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## **TRUNK MAINS FAILURES: THE EFFECT OF CORROSION ON RESIDUAL PIPE STRENGTH**

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### **ABSTRACT**

Trunk mains are critical components of any water supply network and their failures can have significant consequences. This paper investigates nine (9) cast iron mains recovered from service using a deterministic model to predict the likelihood of failure, denoted by the factor of safety. The investigation is made on the basis of their corrosion defects and material strengths, collected as part of a larger study (where it was shown that corrosion morphology can have a significant effect on the measured residual strength). The integrity of the deterministic model to proactively predict failure is sustained by choosing a lower limit strength value of 40 MPa as the input failure stress, which leads to failure being expected when the corrosion pits are more than 40% of pipe wall thickness.

**Keywords:** trunk mains, strength, probability, model, factor of safety, corrosion.

### **1. INTRODUCTION**

For centuries cast iron trunk mains have been used worldwide to transport potable water from treatment works to communities with notable successes achieved. In contrast with distribution mains which are comprised of pipes of diameter around 3 – 8 inches (~ 75 – 200 mm), with a wall thickness typically 0.5 inches (~12.5 mm), the trunk mains are typically between 12 and 60 inches (~ 300 – 1500 mm) in diameter and of much larger wall thickness of around 1.2 inches (~ 30 mm). (As such, when characterising these pipes, they are typically considered as thin walled structures). Although cast iron mains are being phased out of water networks, a significant proportion of network components in many countries are still comprised of aging cast iron mains (Mohebbi et al., 2010). A major problem for the water industry is that these cast iron mains deteriorate at different rates (driven by the type of cast iron, nature of corrosion defects, the geology of the surrounding soil and other conditions) which, if not mitigated, can lead to failures, both critical (bursts) and non-critical (leakage).

The deterioration and residual properties of distribution cast iron mains have been considered in the literature (e.g. Atkinson et al., 2003; Belmonte et al., 2007) in which Weibull statistics were used to characterise the strength distribution of sets of different pipe samples from a given street and other samples from a single length of pipe. It was found that in each case the introduction of a defect population was a consequential effect of in-service corrosion, which lowered the pipe (mean) strength and increased the variability within the sample set compared to the pipes in the as-manufactured conditions. The relationship between the pipe strength and

the corrosion pit depth measured on the fracture surface was shown to be in agreement with either a loss-of-section model or a fracture mechanics one, which is consistent with previous studies (e.g. Yamamoto et al., 1983; Conlin and Baker, 1991; Makar and Rajani, 2000a).

The use of deterioration models for predicting the likelihood of mains failures is thriving and well documented. Rajani and Kleiner (2001a; b) presented a review of statistical and physically based failure deterioration models and described the various models including their background, governing equations, as well as critiques and comparisons. Some models were shown to address only one or a few of the contributing factors (including, but not limited to, pipe-soil interaction, residual strength, corrosion pits, temperature) controlling the engineering process that leads to failure, while other models pursued a more comprehensive approach. In their recent review, St. Clair and Sinha (2012) focussed on over-arching categories of the failure deterioration models for predicting the condition and performance of water mains around the world. These categories include: deterministic, statistical, probabilistic and advanced mathematical models, such as artificial neural networks (ANN), fuzzy logic and heuristic. The input parameters and the output results of the pipe deterioration models are heavily dependent on the categories and methodologies incorporated.

Probabilistic modelling entails the use of statistical analysis to determine the probability, or relative frequency, of failure occurring. Deterministic models on the other hand are required and developed for situations where historical failure data are sparse or unavailable. Rajani and Makar (2000b), with substantial improvements by Rajani and Abdel-Akher (2012), developed a physical deterministic model based on Monte Carlo simulations for calculating the likelihood of main failure, and attributed a term called the factor of safety (FS) as the ratio of the failure stress ( $\sigma_{fail}$ ) of the pipe to the imposed stresses, axial ( $\sigma_x$ ) and hoop ( $\sigma_\theta$ ) (Fig. 1).

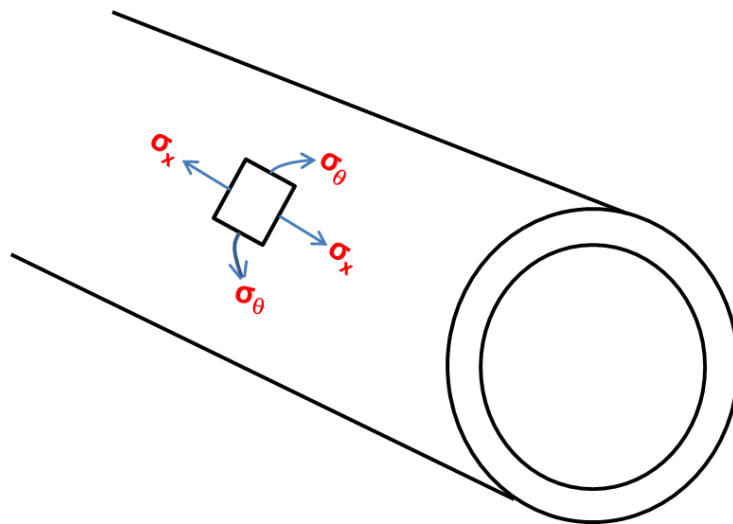


Fig. 1 Schematics of stresses imposed on a main.

In view of the critical function of trunk mains for transporting water across a network, it is discouraging to note that there appear to be limited previous studies aimed at investigating the in-service deterioration and corrosion defects in cast iron trunk mains, and how deterministic models might be used to process the in-service pipe conditions and reliably determine the likelihood of failure prior to actual failure. The aim of the present work, which is part of a larger study of understanding cast iron trunk mains and developing tools and models for performance assessment and risk mitigation, is to address this knowledge gap and to investigate how pipes fail due to in-service corrosion defects. The experimental data from

pipes recovered from service are fed into the deterministic model in order to improve the accuracy of predictions regarding asset life, and to proactively implement protocols for mitigating failure, particularly in high consequence situations.

The structure of this paper is as follows: Section 2 presents an overview of the Monte Carlo based deterministic model as developed by the National Research Council (NRC), Canada – its methodology and a protocol for combining the axial and hoop stresses imposed on a main; Section 3 is comprised of the pipe sample preparation and flexural test method used to derive the strength values and the simulation procedures by the deterministic model; followed by model simulation results and a discussion (Section 4) on the factor of safety obtainable for varying depth of graphitisation, as informed by the pipe strength measurements.

## 2. MONTE CARLO BASED DETERMINISTIC MODEL

### 2.1 Methodology

The work of Rajani and Abdel-Akher (2012) has resulted in a Monte-Carlo based deterministic model, which is comprised of a comprehensive suite of sub-models developed from cast iron material and component properties and the surrounding trench conditions. This model is used by Thames Water Utilities Limited as part of a suite of asset management tools. Being physical and deterministic, this model evaluates the input data entered into a Microsoft Excel-VBA programme (developed by NRC Canada) for a section length (or “stick”) of main, and then performs Monte Carlo simulations to produce probabilistic estimates of the factor of safety (FS), represented by frequency histograms.

Monte Carlo simulations involve a series of mathematical calculations of probability distributions for modelling the variability or uncertainty in the input data. In this particular model symmetrical triangular distributions are used for the input data *in lieu* of precise distributions, and these distributions are defined by the mode (or most likely value, MLV), the minimum and maximum values. The minimum and maximum values are given as variations from the mode ( $\pm$  EV), expressed as a percentage of the mode, i.e.  $(1 - \text{EV}) \times \text{MLV}$  and  $(1 + \text{EV}) \times \text{MLV}$  respectively. The Monte Carlo simulations, comprising 1000 runs, are then presented in the form of frequency histograms. The factor of safety is defined as the ratio of the failure stress (or resistance capacity) to the imposed stresses, which could be in the axial ( $\sigma_x$ ) or hoop ( $\sigma_\theta$ ) directions (Eq. 1).

$$\text{FS} = \frac{\text{failure stress}(\sigma_{\text{fail}})}{\text{imposed stresses}(\sigma_x, \sigma_\theta)} \quad (1)$$

It should be noted that these factors of safety are treated independently, i.e. a factor of safety is determined for either  $\sigma_x$  or  $\sigma_\theta$  but not both. Hence, the factors of safety determined may be more pessimistic or optimistic than the actual case. This is discussed in more detail in Section 2.2. In the case of cast iron mains, the failure stress ( $\sigma_{\text{fail}}$ ) is equal to the pipe tensile strength at failure which can be influenced by in-service corrosion defects. (The model deals with such defects by treating corrosion simply as a loss of section). The imposed stresses in the hoop and axial directions are comprised of stress components from external loads, internal pressure, temperature and longitudinal bending or flexure. For a trunk main to be considered theoretically safe, the FS must be greater than 1, i.e. the failure stress is greater than the imposed stresses. However, a trunk main may be expected to fail for cases where  $0 \leq \text{FS} < 1$ .

The degree of safety, another characterisation parameter, is based on the amount of overlap between the tails of the histograms for failure and imposed stresses (Rajani and Abdel-Akher, 2012).

## 2.2 Von Mises theory for combining imposed stresses in axial and hoop stress

According to Rajani and Tesfamariam (2004), the axial and hoop stresses imposed on a buried trunk main are given by Eqs (2) and (3):

$$\sigma_x = \sigma_x^w + \sigma_x^{pi} + \sigma_x^T + \sigma_x^f \quad (2)$$

$$\sigma_\theta = \sigma_\theta^w + \sigma_\theta^{pi} + \sigma_\theta^T + \sigma_\theta^f = \sigma_\theta^w + \sigma_\theta^{pi} + \sigma_\theta^T - \nu_p \sigma_x^f \quad (3)$$

where

$\sigma_x^w$  = axial stress due to external loads

$\sigma_x^{pi}$  = axial stress due to internal pressure

$\sigma_x^T$  = axial stress due to temperature differential

$\sigma_x^f$  = stress in the longitudinal direction due to flexural action

$\sigma_\theta^w$  = hoop stress due to overburden loads

$\sigma_\theta^{pi}$  = hoop stress due to internal pressure

$\sigma_\theta^T$  = hoop stress due to temperature differential

$\sigma_\theta^f$  = hoop stress due to Poisson's effect of longitudinal bending

$\nu_p$  = pipe Poisson's ratio

The cast iron bi-axial failure criterion for non-linear conditions can be represented by the distortion energy theory (Fig. 2) developed by von Mises (Eq. 4). This theory states that failure (by yielding or fracture) occurs when, at any point in the body, the distortion energy per unit volume in a state of combined stress becomes equal to that associated with yielding or fracture in a simple tension test (e.g. Ugural and Fenster, 1987).

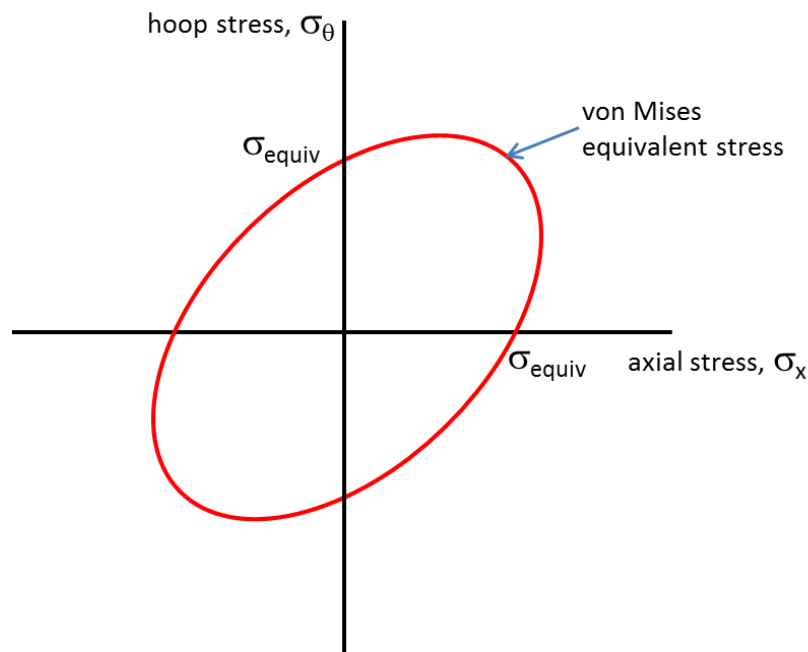


Fig. 2. Projection of von Mises combined stress distribution in the axial and hoop directions.

$$\sigma_{equiv}^2 = \sigma_{\theta}^2 + \sigma_x^2 - \sigma_{\theta}\sigma_x \quad (4)$$

Hence, it is possible to determine a factor of safety that accounts for both stresses simultaneously:

$$FS_{equiv} = \frac{\sigma_{fail}}{\sigma_{equiv}}, \text{ i.e. } \sigma_{equiv}^2 = \left( \frac{\sigma_{fail}}{FS_{equiv}} \right)^2 \quad (5)$$

Similarly,

$$FS_{\theta} = \frac{\sigma_{fail}}{\sigma_{\theta}}, \text{ i.e. } \sigma_{\theta}^2 = \left( \frac{\sigma_{fail}}{FS_{\theta}} \right)^2 \quad (6)$$

$$FS_x = \frac{\sigma_{fail}}{\sigma_x}, \text{ i.e. } \sigma_x^2 = \left( \frac{\sigma_{fail}}{FS_x} \right)^2 \quad (7)$$

Substituting Eqs (5), (6) and (7) into Eq. (4) gives:

$$\begin{aligned} \Rightarrow \left( \frac{\sigma_{fail}}{FS_{equiv}} \right)^2 &= \left( \frac{\sigma_{fail}}{FS_{\theta}} \right)^2 + \left( \frac{\sigma_{fail}}{FS_x} \right)^2 - \left( \frac{\sigma_{fail}}{FS_{\theta}} \right) \left( \frac{\sigma_{fail}}{FS_x} \right) \\ \Rightarrow \frac{\sigma_{fail}^2}{FS_{equiv}^2} &= \frac{\sigma_{fail}^2 (FS_{\theta}^2 + FS_x^2 - FS_{\theta} FS_x)}{FS_{\theta}^2 FS_x^2} \\ \Rightarrow FS_{equiv} &= \frac{FS_{\theta} FS_x}{\sqrt{FS_{\theta}^2 + FS_x^2 - FS_{\theta} FS_x}} \end{aligned} \quad (8)$$

where

$\sigma_{equiv}$  = the von Mises equivalent stress combination of  $\sigma_{\theta}$  and  $\sigma_x$

$FS_{equiv}$  = von Mises combined factor of safety

$FS_{\theta}$  = factor of safety in the axial direction

$FS_x$  = factor of safety in the hoop direction

### 3. EXPERIMENTAL

#### 3.1 Sample preparation and flexural test method

Three plates have been cut from each of nine lengths of failed water mains, Pipes 1-9, with the exception of Pipe 8, where only two plates were available (Table 1). Flexure testing was carried out using an Instron 1185 with a 100 kN load cell. A set of 10 specimens from each plate was prepared, with a total of 30 specimens produced from each pipe. Three randomly selected specimens in each set were strain gauged (using Vishay General Purpose strain gauges) on both the tension and compression faces. The deduced tensile strength at failure was correlated with the depth of graphitisation measured in the fracture face of each specimen (as discussed in Jesson et al., 2013).

Table 1 – Details of the available nine failed pipes recovered from service

Pipe	Nominal diameter / inches	Nominal external diameter / m	Nominal wall thickness / mm	Age* / years
1	48	1.22	28	82
2	42	1.07	32	~85
3	30	0.76	22	82
4	18	0.46	21	125
5	24	0.61	23	115
6	36	0.91	23	151
7	12	0.31	18	~70
8	18	0.46	22	~120
9	21	0.53	28	150

\*Age is the duration from installation to removal from service and is to the nearest year, except for those pipes where the age is indicated as approximate and duration is less certain.

### 3.2 Lower values of strength measurements

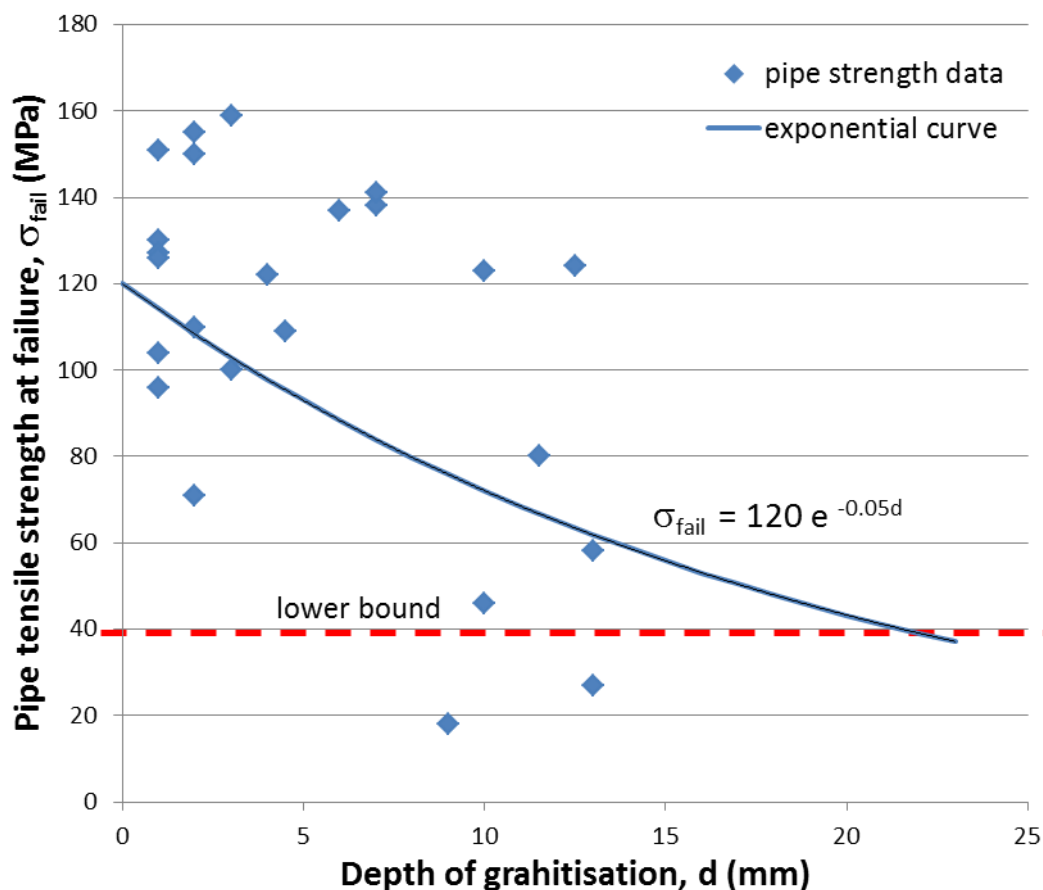


Fig. 3. Effect of the depth of graphitisation on pipe strength as determined experimentally

Fig. 3 shows the plots of the nominal tensile bending stress at failure as a function of the depth of graphitisation measured on the fracture surface. The values presented are the lowest 25 from a total of 260 specimens tested (Jesson et al., 2013). The flexure testing results show a variation of the strengths of the samples from different pipes, together with a trend of

decreasing pipe strength with increasing depth of graphitisation. The loss of section and fracture mechanics approaches have been used to describe the relationship between the depth of graphitisation and the residual pipe strength, and to explain the different morphologies of graphitisation. Focusing on these values, it is possible to apply an exponential expression of the form:

$$\sigma_{\text{fail}} = Ae^{-bd} \quad (9)$$

where

A=120 MPa – the typical tensile strength of the cast iron with no graphitisation

b = 0.05 mm<sup>-1</sup> – an arbitrary constant

d = depth of graphitisation in mm

Whilst it is possible to observe a full wall thickness graphitisation in a pipe in active service, it can be seen that 40 MPa represents a useful, arbitrary lower limit for the pipe residual strength (as shown by the red dotted line in Fig. 3), particularly in situations where it is not possible to assess the extent of graphitisation for a pipe in service.

### *3.3 Monte Carlo deterministic model: Simulation of the factor of safety using the strength measurement data*

#### *3.3.1. Establishment of a reference main*

A reference or typical main is required in order to establish a baseline for comparing effect of corrosion on the residual pipe strength. The reference main is also useful for evaluating the effects of mitigating strategies, such as repair techniques and network management. The characteristics of this reference main were determined, following a review of the Sampling Programme (SP) conducted by Thames Water Utilities Limited, which collected data on trunk mains laid in the highest consequence locations using non-destructive testing (NDT) techniques (Belmonte, 2008). The rationale for choosing the reference main is based on the average / prevalent conditions in the SP data rather than a focus on a specific part of Thames Water's network. The pipe characteristics and operating conditions of the reference main are detailed in the following:

#### *(i) Pipe characteristics*

- a) Pit cast iron – manufactured before 1914
- b) 30 inches pipe diameter – the modal diameter of the cast iron trunk mains tested in the SP (i.e. 81 out of total 357).
- c) 100 years old – 95% of pipes tested range between 76 – 165 years. More than 50% of water mains in London have been in service for at least 100 years.
- d) Soil corrosivity of 3 (moderately aggressive) – most prevalent in the SP data which provides a good perspective of London clay soils.
- e) 25.4 mm nominal wall thickness – representing the mean thickness value of pipes tested which were within the range of 17.3 – 33.9 mm.

(ii) *Operating conditions*

- a) Internal water pressure = 10 bar
- b) Pipe burial depth = 1000 mm
- c) Trench width = 1000 mm

3.3.2 Calibration of the model

The Monte Carlo deterministic model was calibrated by adjusting the general input section of the Excel-VBA programme to the characteristics of the trunk main given. A  $\pm 5\%$  variation default was applied to each input data to cater for variability. The input data required for sampling are categorised as follows:

- a) *Pipe material information*: describes the pipe material properties, such as elasticity, material strength at failure in tension, fracture toughness.
- b) *Pipe geometry information*: comprises the pipe physical dimensions and related information, such as pipe size, pipe thickness class, pipe segment length, pipe dimensions.
- c) *Trench characteristics*: describes excavation trench characteristics, such as trench depth and width, pipe laying condition, pipe construction conditions, backfill material properties.
- d) *Traffic/ pavement data*: describes the surrounding external environment, such as pavement thickness, pavement type as well as traffic description.
- e) *Operating conditions data*: describes basic factors related to operational and hydraulic conditions, e.g. external pipe loads, water pressure.

The range of cast iron tensile strength from the literature (Angus, 1976) as well as carefully selected sets of lower strength values from the flexural tests were fed as input failure stresses into the Monte Carlo deterministic model. These failure stresses were varied for corrosion pit depths between 0 and 90% wall thickness, and then based on the operational service conditions the factors of safety in the hoop ( $FS_x$ ) and axial directions ( $FS_\theta$ ) were calculated. Finally, the von Mises combined factor of safety ( $FS_{equiv}$ ) was evaluated from  $FS_x$   $FS_\theta$  using the relationship derived in Eq. 8.

## 4. RESULTS AND DISCUSSION

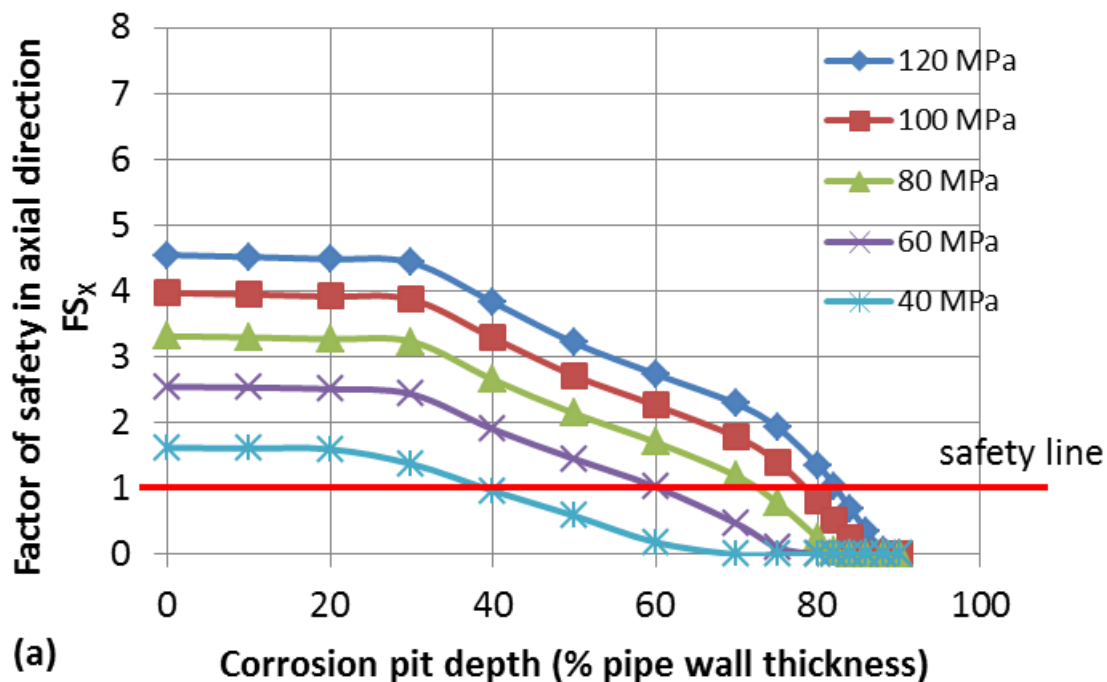
To ensure proactive asset management of trunk mains in the utilities network, a “traffic-light” colour code is proposed which is aimed at pre-emptive rehabilitation of mains likely to fail (i.e. with very low  $FS_{equiv}$ ). A combined factor of safety  $FS_{equiv} < 1$  represents a severely deteriorated main with imminent likelihood of failure, and therefore requires an urgent replacement/ rehabilitation. For cases where  $1 < FS_{equiv} < 4$ , the main has moderate likelihood of failure and must be routinely kept under check, particularly when the  $FS_{equiv}$  is close to the safety line of 1. The mains which are in good condition would have  $FS_{equiv}$  more than 4 and these mains are designated as having low likelihood of failure.

The factor of safety outputs based on the lower strength values (40 – 120 MPa) from the flexural tests fed into the Monte Carlo deterministic model at varying corrosion pit depth between 0 and 90 % pipe are shown in Fig. 4. The factors of safety in the axial direction



shown in Fig. 4a are generally of lower magnitude than those in the hoop direction in Fig. 4b, suggesting that at constant pipe strength the imposed axial stresses on the pipe are greater than the imposed hoop stresses. Although the increase in corrosion pit depth has a detrimental impact on both  $FS_x$  and  $FS_\theta$ , it is however clear that this impact is more predominant in the hoop direction as the curves in Fig. 4b have steeper slopes at corrosion pit depth greater than 10% pipe wall. The combined factor of safety  $FS_{equiv}$  shown in Fig. 4c is fairly constant between 0 and 20 % wall corrosion pits, and then falls sharply afterwards until the tails of the curves reach  $FS_{equiv}$  of zero at full pipe wall corrosion. This critical relationship between the corrosion pits and the likelihood of pipe failure, represented by the  $FS_{equiv}$ , is similar to the loss of section analysis seen in some sections of strength/ graphitisation data of the flexural test. The interpretation of this phenomenon is that the a main is unlikely to experience a reduced strength, and therefore unlikely to fail, in service when the corroded portions are less than 20% wall thickness – unless the initial pipe strength is very low and already in the imminent failure region.

The simulation results in Fig. 4c also show that the  $FS_{equiv}$  reduces with the decrease in the pipe tensile strength fed into the deterministic model which is in line with what would be expected at constant hoop and axial stresses imposed on the main (see Eqs. 1 and 8). Very high  $FS_{equiv}$  of around 3 – 5 were computed for pipe strengths of 100 and 120 MPa when the corroded pit depth is below 40 % wall. There was reduction in the  $FS_{equiv}$  values for strengths of 80 and 60 MPa, while the minimum  $FS_{equiv}$  values were achieved for the lowest strength of 40 MPa. In the case of 40 MPa, the  $FS_{equiv}$  plateaued initially at around 1.7 and later decreased proportionally with the increase in pit depth after 20% wall, dropping to values less than 1 (imminent safety line) at the onset of 40% wall pit depth. Therefore, proactive and targeted strategies for asset management would require choosing a lower limit strength value from the flexure testing of around 40 MPa to determine the maximum pit depth threshold (in this case 40% wall thickness at  $FS_{equiv} = 1$ ) above which failure is imminent.



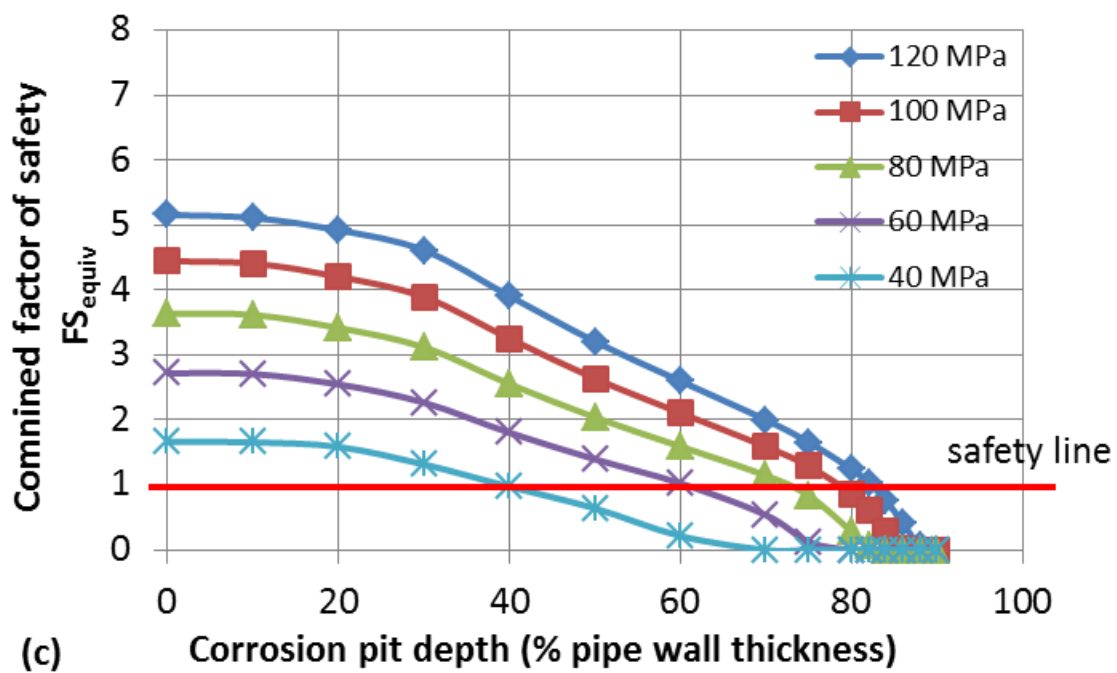
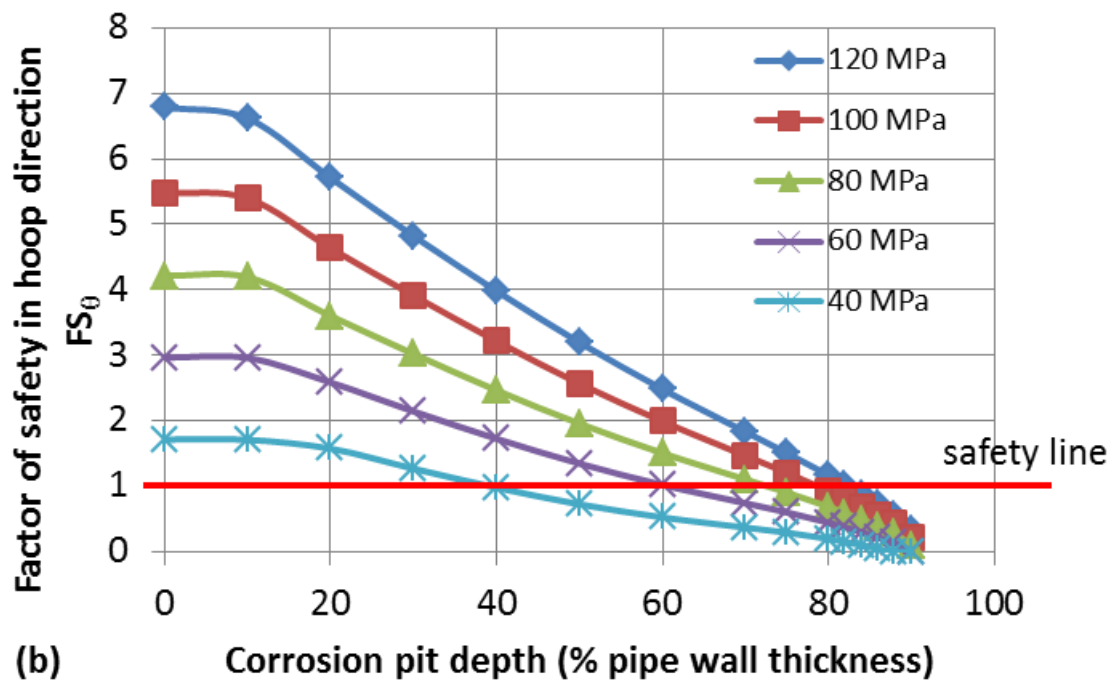


Fig. 4. Relationships between the factor of safety and corrosion pit depth at different pipe strengths: (a) axial ( $FS_x$ ); (b) hoop ( $FS_{\theta}$ ) and (c) combined ( $FS_{equiv}$ ).

## **5. CONCLUDING REMARKS**

Trunk mains are critical water utilities assets and their conditions in service should be properly monitored and related to asset management strategies supported by realistic failure deterioration models. This study has investigated corrosion defects and flexural tensile strengths of samples from nine cast iron trunk mains recovered from service, and the strength measurements were fed into a Monte Carlo deterministic model to improve its fitness at predicting the likelihood of failure. A protocol was established for deriving an equivalent factor of safety  $FS_{equiv}$  by combining the axial and hoop stresses imposed on a buried pipe using the von Mises distortion energy theory.

Noticeable spatial variations were seen in the strength of the samples from nine different pipes, together with the trend of decreasing pipe strength with increasing depth of graphitisation. The inputting of the lower strength values into the Monte Carlo deterministic model produced a relationship between the equivalent factor of safety  $FS_{equiv}$  and the corrosion pit depth, which was properly described by the loss of section analysis approach. Importantly lower  $FS_{equiv}$  values were obtained for reduced pipe strength inputs which was in agreement with what should be expected at constant hoop and axial stresses imposed on the main. It was shown that proactive and targeted strategies for asset management would require choosing a lower limit strength value from the flexural testing of around 40 MPa to determine the maximum pit depth threshold (in this case 40% wall thickness at  $FS_{equiv} = 1$ ) above which failure is imminent.

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