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FAILURE PREDICTION OF PITTED BRITTLE METAL PIPES

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ABSTRACT

Numerical modelling is used to trace the development of cracks starting from pits that from on the surface of corroded, brittle metal pipe. Under internal pressure applied to the pipe, two general cracking patterns are found to occur and these are related to pit shape. The numerical analysis used allows estimation of the area of the cracked region and of the pressure under which failure occurs. These results also facilitate Stress Corrosion Cracking (SCC) studies by estimating the critical area of the crack stemming from a pit. This may result in a more realistic approach to estimating the likelihood of occurrence of critical cracks in brittle pitting corroded pipes.

KEYWORDS

Failure prediction, pitted pipes, brittle pipes.

INTRODUCTION

This paper uses numerical modelling to develop improved understanding of the effect of the shape of a corrosion pit on the initiation and development of cracking starting from the pit. Specifically it deals with pitting and cracking for pipes made from brittle materials such as cast iron.

Corrosion pits are deemed the most common sites from which cracks initiate. These sites could also host stress corrosion cracks developing under deposit and scale (Cheng 2013). In the case of ductile pipes failure is usually predicted when the through-thickness stress in the corrosion ligament exceeding the ultimate tensile strength (Bedairi, Cronin et al. 2012). Cracks stem from corrosion pits are not well investigated and documented in codes (Bedairi, Cronin et al. 2012) including API 579 (Institute 2000) and BS 7910 (Institute 2005). It has been proposed that in the case of brittle materials the assessment methods need to be further developed (Bjornoy and Marley 2001). A minimum toughness criterion has been suggested (VERITAS 2010) when failure is controlled by plastic collapse (plastic flow) (Cosham and Hopkins 2004).

Crack initiation from corrosion pits has received much research attention using both experimental and numerical studies, regardless of estimating pipes strength. For numerical and other analyses usually it is assumed that the base of a pit is the location where crack initiation occurs (Cheng 2013). Models, largely based on experimental observations, have been proposed for the pit-to-crack transition (Hoeppner 1979; Lindley, McIntyre et al. 1982; Kondo 1989; Turnbull, McCartney et al. 2006) and these include the relationships between stress condition, pit shape and the crack initiation threshold. Pit depth is the only shape parameter in these models. They also consider the pit as a small pre-existent flaw in the metal surface (Cheng 2013). This follows the assumption that material toughness is a key parameter. It is used in the formulations as the criterion for approximating the pit-to-crack transition

Numerical modelling of the stress analysis of corroded aluminium plates, which showed that for hemispherical pits the stresses usually are higher at the maximum depth of the pits (Pidaparti and Patel 2008; Pidaparti and Rao 2008). This is then the location for crack initiation. In contrast, for cylindrical pits the maximum elastic stress occurs just below the pit mouth (Cerit, Genel et al. 2009; Cerit 2013). This is also the location of the plastic zone that usually precedes crack initiation (Turnbull, Wright et al. 2010). Experimental and numerical analyses of cylindrical pits confirm that cracks usually initiate from the shoulders of pits (Horner, Connolly et al. 2011), a possibility that appears to have been reported first by Turnbull et al. (Turnbull and Zhou 2004).

As described below, in the present work various pit shapes are modelled numerically with the aim of finding and categorizing the cracking behaviour associated with corrosion pits under realistic stress conditions.

METHOD OF SOLUTION

To provide new insight into initiation and propagation characteristics of cracks stemming from corrosion pits numerical modelling of pits with different shapes is conducted. The loading on the pipe is considered to be internal pressure, which may include the effect of water hammer. The pipe is modelled geometrically as a quarter slice of pipe and this is in the neighbourhood of elliptical pits. Appropriate symmetry conditions are applied on faces A, B and D (Figure 1). Plane strain conditions are assigned to the faces parallel to the hoop stress - these faces are called A and C in Figure 1. As a result of symmetry, every section of a pipe has same deflection and no strain may occur between two sections perpendicular to axis 1 (Figure 1) (plane strain condition). In the vicinity of a pit, however, the sections obviously are not similar. It follows that plane strain condition can be assigned to the faces perpendicular to direction 2 in Figure 1, but only when they are far enough from the pit. In this regard a set of primary analyses were carried out to find the size of the model on which plane strain condition can be applied.

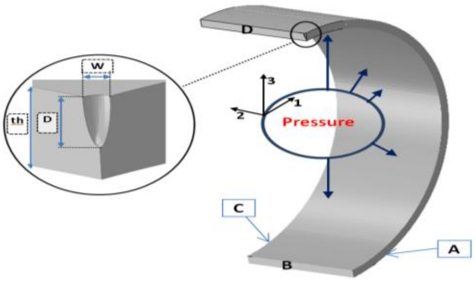

Figure 1. Modelled quarter of a pipe slice

For the numerical modelling of pitted corroded pipes Abaqus 6.11-2 was used. Extended finite element method (XFEM) with cohesive behaviour and linear hexahedral elements were employed in the analyses.

Material properties were adopted from references (Seica and Packer 2004; Spiteri, Ho et al. 2007). The Maximum Principle Stress criterion was used for crack initiation since this criterion is widely accepted for brittle materials (Abaqus 2011). Values of 80 GPa, 0.3 and 80MPa are assigned to Young’s modulus, Poisson’s ratio and Maximum Principal Stress, respectively. The energy release rate was assumed to be 2500 J/m2 in all modes.

RESULTS AND DISCUSSIONS

Crack Initiation and Propagation near a Pit

Regarding the location of crack initiation, a crack may start from top of the pit, namely crack shoulder (Figure 2) or from the bottom of the pit (Figure 2).

The results show that cracks propagate in a plane perpendicular to axis 2 (Figure 2) and start either from the shoulder or from the bottom of the pits. This planar development is expected due to the symmetry in pit shape, pipe and loading. After initiation, the crack propagates along the pit wall. Once it reaches the end of the pit wall, the crack grows with a greater rate at the top, thereby making it more inclined with respect to the pit wall. This behaviour can be tracked in Figure 2-c to Figure 2-g. Eventually, the crack penetrates completely through the wall (Figure 2-g) - let this be termed a fully penetrating crack. As shown in Figure 2-h the crack front tends to become parallel to axis 3. This then facilitates the crack propagating further in an opening or tension mode (which has been termed Mode 1 (Sun and Jin 2012)).

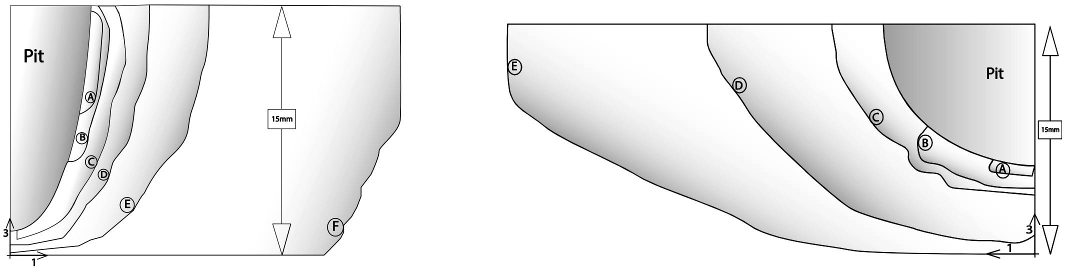

Figure 2. Process of crack initiation and propagation from pit shoulder (left) and from bottom of a pit (right)

When crack initiates from bottom of a pit a generally similar process of crack development is observed. The main difference is the specific location and the precise direction of cracking. Figure 1 shows the propagation of a crack of this type near a pit.

It should be clear from the above that the type of crack emerging from a pit depends very much on the pit shape. The location from which a crack initiates is dictated by stress field in the vicinity of a pit and this stress field is determined by the pit shape. Both the ratio of W to D and D to T (Figure 1) are important in this regard. Table 1 summarizes the type of crack formation that occurs as a function of the pit geometry factors W/D and D/T for pipes under internal pressure.

The crack type emerging from a pit in a pipe wall also is slightly different when tensile stress is applied to a plate far from the pit compared with the case of tensile stress in a pipe wall resulting from applied internal pipe pressure. This is despite the fact that hoop stress (which is inherently tensile stress) is the most important factor in pressurized pipe cracking (Cheng 2013). Therefore, it can be inferred that for pipes hoop stress is not the only stress of importance and that other stresses resulting from internal pressure play a role in crack initiation. Table 1 shows the crack types that occur for pits under local conditions of uniform tensile stress applied far from the location of the pits.

Table 1. Crack type versus pit shape parameters (I: crack initiates form pit shoulder and II: crack initiates from bottom of the pit) (Left: Pipe, Right: Plate)

	D/T		
W/D	0.4	0.6	0.9
0.3	I	I	I
0.5	I	I	II
0.7	I	I	II
1	I	I	II
2	II	II	II

	D/T		
W/D	0.4	0.6	0.9
0.3	I	I	I
0.5	I	I	I
0.7	I	I	I
1		I	
2	II	II	II

There is also considerable difference between the form of propagation in last stages of crack growth under the condition of tensile stress resulting from pipe internal pressure. Analyses show that in the case of internal pressure, the crack front generally has a greater tendency to become parallel to axis 3 (Figure 2). This implies that the resultant shear stress due to internal pressure helps the crack to transfer into mode I (opening or tension mode of cracking, and in which two crack surfaces move away symmetrically with respect to the 1-3 plane (see Figure 2).

Growth of the area of cracked surfaces depends strongly on pit shape. Crack growth rate increases considerably with parameter W/D, as illustrated in Figure 3. For a constant W/D, shallow pits are more likely to lead to crack growth than do the deeper pits (Figure 3). Analyses show a dramatic growth in the rate of crack propagation after the fully penetrated state has been reached (recall that this is defined above as the condition that a crack has reached the internal surface of the pipe). These observations lead to the general conclusion that pipe strength against internal pressure declines rapidly when the crack has fully penetrated to the internal pipe wall surface. The points at which the fully penetrating state occurs are shown on Figure 3.

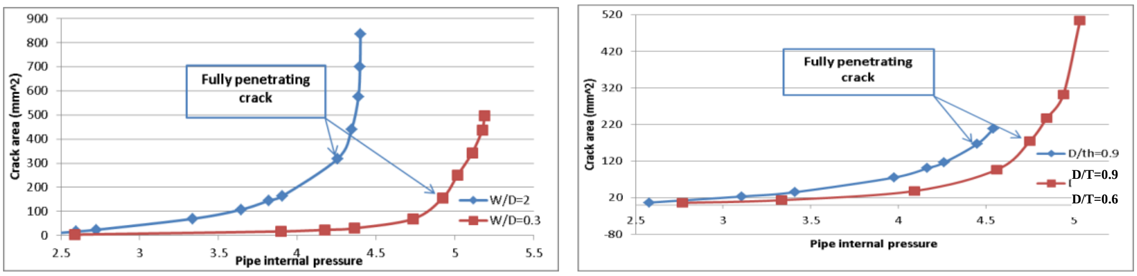

Figure 3. Area of cracked region versus pressure (Left: D/T=0.6, Right: W/D=0.5)

At the full penetration state the area of the cracked region is almost the same for D/T = 0.9 and D/T = 0.6. However, the area increases with W/D in the case of shallower pits (D/T=0.6).

Pipe Strength versus Crack Propagation Near Pits

Two levels of pipe internal pressure are discussed in this section - the pressure under which a crack initiates, P0 and the pressure that causes fully penetration of the crack, P1.

Figure 4 shows the dependence of P0 on W/D and D/T. It shows that for narrower pits P0 depends to an increasing extent on pit depth Figure 9 also shows that when W/D is 0.3 then P0 is almost independent of pit depth. Further, P0 declines when pits become wider and the rate of decrease is greater when they are deeper.

The full penetration state of cracking (Figure 2-g and Figure 2-h) is crucial in the study of cracking behaviour of pitted brittle pipes. This is due to the fact that the contents of the pipe can leak out, but of course only after this stage is reached. Moreover, as Figure 3 illustrate, the area of the cracked region increases rapidly when the crack reaches the internal surface of the pipe (fully penetrating condition). As a practical result it may be assumed that almost negligible pipe resistance can be considered to apply when the crack has become fully penetrating. Finally, a fully penetrating crack is a prerequisite for running crack, due to the fact that a running crack completely penetrates through the pipe wall thickness. In this sense if the existence of a fully penetrating crack is probable on a brittle pipe, then the pipe is likely to be susceptible to running cracks.

As shown in Figure 4, P1 depends both on W/D and D/T. The two plots in Figure 4 tend to approach one point when the geometry of the pits becomes narrow (i.e. smaller W/D) and the plots trend to become more separated when the pits become wider (i.e. larger W/D). Figure 4 also shows that P1 decreases with a slightly greater rate when W/D increases, particularly in the case of deeper pits (i.e. those with larger D/T).

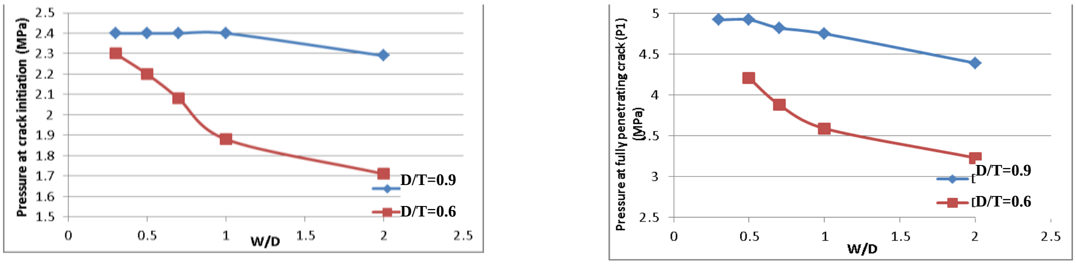

Figure 4. Pipe internal pressure initiates crack and internal pressure resulting in fully penetrating crack versus W/D

Discussion

As noted above the base of the pit usually is taken as the location of crack initiation from pits (Cheng 2013). Also, pit-to-crack transition models (Hoeppner 1979; Lindley, McIntyre et al. 1982; Kondo 1989; Turnbull, McCartney et al. 2006) conventionally apply an empirical, experimentally-derived relation between stress condition, pit shape and the possibility of crack initiation. The only shape parameter incorporated by these models in estimation of the crack initiation threshold from a pit is that of pit depth. In contrast to this classical approach, the results presented herein show that, in addition to pit depth, the parameter W/D (width to depth ratio) also is a substantial factor in crack initiation and in the development of the resulting pattern of crack growth. Further, it follows that since the location of the initiation of a crack depends both on width and on the depth of the pit, it would be more realistic for the models to be applied so as consider pit growth both in the horizontal and in the vertical directions.

It is possible that some of the inconsistencies noted in the various reports are the result of only limited ranges of pit shapes and geometries having been used in the various experimental studies. Typically the tests considered one or only a few materials. The most likely result of this is that the shapes of the pits considered inn these studies were almost same. If, as shown herein, crack initiation is highly dependent of pit shape, the discrepancy between the previous results obtained for different metals most likely is due to differences in those studies of corroded surface geometry and boundaries, loading conditions for the test and the history of loading used for the specimens. In the case of loading condition, for example, although hoop stress plays the main role in crack initiation from pits on a pipe, other resultant stresses due to pipe pressure can play a role in determining the location of crack initiation. The differences between the locations of crack initiation can be seen by comparing the results in Table 1.

The results presented herein show that the pressure (P0) required to start a crack from a pit varies through the life time of the pit as it grows and changes in shape. Both pit depth and pit mouth widths are important particularly when pits become deeper. This is illustrated in Figure 4 where increasing pit depth causes P0 to decrease. However, P0 increases when W/D is reduced to 0.3. This implies that a narrow and deep pit (say W/D=0.25, D/T=0.9) may host a crack at a lower stress state than a wide and shallow pit (say W/D=2, D/T=0.6).

Figure 3 shows that in many cases a crack initiating from a pit needs to grow considerably before becoming a critical crack (cf. (Meyers and Chawla 2009; Wei 2010)). This implies that irrespective of whatever other factors might be involved in a practical case of development of crack size, both W/D and D/T need to be sufficient to result in a large cracked area before failure can occur. In this regard, the cracked area at P1 is the minimum area under which the critical cracked condition can occur.

CONCLUSIONS

The present results using detailed finite element modelling show that the location where cracks initiate relative to corrosion pit geometry depends largely on the pit geometry, as defined by W/D (ratio of mouth size to depth) and by D/T (ratio of depth to pipe thickness). It is not always the case, as often assumed, that cracks initiate at the pit base.

It was found that pit-to-crack transition modelling can be improved if pit growth in both horizontal and vertical directions is considered. It was also found that the loading condition has a significant effect on the way cracks develop from pits and that stress resultants other than hoop stress can influence the location of crack initiation. This is considered the reason results obtained from experimental tensile tests on pitted plates cannot be generalised to pitted pipes.

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