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An experimental investigation of the effect of defect shape and orientation on the burst pressure of pressurised pipes

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ABSTRACT

The burst pressure of commonly used ductile steel pipes in oil and gas industries, i.e. X52 and X60, is measured under internal pressure loading. The pipes were machined with circular and boxed defects at different orientations to simulate actual metal loss defects. Defect shapes and orientations were investigated in detail to study how they affect the failure behaviour of interacting defects. The experimental burst pressure results were compared with those obtained using existing analytical methods from Design Codes. Comparison of the results showed conservatism in the existing analytical methods which may potentially lead to unnecessary plant shutdowns and pipe repairs. The outcome of the experimental tests revealed that the shapes of the defects have very small influence on the defect interaction behaviour. The burst tests interestingly showed that the defect orientation has an important effect on defect interaction. Defects oriented in the hoop and diagonal directions showed no defect interaction even when spaced by a distance of one wall thickness, while defects oriented in the longitudinal directions showed that defects interact even when the spacing is up to six wall thickness but the interaction fades away for defects spaced at longer distances.

1. Introduction

Metal loss defects as a result of corrosion, both internal and external, are insidious forms of pipe damage that have the potential, when unrecognized, to result in premature pipe failure. Corrosion defects occur in the form of single and cluster defects with each having different consequences, either localised leak or rupture. Between 2010 and 2013, pipe failures due to corrosion and material degradations resulted in financial loss of more than $466 million of estimated total costs to gas pipe network operators [1]. The ability to predict the failure pressure of each of these forms of corrosion defects is extremely valuable to pipe operators to safeguard integrity. Better understanding of pipe failure also paves the way to improvements in future repair and maintenance related strategies.

Defect assessment has been researched since the 1970's right up to the present time. In chronological order, a number of examples, both experimental and numerical, are given in references [2–15]. The most widely used code for single defect assessments is ASME B31G which utilizes semi-empirical method [16]. However, this code provides no guidance for assessing defects that are closely spaced to each other. Interacting defects that are sufficiently spaced close to each other, result in failure pressures that are

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lower than those for single or individual defects and tend to fail in a rupture manner. API 579 formulae were derived from the modified ASMEB31G code as the origin where these were considered in detail in the study.

The DNV RP F101 code [17] recommended practice is widely used in industry for predicting the failure pressure of both single and interacting defects. Though both codes are widely used in the oil and gas sectors, conservatism in evaluating the safe working pressure has been cited in several research works [7, 10, 14, 15, 18–20]. Literature reviews [21–23] have indicated that around 360 pipe burst tests have been conducted since 1970. The vast majority of these tests were mainly conducted on single defects. There are a few experimental burst projects carried out on interacting defects, such as the early work of Mok et al. [24] in 1990 and, more recently, Freire José et al. [25] in 2013. Due to insufficient data available on parameters such as defect dimensions, actual vs nominal pipe wall thicknesses and material properties, it is difficult to replicate the majority of the tests referred to in the literature for further research. The work described herein is aimed at analysing, for the first time, experimentally the sensitivity of the shapes and orientations of interacting metal loss defects in two different grades of ductile carbon steel, X52 and X60, commonly used in the oil and gas industries. An internal pressure is applied in closed-end pipes until burst occurs. The applied pressure increases the likelihood of failure being controlled by the stress state in and around the vicinity of the machined defects leading to two modes of failures; either local leak or rupture if the defects are interacting.

2. Defect assessment codes and recommended practices – single and interacting

The manual of corrosion defect assessment was initially published in 1984 by the American Society of Mechanical Engineers (ASME) following extensive work by the American Gas Association (AGA) in the early 1970’s [5]. AGA carried out experiments on pipes with various sizes of single corrosion metal loss defects to develop methods for predicting burst pressures. The ASME B31G committee further validated the methodology adopted by AGA through an experimental program of 47 full-scale tests of pipelines containing actual corrosion defects [21]. Unfortunately, specific details with regards to the defects morphology and steel mechanical properties used are not available. The tests performed were limited up to API 5 L Grade X52 pipelines with a diameter of 762 mm and up to a wall thickness of 9.5 mm [26]. Both the 1984 and 1991 revisions of ASMEB31 are described by several papers, see for example [27, 28], as overly conservative methods as they have the following limitations:

- They take into account only the specified minimum yield strength (SMYS) compared to the value of the ultimate tensile strength of the material, which is in fact the dominant material property for the rupture of pipes made from reasonably tough materials in areas with blunt metal losses and when cracks are not present.
- They are not valid for defects occurring in welds or heat affected zones.
- They are based on single defects with a parabolic shape.
- They give conservative results for long defects, as any defect with a length greater than $(20\ Dt)^{0.5}$, where D is the external diameter and t is the wall thickness, is considered as an infinite defect. In other words, the values for burst pressures predicted for longer defects are excessively low. The main reason for the conservative estimation of the burst pressure is the hypothesis of infinite length mentioned above together with the expressions adopted to calculate the flow stress.

The failure pressure (P_f) based on the original ASME B31G-1984 is calculated as per the below equations.

For short length defects that have parabolic shapes where L is ≤ $(20\ Dt)^{0.5}$, the failure pressure, P_f, is defined by the following equation:

$$P_f = \frac{2\,(1.1\,\sigma_y)\,t}{D}\left[\frac{1-\frac{2d}{3t}}{1-\frac{2d}{3tM}}\right] \tag{1}$$

where, D is the external diameter, t is the wall thickness, σ_y is the Specified Minimum Yield Strength (SMYS), and M is the Folias Factor (Bulging Factor).

For longer length defects that have rectangular shapes where L is > $(20\ Dt)^{0.5}$, the failure pressure, P_f, is calculated by the following equation:

$$P_f = \frac{2\,(1.1\,\sigma_y)\,t}{D}\left[\frac{1-\frac{d}{t}}{1-\frac{d}{tM}}\right] \tag{2}$$

The Folias factor, bulging factor, M is a geometric parameter developed to account for the stresses induced by the bulging which occurs at the corrosion defect of a pressurised pipelines [29]. For the above failure pressure cases, M is calculated by the following equation:

$$M = \sqrt{1 + 0.6275\frac{L^2}{Dt} - 0.003375\left(\frac{L^2}{Dt}\right)^2} \tag{3}$$

Based on further experiments, ASME B31G was revised in 1991 [30], by modifying both the Folias factor and the failure pressure for long defects as follows: