Engineering Failure Analysis 155 (2024) 107731

Contents lists available at ScienceDirect

Engineering Failure Analysis

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

Pressure-induced fatigue failures in cast iron water supply pipes

Carlos Jara-Arriagada *, Ivan Stoianov

Department of Civil and Environmental Engineering, Imperial College London, London, SW7 2AZ, UK

A R T I C L E I N F O

Keywords:
Water supply networks
Water pipes
Cast iron
Fracture mechanics
Fatigue failure
Pressure transients
Pressure management

A B S T R A C T

Cast iron pipes have been extensively utilised in water supply networks worldwide. Many of these pipes are either at the onset or within their wear-out phase, during which failure rates rapidly increase, and the pipes should be repaired or replaced. However, the replacement and rehabilitation of these pipes might require extensive resources and time. Therefore, it is essential to investigate the effects of operational practices that might reduce failure rates for ageing cast iron pipes. In this paper, we investigate the conditions under which water pressure fluctuations may impact and accelerate fatigue failures in cast iron pipes. We carried out a systematic review of the mechanical properties of cast iron pipes and conducted sensitivity analyses to estimate fatigue crack propagation using fracture mechanics. Our investigation suggests that cast iron pipes which are affected by reduced wall thickness due to corrosion may experience a significant decrease in their operational life when subjected to water pressure fluctuations. Moreover, this negative influence of pressure fluctuations is exacerbated with an increase in the mean operating pressure. As an example, a 150 mm pipe featuring a corrosion patch of about 7 mm depth could extend its remaining fatigue life by over fourfold through a minor reduction of both mean pressure and pressure fluctuations of approximately 10 mH_2O each. The manuscript further explores various pressure reduction combinations and trends, demonstrating the beneficial effects of reducing both mean pressure and pressure fluctuations. Consequently, the presented analysis suggests that water operators should proactively manage (reduce) the magnitude of both pressure components to extend the operating life of ageing cast iron pipes.

1. Introduction

A significant portion of the total pipe length within water supply networks (WSNs) in many cities, commonly between 30% to 60%, consists of cast iron pipes [1–3]. Most of these pipes are nearing the final phase of their useful life, during which deterioration and failures rapidly increase. This phase is referred to as the wear-out phase [4] (Fig. 1). The wear-out phase indicates that the components of the system are deteriorated and should be repaired or replaced. However, with current replacement and rehabilitation rates of 0.8% to as low as 0.1% per annum imposed by financial constraints, the replacement and rehabilitation of cast iron pipes will require multiple decades, potentially exceeding 200 years [2,5].

The increase in the deterioration and failures for cast iron pipes combined with the need to meet targets for key performance indicators, such as leakage and interruptions to supply, have forced water utilities to investigate and implement strategies to reduce current rates of pipe failures. A common strategy is to prioritise pipe replacement and rehabilitation by either targeting pipes with the highest number of breaks or applying predictive models based on statistical and/or machine learning methods [6–8]. However, a key challenge for the successful application of such predictive models is that the deterioration processes that lead to breaks of cast iron pipes are highly complex [9], and depend on manufacturing, installation and operational practices [10,11].

* Corresponding author.
E-mail address: cij18@imperial.ac.uk (C. Jara-Arriagada).

https://doi.org/10.1016/j.engfailanal.2023.107731
Received 17 July 2023; Received in revised form 11 October 2023; Accepted 16 October 2023
Available online 18 October 2023
1350-6307/

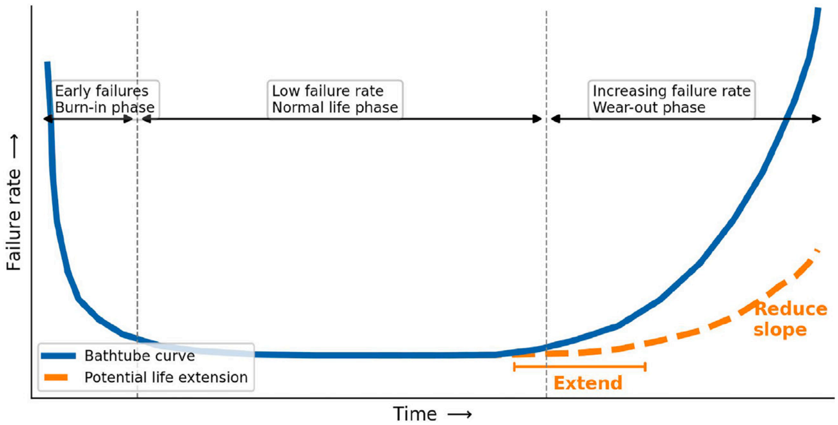


Fig. 1. Schematic of failure rates in the life of cast iron pipes (bathtub curve).

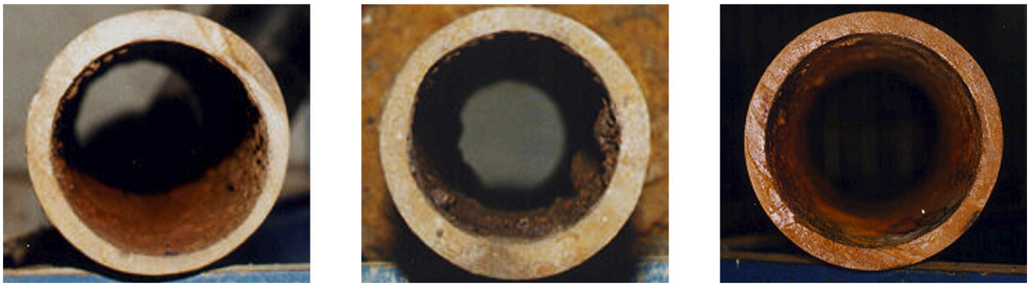
Current research have attempted to capture these complex processes that lead to pipe breaks by exploring a wide range of statistical and machine learning models [7,8,12,13]. However, a major challenge for such analyses is the lack of data that could be directly related to the mechanical and loading conditions under which water distribution pipes break. Water pressure, for example, is the main loading condition affecting water pipes [14]. However, this variable has not been extensively investigated in current modelling approaches due to lack of recorded data. Recently, Fan et al. [8] had to utilise a surrogate covariate for the pipes' elevation to account for the water pressure in the pipes. Rifaai et al. [7] used a covariate for pressure zones as proxy for water pressure. A major limitation of these approximations is that the dynamic conditions of water pressure are not considered. These dynamic conditions could be of major significance for the propagation of cracks, which ultimately lead to pipe breaks [15,16]. The recurrent lack of "significant" covariates in pipe breaks prediction models suggests a knowledge gap, which should be filled by studying and investigating mechanical processes that lead to pipe breaks in order to derive the appropriate covariates in decision making models.

In addition to prioritising pipes for replacement, another potential solution to reduce cast iron pipe failures is to implement pressure management [3,17,18]. Martinez-Codina [18] showed that a high pressure range is linked to cast iron pipe breaks in WSNs. Jara-Arriagada and Stoianov [3] also showed that a reduction in the pressure range and mean pressure can decrease breaks in cast iron pipes. However, the magnitudes of observed mean pressure and pressure range in operational systems in the UK is considered to be low to cause breaks in cast iron pipes, and a mechanical analysis is required to explain the observed correlations. A potential explanation based on mechanical properties and loading mechanisms is that the pressure range in combination with mean pressure act as a surrogate for water pressure fluctuations, which could cause pressure-induced fatigue failures for cast iron pipes.

The mechanisms for pressure-induced fatigue failures in cast iron pipes have been discussed in several studies [19–23]. Most studies, however, have focused on investigating the effects of fatigue on the overall life span of a pipe. As a result, published studies have presented S-N curves that do not reflect the particular impact of fatigue on deteriorated cast iron pipes at the onset of and during the wear-out phase. Other studies have performed fatigue crack propagation analysis from initial cracks sizes, which may not be representative for ageing pipes. Consequently, these analyses have concluded that the role of fatigue on the overall life of a pipe is limited. We hypothesise, however, that pressure-induced fatigue in cast iron pipes could be more relevant than it has been previously acknowledged when the deterioration of pipes at the onset of and during the wear-out phase is considered. To the best of our knowledge, pressure-induced fatigue failures at the onset of and during the wear-out phase of cast iron pipes have not been previously investigated. Furthermore, most studies have not considered the effect of mean pressure in their fatigue estimations, although it is known that mean pressure impacts the rate of fatigue crack propagation [24].

This paper aims to investigate the potential influence of pressure fluctuations on pipe breaks by presenting and applying a theoretical mechanical analysis. Our analysis applies a systematic approach, which takes into account properties of pipes in the wear-out phase in combination with hydraulic and loading conditions that include pressure fluctuations and mean pressure in operational systems. This investigation examines the following research questions: (1) What types of deterioration are observed in cast iron pipes; (2) What magnitude and frequency of pressure fluctuations can lead to pressure-induced fatigue failures; (3) To what extent mean pressure does influence pressure-induced fatigue failures; (4) Should pressure reduction schemes aim to reduce mean pressure, pressure fluctuations or both in order to reduce the occurrence of pipe breaks in ageing cast iron pipes. We believe that the proposed research would be of major benefit to hydraulic control engineers for the design of pressure management schemes and reliability engineering modellers for the inclusion of the appropriate pressure-related covariates into their causality and pipe prediction models. Consequently, more reliable modelling outcomes can be achieved with greater benefits from the implementation of pressure management schemes for reducing pipe breaks in ageing water supply networks.

The structure of the paper is as follows: In Section 2, we include a comprehensive review of relevant material properties for cast iron pipes and mechanisms that affect their degradation. In Section 3, a methodology for theoretically assessing the impact of



(a) (b) (c)

Fig. 2. Variability and non-uniformity in pipe wall thickness due to manufacturing practices. (a) & (b) Large non-uniformity in pipe wall thickness, potentially from horizontal or vertically pit casting processes. (c) Spun cast iron pipe. Photos provided by Bristol Water, UK.

water pressure fluctuations on the breaks of cast iron pipes using fracture mechanics is presented. The results from applying the presented methodology are summarised in Section 4, followed by a discussion in Section 5. The concluding Section 6 summarises the key contributions from this investigation.

2. Cast iron pipes in water supply networks

This section presents key factors and theory for the application of fracture mechanics in cast iron pipes. In particular, manufacturing processes, microstructure, effect of corrosion on pipe wall thickness, and fatigue experiments are discussed. These were then included in the application of the fracture mechanics and fatigue crack propagation theory presented in Section 3.

Cast iron is in essence an iron and carbon alloy with additions of silicon, manganese and other elements in minor quantities to improve the casting process and its corrosion resistance [25]. The carbon content usually varies between 2.5% to 4%. This content of carbon significantly reduces the melting point of cast iron in comparison to steel, thus providing greater fluidity to cast complex shapes [10]. The carbon content in cast iron pipes is usually observed as graphite flakes, spread within the mass of metal. These graphite flakes control most of the mechanical properties of cast iron [25,26]. The metal part of cast iron can be either ferrite, pearlite or a mixture of both [10]. An extensive body of research has studied the material properties of cast iron [26–31]. The following sub-sections summarise the metallurgy of cast iron and its mechanical properties, which are utilised in the mechanical analyses presented in Section 4.

2.1. Manufacturing processes of cast iron and the effect on pipe wall thickness

Four distinct manufacturing processes were developed and implemented for cast iron pipes. These processes are horizontal casting, vertical or pit casting, centrifugal or spun casting in sand mould, and centrifugal or spun casting in metal moulds [25]. All cast iron pipes were horizontally cast until 1845, which included the pouring of the melted iron in a horizontal mould. This procedure caused an uneven distribution of the metal in the mould leading to large variability and non-uniformity in circumferential pipe sections (Fig. 2(a)) and wall thickness. Cast vertically in a pit was introduced in around 1845, in which the moulds were vertically placed. However, variability and non-uniformity in pipe wall thickness continued to be observed. In 1918, centrifugal or spun casting was introduced. This manufacturing process resulted in a more uniform pipe wall thickness (Fig. 2(c)).

The adoption and use of new manufacturing processes for cast iron pipes were not governed by appropriate standards for a prolong time period, during which cast iron pipes were extensively installed. For example, British standards for pit cast iron and spun cast iron manufacturing processes were introduced in 1917 [32] and 1945 [33] respectively. Consequently, there were significant variations in the manufacturing processes and quality controls for a large stock of cast iron pipes, which are still in use.

2.2. Microstructure of cast iron pipes

Manufacturing processes also influenced variations in the metal composition and the geometry of the graphite flakes in cast iron pipes [10]. These graphite flakes play a major role in defining the mechanical properties of cast iron pipes; and in particular, the tensile strength, fracture toughness, and the stress intensity threshold for fatigue [26]. The form, size, and distribution of the graphite flakes are defined in the ASTM A247 [34].

In terms of the type of graphite flakes, there are no major differences resulting from the manufacturing processes for cast iron pipes. The four types of manufacturing processes produce type VII graphite flakes according to ASTM A247 [34]. However, the matrix (size and distribution) of the graphite flakes, as well as the metal part largely vary between static and centrifugal castings. These variations result from the different cooling rates. Large flakes and ferrite are produced by slow cooling rates, while a faster cooling rate tends to produce smaller graphite flakes and pearlite. A quick cooling rate leads to fine flakes and ferrite [10].

Table 1
Reported measured mechanical properties for cast iron (pit and spun).

Material property	Pit cast iron	Spun cast iron	Observation*	References
Tensile strength [MPa]	68–156	157–305		[10,22,35]
Fracture toughness [MPa$\sqrt{m}$]	7.9–24.3	11.9–20.36		[10,22,35]
	2	–	R = 0.7	[24]
Stress intensity threshold [MPa$\sqrt{m}$]	5.7	–	R = 0.5	[24]
	8	–	R = 0.1	[20]
	1.806e−12	–	R = 0.7	[24]
Paris constant C [m/cycle]	1.213e−14	–	R = 0.5	[24]
	6.559e−15	–	R = 0.1	[20]
	7.255	–	R = 0.7	[24]
Paris constant m [-]	7.647	–	R = 0.5	[24]
	7.379	–	R = 0.1	[20]

* R is the ratio $\frac{pressure_{min}}{pressure_{max}}$ at which the fatigue experiments were performed.

Horizontal and vertical cast iron pipes require a longer cooling time than spun cast iron pipes. Consequently, it is usual to observe graphite distribution of types A, B, and C in horizontal and pit cast iron pipes, while spun cast iron pipes are characterised by type D distribution of graphite flakes [10]. In terms of the metallic grains, pit cast iron pipes exhibit predominantly pearlite grains, while spun cast iron pipes are predominantly ferrite. Grain sizes in pit cast iron pipes are also much larger than in spun cast iron pipes due to the slow cooling process, which allows more time for individual grains to form [10].

2.3. Graphite flakes as crack initiators

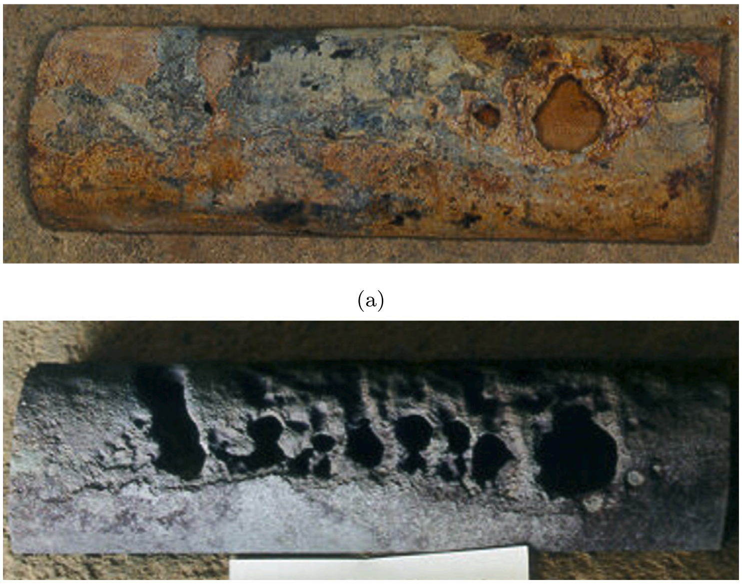
The size of the carbon flakes significantly affects the mechanical properties of cast iron pipes. Graphite flake sizes are classified in eight descending categories from class 1 to 8. For the case of pit cast iron pipes, the graphite flakes can reach sizes of the class 3, 2 and 1. The usual range is between 0.3 mm to 0.6 mm. However in some instances, graphite flakes can reach up to 1 mm to 2 mm [26]. Much smaller graphite flakes are seen in spun cast iron pipes (<20 μm). This difference in graphite flakes has been identified as the cause for large differences in the tensile strength and fracture toughness between pit and spun cast iron pipes [10]. The larger carbon flakes in pit cast iron makes it easier for cracks to initiate and propagate [10]. Table 1 presents a summary of common values reported in the literature for the main mechanical properties for cast iron pipes.

In summary, pit cast iron pipes are more likely to develop large cracks as the size of the graphite flakes produced in these pipes are larger than in spun cast iron pipes. Nevertheless, because of the variable and non-uniform pipe wall thickness, greater safety factors were used for pit cast iron pipes, and therefore pipes with thicker walls than required were produced. In contrast, thinner pipe walls were used in spun cast iron pipes because of the uniformity of the pipe wall thickness, and the larger tensile strength of the material. These thinner pipe wall thicknesses, however, makes spun cast iron pipes more susceptible to pit corrosion damage, which is discussed in the next section.

2.4. The effects of corrosion on pipe wall thickness, pits and cracks

Corrosion describes processes involving electrochemical reactions, in which a refined metal is converted to a more stable form such as an oxide, hydroxide or sulphide [36]. During these processes metal is lost, and therefore, the structural resistance of the material is degraded [37]. The most common type of corrosion process observed in cast iron pipes is pitting corrosion with graphitisation [9]. The graphitisation process includes the leaching of the metallic components from the cast iron, and the accumulation of graphite on top of the corrosive layer when a pit is formed in the metal. This layer of graphite provides the metal with the appearance of a non-corroded surface [9]. However, the resistance of the material filling the pit is of much lower strength than the cast iron, making it prone to failure at low loadings [9]. Usually, a corrosion pit due to graphitisation can only be identified by sandblasting a pipe (Fig. 3). In addition, corrosion pits can occur almost everywhere in a pipe [38], and because corrosion processes are affected by various factors, precise locations of corrosion spots are difficult to predict. [9].

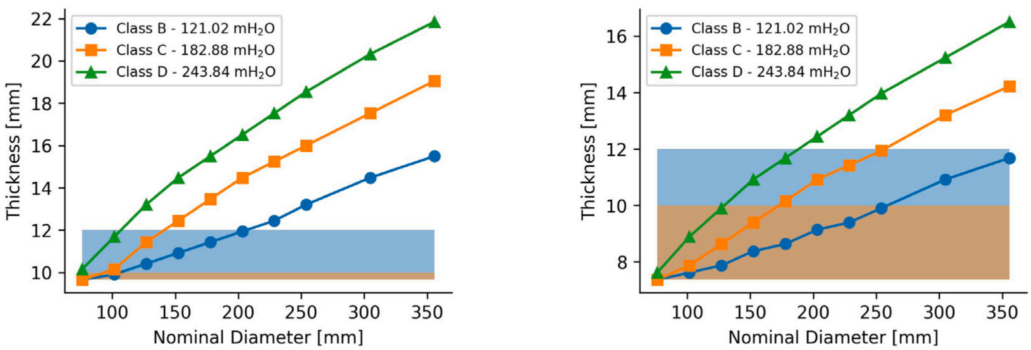
There are various phases in the corrosion process for cast iron pipes [9,39]. For this investigation, the last phase, in which the corrosion process reaches a steady state, is of particular interest to assess the long term impact of corrosion at the onset of and during the wear-out phase [9]. Published research has suggested that in the long term (+30 years installation of a cast iron pipe), pitting corrosion can reach a steady state [40–42]. The suggestion comes from evidence that maximum observed corrosion pit depths in cast iron pipes do not exceed 10 to 12 mm in very aged pipes. Also for most pipes, it seemed that 7 mm is a common minimum corrosion pit depth independently of pipe age [40,41]. Soltani Asadi and Melchers [41] have suggested that the build-up of material, which is generated during pitting corrosion tend to isolate the corrosion interface from the exterior and thus reducing its rate of vertical propagation during longer exposure periods. As a conclusion, it is reasonable to assume a minimum value of 6–7 mm for existing corrosion pits or amalgamated corrosion patches in cast iron pipes independently of their age.



(a)

(b)

Fig. 3. The extent of graphitic corrosion in a cast iron pipe as identified by sandblasting. (a) Pipe sample before sandblasting. (b) Pipe sample after sandblasting. Samples provided by Bristol Water, UK.



(a) (b)

Fig. 4. Pipe wall thicknesses for pit and spun cast iron pipes according to British Standards BS-78 and BS-1211, and comparison to maximum observed corrosion pit depths (between 10 and 12 mm). (a) Pit cast iron pipe thicknesses. (b) Spun cast iron pipe thicknesses.

Typical maximum values for corrosion depths (10 mm to 12 mm) can also be compared against the proposed wall thicknesses for cast iron pipes given by British Standards (i.e. BS 78:1917 and BS 1211:1945). Fig. 4 shows design pipe wall thicknesses for different diameters and classes of cast iron pipes. These thicknesses are visually compared to the limits of 10 mm and 12 mm for maximum observed corrosion depths whose areas of influence are marked in colour. From Fig. 4, it can be observed that small diameter pipes seem at most risk to be affected from wall thickness reduction because of their reduced thickness, which falls within maximum corrosion pit depths. This observation is reinforced by the analysis of historic pipe failures, which show that small diameter cast iron pipes have much higher failure rates [3]. A similar conclusion can be drawn from the wall thickness difference between pit and spun cast iron pipes (Fig. 4(b)). The reduced wall thickness of spun cast iron pipes makes these pipes more vulnerable to corrosion.

In addition to the pipe wall thickness reduction that corrosion generates on pipes, it has been recently investigated that corrosive soil environments, especially with high moisture contents and pH of around 5 can produce a reduction on the nanomechanical properties of cast iron [43]. This reduction in nanomechanical properties affects in turn bulk properties such as elastic modulus, tensile strength and fracture toughness [43]. In this research, for simplicity, and as a conservative approach, it is considered that corrosion only reduces pipe wall thickness, and does not affect the mechanical properties of cast iron pipes.

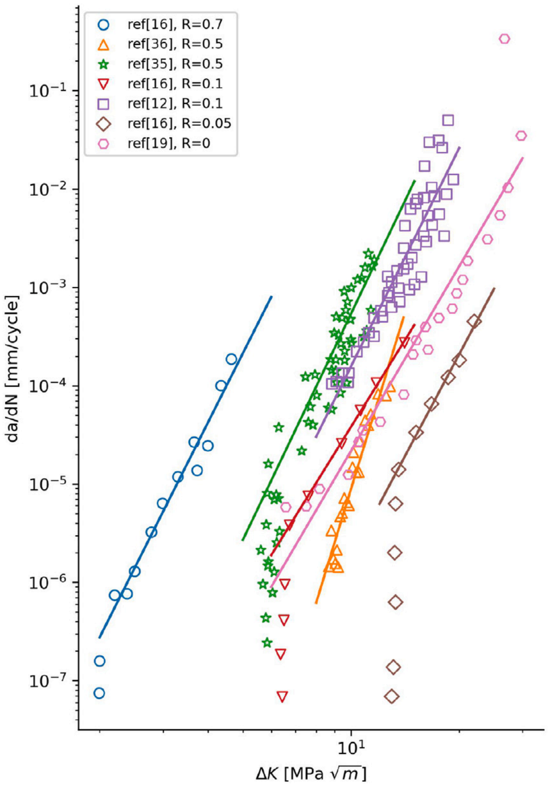


Fig. 5. Fatigue crack propagation curves for cast iron at different R ratios and sources. *Ref stands for reference [20,24,27,44,45].

2.5. Fatigue experiments on cast iron pipes

As the main objective of this paper is to mechanically analyse the impact of pressure fluctuations and mean pressure on the occurrence of pipe failures in deteriorated cast iron pipes at the onset of and during their wear-out phase, we next review and present research on fatigue-induced failures in cast iron pipes. This review together with key conclusions drawn in the previous sections are used for the mechanical analysis presented in Section 4.

In general, fatigue of materials can be analysed by the use of S-N curves, ϵ-N curves, and fatigue crack propagation experiments. The first two approaches deal with the total fatigue life of a specimen given their initial conditions. The results of such approaches are only valid to explain the failure of a material under the original conditions at which it was tested. In contrast, fatigue crack propagation experiments offer major generalisation as the results from testing can be used by any type and size of cracks. Given the different states of deterioration of buried cast iron pipes, fracture mechanics is more appropriate to perform pressure-induced fatigue analysis.

Published research describes various studies for fatigue crack propagation in grey cast iron. As a result, fatigue crack propagation curves for various samples of cast iron including cast iron used in WSNs have been obtained. Fig. 5 presents a summary of representative grey cast iron fatigue crack propagation curves obtained from published studies [20,24,27,44,45]. These studies show large variations between laboratory results for fatigue crack propagation in cast iron pipes. The axes in Fig. 5 are in a logarithmic scale, which further amplifies the large variations in the fatigue curves.

A key difference between these curves is their spread locations within the x-axis. The main cause for these deviations in the curves, apart from the heterogeneity that can exist between the cast iron samples, is the loading ratio R at which the fatigue experiments were conducted. The loading ratio R is the quotient of the minimum (valley) loading divided by the maximum (peak) loading of a loading cycle, and serves as a surrogate of the mean pressure. For a same magnitude of a cyclic pressure (stress) range, a higher loading ratio R defines that the cyclic pressure range is applied under a higher mean pressure.

As observed in Fig. 5, for a same referenced material, higher R ratios (e.g. higher mean pressures) under a constant cycle range lead to a faster fatigue crack propagation. An explanation for this phenomenon is the theory for crack closure proposed by Elber [46]. The basics of this theory is that unless a crack is affected by a minimum loading called K_{op}, the crack will stay closed, and pressure fluctuations will not cause fatigue. This means that under a low mean pressure, only a portion of the full range of a pressure cycle (ΔK_{eff}) contributes to fatigue crack propagation. In comparison, under higher mean pressures, the full range of a cyclic loading (ΔK) is contributing to fatigue crack propagation. Various modelling theories exists to account for the dependence of a fatigue crack propagation and the loading ratio R. Section 3.5 describe some of these, and the model used in this study.

(a)

(b)

Fig. 6. Example of an exhumed pipe provided by the water utility. (a) Cross-sectional section before sandblasting. (b) Longitudinal section view after sandblasting. Samples provided by Bristol Water, UK.

Published studies such as the one in Mohebbi et al. [20] have applied fracture mechanics to assess the fatigue life of pipes. In contrast to the current study, the authors focused on the role of pressure-induced fatigue in the whole life span of pipes. Under such consideration, it is expected that the contribution of fatigue in crack growth may be rather limited given the strong dependence of fatigue to the initial crack size. However, when considering highly deteriorated pipes, as most cast iron pipes currently in operation are, fatigue could be a major damaging factor that can accelerate failure. In addition, most published analyses, have performed fatigue estimations using fatigue crack propagation curves obtained at R ratios of 0.1. Such R ratio does not represent actual R ratios observed for water pipes in operation. In reality, it has been observed that R ratios in WSNs can be as high as 0.7. This high R ratio indicates that loading conditions do not necessarily need to be close to the critical load to generate fatigue on pipes. Therefore, fatigue life estimations should consider more realistic scenarios for fatigue crack propagation curves.

Furthermore, corrosion can also shift the fatigue crack propagation curves for cast iron pipes. Corrosion can produce a synergistic combination with fatigue causing accelerated fatigue in pipes at lower pressure-induced stress. Studies such as the one of Cullin et al. [22] have shown evidence of this effect. However, no experimental studies that include the acceleration of fatigue crack growth due to corrosion have been performed. A common practice to model corrosion fatigue is to treat the rate of propagation of cracks due to fatigue and the rate of propagation of pits due to corrosion as separate processes that add together [47]. However, this does not capture the synergistic effect of both processes. The effect of corrosion indicates that results from pure fatigue crack propagation analysis must be considered as a suggestion of the minimum damage that a cast iron pipe could be exposed to.

2.6. Observed failures in cast iron pipes

Observed failures in cast iron pipes are well documented and presented in published research papers [48–50]. Common failure types include circumferential failure, bell split, longitudinal failures, corrosion holes and pipe blowouts [51]. It has been observed that circumferential failures are more frequent in water distribution pipes, while longitudinal failures are more frequent in large diameter transmission mains [51]. These observations, however, are highly dependant on the analysed WSN. Also, the described failure modes commonly refer to the actual shape of the observed fracture after inspection of a failed pipe (e.g. Fig. 9), and do not describe the mechanism at which a pipe actually failed [52].

Fig. 7. Examples of pipe deterioration due to corrosion pits and patches after sandblasting pipes. Samples provided by Bristol Water, UK.

Various examples of multistage failures in cast iron have also been reported in the literature [48,50]. Makar [48] presented a post-mortem analysis of an exhumed pipe. The analysis concluded that a corrosion hole initiated a crack, which gradually extended until the pipe failed. Within the same study another analysis on a circumferential failure showed a similar pattern; namely, a corrosion hole initiated a crack, which then rapidly propagated. These two-stage failures had different chemical compositions within the hole and the crack surfaces. The corrosion hole exhibited the presence of elements from the surrounding soil, which indicates longstanding existence. In comparison, the crack surface did not show the presence of these elements, which suggests that the crack had developed in a shorter time period before the failure [51]. Furthermore, three-stage failures were observed in some of the analysed samples of cast iron pipes [51].

In addition to the published studies presented in this section, we reviewed over 3000 pipe failure reports provided for this investigation by a water utility in England. The reports included photographs of exhumed failed cast iron pipes taken from a period of approximately 10 years from 1996 to 2006. Most reports included a view of the pipe cross-sectional area before sandblasting and the longitudinal section after sandblasting (Fig. 6). Various pipes showed a large degree of deterioration caused by corrosion as corrosion pits and patches (Fig. 7). Most recurrent observed damage were corrosion pits. Some pipes that presented corrosion holes also showed longitudinally propagated cracks (Fig. 8). Various pipes also showed signs of a failure caused by the blowout of a corrosion patch, possibly because of the propagation of a longitudinal crack within the patch (Fig. 9).

In Fig. 7, various sections of the presented pipes are highly reduced by corrosion, however, without the presence of cracks, the pipes only show small localised corrosion holes, without major blowouts. In contrast, it seems that in Fig. 10, the presence of a longitudinal crack within the deteriorated corroded section of the pipe aided in the final blowout of the corroded section. Moreover, in most cases of pipe blowouts, the largest dimension of the blowout is in the longitudinal section (Fig. 9). This evidence seems to support the hypothesis that the propagation of a crack within a corrosion patch causes the breakage of the pipes. This scenario is considered in this investigation.

3. Assessment of water pressure fluctuations on fatigue failures in cast iron pipes using fracture mechanics

In this investigation, we theoretically assess the impact of water pressure fluctuations on fatigue failures in ageing cast iron pipes. This allows us to hypothesise whether and under which conditions a reduction in water pressure fluctuations in a WSN can reduce failure rates and extend the life of cast iron pipes at the onset of and during their wear-out phase. The potential for fatigue

Fig. 8. Longitudinal failures in water distribution pipes due to initial corrosion pits. Samples provided by Bristol Water, UK.

failure was evaluated with the use of fracture mechanics fatigue crack propagation in combination with data gathered for material properties, the reduction in pipe wall thickness, and pressure loading conditions observed in water supply networks. This section describes the modelling theories used for the applied mechanical analyses.

3.1. Loading conditions for water supply pipes

The main loading conditions for buried water supply pipes include internal water pressure, external bending forces, external forces that can crush a pipe, and forces caused by ground movement and thermal expansion [52]. It has been estimated that the normal operational internal water pressure can be between 6 to 7 times greater than common external crushing loadings [14].

The magnitude and dynamic behaviour of water pressure in water distribution pipes continuously vary because of diurnal changes in water demand as well as the operation of pump and valve controls. The stochastic water demand and variations in controls cause unsteady-state pressure fluctuations. Studies of the dynamic pressure fluctuations in operational water supply networks have shown that pressure fluctuations might either be rapid events also known as pressure transients and/or gradually developing events [15,53]. Further monitoring campaigns in operational water supply networks, which we carried out, have also shown that, although not ubiquitous, frequent pressure fluctuations over 30 mH_2O may commonly occur [54,55]. This magnitude of pressure variations pose a risk for fatigue induced breaks in pipes. Fig. 11 shows an example of an observed pressure transient event in a water distribution pipe logged by an UK water utility. Based on the gathered pressure data, we analyse the impact of constant amplitude loadings at 20 mH_2O, 30 mH_2O, 40 mH_2O and 50 mH_2O pressure head on fatigue failures in ageing cast iron pipes.

Fig. 9. Examples of cast iron pipe blowouts. Samples provided by Bristol Water, UK.

Fig. 10. Pipe blowout with the presence of longitudinal crack. Samples provided by Bristol Water, UK.

3.2. Distributions of size and pipe wall thickness for cast iron pipes

The manufacturing of cast iron pipes has been regulated in the UK by British Standards (e.g. BS 78, BS 1211, BS 2035, BS 4622), which had multiple revisions over the years. For this investigation, we used pipe sizes and wall thicknesses provided by British

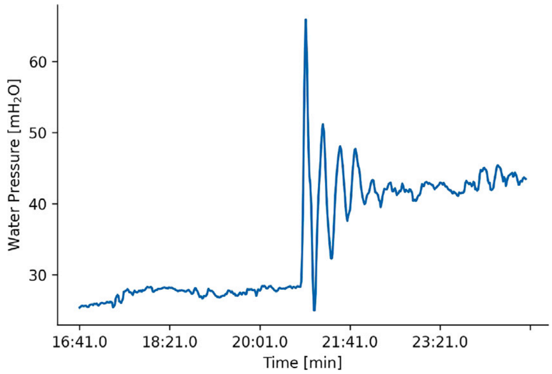


Fig. 11. Pressure transient in a water distribution pipe acquired from an operational network.

Standard 78:1917 for pit cast iron pipes and British Standard 1211:1958 for spun cast iron pipes. Fig. 4 shows the wall thickness by the diameter size for different classes of cast iron pipes. The classes define the design pressure that the pipe should withstand.

3.3. Stress variations due to a reduction in pipe wall thickness

As discussed in Section 2.4, pitting corrosion is a pervasive issue in cast iron pipes. In some instances, corrosion pits amalgamate and create large corrosion patches that reduce significant portions of a cast iron pipe section, and increase the stresses in the pipe [40,56]. Recently, Fu et al. [57] proposed an empirical equation based on a finite element analysis to predict the stress concentration factor for pipes with different size corrosion patches. Their analysis showed wide variations in stress concentration factors. For example, they showed that stress concentration factors for corrosion patches can vary in between 3 to 9 for different ranges of the length/width ratio and between 10 to 5 for 2×(width/depth) ratios greater than 5. The analysed factors suggest that the assumption of uniform wall thickness reduction using thin wall cylinder theory as done for the presented analysis is adequate for assessing the impact of pressure fluctuations on pipes with reduced wall thickness (see Fig. 14). Therefore, in order to assess the impact of pipe wall thickness reduction on ageing cast iron pipes, we estimated the stresses in a pipe using thin wall cylinder theory for different pipe wall thicknesses.

3.4. Fracture mechanics analysis

As discussed in Sections 2.2 and 2.3 , the microstructure of cast iron pipes would lead to the development of cracks. Even a new cast iron pipe can have graphite flakes up to 2 mm, which can produce a similar effect to a crack [26]. Corrosion pits can also simulate sharp cracks in some cases. Under these circumstances, the use of fracture mechanics is the most suitable approach to assess the resistance of a pipe to external loadings. This section presents an overview of the fracture mechanics analysis performed in this paper.

In fracture mechanics, single or multiple parameters are used to describe the stress intensification in a material due to the presence of cracks and loadings [36]. The single or multiple parameters can be compared to the maximum value that a material can withstand, which can be determined experimentally, and be generalised for the material as long as its properties remain unchanged. The type of single or multiple parameters to be used in fracture mechanics depend on the level of yielding that a load generates near the tip of the crack. In cases of very low or no yielding, the concept of stress intensity factor can be applied [58]. This research makes use of the stress intensity factor.

The stress intensity factor K [MPa$\sqrt{m}$] can be defined as follows:

$$K = Y \cdot \sigma \cdot \sqrt{\pi \cdot a} \tag{1}$$

where Y is a dimensionless geometry function that depends on the shape of a material and the crack length, σ is the stress applied to the material, and a is the crack length or half the crack length depending on the formulation. The value of the stress intensity factor represents a comparable numerical magnitude of the stress field near the tip of a crack. The stress intensity factor can be compared to the fracture toughness of the material, which is a measure of the maximum stress intensity factor that a material can withstand [36].

In case of complex geometries, the value of the stress intensity factor can be also estimated by a finite element analysis. For pipes, general empirical expressions have been proposed and are commonly applied. Such expressions include longitudinal through cracks, longitudinal surface cracks, and penny-shape cracks. Some research studies have evaluated more detailed formulations by simulating stress intensity factors in a pipe due to sharp cracks [59]. These studies have shown that the results of the prior empirical formulation can overestimate results from more detailed analyses. Nevertheless, such an overestimation can be used as a factor of safety in the calculations. Given the various formulations, this investigation utilises fracture mechanics calculations based on the formulation of a longitudinal through crack in a cylinder [60].

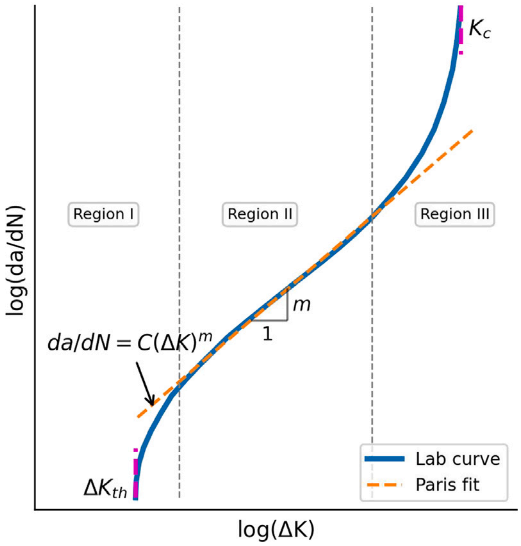


Fig. 12. Illustration of the empirical relation between the rate of crack propagation (da/dN) and stress intensity factor range (ΔK).

In particular, the stress intensity factor formulation was used to determine the maximum crack length for a break in a pipe. This stress intensity factor formulation was also used to determine values for minimum water pressure fluctuations required to start the process of fatigue, and in the fatigue crack propagation analysis. Maximum crack lengths were calculated by solving the value of crack length that produces a stress intensity factor which reaches the fracture toughness of a cast iron pipe for different values of water pressure. A similar approach was performed to obtain the minimum magnitude of cyclic water pressure required to start causing fatigue crack propagation in a cast iron pipe. In this case, the value of water pressure that generates a stress intensity factor equal to the stress intensity threshold for different values of crack lengths was calculated. The procedure for the fatigue crack propagation analysis to estimate fatigue-induced failure is presented in the next section.

3.5. Fatigue crack propagation

Fatigue crack propagation deals with the propagation of cracks due to cyclic loadings. In particular, the fatigue crack propagation theory is based on the observation that, under controlled laboratory conditions, the rate of crack growth per loading cycle (da/dN) is correlated with the magnitude of the stress intensity range (ΔK) exerted on a material per cycle (Fig. 12). This stress intensity range is the range of the cyclic loading applied converted to stress intensity factor.

Important information derived from Fig. 12 includes: (1) The curve for fatigue crack growth can be expressed in general terms as presented in Eq. (2). (2) For every material, there is a minimum stress intensity threshold range (ΔK_{th}), below which, there is no fatigue crack propagation. (3) Three regions are observed in a fatigue crack propagation curve. Region two is the common region used for fatigue crack propagation analysis, as loading conditions usually lie in this region. (4) The steepness of the curve slope, m, provides indication of the usefulness of fatigue crack propagation assessment for different materials. If the slope is too steep, then there is little difference between the minimum load to start causing fatigue (K_{th}) and the maximum load to break a material (K_c). In this research, we consider that the slope of the fatigue crack propagation curves for cast iron pipes presented in Fig. 13(b), at approximately 6.8, provides sufficient difference between K_{th} and K_c for fatigue crack propagation analysis.

$$\frac{da}{dN} = f(\Delta K, R, \ldots) \tag{2}$$

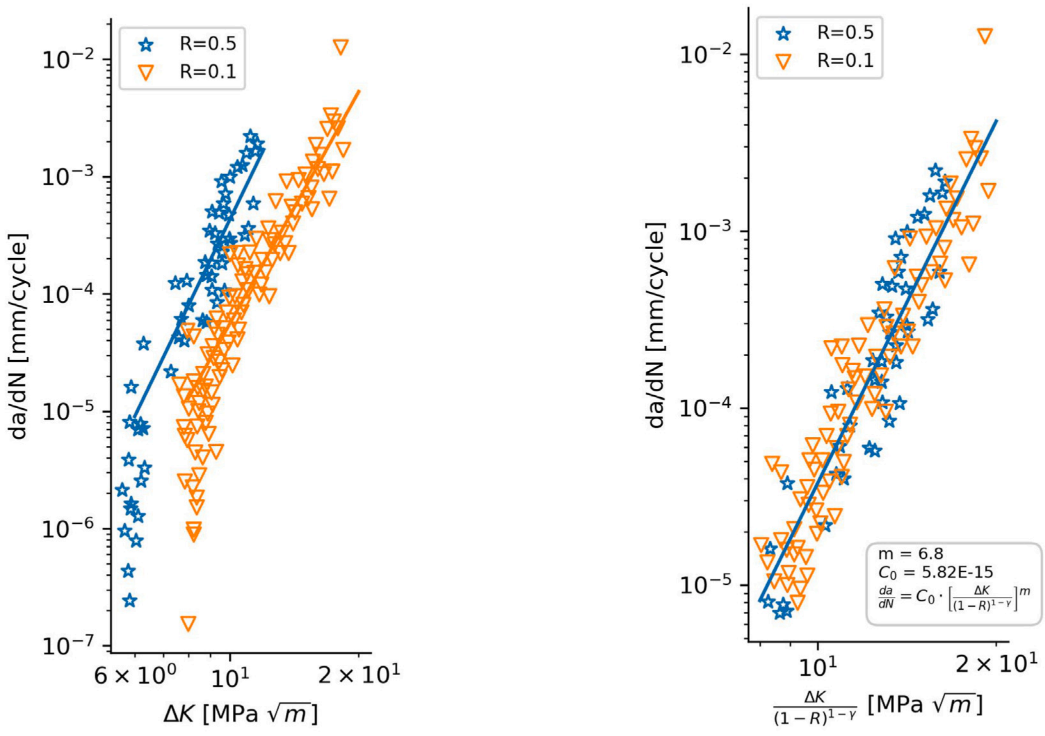
On the basis of the empirical relation shown in Fig. 12, the proposed functional form of Eq. (2), and also assuming a constant cyclic loading, the number of cycles, N, required for a crack to reach a specific final crack can be estimated as follows:

$$N = \int_{a_i}^{a_f} \frac{1}{f(\Delta K, R, \ldots)} da = \int_{a_i}^{a_f} \left(\frac{dN}{da}\right) da \tag{3}$$

3.5.1. Fatigue crack propagation laws

To utilise the functional form of Eq. (2), several detailed expressions for the function of da/dN have been proposed. A basic expression is the Paris law (Eq. (4)). This equation relates the rate of crack propagation with the stress intensity range in the region II of the crack propagation curve in Fig. 12:

$$\frac{da}{dN} = C \cdot \Delta K^m \tag{4}$$



(a) (b)

Fig. 13. Walker equation fit for a selected representative cast iron material. (a) Selected fatigue crack propagation data from [44]. (b) Fitted Walker equation to data.

The Paris law is commonly used since it describes well the region II in Fig. 12. However, this equation only works on a fix loading ratio R, which is the loading ratio used to obtain the fatigue crack propagation curve. A more general expression to assess fatigue crack propagation for different loading ratios Rs is the Walker equation (Eq. (5)) [61].

$$\frac{da}{dN} = C_0 \cdot \left[\frac{\Delta K}{(1-R)^{1-\gamma}}\right]^m \tag{5}$$

Similarly to the Paris law, the Walker equation only describes fatigue crack propagation in region II. The most complete mathematical fit for the fatigue crack propagation curve presented in Eq. (2) and Fig. 12 is the NASGRO equation (Eq. (6)). This equation provides a result for any stage of the fatigue curve, but requires multiple constants to be fitted.

$$\frac{da}{dN} = \frac{C\,(1-f)^n\,\Delta K^n \left(1-\frac{\Delta K_{th}}{\Delta K}\right)^p}{(1-R)^n\left(1-\frac{\Delta K}{(1-R)K_c}\right)^q} \tag{6}$$

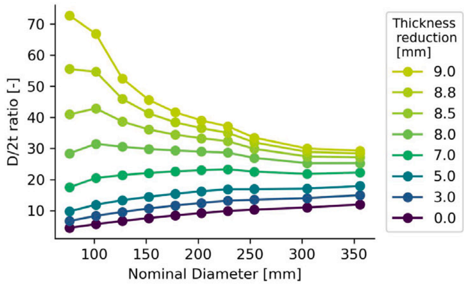
Although additional factors such as temperature can play a role in a fatigue crack propagation analysis, the conducted analysis does not intend to provide exact estimations for fatigue life, which would be extremely difficult. The main aim of this research is to assess the general magnitude and the effects of varying water pressure fluctuations and the mean pressure on deteriorated cast iron pipes. Therefore, it was considered that the use of the Walker equation fitted for a selected representative cast iron material was adequate to estimate the rate of crack propagation in ageing cast iron pipes.

3.5.2. Fitting the fatigue crack propagation equations

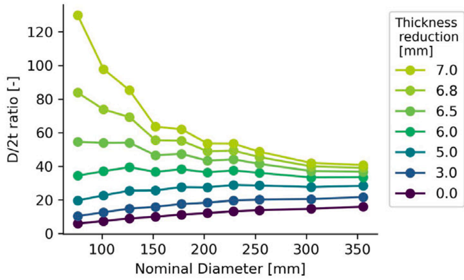
From the fatigue crack propagation curves presented in Section 2.5, we selected the data provided in Ref. [44] to fit the Walker equation. This data included fatigue crack propagation curves for cast iron at loading ratios of 0.5 and 0.1 (Fig. 13(a)). This data was fitted for the Walker equation with $\gamma = 0.5$ to obtain a fatigue crack propagation curve that can be used for any loading rate scenario (Fig. 13(b)), and therefore to perform an analysis for varied cases of pressure fluctuations and mean pressure.

4. Results from fracture mechanics evaluation and fatigue crack propagation for cast iron pipes

This section presents the results of the theoretical analyses, which were carried out to investigate the impact of water pressure fluctuations on fatigue failures in deteriorated cast iron pipes. We first conduct an analysis of the effect of the reduction in pipe



(a)



(b)

Fig. 14. Effect of pipe wall thickness reduction on the D/2t ratio for different cast iron pipe diameters. (a) Pit cast iron pipe. (b) Spun cast iron pipe.

wall thickness on the hoop stresses in cast iron pipes to assess the detrimental effect of corrosion patches. We then perform fracture mechanics analysis to understand the limits for maximum crack lengths, and minimum magnitudes of water pressure for cast iron pipes to start experiencing fatigue failures. These results inform the fatigue crack propagation analyses, which show the conditions under which a reduction in water pressure fluctuations can considerably affect the fatigue life of a pipe. The analyses were performed for both pit and spun cast iron pipes with the exception of the fatigue crack propagation analysis, which was done for pit cast iron pipes because of the available data.

4.1. Effect of the reduction in pipe wall thickness on pipe stresses

This analysis investigates the increase in hoop stresses with the reduction in pipe wall thickness. The values for the considered pipe wall thicknesses were based on the British Standards 78:1917 and 1211:1945 for pit and spun cast iron pipes. The plots in Fig. 14 show how the ratio $D/2t$ changes for different diameters, and how wall thickness reduction affect its magnitude. According to the wall cylinder theory, hoop stresses can be approximated in a pipe by multiplying the stress produced due to water pressure by the factor $D/2t$. Therefore, the plots in Fig. 14 show how the magnitude of applied stresses vary due to water pressure fluctuations for different pipe diameters and values for the reduction in pipe wall thickness.

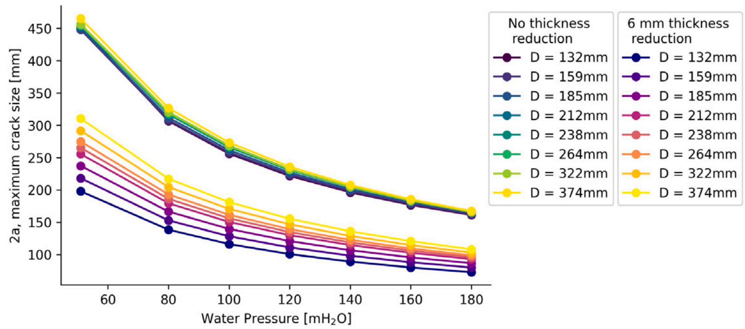
The results show that there is a considerable increase in applied stresses especially for small diameter pipes following a reduction of 6 mm and 8 mm in pipe wall thickness in spun and pit cast iron pipes respectively. This rate of increase in stresses, however, is less pronounced for pipes with diameter above 250 mm, such as transmission mains. This basic analysis indicates that stresses can easily increase between 4 and 6 times considering the typical corrosion patches observed in ageing pipes as presented in Section 2.4.

4.2. Maximum crack lengths in cast iron pipes

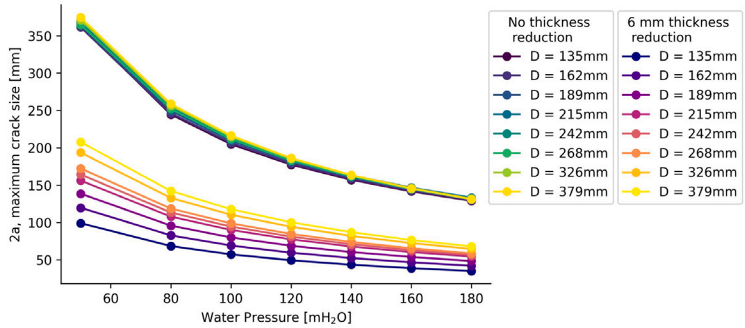
This analysis investigates the maximum theoretical crack length at which a crack can propagate before the fracture of a material. This maximum crack length affects the number of pressure cycles required to break a pipe from an initial crack length. Therefore, the values presented here inform the calculation for the fatigue crack propagation estimations further presented in Section 4.4.

The plots in Fig. 15 show the maximum crack length before the break of a pipe when different magnitudes of water pressure are applied. This crack length was calculated by solving the value of crack length which produces a stress intensity factor (Eq. (1)) equal to the fracture toughness of the pipe for a given magnitude of water pressure. We assumed values of 18.1 $\mathrm{MPa}\sqrt{\mathrm{m}}$ and 20.36 $\mathrm{MPa}\sqrt{\mathrm{m}}$ for the fracture toughness of pit and spun cast iron pipes respectively, on the basis of the references provided in Table 1. The analysis is done for different pipe diameters, which are taken from British Standards (see Section 3.2). The applied water pressure ranges from 50 $\mathrm{mH_2O}$ to 180 $\mathrm{mH_2O}$. Two clusters of plotted lines can be observed in Figs. 15(a) and 15(b). The clusters of plotted lines at the bottom show the maximum crack lengths when considering a reduction in pipe wall thickness of 6 mm for the different pipe diameters. The upper clusters of plotted lines show the expected maximum crack lengths for pipes with intact pipe walls. Note that the maximum crack length calculated for a pressure of 50 $\mathrm{mH_2O}$ for a pipe with a reduced wall thickness agrees with the approximate maximum crack length observed in a physical fatigue experiment performed by Wong et al. [62].

The results presented here show the trade-off between pipe wall thickness and material resistance for spun and pit cast iron pipes. Although spun cast iron pipes have a greater tensile strength and fracture toughness, the reduced wall thickness of spun cast iron pipes makes these pipes more prone to failures in comparison with pit cast iron pipes. In addition, the presented results can be used to indicate a maximum crack size that could withstand a maximum expected pressure transient in a network without resulting in a pipe failure. For the fatigue analysis presented in this paper, it has been assumed that a pipe should withstand a maximum pressure transient of 100 $\mathrm{mH_2O}$. Although not frequent, such magnitude of a pressure transient occurs in water distribution pipes as reported by the UKWIR [55].



(a)



(b)

Fig. 15. Maximum crack length for cast iron pipes as a function of increasing water pressure and pipe wall thickness reduction. (a) Pit cast iron pipe. (b) Spun cast iron pipe.

4.3. Minimum magnitude of water pressure cycles for pressure-induced fatigue

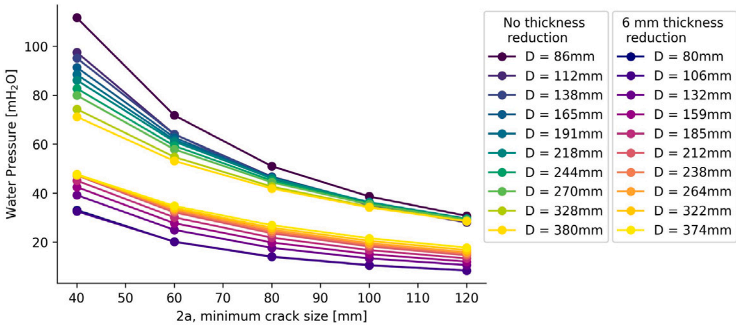
This section describes the results of the minimum magnitude of water pressure cycles required to initiate fatigue crack propagation in cast iron pipes. The magnitude of the pressure cycles are combined with a crack length that produces a stress intensity factor equal to the stress intensity threshold of a pipe (ΔK_{th}). The value of ΔK_{th} highly depends on the loading ratio R used in the fatigue experiment to determine the fatigue crack propagation curve of a material. Most fatigue crack propagation curves for cast iron have been determined using a loading ratio R between 0.1 and 0.3, although the loading ratio R in WSNs can exceed 0.5. The difference in loading ratios Rs can produce substantial differences in calculations for the stress intensity factor for fatigue and therefore in the life expectancy of a pipe exposed to fatigue cycles.

In order to compare results for both pit and spun cast iron pipes, we used a minimum ΔK_{th} of 2 MPa$\sqrt{m}$ (at loading ratio R of 0.7 Fig. 5) for pit cast iron and 4 MPa$\sqrt{m}$ for spun cast iron (assumed). Fig. 16 shows that when pipes are not affected by a reduction in wall thickness, higher magnitudes of water pressure cycles are required in spun cast iron pipes than pit cast iron pipes to exceed the stress intensity threshold over which fatigue crack propagation occurs. However, as the wall thickness is reduced, the spun cast iron pipes become more susceptible to fatigue failures than pit cast iron pipes. A key observation from both plots in Fig. 16 is that for pipes not affected by a reduction in wall thickness, commonly observed pressure cycles in water distribution pipes (~10–30 mH_2O pressure head) are unlikely to cause fatigue failures even for scenarios when a long crack had been generated by an external factor. Only pipes with long cracks and under large pressure fluctuations could be affected by pressure-induced fatigue if there is no reduction in pipe wall thickness. However, most pipes at the onset of and during their wear-out phase are commonly affected from a high level of deterioration, which significantly reduces the minimum water pressure for pressure-induced fatigue.

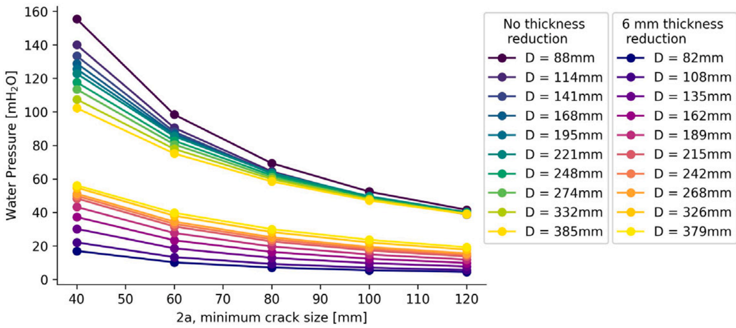
4.4. Fatigue crack propagation

This section presents the results from fatigue crack propagation analyses on a representative ~150 mm pit cast iron pipe. The main goal is to assess conditions under which pressure-induced fatigue can cause failures in deteriorated cast iron pipes, and how to reduce their rate of fatigue deterioration.

Fig. 17 shows the effect of pipe wall thickness on the number of cycles to failure for different initial crack lengths and pressure fluctuations at a constant loading ratio R of 0.5. Two cases illustrated by the areas in colour were defined. The upper scenario considers pipes with no reduction in wall thickness. The scenario at the bottom of the plot considers a reduction in pipe wall



(a)



(b)

Fig. 16. Minimum water pressure to reach stress intensity threshold for cast iron pipes. The effect of reduction of thickness is estimated. (a) Pit cast iron pipe. (b) Spun cast iron pipe.

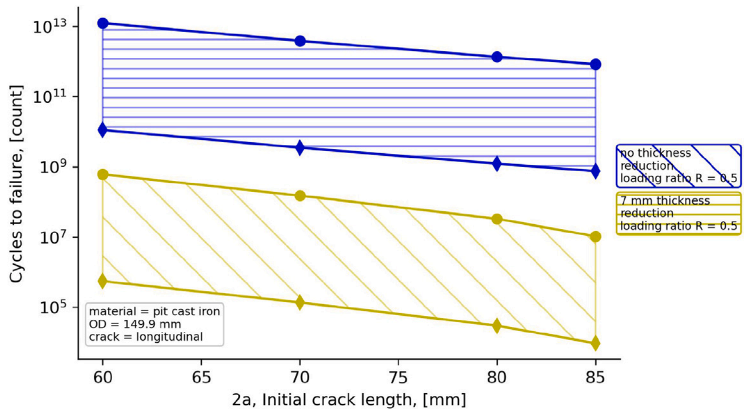


Fig. 17. Effect of pipe wall thickness on the number of cycles to failure for different initial crack lengths and water pressure fluctuations.

thickness of 7 mm caused by a corrosion patch. The x-axis indicates an increasing crack length, and the y-axis represents the number of cycles of water pressure at constant magnitude to reach the maximum crack length before a break in a pipe. For every coloured area, the lower bound represents a constant cyclic pressure of 50 mH_2O and the upper bound represents a constant cyclic pressure of 20 mH_2O. The minimum water pressure cycle to cause fatigue was not included in this analysis for cases when the pressure is below a fatigue threshold. This omission was performed for clarity.

From the two presented scenarios, it can be observed that only the scenario that considers a reduction in pipe wall thickness is of relevance for this investigation. Pipes that are unaffected by a reduction in wall thickness are unlikely to be damaged by fatigue as the required number of cycles largely exceeds observed pressure cycles in WSNs. For example, cyclic pressure loadings in the range of 20 mH_2O to 50 mH_2O are observed to normally vary between 2000 to 8000 cycles per year approximately [54]. Given

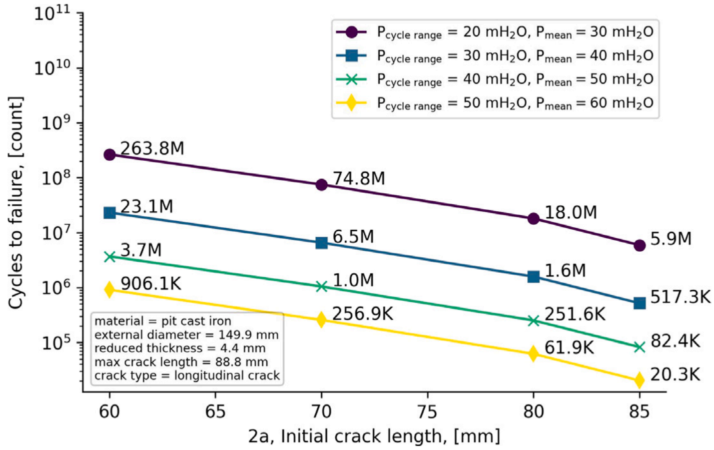


Fig. 18. Fatigue life estimation with a reduction in pipe wall thickness at varied cyclic pressure loadings and mean pressure.

this number of observed pressure cycles and magnitudes, we conclude that only the scenario, which considers a reduction in pipe wall thickness can lead to pressure-induced fatigue.

Fig. 18 illustrates the scenario with a reduction in pipe wall thickness, and how changes in pressure cycle range and mean pressure affect the number of cycles to break a cast iron pipe. The lower curve shows the number of cycles needed to break a pipe under constant cycle ranges of 50 mH_2O and a mean pressure of 60 mH_2O. The successive upper lines show how a combined reduction of both pressure cycle range and mean pressure affects the number of cycles to break a pipe. It can be observed that the initial crack length plays a critical role in the number of cycles to failure, and pressure-induced fatigue is relevant for pipes that are about to break from a few 9 mm to 4 mm of crack increase. Fig. 18 also show that the reduction of both pressure cycle range and mean pressure can significantly increase the number of cycles to break a pipe.

Figs. 19 and 20 show the individual contributions of reducing the magnitude of pressure fluctuations and mean pressure on the fatigue life of a pipe. Fig. 19 shows various scenarios for the number of cycles needed to break a pipe by varying the magnitude of water pressure fluctuations under a constant magnitude of the mean pressure. Fig. 20 compares the individual contribution of only reducing pressure fluctuations versus only reducing mean pressure from a starting case of 50 mH_2O of pressure cycle range and 60 mH_2O of mean pressure. From this figure, it can be observed that reduction of the magnitude of pressure fluctuations is more impactful than reduction of mean pressure to increase the life of deteriorated pipes. For the proposed case, a reduction of mean pressure from 60 mH_2O to 30 mH_2O under a constant pressure cycle magnitude increases in excess of 4 times (4.37) the number of cycles required to break a pipe. In contrast a reduction of the magnitude of cycles from 60 mH_2O to 30 mH_2O increases the number of cycles to failure in almost 9 times (8.62).

Nevertheless, when the individual effects of reducing both the magnitude of pressure fluctuations and mean pressure are compared to the effect of reducing both pressure metrics at the same time, the difference is considerable. From Fig. 18, it is observed that a combined reduction in the magnitude of pressure cycles from 50 mH_2O to 30 mH_2O, and mean pressure from 60 mH_2O to 40 mH_2O can increase the fatigue life 25.5 times with respect of the original scenario of 50 mH_2O of pressure cycle range and 60 mH_2O of mean pressure. It is also noticeable, that even a small combined reduction of 10 mH_2O of mean pressure and 10 mH_2O of pressure fluctuations has the theoretical potential to quadruple the required number of cycles to failure of the pipe. These examples show that the combination of reducing the magnitude of pressure cycles and mean pressure have a synergistic effect.

Finally, we present in Fig. 21 the what if case of reducing mean pressure but slightly increasing pressure fluctuations. The plot shows that the benefit of mean pressure reduction is outweighed by the negative effect of increasing the magnitude of pressure cycles, leading to less cycles to break a pipe. This finding is important as various schemes for reduction of average zone pressure rely on the use of pressure control devices, such as valves, which, if improperly manipulated, can increase the magnitude and frequency of pressure fluctuations, which could lead to a decreased fatigue life in pipes, and consequently more pipe breaks.

5. Discussion

This research investigated the potential impact of pressure-induced fatigue on breaks of ageing cast iron pipes, which are at the onset of and within their wear-out phase. The research has focused on: (1) examine typical deterioration conditions in cast iron pipes; (2) evaluate the magnitude and frequency of pressure fluctuations that may lead to pressure-induced fatigue failure; (3) quantitatively estimate of the influence of mean pressure on pressure-induced fatigue; and (4) assess the application of advanced pressure control for reducing deterioration in cast iron pipes. These research questions were addressed through a comprehensive review of published literature, the analysis of an extensive and unique collection of pipe break sample reports from a UK water utility, and mechanical analyses using fracture mechanics fatigue crack propagation.

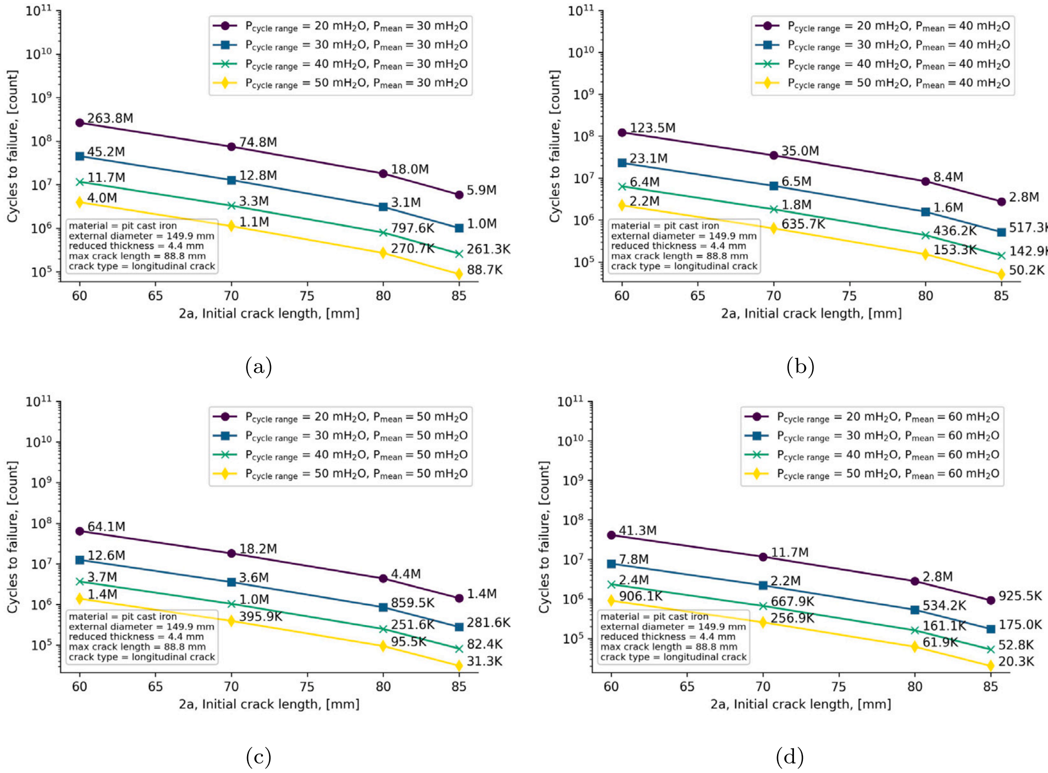


Fig. 19. Fatigue life estimations for varying magnitudes of pressure fluctuations at constant magnitudes of mean pressure. (a) Mean pressure at 30 m. (b) Mean pressure at 40 m. (c) Mean pressure at 50 m. (d) Mean pressure at 60 m.

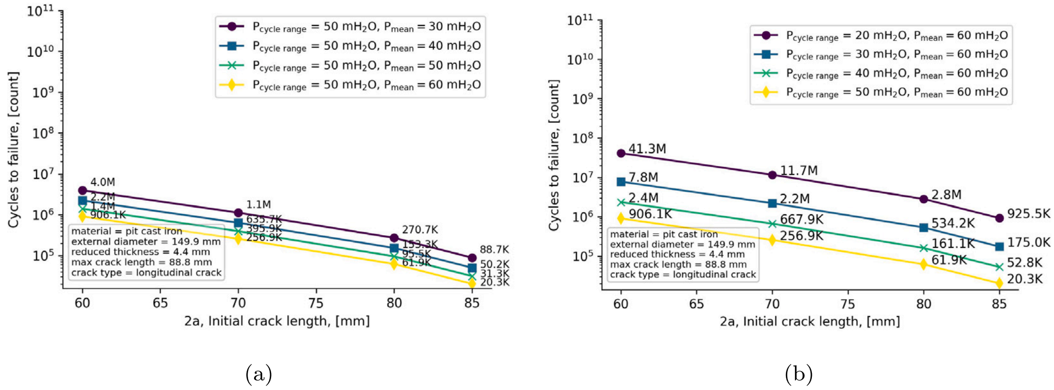


Fig. 20. Comparison cycle range reduction versus mean pressure reduction. (a) Varied mean pressure and constant magnitude of cycle range. (b) Varied magnitudes of cycle range and constant mean pressure.

The review for cast iron pipes in WSN together with the observations from pipe failure reports showed that pitting corrosion is the most recurrent type of deterioration in cast iron pipes. Corrosion pits also usually amalgamate creating large corrosion patches (Fig. 7). Published research have reported observed depths of pitting corrosion and corrosion patches to be approximately 6 mm to 7 mm in old pipes irrespective of their age. The presence of corrosion patches in deteriorated cast iron pipes was found to be relevant for the occurrence of pressure-induced fatigue. Our analysis (Fig. 17) suggest that pipes must have a reduced pipe wall thickness in order for pressure-induced fatigue to significantly contribute to pipe failures. This conclusion complements previous studies, which only considered "new" pipes with intact pipe wall thickness for fatigue calculations in cast iron pipes.

For ageing cast iron pipes with reduced pipe wall thickness, the presented analysis indicates that commonly occurring operating pressure fluctuations can extend existent cracks to a critical length. A key observation from the results presented in Fig. 18 is that the number of pressure fluctuations required to break a pipe are highly dependent on the initial crack length. Moreover, when a

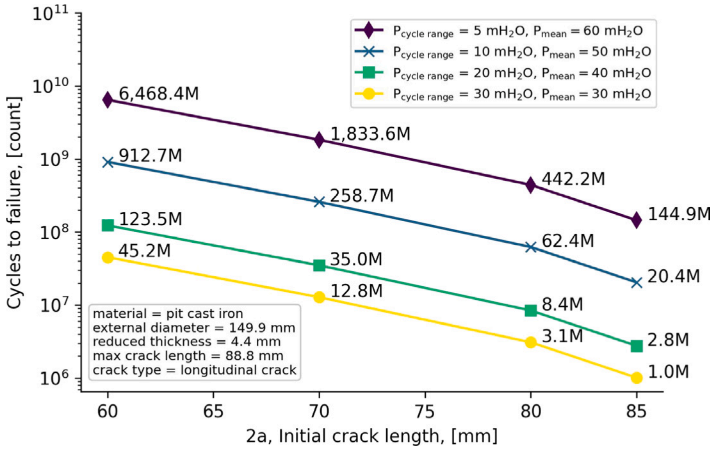


Fig. 21. Effect of mean pressure reduction and increase of pressure cycles.

pipe has developed a crack near the critical length from external factors such as corrosion, few millimetres of crack extension could significantly reduce the structural resistance of a pipe. Therefore, operational interventions that reduce the crack growth mechanisms could be highly beneficial to minimise the occurrence of imminent breaks in cast iron pipes.

The influence of the magnitude and frequency of pressure fluctuations, and mean pressure on fatigue induced pipe failures was evaluated and presented in Figs. 18 to 21. These figures provide quantitative insights of the potential changes in fatigue life in a pipe due to variations in the magnitude of pressure fluctuations and mean pressure. The presented estimates were not intended to be precise but to define the trends of the variations in pressure-induced fatigue due to changes in water pressure.

The results suggest that an effective method to reduce pressure-induced fatigue in cast iron pipes is to reduce mean pressure. It was calculated that a reduction in mean pressure of approximately 20 mH$_2$O (while maintaining constant the magnitude of cycles) can more than double the fatigue life of ageing cast iron pipes. Technologies and optimisation methods for implementing advanced pressure reduction have been discussed and implemented in [63–65]. An important consideration, however, is that the reduction of mean pressure must not increase pressure fluctuations. The magnitude of pressure fluctuations is more impactful than mean pressure on pressure-induced fatigue, and a decrease in mean pressure with an increase in pressure fluctuations can lead to reduced fatigue life (Fig. 21).

As mentioned, the magnitude of pressure fluctuations has a larger impact than mean pressure on pressure-induced fatigue in ageing cast iron pipes. This is an obvious conclusion since there must exist cyclic loadings due to pressure fluctuations for fatigue to occur. Nonetheless, as shown in Fig. 20, small reductions in the magnitude of pressure cycles (without reducing the number of cycles) can provide significant reductions on the rate of propagation of cracks in cast iron pipes. The benefits from relatively small reductions in the magnitude of pressure fluctuations show to be more than double of the benefits in reduction of mean pressure for a similar pressure reduction range. However, the control of water pressure fluctuations is a more challenging task. In order to consider a cost-effective solution to reduce such pressure component, it is of critical importance to continuously assess the causes for pressure fluctuations (including pressure transients), and how they propagate and dissipate in WSN. The continuous monitoring of the hydraulic dynamics in WSN is therefore critical to have these operational insights.

In the case that it is possible to control water pressure fluctuations, this investigation indicates that a significant benefit can be obtained if both mean pressure and pressure fluctuations are reduced at the same time (Fig. 18). This means that it is possible to balance the reduction of both pressure components according to operational needs and capabilities of pressure control. The results presented in Section 4.4 were performed for a representative 150 mm pipe with a 7 mm depth corrosion patch. Practitioners can use the provided methodology in Section 3 to perform fracture mechanics evaluations for other pipe diameters of interest, and perform similar plots to Figs. 18 and 20 to assess and balance the benefits of pressure control for particular needs and systems.

As indicated, the number of cycles to failure greatly depend on the initial crack length. As a crack increases, the damage caused by a same magnitude of cycle range also increases. If we consider an initial crack length just about a millimetre before reaching the critical crack length, it is possible to suggest that cycles of maximum magnitude of 20 mH$_2$O at a mean pressure of 30 mH$_2$O could be tolerated without expecting pressure-induced fatigue failure in the long term. This is valuable information to assess and balance pressure management schemes. However, it is important to consider the limitations of the presented study; pressure fluctuations in WSN are generally not constant, very large cycles can occur in between smaller cycles which can alter the rate of crack propagation; the effect of corrosion fatigue was also not considered. Corrosion fatigue could significantly decrease the fatigue life of a pipe; Besides, the fatigue analysis was performed for one pipe diameter with conservative assumptions. Therefore, we emphasise that the main contribution of the presented calculations are the trends in the changes in fatigue life due to variations in the pressure fluctuations and mean pressure, instead of the presented absolute values. Current work builds upon the findings of this study to provide more quantitative insight and validation of the specific contributions of pressure management on pipe breaks through the design of a controlled experimental programme.

As a separate consideration, the review and analysis of the mechanical differences between pit and spun cast iron have also suggested that spun cast iron pipes are at most risk of failure than older pit cast iron pipes. Although spun cast iron pipes are stronger than pit cast iron pipes, the thinner pipe walls of spun cast iron pipes make these pipes more vulnerable to corrosion patches (Fig. 7). Such information can serve water utilities to better fine tune selection criteria for pipe replacement and rehabilitation. In addition, count of water pressure fluctuations with their range within a time period, and the associated mean pressure would also greatly benefit pipe break prediction models. Pressure fluctuations can be obtained by the use of high frequency pressure monitoring, and edge data processing on a pressure monitoring device using cycle counting algorithms, such as the rainflow cycle counting [54].

In summary, this research has demonstrated that pressure-induced fatigue can play a critical role in defining the remaining life of ageing cast iron pipes, which are at the onset of and within their wear-out phase. As presented, minimal changes in the length of cracks due to fatigue crack propagation can result in the break of pipes. Due to the large stock of deteriorated cast iron pipes in water supply networks and current rates of replacement, water utilities should proactively consider and implement cost-effective strategies to reduce pipe breaks. This research shows that an appropriate reduction of both mean pressure and water pressure fluctuations could be extremely beneficial to reduce pipe breaks in deteriorating cast iron pipes and allow a phased cost-efficient pipe replacement.

6. Conclusion

This paper has investigated the impact of water pressure fluctuations on pressure-induced fatigue failures in cast iron pipes, which are at the onset and/or within their wear-out phase. An extensive review of the material properties and differences for both pit cast iron pipes and spun cast iron pipes was carried out. Based on the this review, and an analysis of reports for failed exhumed cast iron pipes in a water distribution network, various mechanical analyses were performed utilising fracture mechanics. The key conclusions and contributions from this work are as follows:

(1) Pressure-induced fatigue failures may impact pipes with reduced wall thickness. In particular pipes observing corrosion patches of depths greater than 7 mm are at most danger of failure due to pressure fluctuations.
(2) Spun cast iron pipes are more vulnerable than pit cast iron pipes. Although spun cast iron pipes are stronger, their thinner pipe walls makes them more susceptible to corrosion and fatigue loading than pit cast iron pipes.
(3) Ageing cast iron pipes with reduced wall thickness and cracks near the critical length could extend their operational life if pressure fluctuations are reduced. Otherwise, a few ten of thousand a cycles can imminently break a deteriorated pipe. This statement, however, does not consider corrosion fatigue or hydrogen embrittlement which could further reduce the number of required cycles to failure.
(4) Reducing the magnitude of pressure fluctuations is more impactful than reducing mean pressure to decrease the impact of pressure-induced fatigue. A simultaneous reduction of both pressure components should be preferred, as such combined reduction provide a larger synergistic impact. A water network should aim at not exceeding a maximum magnitude of cyclic loadings of 20 mH_2O at a mean pressure of 30 mH_2O.
(5) Our analysis motivates that the implementation of pressure reduction schemes, which could reduce both pressure fluctuations and mean pressure, could decrease the occurrence of pipe breaks and extend the life expectancy of ageing cast iron pipes, which can have a major impact on investment decisions.

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.

Acknowledgements

This work was funded by the National Agency for Research and Development (ANID), CL/ Scholarship Program/DOCTORADO BECAS CHILE/2020–72210314; and EPSRC, UK EP/P004229/1 (Dynamically Adaptive and Resilient Water Supply Networks for a Sustainable Future).

References

[1] D. Marlow, S. Gould, B. Lane, An expert system for assessing the technical and economic risk of pipe rehabilitation options, Expert Syst. Appl. 42 (22) (2015) 8658–8668, http://dx.doi.org/10.1016/j.eswa.2015.07.020.

[2] S. Folkman, Water Main Break Rates In the USA and Canada: A Comprehensive Study, Vol. Paper 174, 2018, URL https://digitalcommons.usu.edu/mae_facpub/174.

[3] C. Jara-Arriagada, I. Stoianov, Pipe breaks and estimating the impact of pressure control in water supply networks, Reliab. Eng. Syst. Saf. 210 (2021) http://dx.doi.org/10.1016/j.ress.2021.107525.

[4] A.M. Bubtiena, A.H. El Shafei, O. Jafaar, Review of rehabilitation strategies for water distribution pipes, J. Water Supply: Res. Technol. - AQUA 61 (1) (2012) 23–31, http://dx.doi.org/10.2166/aqua.2012.002.
[5] Economic Insight, Options for a Sustainable Approach to Asset Maintenance and Replacement. A Report for Water UK, Tech. Rep., 2022.
[6] A. Robles-Velasco, P. Cortés, J. Muñuzuri, L. Onieva, Prediction of pipe failures in water supply networks using logistic regression and support vector classification, Reliab. Eng. Syst. Saf. 196 (2020) http://dx.doi.org/10.1016/j.ress.2019.106754.
[7] T.M. Rifaai, A.A. Abokifa, L. Sela, Integrated approach for pipe failure prediction and condition scoring in water infrastructure systems, Reliab. Eng. Syst. Saf. 220 (2022) http://dx.doi.org/10.1016/j.ress.2021.108271.
[8] X. Fan, X. Wang, X. Zhang, P.E. ASCE Xiong (Bill) Yu, Machine learning based water pipe failure prediction: The effects of engineering, geology, climate and socio-economic factors, Reliab. Eng. Syst. Saf. 219 (2022) http://dx.doi.org/10.1016/j.ress.2021.108185.
[9] R.B. Petersen, R.E. Melchers, Long-term corrosion of cast iron cement lined pipes, in: Corrosion & Prevention 2012, Melbourne, Australia, 2012.
[10] J.M. Makar, B. Rajani, Gray cast-iron water pipe metallurgy, J. Mater. Civ. Eng. 12 (3) (2000) 245–253, http://dx.doi.org/10.1061/(ASCE)0899-1561(2000)12:3(245).
[11] R. Jiang, B. Shannon, R.N. Deo, S. Rathnayaka, C.R. Hutchinson, X.L. Zhao, J. Kodikara, Classification of major cohorts of Australian pressurised cast iron water mains for pipe renewal, Aust. J. Water Resour. 21 (2) (2017) 77–88, http://dx.doi.org/10.1080/13241583.2017.1402979.
[12] D. Valis, K. Hasilová, M. Forbelská, K. Pietrucha-Urbanik, Modelling water distribution network failures and deterioration, in: 2017 IEEE International Conference on Industrial Engineering and Engineering Management, IEEM, Singapore, 2017, pp. 924–928, http://dx.doi.org/10.1109/IEEM.2017.8290027.
[13] C. Konstantinou, I. Stoianov, A comparative study of statistical and machine learning methods to infer causes of pipe breaks in water supply networks, Urban Water J. 17 (6) (2020) 534–548, http://dx.doi.org/10.1080/1573062X.2020.1800758.
[14] D.J. Robert, D. Chan, P. Rajeev, J. Kodikara, Effects of operational loads on buried water pipes using field tests, Tunn. Undergr. Space Technol. 124 (2022) http://dx.doi.org/10.1016/j.tust.2022.104463.
[15] H. Rezaei, Impact of Pressure Fluctuations on Pipe Failures in Water Distribution Networks (Ph.D. thesis), Imperial College London, 2017.
[16] R.A. Leishear, R.A. Leishear, Water hammer causes water main breaks, J. Pressure Vessel Technol. Trans. ASME 142 (2) (2020) http://dx.doi.org/10.1115/1.4044423.
[17] H. Rezaei, B. Ryan, I. Stoianov, Pipe failure analysis and impact of dynamic hydraulic conditions in water supply networks, Procedia Eng. 119 (1) (2015) 253–262, http://dx.doi.org/10.1016/j.proeng.2015.08.883.
[18] Martínez-Codina, M. Castillo, D. González-Zeas, L. Garrote, Pressure as a predictor of occurrence of pipe breaks in water distribution networks, Urban Water J. 13 (7) (2016) 676–686, http://dx.doi.org/10.1080/1573062X.2015.1024687.
[19] H.M. Belmonte, M.J. Mulheron, P.A. Smith, Some observations on the strength and fatigue properties of samples extracted from cast iron water mains, Fatigue Fract. Eng. Mater. Struct. 32 (11) (2009) 916–925, http://dx.doi.org/10.1111/j.1460-2695.2009.01395.x.
[20] H. Mohebbi, D.A. Jesson, M.J. Mulheron, P.A. Smith, The fracture and fatigue properties of cast irons used for trunk mains in the water industry, Mater. Sci. Eng. A 527 (21–22) (2010) 5915–5923, http://dx.doi.org/10.1016/j.msea.2010.05.071.
[21] B. Rajani, Y. Kleiner, Fatigue failure of large-diameter cast iron mains, in: Water Distribution Systems Analysis 2010, 2010, pp. 1146–1159.
[22] M.J. Cullin, T.H. Petersen, A. Paris, Corrosion fatigue failure of a gray cast iron water main, J. Pipeline Syst. Eng. Pract. 6 (2) (2015) 05014003, http://dx.doi.org/10.1061/(asce)ps.1949-1204.0000188.
[23] R. Jiang, S. Rathnayaka, B. Shannon, X.L. Zhao, J. Ji, J. Kodikara, Analysis of failure initiation in corroded cast iron pipes under cyclic loading due to formation of through-wall cracks, Eng. Fail. Anal. 103 (2019) 238–248, http://dx.doi.org/10.1016/j.engfailanal.2019.04.031.
[24] J.H. Bulloch, Near threshold fatigue behaviour of flake graphite cast irons microstructures, Theor. Appl. Fract. Mech. 24 (1) (1995) 65–78, http://dx.doi.org/10.1016/0167-8442(95)00032-A.
[25] Cast Iron Pipe Research Association, Handbook of Cast Iron Pipe Water, Gas, Sewerage and Industrial Service, second ed., Cast Iron Pipe Research Association, 1952.
[26] T.J. Baker, The fracture resistance of flake graphite cast iron, Int. J. Mater. Eng. Appl. 1 (1) (1978) 13–18, http://dx.doi.org/10.1016/0141-5530(78)90003-1.
[27] M.O. Speidel, Bruchzähigkeit und Ermüdungs-Rißwachstum von Gußeisen, Mater.wiss. Werkst.tech. 12 (11) (1981) 387–402, http://dx.doi.org/10.1002/mawe.19810121106.
[28] O.N. Romaniv, A.N. Tkach, T.Y. Yus'kiv, V.I. Ovchinnikov, V.A. Sharkov, Growth of a fatigue crack in cast irons. II. Gray and malleable cast irons, Soviet Mater. Sci. : Transl. of Fiziko-Khimicheskaya Mekhanika Materialov / Academy of Sciences of the Ukrainian SSR 26 (3) (1990) 274–281, http://dx.doi.org/10.1007/BF00727357.
[29] E. Hornbogen, Fracture toughness and fatigue crack growth of grey cast irons, J. Mater. Sci. 20 (1985) 3897–3905.
[30] R.M. Conlin, The Application of Fracture Mechanics to Grey Cast Iron Pipework (Ph.D. thesis), Imperial College London (University of London), 1991.
[31] J.M. Makar, S.E. Mcdonald, Mechanical behavior of spun-cast gray iron pipe, J. Mater. Civ. Eng. 19 (10) (2007) 826–833, http://dx.doi.org/10.1061/(ASCE)0899-1561(2007)19:10(826).
[32] British Standards Institute, BS 78-1917 Cast Iron Pipes, 1917, British Standards Institute.
[33] British Standards Institute, BS 1211–1958–[2022-06-06–01-42-01 PM], 1958, British Standards Institute.
[34] ASTM, ASTM 247-19 Standard Test Method for Evaluating the Microstructure of Graphite in Iron Castings 1, American Society for Testing and Materials, 2019, http://dx.doi.org/10.1520/A0247-19, URL https://www.astm.org.
[35] S. Debnath, I.M. Ali, A.S. Dhar, P. Thodi, Material properties for fracture mechanics based strength assessment of cast iron water mains, Can. J. Civil Eng. 48 (1) (2021) 62–74, http://dx.doi.org/10.1139/cjce-2019-0229.
[36] T.L. Anderson, Fracture Mechanics: Fundamentals and Applications, fourth ed., CRC Press, Taylor & Francis Group, Boca Raton, 2017.
[37] R. Melvin, Underground Corrosion, National Bureau of Standards Circular 579, 1957.
[38] C.Q. Li, M. Mahmoodian, Risk based service life prediction of underground cast iron pipes subjected to corrosion, Reliab. Eng. Syst. Saf. 119 (2013) 102–108, http://dx.doi.org/10.1016/j.ress.2013.05.013.
[39] Z. Soltani Asadi, R.E. Melchers, Extreme value statistics for pitting corrosion of old underground cast iron pipes, Reliab. Eng. Syst. Saf. 162 (2017) 64–71, http://dx.doi.org/10.1016/j.ress.2017.01.019.
[40] Z. Soltani Asadi, R.E. Melchers, Pitting corrosion of older underground cast iron pipes, Corros. Eng. Sci. Technol. 52 (6) (2017) 459–469, http://dx.doi.org/10.1080/1478422X.2017.1330025.
[41] Z. Soltani Asadi, R.E. Melchers, Clustering of corrosion pit depths for buried cast iron pipes, Corros. Sci. 140 (2018) 92–98, http://dx.doi.org/10.1016/j.corsci.2018.06.015.
[42] J. Kim, C. Bae, H. Woo, J. Kim, S. Hong, Assessment of residual tensile strength on cast iron pipes, in: International Conference on Pipeline Engineering and Construction, 2007.
[43] M. Wasim, D. Robert, C.Q. Li, Corrosion effects on the granular nano mechanical properties of buried cast iron, Eng. Fail. Anal. 119 (2021) http://dx.doi.org/10.1016/j.engfailanal.2020.104970.
[44] P. Baicchi, L. Collini, E. Riva, A methodology for the fatigue design of notched castings in gray cast iron, Eng. Fract. Mech. 74 (4) (2007) 539–548, http://dx.doi.org/10.1016/j.engfracmech.2006.04.018.
[45] M.N. James, L. Wenfong, Fatigue crack growth in austempered ductile and grey cast irons-stress ratio effects in air and mine water, Mater. Sci. Eng. 265 (1999) 129–139, http://dx.doi.org/10.1016/S0921-5093(98)01140-X.

[46] W. Elber, Fatigue crack closure under cyclic tension, Eng. Fract. Mech. 2 (1) (1970) 37–44, http://dx.doi.org/10.1016/0013-7944(70)90028-7.

[47] N.O. Larrosa, R. Akid, R.A. Ainsworth, Corrosion-fatigue: A review of damage tolerance models, Int. Mater. Rev. 63 (5) (2018) 283–308, http://dx.doi.org/10.1080/09506608.2017.1375644.

[48] J.M. Makar, A preliminary analysis of failures in grey cast iron water pipes, Eng. Fail. Anal. 7 (1) (2000) 43–53, http://dx.doi.org/10.1016/S1350-6307(99)00005-9.

[49] B. Rajani, Y. Kleiner, Comprehensive review of structural deterioration of water mains: Physically based models, Urban Water 3 (2001) 151–164, http://dx.doi.org/10.1016/S1462-0758(01)00032-2, URL www.elsevier.com/locate/urbwat.

[50] B. Rajani, J. Lewandowski, A. Margevicius, Failure analysis of cast iron trunk main in Cleveland, Ohio, J. Failure Anal. Prevent. 12 (3) (2012) 217–236, http://dx.doi.org/10.1007/s11668-012-9567-z.

[51] J. Makar, Failure analysis for grey cast iron water pipes, in: AWWA Distribution System Symposium, 1999.

[52] J. Makar, R.. Desnoyers, S.. Mcdonald, Failure modes and mechanisms in gray cast iron pipe NRCC-44218, in: Underground Infrastructure Research: Municipal, Industrial and Environmental Applications, Kitchener, Ontario, 2001, pp. 1–10, URL https://www.nrc.ca/irc/ircpubs.

[53] A.J. Hoskins, Monitoring the Hydraulic Dynamics in Water Distribution Systems (Ph.D. thesis), Imperial College London, 2015.

[54] C. Jara-Arriagada, I. Stoianov, High resolution water pressure monitoring for the assessment of fatigue damage in water distribution pipes, in: 2nd International Joint Conference on Water Distribution System Analysis & Computing and Control in the Water Industry, 2022.

[55] UKWIR, 22/WM/04/14 - The Occurrence and Causes of Pressure Transients in Distribution Networks, Tech. Rep., 2022.

[56] S. Rathnayaka, B. Shannon, C. Zhang, J. Kodikara, Introduction of the leak-before-break (LBB) concept for cast iron water pipes on the basis of laboratory experiments, Urban Water Journal 14 (8) (2017) 820–828, http://dx.doi.org/10.1080/1573062X.2016.1274768.

[57] G. Fu, C. Zhang, R. Deo, S. Rathnayaka, B. Shannon, J. Kodikara, A model of stress concentration factors for external corrosion patches on large-diameter underground cast iron pipes, Sustainable and Resilient Infrastructure (2020) http://dx.doi.org/10.1080/23789689.2020.1828022.

[58] G.R. Irwin, Onset of fast crack propagation in high strength steel and aluminum alloys, Naval Research Laboratoy, Washington D.C., 1956.

[59] W. Wang, A. Zhou, G. Fu, C.Q. Li, D. Robert, M. Mahmoodian, Evaluation of stress intensity factor for cast iron pipes with sharp corrosion pits, Eng. Fail. Anal. 81 (2017) 254–269, http://dx.doi.org/10.1016/j.engfailanal.2017.06.026.

[60] J.C. Newman, Fracture Analysis of Surface and Through Cracks in Cylindrical Pressure Vessels, Tech. Rep., NASA Technical Note, 1976.

[61] K. Walker, The effect of stress ratio during crack propagation and fatigue for 2024-T3 and 7075-T6 aluminum, in: Effects of Environment and Complex Load History on Fatigue Life, ASTM, 1968, pp. 1–14.

[62] L. Wong, S. Rathnayaka, W.K. Chiu, J. Kodikara, Fatigue damage monitoring of a cast iron pipeline using distributed optical fibre sensors, Procedia Eng. 188 (2017) 293–300, http://dx.doi.org/10.1016/j.proeng.2017.04.487.

[63] J. Changklom, I. Stoianov, Redundant flow estimation methods for robust hydraulic control in water supply networks, J. Hydroinform. 21 (4) (2019) 571–592, http://dx.doi.org/10.2166/hydro.2019.099.

[64] F. Pecci, E. Abraham, I. Stoianov, Model reduction and outer approximation for optimizing the placement of control valves in complex water networks, J. Water Resour. Plan. Manag. 145 (5) (2019) http://dx.doi.org/10.1061/(asce)wr.1943-5452.0001055.

[65] A.J. Ulusoy, F. Pecci, I. Stoianov, Bi-objective design-for-control of water distribution networks with global bounds, Opt. Eng. 23 (1) (2022) 527–577, http://dx.doi.org/10.1007/s11081-021-09598-z.