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FATIGUE FAILURE OF LARGE-DIAMETER CAST IRON MAINS

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Abstract

Water utility engineers have reported on large diameter water main failures that occurred suddenly without warning, no signs of prior leaks and no visual evidence of corrosion on the fracture surfaces. Often these failed mains had been operating without major problems for over 80 years. A possible explanation may be attributed to alternating or fluctuating stresses such as those caused by heavy traffic and cyclical operating water pressure with occasional occurrences of transients. These fluctuating stresses are accentuated if the pipe impinges on an object with sharp geometry and high stiffness like a rock or a stone.

Fatigue of cast iron has been extensively studied in the context of cast iron bridges, structural elements such as columns, engine blocks, etc, but not in the context of buried, grey cast iron water pipes. Fatigue analysis methods developed over the years involve a lot of empiricism and combine engineering principles with experimental observations. Consequently, it is fair to say that fatigue analysis results should be taken more as a guide than as precise or accurate answers.

A mechanistic approach to explain fatigue failures of buried cast iron pipes had not been previously explored. This paper explores the application of the fracture mechanics approach (LEFM) to explain some failures in cast iron pipes that occur through the fatigue mechanism. It endeavors to provide insight into the plausibility of fatigue failures in grey cast iron pipes when and if subjected to alternating (also often referred to as repeated or variable) stresses due to surface traffic loads, operating pressure variations and transient pressure occurrences. It is important to note that the proposed analysis refers to grey cast iron pipe type, with carbon in form of flake graphite, which is the predominant material of existing iron trunk mains in North America and Europe.

Keywords
Cast iron mains, large diameter, alternating stresses, fatigue failures.

1. BACKGROUND

Anecdotes told by engineers from water utilities on some cast iron main failures follow these lines: " We had a large diameter water main fail suddenly and visual examination of the fracture surfaces showed no signs of corrosion. There was no prior warning or a leak that surfaced to indicate that anything imminent was about to happen. This main has been operating without major problems for over 80 years. Why and how did this failure occur?" Typical examples of such failures in Cleveland, Ohio (1926) and in London, England (2004) are shown in Fig. 1.

Besides present day stories like the one cited above, anecdotal speculation(s) (CIPRA, 1927; Handover, 1930) suggest that some cast iron mains may have failed due to alternating or fluctuating stresses such as

(a) Cleveland, 1926 (b) London, 2004

Figure 1. Typical breaks in large diameter cast iron mains with no visual corrosion.

those due to surface traffic and unsteady operating water pressure with occasional occurrences of pressure transients. The fluctuating stresses are accentuated if the pipe happens to impinge on an object with sharp geometry and high stiffness like a rock or a stone.

No documented descriptions of fracture surfaces that could be attributed to fatigue in cast iron are found in the literature, except of mention in the report commission by Cleveland Water Department (2001) on trunk mains failures. This report includes a document prepared by Professional Service Industries (1994) on the metallurgical examination of failure in a 30 in cast iron main. The report states that fatigue failure surface exhibits a smooth, more uniform fracture surface perpendicular to the wall thickness and is accompanied by concentric clamshell like striations. These striations were not found in the specific pipe failure they examined. It therefore seems that this description was inferred from evidence found in ductile materials (Brooks and Choudhury, 1993) but has not been documented for brittle materials like cast iron.

Fatigue of cast iron has been extensively studied in the context of cast iron bridges, structural elements such as columns, engine blocks, etc, but not in the context of grey cast iron water pipes. The fatigue analysis methods developed over the years involve a lot of empiricism and combine engineering principles with experimental observations. Consequently, it is fair to say that fatigue analysis results should be taken more as a guide and not as being able to provide precise or accurate answers.

Fatigue failure occurs when a material is subjected to repeated or varying load(s), never reaching a high enough level to cause failure in a single realization. The fatigue process that typically takes place in metals can be divided into two phases or lives (Fig. 2), namely, the initiation phase and the propagation phase. A crack initiates and grows into a small crack in the initiation phase, while the small crack grows bigger and leads to failure in the propagation phase. The duration of these two phases is typically expressed in number of cycle reversals of stress or strain and is dependent on many variables such material type, geometry of component, etc.

A mechanistic approach to explain fatigue failures of cast iron pipes has not been explored previously except for a very preliminary and limited assessment by Bonacuse (2001). This paper explores the application of the fracture mechanics approach (LEFM) to explain some failures in cast iron pipes that occur through the fatigue mechanism. Further, it endeavors to provide insight into the plausibility of fatigue failures in grey cast iron pipes when and if subjected to alternating stresses due to surface traffic loads, operating pressure variations and transient pressure occurrences. It is important to note that the discussion in this paper refers to grey cast iron pipe type, with carbon in the form of flake graphite, which is the predominant material of existing iron trunk mains

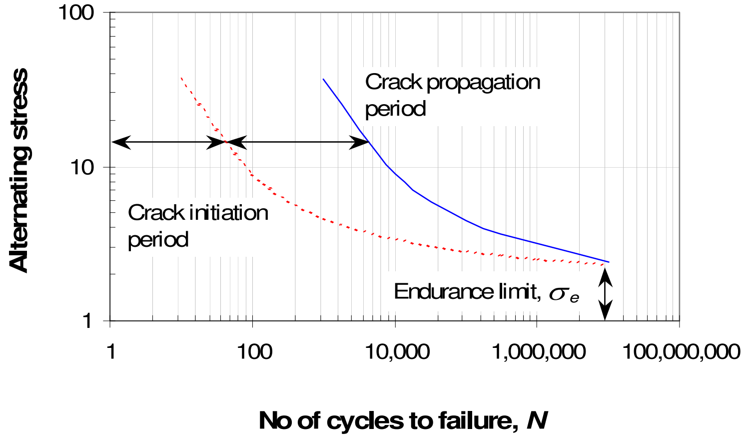

Figure 2. Initiation and propagation periods of fatigue crack growth.

2. BRIEF REVIEW OF FRACTURE MECHANICS METHOD FOR FATIGUE ANALYSIS

The approach based on fracture mechanics method is suitable to predict crack propagation, which means that initial crack size or defect size is known or can be reasonably assumed. As stated earlier, presence of graphite flakes in grey cast iron introduces a large population of internal flaws even before any loads (stresses) are applied. New cracks can develop or existing cracks can grow if a cast iron pipe is mishandled during delivery or during caulking of bell-spigot joints. Of course, the only means to ascertain the existence of crack(s) of significant size is to conduct inspection of the pipes to uncover if and where these cracks exist.

In addition to cracks initiating at delivery or caulking, it is well known that cast iron pipes that were manufacture by early (probably between 1850s and 1930s) techniques were fraught with voids and inclusions in the iron matrix. Some of these voids in small and large diameter cast iron mains could have a significant size in comparison to pipe wall thickness, as seen in Fig. 3. Again, it is difficult to know *a priori* where these voids are except through the use of an appropriate inspection technology, if available. It is therefore postulated that an assumption about the existence of cracks or voids in cast iron pipes is not far-fetched but realistic. In the following discussion, the term *crack* is used to mean a *fracture* or *casting void* or *defect* as the case may be.

Some important elements of the fracture mechanics approach are:

- Initial crack size is known or can be estimated.
- Plastic zone at the crack tip is assumed to be small compared to crack length and size of cracked component.
- Local stresses and strains are related to the remote or nominal stresses and strains by the stress intensity factor, K, which is defined in total or incremental form as,

[1] $$K = f(g)\sigma\sqrt{\pi a} \quad \text{or} \quad \Delta K = f(g)\Delta\sigma\sqrt{\pi a}$$

where σ is the remote or nominal stress, a is the crack length and $f(g)$ is the correction factor that depends on specimen and crack geometry. The stress intensity factor value that leads to the development of unstable fracture is known as the toughness factor, K_c. Fracture toughness is typically measured (ASTM E 399-90) in plane strain condition since this state offers the maximum constraint conditions. This fracture toughness is designated, K_{Ic}, since the test corresponds to opening or tensile mode, or *Mode I*, loading condition.

Figure 3. Typical casting voids and defects in small and large diameter grey cast iron pipes.

Fatigue analysis based on principles of linear elastic fracture mechanics (LEFM), essentially relates crack growth rate with stress intensity. This relationship is expressed in the form of power equations such as those proposed by Paris, Walker and Forman. The application of linear elastic fracture mechanics to conduct fatigue analyses are documented in several textbooks, most prominent of which are those by Broek (1988) and Ewalds and Wanhill (1984). Therefore, reference is made to the theory only when required in the context of fatigue failure of cast iron mains.

The essential steps in this method are: (1) conduct tests to obtain threshold and plane strain fracture toughness, (2) conduct tests at different stress intensities to obtain crack growth data (3) generate load spectrum based on realistic load occurrences for the pipe under consideration, (4) integrate the power equation to determine crack size as a function of number of stress cycles for a given initial crack size and data generated in steps 1, 2 and 3. The fatigue crack propagation analysis (step 4) in this study is conducted using a software application, AFGROW, developed at the US Air Force Wright Aeronautical Laboratories (Harter, 2008). All of the above steps are discussed in detail below, as appropriate.

2.1 Fracture toughness

Rajani *et al.* (2000) conducted fracture toughness measurements on pit and spun cast iron pipes of different vintages, manufactured in US and Canada. The specimens for these tests came from pipes installed between 1881 and 1969 in 16 different water utilities across the United States and Canada. The range of fracture toughness for these pit and spun cast iron pipes were 9.9 ± 2.3 and 13.3 ± 1.5 MPa√m, respectively. Fracture toughness of spun cast iron pipes is on average higher than of pit cast iron pipes. Also there is a general indication that facture toughness of pit cast iron improved as improvements were introduced in the manufacturing process to combat the brittleness of cast iron. Nonetheless, fracture toughness for both pit and spun cast iron varies widely.

Deb et al. (2002) also reported fracture toughness tests on spun cast iron pipes from US and Canada but only test results for pipes from Canada fall within acceptable range for cast iron. Reported results from US utilities were in the 17 to 100 MPa√m range which seems to be rather high compared with other measured values.

2.2 Fatigue growth parameters

In the linear elastic fracture mechanics approach to fatigue analysis, fatigue cracking is assumed to take place in three stages as shown in Fig. 4. In *stage I*, crystals slip and extend through contiguous grain boundaries, voids and surface imperfections and are not visible to the observer. In *stage II*, the crack grows monotonically and is observable on micrographs taken by means of electron microscope. In *stage III*, final fracture occurs in an uncontrolled or unstable crack growth. Only *stage II* crack growth is discussed in this paper.

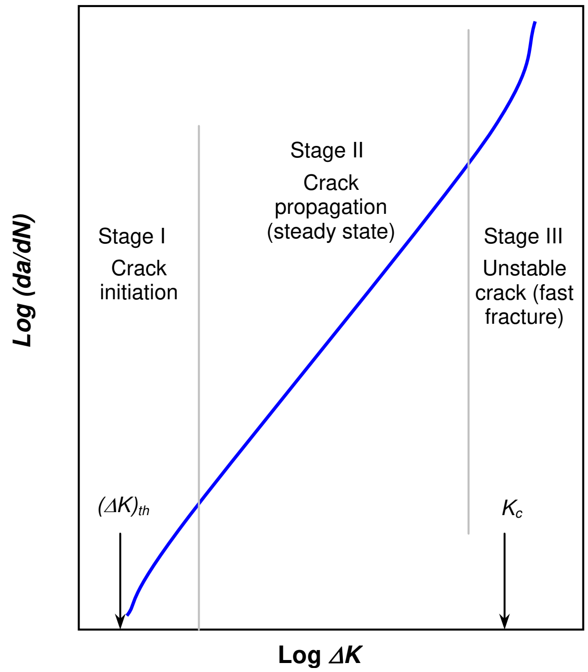

Figure 4. Crack growth development as a function of stress intensity factor.

Fatigue crack growth will not occur if the stress intensity factor in *stage I* is below a certain threshold value, ΔK_{th}. Crack growth (*da/dN* vs. ΔK) in *stage II* is represented by the Paris expression, as follows,

[2] $$\frac{da}{dN} = A(\Delta K)^m$$

where N is number of cycles, A and m are material constants and ΔK is the stress intensity range (= $K_{max} - K_{min}$). Constants A and m are obtained by fitting the above expression to experimental test results. It is important to note that units of constant A are specific to the exponent m, i.e., [Stress^{-m} Length$^{(1-m/2)}$]. Two important factors that affect the constants A and m to describe crack growth are stress ratio, R, and environmental effects. Appropriate test conditions have to be used so that constants A and m reflect the desired and expected environment.

The number of cycles to failure, N_f, may be calculate from [2] by integrating with respect to crack size,

[3] $$N_f = \int_{a_i}^{a_f} \frac{da}{A(\Delta K)^m}$$

The integration of the equation [3] is typically carried out numerically since ΔK is function of the crack length, a, and of the correction factor *f(g)* as shown in [1].

Higher A values in [3] will lead to shorter fatigue lives (in terms of cycles to failure). It is generally observed (Stephens *et al*., 2000) that fatigue life estimation is strongly dependent on the initial crack length, a_i, and not very sensitive to the final crack length, a_f,.

Over the past several years, values for constants A_p and m_p that correspond to the Paris crack growth expression have been published for different cast irons. These values for different stress ratios, *R*, are shown in Table 1. In general, caution should be exercised when comparing constants from different cast irons since they all have their own metallography, which can significantly influence fatigue properties.

Table 1. Fatigue constants for Paris fatigue expression.

Reference	Stress ratio, *R*	Paris† exponent, m_p	Paris† coefficient, A_p $MPa^{-m_p} m^{(1-m_p/2)}$
Baicchi *et al.* (2007)	0.1	6.95	5 x 10^{-15}
	0.5	7.53	1 x 10^{-14}
Bulloch (1995)	0.05	6.7	6.12 x 10^{-16}
	0.3	6.2	1.35 x 10^{-14}
	0.7	6.5	2.59 x 10^{-12}
James and Wenfong (1999)§	0.1	10.8	2.50 x 10^{-20}
	0.2	11.2	1.75 x 10^{-20}
	0.3	11.8	7.50 x 10^{-21}
	0.4	13	8.50 x 10^{-22}
	0.5	13.7	2.10 x 10^{-22}
This study			
Paris			
Lower bound		7.8	1.29 x 10^{-16}
Upper bound		9.2	5.60 x 10^{-16}

† Unit for stress intensity factor is MPa√m and for length dimension is m.
§ Constants estimated from graphical plots.

2.3 Load spectra and stress histories for cast iron mains

Implicit in the applications of equations [1] (in range form) and [3] that describe fatigue crack propagation, is the assumption that alternating stress has a constant amplitude. Cast iron water mains can experience stresses due to operational water pressure, earth loads (loads due to swelling soils and frost heave, if applicable), pipe self-weight, fluid content, traffic loads and transient (surge or water hammer) pressures. Earth loads, pipe self-weight and fluid content can be safely assumed to be static while all other types of loads are random events that occur at different frequencies. In addition, frost loads will be imposed during winter on pipes buried in soils susceptible to frost heave. Traffic loads and transient pressures are man-induced and depend largely on usage and operational practices, respectively.

As discussed above, load history and consequent stresses need to be determined to conduct a realistic fatigue crack propagation analysis. The load history of random events is usually generated from measured load spectra, i.e., measurement of the frequency with which each load is expected to occur. The load history of random events can be complex and needs to be reduced to a number of constant amplitude events, which involves a process called *cycle counting*. Many different *cycle counting* methods have been proposed and Bannantine *et al.* (1990) provide details on these methods. Broek (1988) commented that it was more important to get the maxima and minima right than the specific method to count cycles. ASTM E 1049-85

(2005) standard that describes the rainflow method for *cycle counting* was used here together with AFGROW.

Table 2 shows the six principal different loads or stresses that a buried pipe might experience, of which earth load, pipe self-weight and fluid content are static while the others have expected frequencies that vary from several events an hour to several events a month. A truck will have two or more axels and the loads imposed by each axel on the buried pipe will occur within seconds. For fatigue analysis, it is sufficient to consider the loads imposed by the two axels as one event since the change in stress in the pipe when the second axel passes is insignificant. The transient pressure wave event will typically reach peak pressure and attenuate over a few seconds. As for traffic loads, only the peak pressure is treated as an event. Frost and swelling loads will raise the mean stress during part of the year if the pipes are geographically located in areas affected by cold season/frost susceptible soils or rainy season/swelling clays conditions. Contrary to traffic and transient pressure, seasonal loads will develop over a number of weeks. For simplicity, the frost and swelling loads are assumed to begin and die out instantaneously, at the start and end of the respective seasons.

The different loads experienced by the pipe can be combined to simulate loading history. In lieu of measured load history, a partial list of a total of 24 possible load combinations is shown in Table 3. Additional load combinations that reflect water pressure fluctuations below and above the mean operating pressure are not shown here. Frost load, if any, is introduced in the load combination through a factor, f_{FL}, between 0 and 1 applied to the earth load. The fluctuations in the operating pressure (Δp_{mo}) are represented through a factor, f_{mo}, between 0 and 1, which is applied to the mean operating pressure (p_{mo}), i.e., $\Delta p_{mo} = p_{mo} (1 + f_{mo})$.

Figure 5 shows a typical stress history that a buried main would experience if earth, frost, traffic and transients loads are considered. The stresses are exaggerated so that stress variations are visually noticeable. It is important to note that mean stresses in the cold season are higher than in the warm season only if the ground freezes and their impact will depend on the properties of native and backfill soils, and on the period of sustained temperatures below freezing point.

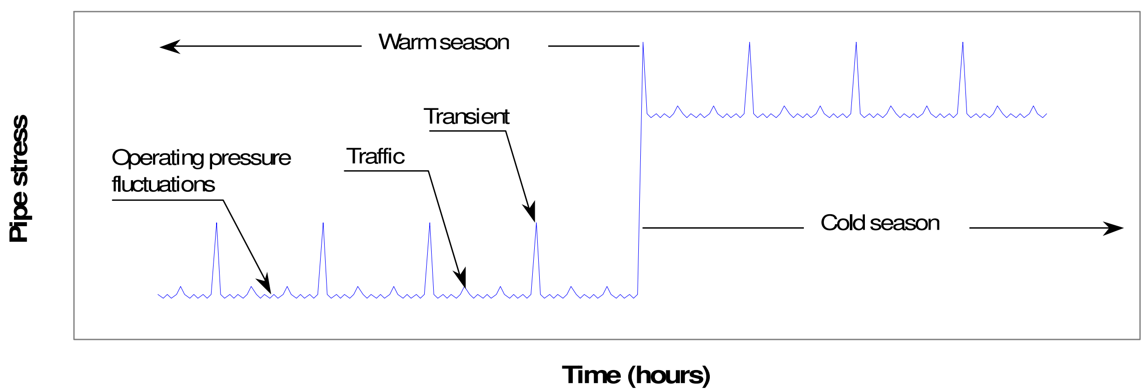

Figure 5. Variations (qualitative) of pipe stress as a function of operational and seasonal loads.

2.4 Crack growth prediction using AFGROW

The software application, AFGROW, developed at the US Air Force Wright Aeronautical Laboratories (Harter, 2008) is used in this study to conduct fatigue crack propagation analysis. AFGROW has many features to conduct a comprehensive fatigue analysis but only a few selected features judged to be applicable to the fatigue analyses of cast iron pipes are discussed here. These features are (i) specifications of crack size and its location, (ii) fatigue material properties discussed in sections 2.1 and 2.2, and (iii) load spectrum discussed in section 2.3.

Table 2 Combinations to generate load spectrum for fatigue analysis of a buried main.

Load or stress	Expected frequency of event(s)	Comment
Earth load, pipe self-weight, fluid content	Static	Defines mean stress in the pipe
Frost load	One event/year	Assumed to starts as soon as ground begins to freeze and peaks in mid-winter and reduces to zero soon after ground thaws. Frost load effectively raises the mean stress in the pipe during the cold season.
Swelling load	One events /year	Starts as soon as the moisture in the surrounding soil the pipe increases which is typically expected to happen during the rainy season. Swelling load effectively raises the mean stress in the pipe during the rainy season.
Traffic load	Several events/hour	Frequency will be high during peak traffic hours.
Operational pressure	Several events /day	Typically operational pressure will fluctuate several times an hour around the mean operational pressure.
Transient pressures	Several events/ month	Occurrence of transient pressure in trunk mains is largely dependent on hydraulic design and on the operational issues such as opening and closing of valves, power-out or failure of pumping station.

Table 3 Expected frequency of loading events for a buried main.

No	Load combination	Comment
1 & 2	Earth load, etc, ($W_e(1+f_{FL})$) + mean operational pressure (p_{mo})	Mean (normal) operating conditions.
3 & 6	Earth load ($W_e(1+f_{FL})$) + mean operational pressure (p_{mo}) ± fluctuations of operational pressure (Δp_{mo})	Operating conditions where water pressure fluctuates around the mean operating pressure.
7 & 8	Earth load, etc, ($W_e(1+f_{FL})$) + mean operational pressure (p_{mo}) + transient pressures (p_t)	Conditions when transient pressure occurs with the mains operating at normal conditions.
9 & 10	Earth load ($W_e(1+f_{FL})$) + mean operational pressure (p_{mo}) + traffic load (W_t)	Conditions when traffic passes overhead with the mains operating at normal conditions.

(i) Crack size and its location: AFGROW allows the consideration of many different options for the type of structure to analyse, i.e., plate, pipe, etc as well as the location of the crack (defect or flaw) and its size. However, it lacks the option for pipe sizes typically encountered in the water industry and moreover considers pipes as thin-wall cylinders. Glinka (2009), who developed the *f(g)* functions implemented in AFGROW, recommends that it is adequate to treat the pipe wall as a thin plate for practical purposes. Glinka's assertion was confirmed by conducting preliminary analyses using dimensions close enough to that of a thin pipe for AFGROW to consider it as a thick pipe.

(ii) Fatigue material properties: AFGROW allows the consideration of several crack growth models. Each of these models has its own constants and parameters. In this study, only Walker's crack growth model with λ=1 (Paris' model) was considered. Other material properties required to conducted crack growth analyses are plane strain fracture toughness, plane stress fracture toughness, threshold fracture toughness and tensile failure strength. The shift due to stress ratio, *R*, is considered approximately since sufficient test data were not available for rigorous consideration of its effects on cast iron.

(iii) Stress (load) spectrum: AFGROW allows the input of one or more sub-spectra to specify cycle-by-cycle load history. A normalized stress (load) spectrum is generated (as discussed in section 2.3) from the specified frequencies of changes in operational pressures, pressure transients and traffic loads. The facility provided by AFGROW to scale the normalized stress (load) spectrum through the stress multiplication factor (SMF) is used to conduct fatigue analysis.

3. ANALYSIS OF FATIGUE FAILURE IN CAST IRON MAINS

Tables 4 and 5 list all the input parameters used the analysis. These include pipe properties, operational, trench and traffic conditions, and mechanical properties (including constants for the different crack growth models). To reflect aleatory uncertainty, most input parameters are provided in the form of most likely value plus or minus expected variation. The steps followed to conduct the analysis were:

1. Specify pipe size, burial depth, etc.
2. Specify the appropriate Walker's (if λ = 1 then Walker's expression reverts to the Paris' expression) constants for cast iron. Alternatively, AFGROW allows for tabular input of *da/dN* vs. ΔK that would be typically obtained from test results.
3. Specify mean operating pressure and type of traffic loading. Also specify if ground is expected to freeze or swell, as appropriate.
4. Assume the expected frequency of events for operating pressure fluctuations, traffic loads, and pressure transients. If the event frequencies are available from field measurements, then these should be used.
5. Determine maximum stresses experienced by the pipe for load combinations indicated in Table 3.
6. Generate a stress history (referred to as spectrum in AFGROW) with the stresses determined in step 5 and expected frequencies specified in step 4. Typically, the stress history is normalized with respect to the maximum stress.
7. Execute AFGROW with the above data to obtained crack growth development as a function of number of cycles.

For practical purposes and to reduce computational effort, fatigue crack growth analysis in cast iron pipes was terminated if the fatigue life (or equivalent number of cycles) exceeds 300 years, as a pipe with a fatigue life that long would not be of immediate concern.

Table 4 Pipe properties, operational, trench and traffic conditions.

Parameters	Most likely value (*MLV*)		Expected variation (*EV*)
48" cast iron pipe	Bell flange	Spigot	
Inside diameter, mm	1,241.4	1,21	-
Wall thickness, mm	72.2	28.7	5%
Trench width, mm	1,800		10%
Pipe segment length, mm (ft)	2,438 (8')		-
Trench conditions			
Pipe burial depth (to crown of pipe), mm	900		10%
Backfill unit weight, kg/m^3	1,800		10%
Laying conditions as per AWWA C101-77	A		
Coefficient of sliding friction (trench wall & backfill)	0.4		-
Operational conditions			
Mean operating pressure and its fluctuations (%)	3.45 bars (50 psi), 20%		
Period of mean pressure fluctuations, per event	12 hour		
Design transient pressure and % of design transient pressure	6.89 bars (100 psi), 60%		
Period of transient pressures, per event	1 day		
Traffic conditions			
No of passing trucks	2		
Traffic type	Heavy		
Period of traffic (truck loads), per event	1/2 hour		

The following only discusses the analysis of through crack at bell flange (thickness and outermost part of bell) of 48" pipe. The stress history generated for 48" diameter cast iron main operating under conditions and parameters specified in Tables 4 and 5 resulted in hoop stresses in the 5.2 to 10.6 MPa range for the spigot end and 23 to 42.3 MPa range for the bell flange. It is likely that actual stresses may have been even higher because typically, aggressive compaction of lead caulking was very likely to put the bell flange in tension (this tension was not considered in the current analysis). The threshold fracture toughness was taken as 2 MPa√m.

The stresses had to be increased by about 3.5 times (SMF = 3.5) the estimated stresses under normal operating loads to obtain fatigue lives of less than 300 years. This indicates that the bell has to be severely stressed if the bell failure is to be explained by a fatigue mechanism. Table 6 exhibits the results of the analyses conducted for 48" bell flange as discussed below.

(a) Fatigue life of the 48" cast iron pipe decreases as the length of initial crack length increases.

(b) Fatigue analyses were only conducted for the upper bound of the *da/dN vs. ΔK* curves since these led to fairly short fatigue lives. Lower bound *da/dN vs. ΔK* lead to even higher fatigue lives, which indicates that pipes with very low values of A_p may deemed to be safe from fatigue failure.

Table 5. Mechanical properties for cast iron pipes for fatigue sensitivity study.

Parameters	Most likely value (*MLV*)	Expected variation (*EV*)
Hyperbolic parameters for cast iron		
Elastic modulus, E_o, GPa	120	10%
Tensile strain at failure, σ_{fT}, %	0.6	10%
Tensile stress at failure, ε_{fT} , MPa	185	10%
Compressive strain at failure, σ_{fC} , %	0.9	15%
Compressive stress at failure, ε_{fC}, MPa	278	10%
Fracture toughness for cast iron		
Plane strain, K_{Ic}, MPa√m	12	10%
Plane stress, K_c, MPa√m	24	10%
Threshold fracture toughness, ΔK_{th}, MPa√m	2	20%
Fatigue Paris constants† for cast iron		
Fatigue exponent and coefficient, m_P, A_P (lower bound)	7.8, 1.29 x 10^{-16}	5%, 5%
Fatigue exponent and coefficient, m_P, A_P (upper bound)	9.2, 5.6 x 10^{-16}	5%, 5%

† Unit for stress intensity factor is MPa√m and for length dimension is m.

(c) The final crack length, a_f, was first determined to be 26.28 mm based on the mechanical properties specified in Table 4 and the given stress conditions defined above. The range of initial crack size ratio, r_a, was varied between 99% and 99.5%, which corresponds to range of initial crack lengths of between 26.02 and 26.15 mm, respectively.

(d) The bell flange wall thickness is much higher than spigot wall thickness. Consequently, stresses due to operational loads at the bell end are much lower than induced in the barrel or the spigot end. However, as discussed above, lead-caulking action can elevate the stresses beyond what would be induced due to operational loads alone. The effect of the increase in stresses was incorporated in the fatigue analysis through the stress multiplication factor (SMF) provided in AFGROW. The analyses show that the bell end needs to be highly stressed to lead to fatigue life of less than 300 years.

Monte Carlo simulations to determine the variation in the estimates of fatigue lives for the 48" bell flange were conducted, and results are exhibited in Fig. 15 in the form of frequency distribution (histogram) plots. Analysis indicates that given a crack length of 26.15 mm, fatigue failures are likely to occur (with a relatively high likelihood of nearly 60%) within the first 50 years. It is important to note that this relatively short fatigue life results because extreme conditions were imposed especially in regards to the stresses in the bell flange.

Table 6 Estimates of fatigue life for bell flange of 48” cast iron pipe.

Crack growth model	Fatigue life as function of initial crack size		
Stress range, σ (MPa) and SMF	5.2 to 10.6 and SMF = 3.5		
Initial crack size ratio, r_a	99.00%	99.25%	99.50%
Paris			
Upper bound, N_f (cycles)	1,384,896	1,034,256	687,696
Upper bound, T_f (years)	79	59	39

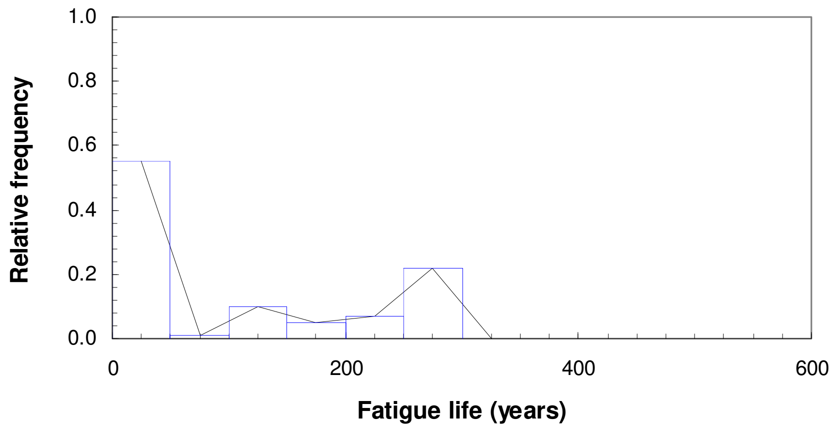

Figure 6. Histogram of fatigue life of 48” CI pipe bell flange with Paris model (a_i = 26.15 mm).

3. FINAL REMARKS

It is important to note that a cast iron main can only undergo fatigue failure if the pipe has existing cracks or voids. Previous analyses show that if the cast iron mains were free of cast iron defects due to manufacturing, then cracks could still have been introduced during the loading/unloading delivery process or during the lead caulking of the bell-spigot joint, with a high likelihood of not being noticed on installation and commissioning.

Analysis shows that long fatigue life is assured if an existing crack size is below a certain limit and the cast iron main is operating under conditions that generate low stresses. Therefore, from an inspection viewpoint, it is crucial to detect cracks that exceed this length limit if sudden failure (uncontrolled crack growth propagation) is to be avoided.

The fatigue crack model described in this paper allows the consideration of a wide variety of scenarios. The analysis described here only consider one specific scenario and a thorough sensitivity study needs to be carried to reach more conclusive understanding of fatigue growth failures in cast iron trunk mains.

The outcome of the application of crack growth models should be judged from a qualitative aspect. The nature of the fatigue analysis is based on considerable empirical relationships and, wherever possible, physical evidence should be sought to confirm fatigue failure. It is recognized that this exercise is not easy and not always possible to pursue rigorously.

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References

American Society for Testing and Materials (ASTM). (1990). *Standard test method for plane-strain fracture toughness of metallic materials*, ASTM E 399-90. ASTM International, West Conshohocken, PA.

American Society for Testing and Materials (ASTM). (2005). *Standard practices for cycle counting in fatigue analysis*, ASTM E 1049-85. ASTM International, West Conshohocken, PA.

Baicchi, P., Collini, L. and Riva, E. (2007). "A methodology for the fatigue design of notched castings in gray cast iron." *Engineering Fracture Mechanics*. Vol. 74, pp. 539–548.

Bannantine, J. A. Comer, J.J. and Handrock, J. L. (1990). *Fundamentals of metal fatigue analysis*. Prentice Hall, Englewood Cliffs, NJ.

Bonacuse, P. J. (2001). Fracture of cast iron pipes. Supporting document in Cleveland Trunk Main Task Force Final Report. City of Cleveland, Division of Water, OH.

Broek, D. (1988). *The practical use of fracture mechanics*. Kluwer Academic Publishers, Boston, MA. 522 p.

Brooks, C.R. and Choudhury, A. (1993). *Metallurgical Failure Analysis*. McGraw Hill, New York. N.Y.

Bullock, J.H. (1995). "Near threshold fatigue behaviour of flake graphite cast irons microstructures." *Journal of Theoretical and Applied Fracture Mechanics*, Vol. 24, pp. 65-78.

Cast Iron Pipe Research Association (CIPRA). (1927). *Handbook of cast iron pipe: for water, gas, steam, air, chemical and abrasives*. Chicago. IL.

Cleveland Water Department. (2001). *Cleveland Trunk Main Task Force Final Report*. City of Cleveland, Division of Water, OH.

Deb, A. K., Grablutz, F. M., Hasit, Y. J. Snyder, J. K., Loganathan, G.V. and Agbenowsi, N. (2002). Prioritizing Water Main Replacement and Rehabilitation. AwwaRF and AWWA, Denver.

Ewalds, H. L. and Wanhill, R.J.H. (1984). *Fracture mechanics*. E. Arnold, London England.

Handover, G., Wilkins, J., Prescott, W. and James, R.W. (1930). *Burst water mains*. Report prepared by members of sub-committee for the Works and Stores Committee of the Board, Metropolitan Water Board. 119 p.

Harter, J.A. (2008). AFGROW Users guide and technical manual, Version 4.0011.14, US Air Force Research Laboratory. OH.

James, M.N. and Wenfong, L. (1999). "Fatigue crack growth in austempered ductile and grey cast irons-stress ratio effects in air and mine water." *Materials and Science Engineering*. Vol. A 265, pp. 129-139.

Rajani, B. B., Makar, J. M., McDonald, S. E., Zhan, C., Kuraoka, S., Jen, C.-K., and Viens, M. (2000). *Investigation of grey cast iron water mains to develop a methodology for estimating service life*, AwwaRF and AWWA, Denver.