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Codified methods to analyse the failures of water pipelines: A Review

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Abstract

Pipelines used for the transportation of water and other services are very important lifelines in modern society. The important role that they play in our present economy is reflected by thousands of kilometres of service laid in urban centres worldwide. As many of these pipelines have been laid few decades earlier, in most cases, their condition has been deteriorated mainly by electro-chemical and (or) micro-biological corrosion. There are several codes of practice available at present to analyse the condition of such deteriorated pipes. This paper identifies and reviews all such relevant standards applicable to corroded water mains with the use of some case studies. Three dimensional finite element analyses are also conducted to investigate the capabilities of simulating the failures of corroded pipelines and thus to ascertain the validity of codified methods. By careful assessment of the current codes of practice in use, it is possible to understand where these codes are lacking and which codes can rightly predict the realistic water pipe failures observed in the past.

Key words: Finite element modelling, pipeline failure, cast iron pipeline, corrosion failure, ABAQUS, fitness for service, Failure assessment diagrams

Introduction

Water authorities around the world are faced with the issue of ageing water distribution networks, with pipeline failure a more prevalent issue today, leading to a severe loss of delivery efficiency. The factors that contribute to a specific pipe failure can be categorized in three principal groups: (a) pipe geometry, material type, pipe-soil interaction and quality of installation, (b) internal loads due to operational and transient pressure and external loads due to soil overburden, traffic loads, frost loads (in cold climate) and third party interference (catastrophic loads), and (c) material deterioration due largely to the external and internal chemical factors; this includes bio-chemical microbiological and electro-chemical activities that lead to corrosion [9]. In addition, the failures can manifest as a result of the combination of one or more factors among such principal groups. For instance, heavy transient event can burst the pipe at the corroded location where there is a deteriorated wall thickness. If these failures can be predicted accurately in advance, not only will water utilities benefit on cost savings, but also society will be served with improved efficiency.

Many authorities and bodies have collaborated and developed a set of codes [2,3,4], which can be used to assess the ‘fitness’ of a pipeline network for operation. They have developed and set out uniquely, in order to convey their own method of assessments to analyse corroded water mains. The corrosion in these water mains can be categorised into three types; general corrosion (also referred to as uniform corrosion), patch corrosion and pitting corrosion [8], with each type of corrosion having differing effects on the structural integrity of the pipeline. The codes of practice choose to assess these types of corrosion in many different ways, adding to the problem of what is the best assessment method.

The current study investigates the applicability of the codes of practice to predict the failure of corroded cast iron water pipes. Due to the nature of cast iron and the size of these pipes, their failure mode is generally attributed to material deterioration through corrosion which could fall into one of aforementioned categories. Codified methods identify ways of analysing such material deterioration and hence pipeline's fitness for service. This paper identifies and reviews all relevant standards applicable to corroded cast iron water mains which fall into pre-identified corrosion patterns. The codified methods are assessed against a past pipeline failure to explore the capabilities of the codes to predict the actual pipe failures. Three dimensional finite element (FE) analyses are also conducted to simulate the failures of corroded pipelines and thus to ascertain the validity of codified methods. By careful assessment of the current codes of practice in use, it is possible to understand where these codes are lacking and which codes can rightly predict the realistic water pipe failures observed in the past.

Methodology

This section identifies the description of the relevant standards for cast iron water mains that are corroded under three different corrosion patterns as identified in Rajeev et al [8]. Corrosion is one of the main reasons for failure in piping systems. The type of corrosion will determine how the pipeline is assessed and how it can be treated in order to maximise its service life.

General Corrosion

General corrosion or uniform corrosion refers to reasonably uniform reduction of thickness over the surface of the pipeline wall. Figure 1 shows an example of a corroded cast iron water main for general corrosion type.

Figure 1 Example of general corrosion in cast iron water mains [8]

API/ASME 2007

API code [2] suggests different levels of assessments for general corroded pipelines. Level 1 assessment, which is suggested as an initial assessment, is proposed to undertake either using point thickness reading (PTR) measurements or critical thickness profile measurements. The type of method is determined using the coefficient of variation of the thickness readings (i.e. former method if coefficient of variance, COV<10% and later method if COV>10%). If the pipe is not satisfied under Level 1 Assessment conditions, the code suggests to undertake Level 2 assessment (acceptance criteria for Level 2 is given in Table 4.4 in API [2]). Level 3 assessments are proposed if the pipe does not satisfy the level 1 & 2 assessment criteria. The detailed descriptions of each level of assessments are given in section 4.4.2 4.4.3 of API [2].

BRITISH STANDARD

The British Standard [4] discusses about the assessment of general corrosion in a slightly different way by providing an annex (annex G in [4]) to deal with all types of corrosion. This standard categorises general corrosion as a corroded region in which metal loss is less than 10% of the original wall thickness. The code gives suggestions to determine the safe working pressure. This is suggested in a few different ways depending on the flaw type and condition. For a single flawed section, safe working pressure is determined by first calculating the failure pressure of the unflawed pipe, by using the equation $P_0 = \frac{2B_0\sigma_u}{(D-B_0)}$, where $B_0 =$ Original measured pipe wall thickness, $\sigma_u = tensile\ strength$ and D= diameter of the pipe. Then, the failure pressure of the corroded pipe is determined by multiplying the unflawed failure pressure with the calculated reserve strength factor. Finally, a factor of safety is applied to produce a safe working pressure, where the factor of safety is determined by multiplying the modelling factor of the corrosion flaw by the original design factor of the corrosion flaw.

ASME B31.G

ASME B31.G [3] is an ageing code of practice but still is an effective tool when undertaking corrosion assessments and subsequent remaining life assessments. However, it does not have separate assessment procedures in order to assess the different types of corrosion flaws. The code can be utilised for general type of corrosion by assessing the amount of corroded area. If the corroded area under assessment results to be less than 10% of the nominal wall thickness, then the code suggests no action and the pipeline can be returned to service and considered to be safe. On the other hand, if it is found to be 80% or greater, immediate replacements or repair actions are proposed. For the range in between, it suggests further assessments by determining the longitudinal extent of the corroded area. Part 3 of the code suggests tables of corrosion limits which can be an effective tool to quickly determine whether a pipeline is suitable for continued service under the required maximum allowable operational pressure (MAOP).

Patch Corrosion

Patch corrosion (Fig. 2) is identified as a patch of corrosion due to graphitization or cluster of geometrically interacting pits, which can be approximated as a patch of corrosion.

Figure 2 Example of patch corrosion in cast iron water mains [8]

API/ASME 2007

Part 5 in API code [2] deals with patch corrosion or as it is known in this standard as local metal loss. The code suggests Level 1 assessment to accommodate for patch corrosion. The first step in this assessment is to determine the critical thickness profile (CTP) for the affected area. In the case of a local thinned area (LTA), a grid is suggested in the code to determine thickness readings and establish a CTP in both the longitudinal (s) and circumferential (c) directions. Once the minimum wall thickness is determined, the remaining thickness ratio (R_t) and longitudinal flaw length parameter (λ) can be determined from the equations $R_t = \frac{t_{mm}-FCA}{t_c}$ and $\lambda = \frac{1.285s}{\sqrt{Dt_c}}$ as suggested in the code.

The acceptable criteria for Level 1 assessment are $Rt \geq 0.20$ and $tmm - FCA \geq 2.5mm$ and $Lmsd \geq 1.8\sqrt{Dt_c}$, where R_t is the remaining thickness ratio, FCA is future corrosion allowance, L_{msd} is the distance to the nearest major structural discontinuity and t_c is the corroded wall thickness. If Level 1 is satisfied, the code suggests assessing MAWP as elaborated in Annex A of API [2]. Figure 5.6 in API [2] determines whether the calculated MAWP is acceptable for the corroded pipe. Further details of this method can be found in section 5.4.2 in API [2]. The code suggests level 2 & 3 if the pipe in concern is not satisfied Level 1 criteria. The detailed descriptions of level 2 & 3 can be found in section 5.4.3 and 5.4.4 respectively in API code.

BRITISH STANDARD

With regards to the patch corrosion, similar strategy has been suggested in British standard as applicable with general corrosion explained earlier (Annex G in [4]). Additional assessments are suggested if the results from the safe working pressure assessment are found to be inadequate for the operational specifications.

ASME B31.G

As this code does not differentiate the assessment procedures for different types of corrosion flaws, the assessment procedure for patch corrosion is similar to that applicable for general corrosion.

Pitting Corrosion

Pitting corrosion can be defined as localized regions of metal loss such as shown in Fig. 3.

Figure 3 Example of pitting corrosion in cast iron water mains [8]

API/ASME 2007

Part 6 of API code [2] discusses the assessments in relation with pitting corrosion.

First step here is to determine the required initial data, that being diameter of the pipe, future corrosion allowance, nominal thickness and previous recorded metal loss. A ratio is determined between the remaining wall thickness to the future wall thickness; $R_{wt} = \frac{t_c+FCA-w_{max}}{t_c}$, where $t_c = t_{nom} - FCA - LOSS$ and w_{max} is the maximum pit depth in most serious pitting damage, where FCA is the Future corrosion allowance and LOSS is the amount of wall thickness lost reported from the previous inspection. If $R_{wt} < 0.2$, then the level 1 assessment criteria is not satisfied. If the criterion is satisfied, MAWP is calculated using the same methods explained earlier. From the pit charts and the tables provided in section 6-21 through to 6-28 in [2] (dependant on the severity of the pitting damage), RSF (remaining strength factor) can be calculated. If the pitting damage is more extensive than the provided figures in the code, RSF is suggested to take similar with R_{wt}. If $RSF \geq RSF_a$ (allowable remaining strength factor which is 0.90), then the section is proposed as acceptable to operate under the MAWP, and if $RSF < RSF_a$, then the section is acceptable to operate under $MAWP_r$ which is determined by the equation, $MAWP(\frac{RSF}{RSF_a})$. Level 2 and 3 assessment procedures can be found in section 6.4.3 and 6.4.4 respectively in the API code [2].

The code also suggests undertaking stress intensity fracture oriented analyses which are based on failure assessment diagrams (FAD) for cracked-like flaws. In FAD diagrams, the horizontal axis (L_r) is ratio of the applied stress to the stress to cause plastic yielding of the structure containing a flaw, and vertical axis (K_r) is the ratio of the applied linear elastic stress intensity factor to the material fracture toughness. Failure is described by limiting line which is a nonlinear function of L_r. The method can be used to asses fully brittle failure (K_r=1) as well as plastic collapse of material (L_r=L_{rmax}). Level 3 assessments are proposed if the pipe does not satisfy the level 1 & 2 assessment criteria. Hence, the code provides different levels of assessments depending on the level of conservativeness required.

Higher assessment levels need more inputs and involve complex calculations in contrast to lower level assessments. The detailed descriptions of each level of assessments are given in section 9 of API [2].

BRITISH STANDARD

The same assessment procedure detailed in patch corrosion (single patch) is suggested to undertake for pitting corrosion in British standard [4]. The code also suggests three levels of fracture assessment methods for pit corroded pipes, depending on the input data available and conservatism required. Further details of these methods can be found in section 7 of British standard [4].

ASME B31.G

The same assessment procedure detailed in general corrosion is proposed for pitting corrosion in [3].

Case Study

A case study of actual pipeline failure has been studied to investigate the capabilities of predicting the failures using codes. The data of the failed pipe, which was shared by a water utility [8], have been presented in Table 1. As it is shown in the table, the case study was on the basis of a cast iron water main, which was installed in 1955, with the diameter and thickness of 375mm and 13.7mm. The selected pipe has been failed through a single through wall pit.

Table 1 Pipe geometry details and failure information

D (mm)	t (mm)	H (m)	L (m)	L' X w (mm)	Nature of failure	Cause of failure
375	13.7	0.8	6.0	140 X 85	Longitudinal fracture	Severe corrosion & valve operation

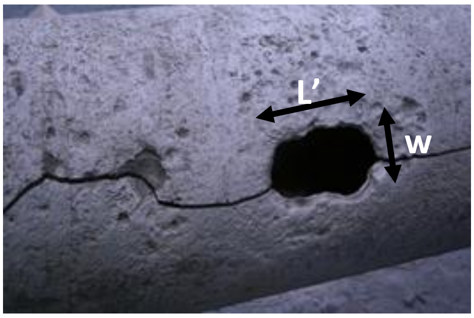


Figure 4 Failed pipe (Rajeev et al, 2013)

The results of the assessments are summarised in Table 2. It can be seen that, following API assessments [2], the pipe was predicted to fail under both Level 1 and 2 assessment procedures. Pipe is failed in Level 1 & 2 assessment due to the calculated remaining wall thickness becomes null ($R_{wt} < 0.2$). Detailed assessments were conducted to investigate the pipe failure state under stress intensity factor based API Level 2 assessments as shown in Fig. 5 (assumed fracture toughness is $10 MPa\sqrt{m}$). The pipe was failed at a water pressure of 0.6MPa. Detailed FE assessments were conducted in the next section to investigate the pipeline response as recommended in API [2]. Similar assessments were conducted using British Standard [3] and found that pipe is not suitable to operate under any circumstances. Furthermore, it is no longer fit for service under ASME B31G assessments [3], as the pipe component under assessment has lost greater than 85% of its wall thickness. Therefore, all the relevant standards predict the pipe failure due to the observed corrosion in field.

Table 2 Failure assessment results for the case study

Code	Level 1	Level 2	Level 3
API	Pipe failed	Fracture failure as explained in Fig. 5	Detailed FE analysis are conducted in next section
BS	Pipe failed		
ASME	Pipe failed		

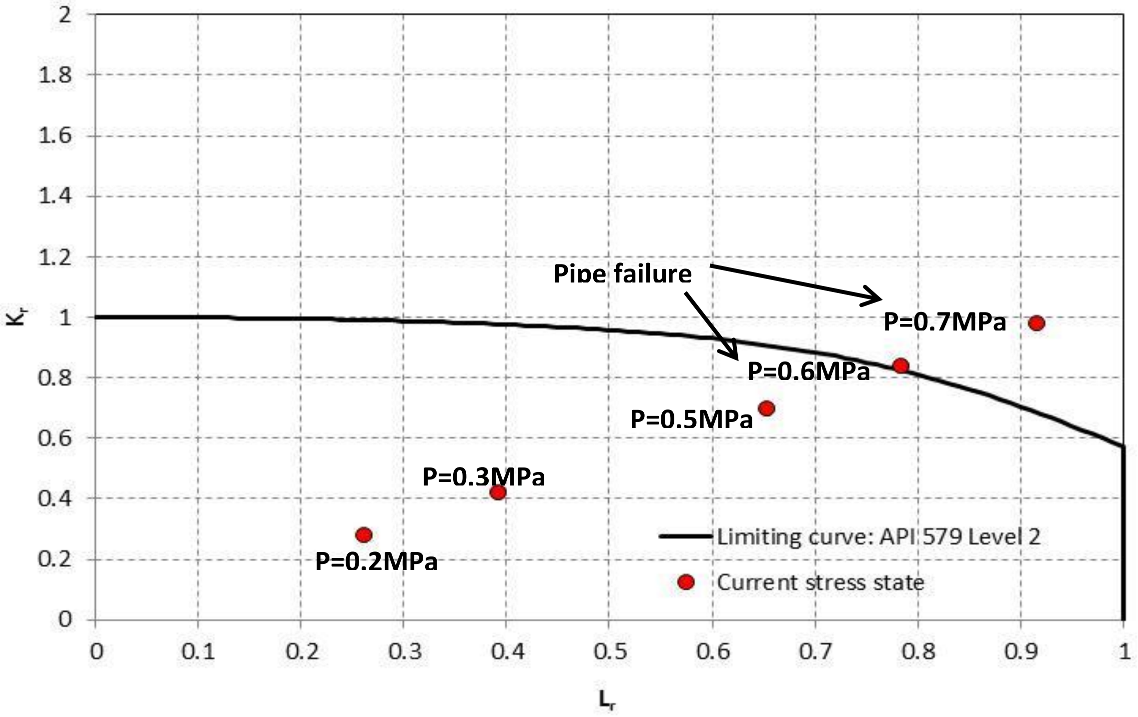


Figure 5 Failure state of the pipe using API Level 2 assessment

Finite Element Analysis

Model description

Three dimensional (3D) finite element analyses were carried out using ABAQUS 6.11 [1] to obtain the stress state of the corroded pipes and to predict the failure observed in the field. The soil and pipe were represented by 8-noded brick reduced integration elements. The behaviour of soil was assumed as a linear elastic material. i.e., soil is assumed to be over-consolidated and behave elastically during the light traffic load (or no traffic) anticipated in the selected case study. The behaviour of the pipe was modelled using both linear elastic model as well as using a specific elasto-plastic constitutive model available in ABAQUS 6.11 [1] for grey cast iron materials. The soil side boundaries of the FE model were assumed to be smooth and are located far (i.e., 5m) from the pipe (& traffic loads) to eliminate any boundary effects. Figure 1 shows the mesh discretization (pipe elements = 41216, soil elements=41310) and model dimensions. The appropriate dimensions and the mesh density of the model were selected after a number of trials to minimise mesh and boundary effects on the calculated pipeline stresses. The FE model idealisation of the corroded pipe used to simulate the failures case has been shown in Fig. 6.

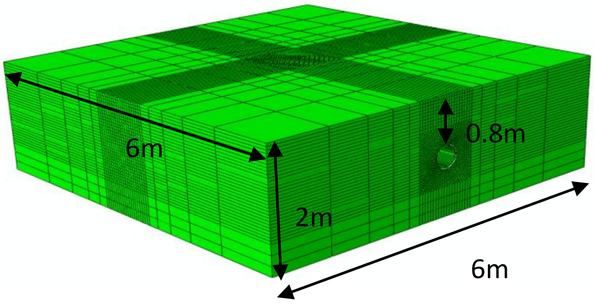
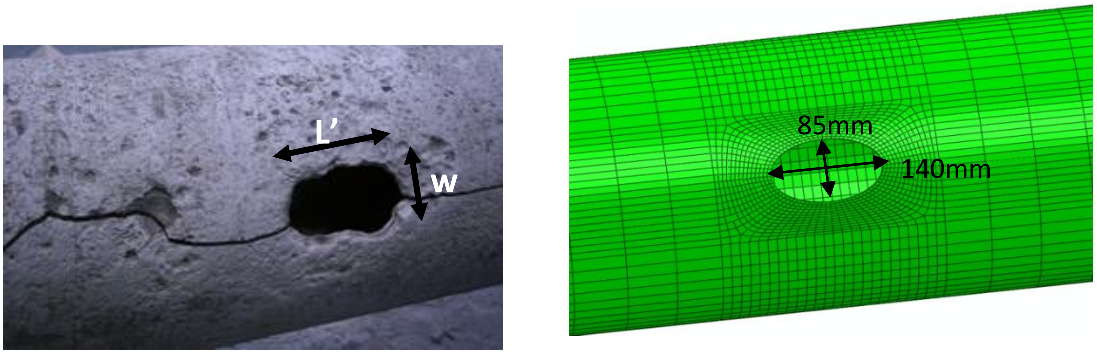


Figure 5 Geometry and mesh discretisation of the FE model



(a) Field observation

(b) FE model idealisation

Figure 6 Field observed corrosion of the failed pipe along with the FE model idealisation

Material properties

The behaviour of the pipe was modelled using both linear elastic model as well as using a specific elasto-plastic constitutive model available in ABAQUS 6.11 [1] for grey cast iron materials. The results from the linear elastic analysis can be served as a basis of comparison with the predictions from the standards which are mostly based on linear elastic material. The analyses conducted using elasto-plastic constitutive behaviour for cast iron provide much robust results which can be effectively utilised to predict the pipe failures.

The behaviour of soil was assumed as a linear elastic material. i.e., soil is assumed to be over-consolidated and behave elastically during the light traffic load (or no traffic) anticipated in the selected case studies.

The properties of the pipe and soil used in the current study are shown in table 3. The elastic-plastic properties of the cast iron material were obtained on the basis of Rajani [12]. The initial yield stress has been assumed as 20MPa as observed from stress-strain characteristics of cast iron.

Table 3 Material properties of the pipe and soil

<table>
<tr><th colspan="6">Pipe</th></tr>
<tr><th>Material type</th><th>E (MPa)</th><th>ν</th><th colspan="2">γ (kg/m^3)</th><th>Behaviour</th></tr>
<tr><td>Cast iron</td><td>76[1]</td><td>0.3[2]</td><td colspan="2">7800[2]</td><td>Elastic[1]/Elasto-plastic[1]</td></tr>
<tr><th colspan="6">Soil</th></tr>
<tr><th>E (MPa)</th><th>ν</th><th colspan="2">γ (kg/m^3)</th><th colspan="2">Behaviour</th></tr>
<tr><td>10[2]</td><td>0.3[2]</td><td colspan="2">1900[2]</td><td colspan="2">Elastic</td></tr>
<tr><td>10[2]</td><td>0.3[2]</td><td colspan="2">1900[2]</td><td colspan="2">Elastic</td></tr>
<tr><td colspan="6">Note [1] Obtained from Rajani [XX]
[2] Assumed</td></tr>
</table>

Results

The results obtained from the FE analyses for the pipe used in the case study have been presented and discussed here. The results are compared between elastic and plastic analyses and the prediction of failures is discussed on the basis of the tensile strength criteria.

Pipe stress states

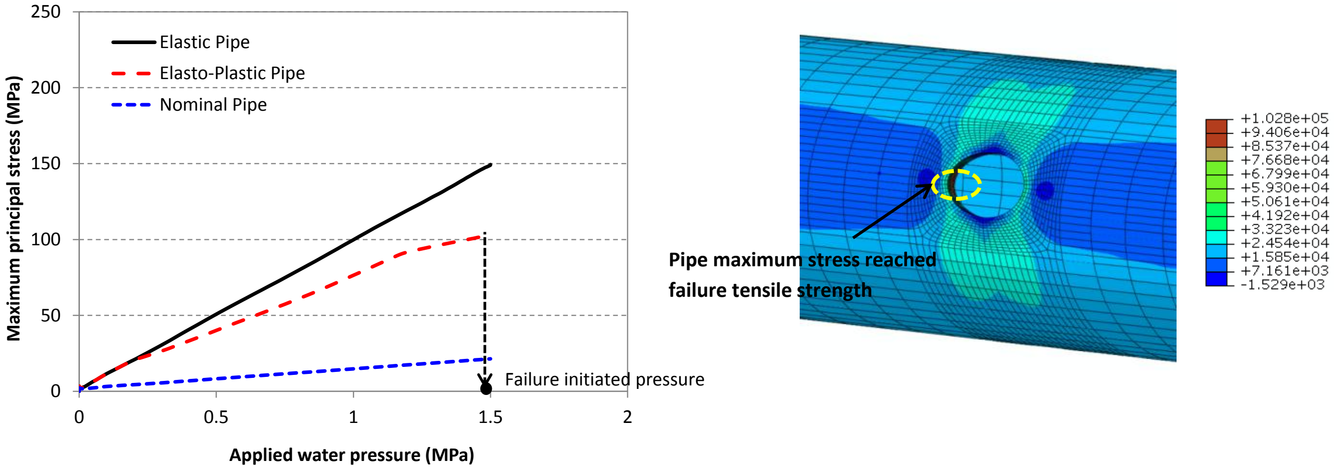
The evolution of the maximum principal stresses with applied water pressure at the critical element of the pipe is shown in Fig. 7a. It can be seen that the stress increase in pipe modelled using elastic approach is linear with applied water pressure. However the elasto-plastic modelling of the pipe behaviour has less stress increase compared to the results from elastic analyses. This is because the strain hardening modelling adopted in plasticity analyses in contrast to linear elastic approach used in the elastic analyses. The stress observed in the nominal pipe has not been affected by the plasticity as the resulted stresses due to the applied water pressure are less than the initial yield stress (20MPa) assumed in the current analyses.

The stress contours of the corroded pipe are shown in Fig. 7b, at the water pressure of 1.5MPa. It can be seen that the maximum stresses are concentrated at the location of the patch in both the cases. This reveals that there is a substantial stress concentration (factor of 7.5) can result due to operating water pressures in corroded pipes. i.e. this stress concentration causes the plastic analyses to reach the failure stresses of the pipe (shown in Fig. 7a).

Pipe failure prediction

The stress paths obtained from the plastic analyses have been shown in Fig. 8. Each of these plots shows the stress path of the critical element in the pipe in principal stress space as well as deviatoric stress space. Stress paths are derived from FE analyses data feeding into a Matlab coding that incorporates the composite yielding of the cast iron plastic model in deviatoric and principal stress spaces. The stresses of the critical element reveal that they remain elastic until reaching 20MPa and afterwards subjecting to yield (strain harden) with the evolution of plastic strains. The failure is initiated once the element stress reaches the tensile strength of cast iron material (104MPa in the current case). It is to be noted here that significant evidences are available from literature for a lower bound of the tensile strength for spun type cast iron pipes than what showed in the current study [6,7, 11]. This would argue the fact that the pipes can be failed at lower water pressures than resulted in the current FE analyses.

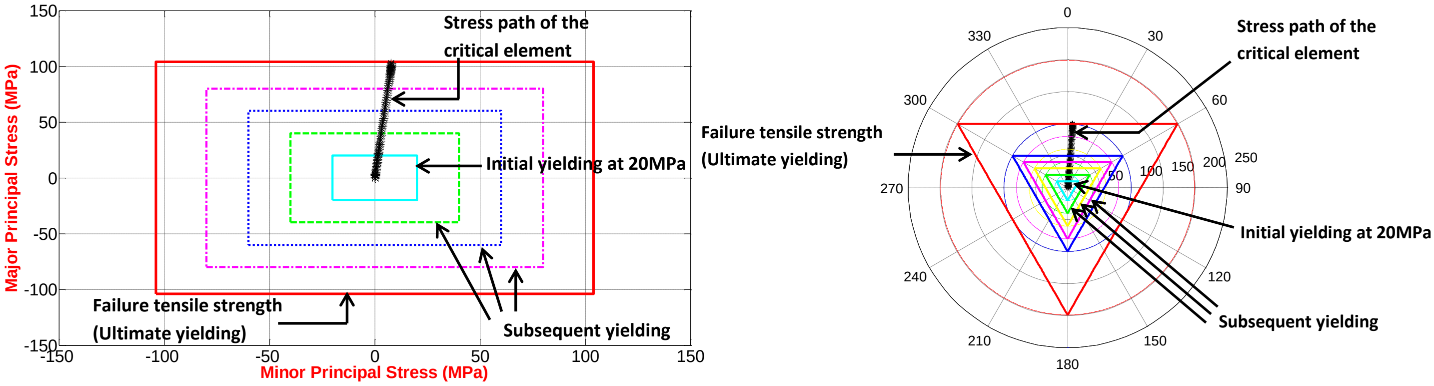
The results from plastic analyses depict that the pipe stresses reach the ultimate tensile strength of the cast iron (~104MPa in current study) at the water pressures of 1.5MPa. Pipes modelled using linear elastic model showed that a water pressure of 0.9MPa is sufficient for the pipe to reach the tensile strength capacity. Unfortunately, there is no record made in the field about the water pressures at the time of failure, but it has been reported that the failure has occurred during a valve operation event. This raises possibilities of generating high transient pressures. Ruus et al [10] has shown that the maximum pressure head rise due to sudden valve closures can be as large as $\geq 1.0 \times static\ head$ (rise will be higher for pipes with large wall friction and smaller vale operational times). Brunone et al [5] also reported that significant transient pressures can be generated due to valve operations (as high as 1MPa).



(a) Maximum principal stress evolution with applied water pressure

(b) Maximum principal stress contours of the pipe pressure

Figure 7 Stresses of the pipe using FE analyses



(a) Principal stress space

(b) Deviatoric stress space

Figure 8 Stress path of the critical element in elasto-plastic pipe of case 1 plotted in; (a) Principal stress space, (b) Deviatoric stress space

Conclusion

With the ever growing need to preserve our water delivery infrastructure, it is becoming more critical that we monitor and control these systems effectively and efficiently. The pipelines, which serve a huge role within these systems, are required to assess for anticipated failures so that any unwanted costs and social impacts can be excluded. Unfortunately, the deterioration to pipes by corrosion cannot be prevented, but is possible to assess and thus to determine their fitness for service using the codified methods. Several codes of practice are available at present (such as [2,3,4]) to determine the suitability of pipes for operation. This paper identifies and reviews all relevant standards applicable to corroded cast iron water mains with the use of some case studies. Three dimensional finite element (FE) analyses are also conducted to investigate the capabilities of simulating the failures of corroded pipelines and thus to ascertain the validity of codified methods.

Although each code under analysis successfully predicted the failure of the pipe in the selected case, it is clear that some codes are more superior to others. For instance, the assessment methods of ASME B31.G propose no alternative methods for flaw type or state. On the contrary, the British standard [4] differentiates between single corrosion and interaction/composite corrosion assessments, but it is lacking to provide differing methods for various corrosion types. On the other hand, API [2] proposes more comprehensive assessment procedures for all three corrosion types with differing levels in assessment, making it the superior fitness for service code among all relevant standards. The three dimensional FE analyses conducted herein (as a part of API suggestions) ascertained that the guidelines by API can reliably predict the corrosion induced pipe failure. It is to be noted that the current study is only limited on the failure assessments when considering common corrosion types, but not considering fracture resistance methods in detail. More rigours assessments methods are required (such as based on fracture toughness) to assess the effect of sharp flaws as recommended in [2] & [4].

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