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A multiaxial notch fatigue methodology to estimate in-service lifetime of corroded cast iron water pipes

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Abstract. The present paper summarises an attempt of using the so-called Modified Wöhler Curve Method (MWCM) to estimate fatigue damage in pitted cast iron water pipes subjected to in-service variable amplitude multiaxial fatigue loading. In this setting, pits are treated as hemispherical/hyperbolic notches whose depth increases over time due to conventional corrosion processes taking places in buried cast-iron pipes. The validity of such an approach is proven by showing, through a case study, that, under particular circumstances, the combined effect of corrosion and fatigue can remarkably shorten the in-service lifetime of cast-iron pipes as observed in the case study.

Introduction

During in-service operations cast iron pipes are subjected to a variety of loading which can be classified as time-dependent and quasi-static events. Quasi-static events include: ground weight, pipe self-weight, weight of contained fluid, swelling load (typically, one event per year), frost load (the expected frequency being on an annual basis), and thermal stresses. At the same time water pipes experience the following time-variable loadings: operational internal pressure on a daily basis, transient internal pressure related to operational changes, control and demand changes, traffic load with an expected frequency of several events per hour. Over years, cast iron water pipes are also damaged by different types of corrosive processes gradually weakening the material, such processes including: uniform corrosion, pitting, stress corrosion, fatigue corrosion, dissimilar metal corrosion, concentration cells, crevice stray current, graphitisation, and impingement attack. Amongst the above corrosion mechanisms, pitting is often the most severe one, resulting in cavities growing through the pipe walls (blowouts).

The aim of the present paper is to formalise and validate a multiaxial fatigue lifetime estimation technique suitable for simultaneously taking into account the damaging effect of the external/internal systems of forces/moments to which pipes are subjected as well as of growing corrosion pits.

Corrosion pits as growing notches

Corrosion pits usually initiate at anodic locations on either the internal or external surface of buried cast iron pipes. Their subsequent growth is a consequence of a gradual loss of matter due to the cathodic processes taking place within the material close to the anodic initiation point (Fig. 1). According to Rajani and co-workers, the pit growth rate in a corroded cast iron pipe can be modelled according to the following exponential law [1]:

$$d_p = a \cdot t + k\left(1 - e^{-c \cdot t}\right) \tag{1}$$

where d_p is the pit depth *[mm]*, t is time *[year]*, whereas a *[mm/year]*, k *[mm]* and c *[year-1]* are constants depending on the corrosive characteristics of the cast iron/ground mutual interactions.

Owing to their geometry (Fig. 1), corrosion pits can be schematised either as hemispherical, K_t=2.23 [2], or as hyperbolic notches, K_t=3.2÷3.6 [2], so that their detrimental effect on the overall fatigue behaviour of pipes can be explicitly modelled in terms of fatigue strength reduction factor, K_f. In particular, as far as cast iron is concerned, according to Haywood [3], K_f can be estimated as:

$$K_f = \frac{K_t}{1 + 2\frac{\sqrt{a_H}}{\sqrt{r_p}}\left(\frac{K_t - 1}{K_t}\right)} \tag{2}$$

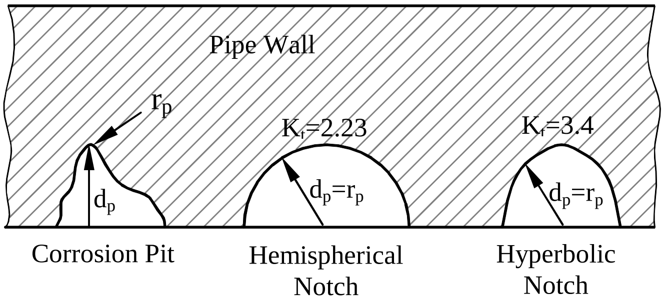

Figure 1: Corrosion pit schematised as either an hemispherical or an hyperbolic notch.

In the above formula, K_t is the stress concentration factor, r_p *[mm]* is the notch root radius (see Figure 1), and, finally, $\sqrt{a_H}$ is a material characteristic length which can be taken equal to $176/\sigma_{UTS}$ mm for cast iron with spheroid and to 0.605 mm for cast iron with flake graphite [3].

The reasoning summarised above suggests that, by simultaneously making use of Eqs (1) and (2), it is possible to directly take into account the detrimental effect of pits on the overall fatigue strength of cast iron water pipes by treating the pits themselves as growing notches, the design fatigue curves being corrected over time accordingly.

Estimating fatigue lifetime of corroded cast iron pipes

The lifetime estimation technique proposed in the present paper is based on the use of the MWCM [4]. The MWCM is a critical plane approach that assumes that the material plane at which fatigue damage reaches its maximum value is the one containing the direction experiencing the maximum variance of the resolved shear stress [5]. Under variable amplitude multiaxial fatigue loading, cycles are counted by post-processing the shear stress resolved along the direction of maximum variance: since such a shear stress component is a monodimensional quantity, cycles can directly be counted by taking full advantage of the classical Rain Flaw method. The MWCM was seen to be successful in estimating fatigue lifetime of notched components by applying it not only in terms of local [6], but also in terms of nominal stresses [7]. In the present study the MWCM is used to post-process time-variable stress states evaluated in terms of nominal net stresses, the criterion being calibrated through the uniaxial and torsional full-reversed fatigue curves.

Consider now a cast iron pipe (Fig. 2b) in the i-th year of service (Fig. 2a) and assume that the relevant pressures/forces/moments (Fig. 2c) can be determined by evaluating them over a representative period of time. As soon as the required input signals are known, the average geometrical features of the pits in the i-th year (i.e., depth and tip radius) have to be estimated (Fig 2d). The aspect ratio of the pits allows then the corresponding axial and torsional K_f values to be estimated (Fig. 2e) - for instance, by using existing empirical relationships such as Eq. (2). By so doing, the notch fatigue curves to be used to calibrate the MWCM can be derived from the corresponding un-notched ones (Fig. 2f). By post-processing the load history damaging the water pipe being investigated, the MWCM can then be employed to estimate the fatigue damage extent associated with the i-th year of service (Fig. 2g) through the following classical formula (Fig. 2i):

$$D_{y-i} = \frac{n_i}{N_{f,i}} \tag{3}$$

where n_i is the number of cycles characterising the i-th year of service, whilst $N_{f,i}$ (Fig. 2h) is the number of cycles which would result in the fatigue breakage under the investigated load history.

The procedure described above can then be used to estimate fatigue damage year by year. Finally, the number of years to failure, Y_f, can directly be predicted according to the following relationship:

$$D_{tot} = \sum_{i=1}^{Y_f} D_{y-i} = \sum_{i=1}^{Y_f} \frac{n_i}{N_{f,i}} = D_{cr}\,, \tag{4}$$

D_{cr} being the critical value of the damage sum.

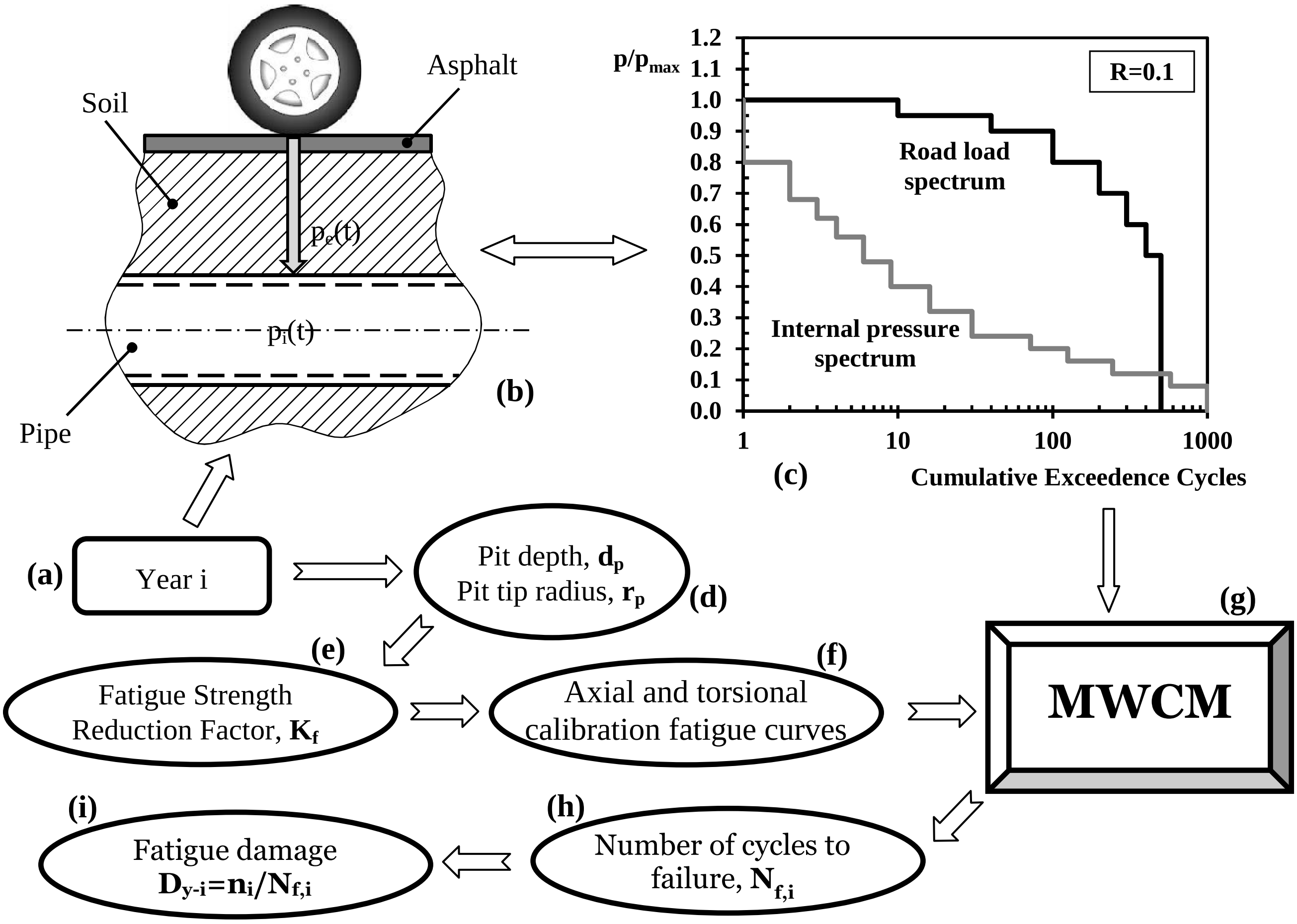

Figure 2: In-field usage of the method to estimate fatigue damage in the i-th year of service.

A case study revisited according to the proposed methodology

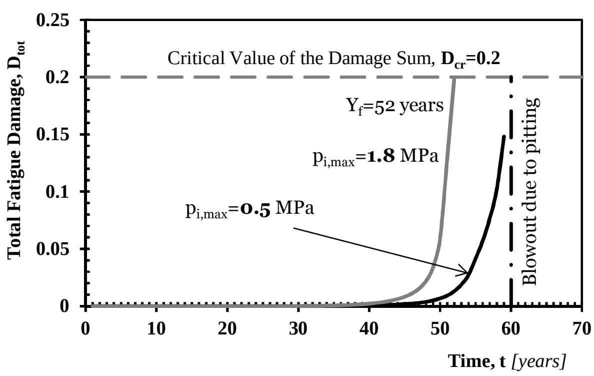

Figure 3: Total Fatigue Damage vs. years of service diagram.

During the summer of 2009 the city of Los Angeles was exposed to an anomalous increase in blowouts resulting in the collapse of the water distribution system. Through a retrospective failure analysis [8], this unexpected situation was ascribed to conventional metal fatigue (accelerating the blowout process) resulting from a cyclic increase of the internal pressure due to water rationing. In the above detailed technical report [8], it is shown that, in a 8" cast iron pipe, a reduction in the wall thickness due to pitting corrosion from an initial value of 13mm down to 4mm, associated with an internal peak pressure of 1.8 MPa, resulted in the fatigue breakage of the pipe itself. Such a case study is re-analysed in what follows according to the approach proposed in the present paper.

Consider a cast iron pipe buried under a road (Fig. 2b). Such a pipe has an internal diameter equal to 203mm and an initial thickness equal to 13mm, and the cast iron having an average UTS of 206.9 MPa [8]. Figure 2c shows the two load spectra adopted to generate the daily load histories. In particular, the external pressure, p_e, due to the traffic (as the average result of the transit of 10 vehicles per hour) was summarised through a Gaussian-like spectrum containing 500 cycles per day, $p_{e,max}$ being taken equal to 1 MPa (i.e., considering the effect of a heavy lorry). Internal pressure p_i was assumed to be characterised by a reduced number of extreme events followed by a large number of cycles of low amplitude. The maximum value for the internal pressure, $p_{i,max}$, was taken equal to 0.5 MPa to consider normal in-service operations as well as equal to 1.8 MPa [8] to model the anomalous situation observed in Los Angeles due to water rationing. The calibration plain fatigue curves were estimated from the material UTS [9]: the fully-reversed endurance limits extrapolated, for a probability of survival equal to 50%, at $5 \cdot 10^7$ cycles to failure were taken equal to 75.5 MPa under axial loading and to 66.2 MPa under torsion, resulting in a negative inverse slope equal to 14.7 and to 8.3, respectively. The pit growth rate was modelled through Eq. (1) by considering a moderate corrosivity level, i.e., a=0.0252 mm/year, k=11.70 mm, and c=0.058 1/year [1], this resulting in a blowout time of 60 years. Finally, the weakening effect of pits (treated as growing hyperbolic notches, K_t=3.4 [2]) was taken into account by correcting the estimated plain fatigue curves through Eq. (2), where $\sqrt{a_H}$=0.605. Considering the detrimental effect of corrosion, D_{cr} was taken equal to 0.2 [10]. The total fatigue damage, D_{tot}, vs. time, t, diagram of Figure 3 clearly shows that, compared to normal in-service conditions (i.e., $p_{i,max}$=0.5 MPa), a peak internal pressure of 1.8 MPa results in a rapid increment of the total damage (this holding true especially after the formation of deep pits) leading to an in-service lifetime shorter than the expected blowout time. Accordingly, it can be said that our approach is successful in explaining the anomalous increase in pipe failures observed, during the summer of 2009, in the city of Los Angeles: the presence of deep corrosion pits together with an anomalous increase of the maximum internal pressure due to water rationing resulted in a very large number of simultaneous breakages.

Conclusions

The approach proposed in the present paper proved to be successful in accurately predicting in-service lifetime of water pipes subjected to fatigue loading. Accordingly, it can be seen as an useful tool suitable for managing the maintenance of and investment in water distribution systems. More systematic effort is needed to accurately quantify all the required parameters.

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