Defect prevalence in fiberglass pipes: a comprehensive review

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1 ABSTRACT

The adoption of fiberglass-reinforced polymer (FRP) pipelines in industries such as oil, gas, water, and sewage has surged in recent years. FRP is favored as an alternative to metallic pipelines due to its superior characteristics like corrosion resistance, reduced weight-to-strength ratio, and customizable properties. However, their complex manufacturing and specific handling processes render them vulnerable to various defects. Moreover, the heterogeneity and anisotropic nature of FRP composites further exacerbate the challenge of defect identification and detection. This study presents a comprehensive review of defects observed in FRP pipelines, drawing insights from the academic literature. The paper systematically classifies these defects based on their occurrence during the pipeline's lifecycle: manufacturing, storage and installation, and in-service stage. As FRP pipes continue to gain traction in the industry, this review aims to provide industry professionals, researchers, and pipeline operators with a consolidated understanding of the potential defects in FRP pipelines, paving the way for improved quality control and pipeline longevity. In addition, the study underscores that the development of non-destructive testing (NDT) techniques for FRP pipelines is in its infancy, emphasizing an attractive avenue for further research and technology development in this realm.

2 INTRODUCTION

For several decades, metallic pipelines have been the backbone of the piping industry, owing to their robustness, reliability, and enduring mechanical properties. Their ability to withstand various industrial demands has made them a default choice in various sectors, such as oil, gas, and water transportation. However, despite their widespread usage, a persistent and critical issue has plagued these metallic conduits: their propensity for corrosion [1, 2]. This vulnerability to corrosion has raised concerns regarding their longevity and safety, prompting considerable research and investment into corrosion prevention and mitigation techniques [3, 4].

In recent years, there has been a paradigm shift in the industry with the emergence and growing popularity of composite pipes, particularly fiberglass-reinforced polymer (FRP) pipes [5, 6]. These materials have captivated the attention of pipeline manufacturers and operators due to their exceptional corrosion resistance—a stark contrast to the challenges faced by metallic pipelines [7, 8]. Beyond their resistance to corrosive environments, FRP pipes offer several other notable advantages. They are highly customizable [9], allowing for tailored solutions to specific industrial needs. Additionally, their superior weight-to-strength ratio presents a significant benefit, particularly in applications where weight reduction is crucial without compromising structural integrity.

Despite the compelling advantages of FRP pipes, their widespread adoption in the industry is not without challenges [10, 11]. One of the primary concerns is the aging of these composite materials. Unlike metallic pipes, whose aging and degradation processes are relatively well-understood, the aging mechanisms in FRP pipes are less clear [12]. This uncertainty is primarily attributed to the heterogeneity and inhomogeneity of composite materials. Unlike their metallic counterparts, composite pipes exhibit a complex interplay of different materials and layers, which can behave differently under various operational conditions.

Understanding the failure mechanisms of FRP pipes is crucial [13]. While research in this area has been initiated, it is still less explored than the extensive knowledge available for metallic pipelines. This knowledge gap encompasses several aspects: the knowledge of the type of defects that could develop in composites, the initiation and propagation of defects, fracture behavior under different stresses, aging behavior over extended periods, and overall performance deterioration with age [14]. Addressing these issues is essential for ensuring the long-term reliability and safety of FRP pipelines in industrial applications.

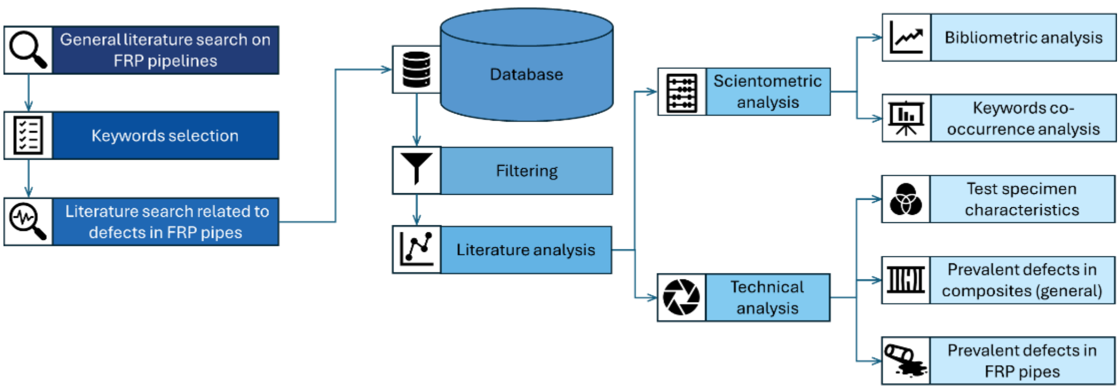
In this paper, we embark on a comprehensive review, focusing on the types of defects prevalent in composite materials, specifically focusing on FRP pipes. This review synthesizes and presents the findings from a wide range of literature, offering a thorough understanding of the various defect types identified and explored in academic and industrial research. The primary aim of this paper is twofold: firstly, to serve as an educational resource for emerging researchers in the field, providing them with a detailed overview of the defect landscape in composite materials, particularly FRP pipes. By consolidating and discussing these defects, we aim to furnish young researchers with a foundational understanding of the current state of knowledge in this area, fostering their learning and encouraging further exploration. Secondly, this review is designed to inform industry professionals about the current status of academic and technological research related to FRP pipe defects. By bridging the gap between academic research and industrial application, we aim to provide industry experts with valuable insights into the latest findings on defects in FRP pipelines. This dual approach ensures that the paper offers a practical guide that reflects the current landscape of research and its applications in the real world.

3 REVIEW METHODOLOGY

The literature search was conducted across critical databases, including Google Scholar, Scopus, Research Gate, and Web of Science. This process, detailed in the flowchart in Figure 1, involved specific keywords targeting composite materials and reinforced polymers, focusing on fiberglass and its variations. The search extended to terms related to pipes and cylinders-like structures. It was further refined to encompass a broad spectrum of defects, such as cracks, delamination, pre-mature failure, defect detection, aging, surface deterioration, and corrosion. This strategy ensured a comprehensive collection of relevant literature on FRP pipeline defects.

A series of filters were applied to refine the literature search for this study. These included removing duplicate articles from different databases to maintain data integrity. Entries inaccessible in full text, particularly those behind paywalls, were excluded. The study focused primarily on literature published between 2018 and 2023. Records discussing FRP as a repair material for metallic pipelines were acknowledged but set aside for their distinctiveness from the core focus of this paper. Additionally, materials other than Glass Reinforced Polymer (GRP) were filtered out to maintain the specific scope of this paper.

Figure 1: Workflow for literature survey and analysis.



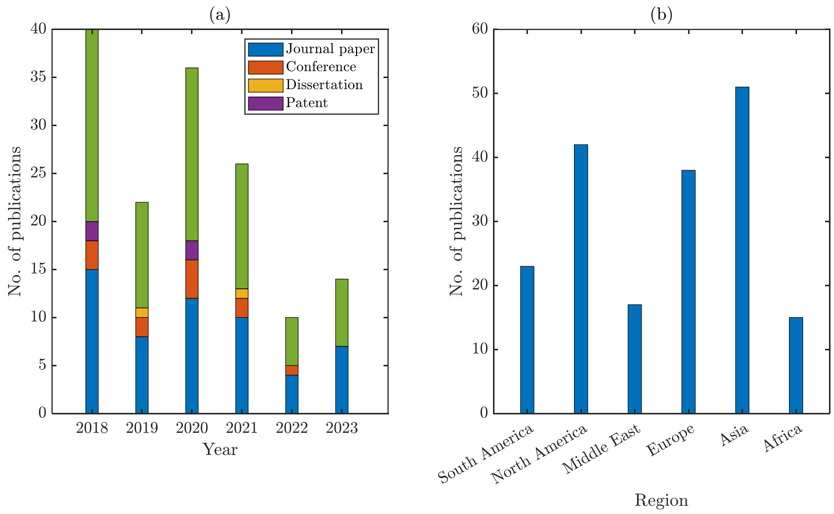
4 LITERATURE ANALYSIS

4.1 SCIENTOMETRIC ANALYSIS

4.1.1 Bibliometric analysis

The screening process began with 1040 entries identified and loaded into a database managed by Zotero, a freely available reference manager [15]. A systematic filtering process was then applied. Initially, the removal of duplicates reduced the count to 780 documents. A further refinement based on open access or author-shared manuscripts brought the number down to 610. Manual screening to exclude articles where FRP was used for repairing steel or concrete structures further narrowed the pool to 474 articles. The final filter, focusing on publications from the past five years to capture recent trends and advancements, resulted in a concise selection of 73 articles. Figure 2 illustrates a stacked bar plot, categorizing these shortlisted articles by document type.

Figure 2: Number of publications concerning (a) document type and publication year and (b) study region.



4.1.1 Cooccurrence analysis

Figure 3 displays a co-occurrence map constructed from the text data fields of document titles and abstracts. Unlike traditional keyword-based maps, this analysis was prompted by the observation that specific defect names/types are seldom used as keywords, with a few exceptions like “delamination” and “cracks”. Therefore, to capture a broader spectrum of relevant terms, the text data from titles and abstracts were scrutinized for co-occurrences. From an initial dataset of over 15,000 words, 293 terms emerged, surpassing a recurrence threshold of 20 instances. Among these, the most prominent terms encapsulating the essence and scientific significance were selected and are depicted in Figure 3. Following are the insights gleaned from this figure:

(i) The term “defect” emerges as the most prominent node, signifying its central role in the corpus of refined literature.

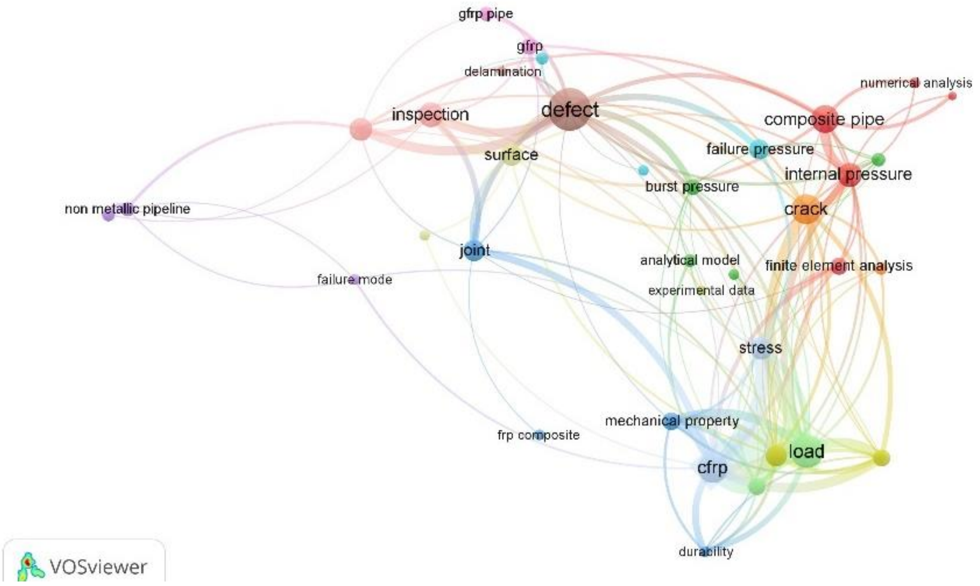
(ii) A marked linkage is evident between the “defect” node and the “composite pipe” node, highlighting the concentrated scholarly attention on composite pipe defects.

(iii) The map delineates both emerging and established research trajectories, with “crack” and “delamination” within FRP materials being notably prevalent, as indicated by their deliberate placement and network connections.

(iv) The illustration further underscores a synthesis of application-oriented keywords, such as "internal pressure," "delamination," and "service life," which are intricately linked to terms associated with failure analysis, including "burst pressure," "crack," and "failure."

This graphical representation, alongside the above observations, advocates for a multidisciplinary research strategy that combines materials science, engineering, and technology management principles. It reflects the intricate interplay between the multifaceted nature of the composite materials and the diverse academic disciplines contributing to this body of research.

Figure 3: Dominant terms derived from the recurrence of keywords within the curated literature database. This figure is obtained using VOSviewer [16].



4.2 Technical analysis

4.2.1 Test-specimen characteristics

The analysis of the refined literature repository reveals several notable trends within the research landscape of FRP pipelines. A striking 60% of the documents report on experimental work, underscoring a shift in the research community's focus toward experimental studies over theoretical numerical models. This trend further suggests a drive toward capturing the complexities of real-world samples. Nonetheless, it's observed that most of these experiments are conducted under controlled laboratory conditions rather than in situ, which may narrow the applicability of their results.

A significant portion of the database, about 40%, centers on studies utilizing glass fiber-reinforced epoxy resin (GRE) material, confirming its popularity and dominance in pipeline research and the pipeline industry. Meanwhile, carbon-fiber-reinforced polymer composites account for 11%, indicating a diversifying material research space for intensive and high-pressure applications. Regarding the pipe dimensions, there is an apparent concentration of samples measuring between 0.5 and 1 meter, representing 72% of the literature. While valuable for foundational research, this focus on shorter pipes potentially overlooks the inherent complexities of real-world pipeline systems, which extend for kilometers and incorporate various ancillary components such as valves, welds, and flow control devices. Such components are critical as defects can occur anywhere within the system, not just on the pipe surfaces, and can have profound implications on the system's operational integrity.

Furthermore, the literature points to a preference for pipe diameters ranging between 50 mm and 120 mm, encompassing 72% of the analyzed documents. This preference suggests a manufacturing trend towards smaller-diameter FRP pipes, increasingly replacing their metallic counterparts. Interestingly, approximately 30% of the literature also examines pipes with diameters exceeding 120 mm, supporting the notion that larger composite structures are feasible and gaining acceptance in low-pressure industries like sewage and water treatment. This trend is a testament to the versatility and scalability of FRP technology in addressing a broad spectrum of industrial needs.

4.2.2 General defects in composites

Unlike the defects commonly known in metallics, there is a broad spectrum of defects, their types, scale, point of initiation, and defect progression in composites. In this section, the types of defects in composites in general are sorted and discussed based on their appearance stage. The forthcoming section discusses the defects that are prevalently found in FRP pipelines. Figure 4 displays the scale-based classification of defects in FRP composites. This figure captures a broad range of defects, along with their potential scales, that have been discussed explicitly and/or implicitly within various studies—additionally, the compilation benefits from background research presented in similar review articles (e.g., [17, 18]). The objective is to provide a holistic and consolidated view of the prevailing defect types in composites. In this figure, the horizontal and vertical axes represent the defect scale and the stages in the lifecycle of the FRP composites where these defects are likely to manifest, respectively. Moreover, the figure is divided into three major segments: manufacturing, storage and installation, and in-service, which correspond to the lifecycle of FRP composites.

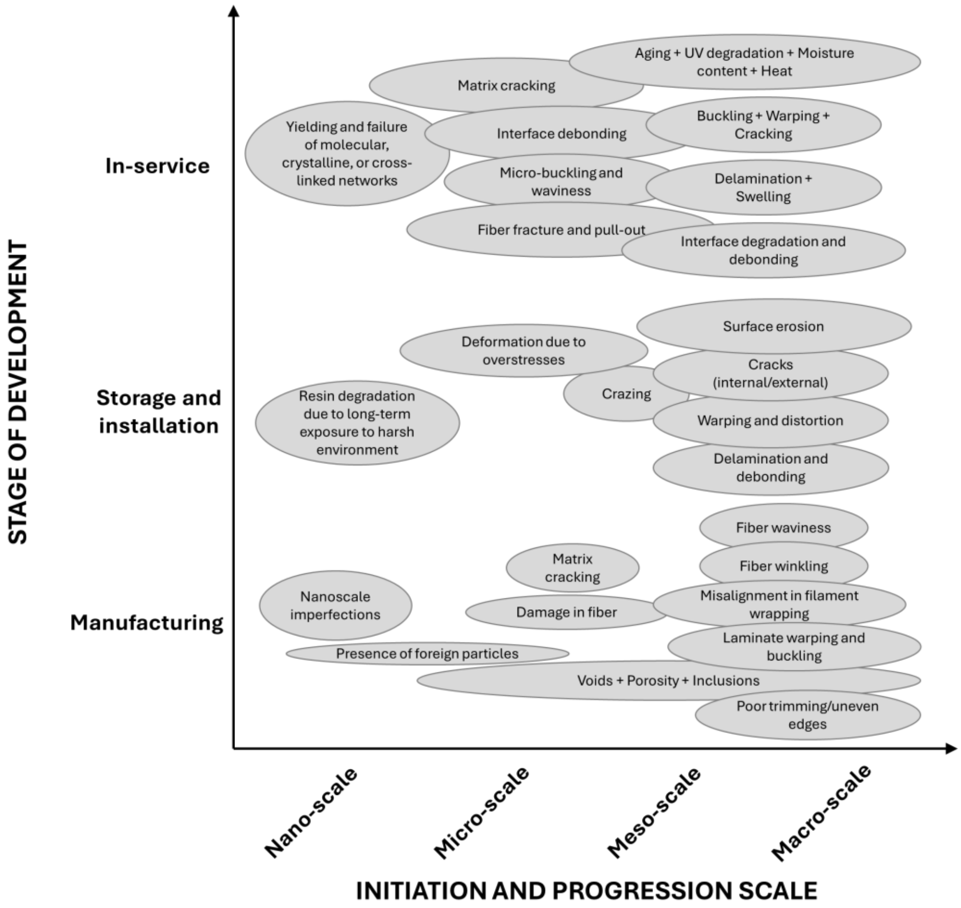
- **(A) Manufacturing stage:** This initial stage is marked by the emergence of nanoscale imperfections, including foreign particles and matrix cracking. It also covers microscale issues like fiber waviness and misalignment in filament wrapping, which are integral to manufacturing. Defects at this stage also include mesoscale challenges such as laminate warping and the presence of voids and porosity, emphasizing the importance of precision in the manufacturing process to mitigate these defects.
- **(B) During storage and installation**: At this stage, the focus turns to more visible, macroscopic defects. The handling and environmental conditions during storage and installation become pivotal, as they can precipitate significant material defects. The figure highlights issues like crazing, surface erosion, and various forms of cracking due to over-stresses and resin degradation, underscored by environmental exposure. This stage underscores the significance of careful handling and the influence of environmental conditions on material integrity.
- **(C) In-service phase:** This stage is crucial as it is characterized by the onset of severe macro-scale defects due to aging. Defects such as matrix cracking, fiber fracture and pull-out, delamination, swelling, and interface degradation become more pronounced, potentially compromising the integrity and functionality of the FRP composite. These defects underscore the operational environment's impact on the progressive deterioration of FRP composites.

Figure 4 also subtly indicates a progression from nanoscale to macro-scale defects, illustrating how initial small-scale defects can develop into more severe, larger-scale problems if not detected and mitigated early on.

4.2.3 Pipeline-specific defects

The foregoing section delineated defect types within general composite structures, but it is imperative to recognize the unique specifications of defects in specialized structures like pipelines. FRP pipelines distinguish themselves from other composite constructs through distinct manufacturing processes, specialized handling requirements, and unique service environments. These pipelines are often buried underground or submerged offshore, exposing them to a set of conditions unlike those encountered by most other composite structures. Identifying defects specific to pipeline applications is, therefore, essential.

Figure 4:Llifecycle and scale-based classification of defects in fiberglass-reinforced polymer composites.



In what follows, several defects relevant to FRP pipes, as reported in the literature, are discussed, and classified based on their type and nature.

1) **Surface degradation:** Surface degradation refers to the wearing away of the internal or external surfaces of FRP pipes, which can lead to significant structural damage and exposure to harsh environmental conditions. In this category, [19] and [11] simulated surface erosion by attaching a Euro coin to the pipe's surface, detecting its presence using ultrasonic guided waves. In a similar effort, [20] used adhesive tape patches to replicate the effects of outer-wall erosion. Real-field evidence of surface erosion was noted by [21], who reported blisters on a 20-year-old GFRP pipeline. Likewise, [22] examined material gain and loss due to erosion.
2) **Delamination:** Delamination occurs when the layers within the composite material separate, potentially compromising the pipe's structural integrity. For delamination, [23] embedding acetate sheets within the specimen during manufacturing, using a material contrast approach to model delamination. In [24], delamination was introduced by embedding Teflon tape to assess the impact on the load-bearing capacity of the pipe specimen. Likewise, [25] induced delamination through mechanical loading and monitored it using acoustic emissions. The authors in [26] also focused on delamination within FRP pipes and used acetate strips (as an intruding material) during specimen manufacturing to simulate delamination/debonding.

3) **Material Degradation:** Material degradation in FRP pipes refers to the deterioration of pipe material, which can reduce local stiffness and create stress concentration points. For this type, [27] discussed material degradation in the context of stiffness reduction. [28, 29] simulated wall thinning (by varying internal pipe diameter) and used vibration data to understand the degradation process.
4) **Debonding:** Debonding, an adhesive-flaw defect, occurs when the bonding between layers or components in FRP pipes fails, which can critically affect the pipe's performance. Debonding has been explored by [30], [26], and [31], each studying the implications of this defect on pipe functionality.
5) **Holes:** Artificial holes are drilled into FRP pipes to simulate the initiation of leakages, which is an important aspect in the study of pipe integrity and NDT techniques. Studies by [32, 33, 34, 35, 36] drilled holes (of various dimensions) in pipes specimens to imitate leaks and study their detection using various NDT methods.
6) **Mechanical Tests-Based Deformations:** A dominant part of the literature was found to be focusing on performance of composite pipe under mechanically loaded situations. In these tests, deformations lead to permanent bending and/or bursting. Such tests serve as a basis for predicting the behavior and integrity of FRP pipes. For instance, [25] utilized mechanical testing and acoustic emission for predictive modelling. [37] developed an analytical model for time-dependent mechanical behavior while [38, 39, 40] applied loads until the pipe burst. [30] observed fiber pull-out and debonding under load, with [41] and [42] studying the impact of manufacturing-induced defects like resin matrix cracking on burst capacity. In these studies, defects were either simulated before applying load to the pipes, or pristine pipes were monitored under load until they burst or fractured.
7) **Other Intensive Defects:** Many other defects that are very relevant to the scope of this paper were also found. For instance, cracks [43, 44], leakage failures [45], sleeve and joint failures [46, 26], poor fabrication [47], matrix cracking and voids [48], and inclusions of foreign objects [49].

A prevalent trend has been identified in the analysis presented: the artificial simulation of defects to emulate natural degradation and theoretically represent flaws in FRP pipelines. Although this approach is widely adopted in the field, it is essential to acknowledge that the frequency and characteristics of these simulated defects, as depicted in the literature, may not fully correspond with actual occurrences observed throughout the lifecycle of FRP pipelines.

5 CONCLUSIONS

In this review paper, we have thoroughly explored potential defects in composite materials, with a specific focus on fiberglass-reinforced polymer (FRP) pipes. The Scientometric analysis of the refined literature corpus reveals an emerging trend in the modelling, analysis, examination, and evaluation of composite pipes, encompassing theoretical and experimental approaches. The key findings of this work are summarized as follows:

1) A significant portion of the research concentrates on engineered defects, intentionally created in specimens, to understand their behavior under internal pressure and develop NDT techniques for detection. While this approach builds foundational knowledge, further research is necessary to address the real-world complexities of pipeline environments, such as offshore or buried conditions.

2) Most studies focused on pipes of smaller lengths (≤1 m) and diameters (≤120 mm). While this provides a basic understanding, it overlooks the intricacies faced in larger, real-field pipeline systems. Continued research is needed to address these complexities.
3) Issued such as aging and lack of understanding in the defect mechanics (initiation and progression) pose a significant concern for FRP pipelines, potentially hindering their widespread adoption in the industry.

In conclusion, the current body of literature offers a solid foundation but also highlights the need for more extensive research into realistic, large-scale applications. Such investigations are vital for the safe, efficient, and sustainable use of FRP pipelines across various sectors.

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