Ocean Engineering 303 (2024) 117773

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Evaluating the reliability and integrity of composite pipelines in the oil and gas sector: A scientometric and systematic analysis

Ummi Salina Farini Bahaman [a], Zahiraniza Mustaffa [a], Mohamed El Amine Ben Seghier [b,c,*], Thar Mohammed Badri [d]

[a] Department of Civil and Environmental Engineering, Universiti Teknologi PETRONAS, 32610, Seri Iskandar, Perak, Malaysia
[b] Laboratory for Computational Mechanics, Institute for Computational Science and Artificial Intelligence, Van Lang University, Ho Chi Minh City, Vietnam
[c] Faculty of Mechanical - Electrical and Computer Engineering, School of Technology, Van Lang University, Ho Chi Minh City, Vietnam
[d] Department of Mechanical Engineering, Universiti Teknologi PETRONAS, 32610, Seri Iskandar, Perak, Malaysia

ARTICLE INFO

Keywords:
Composite flexible pipeline
Failure
Inspection
Monitoring
Reliability
Integrity

ABSTRACT

The use of composite flexible pipelines seems reliable and promising to the oil and gas industry to transport hydrocarbons as it is one of the best alternatives to overcome the major problem of corrosion in conventional carbon steel pipelines. However, throughout the years of operation, composite flexible pipelines can also degrade and tend to experience failures such as cracking, delamination and buckling due to several external or internal factors. It is crucial to periodically inspect and monitor the actual condition of composite pipelines in order to determine their safety and integrity throughout their design life. Therefore, with the scientometric and systematic review method, this paper aims to provide insight and future direction on the reliability and integrity assessment of composite pipelines that may be beneficial to pipeline operators as well as researchers or scholars within this field of expertise. Discussion on the common failure drivers, modes and mechanisms are detailed to better understand the relationship between the failure, reliability and integrity of composite flexible pipelines. A brief discussion about the available inspection and monitoring techniques for composite pipelines is also reported. From this comprehensive review, it is found that available approaches for the structural reliability analysis and integrity assessments of composite flexible pipelines are mainly based on quantitative risk-based inspection (QRBI) to produce a more reliable risk interpretation. Nevertheless, combining multiple inspection techniques and employing machine learning methodologies can aid in improving the real-time damage evaluation and safety performance of composite flexible pipes.

1. Introduction

Since the 1930s, carbon steel has been the most used material in the industry to construct transporting fluid pipelines as it has good mechanical properties such as high strength, toughness and durability, safety and economical uses (Idris et al., 2020a), (Khalid et al., 2020), (Farh et al., 2023). However, carbon steel pipelines are prone to deterioration over time under a constant harsh environment, high pressure and temperature causing any defects or anomalies to occur (Idris et al., 2020a), (Ben Seghier et al., 2022). Deterioration or degradation of metal due to corrosion can cause major problems to carbon steel pipelines, which directly impact the performance of these structures in terms of their efficiency, safety and reliability and eventually lead to failures (Idris et al., 2020b), (Idris et al., 2021), (Ben Seghier et al., 2021). According to statistics, Dai et al. (2017) and Zhu (2021) stated that the top three failure causes recorded for oil pipelines are corrosion, pipe or welding material failures and equipment failures. In comparison, the top three failure causes dominated in gas pipelines are pipe or welding material failures, excavation damage and corrosion. In addition, Webster (2010) stated that 70% of pipeline failures in oil and gas-related industries are due to corrosion while around 58% of the corrosion-related failures were reported to happen internally.

Failures in oil and gas pipeline systems can cause catastrophic impacts, which may lead to injuries and fatalities. Pipeline and Hazardous Materials Safety Administration (PHMSA), U.S. Department of Transportation (DOT) published a report of statistical results and detailed

* Corresponding author. Laboratory for Computational Mechanics, Institute for Computational Science and Artificial Intelligence, Van Lang University, Ho Chi Minh City, Vietnam.
E-mail address: benseghier@vlu.edu.vn (M.E.A. Ben Seghier).

https://doi.org/10.1016/j.oceaneng.2024.117773
Received 26 January 2024; Received in revised form 27 March 2024; Accepted 2 April 2024
Available online 6 April 2024
0029-8018/

information regarding the total incident counts of all pipelines in the U. S. for 20 years (Dai et al., 2017), (Zhu, 2021). Ranging from the year 2003 until 2022, 7556 and 4964 of total incident counts which involved oil and gas pipelines, respectively, are shown in Fig. 1 and the number of fatalities and injuries were recorded as shown in Table 1.

According to the report published in 2016 by National Association of Corrosion Engineers (NACE) entitled "International Measures of Prevention, Application and Economics of Corrosion Technologies Study (IMPACT)", it was stated that the annual cost of corrosion was estimated to be approximately US$ 2.5 trillion, which equivalent to 3.4% of the global Gross Domestic Product (GDP), whereas corrosion control and monitoring had been one of the most invested sectors in oil and gas related industries (Koch et al., 2016), (Terán et al., 2017). Fig. 2 shows an increment trend of the total annual budget authority recorded from 2014, where it is predicted to increase significantly by the year 2024 based on the report published in March 2023 by the Congressional Research Service. In this report, Parfomak (2023) predicted that the total annual budget authority for the PHMSA pipeline safety program in 2024, which covers pipeline inspections and damage prevention, will increase by approximately 20% compared to 2023, resulting in a total amount budget of $228.23 million. This situation shows that failures in the pipeline not only can harm the environment and cause human fatalities or injuries but can also impact the economy of the country as the cost of pipeline inspection and mitigation keeps increasing over the years to ensure the safety and reliable performance of the operated pipelines.

Therefore, one of the emerging strategies to mitigate this major problem as well as to reduce the total cost of inspection and maintenance associated with pipelines is the shifting from using conventional carbon steel material to composite material. This latter can be simply defined as a combination of two or more materials or constituents that have different physical and chemical properties to produce a brand-new material (Ngo, 2020), (Mehta and Vadher, 2017), (Dhakal et al., 2021). In general, composite material comprises two main components: the reinforcement and matrix (Ngo, 2020), (Mehta and Vadher, 2017). By combining these two components, the properties of the composite materials are improved compared to the parent materials, resulting in superior performance in strength, specific stiffness, thermal stability as well as resistance towards corrosion and fatigue (Mehta and Vadher, 2017). The use of composite materials is not limited to engineering applications only but has also been widely used in other industries such as aerospace and automotive (Ngo, 2020), (Dhakal et al., 2021). Some examples of composite materials include reinforced concrete, composite wood (e.g. plywood) and reinforced plastics (e.g. fibreglass and fibre-reinforced polymer) (Ngo, 2020), (Dhakal et al., 2021).

Table 1
Number of fatalities and injuries recorded based on the total incident counts for oil and gas pipelines, extracted from (Pipeline and Hazardous Materials Safety Administration (PHMSA)).

Year	Oil Pipelines		Gas Pipelines	
	Fatalities	Injuries	Fatalities	Injuries
2003	0	5	12	66
2004	5	16	18	44
2005	2	2	15	45
2006	0	2	21	34
2007	4	10	11	39
2008	2	2	6	54
2009	4	4	9	60
2010	1	3	21	105
2011	0	1	13	54
2012	3	4	9	53
2013	1	6	8	38
2014	0	0	19	94
2015	1	0	10	48
2016	3	9	13	78
2017	1	1	6	31
2018	0	2	7	76
2019	0	0	11	36
2020	5	12	10	27
2021	0	1	13	32
2022	0	0	5	22
Total	**32**	**80**	**237**	**1036**

The first application of composite material for offshore pipelines began after World War II and was later commercialized in the mid-1950s as Fibre Reinforced Polymer Pipe (FRP) (Yu et al., 2017). Besides the FRP, other composite pipelines being accepted in the industry are Reinforced Thermosetting Resin (RTR) pipe, Flexible Composite Pipe (FCP), Thermoplastic Composite Pipe (TCP) and the most recent Reinforced Thermoplastic Pipe (RTP) (Khalid et al., 2020), (Yu et al., 2017), (Bakar et al., 2021). These composite pipelines are also known as non-metallic pipes as they comprise both polymers and composites (Khalid et al., 2020). Moreover, the choice of a non-metallic pipeline has been one of the feasible alternatives to overcome corrosion problems in the metallic or carbon steel pipeline (Khalid et al., 2020).

The composite pipelines can be divided into two types which are unbonded and bonded composite pipelines (Veritas, 2018), (Bai et al., 2005a). The unbonded pipeline is defined as a flexible composite pipeline, which consists of separate unbonded polymeric and metallic layers to allow relative movement between layers. The bonded pipeline is a

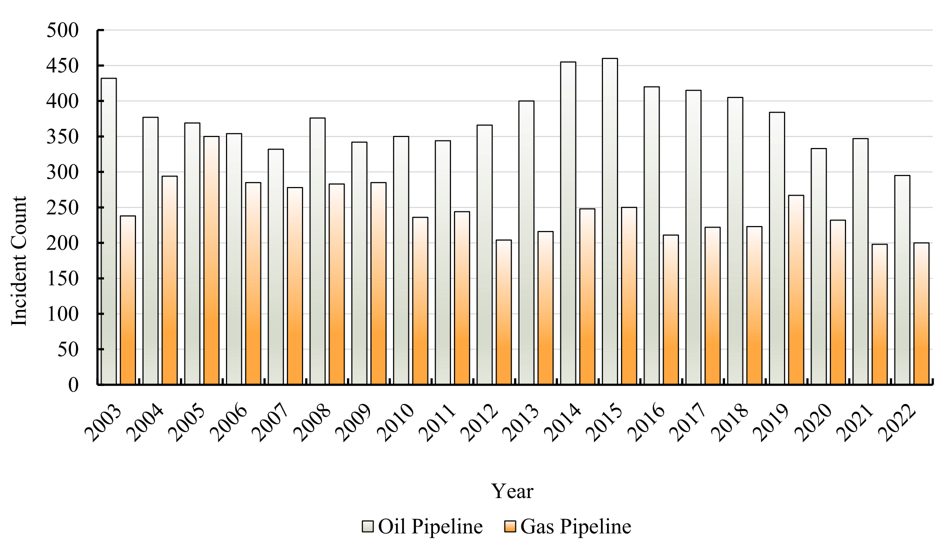

Fig. 1. Total incident counts of oil and gas pipelines according to PHMSA (Pipeline and Hazardous Materials Safety Administration (PHMSA)).

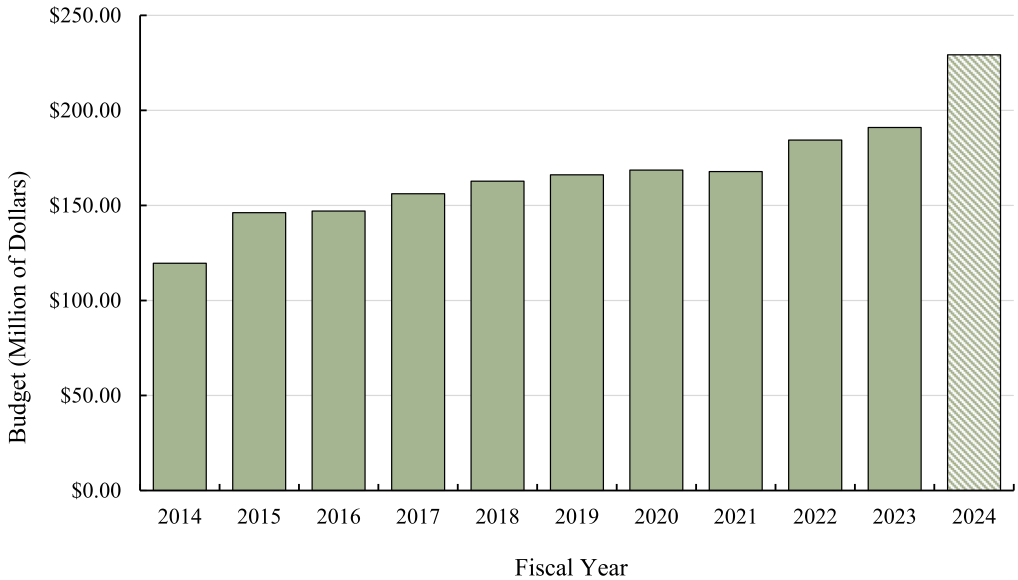

Fig. 2. Total of annual budget authority for PHMSA Pipeline Safety Program from 2014 until predicted year 2024, modified from (Parfomak, 2023).

flexible pipe integrated with steel reinforcement and bonded to a different layer of material, to obtain an additional structural reinforcement or to separate layers (A. P. I. (API), 2008). Each layer of the unbonded pipeline is a multi-start stack, which is specially made of pre-cured unidirectional composite tapes. Each layer has its purpose or function in protecting or providing strength to the performance of the unbonded composite pipeline. Bai (Bai et al., 2005a) stated that there are five main components of an unbonded pipeline namely carcass, internal polymer sheath, pressure armour, tensile armour and lastly is external polymer sheath.

Different from an unbonded pipeline, a bonded pipeline can be simplified as a composite pipeline with different layers of materials, glued or stuck to each layer to strengthen and provide additional strength and reinforcement to the pipeline. Khalid et al. (2020) stated that in bonded pipelines, the reinforcement is embedded in polymer and as a result of swelling and blistering, bonded pipelines cannot be reliable if there is a presence of gas or crude oil mixtures. One example of the bonded pipeline is Reinforced Thermoplastic Pipe (RTP) which can be considered a relatively new type of bonded composite pipeline and started to be used extensively in the oil and gas industry, for both onshore and deep-water offshore applications (Khalid et al., 2020), (Yu et al., 2017), (Liu and Wang, 2019). The RTP has been chosen to replace the use of carbon steel pipeline as a transporting medium for hydrocarbon as well as an emerging alternative to overcome internal corrosion as well as due to its outstanding advantages and excellent combination of strength, flexibility, lightweight, fatigue and most importantly, corrosion resistance. (Khalid et al., 2020), (Yu et al., 2017), (Liu and Wang, 2019), (Kruijer et al., 2005), (Bai et al., 2014a), (Bai et al., 2014b), (Bai et al., 2011).

RTP is usually made up of three main structural components, namely thermoplastic liner, reinforcement layer and thermoplastic as shown in Fig. 3 (Khalid et al., 2020), (Yu et al., 2017), (Liu and Wang, 2019), (Kruijer et al., 2005), (Bai et al., 2014a), (Bai et al., 2014b), (Bai et al., 2011), (Bai et al., 2015a). Each layer of RTP is made up of different materials and functions to strengthen and provide the best performance for RTP. Thermoplastic liner or internal liner functions as the corrosion-resistant containment and prevents the transported product from leaking, while the outer layer or thermoplastic cover is a protection for the whole layers (especially for the reinforcement layers) from external damage and corrosion (Khalid et al., 2020), (Bai et al., 2014a), (Badeghaish et al., 2019), (Wang et al., 2021). There are several types of

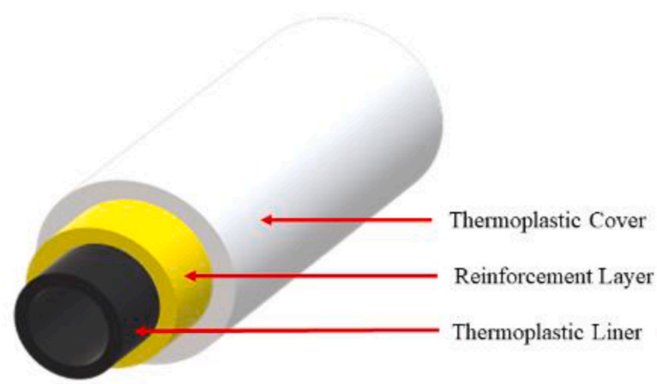

Fig. 3. Structural components of RTP.

thermoplastic materials being used for both the inner and outer layers of RTP, such as polyethylene (PE), cross-linked polyethylene (PEX), polyamide (PA11, PA12), polyvinylidene fluoride (PVDF) and the most common is high-density polyethylene (HDPE). The reinforcement layer of RTP is made up of various types of fibres (e.g. glass fibre, carbon fibre and aramid fibre) being helically wrapped or embedded in the inner layer at a winding angle of $\pm 54.7^{\circ}$ to fully utilize the strength of the fibre reinforcement (Bai et al., 2014a), (Badeghaish et al., 2019), (Wang et al., 2021). Moreover, the reinforcement layer also helps to withstand the applied internal pressure and other loads exerted on the RTP (Wang et al., 2021).

The use of RTP in the oil and gas industry has proved to be more favourable as it is easy to install and relatively low cost in terms of installation and maintenance (Bai et al., 2014a), (Bai et al., 2014b), (Bai et al., 2011). An approximate reduction of 27% in total overall cost savings was reported by (Luhrsen, 2001) for instance, covering the costs of maintenance when compared to the conventional steel pipe, as shown in Fig. 4.

This further supports the use of RTP to replace the conventional steel pipeline, however, degradation and deterioration remain an issue in composite pipelines as well. Similar to the carbon steel pipeline, several failure drivers such as temperature and pressure fluctuations, excessive service loads as well as third-party impact can cause multiple failure

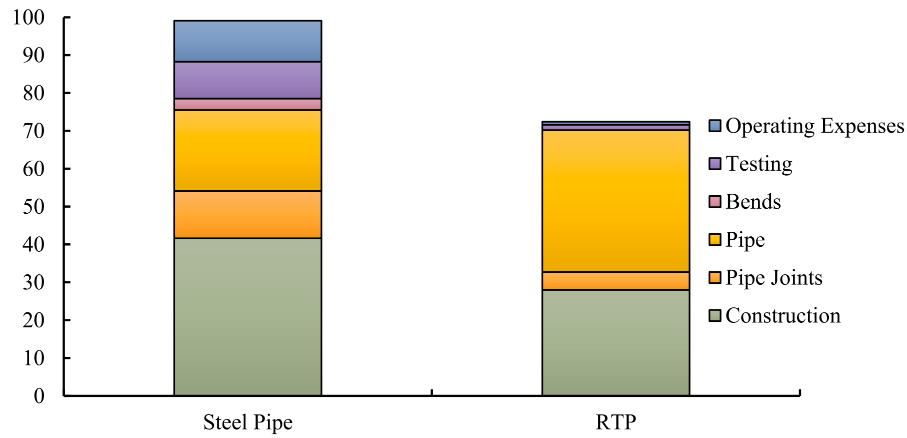

Fig. 4. Comparison of overall cost savings of conventional steel pipe and RTP, extracted from (Luhrsen, 2001).

modes in composite pipelines like delamination, cracking, buckling and fatigue (Veritas, 2018), (Bai et al., 2005b). The carbon steel pipeline has been established for its various types of inspection and monitoring techniques and technologies (e.g. in-line inspection, sensing technologies, robotic vehicles and fibre optic sensors (FOS)) (Ho et al., 2019). The inspection and monitoring technologies for composite pipelines however are limited and insufficient. This is because existing inspection and monitoring techniques for composite pipelines (e.g. coupon sampling and other NDT techniques) are not capable of inspecting the damages or failures completely in operating composite pipelines. To obtain a more reliable, accurate and complete data analysis from the inspection and monitoring of composite pipelines, it is recommended to combine the existing NDT techniques such as acoustic-based, instrumentation-based, x-ray radiography and tomography and microwave-band inspection techniques as each of these techniques has its own strength and specific damage that can be detected. The data obtained from the in-line inspection and monitoring of pipelines are crucial for the structural reliability or integrity assessment to ensure the safe operation within their design life. Thus, the reliability or integrity assessment of composite pipelines can be a challenging topic.

Studies related to reliability or integrity assessment of composite pipelines have been explored since year 2000s. Several methods and approaches have been proposed to perform the reliability assessment of composite pipelines. Initiated by Richard et al. (Richard and Perreux, 2000), the reliability of fibre composite pipes subjected to micro-cracking failure at the matrix of the pipe was evaluated using the First Order Reliability Method (FORM). FORM was chosen to evaluate the fibre composite pipes based on the principle of maximizing the failure probability and considering the statistical uncertainties. Kogiso et al. (2001) expanded the reliability assessment study of laminated composite pipe subjected to bending, tension and torsion loadings by performing two analyses, deterministic strength analysis and reliability analysis, considering and using Tsai Wu failure criterion and FORM, respectively. Some significant outcomes were distinguished from both deterministic strength analysis and reliability analysis such as the influence of the variations of Young's Modulus for the elastic deformation failure mode as well as sensitive parameters like shear modulus, longitudinal tensile strength and the applied torque for both analyses gave significant results to the reliability of the laminated composite pipe.

In 2015, Bai et al. (2015b) provided an approach for the reliability-based determination of subsea lightweight pipelines with additional weight allowance against on-bottom lateral instability. A response surface model was developed from the probabilistic analysis of non-linear finite element modelling (FEM) of the fluids-pipe-soil interaction model to predict the horizontal displacement of the pipeline and with the combination of Monte Carlo Simulation (MCS), the safety indices and targeted levels of failure probability were obtained. The serviceability limit state (SLS) function was considered in this study as a failure function with the excessive lateral displacement and loss of on-bottom stability of the pipeline due to hydrodynamic loads. From this study, 10,000 cases of MCS were generated to predict the horizontal pipeline displacement and the pipeline lateral displacement calibration factor was introduced into the limit state function (LSF) for the reliability-based analysis method to determine the required additional submerged pipeline weight for the assessment of pipeline on-bottom stability.

In line with the developments of various advanced technologies for the inspection and monitoring of composite pipelines, Alexander et al. (Alexander and Kulkarni, 2018) introduced the concept of Technology Readiness Levels (TRLs), which is commonly used in aerospace and defence industries as a tool to evaluate and assess composite pipelines as well as enhancing the integrity management efforts. This approach was introduced to overcome the challenge faced by the pipeline operators which is the deployment of unproven technologies for the inspection, assessment, monitoring and rehabilitation of pipeline systems. Hence, the implementation of the TRL approach for the integrity assessment of composite pipelines can help minimize pipeline operators' risk and adopt the implementation of advanced technologies. TRL ladder consists of 7 levels, starting from TRL 0: Basic Unproven Concepts until TRL 7: Field Proven, which was introduced to provide an effective evaluation of the "operational readiness" of the technology. Three onshore-related case studies were presented – monitoring and evaluation of pipelines using fibre optics, 3D imaging inspection and reinforcement using optimized composite technologies. From these three case studies, only TRL 2: Demonstration by Testing and TRL 5: System Integration Testing were assigned as all the case studies only achieved up to the validating of prototype or technology and can be further improved to achieve the "operational readiness" of the given technology.

Condition Performance Monitoring (CPM) was introduced by Escuer et al. (2018) in 2018 to demonstrate the automatized use of data from the sensors allows for dynamic and optimized integrity management. It also adds value in monitoring the integrity of flexible pipes for optimizing operating expenditures and reducing the need for offshore interventions. CPM is a web-based software solution that captures available information-based analysis from the field to provide support for an optimized integrity management strategy. CPM implementation comprises three main processes: gathering all the relevant project design data, conducting a gap analysis between the original design rules with the most recent design rules and gathering the information from all monitoring devices. Through CPM, it was proven that there is a reduction in the number of abnormal events or incidents and failures in the pipeline system. This is because the risk assessment through the CPM implementation can help in identifying the potential failure modes and evaluate the associated risk with each of them. Additionally, CPM can also assist in monitoring and enable the direct analysis of the detection of the instantaneous operations that were outside of the design scope. CPM application for the integrity assessment of composite pipelines provides long-term benefits such as allowing the lifecycle consideration of the flexible pipe product and a monitoring approach can help to optimize the safety margins at the design stage.

In 2022, Syuryana et al. (2022) conducted a study on the integrity assessment of flexible pipelines by utilizing Muhlbauer's Index Method and Quantitative Risk Based Inspection (QRBI) approach with several adjustments. Muhlbauer's Index Method is one of the methodologies of pipeline risk assessment commonly used in the oil and gas industry, alongside other codes, standards and recommended practices such as ASME B31.S (The American Society of Mechanical Engineers (ASME), 2022), API RP 1160 (American Petroleum Institute (API), 2019) or DNV RP F116 (DNV, 2009) while QRBI is a set of programs that consists of inspection, maintenance and repair actions as well as a cost-effective decision framework for providing any necessary maintenance activities and considering the final risk value of every flexible pipe segment. A combination of these two approaches for the integrity assessment of a flexible pipeline can produce a significant outcome in terms of the probability of failure (PoF) and consequence of failure (CoF) in the integrity assessment of a flexible pipeline system.

Application of artificial intelligence (AI) based algorithms such as machine learning approaches for enhancing the real-time evaluation and prediction of failure or damage in pipelines has been a main topic in the academic society, especially for steel pipelines (Ben Seghier et al., 2022), (Ben Seghier et al., 2023), (Keshtegar and el Amine Ben Seghier, 2018). However, for composite pipelines, only a few attempts have been conducted. Altabey et al. (2023) published a study on the combination of an AI-based algorithm with an Enhanced Convolutional Neural Network (ECNN) to provide automatic early damage detection and locate the damage in basalt fibre-reinforced polymer pipe (BFRP). Finite element modelling (FEM) was developed to generate the distributed strain patterns in BFRP. The data was then used for training the algorithm and predicting the pipeline damage mechanism. The outcome of this study proves that high performance and prediction from the ECNN algorithm can be achieved with 93.33% accuracy, 91.18% regression rate and 90.54% F1-score. Apart from that, only a 0.093% difference was discovered when comparing the output data of ECNN with the data from Fibre Bragg grating (FBG) embedded with the BFRP. This demonstrates the promising use of AI approaches to improve the safety of flexible composite pipelines.

Since pipeline operators need to assess the safety and reliability of composite flexible pipelines, the scientometric analysis and systematic review approaches are presented in this paper to provide a comprehensive overview of the current structural reliability and integrity assessment of these structures. The in-depth overview of this topic not only can highlight and fill the existing knowledge and research gaps but can also provide information regarding the level of progress that is being reached towards developing such technologies. To achieve the aims of this paper which are to (i) discuss the common failure drivers, modes and mechanisms that occur in composite pipelines, (ii) provide an overview of the available inspection and monitoring methods for these structures, (iii) identify the available structural reliability and integrity assessment techniques, and (iv) suggest future directions and insights for structural reliability analysis and integrity assessment of composite pipelines, a detailed description of the methodology is introduced with three main stages involved, which are data collection based on keywords designation, data refining and lastly, data analysis and discussion. The collected data is analysed for the scientometric analysis considering several parameters such as keyword occurrence analysis from the database collected and publication distribution per year and country. Later, the structural reliability and integrity assessment of composite flexible pipelines are discussed according to the aims of this paper. Finally, the future directions for the structural reliability and integrity assessment of composite flexible pipelines are discussed at the end of this comprehensive review to benefit not only the pipeline operators, but researchers in this field of expertise too.

2. Methodology and Data analyses

In order to achieve the objectives of this review paper, the proposed procedure illustrated in Fig. 5 is referred to and adopted accordingly by Al-Qadami et al. (2022). There are three main stages involved in the proposed methodology of this review paper which are (i) data collection, (ii) data refining or screening and (iii) data analysis and discussion, including the scientometric and systematic reviews.

The research methodology began with data collection at which the scope of the study was identified, and the collections of publications were gathered based on the widely and commonly used databases: Web of Science (WoS), Scopus and Science Direct. The time range or duration of publications was set to be within 20 years, starting from 2002 until 2022. As for this review, the study scope and the common keywords related were identified as "reliability assessment", "integrity assessment", "structural reliability analysis", "composite pipelines", "flexible pipelines" and "oil and gas". Hence, the keyword combination to retrieve the publication from a specific database is shown in Table 2. From the combinations of the keywords for 20 years of duration, 184 publications were retrieved which consists of 26, 29 and 129 publications from WoS, Scopus and ScienceDirect, respectively.

The total retrieved 184 publications were manually filtered and refined based on two criteria: (i) exclude articles or publications published in languages other than English, and (ii) exclude all repetitive or same articles and publications, resulting in the exclusion of 17 publications. The remaining papers were narrowed further by examining the title and abstract to select publications and articles that were strictly linked to the topic. Following the exclusion of 136 papers based on the title and abstract evaluation, the remaining publications were refined by full-text review. From this data screening process, only 10 articles were extracted and related to this topic. As a result, the snowballing search was implemented to choose some additional articles from other than the three main sources (i.e., WoS, Scopus and ScienceDirect). The process resulted in 16 additional articles and publications, resulting in 26 total relevant literature or studies.

The data analysis process is divided into scientometric and systematic reviews. The scientometric review provides the data analysis and discussion on the publications or literature collected based on (i) annual publication trend, (ii) publication distribution per country and (iii) keyword occurrence analysis, whereas the systematic review focuses on the data extraction from the literature or articles, (i) general reviewing on the common methods or techniques, (ii) identifying the research gaps and (iii) providing future directions and recommendations related to the research topic. Both scientometric and systematic reviews are discussed in the following sections.

2.1. Scientometric review

2.1.1. Annual publication trend

Inspection, monitoring and maintenance are crucial to ensure the safety performance and integrity of composite pipelines during the operation lifetime. Due to the limitations of studies related to this topic, it can be seen in Fig. 6 that only a small increment in the publication trend throughout the 20 years is observed, which indicates that related studies to the reliability and integrity assessment of the composite pipelines remained unexplored and concurrently, exhibits a huge research gap. Based on Fig. 6, after the year 2014, researchers started to give attention to studying the reliability and integrity assessment of composite pipelines, as there are three articles were published in the years 2017 and 2021, while the highest number of publications related to this topic is four, in the year 2018. Although the study on the

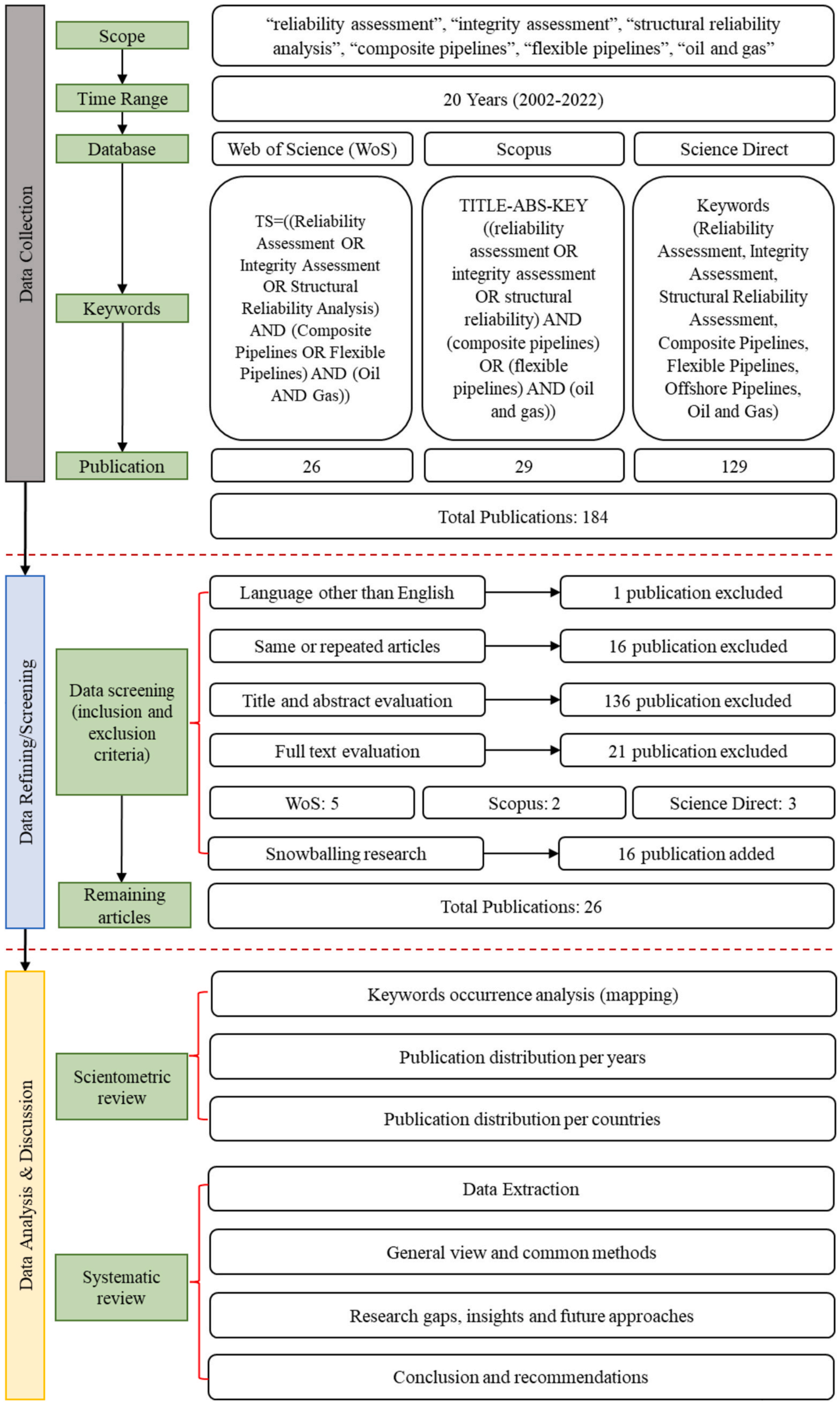

Fig. 5. Flowchart of methodology.

Table 2
Combination of keywords and number of retrievable publications from three different databases - Web of Science (WoS), Scopus and ScienceDirect.

Database	Keywords	Duration	Publications
Web of Science (WoS)	TS=((Reliability Assessment OR Integrity Assessment OR Structural Reliability Analysis) AND (Composite Pipelines OR Flexible Pipelines) AND (Oil and Gas))	2002–2022	26
Scopus	TITLE-ABS-KEY ((reliability assessment OR integrity assessment OR structural reliability) AND (composite pipelines) OR (flexible pipelines) AND (offshore pipelines) AND (oil and gas))	2002–2022	29
ScienceDirect	Keywords (Reliability Assessment, Integrity Assessment, Structural Reliability Assessment, Composite Pipelines, Flexible Pipelines, Offshore Pipelines, Oil and Gas)	2002–2022	129

reliability and integrity assessment of composite pipelines is limited and challenging, some of the researchers adopted reliability assessment approaches for composite materials to be applied and implemented for composite pipelines.

2.1.2. Publication distribution per country

Understanding the primary countries engaged in these research topics can provide an opportunity for knowledge exchange and future collaborations as well as an overview of the technology and knowledge readiness. The classification based on countries was represented in the form of a pie chart as shown in Fig. 7. Based on this latter, the dominant country that has been extensively conducting research regarding the reliability and integrity assessment of composite pipelines was the United States of America with a percentage of 48%, followed by the Netherlands and the United Kingdom with a percentage of 20% and 12%, respectively. The other 20% is the countries that published at least 1 publication, which includes France, Indonesia, Malaysia, and Norway.

2.1.3. Keyword occurrence analysis

Keyword occurrence analysis for the scientometric review was done by using an open-source software, *VOSviewer* to construct and visualize the bibliometric networks from the collected database (Van Eck and Waltman, 2010). The keywords occurrence analysis is crucial as it serves as an initial step in determining whether the available articles align with the research topic, avoiding the necessity to extensively go through the entire contents of the articles. The keywords occurrence analysis was done by creating a network map based on the bibliographic data such as co-authorship, keyword co-occurrence, citation and bibliographic coupling. The network map of 26 relevant publications and the collected database is shown in Fig. 8. There are 90 keywords with 5964 of total link strength that were matched and related with each other based on the 26 relevant articles. The top 20 keywords from this keyword occurrence analysis are presented in Table 3. From the keyword occurrence analysis of 26 relevant articles, the most prominent keywords are flexible pipe, pipeline, integrity management, technique and analysis. This provides insight into the classification of the studies related to these 26 relevant articles.

2.2. Systematic review

The systematic review is different from the scientometric review as it not only provides an overview or insight related to the topic based on the keywords and data analysis but through the systematic review, in-depth understanding regarding the topic is discussed for future studies and research. In line with the objectives of this review paper, the systematic review was done by classifying the most important topics to focus on the reliability and integrity assessment of the composite flexible pipelines, which are a review of the failures associated with composite pipelines, the current and available inspection and monitoring techniques and lastly, a review of the reliability assessment and integrity management of composite pipelines.

The failures associated with composite pipelines were studied based

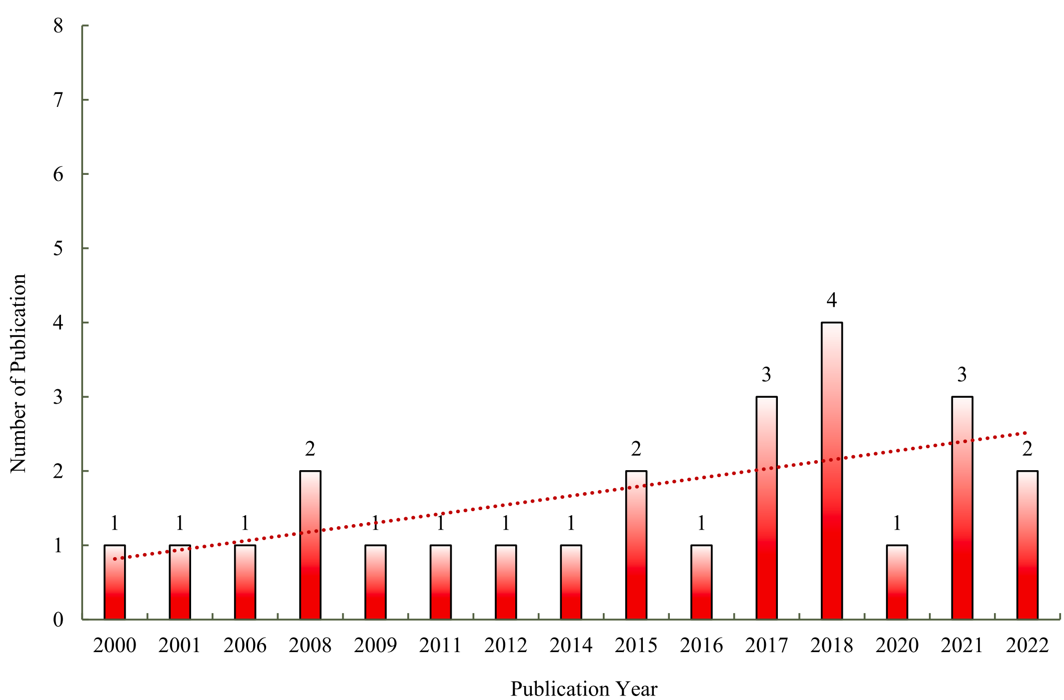

Fig. 6. Annual trend of publication related to the reliability and integrity assessment of composite pipelines.

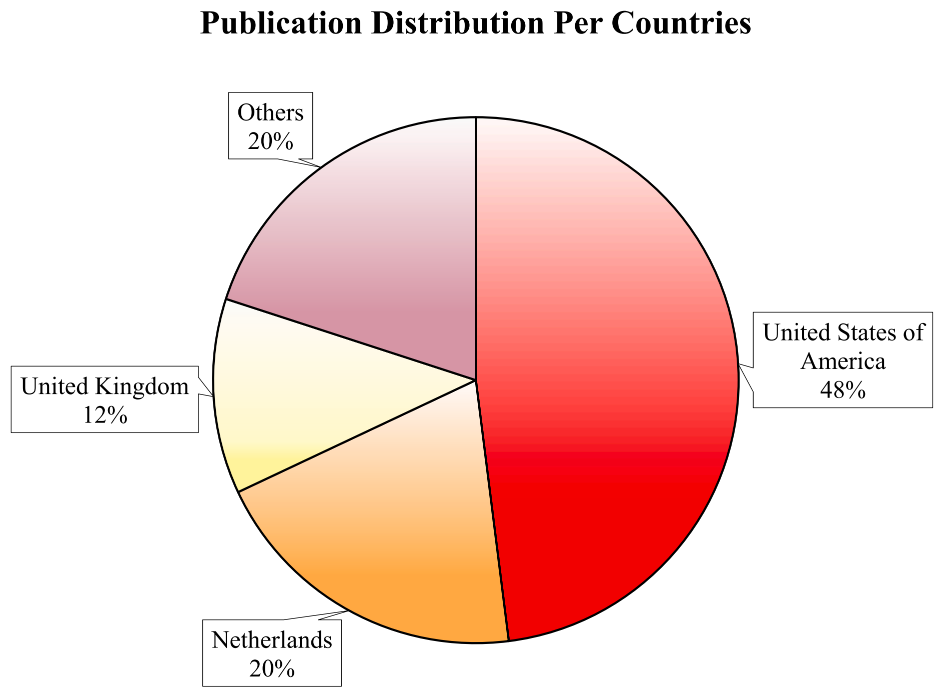

Fig. 7. Percentage of publication across the countries.

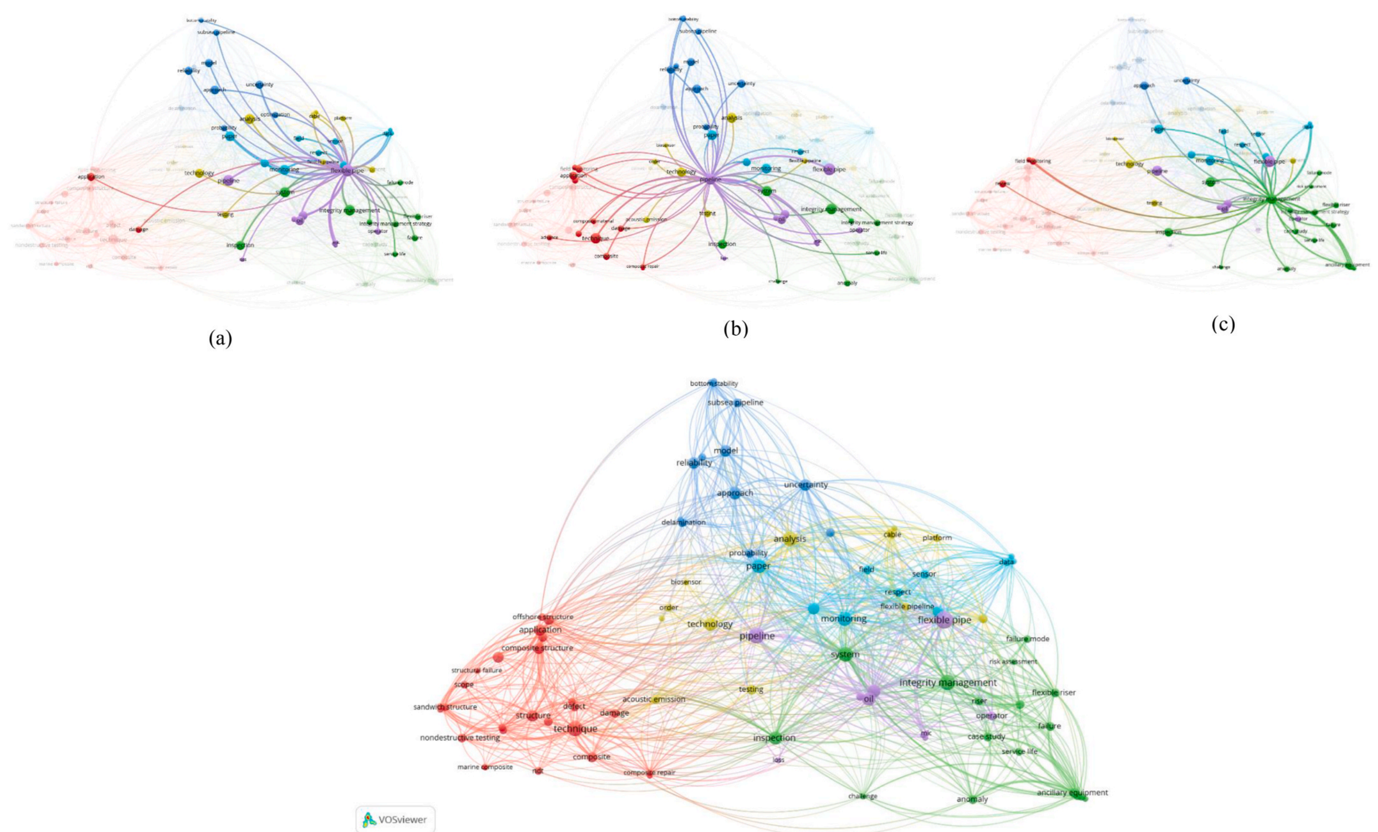

Fig. 8. Keywords occurrence visualization of 26 relevant articles (a) flexible pipe, (b) pipeline, (c) integrity management.

on the failure drivers, failure modes and failure mechanisms experienced by the composite pipelines during the operating stage. From the relevant articles and publications, it can be seen there are various failure drivers can trigger the failures to occur in the composite pipelines such as the changes in temperature and pressure, excessive loadings and third-party damage. The failure modes of the composite pipelines provide a general overview of the failures that occurred in the composite pipeline such as matrix cracking, delamination, crazing and others. From the failure drivers and failure modes, the failure mechanisms in which the behaviour of the failures occurred in the composite pipelines

Table 3
Top 20 keywords from the 26 related articles.

No.	Keyword	Occurrence	Total Link Strength
1	Flexible pipe	15	512
2	Pipeline	13	331
3	Integrity management	12	296
4	Technique	12	332
5	Analysis	11	251
6	System	11	328
7	Monitoring	10	354
8	Inspection	9	282
9	Oil	9	293
10	Technology	9	182
11	Approach	8	178
12	Integrity	8	314
13	Application	7	222
14	Assessment	7	254
15	Model	7	179
16	Reliability	7	143
17	Structure	7	207
18	Uncertainty	7	236
19	Composite structure	6	133
20	Risk	6	205

were identified. The importance of studying and acknowledging the failure associated with the composite pipelines can ease the process of identifying the suitable inspection and monitoring techniques to be conducted as well as the methods for reliability assessment of the pipelines.

Next, the inspection and monitoring techniques for composite pipelines seem to be restricted and limited due to the unavailability of unified codes, standards or recommended practices for composite pipelines. Hence, some researchers suggested a few methods of inspection and monitoring for composite pipelines such as using the remotely operated vehicles (ROVs), coupon samplings and non-destructive testing (NDT) techniques. However, the inspection and monitoring system for composite pipelines cannot depend on only one of these methods. Hence, it is suggested to combine or integrate the inspection and monitoring methods to produce a more reliable and accurate output as well as to ensure the condition of the composite pipelines can be evaluated thoroughly (Duchene et al., 2018).

To achieve the final objective of this review paper, the available methods and approaches for the reliability assessment and integrity management of composite pipelines were discussed. Some of the researchers conducted the reliability assessment of composite pipelines by implementing common approaches of structural reliability analysis (SRA) such as the probabilistic approach, First Order Reliability Method (FORM) and Monte Carlo Simulation (MCS). However, by integrating the common approach with the quantitative risk-based approach (QRBI), the outcome of the reliability and integrity assessment of composite pipelines is enhanced and improved as the risk was evaluated and interpreted completely, providing the overall consequences and impacts on the operated composite pipelines. However, from these preceding studies, the limitations and improvements for the reliability and integrity assessment of composite pipelines can be identified and future improvements can be addressed.

3. Review on failures in composite pipelines

Composite offshore pipelines are considered the safest option for hydrocarbon transportation as well as one of the most reliable strategies to overcome the major problem in carbon steel pipelines – corrosion. However, statistics reported by United Kingdom Continental Shelf (UKCS) operators found that from a total of 106 flexible pipes, 20% of the composite flexible pipeline encountered some form of damage or failure (Bai et al., 2005b). Failures in composite pipelines can be defined as any incidents that would result in the loss of containment which requires the pipe-segment replacement (Bai et al., 2005b). This statistic can be supported by a graph shown in Fig. 9, which represents a comparison between carbon steel and composite flexible pipeline failures according to Pipeline and Riser Loss of Containment (PARLOC).

Based on Fig. 9, the top three causes of failures in composite pipelines are material degradation, third-party impact followed by structural failure. Although the application of these types of pipelines seems reliable and benefits the oil and gas industry as a substitution for the existing carbon steel pipeline, failure due to corrosion still can occur in composite pipelines. In order to avoid any occurrence of unfortunate accidents and reduce the number of failures in composite pipelines, it is important to understand the types of failures or defects that possibly occurred which can also be helpful for reliability and integrity assessment purposes. It is important to highlight that composite materials may be subjected to low-velocity impacts, resulting in a non-visible surface impact or small indentation which is difficult to detect by visual inspection (s David-West et al., 2017).

3.1. Failure drivers, failure modes and failure mechanisms

Factors affecting the failure or how defects arise, simply known as failure drivers, are important to be determined. According to Ibrahim (2016) for instance, failures or defects in marine composite structures can occur in two main stages, which are manufacturing and in-service stages. Manufacturing defects can appear due to human factors such as unevenly distributed or bunched fibres, shrinkage in the polymer matrix and poor resin infusion. The in-service defects are majorly contributed by the operating environment and surface impacts such as collision with another vessel or fixed structure, ingress of moisture and various fluid contaminants as well as incipient heat damage (Ibrahim, 2016). With the failure drivers known, the failure modes or failure mechanisms that occur in composite pipelines can be assessed. This latter generally explains the failure behaviours or failure morphologies such as intralaminar or interlaminar failures (s David-West et al., 2017).

Table 4 compiles the summary of the common failure drivers, failure modes and failure mechanisms that possibly occur in composite pipelines according to Bai et al. (2005b) and a standard published by Det Norske Veritas (DNV), DNVGL-ST-F119 for thermoplastic composite pipes (Veritas, 2018). The most common factors triggering failure in composite pipelines are temperatures, pressure, product fluid composition, service loads and third-party damage. These failure drivers may lead to various failure modes such as cracking, buckling, dent and degradation of composite material which can affect the performance and strength of the operating composite pipeline, while the common failure mechanisms associated with composite materials are matrix cracking, delamination, polymer or fibre fracture, debonding and micro buckling (Veritas, 2018), (s David-West et al., 2017).

The studies on the failure drivers, failure modes and failure mechanisms from the previous literature are compiled as shown in Table 5. Based on previous studies, failure in composite pipelines usually occurs in the thermoplastic liner. This is because the thermoplastic liner is the first structural layer in a composite pipeline that comes in contact directly with the transported fluid or hydrocarbon and experiences changes in pressure or temperature in the pipeline. The brief explanation of the failure mechanisms and consequences of the failure modes are briefly described in Table 5.

It is crucial to acknowledge and understand the potential failures that occur in composite pipelines in order to ensure the safety and integrity assessment for composite pipelines. Understanding the typical failure drivers such as changes in temperature and pressure, third-party impact and excessive external loadings, which may lead to various failure modes such as matrix cracking, delamination, buckling and collapse helps in explaining the failure mechanisms or behaviours of the composite pipelines. Through the insight from failure drivers, failure modes and failure mechanisms in composite pipelines, the appropriate strategies for structural reliability and integrity assessment of composite pipelines can be developed or conducted, aligned with occurred failure

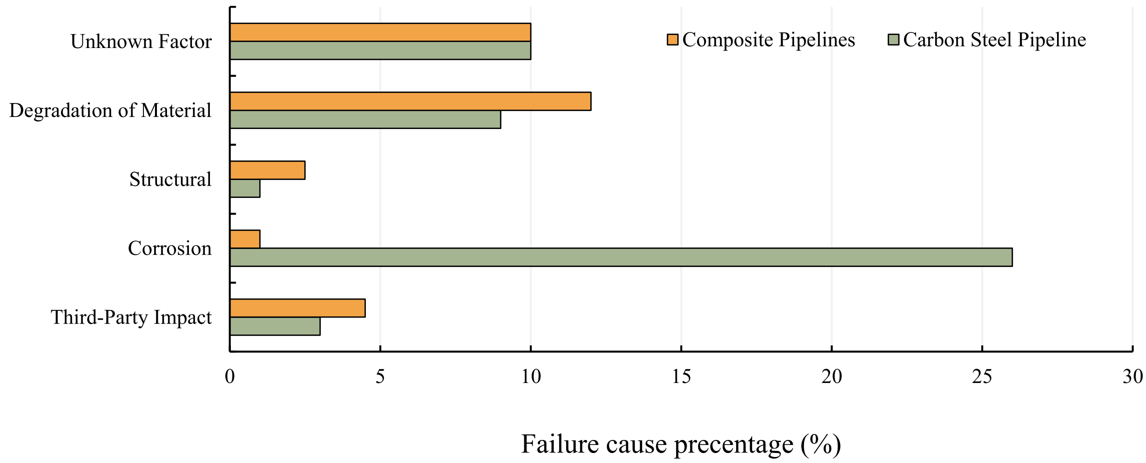

Fig. 9. Comparison of the failure causes observed in carbon steel and composite flexible pipelines according to Pipeline and Riser Loss of Containment (PARLOC).

Table 4
Common failure drivers and failure modes of composite pipelines simplified from DNV (Veritas, 2018) and Bai et al. (2005b)

Failure Drivers	Failure Modes	Failure Mechanisms	Description
Temperature	•Crazing •Cracking •Ageing of the liner	•Matrix cracking •Delamination	•Repeated temperature cycling will cause increased stress in the polymer matrix material, usually the liner of the composite pipeline. •The presence of craze may reduce the polymer's strength and increase permeation rates.
Pressure	•Fatigue •Collapse •Buckling (Buried Composite Pipeline)	•Matrix cracking •Polymer fracture	•Excessive pressure will cause failure to the liner of the composite pipeline. •Fatigue and buckling of the composite pipeline may be caused by the thermal and pressure cycling experienced by the composite pipeline during operation. •Hydrostatic collapse happens due to the diffusion of gas within the pipeline layers. •Composite pipelines such as thermoplastic composite pipe (TCP) may fail due to the wedge-shaped matrix cracks in compression.
Product Fluid Composition	•Corrosion •Erosion •Degradation of liner •Cracking •Blockage or flow restriction	•Fluid tightness - permeability	•Deleterious effects on the pipe wall materials due to the presence of water, CO_2 and H_2S are the causes of general, pitting, hydrogen-induced cracking (HIC) and sulphur stress cracking (SSC) corrosion. •Abrasion of other particles such as sand in the liner of the composite pipeline causing degradation or deterioration of the layer simultaneously, erosion happens. •Inhibitors and acids transported in the pipe can also accelerate the degradation of the polymer material of the liner. •Formation of wax or hydrate at the inner wall of the liner causing blockage and disrupting the flow of the transported product. •Any cracks or puncturing shall be considered as a local leak – very high permeability.
Service Loads	•Collapse •Buckling	•Fluid tightness – permeability •Polymer fracture •Maximum deformation	•Excessive stress exerted on the composite pipeline causing the liner to collapse and overbend. •Polymer fracture may occur due to load bearing (typically in the end-fitting) or displacement controlled (typically liners and covers connected to the laminate or reinforcement layer). •Axial forces and pressure may cause the composite pipeline to experience axial elongation and deformation. •Accumulated longitudinal displacement could be caused by pipeline walking and may occur during the start-up or shutdown process.
Third-Party Damaged	•Dent	•Maximum deformation	•Dent of the composite pipeline happens at the outer layer of the pipeline due to dropped objects or excessive motion.

types.

4. Inspection and monitoring techniques of composite pipelines

Extensive use of composite pipelines without proper inspection and monitoring can increase the likelihood of failure occurrences. Hence, the inspection and monitoring techniques are important to be done periodically to detect and identify the anomalies in the composite pipelines. The inspection and monitoring techniques incorporated with reliability assessment or structural reliability analysis (SRA) can enhance the evaluation of the integrity and safety performance of the pipeline systems. Structural health monitoring (SHM) is one of the inspection and monitoring techniques that can help to detect and measure the defects or damage in composite pipelines, as well as provide key information for reliability and integrity management (s David-West et al., 2017), (Cook et al., 2006).

Wen-hua et al. (Wen-hua et al., 2022) highlighted a few common technologies to monitor and analyse the hydrodynamic and structural mechanics of floating offshore structures at which these monitoring technologies can also be implemented for monitoring the mooring and pipeline systems. Pre-positioned measurement schemes using fibre optic grating sensors, underwater inspection using remotely operated vehicles (ROVs) and hot spot stress monitoring techniques using strain monitoring sensors are common approaches that have been used currently for pipeline inspection and monitoring.

On the other hand, coupon sampling is one of the inspection and monitoring techniques suggested by Khalid et al. (2020) that can be implemented to inspect non-metallic or flexible composite pipes at regular intervals. The idea of using coupons as shown in Fig. 10 for inline monitoring of composite pipelines is to overcome the problems of limited sensing coverage of point sensors and to detect the polymer ageing of flexible composite pipelines or risers. However, the coupon sampling method is not feasible as it does not represent the most critical bore environment and is time-consuming due to installation, removal and lab analysis processes to obtain results.

Non-destructive testing (NDT) techniques are another structural

Table 5
Studies on failure drivers, failure modes and failure mechanisms of composite pipelines.

Ref	Failure Drivers	Failure Modes	Failure Mechanisms and Findings
(Szklarz and Baron (2004))	•Gas permeation •Pressure fluctuations	•Degradation of material •Radial buckling (collapse) •Axial buckling (inversion)	•Thickness of the thermoplastic liners was thin, causing H_2S to permeate through the layer of the liners' materials. Hence, the thermoplastic liners degraded. •Due to the loose fitter liners, the pipelines buckled in both directions, radially and axially.
(Krishnaswamy (2005))	•Changes in temperature and pressure	•Creep rupture fracture	•Several HDPE pipes were tested for creep rupture failure under various temperatures and hoop stress levels. •Increment of temperature can cause the residual stresses of the pipes to relax to some extent but it can also accelerate the fracture process. •Slow crack growth (SCG) was one of the causes of most of the field failures in pressure pipe applications.
(R et al. (2008))	•Presence of residual stresses •Pressure fluctuation	•Fatigue	•The changes in the HDPE pipe occurred due to the presence of residual stresses and morphological variances induced by the extrusion process and subsequent cooling. •The thermoplastic PE of the gas pipeline experienced a fatigue condition due to the fluctuation of operating pressure.
(Mertiny (2008))	•Increment of internal pressure	•Micro-cracking •Leakage	•Three specimens of fibre-reinforced polymer (FRP) composite pipes with three different fibre materials were tested to assess the damage and provide consistent failure. •It was found that the leakage in FRP specimens was driven by the damage within the polymer matrix phase at which the initiation and growth of the micro-cracks allowed the pressurized fluid to penetrate the tube wall. •Fibre volume fraction can also contribute to the leakage properties of the FRP.
(Liu et al. (2009))	•Improper joint attachment •Thermal stress and high temperature •Third-party impact	•Leakage •Matrix cracking •Delamination	•Some of the failures were caused during the manufacturing and installation processes such as improper joint attachment and poor-quality assurance system. •Excessive bending load and fluctuation of internal pressure and temperature may cause the delamination, internal shrinkage and matrix cracking of FRP during operation.
(Gonzalez et al. (2011))	•Changes in temperature and pressure	•Fatigue	•HDPE pipe specimens were tested for fatigue test in two directions, circumferential and longitudinal directions. •Stress was developed in the circumferential, radial and longitudinal direction due to the exerted internal pressure and change in temperature. •A crack in the inner layer of the pipe was noticed, resulting in the failure of the specimens of the HDPE pipe.
(Qi et al. (2011))	•Changes in temperature •Weak connection at joint •External forces	•External damages	•Mechanical properties of RTP can reduce up to 40% with the increment of temperature from 25 °C to 60 °C. •High pressure and stress concentration at the joint of the composite pipelines can reduce the strength of the pipeline. •External forces such as stone, construction equipment, sharp materials or dropped objects can damage the composite pipeline, especially the outer layer and reduce the strength of the pipeline excessively.
(afarullah Khan (2012))	•Cyclic load •Changes in temperature	•Fatigue •Crack and craze	•Increment of loading frequencies caused the HDPE pipe to fatigue and the crack tip started to be noticeable. •With the influence of temperature, the crack tip started to propagate through the crazing process.
(Brown and Crate (2012))	•Compressive stress	•Brittle fracture •Slow crack growth (SCG)	•Excessive amount of compressive stress applied to squeeze off the polyethylene gas pipe caused it to undergo brittle fracture and crack to occur. •The pipe took 9 months of SCG to begin leaking and an additional 5 months for the explosion to occur.
(Qi et al. (2012))	•Degradation of material	•Leakage	•The inner surface of GRPs degraded due to high temperature,

(continued on next page)

Table 5 (*continued*)

Ref	Failure Drivers	Failure Modes	Failure Mechanisms and Findings
	•Improper joint connection		causing the reduction of service pressure, appearance of cracks along the radial direction and leakage of oil in the pipeline.
(Hutař et al. (2013))	•Internal pressure	•Crack	•Cracks were initiated at both the inner and outer layers of the pipe and the same amount of internal pressure was exerted on the pipe to observe the crack propagation at the inner and outer layers of the pipe. •The crack initiated at the inner surface of the pipe had a significant impact and failure on the pipe as the crack can propagate through the three layers of pipes. •The outcome from the crack initiated at the outer layer of the pipe was not significant as the crack did not propagate. However, longitudinal cracks formed at the outer layer of the pipe can be dangerous with the application of external load.
(Reis et al. (2017))	•Changes in pressure and temperature	•Thermal ageing	•Glass fibre-reinforced polymer (GFRP) pipes were tested for the ageing test by changing the exerted internal pressure and temperature. •Based on the tensile and burst test, it showed that the ageing GFRP pipelines were affected by the fluctuation of pressure and temperature, causing the strength properties of the GFRP pipelines to decrease significantly compared to the elastic properties.
(Guoquan et al. (2019))	•Presence of acidic gas	•Cracking •Degradation of material	•The presence of acidic gas was causing the polyvinylidene fluoride (PVDF) liner of the reinforced thermoplastic pipe to deteriorate. •Weld line appears in the liner layer causing the liner to crack longitudinally.

health monitoring (SHM) technique commonly used to inspect, detect, monitor and characterize the mechanical damage that occurs in composite materials under in-situ or ex-situ service conditions (Duchene et al., 2018), (Ibrahim, 2016). The use of NDT for composite pipelines can be classified into direct and indirect techniques. Direct NDT techniques allow the detection of microstructural damage mechanisms such as matrix cracking, fibre breakage and debonding, while indirect NDT techniques monitor the effect of the global material degradation on mechanical or physical properties such as energy dissipation, stiffness loss and high-strain localisation (Duchene et al., 2018). Fig. 11 shows four different categories of NDT techniques for SHM of composite pipelines which are acoustic-based, instrumentation-based, x-ray radiography and tomography and microwave-band inspection. Each category of NDT techniques has different approaches to identify the damage or defect in composite pipelines.

4.1. *Acoustic-based techniques*

Acoustic-based techniques including acoustic emission, ultrasonic inspection, acousto-ultrasonic and vibro-acoustic are aimed to determine and observe the disturbance in the velocity and attenuation of wave propagation when a sensor is placed as a medium to detect the defects or failure on the composite pipeline. Acoustic emission (AE) and ultrasonic inspection are the most commonly used in the industry to detect the presence of cracks, e.g., matrix cracking and fibre breakage. The AE is defined as the occurrence of transient elastic waves caused by the defect evolution when the structure or material is subjected to stress, resulting in the disturbance in ultrasonic frequencies (Duchene et al., 2018), (s David-West et al., 2017), (Ibrahim, 2016). AE is normally conducted by placing a series of sensors or piezoelectric transducers permanently to the structure and the transient elastic waves generated by the defect or anomaly such as crack growth and propagation will be monitored and analysed (s David-West et al., 2017). For composite material with anisotropic properties, one of the best NDT techniques to inspect the defect occurrence is by implementing ultrasonic testing (UT) as this technique is carried out by measuring the reflection, transmission or backscattering of elastic waves in the arrangement of composite laminate (Duchene et al., 2018).

4.2. *Instrumentation-based techniques*

Sensor networks, eddy current, electrical resistance and nonlinear elastic wave spectroscopy are classified as instrumentation-based NDT techniques. Sensor networks integrated with several methods or approaches are used to enhance the effectiveness of monitoring and detection of damage initiation and progression and it is normally applied to carbon fibre reinforced polymer (CFRP) at which the sensors are embedded in the composite laminate (s David-West et al., 2017). Embedment of piezoelectric sensors integrated with the *k-means* classification method had been reported to detect the bending fatigue strength of the composite laminate (Masmoudi et al., 2016). A case study by Lu et al. (2015) used the fibre Bragg grating (FBG) sensors in CFRP structures to detect the structural dynamic response signals and extract the damage characteristics through Fourier transform and principal component analysis (PCA) methods.

Different from sensor networks, eddy current is an instrumentation-based NDT technique that uses electromagnetic induction to detect and characterize the anomalies on the surface as well as subsurface of composite laminate but is limited to in-depth inspection due to the limit of material attenuation (Duchene et al., 2018), (s David-West et al., 2017). Delamination of CFRP composite laminate can be detected by monitoring the fractional change in impedance between the intact and damaged positions (Duchene et al., 2018). Apart from delamination, fibre breakage in the composite laminate can also be detected by using the eddy current technique.

4.3. *X-ray radiography and tomography*

Another type of NDT technique for SHM composite is X-ray radiography and tomography. X-ray radiography and tomography can be considered the longest NDT technique that has been established to detect anomalies in composite laminate by scanning the internal

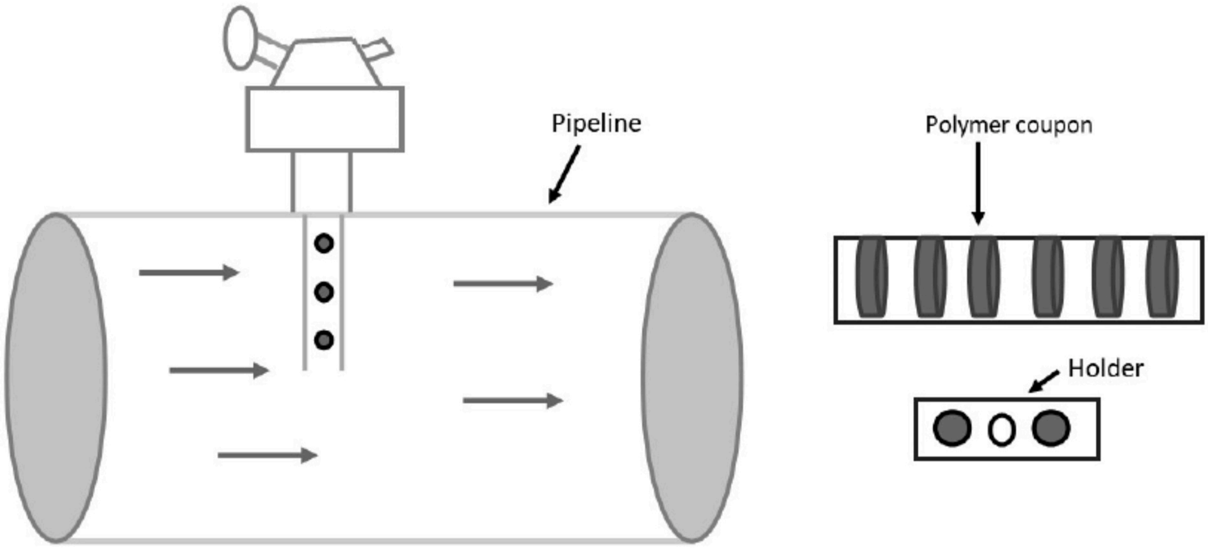

Fig. 10. Coupon sampling for inspection and monitoring of non-metallic or flexible composite pipeline, extracted from Khalid et al. (Khalid et al., 2020).

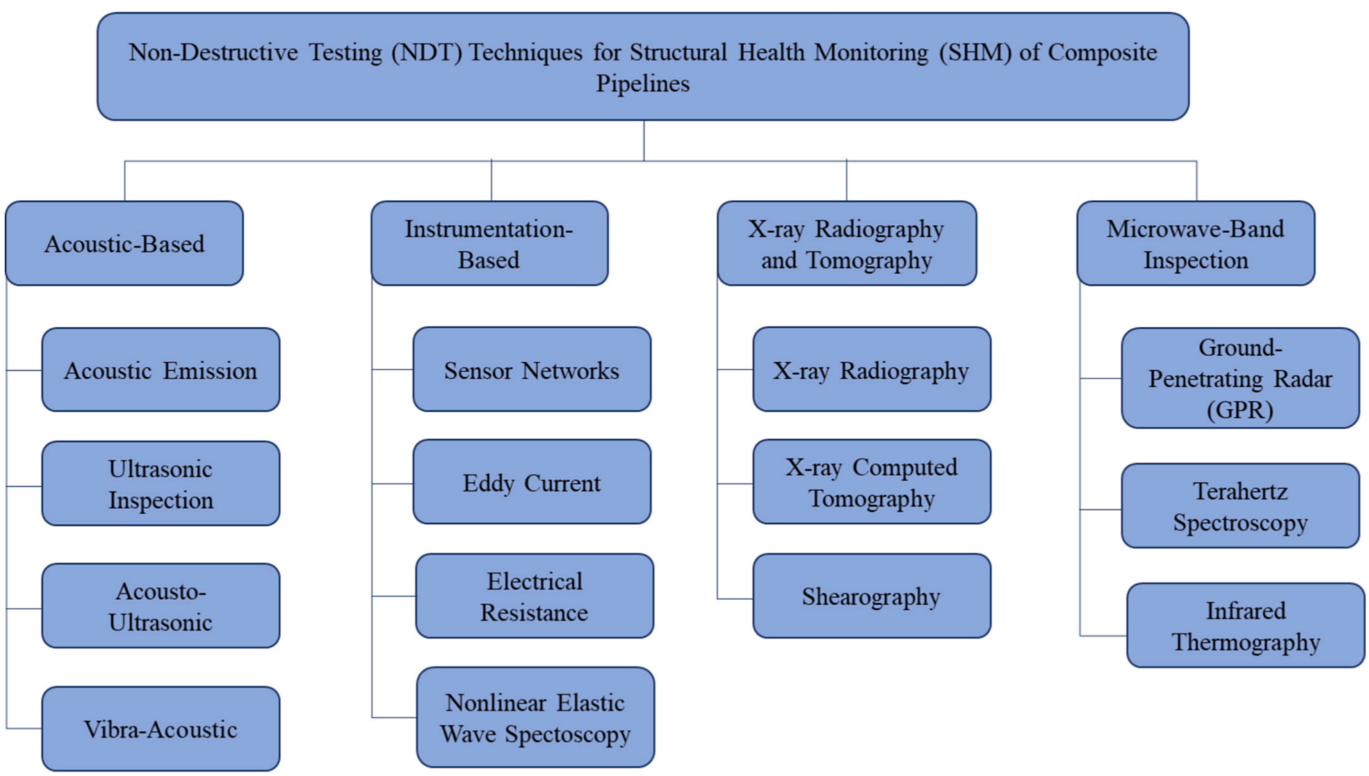

Fig. 11. Classification of NDT techniques of SHM of composite pipelines.

structure of the composite. However, this technique is not well used for the inspection of composite materials due to some disadvantages, such as the danger of ionising radiation and the influence of the atomic weight of molecules as the low atomic weight in the composite polymer can be significantly reduced compared to metal alloys (Ibrahim, 2016). X-ray radiography is normally used for the detection of mesoscale and macroscale defects in composite such as delamination and translaminar cracks (Duchene et al., 2018). In the field of composite, shearography is widely used as an optical method laser by providing wide-area qualitative imagery of both in-plane and out-of-plane displacement variation at the surface of a structure (Duchene et al., 2018). This method is commonly used in the aeronautics industry and frequently utilized to detect the initiation of delamination or debonding of composites, given the increased risk of composite failure caused by stress concentration around the defect or anomaly (Duchene et al., 2018).

4.4. *Microwave-band inspection*

Infrared thermography, terahertz spectroscopy and ground penetrating radar (GPR) are examples of NDT techniques that are based on microwave inspection. Infrared thermography is an advanced non-contact NDT technique that employs electromagnetic radiation within the infrared spectrum and is generally used for measuring temperature evolution on a large scale (Duchene et al., 2018), (Ibrahim, 2016).

According to Amafabia et al. (s David-West et al., 2017), the application of infrared thermography for SHM is normally for the monitoring and detection of the porosity in composite laminates as the existence of porosity can reduce the mechanical properties of the composite laminates. Duchene et al. (2018) added that the utilization of infrared thermography can provide both qualitative and quantitative information about the heat dissipation heterogeneities based on the recorded variations of temperature at the surface of the composite material.

The development of terahertz spectroscopy technique for SHM of composite materials had been widely unexplored for the past two decades due to some limitations such as lack of sources and detectors as well as incapability to produce and detect the picosecond-length pulses due to high energy requirement (Duchene et al., 2018), (Ibrahim, 2016). Terahertz spectroscopy technique was also considered as an extension of microwave testing at the lower end frequency (0.1–4 THz) which can allow the production of high-resolution images (Ibrahim, 2016). Application of the terahertz spectroscopy technique can allow the assessment of delamination damage in composite materials as well as the identification and detection of the changes in fibre volume fraction in glass-fibre reinforced polymer (GFRP) (Duchene et al., 2018). However, due to the sensitivity to environmental disruptions, the application of the terahertz spectroscopy technique for industrial purposes was considered difficult, hence, its application was limited to laboratory applications and certain composite structures only (Duchene et al., 2018).

Additionally, the application of NDT techniques can also help to distinguish the damage evolution in composite materials, which may include matrix crack, debonding, delamination and fibre breakage as shown in Fig. 12. Duchene et al. (2018) compiled and summarized the application of NDT techniques for composite damage detection and the advantages and limitations of these NDT techniques from previous literature as shown in Fig. 12 and Table 6, respectively. The damage scale in the composite material can be categorized into three different scales, micro, meso and macro scales which cover three different compositions of the composite material, fibre, ply and specimen, respectively. Since one NDT technique is not capable of inspecting the structural flaws or damages in composite material thoroughly, combining two or more NDT techniques can produce a reliable, more accurate and complete analysis of SHM. Incorporating one NDT method with another NDT method can complement each other limitations and hence, help in producing a full-scale damage evolution and damage scale of the composite material.

5. Review on reliability assessment and integrity management of composite pipelines

Structural reliability analysis (SRA) simply known as reliability assessment is an impactful approach commonly used in the oil and gas industry for the evaluation of the safety levels, integrity and performance of pipeline systems through pipeline integrity management (PIM) (Liu et al., 2019), (Zheng et al., 2021), (Bahaman et al., 2022). Combining inspection and monitoring techniques with reliability assessment can help enhance the evaluation of the reliability and safety performance of the composite pipeline. Additionally, integrating the

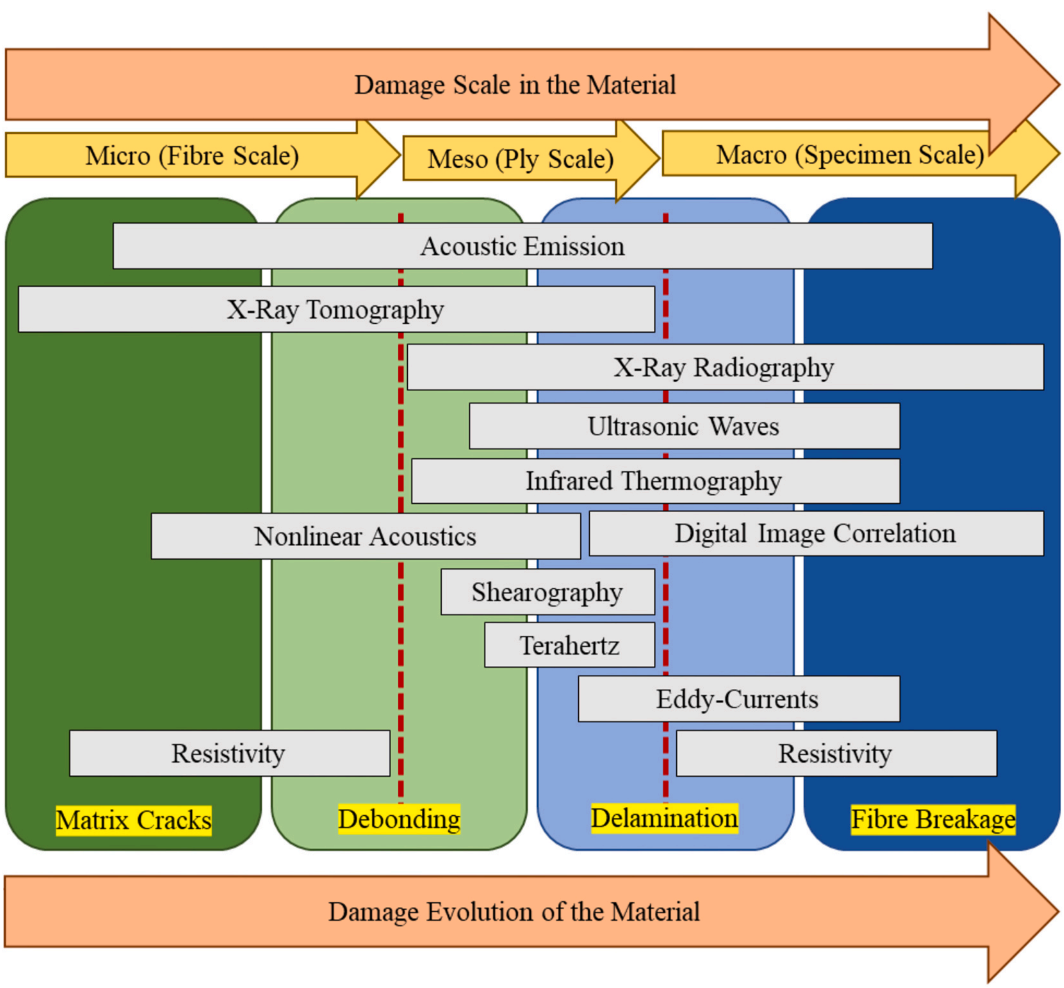

Fig. 12. Summary of the application of NDT techniques for composite damage detection, modified from Duchene et al. (Duchene et al., 2018).

Table 6
Summary of the advantages and limitations of NDT techniques for composite damage detection, extracted from Duchene et al. (2018)

NDT Techniques	Advantages	Limitations	Types of Damage Detection			
			• Matrix Cracking	Debonding	Delamination	Fibre Breakage
Acoustic emission	•Provide real-time structural health monitoring	•Require mechanical loading	✓	✓	✓	✓
Ultrasonic inspection	•Provide quantitative method and full damage characterization such as location and sizing	•Difficult to interpret and analyse •Require coupling agent	✓		✓	✓
Eddy current	•Fast testing •Does not require additional contact surface	•Only applicable for electrically conductive materials •Provide surface analysis only			✓	✓
X-ray radiography	•Imaging method with a 3D reliability analysis •Provide a full damage characterization of the materials	•Affect human health due to ionising radiation and laboratory work	✓	✓	✓	✓
Shearography	•Imaging method with non-contact testing	•Provide surface analysis only •Require mechanical loading		✓	✓	
Infrared thermography	•An active imaging contact with passive contact or interaction	•Provide surface or sub-surface analysis only		✓	✓	
Terahertz spectroscopy	•Provide a high-resolution analysis image	•Require high attenuation for electrically conductive materials			✓	✓

SRA with life-cycle assessment contributes to developing accurate and comprehensive integrity management plans, which benefits in minimizing the cost of repair and maintenance throughout the pipeline service life (Mishra et al., 2019), (Tee et al., 2014), (Valor et al., 2013), (Wang et al., 2015).

With the uncertain, random and inadequate attributes, probability approaches can be implemented to describe the performance of the structure or system (Negro et al., 2014), (Nizamani, 2015). In SRA, the failure probability can be adopted and used to quantify the safety of the structure (Mat Soom et al., 2021). Batzias et al. (2011) designed a reliable leak bio-detection system for the Greece-Italy natural gas pipeline with a length of 807 km by using a biosensing and segmentation approach. From their study, the term "reliability" can be defined as the ability of the leak bio-detection system to measure and render the accurate results of the potential presence of a leak on the pipeline as well as the function of the probability of detecting a leak at which the leak bio-detection system is considered reliable when the probability is low (Batzias et al., 2011).

Risk-based inspection for composite pipelines can be implemented as an integrity management strategy, as it is considered the basis of the integrity management program of American Petroleum Institute Recommended Practice 580 (API RP 580), Risk-Based Inspection (Cook et al., 2006). Cook et al. (2006) suggested four important steps that need to be taken to conduct the criticality and risk assessment which are defining the boundaries and limits of the system, identifying the primary failure mechanisms and consequences, separating the pipeline systems based on the failure modes and lastly determining the probability based on the design, operation, inspection and monitoring data. It is also suggested that the integrity management program and risk assessment are best developed and performed, respectively, during the project and construction design stage as any changes can be obtained and incorporated directly into the new facility compared to the old facility (Cook et al., 2006). Moreover, the implementation of any changes during the early phase of the project (e.g., the design and construction stage) can easily be done prior to the availability of the data and records.

Bai et al., (Bai and Bai, 2014) stated that the integrity management strategy for flexible pipelines can be divided into three stages which are the design stage, the manufacturing stage and the installation and commissioning stage. Each stage had different focuses and approaches. For example, the design stage for flexible pipelines involves the selection of materials, pipeline geometries and global design assumptions such as metocean data and operational conditions while the manufacturing stage focuses more on quality assurance (QA) and quality control (QC) to adequately cover the whole element of the flexible pipelines before installation and operation (Bai and Bai, 2014). The integrity management strategy involved in the installation and commissioning stage mainly targets the prevention of any damages to the flexible composite pipeline during the installation process and operational use by creating detailed installation procedures (Bai and Bai, 2014). Fig. 13 illustrates the available and existing methods or approaches related to the reliability or integrity assessment of composite pipelines including the First Order Reliability Method (FORM), Monte Carlo Simulation (MSC) and risk-based assessment, subjected to different or multiple failure modes. The findings from previous studies are summarized in Table 7.

Table 7 shows that prior literatures used a variety of methodologies to explore the reliability assessment and integrity management of composite pipelines. Starting with the deterministic and probabilistic approaches until the current technology, which is the machine learning method, each of these approaches have advantages and limitations for assessing the integrity and safety of the operated pipelines subjected to various failure modes.

The First Order Reliability Method (FORM) and Monte Carlo Simulation (MCS) were conducted based on the combination of deterministic and probabilistic approaches in which the parameters used were treated as random variables and utilized to estimate the failure probability according to certain failure modes or failure criteria. Composite pipelines are composed of several layers. Hence, these two methods only assessed the failures at specific layers of pipelines, instead of the whole unit pipelines (Kogiso et al., 2001), (Lin et al., 1998). On the other hand, Lin et al. (1998) and Richard et al. (Richard and Perreux, 2000) suggested considering other parameters such as the strength of the composite pipeline's materials, the number of plies and winding angles of the fibres used, instead of evaluating the reliability of the composite pipelines based on the failure types as the only criteria.

Bai et al. (2015b) took an approach to integrate the Monte Carlo Simulation (MCS) with the probabilistic analysis of non-linear finite element modelling (FEM). Through this combination, the response model generated from the FEM with the MCS was able to calculate the safety indices and failure probability of the pipelines subjected to lateral displacement. However, it was found that the predicted response model may be inaccurate due to the limited scope of the variables and the imprecise location of the random variable in the failure domain. Hence, this results in a drawback to the MCS results, which may lead to low precision at low failure probability. Hocine et al. (2008) introduced a finite element probabilistic solver called "PERMAS" to perform the reliability based on the limit state function. Although this method claimed to offer various capabilities such as statics either linear or nonlinear analysis and dynamic analysis, there were some uncertainties can be noticed when performing the reliability analysis for the

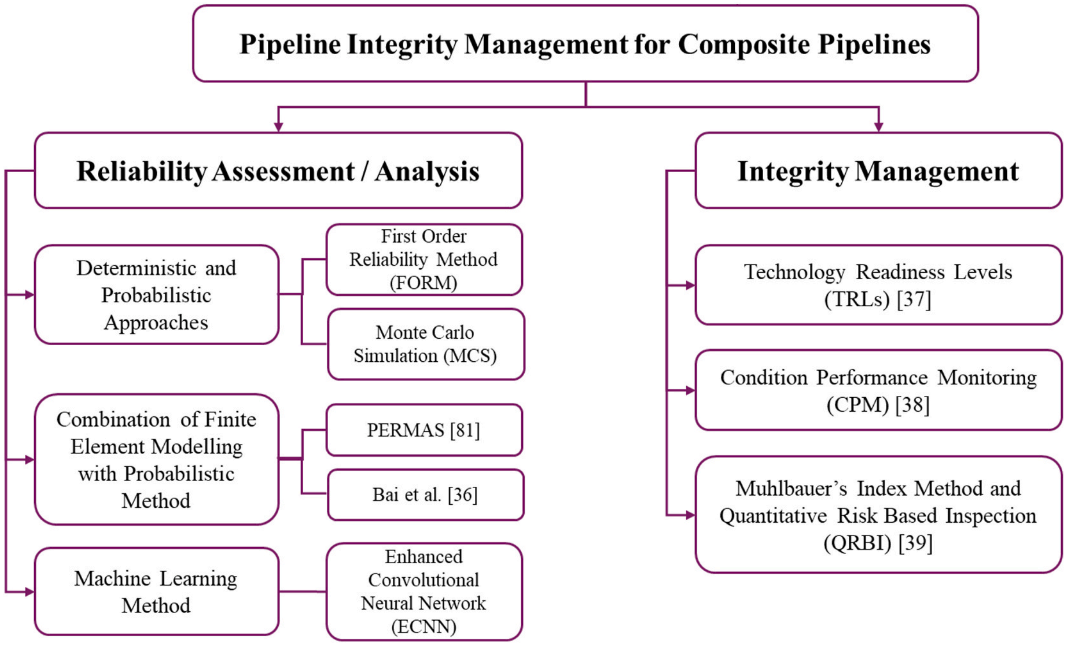

Fig. 13. The current existing methods and approaches for structural reliability and integrity management of composite pipelines.

composite pipelines. Thus, to implement this method, Hocine et al. (2008) suggested performing the sensitivity analysis as it is proven to provide a significant improvement to the structural reliability and minimize the uncertainties.

Escuer et al. (2018) stated that the integrity management plan can be developed at the design stage. However, the integrity strategy might not reflect the actual condition of the operated pipelines, which concurrently does not reflect the overall level of risk. Therefore, Escuer et al. (2018) introduced Condition Performance Monitoring (CPM) to capture the available and real data from the field and analyse it for an optimized integrity management plan. From the utilization of the CPM approach for the dynamic integrity management of flexible pipe, it was found that CPM allows to alert the operator on risks that may arise during operation without requiring to call upon a team of flexible pipe experts and concerns related to the maturity in new frontiers application domain of flexible pipes may arise too. The long-term application of the CPM approach for the integrity management of the flexible pipeline can benefit in optimizing the safety margins at the design stage as the lifecycle of the flexible pipeline was considered and monitored thoroughly (Escuer et al., 2018).

Altabey et al. (2023) proposed the application of artificial intelligence (AI) based on an algorithm using a deep learning method with satisfactory performance of 93.33%, 91.18% and 90.54% accuracy, regression rate and F1-score, respectively, to evaluate the damage in the composite pipelines. Comparing this method with other approaches, Altabey et al. (2023) stated that the proposed AI method which is an Enhanced Convolutional Neural Network (ECNN) can provide some advantages in terms of effectiveness in predicting the response of the composite pipelines, work faster and time saving for computational analysis.

6. Research gaps and future directions

Investigating the reliability and integrity assessment of composite flexible pipelines is crucial, where more discussion and further studies in this regard can benefit the oil and gas industry in various aspects such as operational cost, repair and maintenance cost, the lifecycle sustainability as well as its outstanding performance for deep water operation. Hence, this review paper is an opportunity and initial step to address the existing research gaps and propose future directions for this topic as shown in Fig. 14.

Referring to Fig. 14, the disadvantages of NDT techniques for the inspection and monitoring system of composite flexible pipelines can pose a strong limitation as the reliability assessment and integrity management of composite flexible pipelines requires the extraction of actual condition data from inspection and monitoring operations. Hence, Duchene et al. (2018) suggested combining multiple NDT techniques to inspect the operated composite pipelines so that the actual condition of the composite pipelines can be evaluated comprehensively and concurrently, enhancing the damage evaluation of the composite pipelines. In addition, combining these several NDT techniques can also contribute to producing a complete diagnosis of the composite pipeline through the SHM system, resulting in a more reliable and accurate output.

A short-term prediction model for the reliability assessment of composite pipelines can be developed from the inspection and monitoring data. By utilizing machine learning models or deep learning approaches to analyse the inspection and monitoring data, a real-time evaluation as well as the prediction of the safety performance of the composite pipeline can be produced for the reliability assessment of the composite pipeline (Wen-hua et al., 2022). Altabey et al. (2023) proved that using an artificial intelligence (AI) algorithm (i.e. Enhanced Convolutional Neural Networks (ECNN)) to evaluate the early warning for detecting the damage in composite pipelines can provide more than 90% high-performance prediction in terms of accuracy, regression rate and F1-score. Escuer et al. (2018) suggested implementing Condition Performance Monitoring (CPM) to provide support for an optimized integrity management strategy. However, this approach is not favourable to be implemented at the design stage as the integrity strategy could not reflect the actual way the composite pipelines are operated as well as not reflecting the overall level of risk. Therefore, Escuer et al. (2018) suggested the implementation of CPM can be optimized by combining the actual integrity data from the subsea equipment such as operated composite pipelines with the in-house system engineering expertise to maximise the uptime and minimize any interventions between the composite pipeline systems. Those data can be converted into analysis that provides a definite degree of certainty for the risk evaluation as well as developing a systematic and thorough integrity management strategy.

The failure probability generated through probabilistic approaches can be implemented to evaluate and assess the structural reliability of

Table 7
Studies on the reliability assessment and integrity management of composite pipelines.

Ref.	Year	Failure Mode	Reliability/Integrity Management Approach	Finding
(Lin et al. (1998))	1998	•Buckling •First ply failure	•Deterministic and probabilistic approaches	•Buckling failure was evaluated by using a deterministic approach while the Tsai-Wu criterion was adopted to analyse the first ply failure. •Covariance of the two strength parameters from both analyses, buckling strength (λ_p) and first ply load (λ_b), were correlated and assumed to be lognormal for the probability density function. •The type of probability distribution (lognormal or normal distribution) may affect the reliability prediction of the composite laminate. •Reliability analysis of the correlation of these two failure modes was represented in terms of probability of failure. $P[C_1] = P[\textit{laminate fails due to first} - \textit{ply failure}] = \int_0^1 f_{\lambda_p}(u)du$ $P[C_2] = P[\textit{laminate fails due to buckling}] = \int_0^{P_c} f_{\lambda_b}(u)du$ $P_s = 1 - P_f$ $P_s = 1 - \{P[C_1] + P[C_2] - P[C_1 \cap C_2]\}$ Where P_s is reliability and P_f is the probability of failure
(Richard and Perreux (2000))	2000	•Microcracking of the matrix	•First Order Reliability Method (FORM)	•The microcracking of the matrix was identified using the mechanical analysis of damage behaviour based on the thermodynamics framework. •Deterministic analysis was performed to calculate the safety margin of the fibre-reinforced composite pipes based on the winding angle and circumferential stress while the probabilistic approach was used to predict and find the optimum winding angle in order to obtain the reliability-based optimum design as well as optimize the damage strength of the laminate. •FORM was used to evaluate the reliability of the fibre-reinforced composite pipes subjected to microcracking in the matrix, not only including the randomness but also considering the statistical uncertainties for the calculation of the probability of failure. •The probability of failure was calculated in two ways – failure probability of laminate and failure probability of lamina. •Failure probability of laminate: $P_f^k = Prob\,[M_k \leq 0]$ Where P_f^k is the failure probability and M_k is the safety margin. •Failure probability of kth lamina: $P_f^k = \int_{g_k(y) \leq 0} \varphi(y)dy$ Where P_f^k is the failure probability, $g_k(y)$ is the safety margin and φ is the uncorrelated standard normal probability density function.
(Kogiso et al. (2001))	2001	•Bending •Tension •Torsion	•First Order Reliability Method (FORM)	•The reliability of the thin laminated composite pipes was evaluated by modelling the pipe as a series system that consists of each ply failure and elastic deformation. •Ply failure was evaluated based on the Tsai-Wu criterion while the mode reliabilities were evaluated by using FORM at which both applied loads and material properties have probabilistic variations. •The difference between the deterministic analysis and the reliability-based optimum design analysis was not significant unless the ply failure was considered, and the elastic deformation failure mode can influence the reliability-based design compared to the deterministic design. •Elastic properties of the composite pipe's material such as Young's modulus in the fibre direction and the bending load can have a huge impact on the elastic failure mode while the shear modulus, longitudinal tensile strength and applied torque can significantly affect the ply failure mode.
(Hocine et al. (2008))	2008	•Tension and compression loads	•Finite element probabilistic solver - PERMAS	•Probabilistic solver was involved in generating the random variable vector realizations, carrying out the iso probabilistic transformation and validating the calculation steps and convergence in order to get the failure probability, reliability index and sensitivity analysis. •Finite element solver – PERMAS can offer various analysis capabilities such as statics (linear or nonlinear), dynamics, electromagnetics and laminate analysis was used to provide the evaluations of the limit state function. •Considering the quadratic form of the failure criteria, the second-order reliability method (SORM) was used to perform the reliability calculations and the limit state function for this reliability analysis was introduced through a subroutine written in FORTRAN. •The reliability model developed for the evaluation of the mono-material structure shows that it can predict the probability of failure of the carbon composites correctly with a lower reinforcement ratio and mechanical performances.
(Bai et al. (2015b))	2015	•On-bottom lateral stability	•Monte Carlo Simulation (MCS) combined with probabilistic analysis of non-linear finite element modelling (FEM)	•The non-linear finite element modelling (FEM) by introducing the fluids-pipe-soil interaction was modelled and the probabilistic analysis was performed based on all relevant parameters and uncertainties in the FEM. •A response model based on the FEM was developed with the ability to predict the horizontal pipeline displacement. •A serviceability limit state (SLS) function was considered as the failure function at which the excessive lateral displacement and loss of on-bottom stability of the pipeline due to hydrodynamic loads.

(continued on next page)

Table 7 (*continued*)

Ref.	Year	Failure Mode	Reliability/Integrity Management Approach	Finding
				•A calibration factor for pipeline lateral displacement was introduced into the limit state function to determine the required additional submerged pipeline weight for the assessment of pipeline on-bottom stability. •The reliability analysis was performed by integrating the Monte Carlo Simulation (MCS) with 10,000 cases generated by the response model in order to calculate the safety indices and probability of failure for lateral displacement of the pipeline.
(Alexander and Kulkarni (2018))	2018	–	•Technology Readiness Levels (TRLs)	•By adopting and implementing the TRLs approach which is commonly used in aerospace and defence industries for the evaluation and assessment of the integrity and performance of the pipeline, it can help to minimize operator risk, foster the deployment of advanced technologies as well and enhance the safe operation of high-pressure pipelines. •Three onshore-related case studies were presented which are monitoring and evaluation of pipelines using fibre optics, 3D imaging inspection and reinforcement using optimized composite technologies. •Among these three case studies, two of them were assigned to the TRL 5 level (system integration testing) due to the completion of the prototype validation testing and another case study was assigned to the TRL 2 level (demonstration by testing) due to the absence of a working prototype.
(Escuer et al. (2018))	2018	–	•Condition Performance Monitoring (CPM)	•A web-based software solution called Condition Performance Monitoring (CPM) was implemented to capture the available information and data from the field and analyse it to provide support for an optimized integrity management strategy. •Implementing risk assessment using the CPM approach can assist in identifying the potential failure modes and evaluating the risk associated with each of them.
(An et al. (2021))	2021	•Delamination •Material properties uncertainties	•Monte Carlo Simulation (MCS)	•Mixed continuous-discrete random variables were involved and the formula of total probability was first employed to formulate the reliability constraint so that discrete and continuous random variables were decoupled. •Monte Carlo simulation (MCS) was used for the reliability analysis, but it was found that the use of MCS was quite time-consuming. •An alternative way to improve the efficiency was to adopt the surrogate model in MCS to replace the direct evaluation of performance function and use the Gaussian process regression (GPR) model to estimate the fundamental frequency
(Syuryana et al. (2022))	2022	–	•Muhlbauer's Index Method and Quantitative Risk Based Inspection (QRBI) approach with several adjustments	•Probability of failure assessment was conducted after the pipeline segmentation was completed to derive an actual estimate of the risk and failure frequency along each failure segment of the pipeline over a year. •The probability of failure was obtained based on the potential damage mechanisms according to the interaction between the flexible pipe material, the transported fluid and the environmental conditions. •From the QRBI approach, a risk matrix and bow tie analysis were developed. •By combining the value of the probability of failure and consequence of failure, the total risk can be obtained for the risk matrix while bow tie analysis was performed by visualizing an overview of the hazard, providing all the critical information of risks and ease the risk interpretation procedure.
(Altabey et al. (2023))	2023	•Cyclic load	•Machine learning method – Enhanced Convolutional Neural Network (ECNN)	•Artificial intelligence (AI) based algorithm using deep learning method which is an Enhanced Convolutional Neural Network (ECNN) was implemented to evaluate and provide automatic early warning for detecting damage and its location in basalt fibre-reinforced polymer (BFRP) pipeline. •The distributed strain patterns were developed using finite element modelling (FEM) to predict the algorithm for pipeline damage mechanisms. •The ECNN was designed and trained to identify the deterioration condition of BFRP pipelines. •The output data of ECNN was then compared with the data from the Fibre Bragg grating (FBG) sensory system. With the difference of 0.093%, it was proven that ECNN had achieved a high performance with 93.33% accuracy, 91.18% regression rate and 90.54% of F1-score.

composite pipelines. Hence, to produce a more reliable risk interpretation of the composite pipelines, it can be enhanced and improved by integrating the probabilistic approach, in terms of failure probability, with the quantitative risk-based inspection (QRBI) (Syuryana et al., 2022). On the other hand, a specific and effective integrity management strategy can be developed by implementing the risk-based approach to ensure the best possible chance to extend the lifecycle of the composite pipelines based on the known operating parameters. However, it is necessary to acknowledge that this approach cannot guarantee the certainty or suitability of the life extension or life cycle of the composite pipelines for a long period (Marsh et al., 2009).

Throughout this comprehensive review, it can also be seen that there are no unified codes, standards or recommended practices yet to be established, either for inspection and monitoring systems or reliability assessment and integrity management of composite pipelines. It shows that there are many aspects related to composite pipelines yet to be fully explored. Therefore, the research on the topic related to composite flexible pipelines is still ongoing to seek and fill the knowledge and research gaps as well as for better future improvements and implementation.

7. Conclusions

From this comprehensive review, the study on the reliability and integrity assessment of composite pipelines for the oil and gas industry is explored and discussed. Several significant aspects are highlighted and concluded as follows.

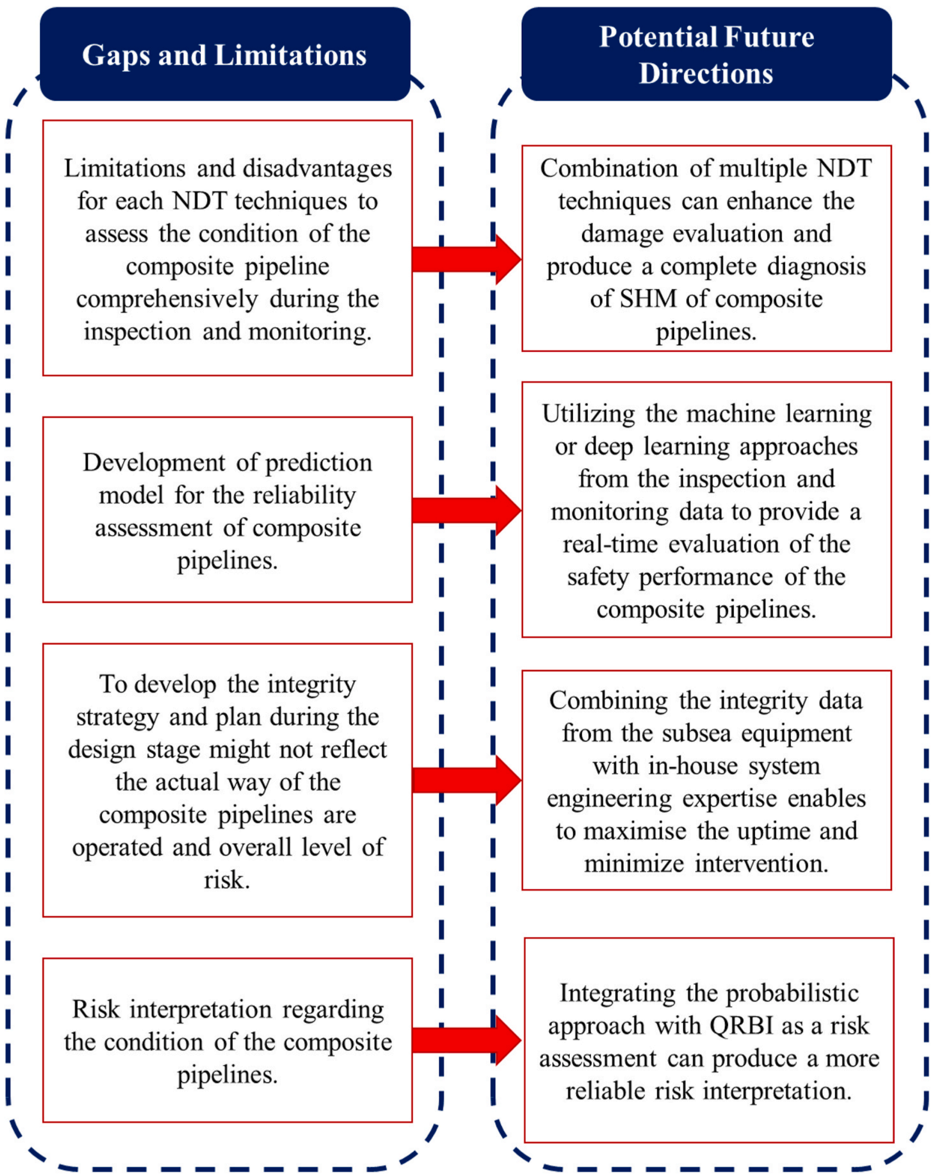

Fig. 14. Research gaps and limitations as well as the potential future recommendations for the reliability assessment and integrity management plan of composite flexible pipelines.

- ➢ Over certain periods of operation, failures tend to occur in composite pipelines just like carbon steel pipelines. Determining the failure modes and failure drivers that occur in the composite pipeline can lead to a better description of the failure mechanisms, describing the behaviour of the failure that occurs in the pipelines. With this, it can help to give an overview and ideas to mitigate the failure.
- ➢ Inspection and monitoring techniques for composite pipelines are also discussed in this paper. Several NDT techniques were proposed to be implemented as a structural monitoring technique for composite pipelines. However, none of the NDT techniques available is capable of detecting the whole structural failure. Hence, a combination of several NDT techniques to detect the failures or structural damage in the composite pipeline is proposed, simultaneously producing more reliable and accurate results.
- ➢ Reliability assessment and integrity analysis of the composite pipeline is not only limited to numerical calculations such as the probabilistic method, Monte Carlo Simulation (MCS) or First Order Reliability Method (FORM), but risk assessment tools such as Quantitative Risk-Based Inspection (QRBI), Condition Performance Monitoring (CPM) and Technology Readiness Levels (TRLs) are proposed and discussed as an alternative to evaluate the reliability of the operated composite pipeline.
- ➢ Some researchers also suggested integrating the monitoring data with the risk assessment tools (e.g. QRBI, TRLs) to produce and measure the risk and reliability accurately. On the other hand, the application of artificial intelligence (AI) based algorithms such as machine learning methods for the analysis of the inspection and monitoring data can be implemented in order to provide a real-time evaluation of damage mechanisms and prediction of the safety performance of the composite pipelines.

Overall, the objectives of this paper to discuss and review the reliability and integrity assessment of the composite pipeline are achieved. Several methods and techniques can be adopted and implemented to evaluate the structural integrity, reliability and safety performance of the composite pipelines. Similar to carbon steel pipeline that tends to fail due to several factors, it is necessary and important to identify the failures that occur in the composite pipeline and evaluate the reliability of the composite pipeline for a certain period of operation. Hence, this paper is an initial initiative to explore and determine the recent methods and approaches for the reliability assessment of the composite pipeline. Further studies need to be done to establish proper reliability and structural integrity procedures for the evaluation of composite pipelines subjected to different failure modes and failure mechanisms.

CRediT authorship contribution statement

Ummi Salina Farini Bahaman: Writing – original draft, Formal analysis, Data curation, Conceptualization. **Zahiraniza Mustaffa:** Writing – review & editing, Validation, Supervision, Project administration. **Mohamed El Amine Ben Seghier:** Writing – original draft, Methodology, Formal analysis, Conceptualization. **Thar Mohammed Badri:** Writing – review & editing, Investigation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgement

The authors would like to express their great appreciation to Universiti Teknologi PETRONAS for the financial support provided under the Yayasan Universiti Teknologi PETRONAS (YUTP) Grant (015LC0-318).

References

A. P. I. (API), 2008. ANSI/API Specification 17J - Specification for Unbonded Flexible Pipe. API Publishing Services, Washington D.C.

afarullah Khan, Z., 2012. Fracture surface analysis in HDPE pipe material fatigued at different temperatures and loading frequencies. J. Mate. Eng. Perform. 21, 1–6. https://doi.org/10.1007/s11665-011-0024-z.

Al-Qadami, E.H.H., Mustaffa, Z., Al-Atroush, M.E., 2022. Evaluation of the pavement geothermal energy harvesting technologies towards sustainability and renewable energy. Energies 15 (3), 1201. https://doi.org/10.3390/en15031201.

Alexander, C., Kulkarni, S., 2018. Program to evaluate readiness levels of pipeline-oriented technologies. In: PROCEEDINGS OF THE 12TH INTERNATIONAL PIPELINE CONFERENCE, 2018, vol. 2. Proceedings of the International Pipeline Conference.

Altabey, W.A., Wu, Z., Noori, M., Fathnejat, H., 2023. Structural health monitoring of composite pipelines utilizing fiber optic sensors and an AI-based algorithm—a comprehensive numerical study. Sensors 23 (8), 3887. https://doi.org/10.3390/s23083887.

American Petroleum Institute (API), 2019. API RP 1160: Managing System Integrity for Hazardous Liquid Pipelines.

An, H., Youn, B.D., Kim, H.S., 2021. Reliability-based design optimization of laminated composite structures under delamination and material property uncertainties. Int. J. Mech. Sci. 205 https://doi.org/10.1016/j.ijmecsci.2021.106561.

Badeghaish, W., Noui-Mehidi, M., Salazar, O.F., 2019. The Future of Nonmetallic Composite Materials in Upstream Applications. Day 2 Tue. (Accessed 22 October 2019).

Bahaman, U.S.F., Mustaffa, Z., Ben Seghier, M.E.A., Idris, N.N., 2022. Integrity of API 5L X56 offshore pipeline subjected to girth weld anomalies and corrosion using probabilistic methods. J. Perform. Constr. Facil. 36 (5), 4022038 https://doi.org/10.1061/(ASCE)CF.1943-5509.0001750.

Bai, Y., Bai, Q., 2014. Integrity Management of Flexible Pipes. Subsea Pipeline Integrity and Risk Management, pp. 101–124. https://doi.org/10.1016/B978-0-12-394432-0.00005-6.

Bai, Y., Bai, Q., 2005a. Chapter 28 - flexible risers and flowlines. In: Bai, Y., Bai, Q. (Eds.), Subsea Pipelines and Risers. Elsevier Science Ltd, Oxford, pp. 497–507. https://doi.org/10.1016/B978-008044566-3.50030-0.

Bai, Y., Bai, Q., 2005b. Chapter 31 - integrity management of flexibles and umbilicals. In: Bai, Y., Bai, Q. (Eds.), Subsea Pipelines and Risers. Elsevier Science Ltd, Oxford, pp. 549–562. https://doi.org/10.1016/B978-008044566-3.50033-6.

Bai, Y., Xu, F., Cheng, P., Badaruddin, M., Ashri, M., 2011. Burst Capacity of Reinforced Thermoplastic Pipe (RTP) under Internal Pressure, vol. 4. https://doi.org/10.1115/OMAE2011-49325.

Bai, Y., Xu, W., Cheng, P., Wang, N., Ruan, W., 2014a. Behaviour of reinforced thermoplastic pipe (RTP) under combined external pressure and tension. Ships Offshore Struct. 9 https://doi.org/10.1080/17445302.2013.835147.

Bai, Y., Ruan, W., Cheng, P., Yu, B., Xu, W., 2014b. Buckling of reinforced thermoplastic pipe (RTP) under combined bending and tension. Ships Offshore Struct. 9 https://doi.org/10.1080/17445302.2014.887171.

Bai, Y., Tang, J., Xu, W., Cao, Y., Wang, R., 2015a. Collapse of reinforced thermoplastic pipe (RTP) under combined external pressure and bending moment. Ocean Eng. 94, 10–18. https://doi.org/10.1016/j.oceaneng.2014.10.002.

Bai, Y., Tang, J., Xu, W., Ruan, W., 2015b. Reliability-based design of subsea light weight pipeline against lateral stability. Mar. Struct. 43, 107–124. https://doi.org/10.1016/j.marstruc.2015.06.002.

Bakar, M.A.A., Mustaffa, Z., Idris, N.N., Ben Seghier, M.E.A., 2021. Experimental program on the burst capacity of reinforced thermoplastic pipe (RTP) under impact of quasi-static lateral load. Eng. Fail. Anal. 128, 105626 https://doi.org/10.1016/j.engfailanal.2021.105626.

Batzias, F.A., Siontorou, C.G., Spanidis, P.-M.P., 2011. Designing a reliable leak bio-detection system for natural gas pipelines. J. Hazard Mater. 186 (1), 35–58. https://doi.org/10.1016/j.jhazmat.2010.09.115.

Ben Seghier, M.E.A., Keshtegar, B., Taleb-Berrouane, M., Abbassi, R., Trung, N.-T., 2021. Advanced intelligence frameworks for predicting maximum pitting corrosion depth in oil and gas pipelines. Process Saf. Environ. Protect. 147, 818–833. https://doi.org/10.1016/j.psep.2021.01.008.

Ben Seghier, M.E.A., Mustaffa, Z., Zayed, T., 2022. Reliability assessment of subsea pipelines under the effect of spanning load and corrosion degradation. J. Nat. Gas Sci. Eng. 102, 104569 https://doi.org/10.1016/j.jngse.2022.104569.

Ben Seghier, M.E.A., Knudsen, O.Ø., Skilbred, A.W.B., Höche, D., 2023. An intelligent framework for forecasting and investigating corrosion in marine conditions using time sensor data. npj Mater. Degrad. 7 (1), 91. https://doi.org/10.1038/s41529-023-00404-y.

Brown, N., Crate, J.M., 2012. Analysis of a failure in a polyethylene gas pipe caused by squeeze off resulting in an explosion. J. Fail. Anal. Prev. 12 (1), 30–36. https://doi.org/10.1007/s11668-011-9527-z.

Cook, H.H., Dopjera, D.E., Thethi, R., Williams, L., 2006. Riser Integrity Management for Deepwater Developments. Offshore Technology Conference. https://doi.org/10.4043/17891-MS.

Dai, L., Wang, D., Wang, T., Feng, Q., Yang, X., 2017. Analysis and comparison of long-distance pipeline failures. J. Petrol. Eng. 2017, 3174636:1-3174636:7.

Dhakal, H.N., Ismail, S.O., 2021. 1 - introduction to composite materials. In: Dhakal, H. N., Ismail, S.O. (Eds.), Sustainable Composites for Lightweight Applications. Woodhead Publishing Series in Composites Science and Engineering, Woodhead Publishing, pp. 1–16. https://doi.org/10.1016/B978-0-12-818316-8.00001-3.

DNV, D.N.V., 2009. DNVGL-RP-F116: Integrity Management of Submarine Pipeline Systems.

Duchene, P., Chaki, S., Ayadi, A., Krawczak, P., 2018. A review of non-destructive techniques used for mechanical damage assessment in polymer composites. J. Mater. Sci. 7915–7938. https://doi.org/10.1007/s10853-018-2045-6.

Escuer, C., Mahieu, C., Sicsic, P., 2018. Dynamic integrity management of flexible pipe through condition performance monitoring. In: Offshore Technology Conference Asia 2018, OTCA 2018. https://doi.org/10.4043/28347-ms.

Farh, H.M.H., Ben Seghier, M.E.A., Zayed, T., 2023. A comprehensive review of corrosion protection and control techniques for metallic pipelines. Eng. Fail. Anal. 143, 106885 https://doi.org/10.1016/j.engfailanal.2022.106885.

Gonzalez, M., Machado, R., Gonzalez, J., 2011. Fatigue analysis of PE-100 pipe under axial loading. In: Materials and Fabrication, Parts A and B, vol. 6. ASMEDC, pp. 905–911. https://doi.org/10.1115/PVP2011-57631.

Guoquan, Q., Hongxia, Y., Dongtao, Q., Bin, W., Houbu, L., 2019. Analysis of cracks in polyvinylidene fluoride lined reinforced thermoplastic pipe used in acidic gas fields. Eng. Fail. Anal. 99, 26–33. https://doi.org/10.1016/j.engfailanal.2019.01.079.

Ho, M., El-Borgi, S., Patil, D., Song, G., 2019. Inspection and monitoring systems subsea pipelines: a review paper. Struct. Health Monit. 19 (2), 606–645. https://doi.org/10.1177/1475921719837718.

Hocine, D., Welemane, H., Karama, M., Tahar, K., 2008. Reliability approach for fibre-reinforced composites design. Int. J. Simul. Multidiscip. Des. Optim. 2, 1–9. https://doi.org/10.1051/smdo:2008001.

Hutař, P., Zouhar, M., Náhlík, L., Ševčík, M., Máša, B., 2013. Multilayer polymer pipes failure assessment based on a fracture mechanics approach. Eng. Fail. Anal. 33, 151–162. https://doi.org/10.1016/j.engfailanal.2013.04.022.

Ibrahim, M.E., 2016. Nondestructive Testing and Structural Health Monitoring of Marine Composite Structures. Marine Applications of Advanced Fibre-Reinforced Composites, pp. 147–183. https://doi.org/10.1016/B978-1-78242-250-1.00007-7.

Idris, N.N., Mustaffa, Z., Fauzi, A., 2020a. Experimental study on radial interacting corrosion for X42 pipelines. IOP Conf. Ser. Earth Environ. Sci. 476, 12068 https://doi.org/10.1088/1755-1315/476/1/012068.

Idris, N.N., Mustaffa, Z., Ismil, N.N.A., 2020b. Burst capacity due to corrosion acting at radial orientation of pipeline. J. Phys. Conf. Ser. 1529, 32086 https://doi.org/10.1088/1742-6596/1529/3/032086.

Idris, N.N., Mustaffa, Z., Ben Seghier, M.E.A., Trung, N.-T., 2021. Burst capacity and development of interaction rules for pipelines considering radial interacting corrosion defects. Eng. Fail. Anal. 121, 105124 https://doi.org/10.1016/j.engfailanal.2020.105124.

Keshtegar, B., el Amine Ben Seghier, M., 2018. Modified response surface method basis harmony search to predict the burst pressure of corroded pipelines. Eng. Fail. Anal. 89, 177–199. https://doi.org/10.1016/j.engfailanal.2018.02.016.

Khalid, H.U., Ismail, M.C., Nosbi, N., 2020. Permeation damage of polymer liner in oil and gas pipelines: a review. Polymers 12 (10). https://doi.org/10.3390/polym12102307.

Koch, G., Varney, J., Thompson, N., Moghissi, O., Gould, M., Payer, J., 2016. In: Jacobson, G. (Ed.), NACE International IMPACT (International Measures of Prevention, Application, and Economics of Corrosion Technologies) Study.

Kogiso, N., Katou, S., Murotsu, Y., 2001. RELIABILITY-BASED optimization of thin composite pipe. In: The Proceedings of Design & Systems Conference, vol. 10. https://doi.org/10.1299/jsmedsd.2001.10.219, 2001.

Krishnaswamy, R.K., 2005. Analysis of ductile and brittle failures from creep rupture testing of high-density polyethylene (HDPE) pipes. Polymer (Guildf) 46 (25), 11664–11672. https://doi.org/10.1016/j.polymer.2005.09.084.

Kruijer, M., Warnet, L.L., Akkerman, R., 2005. Analysis of the mechanical properties of a reinforced thermoplastic pipe (RTP). Compos Part A Appl Sci Manuf 36, 291–300. https://doi.org/10.1016/j.compositesa.2004.06.018.

Lin, S.C., Kam, T.Y., Chu, K.H., 1998. Evaluation of buckling and first-ply failure probabilities of composite laminates. Int. J. Solid Struct. 35 (13), 1395–1410. https://doi.org/10.1016/S0020-7683(97)00113-3.

Liu, W., Wang, S., 2019. Analytical prediction of buckling collapse for reinforced thermoplastic pipes based on hoop stress analysis of crushed rings. Ocean Eng. 187, 106203 https://doi.org/10.1016/j.oceaneng.2019.106203.

Liu, Y., Shao, X., Han, X., Zhuang, C., He, X., 2009. Failure Types of FRP Pipe in Oil and Gas Engineering. ICPTT, pp. 2084–2091. https://doi.org/10.1061/41073(361)221.

Liu, A., Chen, K., Huang, X., Chen, J., Zhou, J., Xu, W., 2019. Corrosion failure probability analysis of buried gas pipelines based on subset simulation. J. Loss Prev. Process. Ind. 57, 25–33. https://doi.org/10.1016/j.jlp.2018.11.008.

Lu, S., Jiang, M., Sui, Q., Sai, Y., Jia, L., 2015. Damage identification system of CFRP using fiber Bragg grating sensors. Compos. Struct. 125, 400–406. https://doi.org/10.1016/J.COMPSTRUCT.2015.02.038.

Luhrsen, H., 2001. Reinforced Thermoplastic Pipes. State of Development.

Marsh, J., Duncan, P., MacLeod, I., 2009. Offshore pipeline and riser integrity - the big issues. In: Society of Petroleum Engineers - Offshore Europe Oil and Gas Conference and Exhibition 2009, OE 2009, pp. 1138–1150.

Masmoudi, S., El Mahi, A., Turki, S., 2016. Fatigue behaviour and structural health monitoring by acoustic emission of E-glass/epoxy laminates with piezoelectric implant. Appl. Acoust. 108, 50–58. https://doi.org/10.1016/J.APACOUST.2015.10.024.

Mat Soom, E., et al., 2021. Comparative Study of Structural Reliability Assessment Methods for Fixed Offshore Structures. https://doi.org/10.20944/preprints202108.0099.v1.

Mertiny, P., 2008. Effect of fiber-reinforcement material on the leakage failure in polymer composite pressure piping. In: American Society of Mechanical Engineers, Pressure Vessels and Piping. Division (Publication) PVP, pp. 591–596. https://doi.org/10.1115/PVP2008-61540.

Mishra, M., Keshavarzzadeh, V., Noshadravan, A., 2019. Reliability-based lifecycle management for corroding pipelines. Struct. Saf. 76, 1–14. https://doi.org/10.1016/j.strusafe.2018.06.007.

Negro, V., Lopez-Gutierrez, J., Esteban, M.D., Matutano, C., 2014. Uncertainties in the design of support structures and foundations for offshore wind turbines. Renew. Energy 63, 125–132. https://doi.org/10.1016/j.rene.2013.08.041.

Ngo, T.-D., 2020. Introduction to composite materials. In: Composite and Nanocomposite Materials - from Knowledge to Industrial Applications. IntechOpen. https://doi.org/10.5772/intechopen.91285.

Nizamani, Z., 2015. Environmental Load Factors and System Strength Evaluation of Offshore Jacket Platforms.

Parfomak, P.W., 2023. DOT's Federal Pipeline Safety Program: Background and Issue for Congress [Online]. Available: https://crsreports.congress.gov. (Accessed 22 August 2023).

Mehta, M.J., Vadher, J.A., 2017. A study on different failures of composite materials. Int. J. Adv. Eng. Res. Dev.(IJAERD) 4 (9), 302–307.

Pipeline and Hazardous Materials Safety Administration (PHMSA), "Pipeline Incident 20 Year Trends," U.S. Department of Transportation. Accessed: August. 22, 2023. [Online]. Available: https://www.phmsa.dot.gov/data-and-statistics/pipeline/pipeline-incident-20-year-trends..

Qi, D., Ding, N., Cai, X., Li, H., Shuhui, Z., Yan, M., 2011. Application and qualification of reinforced thermoplastic pipes in Chinese oilfields. In: ICPTT 2011. American Society of Civil Engineers, Reston, VA, pp. 267–275. https://doi.org/10.1061/41202(423)31.

Qi, D., Li, H., Cai, X., Ding, N., 2012. Application of Non-metallic Composite Pipes in Oilfields in China, pp. 283–291. https://doi.org/10.1061/9780784412619.032.

R, N, Z., Chaoui Kamel, C.A., Khelif, 2008. Failure analysis of polyethylene gas pipes. In: Pluvinage Guy, M.H., Elwany (Eds.), Safety, Reliability and Risks Associated with Water, Oil and Gas Pipelines. Springer Netherlands, Dordrecht, pp. 131–163.

Reis, J.M.L., Martins, F.D.F., da Costa Mattos, H.S., 2017. Influence of ageing in the failure pressure of a GFRP pipe used in oil industry. Eng. Fail. Anal. 71, 120–130. https://doi.org/10.1016/j.engfailanal.2016.06.013.

Richard, F., Perreux, D., 2000. Reliability method for optimization of [+φ, -φ]n fiber reinforced composite pipes. Reliab. Eng. & Syst. Safety 68, 53–59. https://doi.org/10.1016/S0951-8320(00)00002-8.

s David-West, O., Amafabia, D., Haritos, G., Montalvão, D., 2017. A review of structural health monitoring techniques as applied to composite structures. SDHM Struc. Durab. Health Monitor. 11, 91–147. https://doi.org/10.3970/sdhm.2017.011.091.

Syuryana, E.P., Puja, I.W., Hanifan, B., Marina, D., Irvan, M., Nusantara, P.T.D.E., 2022. Risk assessment and integrity analysis of flexible subsea pipeline in Indonesia. In: ICONIC-RS 2022: Proceedings of the 1st International Conference on Contemporary Risk Studies, ICONIC-RS 2022, 31 March-1 April 2022. European Alliance for Innovation, South Jakarta, DKI Jakarta, Indonesia, p. 1.

Szklarz, K.E., Baron, J.J., 2004. Learnings from thermoplastic liner failures in sour gas pipeline service and replacement liner design and installation. Corrosion 2004.

Tee, K.F., Khan, L.R., Chen, H.P., Alani, A.M., 2014. Reliability based life cycle cost optimization for underground pipeline networks. Tunn. Undergr. Space Technol. 43, 32–40. https://doi.org/10.1016/j.tust.2014.04.007.

Terán, G., Capula-Colindres, S., Velázquez, J., Fernández-Cueto, M., Angeles-Herrera, D., Hernández, H., 2017. Failure pressure estimations for pipes with combined corrosion defects on the external surface: a comparative study. Int. J. Electrochem. Sci. 11, 10152–10176. https://doi.org/10.20964/2017.11.86.

The American Society of Mechanical Engineers (ASME), 2022. ASME B31.8S Managing System Integrity of Gas Pipelines. New York.

Valor, A., Caleyo, F., Hallen, J.M., Velázquez, J.C., 2013. Reliability assessment of buried pipelines based on different corrosion rate models. Corrosion Sci. 66, 78–87. https://doi.org/10.1016/j.corsci.2012.09.005.

Van Eck, N.J., Waltman, L., 2010. Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics 84 (2), 523–538. https://doi.org/10.1007/s11192-009-0146-3.

Veritas, D.N., 2018. STANDARD: DNVGL-ST-F119 (THERMOPLASTIC COMPOSITE PIPES). Section 5: Failure Mechanisms and Design Criteria.

Wang, H., Yajima, A., Liang, R., Castaneda, H., 2015. Reliability-based temporal and spatial maintenance strategy for integrity management of corroded underground pipelines. Struc. Infrastruc. Eng. 12, 1–14. https://doi.org/10.1080/15732479.2015.1113300.

Wang, Y., Lou, M., Zeng, X., Dong, W., Wang, S., 2021. Burst capacity of reinforced thermoplastic pipes based on progressive failure criterion. Ocean Eng. 234, 109001 https://doi.org/10.1016/j.oceaneng.2021.109001.

Webster, D.%J.W.P., 2010. Pipeline Construction Drivers, Corrosion Costs and Engineering Issues.

Wen-hua, W., et al., 2022. An overview of structural design, analysis and common monitoring technologies for floating platform and flexible cable and riser. China Ocean Eng. 36 (4), 511–531. https://doi.org/10.1007/s13344-022-0044-5.

Yu, K., Morozov, E., Ashraf, M., Shankar, K., 2017. A review of the design and analysis of reinforced thermoplastic pipes for offshore applications. J. Reinforc. Plast. Compos. 36, 073168441771366 https://doi.org/10.1177/0731684417713666.

Zheng, T., Liang, Z., Zhang, L., Tang, S., Cui, Z., 2021. Safety assessment of buried natural gas pipelines with corrosion defects under the ground settlement. Eng. Fail. Anal. 129, 105663 https://doi.org/10.1016/j.engfailanal.2021.105663.

Zhu, X.-K., 2021. A comparative study of burst failure models for assessing remaining strength of corroded pipelines. J. Pipeline Sci. Eng. 1 (1), 36–50. https://doi.org/10.1016/j.jpse.2021.01.008.