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REVIEW

A Detailed Structural Review of Onshore and Offshore Pipelines Containing Defects

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ABSTRACT

This study presents a thorough and holistic review of various studies focusing on the structural analysis of Oil and Gas (O&G) pipelines, with an emphasis on various defect modes. The study appraised pipeline-related articles from the empirical, semi-empirical, analytical, and numerical studies. However, the study's core objective remains to address the persistent challenge that often leads to Burst Pressure Loss (BPL) in a pipeline. These mechanical-associated damages, which can result in BPL, may include pipe scratches, dents, or cracks. Therefore, training a large volume of datasets in neural network architectures or the finite element domain is crucial in this context. The study further explores previous research to gain a deeper insight into how many modes of damage enhance loss in Burst Pressure (BP). The study further synthesises significant reasons why pipeline Structural Health Failures (SHFs) occur, as drawn from existing literature. Failure scenarios in pipeline dent, crack, fracture, buckling, fatigue, corrosion, BPL, and Third-Party Damage (TPD) could result from mechanical deformation, ageing, insufficient real-time monitoring, and TPD influences. Many of the assessed articles conclude that the

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experimental approach and Finite Element Method (FEM) are valid and can accurately validate one another in the analysis and prediction of pipeline failures. However, this study offers valuable and comprehensive resources for pipeline engineers, academic researchers, and industry professionals. Again, the study is crucial for pipeline fabricators, installers, and operators to keep up with maintenance, repairs, and predictions.

Keywords: Oil and Gas (O&G); Onshore and Offshore Pipelines; SHFs; FEM; BPL; Several Failure Modes

1. Introduction

The operational pipeline system for both onshore and offshore oil and natural gas has long been recognised as the most efficient, effective, economical, and safest method for energy transport. The above assertion is supported by numerous scholarly research articles [1–5]. Notably, the long decade of significant shift from oil to natural gas has triggered an increase in pipeline construction and installation worldwide [6]. This change has attracted greater attention from the Oil and Gas (O&G) industry, academic sector, and research institutions. From a practical and traditional perspective, API 5L X42-120 seamless grade carbon steel pipelines are considered more suitable and efficient for transporting this energy. The longitudinal Seam Submerged Arc Welded (LSSAW) is the closest alternative to API 5L X42-120 seamless pipelines; however, there is no comparison between the two grades of pipeline.

A dearth in numerically and remotely real-life monitoring and prediction programmes for operational pipelines has inspired this study. The research gap in computationally and artificially trained datasets in this regard is a great concern. This acute problem in the O&G sector demands urgent attention as we prepare for alternative energy through carbon emission reduction and a new energy source by 2050. Solving this problem would have reduced emissions due to catastrophic events upon explosion. Therefore, harnessing datasets of pipeline scratches, micro-dents, and cracks can collectively or individually address the persistent pipeline BPL and its accurate prediction. To accurately enhance the prediction of BPL damage in isotropic carbon steel oil and natural gas pipelines, it is vital to gather extensive and detailed field datasets. Training these datasets is therefore necessary. Employing advanced Neural Network Architectures (NNAs) and Finite Element Analysis (FEA) is aimed at refining Burst Pressure Loss (BPL) calculations and predictions of pipeline behaviour.

Several significant challenges, however, should be addressed throughout this process. These include strict time constraints that can limit both data collection and analysis. The availability of essential resources, such as equipment and skilled personnel, and complex bureaucratic procedures that differ from country to country, can impede swift project implementation. Furthermore, challenges related to right-of-way permissions may complicate access to pipeline locations, ultimately impacting the speed and effectiveness of data gathering efforts. Overcoming these obstacles is crucial through the successful utilisation of NNAs or alternative software in the vital field of pipeline integrity studies.

The study aligns with the recent research conducted by Chen et al. [7] on the use of artificial intelligence for monitoring onshore TPD pipelines. As such, it serves as a framework for addressing the issues previously discussed. Consequently, the study introduces a novel approach for predicting BPL defects in pipelines, through some damage modes of failure detailed in the following tables. This information will also provide a foundational basis for enhancing future calculations and predictions of pipeline BPL.

1.1. Brief History of Carbon Steel Pipeline Design and Installation

Pipeline defects are of great concern as they threaten the safety of oil and natural gas transport across the globe [8,9]. A China Daily newspaper reported how hollow bamboo plants were used in transporting the first encountered brine while mining for salt in Sichuan province centuries ago (220 BC) [10,11]. Vogel's [12] research study validated the brine transport in bamboo tubes in China about 2000 years ago. Moreover, the first-ever water piping network used the same hollow bamboo plants [10,11]. At the brine mining station for salt refinement, the transported natural gas encountered from the brine well to the surface was the same array of bamboo tubes [13]. Again, the first-ever carbon steel pipeline for natural gas transport was used in Fredonia, New York, United States of America, in 1821. Between the 1930s and 1970s, carbon steel pipeline installation for oil and natural gas transport grew and revolutionised the world. The pipeline defects review contained here is a synopsis of oil and natural gas pipelines, fundamental approaches to structural defect analysis, remediation, structural integrity, and simulations for prediction as evaluated from various previous articles. The information about the empirical, numerical, analytical, and other approaches used for pipeline defect resolutions is well explored, demonstrated, and utilised.

1.2.Onshore and Offshore Oil and Natural Gas Pipeline Overview

Carbon steel and composite pipeline technological design have faced structural challenges globally. These challenges are, however, felt in structural analysis, which has confronted pipeline integrity over the years. Nevertheless, an efficiency optimisation analysis and structural stability prediction are always in view to benchmark cutting-edge pipeline designs [9,14,15]. BPL, crack growth, and corrosion fatigue are some of the structural challenges that have bedevilled pipelines in operation over the years [16–18]. Hence, they are essential parameters for investigating and analysing O&G pipeline integrity globally.

However, these essential parameters are vigorously synchronised using some of the best approaches from the cited literature to validate experimental procedures with numerical or computational models. Maintaining standard operational practice and safety procedures in a pipeline is critical to maximise flow. Flow obstructions due to defects have required structural assessment and operational control to optimise pipeline functionality and integrity. This study extensively summarises different defect modes and those parameters that ensure pipeline safety to maximise energy profit across the O&G sector globally [8,19,20].

Several authors, including Nešić [21], Race [22], Tse and Wang [20], Zhang and Zhou [23], and Ghavamian et al. [8], have proved that corrosion poses the most endemic and catastrophic threat to the operational integrity of natural gas pipelines. In this context, internal corrosion is identified as the primary cause of subsea pipeline failure. Usually, it leads to an attrition in pipeline thickness that can ultimately result in Stress Corrosion Cracking (SCC) and a loss of internal Burst Pressure (BP). In contrast, the research of Durowoju et al. [24] expressed different opinions regarding pipeline damage in a more general context. Their opinion suggested that Third-Party Damages (TPDs) and installation challenges are the primary factors contributing to pipeline failures. Again, Durowoju et al. [24] pointed out that most TPDs are due to anthropogenic influences occurring along the first 180^0 part of the buried pipeline near the surface. The 180^0 exposed part of the pipeline to the pseudo intender, which can cause a dent in a pipeline and potentially initiate a micro crack in some cases. However, concurrent Static Burst Pressure (SBP) analysis is another mode of damage that employs slightly different shear stress failure criteria for corrosion defect evaluation [25]. Notably, the dent impact on a pipeline may lead to other damage modes if prompt repair action is not deployed to fix the operational pipeline. Alexander et al. [26] have uncovered dent behaviour in a pipeline and tagged it as mechanical damage caused by a Third Party (TP). Such damage can lead to additional damage throughout the pipeline's service life. This damage drops the fatigue life and becomes more severe with an increase in the dent at the cause of the service pipeline lifecycle.

The whole idea of pipeline specification before design and construction is optimal to withstand the proposed environmental conditions of application. The environmental conditions may be harsh marine environments, external loading conditions, and several operational conditions that challenge structural integrity and safety. The Finite Element Method (FEM) has emerged as a powerful computational technique for analysing the operational behaviour of pipelines under various loading conditions. This study provides a comprehensive overview of the FEM application and analysis of pipelines, focusing on modelling techniques, material behaviours, environmental loading conditions, and failure mechanisms. Insightfully, various case studies are assessed in detail in this study to highlight the effectiveness and challenges associated with computational FEM and empirical formulation in the context of pipelines' O&G transport systems.

2. Structural Advantages of FEM and its Application in O&G Pipeline Analysis

The FEM has proven to be highly effective for structural analyses over the years, making it a recommended approach for solving boundary value problems in engineering structures. Most of the research work reviewed in this study employed FEM for comprehensive structural analysis, validating various analytical, experimental, or semi-empirical approaches, as cited in several articles included in this structural review. For instance, Shahid et al. [27] demonstrated the capabilities of FEM in analysing fibre-reinforced polymer (FRP) sleeves used for repairing subsea carbon steel pipelines under different operating conditions. As a simulation technique, FEM can numerically assess the physical and mechanical properties of a pipeline composite material, particularly its resistance to corrosion and mechanical damage [1,28,29]. The efficiency and reliability of FRP extend beyond repairing isotropic carbon steel pipelines. They are also crucial in the fabrication and construction of flanges to enhance integrity in the operational phase of the pipeline lifecycle [30]. Furthermore, the failure pressure calculations provided by pipeline specification agencies such as American Society of Mechanical Engineers (ASME) B31G, Det Norske Veritas (DNV), and Predictive Corroded Pipe Rupture Criteria (PCORRC) can validate the results obtained from FEM analysis from the literature assessed.

Pipeline Operation and Structural Defects

The operational phase of the O&G pipeline is crucial, as it significantly impacts the stability and integrity of the pipeline during its lifecycle. However, conducting routine checks during operation enhances structural integrity. Structural damages may arise from environmental factors, Maximum Allowable Operating Pressure (MAOP), natural frequency of pipe, and the pipeline's service life challenge. Witek [31] conducted a structural integrity investigation focused on a buried onshore natural gas pipeline, specifically evaluating defects associated with natural phenomena and the ageing of pipelines. Surface corrosion defect in this scenario was the common defect analysed [31]. Structural defects represent tough challenges in maintaining robust infrastructures, including pipelines. Therefore, adhering to structural regulations and operational protection protocols is vital for ensuring safety. Cosham and Hopkins [32] provided several recommendations after assessing various structural defects in pipelines by validating the Standard Operating Procedure (SOP) outlined in ASME B31G, Remaining Strength (RSTRENG) of corroded pipe, American Petroleum Institute (API), and related guidelines. Furthermore, their pipeline defect appraisal document offered valuable insights for preventing and controlling defects in O&G pipeline operations, applicable to both onshore and offshore environments. Witek [31] emphasised the need for regular inspections and maintenance to manage structural defects and prevent potentially catastrophic damage to pipelines.

3. Review Methodology and Applications

A systematic review methodology has been established for this structural review, enabling the study to effectively analyse literature based on structural parameters and arguments presented in each reviewed article. The idea of data extraction and synthesis from previous literature is to ensure thorough analysis, evaluation, and documentation throughout the review process. The purpose of this information is to address structural research inputs and gaps. The graphical representation of O&G pipeline publications in **Figure 1** portrays article tracking and harmonisation over the years. Of course, **Figure 1** clearly illustrates the collected literature publications with fluctuations over the past five and a half decades. The sharp exponential jump between 2007 and 2010 in **Figure 1** significantly addresses the period of the energy production and transportation boom.

However, the steady and consistent publication period between 2010 and 2018, for about a decade, could have resulted from the alternative energy decision stage. The decline in publications in the literature between 2017 and 2020 reflects the net-zero carbon emission phase (**Figure 1**). The increasing momentum aimed at achieving net-zero carbon emissions by 2050 may be responsible for the significant decline in gas pipeline publications in the literature. However, as the transition to alternative green energy progresses, publications related to the net-zero carbon agenda are expected to rise geometrically between 2030 and 2050. A key issue in this transition is the decommissioning process of old pipelines.

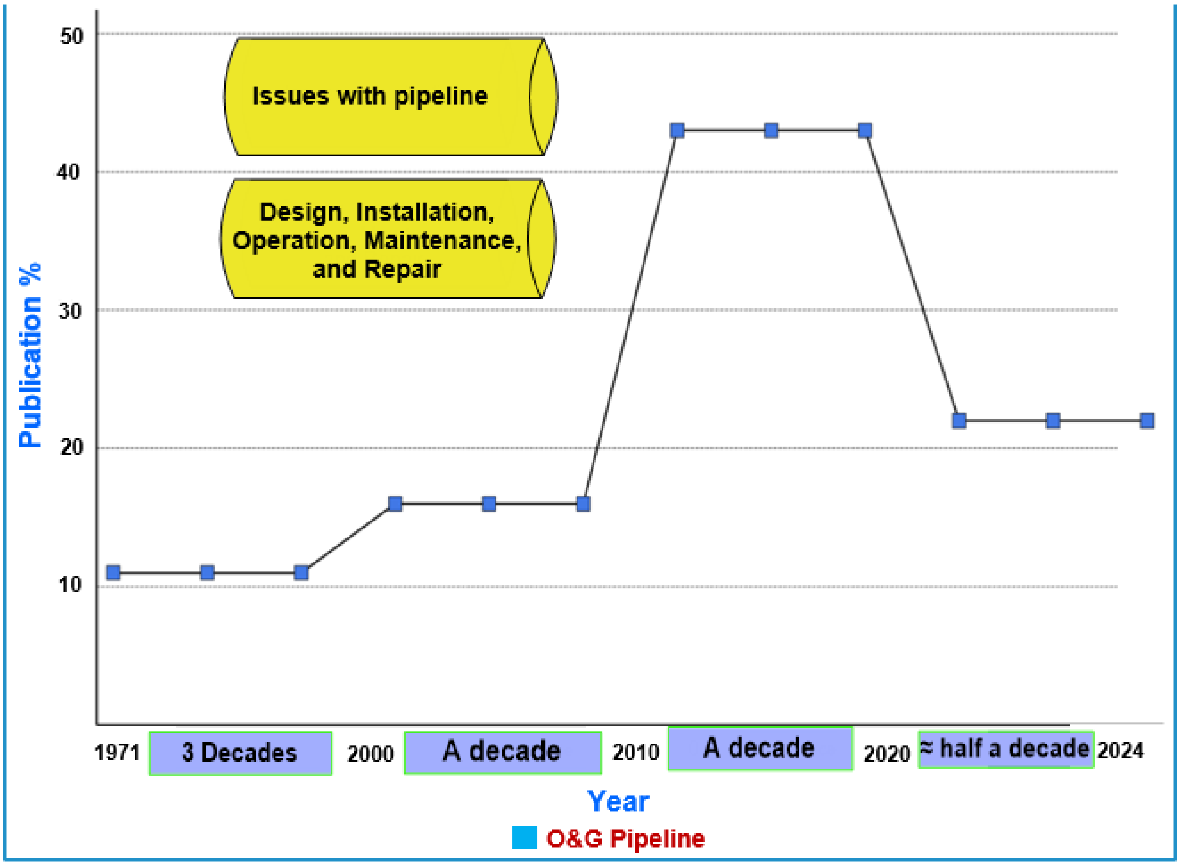

Figure 1. O&G pipeline structural publication distribution for over five and half decades.

This topic raises crucial discussions about the best methods for transporting new energy and the maintenance process of existing energy sources. The rehabilitation of existing pipelines for alternative green energy, as well as the construction and installation of new green energy pipelines, is frequently highlighted in many sustainable marine and energy journals [33–37]. Consequently, there is a rapid growth in the development of new materials designed to enhance carbon steel pipelines with advanced composite structural materials suitable for alternative green energy. Moreover, repurposing existing pipelines for alternative energy could present promising research opportunities in the future. This review study focuses on the existing literature surrounding the structural analysis of carbon steel pipeline publications. A good example is the Lancaster and Palmer's [38] pipeline structural analysis of dent and gouge combination for BPL influence.

The yearly publication distributions, as presented in **Figure 1**, clearly demonstrate the trend in the quantity of literature in this field of study. The publication in percentage (%) of the Y-axis gives information on the number of publications in % over the years on the X-axis. This information assisted in the collection and assessment of existing related articles.

3.1. Datasets Application for Pipeline BPL Prediction

To significantly improve BPL damage predictions in pipelines, it is essential to account for mechanical damage modes like scratches, dents, and cracks. Collecting datasets before and after installation is critical to this process. Moreover, employing advanced remote sensing technology, such as wireless ultrasonic and sunspot sensors, provides a reliable and efficient way to gather this vital data. By prioritising these practices, pipeline safety and performance are enhanced.

- **Datasets** can systematically serve as the foundation for training a machine learning model. Equipment for data collection, such as Shogun, a real-time monitoring remote sensor, is possible for this assignment. This data should encompass various scenarios of a particular damage mode. An example is a scratch or dent to ensure comprehensive learning.
- **Pre-processing** involves cleaning to remove inaccuracies, handling missing values, and standardising the formats. Additionally, transforming the data into a more suitable structure or representation, such as normalising numerical values or encoding categorical variables, allows for preparing it effectively for model training.
- **Training Process** involves the utilisation of the cleaned and pre-processed datasets through a machine learning algorithm that aligns best with the specific objectives of the task. During this phase, the model could draw on historical data, thereby adjusting its internal parameters to minimise errors and improve its predictive performance. This process may involve multiple iterations based on the feedback from the model's initial performance.
- **Predictions** are possible with an adequately trained model. However, numerically, predictive models can be implemented and used to validate subsequent research results. This application enables the model to demonstrate its ability to generalise from past examples and make informed decisions.
- **Optimisation** is the final phase after the deployment of the whole process. A rigorous assessment of the model's performance using an appropriate computational tool, such as FEA in ANSYS, FEA in ABAQUS, and Workbench Optimisation Domain, depending on the task objective. Based on this evaluation, an optimisation programme is necessary in this regard. It may include fine-tuning parameters involved and employing advanced techniques, such as cross-validation, or retraining with additional data to enhance performance and accuracy.

3.2. Different Failure Modes of Onshore and Offshore Pipelines

Real-time investigations of pipelines in operation and those that have suffered a catastrophic event, such as explosions caused by BPL, require critical insights into data collection and analysis. Over the years, researchers have explored this area by examining various structural defects in pipelines. However, for more accurate and detailed analysis and predictions, particularly regarding BPL, training large datasets and FE analysis are essential. The reviewed literature has utilised software simulation tools to predict potential future damages in pipelines. The study not only connects these various structural investigations but also seeks to bridge the existing gaps in the study domain, considering this study's aim and objectives.

Figure 2 is a schematic representation of possible generic onshore oil and natural gas defects, starting from human external interference, design/mechanical, operational lifecycle, and natural disasters that could result in pipeline failure. The cylindrical pipeline damage representation includes different colour captions. The anthropogenic activities (external interferences) on onshore O&G pipelines are considered TPDs. The TPD in **Figure 2** is the first captioned in the red cylinder. The TPDs' influence on the onshore pipeline encompasses land excavation for new projects, drilling, theft, and heavy-duty truck vibration, which are all capable of causing pipeline damage. The brown captions are for the pipeline damage modes associated with mechanical impacts during pipeline transportation and installation, while the yellow captions are examples of the operational phase in the pipeline. The blue caption indicates natural disasters.

The damages in subsea pipelines share a similar fate to those onshore during installation and operation. However, there are notable differences in the types of TPDs and the natural disasters, which have the potential to destroy the pipeline. For subsea pipelines, TPDs include anchor drops, heavy object impacts (rockfall), trawling gear, and ships running aground. The natural disasters affecting subsea pipelines encompass tectonic eruptions, strong sea currents, tsunamis, earthquakes, and many more.

Johnson and Vigilante [39] clarify this issue by referencing findings from the Pipeline and Hazardous Materials Safety Administration (PHMSA) and the European Gas Pipeline Incident Data Group (EGIG). Their findings indicate that TPDs and corrosion are the primary causes of pipeline damage and failures. In the context of natural gas pipelines in the USA, welded joints, particularly in the butt weld sections of pipes, are identified as the most common type of defect. Guedes and Caro [40] further emphasise that external interference, whether onshore or offshore, ranks as the second leading cause of failures, following corrosion. For a comprehensive overview of TPDs, refer to the Handbook of Pipeline Engineering by de França Freire et al. [41]. **Figure 3** schematic portrays information about subsea O&G pipeline challenges. The damage types are in an array of dwarf-coloured cylinders that represent different damage modes of the subsea pipeline. The yellow arrow pointer indicates the TPDs, and the overlapping yellow rectangular boxes with the light green dwarf cylinder indicate design/mechanical damage. Again, the light blue cylinders represent operational/lifecycle problems, while the deep blue cylinder depicts natural disasters. Other than the TPDs and natural disasters, the design/mechanical and operational/lifecycle problems remain the same with the onshore pipelines.

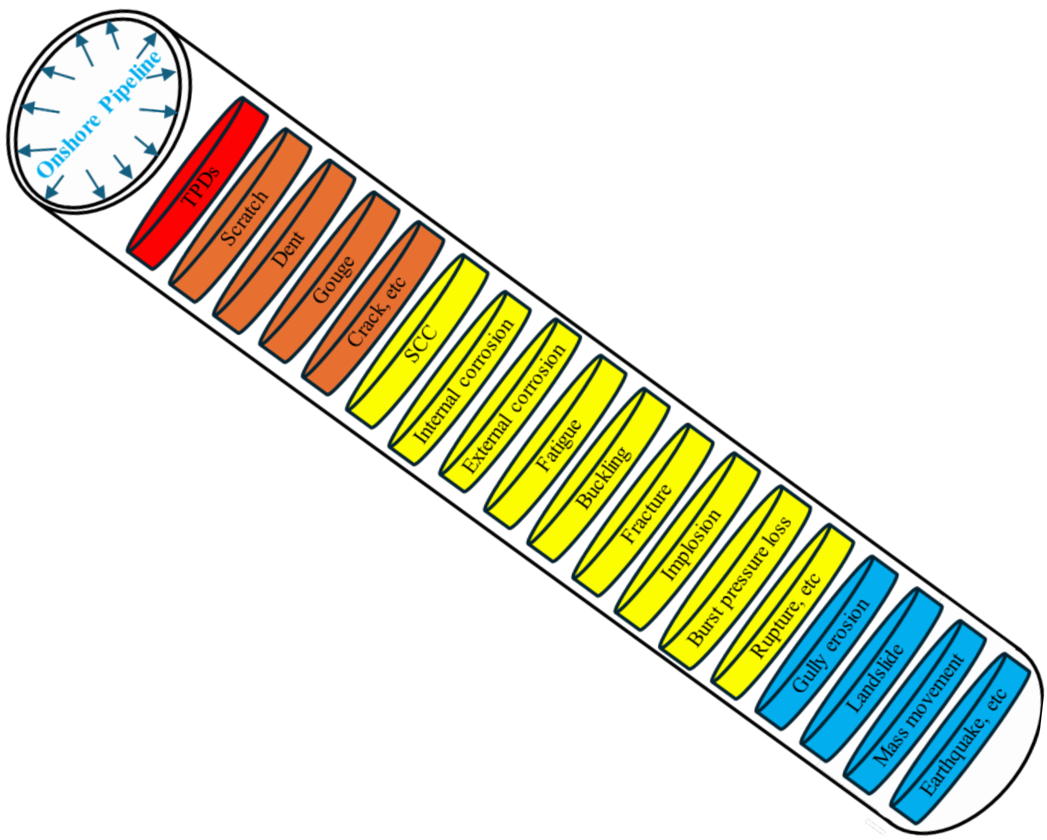

Figure 2. Damages associated with onshore oil and natural gas pipeline.

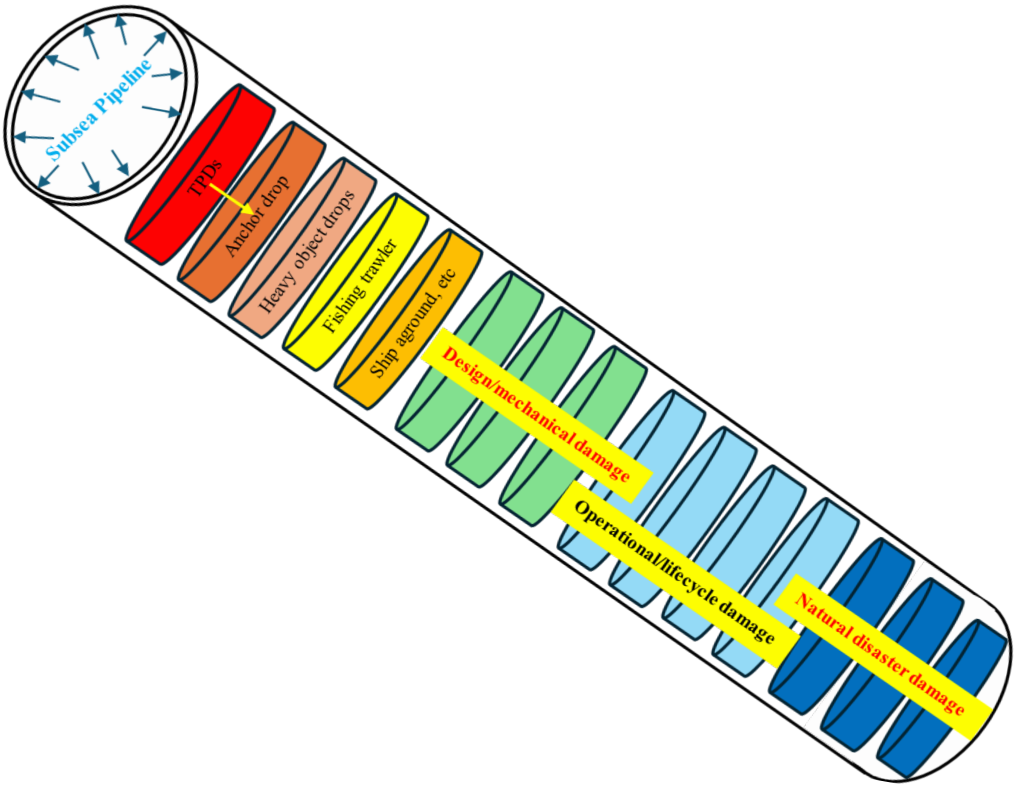

Figure 3. A special schematic of possible defects to the subsea O&G pipeline.

3.3.Indentation

Dent formation in a pipeline has consistently posed a difficult challenge to onshore and offshore oil and natural gas pipelines. This damage mode, however, is an inevitable defect during the pipeline fabrication and installation process, and very often it degenerates into a BPL challenge after micro-crack initiation. Micro-dents and micro-crack data mining, however, is one of the best pieces of information for studying damage like BPL in a pipeline. Pipeline standardisation and specification manuals offer more information to caution pipeline engineers and operators. The pipeline manual also helps with decision-making during pipe procurement for energy transport. In the same vein, dent evaluation and depth acceptability levels are further investigated by Wu et al. [42]. Note that a dent in the pipeline compromises BP resistance, collapse, and local buckling resistance in operation. Additionally, experimental and numerical investigations by Zeinoddini et al. [14] prove that the reduction in BP increases the risk of pipeline failure. This risk could result from elevated internal pressure due to the combination of dents. Following tables present an in-depth analysis and comparison of various onshore and offshore pipeline failure modes. Differences in pipeline structural defects from appraised articles based on empirical, semi-empirical, analytical, and numerical analyses reveal previous pipeline failures and possible solutions. The study introduces a new perspective, the possibility of utilising a trained dataset from pipe scratches or dents for FE simulation of BPL damage prediction. It highlights the significance of the pipeline operational environment and emphasises the need to consider different pipeline grades. The simple reason for multiple grades of pipeline is to generate more data for adequate training and analysis to improve safety and efficiency in pipeline operation. Persistent BPL drives this idea for this innovative study.

Figure 4 schematic portrays a pseudo-indenter used for creating a deep dent on the surface of an offshore pipeline structure. The pipe thickness remains unchanged even at the indentation spot. However, the indenter causes a deep depression, which in turn creates a high stress concentration. Such indentation may lead to several other damages around the dent region. The dent could initiate a micro-crack due to high-stress field concentration within the dent environment, due to flow pressure inside the pipeline. Residual stresses around the dent's internal and external surfaces are the differences between a possible observed stress value and the predicted value. According to Hyde et al. [43], Other pipeline damage problems, like fatigue in an operational gas pipeline, were investigated using the practical indentation examples. However, to ensure operational stability in O&G pipelines, there should be a routine Structural Health Monitoring (SHM) as set by industrial pipeline experts [1]. Consequently, the structural integrity of pipelines should be a top priority for operators to ensure stability, as this study demonstrates.

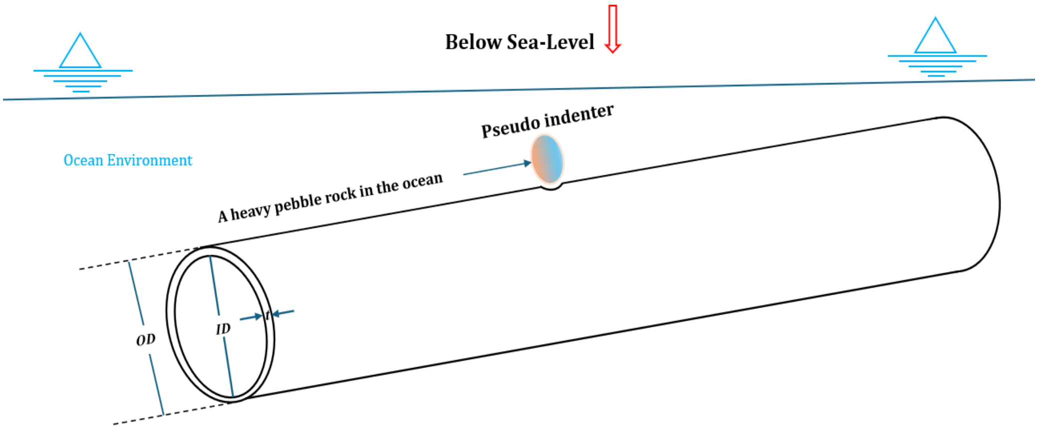

Figure 4. A schematic view of practical example of indentation possibility in the offshore environment.

3.4.Crack Initiation and Propagation in a Pipeline

Simulation methods for structural analyses are profoundly and exponentially advancing with technological improvement to stabilise the health of marine structures, especially the O&G pipelines. The FEM for crack investigation is mostly cross validated using empirical results to optimise the structural analysis of different models used in discussing various structural parameters in this study. **Figure 5** further illustrates the study of Valadi et al. [44] on the strength of the eXtended Finite Element Method (XFEM) for crack investigation. Most O&G pipeline crack problems could occur due to pipeline stress-related loading, which is known as material Sulphide Stress Cracking (SSC). However, crack repair in the pipeline is possible as illustrated in **Figure 6**. The composite reinforced sleeve is a good material for wrapping pipelines during crack repair, as well as pipe joining.

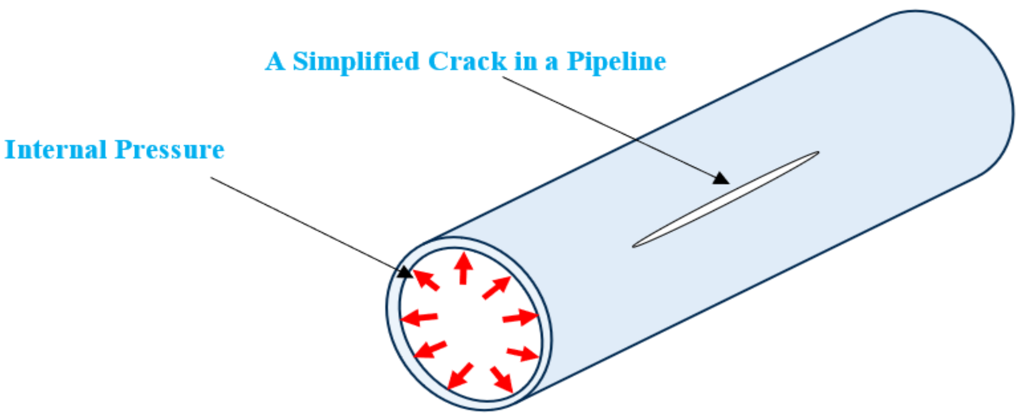

Figure 5. A pipe with simplified crack defect under internal pressure.

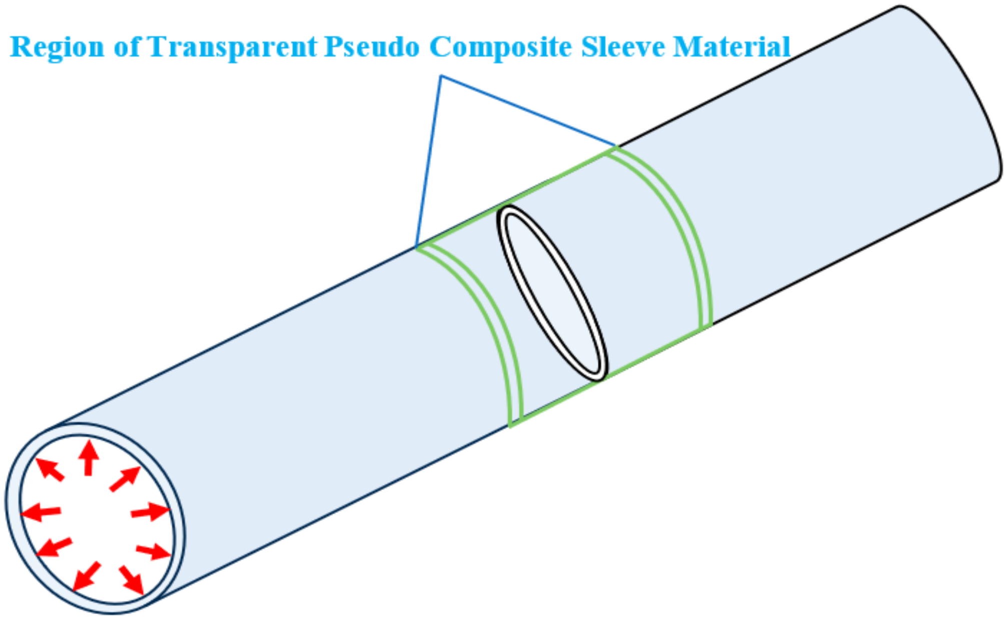

Figure 6. Schematic of imaginary composite sleeve materials for possible joining or repairing of cracked pipeline.

The Finite Element (FE) numerical approach can effectively identify micro-cracks in pipelines, which often degenerate into crack propagation through element paths instead of node grid paths of the model [44]. However, cracks can also propagate through node grids depending on their orientation. The limitations of Classical Continuum Mechanics (CCM) and the foundation of traditional FEM are, however, addressed by the XFEM. Nevertheless, the propagation challenge persists in visualising the portion of the element that is affected once the crack loses its continuity. Thus, the capabilities of CCM remain relevant within the context of XFEM. In **Figure 5**, the red arrows indicate internal pressure, which often poses a potential threat to an already cracked pipeline, whether from internal or external surfaces of the pipe.

A powerful and robust approach, known as the peridynamic (PD) theory, has been developed to effectively address the limitations of XFEM and CCM in crack problems. This innovative approach, called PD, was first proposed by esteemed scientist Stewart A. Silling, who aimed to find solutions to the aforementioned challenges in crack propagation. PD focuses on managing crack-related damages in solid mechanics and beyond. Numerous studies have explored this area, including Kilic and Madenci [45,46], Silling and Lehoucq [47], Oterkus and Madenci [48], and Madenci and Oterkus [49], among others.

Additionally, Candas et al. [50], Shi et al. [51], and Candas et al. [52] have carefully demonstrated the effectiveness and efficiency of PD for structural analysis. Their findings highlight the structural capacity of PD for material advancement and development based on the following:

- Micro-crack identification and propagation envision under a sudden and transient force of application on Functionally Graded Materials (FGMs) [50].
- Analysis of SCC on carbon steel pipeline materials based on initial crack stage formation and propagation resulting from mechanical agitation and corrosion effect [51].
- Investigation of dynamic fracture in FGMs to understand optimal variation and formulation pattern of material property [52].

In the same line of idea is the innovative contribution of Imachi et al. [53] on dynamic crack propagation. Conclusively, the PD approaches appraised for crack investigations demonstrate that both non-ordinary and ordinary state-based, along with bond-based methods, are numerically feasible within the PD crack analysis framework. The above structural studies are potentially possible for O&G carbon steel pipelines to improve stability and integrity.

3.5.Buckling-Collapse Failure in Pipelines

Buckling in pipeline structure is one of the critical and challenging damage modes of a pipeline, which often results from overloading of a structure or design errors, like dents or ovalisation in a pipeline [54,55]. This sudden mechanical deformation occurs from the axial compression load, and it is only when the compressive load on the pipeline reaches a critical value. According to Kyriakides and Corona's study [55], an experimental approach can predict pipeline buckling under a high bending pressure load (external force) at the installation stage of the pipeline. On the other hand, the collapse behaviour of pipelines under bending and axial loads is primarily caused by a dent in the pipeline. Both problems could result in catastrophic failure and create a highly undesired scenario within a specific region of the pipeline location. These two damage modes are discussed further in following tables along with other damage types.

The buckling of a pipeline due to external pressure, thermal expansion, or lateral loads is discussed extensively by Sun et al. [56], Wang et al. [57], and Cai and Grognec [58]. The FEM serves as a certified approach for predicting critical buckling modes, such as global buckling or local buckling occurring at welds or supports of a pipeline. Additionally, Gong et al. [59] highlighted that buckling occurs due to various types of loading, including axial tension, bending moments, and external loading regimes. Collapse failures in subsea oil and natural gas pipelines could be due to external pressures, such as hydrodynamic loads. Gong et al. [59] predicted that the ability to withstand extreme external pressure loading conditions revolves around compliance with design safety standards and installation rules with operational limits in a pipeline. In this scenario, an imperfection in the cylindrical shape of a pipeline can be a potential buckling threat in the operational pipeline. Gong et al. [59] reiterated these imperfections in pipe design geometry to predict possible failure in an operational pipeline. Additionally, Dadfar et al. [54] and Gong et al. [59] provided separate simple approaches to practically aid in minimising this imperfection during design and fabrication. Kyriakides and Corona [55] stated that a micro-wrinkled pipeline could lead to buckling challenges and potential failure in existing onshore or offshore operational O&G pipelines. In the O&G sector, most radiographic testing of pipelines for wrinkles may also go through a Scanning Electron Microscope (SEM) to certify it for installation and commissioning for operation deployment.

The **Tables 1–4** framework is structured based on one of the study's core objectives, which was to systematically filter and summarise all necessary information from each appraised literature. Each table header and sub-header thematically portrays the general structural review pattern. The detailed appraised literature in **Tables 1–4** presents various structural problems associated with pipelines, such as dent, crack, buckling, fracture, fatigue, stress, and TPD. Again, **Tables 1–4** summarise the overview of several studies on defect pipelines. An example is the detailed study of Xu et al. [60] expressing different corrosion predictive models in **Table 2**. Xu et al. [60] listed predictive models, such as Back Propagation Neural Network (BPNN), Complete Ensemble Empirical Mode Decomposition with Adaptive Noise (CEEMDAN), Genetic Algorithm (GA), Improved Particle Swarm Optimisation (IPSO), Particle Swarm Optimisation (PSO), and Support Vector Machine (SVM). Among the structural defects appraised in **Tables 1–4**, pipeline corrosion damage is imminent, especially for offshore pipelines. **Table 2** presents an assessment of corrosion damage and corrosion reduction tests, with a higher number of damage modes compared to others. The buckling, TPD, and general damage are all listed in **Table 4**. The grouping is for no specific reason, but with the idea of simplifying the assessed pipeline damage modes. All assessed pipeline defect types are written boldly across all tables.

Table 1. Dent and cracks associated damages and their likes in O&G pipeline.

S/N	Cited Author(s)	Material Type	Environment of Application	Structural Tools/Methods	Damage Mode/Type	BCs and Loads	Structural Validation	Research Output
1	Zeinoddini et al. [14]	X80 carbon steel pipe	Seafloor region installation	Empirical, semi-empirical, and computational simulation methods in ABAQUS software	Wrinkle, buckle, and collapse challenges investigated in a dented pipe	Displacement and monotonic axial compressive loading applied	This study is validated numerically with the dented API X80 grade steel pipe	The empirical and computational results agreed with the semi-empirical equations to predict residual pressure under minor dent defects in pipelines
2	Wu et al. [42]	API-X52 carbon steel pipe	This pipe grade is applicable in onshore and offshore environment	Numerical FEA in ANSYS was used to investigate pipeline dent damage. Parameters of the material geometry of the pipeline are of great importance in Wu et al. [42] study	Dent damage mode is imminent in this analysis	The model is constrained to prevent rigid body motion with varying internal pressure	A structural computational approach for pipeline model analysis is validated analytically with nonlinear regression	A type II plain dented pipeline damage is investigated using Oyane's ductile fracture approach with FEA and nonlinear regression analysis
3	Race [61]	The reviewed API X-grades pipes (X46-80), without the X65 grade type, are indeed a detailed study	The pipeline models for O&G are suitable for onshore and offshore regions	This article studied several established dent analysis methods: experimental data analysis, algorithm formulation, numerical simulation, and analytical equation method	Plain dent resulted from fatigue loading	The internal pressure load model has different failure modes from the unconstrained model setting	Most reviewed articles on dent used numerical methods and validated against different experimental approaches	The study reinforced Fowler's idea of steeper dents leading to lower fatigue life and higher Specific Minimum Yield Strength (SMYS). However, relying on strain alone is insufficient for predicting dent strain based on depth
4	Hyde et al. [43]	Carbon steel X52 and X65 grade pipe	Both pipe grades are applicable in the onshore and offshore regions	The method used here is FEA to benchmark existing semi-empirical results	Initiated dents (TPD) on X52 and X65 were to analyse failure caused by mechanical denting	Internal pressure load and quarter symmetry operation were applied	Semi-empirical results validated against a computational analysis using FEM	Indentation depth significantly influences pressure fluctuations and the fatigue life of pipelines, with deeper indentations generally resulting in a shorter fatigue life of the pipeline. The evaluation was based on unpressurised grade X52 and pressurised X65, without dent and indented, respectively, to predict the fatigue life of pipelines

Table 1. *Cont.*

S/N	Cited Author(s)	Material Type	Environment of Application	Structural Tools/Methods	Damage Mode/Type	BCs and Loads	Structural Validation	Research Output
5	Mackintosh [62]	Carbon steel pipe	Onshore subsurface environment	The FEA is based on assessment using ASME B31.8 specification	Kinked dent (a short tight twist nature) on a pipeline	Strain and stress concentration BCs	Validated using ASME B31.8 of pipeline standard code	The study provides a solution for calculating longitudinal extension strain using dent depth and length
6	Huang et al. [63]	Generic pipe defect-welded circumference	Practically applicable in the onshore and offshore environment	Theoretical (analytical) and robust computational FEM were strategically employed	(Circumferential Stress) σ_θ = (R-t/2) p/t. However, σθ = C3p. This is as a result of the internal pressure effect on the incomplete weld	Combined tension force with internal pressure bending moment load is applied	The theoretical plastic limit load method of pipeline analysis is validated numerically by FEM	A thin-walled circumferential defect in a generic pipeline (O&G pipelines) is numerically analysed using FEM, and the analysis is potentially applicable to pipeline cracks and safety analysis as proposed
7	Lancaster and Palmer [38]	All API 5L grade pipes from X42-X120	Possible in onshore and offshore environment	Semi-empirical formulation capable of predicting indentation depth	Dents and smooth axial gouges (mechanical) damages analysed	An incremental internal pressure loading	A proposed analytical method to validate the experimental process is necessarily recommended	The interaction between gouges-dents and position relative to the dent is crucial in determining a pipe BPL. An experimental setup with incremental internal pressure is used
8	Zhen et al. [64]	High-grade carbon steel X65 grade	Possible in onshore and offshore environment	FE structural tool in ABAQUS explicit solver	Crack damage analysed	Static loading generated plastic strain	Experimentally conducted approach validated computationally	The practicability of pipe ductility in pipeline fabrication and analysis is significant for crack arrest toughness, fracture resistance, and crack propagation resistance at the design stage of every natural gas pipeline
9	Okodi et al. [65]	API X70 pipe grade	This pipe grade is applicable for both onshore and offshore regions	FEM in ABAQUS software	Dent-crack for the study of BPL in a full-scale pipeline	A half symmetry BC was not possible due to the crack location on the dent flank	The study validated the experimental work of Ghaednia et al. [66] with a calibrated pipe geometry in the FE domain	Dent-crack associated damage in a pipeline was critically studied to determine whether different sizes of cracks and their nearness to dent have different impact on bust pressure of a pipeline

Table 2. Corrosion damages and corrosion reduction test in O&G pipeline.

S/N	Cited Author(s)	Material Type	Environment of Application	Structural Tools/ Methods	Damage Mode/Type	BCs and Loads	Structural Validation	Research Output
1	Qin et al. [17]	X100 carbon steel pipe	Practically acceptable in onshore and offshore environment	The research is robustly conducted with FEM using the COMSOL Multiphysics domain to analyse symmetrically 3D pipeline	The external corrosion damage leads to pipeline internal pressure reduction	There are static axial tensile stresses, internal pressure, and restricted ends of the pipe	The 3D FE model validation is initiated experimentally by field laboratory data analysis	The computational investigation reviews how pipeline internal pressure strength (MPa) reduces with age due to external corrosion. The FE model was used to ascertain pipeline failure prediction as corrosion growth was imminent with time
2	Velázquez et al. [67]	Steel pipe (API-5L Grade B)	Onshore environment pipeline	The research investigation employs a numerical approach in ANSYS software to enhance the experimental study	Different type of external corrosion damage is studied	The opposite ends of the pipe are restricted, and internal BPL is applied	The study is validated numerically with FEM in ANSYS APDL solver	Corrosion reduction techniques are essential for maintaining pipeline internal BP. Comparing BP models from different specification agencies highlights their importance for pipeline safety and integrity
3	Arumugam et al. [68]	Various API 5L (X 42-100) grades pipes were reviewed	The assessed pipelines from the article are applicable in the onshore and offshore environment	Experimental procedures,	Bulge-buckle due to effect of corrosion	Combination of internal and external load, compressive and tensile load	The article experimentally analysed O&G pipelines and further validated them using FEM and the standardisation agencies' document	The literature summarises the response of corroded straight and elbow O&G transmission pipelines under complicated external loading conditions. Remaining strength of pipe after corrosion effect is assessed with DNV-RP-F101
4	Oh et al. [69]	API X65 grade steel pipe	The X65 pipe is possible in onshore and offshore environment	Experimental and numerical investigation methods were employed	Scratch from mechanical damage and corrosion attack from the environment	Symmetrically constrained with internal pressure load	The numerical (FEM) simulation is validated using experimental data results	The study used a local failure criterion to analyse API X65 to predict ductile failure due to corrosion and gouge pressure defects under internal pressure, as experimentally designed
5	Askari et al. [70]	Different API 5L X-grade carbon steel	Applicable in both onshore and offshore environment	Several field empirical and laboratory methods like SEM	Different types of corrosion defects	Effect of load on micro-grain material is pictured from SEM	The experimental work is validated experimentally using a different approach	A systematic and comprehensive cutting-edge review that evaluates different kinds and sizes of corrosion damage to O&G onshore and offshore pipelines

Table 2. *Cont.*

S/N	Cited Author(s)	Material Type	Environment of Application	Structural Tools/ Methods	Damage Mode/Type	BCs and Loads	Structural Validation	Research Output
6	Xu et al. [60]	General carbon steel pipeline	Applicable in both onshore and offshore environment	Empirical and different existing analytical data models were employed	Corrosion damage	Statistical BCs based on differences in model data	The corrosion prediction model was validated using BPNN, SVM, GA–SVM, PSO–SVM, IPSO–SVM, and CEEMDAN–SVM. The models can be found in the ref. list of Xu et al. [60]	The research developed a novel hybrid model approach with four cardinal points: data preprocessing, prioritisation, evaluation, and prediction of corrosion rate in O&G pipelines, considering nonlinearity and noise interference has been removed with an algorithm
7	da Cunha [71]	Carbon steel pipeline	Onshore environment	Empirical, numerical, and analytical methods were used for the quantitative risk assessment review of the onshore pipeline	Different types of onshore pipe damages, like those in **Figure 2**	Different boundary and loading conditions are applied	Most numerical analyses are validated analytically	This literature compared the concurrent consequences of onshore pipelines' internal and external corrosion rate failures for four countries. Most of the explosions had resulted from pipeline leakages
8	Dey et al. [72]	Carbon steel pipeline	Applicable in both onshore and offshore environment	Laboratory sampling of internal and practical inspection for corrosion rate	Internal corrosion, external corrosion, and crack damage	Pressure load on welded joints	The laboratory sampling method is validated against operational pipeline data analysis	This research assesses risks and maintenance to evaluate the corrosion rate in steel pipelines and aims to address the corrosion problems before they escalate
9	Capiel et al. [73]	Composite pipeline material with FRP	The composite pipeline is possible for onshore and offshore energy pipeline transport	Empirical analysis of fibre-reinforced polymer to evaluate deterioration level of pipeline at failure mode and propose an in-situ assessment programme	Pipeline clogging with molecular species, and also bending during installation, and corrosion effects	Necessary experimental and laboratory boundary conditions	Laboratory procedures are validated with existing literature based on hygrothermal effect on composite pipeline	Recommended glass FRP pipe for O&G pipelines for its high resistance to Electro-Chemical Corrosion (ECC) and an alternative to steel pipelines
10	Song et al. [74]	API-5L X70 pipe	The author analysed this pipeline for the onshore environment	Experimental and numerical method of FEA in LS-DYNA domain	Blasting and spallation effect in a pipeline for local pitting corrosion test	Dynamic pressure loading (local impulse loading)	Validated numerically with the FEM in LS-DYNA solver domain	The damage level increases with an increase in the blast load in kg. Pipeline wall thickness determines the yield strength and toughness of the pipe

Table 2. *Cont.*

S/N	Cited Author(s)	Material Type	Environment of Application	Structural Tools/Methods	Damage Mode/Type	BCs and Loads	Structural Validation	Research Output
11	Soomro et al. [4]	Different grades of oil and natural gas pipes	Applicable in both onshore and offshore environment	The systematic review article gives details of different literature on failure data and Bayesian network appraisals	Internal corrosion damage type	BCs here are internal and MAOP pressures based on the research article	The research is validated using Bayesian network (conditional probability)	A certified Bayesian network method can adequately predict pipeline integrity using internal corrosion effects without knowledge of pipe Inline Inspection (ILI) data. This method is more robust and improves informed decision making and management control
12	Ameh and Ikpeseni [75]	X42 and X65 carbon steel pipe	Applicable in onshore and offshore environment	Field experimental implementation and mathematical formulation for carbon steel pipeline coating using the cathodic impressed current coating	Overprotection and coating damage is inevitable if the current distribution is not uniform	The BCs are the anode and cathode calculations and pipe geometry dimensions	Field experimental application was validated using an analytical calculation procedure	The Cathodic impressed current coating plan is necessary after a carbon steel pipe infrastructural design. The idea is to prevent corrosion. However, high application costs have made it less used in O&G pipeline infrastructural facilities
13	Ghavamian et al. [8]	X80 grade carbon steel pipe	The pipeline material is applicable in onshore and offshore environment	A review of different experimental and numerical simulation to detect pipeline defects based on corrosion	Damage mode here is corrosion attack and crack initiation and propagation	Traction-free BCs are applied to achieve adequate results output	The essence of the FEM model and guided ultrasonic wave (non-destructive testing) was to establish the causes of parameters failure in a pipeline system	SHM results from non-destructive testing using guided and ultrasonic wave propagation, and the FEM is optimal in natural gas pipeline defect detection. The review study was based on corrosion

Table 3. BPL and rupture damage in O&G pipeline.

S/N	Cited Author(s)	Material Model	Environment of Application	Structural Tools/Methods	Damage Mode/Type	BCs and Loads	Structural Validation	Research Output
1	Kelil et al. [76]	API 5L-X65 carbon steel pipe	The pipeline analysis is beneficial in the onshore and offshore environment	Laboratory investigation with a microscope and Strain-Based Design (SBD) approaches and FEM were employed	The damage mode investigated is puffiness in a pipeline at all stages in its lifecycle	Bending force, internal pressure, bi-axial forces, and hydrodynamic loads were applicable	The FEM is validated experimentally with microscopic data analysis	The study highlighted the SBD method's ability to analyse puffiness with undulation and ovalisation during a pipeline's fabrication, operation, and maintenance stages. Puffiness in the pipeline can result in BPL due to high stress concentration within the puff region

Table 3. *Cont.*

S/N	Cited Author(s)	Material Model	Environment of Application	Structural Tools/Methods	Damage Mode/Type	BCs and Loads	Structural Validation	Research Output
2	Zhang and Adey [77]	X70 grade carbon steel pipe	The focus on TPD modes suggest that the pipe is for an onshore region	Experimental and analytical tools were practically possible in this literature	Dents and gouges resulting from TP influence could initiate an internal crack in the pipeline	Axial internal pressure applied	The failure frequency analysis validates some equations of the TPD prediction	The predictive model assesses sudden TP failure damage that can cause an immediate leak and rupture (general damage) of the energy pipeline. Hydrogen mix-natural gas pipeline may lead to delayed failure from the hydrogen embrittlement challenge
3	Zhang et al. [78]	X70 grade carbon steel pipeline	The pipe is suitable for onshore and offshore gas transport	The study experimentally and analytically investigated the X70 pipeline	Corroded and plastic collapsed damage due to an increase in flow pressure	Tension force and internal pressure load	Validated against existing experimental and numerical data solutions	The internal BP of a damaged pipeline is analytically studied against the intact pipeline to justify their different BP levels from *the Y/T* of the von Mises criterion
4	James and Hudgins [2]	API X-42, X-46, and X-56 grade carbon steel pipe	The pipe is suitable for onshore and offshore use	Experimentally and computationally addressed accidental defects, TPDs, and pipeline corrosion	Rupture failure due to mechanical impact (dent) on incomplete seam fusion welding of the pipeline	Mostly internal operating pressure	SEM laboratory and near-neutral pH SCC analysis validated against other empirical methods in the literature	Damage from flow pressure may not have acknowledged the MAOP with known SMYS of a pipeline, and real-world failure mechanism analysis in the research could serve as a reference for numerical studies
5	Bhardwaj et al. [79]	Thick and high-grade carbon steel (X60-X120)	Applicable in onshore and offshore environment	The research article applies the First Order Reliability Method (FORM), First Order Second Moment (FOSM), and Monte Carlo simulation processes	Corrosion defect and BPL damage	Internal pressure load	A computational model for BPL capacities of high-grade steel, such as X80-X120, was validated against empirical data	This research article conducted several internal BPL predictions using reliability algorithms and the Monte Carlo method, with increased corrosion defects in a pipeline. The experimental data yielded the expected results for the flawed and unflawed pipeline. Hasan et al. [80] expanded the Monte Carlo simulation method for analysing failure probability

Table 3. *Cont.*

S/N	Cited Author(s)	Material Model	Environment of Application	Structural Tools/Methods	Damage Mode/Type	BCs and Loads	Structural Validation	Research Output
6	Meniconi et al. [28]	A fibre-reinforced material for the repair of API 5L X60 pipe	The API 5L X60 is possible for both onshore and offshore environment	Experimental and numerical applications for repair of corroded pipelines with fibre reinforced composite materials: 20'' outside diameter API 5L X60 steel were hydrostatically tested	Corrosion and BP damage	Hydrostatic internal pressure loading	The FEA for BPL is a validation of experimental procedure of an analysed corroded pipeline	The research studied BP for repairing a corroded X60 pipeline with a fibre-reinforced composite sleeve, focusing on stiffness strength for defect pipes. This method is unsuitable for higher-grade steel from X100 onward
7	Oh et al. [81]	API ranging from X52-X70 grade pipes	Applicable in both onshore and offshore environment	The study utilised three methods: empirical, analytical and numerical applications for impact BPL analysis	Internal BP loading	Pipe symmetry operation under internal pressure	The BPL prediction was validated using analytical and numerical methods	A numerical model for predicting BPL damages in a pipeline using linear and nonlinear approach of FEM in ANSYS domain is established
8	Sebaey [82]	Composite (fibre and matrix) designed pipeline	Applicable in both onshore and offshore environment	Experimental BPL test and impact machine testing set-up	The BPL, matrix crack part of the composite material	Internal pressure load, energy-time load steps, impact energy load, bending, and axial loads are applied	The experimental pipe BPL test validates the low-velocity impact from weight drop by creating a winding angle in the pipeline, like the Tashnizi et al. [83] composite study	The research determines the impact resistance of a composite pipeline under internal pressure and the low-velocity effect of drop weight on a composite pipeline. The winding angle was compared against the internal pressure capacity and the mechanical resistance from the external load to determine the pipe's strength and stiffness
9	Chen et al. [84]	Carbon steel hydrogen mixed natural gas pipeline	Applicable in onshore and offshore environment	The study proposed semi-empirical, analytical and numerical methods for new BPL failure criteria in ABAQUS software domain	Damage assessed: crack, buckling, and BP	Symmetrically constrained X and Z directions of the pipe to avoid free body movement, with internal pressure BCs applied	The E, P, V defines the linear parameter, stress-strain relationship defines the nonlinear parameter. Analytical method validated the empirical and FEM	The hypothesis of a new multi-parameter for BP calculation equation (Y/T) was to generate a new failure criterion using the Tresca Failure Criterion for a thin-walled hydrogen-mixed natural gas pipeline

Table 4. Buckling, TPD, and general damage in O&G pipeline.

S/N	Cited Author(s)	Material Type	Environment of Application	Structural Tools/Methods	Damage Mode/Type	BCs and Loads	Structural Validation	Research Output
1	Vosooghi et al. [85]	General carbon steel pipe	Subsea environment	FE implementation in ABAQUS software	Buckling damage due to lateral and axial movement of the subsea soil (natural disaster)	Axial and lateral frictions activated, and temperature increased	The research article is analytically and numerically validated against Python script to calculate the pipeline out of straightness	The study clarifies pipe-soil interaction and identifies key geometric parameters affecting pipeline buckling resistance
2	Kyriakides and Corona [55]	Various API 5L X-grade pipes	Pipelines can be applied in both onshore and offshore environments	Experimental method with robust laboratory analysis	Buckling and collapse mode of damages (Chapter 9 Kyriakides and Corona [55])	Pipelines are restricted at both ends, with localised deformation by the engineering process.	Validated analytically by the principle of virtual work, see Johns et al. [86] and Sakakibara et al. [87] for more detail	The author introduced a groundbreaking experimental setup with advanced laboratory machinery pipe buckling and collapse test procedures
3	Shin et al. [88]	General carbon steel pipes	Applicable in both onshore and offshore environment	Field investigation of pipeline using acoustic waves technology to monitor TPD	Third party/ mechanical damage	Transient load system (acoustic wave)	The research is validated using a developed algorithm on the Digital Signal Processor (DSP) TMS320C32 Board	A developed real-time monitoring model is used to reveal fresh TPD like anchor drops in the transmission pipeline. Hence, the BP lifecycle is reduced after noticing the first impact and taking adequate operational measures
4	Guo et al. [3]	X60 and X70 grade pipeline of the Shaan–Jing natural gas, China	X60 and X70 grade pipelines are possible for both onshore and offshore region	Experimental set-up and Bayesian network data collection and analysis from pipeline incidents like leakage were employed	Damages associated with TPs: stress, crack, and rupture	Environmental BCs like right-of-way and geological BCs	The pipeline leakage case study is validated using Bayesian theory to identify overlooked problems related to TPD	The study evaluates the danger involved in the O&G pipeline safety by TPD after the catastrophic event. The study justifies the Bayesian theory as one of the best for risk assessment for TPD incidents
5	Ossai et al. [89]	Appraisal of different grades of carbon steel pipe	The pipeline is applicable in onshore and offshore environment	Laboratory microscope and Mackinawite chemical formation and formulation benchmark is used	Collective literature on pipeline damages, such as dents, cracks, SSC, buckles, bulges, and fatigue was analysed	Grain microstructure interaction from microscopic laboratory analysis	Literature validations primarily drawn from experimental approaches and vice versa, creating a robust foundation for reliable results and insights	A distinctive research article that is significantly rooted in the structural analysis of onshore and offshore pipelines to improve pipe design and operational input. The review study was a general pipe assessment

Table 4. *Cont.*

S/N	Cited Authors	Material Type	Environment of Application	Structural Tools/Methods	Damage Mode/Type	BCs and Loads	Structural Validation	Research Output
6	Torres et al. [15]	Different transport pipelines studied	Pipelines are efficient in both onshore and offshore environment	Mathematical modelling and physical measurements based on estimated values to detect defects that result in leakages	Damage types are fatigue, stress, and crack propagation	Load types: hydrodynamic, internal pressure, tensile force, and bending moment	Independent leak assessment in a pipeline with the Kalman filter, Luenberger observers, and other acoustic microphone equipment	Pipeline structural parameters are detected and verified to promote the real-time failure process of leak identification
7	Mondal et al. [90]	Isotropic steel pipe of API X46	Applicable in onshore and offshore environment	FEA in ABAQUS software domain	Damage mode here is the corrosion and bending ratio effect	Symmetry BCs applied to avoid free body movement with internal pressure load	This research article validated the works of Chouchaoui and Pick [91] and Ma et al. [92]	The research evaluates the risks associated with bending pipes to accommodate the harsh installation environment. Bending is often necessary during pipeline installation due to factors such as right-of-way constraints, utility conflicts, and environmental obstructions. This article is categorised based on a general pipeline assessment
8	Pluvinage et al. [93]	X52, X65 carbon steel pipes	Applicable in the onshore and offshore environment	The study experimentally uses a microscope and volumetric method of analysis	Damages are brittle, ductile, fracture, notch, dent gouge, and crack	Displacement, stress, internal pressure	Validated using FEM and specification bodies such as ASME B31G, modified B31G, PCORRC, and DNV	The research article examines the evolution of O&G pipeline grade strengths over the past eighty years, explores various damage modes, and suggests effective failure prediction techniques
9	Biezma et al. [9]	X70-120 pipe grades	Accident pipelines assessed were from the onshore environment	Systematic review and documentation of several pipeline accidents across different locations from different countries	The analysis covers TP-influenced failures such as excavation and theft. And natural disasters like landslides, floods, dike breaks, and erosion	Pressurised pipeline contents led to reduced load-bearing capacity and reduced MAOP	The article uses a pie chart model to calculate the pipeline mode of failures at several pipeline locations as a validation to ascertain failure causes	The documented pie chart model and tables with detailed reasons for past failures could be a tool to predict future occurrences. General pipeline assessment

4. Review Results and Discussion

The results and discussion section of the review study is structured based on a comprehensive analysis that integrates the empirical, numerical, and analytical methods used in all the appraised literature. The study's general structural framework was derived from the configurations and methodologies of the reviewed articles, as reflected in the overall assessment patterns (**Tables 1–4**). These tables present and emphasise various structural implications of an undesired condition in operational O&G pipelines. Notably, some of the most common and inevitable defects in O&G pipelines are scratches, dents, and cracks, which are often indications to enhance BPL in a pipeline.

4.1.Pipeline Integrity Analysis Based on Past Failure Incidents

Subsea pipelines primarily face the risk of internal corrosion in operation, making it a leading cause of offshore pipeline failure. In the same context, the research conducted by Cheng and Chen [94] highlights the external risks faced by subsea pipelines due to hydrodynamic pressure, which can lead to external corrosion fatigue. In this regard, the assessment of pipeline structural integrity focuses on both corrosion and fatigue. In contrast, onshore pipelines are more vulnerable to external factors arising from various third-party (TP) activities, predominantly resulting from human-induced mechanical damage. On the other hand, the damage to subsea pipelines from TP activities typically occurs due to incidents such as ships running aground, dropped anchors, heavy objects falling from vessels, and fishing trawlers.

4.2.Statistics and Probability Assessment of Pipeline Internal Corrosion

Soomro et al. [4] argued that the Bayesian network approach is the most promising method for assessing the impact of internal corrosion damage on the structural integrity of O&G pipelines. Their review also listed some fascinating methods from other researchers, such as Witek [29], Cavalieri et al. [95], Zakikhani et al. [96], and Khan et al. [97]. Many researchers projected how the structural integrity assessment, the BPL, the fault identification, and the ILI models are used for pipeline failure prediction [4]. The Bayesian network stands out for its integrity and risk prediction in the context of corrosion damage of operating pipelines. Guo et al.'s [3] TPD risk assessment using the Bayesian network is another validated work by Soomro et al. [4] and Zakikhani et al. [96]. They have a general experimental setup for pipeline data collection and analysis. Chen et al. [7] itemise the possible onshore pipeline failure influences and initiate how an AI monitoring system can ameliorate the problem due to TPD.

4.3.The Use of Corrosion Reduction to Determine Pipeline Internal BPL

Conventionally, Tse and Wang [20] have noted that corrosion is a prevalent issue in Hong Kong's pipeline system due to extreme environmental conditions. One of the damages related to hydrogen pipeline issues is embrittlement. The concept of mixing hydrogen with natural gas in the same transmission pipeline raises concerns, as introducing hydrogen could lead to a loss of toughness and increased embrittlement. While corrosion in pipelines is a global problem, different types of corrosion are tied to specific environments and tend to be more severe in certain regions, as highlighted by Nešić [21] and Ghavamian et al. [8]. For example, in Hong Kong, environmental factors significantly affect the rate of corrosion damage, particularly concerning external corrosion in buried or surface pipelines [20]. Measuring the depth of internal corrosion in natural gas or oil pipelines is essential for determining the internal BP of transmission pipelines. In this study, we explored the potential of using datasets related to pipeline scratches, dents, or cracks to train models and simulate predictions for BP. Notably, conventional methods for calculating BP include experimental, numerical, and real-world assessments. With the help of advanced machine-aided field evaluations, laboratory setups, and computational software, predicting BP has become more manageable, as demonstrated in some sections of **Table 3**. A notable example is the work of Fahed et al. [98], who conducted experimental and FEM to evaluate the internal BP of corroded API X42, X52, and X70 grade pipes. Su et al. [18] utilise the retained BP of a pipeline as a specific parameter to calculate the remaining strength of corroded steel pipeline structures, which is another method. Nevertheless, the corrosion challenge of steel pipes' grades X42 to X120 could reduce pipe internal pressure, which is an inescapable condition during operation [17,18].

However, Song et al. [74] used various masses of Trinitrotoluene (TNT) as an explosive to blast pipelines of different thicknesses at varying time intervals (in microseconds) to study their BPL capacity. Song et al. [74] also confirmed that the pipe blasting technique to determine the internal BP of a pipe is in contrast to the effect of corrosion as an environmental factor. O&G pipelines are often installed in harsh environments, far from urban or inhabited areas within their operational environment. Hence, they are susceptible to environmental attacks like corrosion and hydrostatic pressure. Thus, continuous advancement in pipeline design and the use of corrosion-resistant material becomes imperative. Qin et al. [17] discussed the internal pressure retained in a pipeline after experiencing corrosion effects on high-grade steel (X100) as the remaining strength of the pipeline. The Near-Neutral Simulation with pH-4 (NS4) is a chemical solution that is slightly acidic, with a pH close to 7. The NS4 solution is assumed to have corroded the steel pipe in the experimental setup by Qin et al. [17]. The simulated corrosion effect, however, is in a localised form, which can manifest as pitting, filiform, or crevice corrosion in real-life scenarios. **Figure 7** depicts a random and irregular pipe pitting corrosion pattern in a long-distance hydrocarbon carrier. The rougher and sharper the corrosion on the X100 steel grade used, the greater the localised stress distribution in that region. Pluvinage et al. [93] used a simple equation to suggest that plastic collapse system analysis can predict BP damage. For example, if a pipe incurs a corrosion crater or experiences spallation due to corrosion, the following **Equation (1)** is possible.

$$\frac{\partial P}{\partial \varepsilon_{eq}} = 0 \tag{1}$$

where P is the internal pressure and ε_{eq} is the equivalent strain. For more detailed analyses and predictions regarding BP, refer to the works of Leis and Stephens [99], Bjørnøy et al. [100], Shuai [101], and Ma et al. [102]. The Pluvinage et al. [93] equation for pipeline BPL defines the use of linear and nonlinear analysis to justify the plasticity of material instability. The deep neural network utilised by Oh et al. [103] adopted a dented O&G pipeline, possibly across all API 5L X42-X120 grade carbon steel pipelines for BPL testing and prediction. The Oh et al. [103] method is an advanced technological approach that could validate the TNT explosive traditional approach of Song et al. [74]. Yan et al. [104] evaluated different BPL predictive models' errors and ascertained that the API RP579 and R6 are more efficient than the Battelle Model concept in O&G pipelines' BPL prediction. However, no specific certified reliable method exists for accurately forecasting BP strength, according to Bhardwaj et al. [79]. The Bhardwaj et al. [79] study further concludes that data collection also modelled a full-sized pipeline with respect to the geometry mirroring the initial quarter section of the pipe as proposed. The mesh sensitivity study of corroded pipe by Qin et al. [17] ascertains that a pipeline can still be in operation even at a corroded level. The level of corrosion is, therefore, a medium to justify the pipe stability in operation. The anodic current density initiated the corrosion defect on the pipeline at a different pressure flow rate, while other parameters like internal and external stress were introduced [17,70]. The Askari et al. [70] study is a proof and an example of the different types of internal corrosion that could happen in any hydrocarbon pipeline. The main factor of this internal corrosion in the pipelines is the sulphide content in hydrocarbons, which results in SSC.

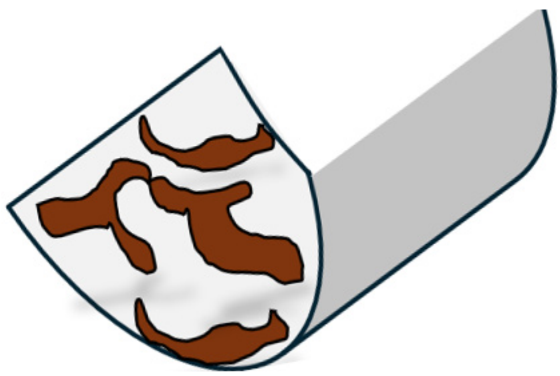

Figure 7. A half symmetry schematic of internal corroded hydrocarbon pipeline.

The damage incidents discussed herein do not indicate any failure propensity related to the design or installation process, but ageing within a steadily operated pipeline. Corrosion is the most significant factor in this context. Clogging is another notable contributor to the corrosion effect in onshore and offshore O&G pipelines, often resulting from dirt or other factors. Clogging in a pipeline increases the Maximum Operating Pressure (MOP) needed to transport the pipeline's content, which may lead to higher operating costs and reduce BP. However, following pigging operations to mitigate the clogging, the flow resistance encountered by low-molecular-weight gas or liquid hydrocarbons can be alleviated, allowing for a potentially faster flow rate. Zhu et al. [105] employed fluid oscillation theory with mathematical models to detect clogs in pipelines, using plugging attenuation parameters to assess the specific location and volume of the blockage. Chern-Tong and Aziz [106] provided an example of a hydrocarbon product that causes coagulation due to low temperatures, which contributes to clogging in oil pipelines, ultimately leading to corrosive impacts on the pipeline. Additionally, hydrate formation in natural gas pipelines can also result in clogging, as Al-Sharify et al. [107] mildly put it.

Crack initiation in carbon steel pipelines often results from mechanical or stress impacts and can propagate when exposed to external loads. Additionally, dents may develop in high-grade carbon steel due to mechanical impact, before and after installation. Zhen et al. [64] evaluated the benefits of material thickness in X65 steel pipeline crack tip openings using a 3D FE model. The thicker the pipeline material, the greater its resistance to crack opening. A high-grade carbon steel, ranging from X42 to X80, falls within Product Specification Levels 1 and 2 (PSL1 and PSL2). It is, therefore, significant to note that butt-weld areas in pipelines are particularly vulnerable to stress corrosion cracking (SCC), which poses a high risk by potentially reducing the BP strength. Such weaknesses could lead to catastrophic incidents, including explosions, within the operational phase of a pipeline.

In another campaign to mitigate corrosion effects, Race [22] and Adib-Ramezani et al. [108] have drawn attention to corrosion management and control in onshore pipelines. This problem remains a global metal infrastructural challenge. In the same light, Dao et al. [109] study provides a valid analytical investigation of internal corrosion as a primary mode of subsea pipeline failure.

4.4.Structural-Empirical Based Analysis of Pipelines with Defects

Zhen et al. [64] have strongly argued against the notion that restricting laboratory carbon steel X-grade samples can effectively limit the prediction of crack and fracture behaviour in operational pipelines. Many of the articles evaluated by Zhen et al. [64] adopt a similar approach to those by Shterenlikht et al. [110], Amara et al. [111], and Shibanuma et al. [112] for studying the effects of cracks in pipelines. However, the use of laboratory specimens is insufficient for accurately assessing crack-related fractures in long and large O&G pipelines [111,112]. Consequently, the trend towards incorporating numerical and computational analysis to predict fracture and crack responses in natural gas pipelines appears to be the most effective strategy. It is essential to recognise that environmental factors play a significant role in many types of pipeline damage, including embrittlement, fractures, and cracks.

4.5.Empirical and Numerical Synthesis of Damaged Pipelines

Empirical and numerical methods for repairing and rehabilitating onshore and offshore O&G pipelines used for transportation have consistently shown reliable results through field investigations and computational validation. However, the welding of damaged sections of the pipeline has remained uncertain throughout the remaining pipeline's operational life. This uncertainty arises from differences in material properties, including the welding rod, the pipeline material itself, and the repair sleeve used.

5. Different Approaches for Flawed and Unflawed Pipeline Structural Analysis

The critically reviewed articles in this study examine both flawed and unflawed pipelines. They utilise a diverse range of methodologies rooted in analytical, semi-empirical, empirical, and numerical approaches to highlight the implications of defects and provide guidance for predicting failures. A newly commissioned pipeline, whether onshore or offshore, is expected to function effectively throughout its lifecycle. However, these expectations for pipeline performance and integrity can often be compromised by various challenges associated with the pipeline. To improve our understanding of different methods for analysing pipeline defects, a summary of several experimental, analytical, and computational tools is provided in **Tables 1–4**.

5.1.Pipeline Repair and Rehabilitation

FEM plays a critical role in assessing damaged pipelines, evaluating repair techniques, and ensuring the integrity of repaired sections. Case studies demonstrate the effectiveness of FEM-based simulations in guiding repair procedures, such as hot tapping, composite repairs, and pipeline replacements. The advanced welding technology for shipbuilding applications highlighted by Wahidi et al. [113] could serve as an adequate alternative for pipeline butt welding. Particularly in pipe joining, reeling, or construction on the badge ship before installation in the offshore environment. Additionally, quality joint welding and repair in pipelines are crucial because these processes are often prone to internal failures after repair. The harsh marine environmental conditions have made subsea pipelines challenging and problematic to repair and rehabilitate.

5.2.Pipeline Monitoring and Maintenance

A monitoring and maintenance programme for marine infrastructure is essential for ensuring efficiency and stability. It is the architectural hallmark of operational integrity in the harsh marine environment. Subsea O&G pipelines are no exception to this necessity. Therefore, constant routine monitoring and maintenance are crucial for transmission pipelines and are significant concerns for the O&G sector. Ho et al. [114] reviewed various articles focusing on the monitoring-inspection of O&G subsea pipelines. Most of these articles debated the best methodologies and technologies for inspecting and monitoring offshore pipelines. Among them are the corrosion-appraised articles in **Table 2**. Evans and Thomas [115] employed the Guided Wave Testing (GWT) principle to inspect corrosion in a straight offshore pipeline. GWT is a non-destructive testing (NDT) approach that uses wave propagation to locate and evaluate the corrosion potential of a pipeline. Dey et al. [72] developed a unique risk-based model called the Analytic Hierarchy Process, designed to monitor and inspect pipelines. However, while pipeline monitoring is not always cost-effective, it is an unavoidable practice to prevent the loss of crude oil or natural gas due to leaks [72]. Witek [29] introduces a mathematical formulation by incorporating fibre-reinforced composites to repair corroded O&G pipelines, thereby preventing BP damage in both onshore and offshore pipelines. The MAOP, SOP, and MOP established by the design engineer are critical considerations in pipeline operations. Design standards, operational safety, and standard repair procedures for corroded pipelines are paramount for a pipeline's optimal function [1,29].

The analytical solution for the maximum theoretical failure pressure of the composite sleeve is given as **Equation (2)**:

$$P_{\max}^{\text{th}} = \frac{f_u(r_0 - r_i)}{\alpha_\theta(r_i - \eta r_0)} \tag{2}$$

where P_{max}^{th} is the maximum theoretical failure pressure, r_o is the outside radius of pipe, r_i is the inner radius of pipe, α_θ is the hoop stress, η is the coefficient of the pipe Young's modulus, and f_u is the Ultimate Tensile Strength (UTS) of the pipe. The hoop stress (α_θ) can be calculated as **Equation (3)**:

$$\alpha_\theta = \frac{1 - \left(\frac{d}{t}\right)\left(\frac{1}{Q}\right)}{1 - \left(\frac{d}{t}\right)} \tag{3}$$

where d d is the defect depth, t t is the pipe thickness, which is the difference between the outside and inner radius, $\frac{d}{t}$ is the defect depth to thickness ratio in %, and QQ is the bulging factor as it is used in the BG/DNV level 1 criterion. The coefficient the pipe Young's modulus is defined as **Equation (4)**:

$$\eta = \left(\frac{r_0^2 E_{\text{pipe}}(r_o - r_i)}{r_i^2 E_{\text{sleeve}}(r_e - r_o)} + \frac{r_o}{r_i}\right)^{-1} \tag{4}$$

where E_{pipe} is Young's modulus of pipe, E_{sleeve} is Young's modulus of sleeve, and r_e is the radius of the sleeve. The bulging factor can be calculated as **Equation (5)**:

$$Q = \sqrt{1 + 0.31\left(\frac{L^2}{Dt}\right)} \tag{5}$$

where L is the defect length in (mm), DD is the sleeve pipe outside diameter, and tt is the sleeve pipe nominal thickness in (mm).

6. Conclusion

Remote and real-time monitoring, along with defect data analysis for BPL prediction, are key to enhancing pipeline operational effectiveness, efficiency, and integrity. In conclusion, this review study offers a comprehensive and high-quality systematic analysis from significant literature resources on both onshore and offshore pipelines. The main objectives outlined in the reviewed articles are pipeline operational capacity expectations depending on the operational environment, as presented by the cited authors. However, these objectives become compromised in the presence of pipeline defects. Addressing this problem, **Tables 1–4** present additional structural defect mechanisms and predictive model reviews to reduce failure frequency and enhance pipeline flow efficiency.

The literature review employs a detailed and comprehensive systematic approach to unravel the application of the experimental, numerical, and analytical models presented in the appraised articles on structural defects. Notably, some of the numerical models assessed include robust FEM applications, which help to identify structural parameters for predicting failure modes in pipeline systems. Again, FEM stands as a foundational backbone of modern engineering design and analysis of onshore and offshore pipelines. The reviewed literature publications in this study have explored the myriad applications of FEM, ranging from modelling techniques and material considerations to environmental loading, failure modes, and case studies. Furthermore, most reviewed articles here ascertained that structural health failure from BP is not often sudden but initiated by one damage mode or the other and coupled with loss of operating pressure. A routine maintenance culture and proper checks while the pipeline is in operation are paramount to safety adherence, accentuation, and streamlining the control of mechanical problems to improve the pipeline's integrity [5].

Again, pipeline Bayesian model network assessment for failure or integrity purposes has proven to be the best choice for risk and integrity evaluation of operational pipelines. As technology advances and challenges evolve, continued research and innovation in FEM will be crucial for ensuring the safety, reliability, and sustainability of pipeline systems. All these environmental and operational factors conjoined to cause immense loading conditions on the O&G pipelines. As offshore exploration ventures into deeper waters and harsher environments, the challenges faced by subsea pipeline engineers continue to evolve. The ability to model nonlinear material behaviour, dynamic environmental loading, and complex interaction phenomena allows engineers to make informed decisions throughout the lifecycle of subsea pipelines. It goes from the design and construction stage to the operation phase, maintenance, and decommissioning stage. Furthermore, the integration of FEM with data analytics, ML, and digital twins presents exciting opportunities for predictive maintenance, real-time monitoring, and risk management strategies.

Author Contributions

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Abbreviations

ANSYS	Commercial Finite Element Software
ASME	American Society of Mechanical Engineers B31G
APDL	ANSYS Parametric Design Language
API 5L	American Petroleum Institute, 5th edition Line Pipe
API RP579	American Petroleum Institute Recommended Practice 579
BCs	Boundary Conditions
BP	Burst Pressure
BPNN	Back Propagation Neural Network
BPL	Burst Pressure Loss
C3p	Dimensionless coefficient of internal pressure
CEEMDAN	Complete Ensemble Empirical Mode Decomposition with Adaptive Noise
DNV-RP-F101	Det Norske Veritas-Recommended Practice-Factor of Safety 101
E	Young's Modulus
ECC	Electro-Chemical Corrosion
FE	Finite Element
FEA	Finite Element Analysis
FEM	Finite Element Method
FGMs	Functionally Graded Materials
FORM	First Order Reliability Method
FOSM	First Order Second Moment
FRP	Fibre Reinforced Polymer
GA	Genetic Algorithm
ID	Inner Diameter of a Pipe
IPSO	Improved Particle Swarm Optimisation
kg	Kilogramme
LSSAW	Longitudinal Seam Submerged Arc Welded
MAOP	Maximum Allowable Operating Pressure in MPa
ML	Machine Learning
MOP	Maximum Operating Pressure in MPa
MPa	Megapascal
NDT	Non-Destructive Testing
NNAs	Neural Network Architectures
NS4	Near-Neutral Simulated with pH-4
O&G	Oil and Gas
OD	Outside Diameter of a Pipe
P	Internal pressure
p/t	Ratio of pressure to pipeline wall thickness
pH	Potential of Hydrogen
PHMSA	Pipeline and Hazardous Materials Safety Administration
Psi	Pounds per square inch
PSL 1&2	Product Specification Level 1 & 2 as always defined by API 5L
PSO	Particle Swarm Optimisation
R6	Rev 4, Amendment 10
RSTRENG	Remaining Strength of corroded pipe
SBD	Strain-Based Design
SCC	Stress Corrosion Cracking
SEM	Scanning Electron Microscope
SHFs	Structural Health Failures
SHM	Structural Health Monitoring
SMYS	Specific Minimum Yield Strength
SOP	Standard Operating Procedure
Spallation	Localised fragments of material ejected from a global material due to stress impaction
SSC	Sulphide Stress Cracking
SVM	Support Vector Machine
t0/D0	Ratio of thickness-to-inside-diameter of a pipe before corrosion damage
TNT	Trinitrotoluene- an explosive material
TP	Third-Party
TPD(s)	Third-Party Damage(s)
v	Poisson's ratio
r.t	with respect to
X80	Key identifier of a specific grade and its associated pipeline properties
XFEM	eXtended Finite Element Method
Y/T	Ratio of yield strength to tensile strength
%	Percentage unit
(R-t/2)	Average radius of pipe minus half pipeline wall thickness

fu	Ultimate Tensile Strength (UTS) of pipe
σθ	Circumferential normal stress
εeq	Equivalent strain
ρ	Density
μs	Time in microseconds
3D	Three dimensional

References

[1] Hosseini, S.A., 2010. Assessment of Crack in Corrosion Defects in Natural Gas Transmission Pipelines [Master's thesis]. University of Waterloo: Waterloo, ON, Canada. pp. 1–92.

[2] James, B., Hudgins, A., 2016. Failure Analysis of Oil and Gas Transmission Pipelines. In: Makhlouf, A.S.H., Aliofkhazraei, M. (eds.). Handbook of Materials Failure Analysis with Case Studies from the Oil and Gas Industry. Butterworth-Heinemann: Oxford, UK. pp. 1–38.

[3] Guo, X., Zhang, L., Liang, W., et al., 2018. Risk identification of third-party damage on oil and gas pipelines through the Bayesian network. Journal of Loss Prevention in the Process Industries. 54, 163–178.

[4] Soomro, A.A., Mokhtar, A.A., Kurnia, J.C., et al., 2022. A review on Bayesian modeling approach to quantify failure risk assessment of oil and gas pipelines due to corrosion. International Journal of Pressure Vessels and Piping. 200, 104841.

[5] Vishnuvardhan, S., Murthy, A.R., Choudhary, A., 2023. A review on pipeline failures, defects in pipelines and their assessment and fatigue life prediction methods. International Journal of Pressure Vessels and Piping. 201, 104853.

[6] Yang, Z.Z., Tian, W., Ma, Q.R., et al., 2008. Mechanical properties of longitudinal submerged arc welded steel pipes used for gas pipeline of oil. Acta Metallurgica Sinica (English Letters). 21(2), 85–93.

[7] Chen, H., Wong, R.C.K., Park, S., et al., 2023. An AI-based monitoring system for external disturbance detection and classification near a buried pipeline. Mechanical Systems and Signal Processing. 196, 110346.

[8] Ghavamian, A., Mustapha, F., Baharudin, B.T., et al., 2018. Detection, localisation and assessment of defects in pipes using guided wave techniques: a review. Sensors. 18(12), 4470.

[9] Biezma, M.V., Andrés, M.A., Agudo, D., et al., 2020. Most fatal oil & gas pipeline accidents through history: a lesson learned approach. Engineering Failure Analysis. 110, 104446.

[10] China Daily, 2011. Bamboo, a symbol of traditional Chinese values. Available from: http://www.chinadaily.com.cn/life/2011-01/19/content_11882983_2.htm (cited 5 May 2025).

[11] Saltwork Consultants, 2016. Ancient salt trade and its value. Saltwork Consultants Pty Ltd. Available from: https://www.saltworkconsultants.com/ancient-salt-trade-and-its-value/ (cited 5 May 2025).

[12] Vogel, H.U., 1993. The great well of China. Scientific American. 268(6), 116–121.

[13] Brantly, J.E., 1971. History of Oil Well Drilling. Gulf Publishing Company: Houston, TX, USA.

[14] Zeinoddini, M., Ezzati, M., Parke, G.A.R., 2015. Plastic buckling, wrinkling and collapse behaviour of dented X80 steel line pipes under axial compression. Journal of Loss Prevention in the Process Industries. 38, 67–78.

[15] Torres, L., Jiménez-Cabas, J., González, O., et al., 2020. Kalman filters for leak diagnosis in pipelines: brief history and future research. Journal of Marine Science and Engineering. 8(3), 173.

[16] Ossai, C.I., 2020. Corrosion defect modelling of aged pipelines with a feed-forward multi-layer neural network for leak and burst failure estimation. Engineering Failure Analysis. 110, 104397.

[17] Qin, G., Cheng, Y.F., Zhang, P., 2021. Finite element modeling of corrosion defect growth and failure pressure prediction of pipelines. International Journal of Pressure Vessels and Piping. 194, 104509.

[18] Su, Y., Li, J., Yu, B., et al., 2021. Fast and accurate prediction of failure pressure of oil and gas defective pipelines using the deep learning model. Reliability Engineering & System Safety. 216, 108016.

[19] Kennedy, J.L., 1984. Oil and gas pipeline fundamentals. PennWell Publishing Company: Tulsa, OK, USA.

[20] Tse, P.W., Wang, X.J., 2009. Semi-quantitative analysis of defect in pipelines through the use of technique of ultrasonic guided waves. Key Engineering Materials. 413, 109–116.

[21] Nešić, S., 2007. Key issues related to modelling of internal corrosion of oil and gas pipelines–a review. Corrosion Science. 49(12), 4308–4338.

[22] Race, J.M., 2009. Management of Corrosion of Onshore Pipelines. In: Richardson, T.J.A. (ed.).

Shreir's Corrosion: Management and Control of Corrosion. Academic Press: Amsterdam The Netherlands. pp. 3270–3306.
[23] Zhang, S., Zhou, W., 2022. Assessment of the interaction of corrosion defects on steel pipelines under combined internal pressure and longitudinal compression using finite element analysis. Thin-Walled Structures. 171, 108771.
[24] Durowoju, M., Pu, Y., Benson, S., et al., 2016. Fatigue assessment of pipeline with plain dents under cyclic pressure loading using finite element method. In Proceedings of the 35th International Conference on Ocean, Offshore and Arctic Engineering, Busan, Republic of Korea, 19–24 June 2016; pp. 1–10.
[25] Zhu, X.K., Leis, B.N., 2007. Theoretical and numerical predictions of burst pressure of pipelines. Journal of Pressure Vessel Technology. 129(4), 644–652.
[26] Alexander, C.R., Kiefner, J.F., 1997. Effects of smooth and rock dents on liquid petroleum pipelines. In Proceedings of the 1999 API Pipeline Conference, Dallas, TX, USA, 10 October 1997; pp. 1–13.
[27] Shahid, M.D.A., Hashim, M.H.M., Mustafa, W.A.W., et al., 2023. Finite element analysis (FEA) of fiber-reinforced polymer (FRP) repair performance for subsea oil and gas pipelines: the recent brief review (2018–2022). Journal of Advanced Research in Applied Sciences and Engineering Technology. 32(3), 366–379.
[28] Meniconi, L.C., Freire, J.L., Vieira, R.D., et al., 2002. Stress analysis of pipelines with composite repairs. In Proceedings of the 4th International Pipeline Conference, Calgary, AB, Canada, September 29–October 3 2002; pp. 2031–2037.
[29] Witek, M., 2016. Gas transmission pipeline failure probability estimation and defect repairs activities based on in-line inspection data. Engineering Failure Analysis. 70, 255–272.
[30] Adisa, A., Olatunji, O., Brando, K., 2020. Design of extrusion machine for offshore corrosion-control composite wrap material manufacture. In Proceedings of The SPE Nigeria Annual International Conference and Exhibition, 11–13 August 2020.
[31] Witek, M., 2021. Structural integrity of steel pipeline with clusters of corrosion defects. Materials. 14(4), 852.
[32] Cosham, A., Hopkins, P., 2002. The pipeline defect assessment manual. In Proceedings of the 4th International Pipeline Conference, Calgary, AB, Canada, September 29–October 3, 2002; pp. 1565–1581.
[33] Khaing, M.M., Yin, S., 2025. Lifecycle management of hydrogen pipelines: design, maintenance, and rehabilitation strategies for Canada's clean energy transition. Energies. 18(2), 240.
[34] Dickinson, R.R., Battye, D.L., Linton, V.M., et al., 2010. Alternative carriers for remote renewable energy sources using existing CNG infrastructure. International Journal of Hydrogen Energy. 35(3), 1321–1329.
[35] Cerniauskas, S., Junco, A.J.C., Grube, T., et al., 2020. Options of natural gas pipeline reassignment for hydrogen: cost assessment for a Germany case study. International Journal of Hydrogen Energy. 45(21), 12095–12107.
[36] Télessy, K., Barner, L., Holz, F., 2024. Repurposing natural gas pipelines for hydrogen: limits and options from a case study in Germany. International Journal of Hydrogen Energy. 80, 821–831.
[37] Wynne, D.P., Naib, S., Mirzoev, G., 2023. A practical guide to repurposing existing pipelines to hydrogen operation. In Proceedings of The SPE Caspian Technical Conference and Exhibition, Baku, Azerbaijan, 21–23 November 2023.
[38] Lancaster, E.R., Palmer, S.C., 1996. Burst pressures of pipes containing dents and gouges. Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering. 210(1), 19–27.
[39] Johnson, C., Vigilante, A., 2024. The Public Perception of Pipelines. In: Handbook of Pipeline Engineering. Springer International Publishing: Cham, Switzerland. pp. 1613–1629.
[40] Gomes, M.G., Caro, A.C., 2024. Pipeline Third-Party Damage and Illegal Tapping. In: Handbook of Pipeline Engineering. Springer International Publishing: Cham, Switzerland. pp. 1–44.
[41] de França Freire, J.L., Gomes, M.R.R., Gomes, M.G. (eds.), 2024. Handbook of Pipeline Engineering. Springer Nature: Cham, Switzerland.
[42] Wu, Y., Xiao, J., Zhang, P., 2016. The analysis of damage degree of oil and gas pipeline with type II plain dent. Engineering Failure Analysis. 66, 212–222.
[43] Hyde, T.H., Luo, R., Becker, A.A., 2011. Predictions of three-dimensional stress variations in indented pipes due to internal pressure fluctuations. The Journal of Strain Analysis for Engineering Design. 46(6), 510–522.
[44] Valadi, Z., Bayesteh, H., Mohammadi, S., 2020.

XFEM fracture analysis of cracked pipeline with and without FRP composite repairs. Mechanics of Advanced Materials and Structures. 27(22), 1888–1899.

[45] Kilic, B., Madenci, E., 2009. Structural stability and failure analysis using peridynamic theory. International Journal of NonLinear Mechanics. 44(8), pp845–854.

[46] Kilic, B., Madenci, E., 2009. Prediction of crack paths in a quenched glass plate by using peridynamic theory. International Journal of Fracture. 156, 165–177.

[47] Silling, S.A., Lehoucq, R.B., 2010. Peridynamic theory of solid mechanics. Advances in Applied Mechanics. 44, 73–168.

[48] Oterkus, E., Madenci, E., 2012. Peridynamic analysis of fiber-reinforced composite materials. Journal of Mechanics of Materials and Structures. 7(1), 45–84.

[49] Madenci, E., Oterkus, E., 2013. Peridynamic Theory. In: Madenci, E., Oterkus, E. (eds.). Peridynamic Theory and Its Applications. Springer: New York, NY, USA. pp.19–43.

[50] Candaş, A., Oterkus, E., Imrak, C.E., 2024. Ordinary state-based peridynamic modelling of crack propagation in functionally graded materials with micro cracks under impact loading. Mechanics of Advanced Materials and Structures. 31(30), 13502–13517.

[51] Shi, C., Gong, Y., Yang, Z.G., et al., 2019. Peridynamic investigation of stress corrosion cracking in carbon steel pipes. Engineering Fracture Mechanics. 219, 106604.

[52] Candaş, A., Oterkus, E., İmrak, C.E., 2023. Peridynamic simulation of dynamic fracture in functionally graded materials subjected to impact load. Engineering with Computers. 39(1), 253–267.

[53] Imachi, M., Tanaka, S., Ozdemir, M., et al., 2020. Dynamic crack arrest analysis by ordinary state-based peridynamics. International Journal of Fracture. 221, 155–169.

[54] Dadfar, B., El Naggar, M.H., Nastev, M., 2015. Ovalization of steel energy pipelines buried in saturated sands during ground deformations. Computers and Geotechnics. 69, 105–113.

[55] Kyriakides, S., Corona, E., 2023. Mechanics of Pipelines: Volume I: Buckling and Collapse. Gulf Professional Publishing: Cambridge, MA, USA.

[56] Sun, J., Jukes, P., Shi, H., 2012. Thermal expansion/global buckling mitigation of HPHT deepwater pipelines, sleeper or buoyancy? In Proceedings of The Twenty-second International Offshore and Polar Engineering Conference, Rhodes, Greece, 17–22 June 2012.

[57] Wang, Z., Tang, Y., van der Heijden, G.H.M., 2018. Analytical study of distributed buoyancy sections to control lateral thermal buckling of subsea pipelines. Marine Structures. 58, 199–222.

[58] Cai, J., Le Grognec, P., 2022. Lateral buckling of submarine pipelines under high temperature and high pressure—a literature review. Ocean Engineering. 244, 110254.

[59] Gong, S., Hu, Q., Bao, S., et al., 2015. Asymmetric buckling of pipelines under combined tension, bending and external pressure. Ships and Structures. 10(2), 162–175.

[60] Xu, L., Yu, J., Zhu, Z., et al., 2023. Research and application for corrosion rate prediction of natural gas pipelines based on a novel hybrid machine learning approach. Coatings. 13(5), 856.

[61] Race, J.M., 2008. Integrity Assessment of Plain Dents Subject to Fatigue Loading. UKOPA: Newcastle-upon-Tyne, UK.

[62] Mackintosh, D.D., 2020. Pipeline Dent Strain Assessment Using ASME B31.8. Available from: https://studylib.net/doc/27250452/pipeline-dent-strain-assessment-using-asme-b31.8 (cited 5 May 2025).

[63] Huang, X., Cheng, B., Zhang, D., et al., 2021. A unified theoretical solution of plastic limit load for the thin-walled pipeline with an incomplete welding defect. International Journal of Pressure Vessels and Piping. 191, 104358.

[64] Zhen, Y., Tian, H., Yi, H., et al., 2018. Constraint-corrected fracture failure criterion based on CTOD/CTOA. International Journal of Fracture. 214, 115–127.

[65] Okodi, A., Li, Y., Cheng, J.J.R., et al., 2021. Effect of location of crack in dent on burst pressure of pipeline with combined dent and crack defects. Journal of Pipeline Science and Engineering. 1(2), 252–263.

[66] Ghaednia, H., Das, S., Wang, R., et al., 2017. Dependence of burst strength on crack length of a pipe with a dent-crack defect. Journal of Pipeline Systems Engineering and Practice. 8(2), 04016019.

[67] Velázquez, J.C., González-Arévalo, N.E., Díaz-Cruz, M., et al., 2022. Failure pressure estimation for an aged and corroded oil and gas pipeline: a finite element study. Journal of Natural Gas Science and Engineering. 101, 104532.

[68] Arumugam, T., Kumar, S.D.V., Karuppanan, S., et al., 2023. The influence of axial compressive stress and internal pressure on a pipeline network: a review. Applied Sciences. 13(6), 3799.
[69] Oh, C.K., Kim, Y.J., Baek, J.H., et al., 2007. Ductile failure analysis of API X65 pipes with notch-type defects using a local fracture criterion. International Journal of Pressure Vessels and Piping. 84(8), 512–525.
[70] Askari, M., Aliofkhazraei, M., Afroukhteh, S., 2019. A comprehensive review on internal corrosion and cracking of oil and gas pipelines. Journal of Natural Gas Science and Engineering. 71, 102971.
[71] da Cunha, S.B., 2016. A review of quantitative risk assessment of onshore pipelines. Journal of Loss Prevention in the Process Industries. 44, 282–298.
[72] Dey, P.K., Ogunlana, S.O., Naksuksakul, S., 2004. Risk-based maintenance model for offshore oil and gas pipelines: a case study. Journal of Quality in Maintenance Engineering. 10(3), 169–183.
[73] Capiel, G., Fayó, P., Orofino, A., et al., 2016. Failure of Glass Fiber-Reinforced Epoxy Pipes in Oil Fields. In: Makhlouf, A.S.H., Aliofkhazraei, M. (eds.). Handbook of Materials Failure Analysis with Case Studies from the Oil and Gas Industry. Butterworth-Heinemann: Oxford, UK. pp. 91–103.
[74] Song, K., Long, Y., Ji, C., et al., 2016. Experimental and numerical studies on the deformation and tearing of X70 pipelines subjected to localized blast loading. Thin-Walled Structures. 107, 156–168.
[75] Ameh, E.S., Ikpeseni, S.C., 2017. Pipelines cathodic protection design methodologies for impressed current and sacrificial anode systems. Nigerian Journal of Technology. 36(4), 1072–1077.
[76] Kelil, T., Amara, M., Meliani, M.H., et al., 2019. Assessment of API X65 steel pipe puffiness by a strain-based design (SBD) approach under bi-axial loading. Engineering Failure Analysis. 104, 578–588.
[77] Zhang, L., Adey, R.A., 2009. Prediction of third-party damage failure frequency for pipelines transporting mixtures of natural gas and hydrogen. In Proceedings of the 3rd International Conference on Hydrogen Safety (ICHS3), Ajaccio-Corsica, France, 16–18 September 2009; pp. 1–12.
[78] Zhang, S.H., Zhao, D.W., Wang, X.N., 2014. Influence of yield-to-tensile strength ratio (Y/T) on failure assessment of defect-free and corroded X70 steel pipeline. Journal of Central South University. 21(2), 460–465.
[79] Bhardwaj, U., Teixeira, A.P., Soares, C.G., et al., 2019. Reliability assessment of thick high strength pipelines with corrosion defects. International Journal of Pressure Vessels and Piping. 177, 103982.
[80] Hasan, S., Sweet, L., Hults, J., et al., 2018. Corrosion risk-based subsea pipeline design. International Journal of Pressure Vessels and Piping. 159, 1–14.
[81] Oh, D.H., Race, J., Oterkus, S., et al., 2020a. A new methodology for the prediction of burst pressure for API 5L X grade flawless pipelines. Ocean Engineering. 212, 107602.
[82] Sebaey, T.A., 2019. Design of oil and gas composite pipes for energy production. Energy Procedia. 162, 146–155.
[83] Tashnizi, E.S., Gohery, S., Sharifi, S., et al., 2020. Optimal winding angle in laminated CFRP composite pipes subjected to patch loading: analytical study and experimental validation. International Journal of Pressure Vessels and Piping. 180, 104042.
[84] Chen, Z.F., Chu, W.P., Wang, H.J., et al., 2022. Structural integrity assessment of hydrogen-mixed natural gas pipelines based on a new multi-parameter failure criterion. Ocean Engineering. 247, 110731.
[85] Vosooghi, N., Ivanović, A., Sriramula, S., 2021. Rogue lateral buckle initiation at subsea pipelines. Applied Ocean Research. 117, 102899.
[86] Johns, T.G., Mesloh, R.E., Winegardner, R.G., et al., 1975. Inelastic buckling of pipelines under combined loads. In Proceedings of The Offshore Technology Conference, Houston, TX, USA, 4–7 May 1975.
[87] Sakakibara, N., Kyriakides, S., Corona, E., 2008. Collapse of partially corroded or worn pipe under external pressure. International Journal of Mechanical Sciences. 50(12), 1586–1597.
[88] Shin, S.M., Suh, J.H., Im, J.S., et al., 2003. Development of third-party damage monitoring system for natural gas pipeline. KSME International Journal. 17(10), 1423–1430.
[89] Ossai, C.I., Boswell, B., Davies, I.J., 2015. Pipeline failures in corrosive environment – a conceptual analysis of trends and effects. Engineering Failure Analysis. 53, 36–58.
[90] Mondal, B.C., Dhar, A.S., Hafiz, H.I., 2022. Burst

pressure assessment of pipe bend/elbow for transmission pipelines. Thin-Walled Structures. 174, 109148.
[91] Chouchaoui, B.A., Pick, R.J., 1994. Behaviour of circumferentially aligned corrosion pits. International Journal of Pressure Vessels and Piping. 57(2), 187–200.
[92] Ma, B., Shuai, J., Liu, D., et al., 2013. Assessment on failure pressure of high strength pipeline with corrosion defects. Engineering Failure Analysis. 32, 209–219.
[93] Pluvinage, G., Capelle, J., Schmitt, C., 2016. Methods for assessing defects leading to gas pipe failure. In: Makhlouf, A.S.H., Aliofkhazraei, M. (eds.). Handbook of Materials Failure Analysis with Case Studies from the Oil and Gas Industry. Butterworth-Heinemann: Oxford, UK. pp. 55–89.
[94] Cheng, A., Chen, N.Z., 2022. Structural integrity assessment for deep-water subsea pipelines. International Journal of Pressure Vessels and Piping. 199, 104711.
[95] Cavalieri, F., Franchin, P., Gehl, P., et al., 2017. Bayesian Networks and Infrastructure Systems: Computational and Methodological Challenges. In: Gardoni, P. (ed.). Risk and Reliability Analysis: Theory and Applications. Springer International Publishing: Cham, Switzerland. pp. 385–415.
[96] Zakikhani, K., Nasiri, F., Zayed, T., 2020. A review of failure prediction models for oil and gas pipelines. Journal of Pipeline Systems Engineering and Practice. 11(1), 03119001.
[97] Khan, F., Yarveisy, R., Abbassi, R., 2021. Risk-based pipeline integrity management: a road map for the resilient pipelines. Journal of Pipeline Science and Engineering. 1(1), 74–87.
[98] Fahed, M., Barsoum, I., Alfantazi, A., et al., 2020. Burst pressure prediction of pipes with internal corrosion defects. Journal of Pressure Vessel Technology. 142(3), 031801.
[99] Leis, B.N., Stephens, D.R., 1997. An alternative approach to assess the integrity of corroded line pipe – Part I: Current status. In Proceedings of The Seventh International Offshore and Polar Engineering Conference, Honolulu, HI, USA, 25–30 May 1997.
[100] Bjørnøy, O.H., Fu, B., Sigurdsson, G., et al., 1999. Introduction and background to DNV RP-F101 "Corroded Pipelines". In Proceedings of The Ninth International Offshore and Polar Engineering Conference, Brest, France, May 30–June 4 1999.
[101] Shuai, J., 2010. Evaluating the failure pressure of corroded pipeline. In Proceedings of the 2010 Pressure Vessels and Piping Division/K-PVP Conference, Bellevue, WA, USA, 18–22 July 2010; pp. 1021–1027.
[102] Ma, B., Shuai, J., Wang, J., et al., 2011. Analysis on the latest assessment criteria of ASME B31G-2009 for the remaining strength of corroded pipelines. Journal of Failure Analysis and Prevention. 11, 666–671.
[103] Oh, D., Race, J., Oterkus, S., et al., 2020b. Burst pressure prediction of API 5L X-grade dented pipelines using deep neural network. Journal of Marine Science and Engineering. 8(10), 766.
[104] Yan, Z., Zhang, S., Zhou, W., 2014. Model error assessment of burst capacity models for energy pipelines containing surface cracks. International Journal of Pressure Vessels and Piping. 120, 80–92.
[105] Zhu, S., Xu, Y., Zu, C., et al., 2023. Study on the method of detecting oil pipeline clogging by fluid oscillation theory. In Proceedings of the 2nd International Conference on Energy, Power and Electrical Engineering (EPEE 2022), Hangzhou, China, 23–25 September 2022; pp. 1–10.
[106] Chern-Tong, H., Aziz, I.B., 2016. A corrosion prediction model for oil and gas pipeline using CMARPGA. In Proceedings of the 3rd International Conference on Computer and Information Sciences (ICCOINS), Kuala Lumpur, Malaysia, 15–17 August 2016; pp. 403–407.
[107] Al-Sharify, Z.T., Faisal, M.L., Hamad, L.B., et al., 2020. A review of hydrate formation in oil and gas transition pipes. In Proceedings of The International Conference on Engineering and Advanced Technology (ICEAT 2020), Assiut, Egypt, 11–12 February 2020; pp. 1–15.
[108] Adib-Ramezani, H., Jeong, J., Pluvinage, G., 2006. Structural integrity evaluation of X52 gas pipes subjected to external corrosion defects using the SINTAP procedure. International Journal of Pressure Vessels and Piping. 83(6), 420–432.
[109] Dao, U., Sajid, Z., Khan, F., et al., 2023. Modeling and analysis of internal corrosion induced failure of oil and gas pipelines. Reliability Engineering & System Safety. 234, 109170.
[110] Shterenlikht, A., Hashemi, S.H., Howard, I.C., et al., 2004. A specimen for studying the resistance to ductile crack propagation in pipes. Engineering Fracture Mechanics. 71(13–14), 1997–2013.
[111] Amara, M.B., Pluvinage, G., Capelle, J., et al.,

2015. Prediction of arrest pressure in pipe based on CTOA. Journal of Pipeline Integrity. hal-02972903, 1–17.

[112] Shibanuma, K., Hosoe, T., Yamaguchi, H., et al., 2018. Crack tip opening angle during unstable ductile crack propagation of a high-pressure gas pipeline. Engineering Fracture Mechanics. 204, 434–453.

[113] Wahidi, S.I., Oterkus, S., Oterkus, E., 2024. Robotic welding techniques in marine structures and production processes: a systematic literature review. Marine Structures. 95, 103608.

[114] Ho, M., El-Borgi, S., Patil, D., et al., 2020. Inspection and monitoring systems for subsea pipelines: a review paper. Structural Health Monitoring. 19(2), 606–645.

[115] Evans, M., Thomas, K., 2014. Design of pipelines for Guided Wave Testing (GWT). In Proceedings of the 11th European Conference on Non-Destructive Testing (ECNDT 2014), Prague, Czech Republic, 6–10 October 2014; pp. 1–9.