crack driving force calculation model. A method for calculating CTOD in subsea pipelines under large deformation conditions was proposed, and the concept of equivalent wall thickness was introduced based on the analysis of biaxial loading effects [74]. Additionally, the concept of equivalent ligament width was introduced to consider the influence of weld strength matching and girth weld misalignment. This concept, conducted by the Norwegian Institute of Science and Technology, is currently one of the most effective methods for evaluating the applicability of cracked pipeline girth welds that has gained wide international recognition. Nourpanah and Taheri [67] focused on cracked subsea pipelines under bending loads in large deformation conditions. The authors proposed a semi-empirical prediction formula for J-integral. They provided the fitted constant values for different diameter-to-thickness ratios, crack sizes, and material yield strength ratios in tabular form. Zhao et al. [75] analyzed the relationship between crack driving force and far-end strain under large deformation conditions for centerline and embedded cracks in subsea pipeline welds. Lastly, the authors proposed a semi-empirical model for calculating CTOD using far-end strain under different crack sizes and misalignment conditions. Jin et al. [76] proposed an improved analytical prediction model for thin-walled pipe circumferential welds, addressing the issue of overly conservative or inaccurate residual stress empirical envelopes in existing assessment criteria. By incorporating equivalent heat sources and thin-shell theory, this method efficiently predicts plastic zones and residual stresses, thereby providing more precise inputs for crack driving force calculations based on semi-empirical formulas such as reference strain.

3.5. Comparison and Analysis

Currently, the calculation methods for pipeline crack driving force include the EPRI, reference stress, reference strain, and semi-empirical formula methods. The EPRI method requires the material constitutive model to meet the Ramberg–Osgood model, limiting its applicability. The reference stress method is restricted by choosing the ultimate load

formula and is fundamentally a stress-based calculation method. Therefore, this method cannot accurately quantify the crack driving force under large-scale yield conditions. The traditional reference strain method is a derivative of the reference stress method that improves the calculation accuracy of the crack driving force under large-scale yield conditions. However, selecting the reference strain still requires extensive research. The semi-empirical formula method is based on many finite element calculation results. Moreover, this method is the most accurate, reliable, and applicable means for exploring the crack driving force under large deformation conditions. As a result, this method has been widely used in solving issues such as submarine pipeline installation.

4. Full-Scale Fracture Test

Full-scale pipeline girth weld fracture tests are the most accurate method for evaluating girth welds' true limit tensile strain capacity. The data obtained from these tests are crucial for correcting small-scale standard specimen fracture toughness testing results, validating numerical models of pipeline girth weld fracture, and assessing girth weld failure methods. Full-scale pipeline girth weld fracture tests mainly include full-scale real pipelines and large-size curved wide plate tests. The full-scale real pipeline test accurately reflects the loading conditions of pipeline girth welds and is the only method that considers the impact of internal pressure on girth weld fracture failure. Bending loading is typically used to apply tensile stress to the girth weld cracks due to the high axial tensile loading in full-scale pipelines. In the early 21st century, Japan's Central Research Institute of Electric Power Industry conducted girth weld tests on 318 mm STPT410 steel pipelines using a four-point bending method, and the results demonstrated that the predicted critical loads and fracture behavior obtained from the EPFM/FAC-based assessment agreed closely with full-scale failure tests, confirming the validity of the developed flaw-evaluation approach for moderate-toughness Class 2 and 3 piping [77]. Similarly, the University of Alberta and TransCanada Pipeline Company tested the strain capacity of 508 mm X52 pipeline girth welds after long-term service using comparable methods, and the results showed that internal pressure and flaw size markedly reduced the tensile strain capacity—where deep flaws dominated the loss of capacity, and internal pressure could lower the strain capacity by more than 40% depending on the flaw geometry [78]. However, due to limitations in testing equipment, load capacity, funding, and facilities, few full-scale real pipeline tests for large-diameter, high-strength pipelines are conducted internationally. In 2024, China University of Petroleum, Beijing (CUP) collaborated with PipeChina to conduct multiple four-point bending full-scale pipeline fracture tests on a 1219 mm in diameter, 21.4 mm thick X80 pipeline. A typical four-point bending full-scale fracture test setup is illustrated in Figure 1.

Curved wide plate tests closely resembling the geometric dimensions of full-scale pipelines are widely used to explore pipeline girth welds' limit tensile strain capacity to balance testing costs and effectiveness. Multiple research institutions, including CRES, C-FER, the Institute of Standards and Technology (NIST), and CUP, have conducted extensive curved wide plate tests, with publicly available literature documenting no fewer than 60 sets of tests involving steel grades from X65 to X100 [79,80]. In 2021, the China University of Petroleum (Beijing) successfully tested a curved wide plate on a 1422 mm diameter X80 pipeline girth weld. The tests obtained data on the overall deformation of the wide plate and the fracture performance of the girth weld cracks by utilizing DIC technology, displacement monitoring (LVDT) technology, and strain monitoring techniques. Hence, the accuracy of the finite element model was further validated [81]. The curved wide-plate test setup and the numerical inversion procedure are illustrated in Figure 2. Recently, Zhang et al. [82] carried out a combined experimental-numerical study on curved wide plate

specimens extracted from X80 girth welds, and quantified the interaction between internal pressure, axial loading and weld strength mismatch on the J-integral and CTOD resistance. Their results provide updated benchmark data for calibrating finite element models and constraint-based fracture parameters under realistic loading paths. Complementary to this, Guo et al. [83] performed a systematic numerical investigation of the influence of weld geometry and weld metal properties on the local stress–strain states in X80 girth welds, revealing the strong sensitivity of crack-driving force to misalignment, wall-thickness transition and weld overmatch/undermatch conditions *BB*. These new data sets and simulations help refine the estimation of crack driving forces for high-strength pipeline girth welds beyond traditional idealized assumptions.



Figure 1. Four-point bending full-scale pipeline girth weld fracture test.

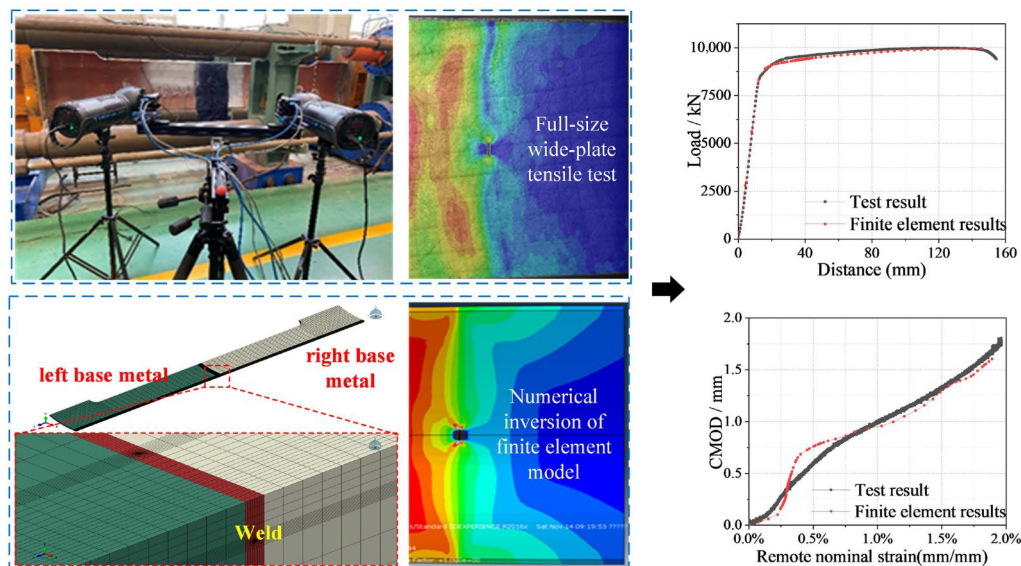


Figure 2. Curved wide plate test and finite element model numerical inversion diagram.

This paper shows 101 full-scale pipeline fracture and curved wide plate tests in the open literature (Table 1). The crack location mainly considers the base metal (BM), weld metal (WM), and heat-affected zone (HAZ). There are 43 groups of full-size pipeline tests; most of them are distributed in X65 and below steel grades. The curved wide plate test comprises 58 groups, mainly X80 and X100 steel grades. Detailed experimental data from PRCI, CRES, and other institutions are available for subsequent verification of the ultimate tensile strain capacity model. As summarized in Table 1, these datasets provide a

comprehensive experimental basis for evaluating the applicability of different tensile strain capacity models over a wide range of steel grades and crack locations. At the same time, the distribution of tests also highlights data gaps for certain grade–location combinations, which should be considered when interpreting the prediction accuracy and applicability limits of the proposed models.

Table 1. Summary of full-size pipeline and curved wide-plate tests by steel grade and crack location.

Classification	Type	Full-Size Pipeline			Curved Wide Plate		
	Crack Location	BM	WM	HAZ	BM	WM	HAZ
	X42		8				
	X52	8					
	X65	4	9	11		4	6
	X80		3			6	4
	X100				2	18	18

5. Failure Assessment Diagram

5.1. Stress-Based Failure Assessment Diagram

The Central Electricity Generating Board (CEGB) of the UK [55] proposed the Failure Assessment Diagram (FAD) method to assess the safety of crack defects in metallic structures. This method considers crack initiation and plastic instability as two failure modes. The method constructs a limit state evaluation curve based on the ratio of the applied load to the structural limit load (referred to as the load ratio L_r) and the ratio of the structural linear elastic fracture parameter to the material fracture toughness (referred to as the fracture ratio K_r). The evaluation point is considered safe within the failure assessment curve [84]; otherwise, it is deemed unsafe. Load (Equation (21)) and fracture (Equation (22)) ratios are defined as follows:

$$L_r = \frac{P}{P_L} \quad (21)$$

$$K_r = \sqrt{\frac{J_e}{J_{mat}}} \quad (22)$$

where J_{mat} is the material's fracture toughness, measured in kJ/m^2 .

The relationship between K_r and L_r for the stress-based FAD is illustrated in Figure 3.

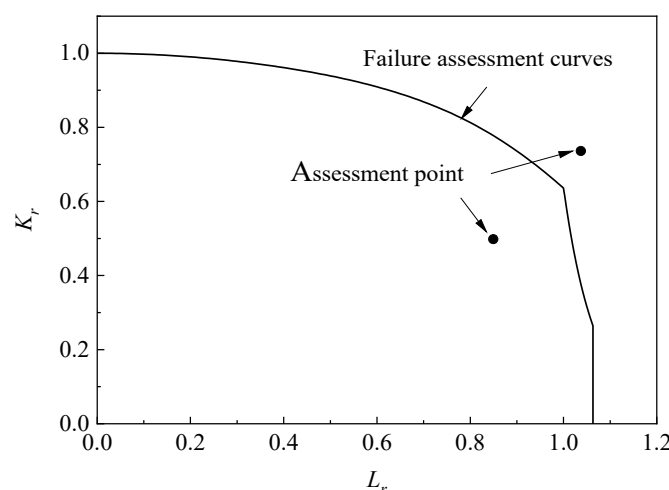


Figure 3. Stress-based failure assessment diagram (FAD) in K_r – L_r space, showing the failure assessment curve and the corresponding assessment point for a specific flaw.

The failure assessment diagram (FAD) method is widely used in engineering due to its simplicity, ease of calculation, and intuitive evaluation results. Many domestic and international standards recommend using the FAD method to assess cracked structures. Each standard further categorizes the evaluation methods into different levels based on the available data and the conservativeness of the evaluation method. Generally, the first-level evaluation's failure assessment curve requires the least material data and is characterized by a high level of conservativeness. Slight differences can be observed in the first-level evaluation curves specified by different standards. The first-level evaluation curves in R6-2001 [85], API 579-2016 [86], and GB/T 19624:2019 [87] are shown in Equation (23), while the first-level evaluation curve in BS 7910:2019 [88] is shown in Equation (24):

$$f(L_r) = (1 - 0.14L_r^2)[0.3 + 0.7 \exp(-0.65L_r^6)] \quad (23)$$

$$\begin{cases} f(L_r) = \left(1 + \frac{1}{2}L_r^2\right)^{-0.5} [0.3 + 0.7 \exp(-\mu L_r^6)] & L_r \leq 1 \\ f(L_r) = f(L_r = 1)L_r^{(N-1)/(2N)} & 1 < L_r < L_{r,\max} \end{cases} \quad (24)$$

where $\mu = \min\left(0.001 \frac{E}{\sigma_y}, 0.6\right)$ and $N = 0.3\left(1 - \frac{\sigma_y}{\sigma_u}\right)$.

As the evaluation level increases, the failure assessment diagram method requires additional detailed material property data, such as the stress–strain relationship curve of the material at the crack location, the degree of constraint, and the material's fracture toughness under conditions similar to the pipeline. The reference stress method proposed by Miller and Ainsworth [89] is currently recommended as a second-level evaluation method in the standards:

$$f(L_r) = \sqrt{\frac{J_e}{J}} = \left(\frac{E\varepsilon_{ref}}{L_r\sigma_0} + \frac{L_r^3\sigma_0}{2E\varepsilon_{ref}}\right)^{-0.5} \quad (25)$$

In the traditional failure assessment diagram, the load ratio is the ratio of the force to the limit load, making it essentially a stress-based evaluation method. Smith [90] found that this method may lead to non-conservative evaluation results if relatively large deformation occurs, the material hardening coefficient is relatively small, or the crack length is short. Smith introduced a correction factor into the failure assessment curve to reduce the potential non-conservativeness. However, the analysis revealed that the conservative nature of the evaluation results after correction remains relatively high in most cases, potentially leading to unnecessary repair work. The correction term, X , is shown in Equation (26):

$$f(L_r) = \left(\frac{X \cdot E\varepsilon_{ref}}{L_r\sigma_0} + \frac{L_r^3\sigma_0}{2E\varepsilon_{ref}}\right)^{-0.5} \quad (26)$$

where X is the correction term related to the load ratio.

In recent years, several studies have further improved the stress-based FAD methodology for welded pipelines. Zhang et al. [82] combined curved wide-plate tests with finite-element simulations to quantify the evolution of the Kr–Lr trajectory under combined pressure and axial loading, providing updated calibration data for FAD curves in high-strength girth welds. Guo et al. [83] numerically demonstrated that weld geometry, misalignment, and weld–metal mismatch significantly influence the reference stress and limit-load solutions, indicating that next-generation FAD formulations should explicitly incorporate weld heterogeneity. Guo et al. [91] conducted a systematic quantitative analysis of commonly used FAD evaluation models. Results indicate that evaluation accuracy is primarily governed by three key input categories: the reference stress (L_r) model, the stress intensity factor (KI) model, and the fracture toughness (Kmat) model. Among these, L_r

and KI exert the most significant influence, while Kmat's impact is comparatively secondary. By comparing 250 sets of validation data, the authors discovered that different codes (such as BS 7910 and API) employ markedly divergent methodologies for calculating Lr, KI, and Kmat, leading to systematic over-conservative or under-conservative prediction outcomes. Consequently, the paper proposes an integrated EFAD approach combining the Lr model from BS 7910 with the KI model from API. This is further calibrated for the safety factor f_r by incorporating different Kmat acquisition methods (DM/IDM), enabling the improved EFAD to demonstrate enhanced consistency and predictive accuracy across the entire dataset.

5.2. Strain-Based Failure Assessment Diagram

Structures undergo extensive yielding and significant plastic deformation under large deformation conditions, making strain-based assessment methods more appropriate. The reference strain-based method for calculating crack driving force proposed by Budden [70] can be transformed into a strain-based failure assessment diagram (Figure 4). The accuracy of the strain-based failure assessment diagram was improved by proposing a reference strain calculation model that considers remote nominal strain, crack size, and pipeline dimensions. The method is based on the relationship between finite element assessment points and failure assessment curve positions [71]. The British Standards Institution introduced the strain-based failure assessment diagram method in BS 7910-2019. The standard recommends using the strain values corresponding to the reference stress on the stress–strain curve as the reference strain. More recent developments have continued to refine strain-based FAD approaches. Zhao et al. [92] proposed a dynamic fracture model for girth-welded pipelines under transient deformation, demonstrating that strain-based assessment curves can be significantly affected by local constraint variations during rapid loading. Zhang et al. [54] further reported that inhomogeneous strain localization in softened HAZ regions alters the normalized plastic-strain parameter used in strain-based FADs, suggesting that weld-specific strain-hardening behavior should be incorporated into future formulations.

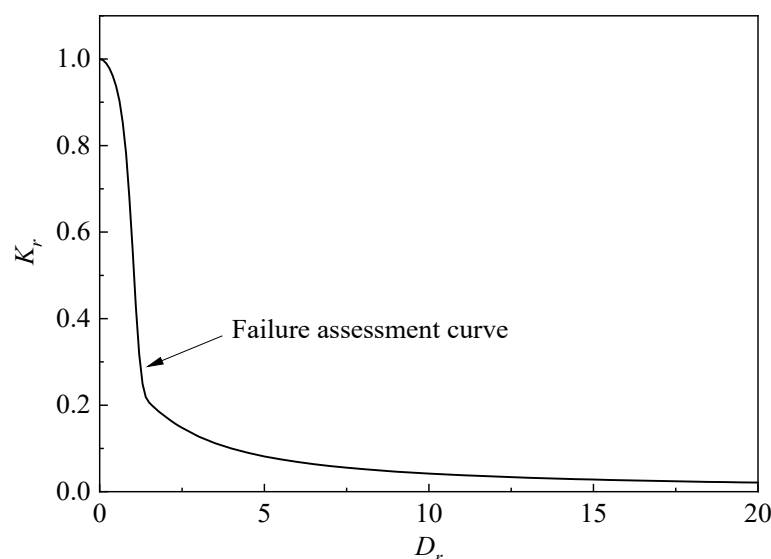


Figure 4. Strain-based failure assessment diagram (FAD) in K_r - D_r space. The curve represents the strain-based failure assessment line, which relates the normalized crack driving force K_r to the normalized plastic displacement parameter D_r . Points located below the curve indicate acceptable flaw conditions, while points above the curve correspond to predicted failure.

5.3. Considering Strength Matching in Failure Assessment Diagram

The failure assessment curve for cracks at the pipe girth weld or fusion line is typically constructed using the material with the lowest strength in the girth weld to achieve the most conservative evaluation results [93,94]. Lei and Ainsworth [59] proposed an equivalent stress–strain relationship method to improve the accuracy of crack assessments in girth welds by treating the heterogeneous material of the girth weld as homogeneous. Lei and Ainsworth [95] developed a method to construct the failure assessment curve based on the equivalent stress–strain relationship for evaluating cracks at weld locations. This method is now incorporated into Appendix I of BS 7910-2019 for assessing the safety of welded structures with crack defects. However, research by Lei and Ainsworth [59] indicates that the evaluation results may sometimes lack sufficient conservatism, even though the equivalent stress–strain relationship method significantly reduces the conservatism of traditional methods. Therefore, Wu et al. [96] investigated pipelines with local girth cracks on the outer surface under tensile loading. The authors refined the girth weld limit load calculation model. They proposed a failure assessment diagram for girth welds that considers strength matching based on the equivalent stress–strain relationship method by comparing finite element assessment points with the failure assessment curve. As a result, potential non-conservative evaluation conclusions might be avoided while improving the assessment accuracy. Wu et al. [97] recently enhanced the fracture assessment of pipe girth welds by refining the calculation methodology of the load ratio in the failure assessment diagram. By improving the reference stress and limit load solutions for root crack defects, their work significantly reduced the conservatism and scatter of FAD-based assessments for undermatched girth welds. These advances, together with earlier strength-matching-dependent FAD formulations, indicate that future assessment procedures for high-strength pipelines will likely adopt weld-mismatch-sensitive FAD curves rather than generic master curves.

In addition, the Structural Integrity Assessment Procedure for European Industry (SINTAP) proposed a failure assessment diagram method that considers weld strength matching. Different failure assessment curves were presented based on the yield and tensile strengths of the weld and base material, depending on whether there is a noticeable yield plateau in the stress–strain relationship of the weld and base material. Steps to establish the failure assessment diagram using the equivalent stress–strain relationship method were proposed for situations where the complete stress–strain relationships of the weld and base material can be obtained. Kim et al. indicate that the evaluation method proposed by SINTAP can conduct load-bearing capacity assessments for crack-containing welded structures with strength mismatches.

6. Ultimate Tensile Strain Capacity Model

6.1. CSA Z662

The CSA Z662-07 model considers the shape of surface cracks as semi-elliptical, with a length of $2c$, a height of a , and a wall thickness of t [98]. The formula for calculating the ultimate tensile strain for surface cracks is as follows:

$$\varepsilon_{\text{limit}} = \delta_{\text{app}}^{(2.36-1.58\lambda-0.101\zeta\eta)} \left(1 + 16.1\lambda^{-4.45}\right) \left(-0.157 + 0.239\zeta^{-0.241}\eta^{-0.315}\right) \quad (27)$$

where λ represents the yield-to-tensile strength ratio of the pipe, defined as $\zeta = 2c/t$ and $\eta = a/t$. The CSA Z662 model employs the concept of apparent fracture toughness proposed by the Pipeline Research Council International (PRCI) for selecting the material's fracture toughness). Here, δ_{app} denotes the apparent fracture toughness of the pipe, measured in millimeters. The CSA Z662 ultimate tensile strain model employs a structural failure

assessment method based on crack initiation criteria. When the crack tip starts to propagate, the opening displacement at the crack tip corresponds to the pipe's apparent fracture toughness ($\delta_{app} = CTOD_c$); the corresponding remote strain is the maximum tensile strain. The model's application range is defined as $1 \leq \xi \leq 10$, $\eta \leq 0.5$, $D/t \geq 32$, $0.7 \leq \lambda \leq 0.95$, and $0.1 \leq \delta_{app} \leq 0.3$. Since this ultimate tensile strain calculation model is based on the weld's high strength matching, it is unsuitable for low-strength matching of girth welds and does not quantitatively consider the impact of the weld strength matching factor.

The fracture toughness used in the formula under low-constraint conditions can be directly measured through low-constraint state fracture tests or verified using Equation (28). As a result, the fracture toughness obtained from small-scale samples can represent the actual toughness level of the pipeline.

$$\delta_{app} = CTOD_c^{LC} = \min \left(3 \cdot CTOD_{c_min}^{HC}, 2 \cdot CTOD_{c_avg}^{HC}, \frac{0.2}{30} CVN_{min}, \frac{0.2}{45} CNV_{avg} \right) \quad (28)$$

where $CTOD_c^{LC}$ is the fracture toughness of the sample under low-constraint conditions, $CTOD_{c_min}^{HC}$ and $CTOD_{c_avg}^{HC}$ are the minimum and average fracture toughness values under high-constraint conditions, respectively, with units in millimeters. Parameters CVN_{min} and CNV_{avg} are the minimum and average values of the Charpy impact energy of the samples, respectively, with units in J.

6.2. PRCI-CRES

The Center for Reliable Energy Systems (CRES), C-FER, and Microalloy International developed the second-generation limit tensile strain calculation method based on the first-generation PRCI model. This method uses tensile strength as the benchmark for weld strength matching and considers the effects of strength mismatch coefficients, internal pressure, and misalignment. The authors proposed the corresponding limit tensile strain calculation method by analyzing a large number of numerical simulation results based on static cracks, as shown in Equations (29) and (30) [79,80,99–102].

$$TSC_p = A \frac{f(\delta_{app})}{1 + f(\delta_{app})} \quad (29)$$

$$f(\delta) = (C\delta_{app})^{B\delta_{app}^D} \quad (30)$$

where δ_{app} represents the material's apparent fracture toughness, with the crack tip opening displacement at crack initiation ($CTOD_c$) still used as the representation. Parameters A , B , C , and D are functions with crack size, misalignment, strength ratio, and strength mismatch coefficient, respectively, as variables. The strain capacity calculation models for different notch types are consistent in form. However, they differ in the specific values of the coefficients. Since the initial formula of the PRCI-CRES model only applies to a pipe diameter of 1067 mm and a wall thickness of 15.9 mm, the model proposes a correction factor $sf(t)$ for different wall thicknesses:

$$sf(t) = \left(\frac{t_0}{t} \right)^{0.8096(1+1.503\psi^{1.229})} \quad (31)$$

where $t_0 = 15.9$ and ψ is the ratio of misalignment to wall thickness. The modified ultimate tensile strain is obtained by applying the wall thickness correction factor to the ultimate tensile strain value:

$$TSC_p(t) = TSC_p \cdot sf(t) \quad (32)$$

Regarding the influence of internal pressure on the strain capacity of pipelines, Liu et al. demonstrated that when the hoop stress reaches 0.6 times the yield strength, the strain capacity no longer changes with internal pressure. The authors proposed the corresponding correction factor for hoop stress less than 0.6 times the yield strength as follows:

$$TSC = \begin{cases} TSC_p & 0.6 \leq f_p \leq 0.8 \\ TSC_0 + \frac{5f_p}{3}(TSC_p - TSC_0) & f_p \leq 0.6 \end{cases} \quad (33)$$

where TSC_0 is 1.5 times TSC_p . The apparent fracture toughness used in the PRCI-CRES model can be derived from the Charpy impact energy on the platform of the sample and the fracture toughness of samples at high constraint levels. The upper shelf Charpy impact energy can be converted to apparent fracture toughness as follows:

$$\delta_{app} = \begin{cases} (0.0080 \times \lambda - 0.0014) \times CVN_{us} & \text{for X52 - X65} \\ (0.0086 \times \lambda - 0.0021) \times CVN_{us} & \text{for X70 - X80} \end{cases} \quad (34)$$

where λ represents the yield strength ratio; CVN_{us} is the upper shelf Charpy impact energy, measured in joules (J). This formula is applicable for $\delta_{app} \leq 1.2$ mm. A constraint conversion factor must be used if the fracture toughness is calculated using a specimen with a high crack tip constraint level (such as a deeply notched SENB). The conversion factor used in the PRCI-CRES model is between 1.5 and 2.0, with a recommended value of 1.75. The following relationship can be applied if the R-resistance curve of a SENT specimen is used for calculating δ_{app} :

$$\delta_{app} = \delta \cdot \Delta a^n \quad (35)$$

where δ and n are parameters fitted according to the shape of the R-resistance curve; the crack growth increment Δa depends on the wall thickness, where a wall thickness of 12.7 mm corresponds to $\Delta a = 0.5$ mm, and a wall thickness of 25.4 mm corresponds to $\Delta a = 1.0$ mm. The values of Δa for other wall thicknesses are obtained through linear interpolation.

6.3. EXXON MOBIL

In 2011, EXXON MOBIL analyzed the impact of factors such as wall thickness, crack depth and length, misalignment, crack location, material yield-to-tensile strength ratio, weld strength matching coefficient (using tensile strength as a benchmark), CTOD-R resistance curves for welds and heat-affected zones, uniform elongation of pipe material, and internal pressure on strain capacity based on crack instability propagation criteria using a static crack finite element model. The authors proposed the first-generation ultimate tensile strain calculation model by analyzing a large amount of finite element calculation data encompassing various steel grades [103,104]. However, since the first-generation ultimate strain formula is established based on data from a static crack finite element model, it cannot accurately simulate the material's toughness tearing process. As a result, the failure features of the structure and material can be difficult to characterize, limiting the application range for the model.

In 2014, EXXON MOBIL researched the second generation of tensile strain capacity. They directly simulated the process of material damage and structural toughness failure by employing a GTN damage constitutive model to establish a finite element model, addressing the shortcomings of the previous static crack model. The researchers detailed the effects of parameters such as pipe steel grade, geometric dimensions, material properties, and crack size on tensile strain capacity using the extensive computational data obtained

from this model. As a result, the calculation model for the second generation of tensile strain capacity was proposed [105,106]:

$$TSC = \begin{cases} PF \cdot TSC_{0.8} & TSC < 2/3 UEL \\ 2/3 \cdot UEL & TSC \geq 2/3 UEL \end{cases} \quad (36)$$

where PF is the internal pressure correction factor, $TSC_{0.8}$ is the tensile strain capacity when the internal pressure causes the hoop stress to equal 80% of the yield strength, and UEL is the uniform material elongation. If the tensile strain calculated from Equation (36) exceeds $2/3 UEL$, the failure mode of the structure is considered plastic instability. Hence, the corresponding tensile strain capacity is taken as $2/3 UEL$. Otherwise, the internal pressure correction factor and $TSC_{0.8}$ product limit the tensile strain. The specific calculation formula for $TSC_{0.8}$ is as follows:

$$TSC_{0.8} = \frac{\left[\phi \left(N, \frac{K}{\sigma_Y}, \lambda, \frac{e}{t} \right)^{\frac{\delta}{t}} + C_7 \right] \cdot \left(C_1 \frac{D}{t} + C_2 \right)}{C_6 + C_8 \left(\frac{a/t}{1-a/t} \right)^{C_3} \cdot \tanh \left(C_4 \left(\frac{2C}{t} \right)^{C_5} \right)} \quad (37)$$

where D and t are the pipeline diameter and wall thickness, a and C are the crack depth and length, N and K are the material model hardening exponent and strength coefficient, δ is the crack tip opening displacement corresponding to a crack growth of 1 mm, λ is the weld strength mismatch coefficient, and e is the weld offset. Parameter ϕ is the fitting function, and C_1 – C_8 are fitting coefficients. The form internal pressure correction factor PF can be expressed as

$$PF = \begin{cases} (3 \times 10^{-4})(R_h)^2 - (3.3 \times 10^{-2})R_h + 1.85 & R_h < 40 \\ 1 & R_h \geq 40 \end{cases} \quad (38)$$

where R_h is the ratio of the hoop stress to the material's minimum yield strength (SMYS), where $R_h = 40$ indicates that the hoop stress is 40% of the minimum yield strength. The coefficients in the second-generation EXXON MOBIL model are independent of the steel grade of the pipe. The model defines three R-resistance curves in advance (i.e., Equation (35), with $\delta = 0.9, 1.2, 1.5$ and $n = 0.5, 0.6, 0.65$) to calculate the apparent fracture toughness, allowing the selection of a single curve to compute the apparent fracture toughness.

6.4. CUP

The existing predictive models only apply to high-strength matching conditions in welds and are limited in covering large-diameter (1422 mm), thick-walled, high-strength pipelines. Researchers at CUP focused on pipelines with girth root cracks in welds [81,107–110]. Using finite element analysis and parameterized programming, they established a three-dimensional finite element model for the crack driving force in girth welds and, through batch computation and parallel computing, constructed a database of 21,870 crack-driving-force/strain-capacity samples for large-diameter ($D = 1422$ mm) pipelines with wall thicknesses of 21.4, 25.7 and 30.8 mm. On this basis, they systematically quantified the influence of weld strength-matching coefficient, crack depth and length, base-metal yield-to-tensile ratio, HAZ softening, misalignment, wall thickness, internal pressure and crack location on the strain capacity of girth welds, explicitly covering low strength-matching conditions. A machine-learning regression model (XGBoost) was then developed to predict the strain capacity of full-size girth welds by combining the numerical crack-driving-force database with fracture toughness characterized from Charpy impact (CVN) data, and the model was validated against 88 full-scale pipe and curved-wide-plate

tests (X42–X100), achieving relative errors mostly within 15% and overall higher accuracy than the PRCI-CRES and ExxonMobil strain-capacity models, especially for high-grade, large-diameter pipelines.

6.5. Comparison and Analysis

Table 2 summarizes the applicable ranges of various input parameters in the formulas of CSA Z662, PRCI-CRES, EXXON MOBIL, and CUP models. Pipeline wall thickness, defect depth, and defect length are common parameters across all models. The CSA Z662 formula also considers the pipeline yield-to-strength ratio and CTOD under low-constraint conditions. However, it does not account for internal pressure, misalignment, and weld strength matching coefficient factors. The PRCI-CRES formula comprehensively considers the effects of pipeline yield-to-strength ratio, internal pressure, misalignment, and weld strength matching coefficient (ratio of ultimate tensile strength) on tensile strain capacity. The PRCI-CRES uses apparent fracture toughness CTOD and R-resistance curves separately to calculate the crack opening limit state and the crack instability extension limit state. The EXXON MOBIL first-generation model includes internal pressure, misalignment, pipeline uniform elongation rate, and weld strength matching coefficient as input parameters, with the yield-to-strength ratio defaulting to 0.9. The EXXON MOBIL also selects three R-resistance curves to calculate fracture toughness. In the EXXON MOBIL first-generation model formula, misalignment, uniform strain, and resistance curves are unavailable as input parameters but are set to default conservative values. Compared to the first generation, the second-generation EXXON MOBIL formula considers the yield-to-strength ratio and broadens the applicable range of various parameters. The CUP model further considers the low-strength matching conditions of welds and large diameter (1422 mm) pipelines, modifying the pressure coefficient to a common pressure range of 0–12 MPa. We used 18 sets of X80 and X100 steel grade full-size wide plate test data to fully compare the accuracy of each ultimate tensile strain capacity model. The results show that the CUP model demonstrates higher accuracy than commonly used international strain-capacity prediction models (Figure 5).

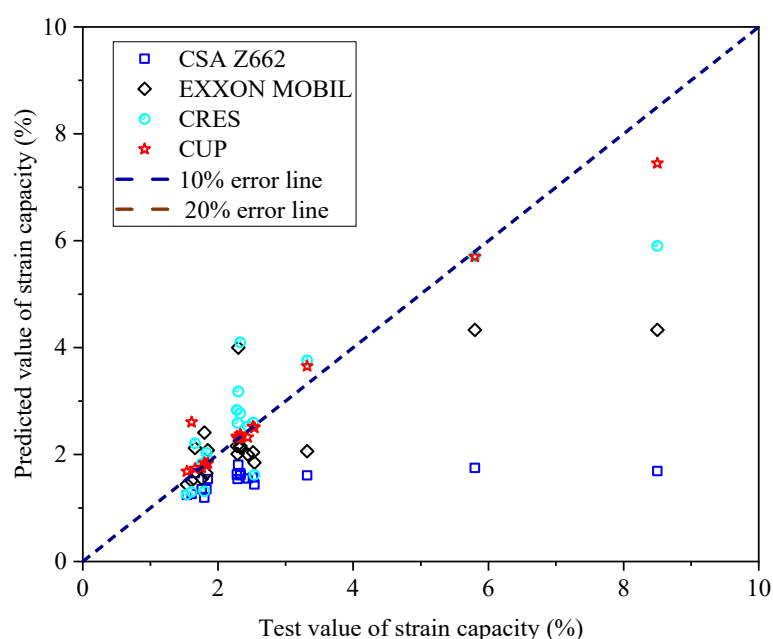


Figure 5. Comparison of ultimate tensile strain capacity models. The predicted strain capacity values from four commonly used models (CSA Z662, EXXON MOBIL, CRES, and CUP) are plotted against full-scale test results.

Table 2. Comparison of the applicable ranges of various models.

Influencing Factor Parameters		CSA-Z622	PRCI-CRES	EXXON MOBIL 2nd	CUP
Geometric dimensions of the pipeline	Wall thickness t	6.35–25.4 mm	12.7–25.4 mm	13–36 mm	21.4–30.8 mm
	Diameter D	≥ 32 t	304–1219 mm	219–1219 mm	≥ 914 mm
	Misalignment e	/	0–0.2 t	0–4.3 mm	0–3 mm
Defect size	Depth a	0–0.5 t	0.05–0.5 t	1.35–6.7 mm	2–15 mm
	Length 2c	1.0–10 t	1.0–20.0 t	15–200 mm	25–200 mm
Material properties	Steel grade	X52–X80	X56–X100	X60–X80	X52–X80
	Yield strength ratio λ	0.70–0.95	0.75–0.94	0.71–0.93	0.85–0.93
	Weld strength matching coefficient m	/	1.0–1.3	1.0–1.4	0.8–1.2
	Base metal elongation UEL	/	/	5.9–13%	/
Load	Apparent fracture toughness CTOD	0.1–0.3 mm	0.2–2.5 mm	0.76–2.3 mm	0.2–2.5 mm
	Pressure pf	/	0–0.8	0–0.8	0–12 MPa

7. Conclusions

In this paper, the international research progress is discussed from the aspects of material fracture toughness, pipeline crack driving force, and pipeline girth weld fracture evaluation method. The problems existing in the research and the future research direction are discussed, which provides theoretical and technical support for improving the intrinsic safety level of high-strength pipeline girth welds. The conclusions are as follows:

- (1) A systematic approach was proposed in material fracture toughness to uniformly describe parameters that characterize in-plane and out-of-plane constraints, including stress triaxiality and the area of the plastic zone at the crack tip. Research has established the relationship between crack tip constraints and material fracture toughness for different structures. However, current studies on the correlation between crack tip constraints and fracture toughness in elastoplastic fracture problems primarily focus on the J-integral and mainly address homogeneous materials. In contrast, as a typical welded structure, pipeline girth welds exhibit significant heterogeneity and often employ crack tip opening displacement as a fracture parameter.
- (2) Several methods have been developed regarding crack driving force in pipelines, including the EPRI, reference stress, reference strain, and semi-empirical formula methods. The EPRI method requires that the material's constitutive model strictly adhere to the Ramberg-Osgood model, limiting its applicability. The reference stress method is based on stress calculations and cannot accurately quantify the crack driving force in structures under extensive yielding conditions. As a derivative of the reference stress method, the reference strain method improves the calculation accuracy of the crack driving force under extensive yielding conditions; however, selecting the appropriate reference strain for different structures requires substantial research. In comparison, the semi-empirical formula method is built upon a large set of finite element analysis results, making it the most accurate and reliable approach for investigating crack driving forces under large deformation conditions.
- (3) Currently, the methods for failure assessment diagrams are primarily used for stress-based suitability evaluations of cracked pipelines. Although methods based on equivalent stress–strain relationships can be found for crack assessments in pipeline girth welds, the conservatism of the evaluation results obtained from this method under different parameter conditions still needs verification. Additionally, further

research is required to investigate the load-carrying capacity of pipeline girth welds under large deformation conditions.

- (4) Semi-empirical predictive models for limiting tensile strain are essential tools for evaluating the ultimate load-carrying capacity of girth welds in the pipeline industry and have been successfully applied under high-strength matching conditions. However, their current applicability does not fully cover the specifications and operating scenarios of new high-strength pipelines being constructed worldwide, especially in cases involving low strength matching in girth welds, which have been implicated in several recent failure incidents. Therefore, future work should focus on refining and extending these models into more comprehensive parameter formulations with a wider range of applicability, so that the strain capacity of girth welds can be predicted more reliably across different material grades, matching conditions, and loading environments.

Overall, current research hotspots mainly focus on: (i) clarifying the effects of weld strength mismatch, HAZ softening, and geometric discontinuities on crack-tip constraint and fracture toughness; and (ii) improving crack-driving-force evaluation and tensile strain capacity models for high-strength, heterogeneous girth welds. The main technical difficulties lie in accurately capturing large plastic deformation, multiaxial constraint, and local heterogeneity within welded joints, as well as in obtaining sufficient full-scale and curved wide-plate test data for model calibration. Looking ahead, development trends are expected to move toward multi-parameter, constraint-based fracture mechanics, mismatch-sensitive FAD procedures, and unified strain-based assessment frameworks that integrate experimental databases, high-fidelity numerical simulations, and data-driven or machine-learning methods for next-generation high-strength pipelines.

Author Contributions: Conceptualization, X.L. and Q.F.; methodology, H.Z.; data curation, Z.A.; writing—original draft preparation, D.Z. and J.Z.; writing—review and editing, D.Z. and Z.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research has been co-financed by Key Science and Technology Project of Ministry of Emergency Management of the People’s Republic of China (Grant No. 2024EMST090903), Young Elite Scientists Sponsorship Program by Beijing Association for Science and Technology (Grant No. BYESS2023261), Science Foundation of China University of Petroleum, Beijing (Grant No. 2462025SZBH007).

Data Availability Statement: No new data were created or analyzed in this study.

Conflicts of Interest: Author Qingshan Feng was employed by China oil & Gas Piping Network Corporation. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

BM	Base Metal
WM	Weld Metal
HAZ	Heat-Affected Zone
TSC	Tensile Strain Capacity
CTOD	Crack Tip Opening Displacement
FAD	Failure Assessment Diagram
EPRI	Electric Power Research Institute
CSA Z662	Canadian pipeline standard CSA Z662
PRCI	Pipeline Research Council International
CRES	Center for Reliable Energy Systems

CUP	China University of Petroleum (Beijing) model
CWP	Curved wide plate (specimen/test)
CT	Compact tension specimen
SENT	Single-edge notched tension specimen
SENB	Single-edge notched bending specimen
σ	Yield strength
K	Stress intensity factor
σ_y	Material's yield strength
α	Material hardening shift coefficient
n	Hardening exponent
J	J-integral (elastic–plastic crack driving force)

References

- Zhang, D.; Liu, X.; Yang, Y.; Chen, P.; Zhang, H.; Hou, X.; Zhang, H. Fracture behavior analysis of X80 pipelines welded joints with unequal wall thickness. *J. Constr. Steel Res.* **2023**, *208*, 108000. [\[CrossRef\]](#)
- Li, L.F.; Yan, X.Z.; Zhu, L.X.; Wu, G.; Zhang, S.X. Failure Analysis of Girth Weld Cracking in Gas Transmission Pipelines Subjected to Ground Subsidence and Traffic Loads. *Materials* **2024**, *17*, 5495. [\[CrossRef\]](#)
- Feng, Q.S.; Li, R.; Nie, B.H.; Liu, S.C.; Zhao, L.Y.; Zhang, H. Literature Review: Theory and Application of In-Line Inspection Technologies for Oil and Gas Pipeline Girth Weld Defection. *Sensors* **2017**, *17*, 50.
- Feng, Q.S. Discussion and thinking of high-grade pipeline girth weld strength matching. *Oil Gas Storage Transp.* **2022**, *41*, 1235–1249.
- Yang, F.P.; Cheng, F.; Zhang, H.B.; Wang, G.F.; Zhang, L.; Jia, P.J. Failure Case and Full Scale Test of Oil and Gas Pipeline Girth Weld. *Pet. Tubul. Goods Instrum.* **2022**, *8*, 80–84.
- Wu, M.; Wang, H.; Wang, L.; Lei, G.; Ming, S.; He, R. Analysis of the influence of girth weld strength matching on pipe deformation mode and failure pattern. *J. Pipeline Sci. Eng.* **2024**, *4*, 100183. [\[CrossRef\]](#)
- Williams, M.L. On the Stress Distribution at the Base of a Stationary Crack. *J. Appl. Mech.* **1957**, *24*, 109–114. [\[CrossRef\]](#)
- Rice, J.R. A Path Independent Integral and the Approximate Analysis of Strain Concentration by Notches and Cracks. *J. Appl. Mech.* **1968**, *35*, 379–386. [\[CrossRef\]](#)
- Hutchinson, J.W. Singular behavior at the end of a tensile crack in a hardening material. *J. Mech. Phys. Solids* **1968**, *16*, 13–31. [\[CrossRef\]](#)
- Rice, J.R.; Rosengren, G.F. Plane strain deformation near a crack tip in a power-law hardening material. *J. Mech. Phys. Solids* **1968**, *16*, 1–12. [\[CrossRef\]](#)
- Wells, A.A. Unstable Crack Propagation in Metals: Cleavage and Fast Fracture. In *Proceedings of the Crack Propagation Symposium: Sponsored by the College of Aeronautics, Cranfield, September 1961*; College of Aeronautics: Cranfield, UK, 1962; Volume 1, pp. 210–230.
- Shih, C.F. Relationships between the J-integral and the crack opening displacement for stationary and extending cracks. *J. Mech. Phys. Solids* **1981**, *29*, 305–326. [\[CrossRef\]](#)
- Kang, J.D.; Gianetto, J.A.; Tyson, W.R. Recent development in low-constraint fracture toughness testing for structural integrity assessment of pipelines. *Front. Mech. Eng.* **2018**, *13*, 546–553. [\[CrossRef\]](#)
- Li, Z.W.; Gong, B.M.; Lacidogna, G.; Deng, C.Y.; Wang, D.P. Strain-based fracture response of X80 steel pipe welded girth based on constraint-modified J-R curves: From SENT specimen to full-scale pipe. *Eng. Fract. Mech.* **2021**, *258*, 108114. [\[CrossRef\]](#)
- Gong, B.M.; Wan, X.B.; Huo, X.T.; Liu, Y.; Deng, C.Y.; Wang, D.P.; Dai, L.S. Development of a strain-based fracture assessment approach for X80 steel pipe welded girth by modified mohr-coulomb model. *Int. J. Press. Vessel Pip.* **2023**, *206*, 105056. [\[CrossRef\]](#)
- Wu, X. Study on Local Constitutive Relations and Fracture Toughness Testing of Circumferential Welds in High-Strength Steel Pipes. Ph.D. Thesis, China University of Petroleum, Beijing, China, 2021.
- Agbo, S.; Imanpour, A.; Mohamadien, A.; Gilde, M.K.; Yoosef-Ghods, N.; Adeeb, S.; Attia, S. Experimental characterization of fracture toughness of X52 pipe steel using CT, SENB, and SENT specimens. *Theor. Appl. Fract. Mech.* **2025**, *138*, 104941. [\[CrossRef\]](#)
- Liu, X.F.; Liu, Y.Q.; Zhen, Y.; Xu, Y.X.; Chen, J.; Wu, G.Y.; Cao, Y.G. Research on fracture toughness of X80 pipeline girth welds based on quantitative assessment of fractal characteristics of fracture surfaces. *Theor. Appl. Fract. Mech.* **2025**, *139*, 105098. [\[CrossRef\]](#)
- Hu, W.T.; Gong, B.M.; Chang, Q.; Zhao, Z.F.; Dai, L.S.; Liu, Y. Strain fracture behaviors and crack equivalence of X80 welded joints with non-sharp notches at weld root. *Int. J. Press. Vessel Pip.* **2024**, *214*, 105414. [\[CrossRef\]](#)
- Tian, Y.; Zhang, S.Z.; Wang, X.; Shuai, Y.; Zhang, T.Y.; Duo, Y.Q. Study on J-integral plasticity factor of high-grade pipeline girth welded joints based on SENT Specimen. *Int. J. Press. Vessel Pip.* **2024**, *214*, 105419. [\[CrossRef\]](#)

21. Betegon, C.; Hancock, J.W. Two-Parameter Characterization of Elastic-Plastic Crack-Tip Fields. *J. Appl. Mech.* **1991**, *58*, 104–110. [[CrossRef](#)]
22. Al-Ani, A.M.; Hancock, J.W. J-Dominance of short cracks in tension and bending. *J. Mech. Phys. Solids* **1991**, *39*, 23–43. [[CrossRef](#)]
23. Chao, Y.J.; Yang, S.; Sutton, M.A. On the fracture of solids characterized by one or two parameters: Theory and practice. *J. Mech. Phys. Solids* **1994**, *42*, 629–647. [[CrossRef](#)]
24. Lam, P.-S.; Chao, Y.J.; Zhu, X.-K.; Kim, Y.; Sindelar, R.L. Determination of Constraint-Modified J-R Curves for Carbon Steel Storage Tanks. *J. Press. Vessel Technol.* **2003**, *125*, 136–143. [[CrossRef](#)]
25. Yang, S.; Chao, Y.J.; Sutton, M.A. Higher order asymptotic crack tip fields in a power-law hardening material. *Eng. Fract. Mech.* **1993**, *45*, 1–20. [[CrossRef](#)]
26. Zhu, X.-K.; Leis, B.N. Application of Constraint Corrected J-R Curves to Fracture Analysis of Pipelines. *J. Press. Vessel Technol.* **2005**, *128*, 581–589. [[CrossRef](#)]
27. O'Dowd, N.P. Applications of two parameter approaches in elastic-plastic fracture mechanics. *Eng. Fract. Mech.* **1995**, *52*, 445–465. [[CrossRef](#)]
28. O'Dowd, N.P.; Shih, C.F. Family of crack-tip fields characterized by a triaxiality parameter—I. Structure of fields. *J. Mech. Phys. Solids* **1991**, *39*, 989–1015. [[CrossRef](#)]
29. O'Dowd, N.P.; Shih, C.F. Two-Parameter Fracture Mechanics: Theory and Applications. In *Fracture Mechanics: Twenty-Fourth Volum ASTM STP 1207*; John, D.L., Donald, E.M., Boulet, J.A.M., Eds.; American Society for Testing and Materials: Philadelphia, PA, USA, 1994; pp. 21–47.
30. O'Dowd, N.P.; Shih, C.F. Family of crack-tip fields characterized by a triaxiality parameter—II. Fracture applications. *J. Mech. Phys. Solids* **1992**, *40*, 939–963. [[CrossRef](#)]
31. Neimitz, A.; Dzioba, I.; Gakiewicz, J.; Molasy, R. A study of stable crack growth using experimental methods, finite elements and fractography. *Eng. Fract. Mech.* **2004**, *71*, 1325–1355. [[CrossRef](#)]
32. Cravero, S.; Ruggieri, C. Correlation of fracture behavior in high pressure pipelines with axial flaws using constraint designed test specimens—Part I: Plane-strain analyses. *Eng. Fract. Mech.* **2005**, *72*, 1344–1360. [[CrossRef](#)]
33. Guo, W.L. Elastoplastic three dimensional crack border field—I. Singular structure of the field. *Eng. Fract. Mech.* **1993**, *46*, 93–104. [[CrossRef](#)]
34. Guo, W.L. Elastoplastic three dimensional crack border field—II. Asymptotic solution for the field. *Eng. Fract. Mech.* **1993**, *46*, 105–113. [[CrossRef](#)]
35. Guo, W.L. Elasto-plastic three-dimensional crack border field—III. Fracture parameters. *Eng. Fract. Mech.* **1995**, *51*, 51–71.
36. Hebel, J.; Hohe, J.; Friedmann, V.; Siegele, D. Experimental and numerical analysis of in-plane and out-of-plane crack tip constraint characterization by secondary fracture parameters. *Int. J. Fract.* **2007**, *146*, 173–188.
37. Huang, Y.; Guo, Y.L.; Alfred, C. Quantifications of crack constraint effects in an austenitic steel. *Int. J. Fract.* **1995**, *71*, 273–291. [[CrossRef](#)]
38. Huang, Y.; Wolfgang, B. Quantification of constraint effects in elastic-plastic crack front fields. *J. Mech. Phys. Solids* **1998**, *46*, 219–241. [[CrossRef](#)]
39. Kim, Y.J.; Chao, Y.J.; Zhu, X.K. Effect of specimen size and crack depth on 3D crack-front constraint for SENB specimens. *Int. J. Solids Struct.* **2003**, *40*, 6267–6284. [[CrossRef](#)]
40. Kim, Y.J.; Zhu, X.K.; Chao, Y.J. Quantification of constraint on elastic-plastic 3D crack front by the J-A2 three-term solution. *Eng. Fract. Mech.* **2001**, *68*, 895–914.
41. Guo, W.L. Recent Advances in Three-Dimensional Fracture Mechanics. *Key Eng. Mater.* **2000**, *183–187*, 193–198.
42. Guo, W.L.; Pitt, S.D.; Jones, R. Three Dimensional Strength Assessment for Damage Tolerant Structures. In *Proceedings of the International Symposium on Strength Theory: Application, Development & Prospects for 21st Century*, Xi'an, China, 9–11 September 1998.
43. Zhao, J.H. Three-parameter approach for elastic-plastic stress field of an embedded elliptical crack. *Eng. Fract. Mech.* **2009**, *76*, 2429–2444. [[CrossRef](#)]
44. Clausmeyer, H.; Kussmaul, K.F.; Roos, E. Influence of Stress State on the Failure Behavior of Cracked Components Made of Steel. *Appl. Mech. Rev.* **1991**, *44*, 77–92. [[CrossRef](#)]
45. Mostafavi, M.; Smith, D.; Pavier, M.J. Fracture of Aluminium Alloy 2024 under Biaxial and Triaxial loading. *Eng. Fract. Mech.* **2011**, *78*, 1705–1716. [[CrossRef](#)]
46. Mostafavi, M.; Smith, D.J.; Pavier, M.J. Quantification of constraint effects in fracture mechanism transition for cracked structures under mixed mode loading. *Fatigue Fract. Eng. Mater. Struct.* **2009**, *32*, 5–17. [[CrossRef](#)]
47. Mostafavi, M.; Marrow, T.J. In situ observation of crack nuclei in poly-granular graphite under ring-on-ring equi-biaxial and flexural loading. *Eng. Fract. Mech.* **2011**, *78*, 1756–1770. [[CrossRef](#)]
48. Mostafavi, M.; Smith, D.; Pavier, M.J. A micromechanical fracture criterion accounting for in-plane and out-of-plane constraint. *Comput. Mater. Sci.* **2011**, *50*, 2759–2770.

49. Mostafavi, M.; Smith, D.J.; Pavier, M.J. Reduction of measured toughness due to out-of-plane constraint in ductile fracture of aluminium alloy specimens. *Fatigue Fract. Eng. Mater. Struct.* **2010**, *33*, 724–739. [\[CrossRef\]](#)
50. Yang, J.; Wang, G.Z.; Xuan, F.Z.; Tu, S.T. Unified correlation of in-plane and out-of-plane constraint with fracture resistance of a dissimilar metal welded joint. *Eng. Fract. Mech.* **2014**, *115*, 296–307. [\[CrossRef\]](#)
51. Yang, J.; Wang, G.Z.; Xuan, F.Z.; Tu, S.T. Unified correlation of in-plane and out-of-plane constraints with fracture toughness. *Fatigue Fract. Eng. Mater. Struct.* **2014**, *37*, 132–145.
52. Zhen, Y.; Chang, Q.; Cao, Y.; Niu, R. A novel unified characterization parameter of in-plane and out-of-plane constraints based on critical CTOA. *Fatigue Fract. Eng. Mater. Struct.* **2021**, *44*, 1305–1317. [\[CrossRef\]](#)
53. Feng, Q.S.; Zhang, Y.H. Review and discussion of strength mismatch of girth welds in high strength pipelines. *Int. J. Press. Vessel Pip.* **2024**, *208*, 105118.
54. Zhang, Z.H.; Ma, Y.; Liu, S.; Su, L.H.; Fletcher, L.; Li, H.J.; Wang, B.S.; Zhu, H.T. Inhomogeneous Strain Behaviors of the High Strength Pipeline Girth Weld under Longitudinal Loading. *Materials* **2024**, *17*, 2855. [\[CrossRef\]](#)
55. Kumar, V.; German, M.D.; Shih, C.F. *An Engineering Approach for Elastic–Plastic Fracture Analysis*; EPRI Report NP-1931; Electric Power Research Institute: Palo Alto, CA, USA, 1981.
56. Kumar, V.; German, M.D. *Elastic–Plastic Fracture Analysis of Through-Wall and Surface Flaws in Cylinders: Final Report*; EPRI Report NP-5596; Electric Power Research Institute: Palo Alto, CA, USA, 1988.
57. Kim, Y.J.; Shim, D.J.; Nikbin, K.; Kim, Y.J.; Hwang, S.S.; Kim, J.S. Finite element based plastic limit loads for cylinders with part-through surface cracks under combined loading. *Int. J. Press. Vessel Pip.* **2003**, *80*, 527–540. [\[CrossRef\]](#)
58. Paredes, M.; Ruggieri, C. Engineering approach for circumferential flaws in girth weld pipes subjected to bending load. *Int. J. Press. Vessel Pip.* **2015**, *125*, 49–65. [\[CrossRef\]](#)
59. Lei, Y.; Ainsworth, R.A. A J integral estimation method for cracks in welds with mismatched mechanical properties. *Int. J. Press. Vessel Pip.* **1997**, *70*, 237–245. [\[CrossRef\]](#)
60. Zhao, D.; Gao, W.T.; Zhao, K.; Zheng, H.; Chen, J.; Yu, J.L.; Zheng, Z.J. A strain-based J-integral formulation for an internal circumferential surface crack of pipeline under inner pressure and large axial deformation. *Int. J. Press. Vessel Pip.* **2024**, *212*, 105316. [\[CrossRef\]](#)
61. Park, S.H.; Lee, S.; Brust, F.W.; Huh, N.S. New engineering J-estimation schemes for complex cracked pipes based on energy equivalence concept. *Eng. Fract. Mech.* **2023**, *277*, 108999. [\[CrossRef\]](#)
62. Ainsworth, R.A. The assessment of defects in structures of strain hardening material. *Eng. Fract. Mech.* **1984**, *19*, 633–642. [\[CrossRef\]](#)
63. Kim, Y.J.; Budden, P.J. Reference Stress Approximations for J and COD of Circumferential Through-Wall Cracked Pipes. *Int. J. Fract.* **2002**, *116*, 195–218. [\[CrossRef\]](#)
64. Tkaczyk, T.; O'Dowd, N.P.; Nikbin, K. Fracture Assessment Procedures for Steel Pipelines Using a Modified Reference Stress Solution. *J. Press. Vessel Technol. Trans. Asme* **2009**, *131*, 031409. [\[CrossRef\]](#)
65. Jia, P.; Jing, H.; Xu, L.; Han, Y.; Zhao, L. A modified fracture assessment method for pipelines under combined inner pressure and large-scale axial plastic strain. *Theor. Appl. Fract. Mech.* **2017**, *87*, 91–98. [\[CrossRef\]](#)
66. Li, Y.Z.; Gong, B.M.; Lacidogna, G.; Carpinteri, A.; Wang, D.P. An improved crack driving force estimation approach for stress-based engineering critical assessment of reeled pipes. *Theor. Appl. Fract. Mech.* **2019**, *103*, 102312. [\[CrossRef\]](#)
67. Nourpanah, N.; Taheri, F. Development of a reference strain approach for assessment of fracture response of reeled pipelines. *Eng. Fract. Mech.* **2010**, *77*, 2337–2353. [\[CrossRef\]](#)
68. Takanashi, M.; Hojo, K.; Itatani, M.; Nakane, M.; Yashirodai, K.; Takahashi, Y.; Okada, H. Extremely low-cycle fatigue crack growth evaluation of carbon steel pipe with circumferential surface crack by reference stress method. *Int. J. Press. Vessel Pip.* **2026**, *219*, 105684. [\[CrossRef\]](#)
69. Tanaka, S.; Htut, T.T.; Okada, H.; Gouda, T.; Tonbe, Y.; Nagano, T. A benchmark elastic–plastic finite element analysis of plate with a surface crack under tensile load for the development of the reference stress method. *Int. J. Press. Vessel Pip.* **2024**, *209*, 105182. [\[CrossRef\]](#)
70. Budden, P.J. Failure assessment diagram methods for strain-based fracture. *Eng. Fract. Mech.* **2006**, *73*, 537–552. [\[CrossRef\]](#)
71. Jia, P.; Jing, H.; Xu, L.; Han, Y.; Zhao, L. A modified reference strain method for engineering critical assessment of reeled pipelines. *Int. J. Mech. Sci.* **2016**, *105*, 23–31. [\[CrossRef\]](#)
72. Zhao, S.X.; Petrov, Y.V.; Volkov, G.A. The modified relaxation plasticity model and the non-monotonic stress–strain diagram. *Int. J. Mech. Sci.* **2023**, *240*, 107919.
73. Jayadevan, K.R.; Østby, E.; Thaulow, C.M. Fracture response of pipelines subjected to large plastic deformation under tension. *Int. J. Press. Vessel Pip.* **2004**, *81*, 771–783.
74. Østby, E.; Jayadevan, K.R.; Thaulow, C.M. Fracture response of pipelines subject to large plastic deformation under bending. *Int. J. Press. Vessel Pip.* **2005**, *82*, 201–215.

75. Zhao, H.S.; Lie, S.T.; Zhang, Y. Elastic-plastic fracture analyses for misaligned clad pipeline containing a canoe shape surface crack subjected to large plastic deformation. *Ocean Eng.* **2017**, *146*, 87–100. [\[CrossRef\]](#)
76. Jin, Z.T.; Dong, P.S.; Song, S.P. An improved closed-form residual stress estimation method for girth welds in thin-walled pipe components. *Thin Walled Struct.* **2025**, *213*, 113343.
77. Miura, N.; Kashima, K.; Miyazaki, K.; Aoike, S.; Hisatsune, M.; Hasegawa, K. Development of flaw evaluation criteria for Class 2 and 3 light water reactor piping. Establishment of flaw evaluation method for moderate-toughness pipes. *Denryoku Chuo Kenkyusho Hokoku* **2003**, 1–4, 1–79.
78. Agbo, S.; Lin, M.; Ameli, I.; Imanpour, A.; Duan, D.M.; Cheng, J.J.R.; Adeeb, S. Experimental evaluation of the effect of the internal pressure and flaw size on the tensile strain capacity of welded X42 vintage pipelines. *Int. J. Press. Vessel Pip.* **2019**, *173*, 55–67. [\[CrossRef\]](#)
79. Wang, Y.Y.; Liu, M.; Zhang, F.; Horsley, D.; Nanney, S. Multi-Tier Tensile Strain Models for Strain-Based Design: Part 1—Fundamental Basis. In Proceedings of the 2012 9th International Pipeline Conference, Calgary, AB, Canada, 24–28 September 2012.
80. Wang, Y.Y.; Zhang, F.; Liu, M.; Cho, W.Y.; Seo, D.H. Tensile Strain Capacity of X80 and X100 Welds. In Proceedings of the ASME 2012 31st International Conference on Ocean, Offshore and Arctic Engineering, Rio de Janeiro, Brazil, 1–6 July 2012.
81. Yang, Y.; Liu, X.B.; Wu, K.; Sui, Y.L.; Feng, Q.S.; Wang, D.Y.; Zhang, H. Full-Scale experimental investigation of the fracture behaviours of welding joints of APL X80 wide plate based on DIC technology. *Eng. Fail. Anal.* **2022**, *131*, 105832. [\[CrossRef\]](#)
82. Zhang, T.; Shuai, Y.; Shuai, J.; Lv, Z. Study on fracture behaviour of pipeline girth welds based on curved wide plate specimens: Experimental and numerical analysis. *Eng. Fract. Mech.* **2024**, *311*, 110522. [\[CrossRef\]](#)
83. Guo, B.C.; Deng, C.Y.; Gong, B.M.; Liu, Y.; Ning, J.A.; Zhang, K. Numerical investigation of the influence of geometric features and weld metal properties on stress and strain states in X80 girth welds. *Metals* **2025**, *15*, 986. [\[CrossRef\]](#)
84. Liu, J.P.; Zhang, H.; Wu, S.S.; Liu, X.B. Ultimate Axial Load Prediction Model for X65 Pipeline with Cracked Welding Joint Based on the Failure Assessment Diagram Method. *Appl. Sci.* **2021**, *11*, 11780. [\[CrossRef\]](#)
85. R6:2001; Assessment of the Integrity of Structures Containing Defects. EDF Energy: London, UK, 2001.
86. API 579-1/ASME FFS-1:2016; Fitness-For-Service. American Petroleum Institute (API): Washington, DC, USA; American Society of Mechanical Engineers (ASME): New York, NY, USA, 2016.
87. GB/T 19624:2019; Safety Assessment of in-Service Pressure Vessels Containing Defects. China National Standardization Administration: Beijing, China, 2019.
88. BS 7910:2019; Guide to Methods for Assessing the Acceptability of Flaws in Metallic Structures. British Standards Institution (BSI): London, UK, 2019.
89. Miller, A.G.; Ainsworth, R.A. Consistency of numerical results for power-law hardening materials and the accuracy of the reference stress approximation for J. *Eng. Fract. Mech.* **1989**, *32*, 233–247. [\[CrossRef\]](#)
90. Smith, S.D. Consideration of a proposed SBAD method for BS7910. *Int. J. Press. Vessel Pip.* **2018**, *168*, 142–147.
91. Guo, L.Y.; Liang, Q.L.; Wang, Q.Y.; Wang, H.X.; Niffenegger, M. A Novel Enhanced Failure Assessment Diagram (EFAD) for predicting axial crack failures in pipelines. *Thin Walled Struct.* **2025**, *215*, 113369.
92. Zhao, Q.K.; Cao, Y.G.; Jiao, Z.H.; Zhen, Y.; Zu, Y.Z. A dynamic fracture model of the pipeline with girth weld considering welding residual stresses. *Fatigue Fract. Eng. Mater. Struct.* **2024**, *47*, 261–274. [\[CrossRef\]](#)
93. Wu, K.; Zhang, D.; Feng, Q.S.; Yang, Y.; Dai, L.S.; Wang, D.Y.; Zhang, H.; Guo, G.F.; Liu, X.B. Improvement of fracture assessment method for pipe girth weld based on failure assessment diagram. *Int. J. Press. Vessel Pip.* **2023**, *204*, 104950. [\[CrossRef\]](#)
94. Wu, K.; Zhang, H.; Yang, Y.; Liu, X.B. Strength matching factor of pipeline girth weld designed by reliability method. *J. Pipeline Sci. Eng.* **2021**, *1*, 298–307. [\[CrossRef\]](#)
95. Lei, Y.; Ainsworth, R.A. Failure assessment diagrams for cracks in welds with mismatched mechanical properties. In Proceedings of the American Society of Mechanical Engineers (ASME) Pressure Vessels and Piping Conference, Montreal, QC, Canada, 21–26 July 1996.
96. Wu, K.; Zhang, H.; Yang, Y.; Liu, X.B.; Sui, Y.L.; Chen, P.C. Fracture assessment method for girth welds of high-grade steel pipelines considering strength matching. *Oil Gas Storage Transp.* **2021**, *40*, 1008–1016.
97. Wu, X.T.; Zhang, H.; Wu, S.S.; Chen, P.C.; Wang, H.; Liu, X.B. Enhancing fracture assessment of pipe girth welds with improved load ratio calculation in failure assessment diagrams. *Mechanika* **2025**, *31*, 169–181. [\[CrossRef\]](#)
98. Z662-07; Oil and Gas Pipeline Systems. Standards Council of Canada: Ottawa, ON, Canada, 2007.
99. Liu, M.; Wang, Y.Y.; Horsley, D.; Nanney, S. Multi-Tier Tensile Strain Models for Strain-Based Design: Part 3—Model Evaluation Against Experimental Data. In Proceedings of the 2012 9th International Pipeline Conference, Calgary, AB, Canada, 24–28 September 2012.
100. Liu, M.; Wang, Y.Y.; Song, Y.X.; Horsley, D.; Nanney, S. Multi-Tier Tensile Strain Models for Strain-Based Design: Part 2—Development and Formulation of Tensile Strain Capacity Models. In Proceedings of the 2012 9th International Pipeline Conference, Calgary, AB, Canada, 24–28 September 2012.

101. Wang, Y.Y.; Liu, M.; Song, Y.X.; Horsley, D. Tensile Strain Models for Strain-Based Design of Pipelines. In Proceedings of the ASME 2012 31st International Conference on Ocean, Offshore and Arctic Engineering, Rio de Janeiro, Brazil, 1–6 July 2012.
102. Wang, Y.Y.; Liu, M.; Song, Y.; Stephens, M.; Petersen, R.; Gordon, R. *Second Generation Models for Strain-Based Design*; Pipeline Research Council International: Houston, TX, USA, 2011.
103. Fairchild, D.P.; Macia, M.L.; KibeySandeep, A.; Wang, X.Y.; Krishnan, V.; Bardi, F.C.; Tang, H.; Cheng, W. A Multi-Tiered Procedure For Engineering Critical Assessment of Strain-Based Pipelines. In Proceedings of the Twenty-First International Offshore and Polar Engineering Conference, Maui, HI, USA, 19–24 June 2011.
104. Tang, H.; Macia, M.; Minnaar, K.; Gioielli, P.; Kibey, S.; Fairchild, D.P. Development of the SENT Test for Strain-Based Design of Welded Pipelines. In Proceedings of the 2010 8th International Pipeline Conference, Calgary, AB, Canada, 27 September–1 October 2010.
105. Fairchild, D.P.; Crapps, J.M.; Cheng, W.T.; Tang, H.; Shafrova, S. Full-Scale Pipe Strain Test Quality and Safety Factor Determination for Strain-Based Engineering Critical Assessment. In Proceedings of the 2016 11th International Pipeline Conference, Calgary, AB, Canada, 26–30 September 2016.
106. Tang, H.; Fairchild, D.P.; Panico, M.; Crapps, J.; Cheng, W.T. Strain Capacity Prediction of Strain-Based Pipelines. In Proceedings of the 2014 10th International Pipeline Conference, Calgary, AB, Canada, 29 September–3 October 2014.
107. Jiang, J.; Zhang, H.; Zhang, D.; Ji, B.; Wu, K.; Chen, P.; Sha, S.; Liu, X. Fracture response of mitred X70 pipeline with crack defect in butt weld: Experimental and numerical investigation. *Thin Walled Struct.* **2022**, *177*, 109420. [[CrossRef](#)]
108. Jiang, J.X. Research on Failure Limit State of High-grade Pipe Girth Welds. Ph.D. Thesis, China University of Petroleum, Beijing, China, 2023.
109. Wu, K.; Zhang, H.; Yang, Y.; Liu, X.B. Numerical Analysis of the Crack Driving Force of Mismatched Girth Welded Pipes Subject to Large Plastic Deformations. In Proceedings of the ASME 2021 Pressure Vessels & Piping Conference, Virtual, Online, 13–15 July 2021.
110. Yang, Y.; Zhang, H.; Wu, K.H.; Chen, P.C.; Sui, Y.L.; Yang, D.; Liu, X.B. Strain capacity analysis of the mismatched welding joint with misalignments of D 1422 mm X80 steel pipelines: An experimental and numerical investigation. *J. Pipeline Sci. Eng.* **2021**, *1*, 212–224. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.