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DEVELOPMENT OF AN ALTERNATIVE CRITERION FOR RESIDUAL STRENGTH OF CORROSION DEFECTS IN MODERATE- TO HIGH-TOUGHNESS PIPE

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ABSTRACT

This paper presents the development of a new, simplified criterion, known as PCORRC, for prediction of the remaining strength of corrosion defects in moderate- to high-toughness pipeline steels that fail by plastic collapse. Comparisons against an experimental database indicate that, when toughness is sufficient, the PCORRC criterion reliably predicts the remaining strength of blunt defects using only the maximum depth and maximum length of the defects with less excess conservatism than existing criteria. The value of PCORRC is demonstrated in comparisons that show it capable of reducing excess conservatism significantly in the class of defects that fail by plastic collapse, potentially resulting in significant reductions in pipeline maintenance and repair costs. This new criterion was developed at Battelle under sponsorship of the Line Pipe Research Supervisory Committee of PRC International.

The new simplified criterion was developed from a finite-element software analysis model. The analysis software was applied in a parametric investigation to evaluate the influence of geometry and material characteristics on the remaining strength of corrosion defects in moderate- to high-toughness steels that fail by plastic collapse. The model development and parametric investigations demonstrated that

- The failure of this class of defects is controlled by the ultimate tensile strength rather than yield strength or flow stress
- Defect depth and length are the most critical defect geometry variables
- Defect width and material strain hardening are of lesser importance.

NOMENCLATURE

D = Pipe diameter
d = Maximum depth of the defect
L = Maximum length of the defect
P_d = Predicted failure pressure of a blunt corrosion defect in moderate- to high-toughness steel
P_P = Upper limit failure pressure of unflawed pipe
P_{LL} = Nominal lower limit on failure pressure of flawed pipe
R = Pipe radius
t = Pipe wall thickness
t^* = Remaining ligament wall thickness in the defect ($=t-d$).
σ_u = Actual ultimate tensile strength of the pipe when predicting actual failure pressure; Specified minimum ultimate tensile strength of the pipe when determining the suitability of defects to remain in service.

INTRODUCTION

Corrosion is an ongoing problem for aging pipelines that can threaten both the structural integrity of the lines and the reliability of oil and gas delivery. The pipeline industry spends millions of dollars annually performing in-line inspections, excavating sites of possible corrosion, and repairing or replacing damaged sections of pipe. Decisions on which sites to excavate and which sections of pipe to repair or replace are based upon integrity criteria, which are used to estimate the remaining strength of the corroded areas of pipe. When these criteria are excessively conservative in predicting remaining strength, unnecessary excavations and other unnecessary remedial actions may occur, thus increasing maintenance costs. In order to control maintenance costs and maintain reliable throughput, pipeline operators need reliable criteria for evaluating the remaining strength of pipeline corrosion defects that ensure safe operations but avoid excess conservatism.

The two primary criteria currently in widespread use by the pipeline industry for evaluation of the remaining strength of corroded pipe are the ASME B31G "Manual for Determining the Remaining Strength of Corroded Pipelines" [1] and PRC*I* RSTRENG software [2]. These criteria are typically conservative when compared against the experimental burst test database, are accepted by regulators, and are widely used for assessing the remaining strength of piping and pressure vessels. While conservative for most pipelines, a number of investigations have shown that they can be excessively conservative when applied to defects in modern, high-toughness pipeline steels [3, 4].

Under the sponsorship of PRCI, Battelle has extended its investigation of the remaining strength of blunt and sharp flaws in pipe to develop a new, simple equation, known as PCORRC, for predicting the remaining strength of corrosion defects in moderate- to high-toughness steels that fail by the mechanism of plastic collapse [5].

CRITERION DEVELOPMENT STRATEGY

This new criterion was developed systematically, beginning with an assessment of the potential failure mechanisms of corrosion defects and identification of the potential variables which may control their behavior. This was followed by the development and validation of a comprehensive PC-based finite element model for remaining strength of corrosion defects. The validated model was exercised in a parametric investigation to understand and evaluate the influence of the variables on plastic collapse failure of corrosion defects. Finally, a simplified criterion was developed by assembly of an algebraic expression that reliably embodies the interaction and relative contribution of each of the primary contributing variables. This was done methodically, considering first the limiting cases and then the functional form of the algebraic relationship. The resulting model, known as PCORRC, and its validation are described in detail in Reference 5. The remainder of this paper is organized as follows:

- Potential failure mechanisms of pipeline corrosion defects
- Potential factors controlling plastic-collapse failure of blunt pipeline defects
- Parametric investigation of the factors controlling failure
- Development of the PCORRC simplified criterion
- Experimental validation
- Application of the PCORRC criterion
- Closure

POTENTIAL FAILURE MECHANISMS OF PIPELINE CORROSION DEFECTS

One of the motivating factors for the development of the remaining strength criterion described in this paper is the recognition by a number of authors that existing ASME and RSTRENG criteria may be excessively conservative for assessment of corrosion defects in modern high-toughness pipe [3,4]. In investigating the reason for the conservatism of these well established criteria on higher toughness pipe, evidence was found that suggests corrosion defects in low toughness pipe may fail by a different mechanism than defects in moderate- to high-toughness pipe. Research outlined in Reference 5 shows that corrosion defects in moderate- to high-toughness pipe fail by plastic collapse and their strength is controlled by their material's ultimate tensile strength. Plastic collapse failure occurs by unstable plastic flow of material, like that occurring after necking in a tensile specimen.

The research summarized in Reference 5 further suggests that corrosion defects in low toughness pipe may fail by a fracture-based mechanism that is controlled by the material's toughness. These toughness-controlled defects tend to fail at lower pressures than strength-controlled defects with otherwise comparable geometries. Remaining strength criteria applicable to defects in low toughness pipe are typically based upon flow stress, a material parameter that falls between the materials yield and ultimate strength. The ASME B31G and PRCI RSTRENG criteria were empirically calibrated against an experimental database that included low and medium toughness pipe, such that they are typically conservative in predicting failure of defects in most pipe.

The new criterion described in this paper was developed for defects which fail by plastic collapse and, consequently, is only applicable to defects in moderate- to high-toughness materials. This is consistent with the approach adopted by other North American and European investigations [3, 6]. The experimental database currently does not have sufficient data to define a conclusive lower bound toughness for plastic collapse failure. Fracture mechanics suggests that low toughness behavior of corrosion defects is a function of strain hardening characteristics, toughness and notch acuity. More research is needed on this topic. For the purposes of this investigation, the following preliminary and intentionally conservative lower bound for plastic collapse failure of defects in moderate- to high-toughness pipeline steels is proposed. Plastic collapse failure is expected to occur in defects in pipe which 1) is operating above its ductile-to-brittle transition temperature (85 percent shear area) and 2) has full thickness Charpy energies of 45 ft-lb or greater at the lowest expected temperature of operation. This preliminary definition of a lower bound is proposed based upon the Battelle's conservative assessment of best available information and may be refined as new analyses and data are developed.

POTENTIAL FACTORS CONTROLLING PLASTIC-COLLAPSE FAILURE OF BLUNT PIPELINE DEFECTS

Evaluation of the integrity of corroded pipe can be viewed as having two components, as illustrated in Figure 1, 1) local "forces" driving the failure (or damage) process, and 2) material resistance to failure. Failure of a corrosion defect occurs when the driving forces exceed the material resistance. Because most corrosion defects are blunt, the local driving force is assessed in terms of local stress and strain. Likewise, the material resistance (failure criterion) should be expressed directly in terms of such local stresses and strains. Table 1 lists specific parameters most likely to have some influence on the behavior of corrosion defects that fail by plastic collapse.

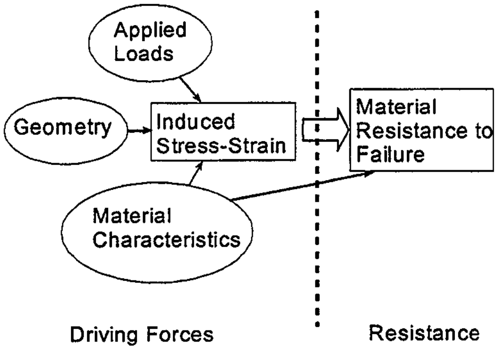

Figure 1. Schematic of the primary factors controlling behavior of corrosion defects.

PARAMETRIC INVESTIGATION OF THE FACTORS CONTROLLING FAILURE

Prior to developing a simplified criterion, a comprehensive PC-based finite element model for remaining strength of corrosion defects, known as PCORR, was developed and validated against the experimental database. Figure 2 shows a comparison of actual failure pressures for corrosion defects in moderate- to high-toughness steels versus failure pressures predicted by PCORR. Further discussion of its theoretical development and its validation are described in Reference 5. This finite element model was exercised in a parametric investigation to understand and evaluate the influence of the variables in Table 1 on plastic collapse failure of corrosion defects. Following is an overview of a parametric investigation using the PCORR analytical software model and the implications of the results for modeling the plastic collapse failure of pipeline corrosion defects. Unless otherwise noted, the results are shown for defects assumed to be in 24-in. diameter × 0.281-in. wall thickness, X52 line pipe with material constants from Table 2.[1]

Defect Dimensions

Figure 3 shows the predicted failure pressure for square, uniform depth defects over a range of defect lengths. Results are shown for uniform depths of 20, 50, and 80 percent. Failure pressure is shown to decrease with increasing defect size until a lower plateau is reached. For uniform depth defects, the plateau pressure is proportional to the defect depth. Not surprisingly, this confirms that defect depth is the primary defect geometry variable controlling failure pressure of uniform depth defects.

One of the early reasons for the development of a comprehensive finite-element model for blunt defects was to evaluate the influence of width and other variables not addressed by currently available empirical models. Figure 4 shows the predicted failure pressure for a range of rectangular, uniform 50 percent deep defects. Each line in the figure represents a different defect width. The burst pressure for this pipe without defects is predicted to be approximately 1780 psi. The results in Figure 3 demonstrate that the defect length is a primary variable, as changing the length can change the failure pressure by as much as 50 percent for a 50 percent deep defect. The results show, however, that width is a secondary variable. In this example, varying the width from 0.5 inches to 12 inches may alter the failure pressure less than 5 percent of the pipe burst pressure. Note that this observation is only true for defects loaded only by internal pressure. Width is a primary variable when axial loads are significant [7, 8].

Defect Shape

Figure 5 shows a basic comparison of results for square, uniform depth defects with defects whose profile is elliptical in both the axial and circumferential direction. There is more wall thickness remaining under the elliptical profile, resulting in a "stiffer" defect than the uniform depth defect. The results in Figure 5 suggest that general defect shape is more important parameter for deeper defects. In this analysis, the difference in failure pressures for elliptical and uniform depth defects can be as much as 5, 11, and 17 percent for 20, 50, and 80 percent deep defects, respectively. Hence, defect shape is generally more important than defect width, particularly for deep defects.

In conjunction with this parametric investigation, selected analyses were performed for defects using measured depth profiles for comparison against assumed profiles. The results of these analyses suggest that reliable failure predictions can be achieved for defects in moderate- to high-toughness pipe which fail by plastic collapse without the need for detailed measurement of the defect depth profile. This observation is discussed in more detail in Reference 5.

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[1] Note that blunt defects in the X52 material in this table were found to fail by plastic collapse, although their Charpy upper shelf energy was 32 ft-lbs. Nevertheless, a value of 45 ft-lbs is recommended as a lower bound toughness for plastic collapse until additional research to establish a conclusive lower bound is completed. The lower bound may be a function of other parameters such as strain hardening characteristics and notch acquity.

Table 1. Parameters likely to influence the behavior of blunt pipeline defects that fail by plastic collapse.

Applied Global Loadings	Geometry	Material Characteristics
Internal pressure Uniform axial loads (tensile or compressive) Bending moment	Pipe dimensions Diameter Wall thickness Defect geometry Depth Length Width Shape/irregular profile	Yield strength Ultimate tensile strength Plasticity/strain hardening Fracture toughness

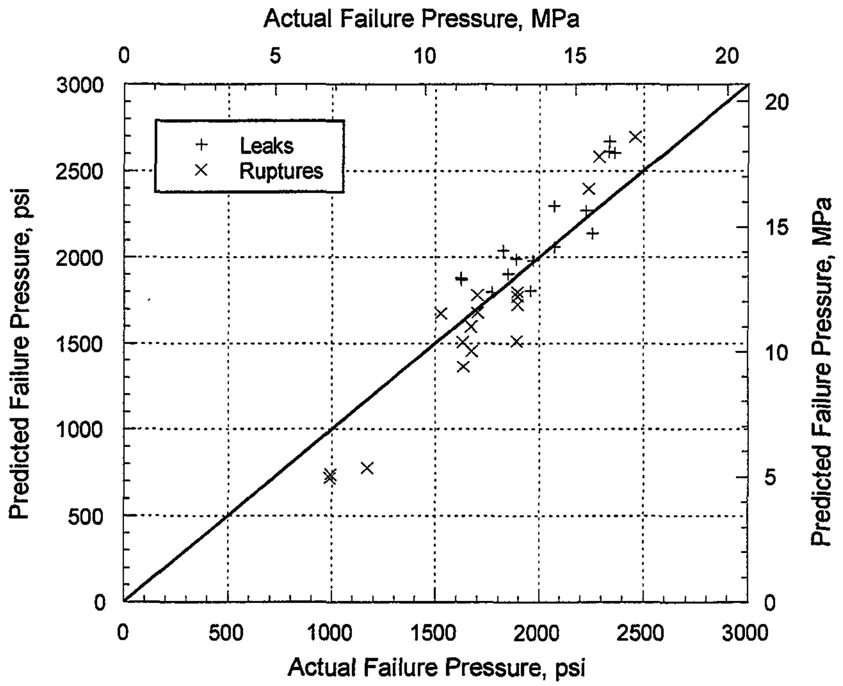

Figure 2. Comparison of actual failure pressures for corrosion defects in moderate- to high-toughness steels versus failure pressures predicted by PCORR finite element software using actual material properties.

Table 2. Example mechanical and fracture properties for some well characterized pipeline steels.

Grade	Yield Stress, ksi (MPa)	Ultimate Tensile Stress,ksi (MPa)	Charpy Upper-shelf Energy (ft-lb)	Strain Hardening Coefficient (=1/*n*)
X52	59.6 (411)	73.6 (508)	32	0.0832
X65	70.1 (483)	90.6 (625)	122	0.0881
X70	76.1 (525)	87.2 (601)	70	0.08564

Note: See Reference 5 for further discussion of these properties.

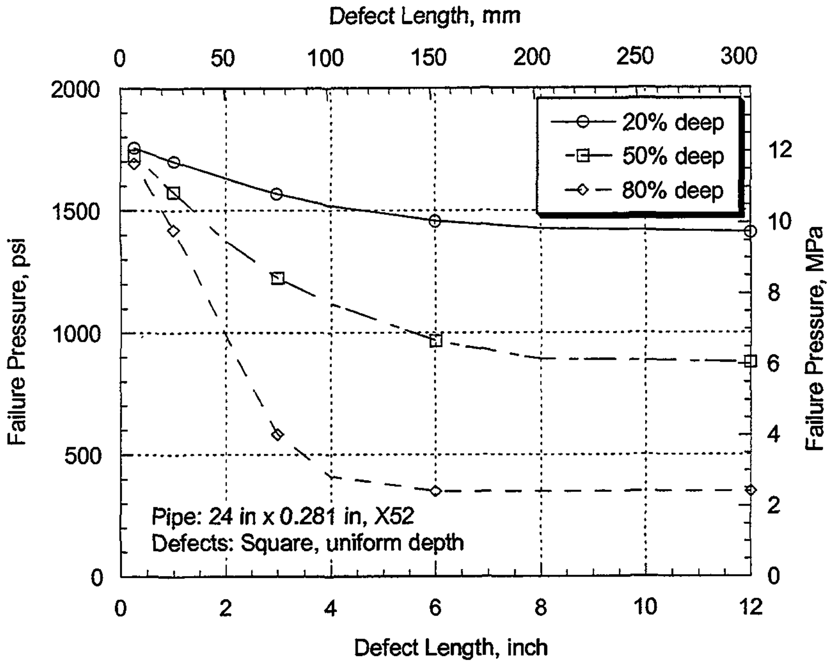

Figure 3. Parametric evaluation of the influence of defect depth on failure pressure.

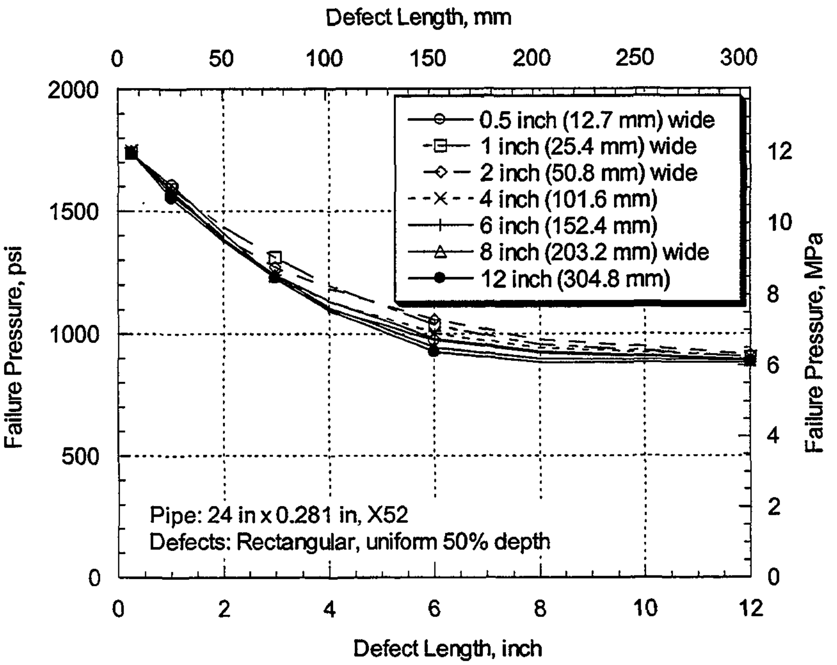

Figure 4. Parametric evaluation of the influence of defect length and width on defect failure pressure.

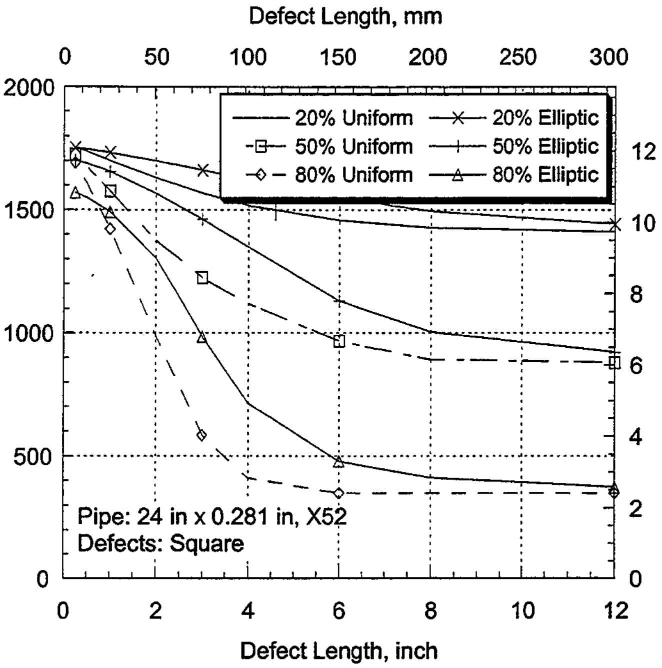

Figure 5. Comparison of the influence of uniform depth and elliptic shape on defect failure pressure.

Material Characteristics

Analyses described in Reference 5 indicate that the remaining strength of defects which fail by plastic collapse is controlled by their ultimate strength. Figure 6 shows the implications of this result by nonlinear plasticity analysis of square, uniform, 50 percent deep defects for the three different pipeline steels in Table 2. As shown in the table, the yield strengths of the X52, X65, and X70 materials are 59.6, 70.1, and 76.1 ksi, respectively, and the strain hardening coefficients for the three materials are similar. Also, the ultimate tensile strength of the X65 material is higher (90.6 ksi) than that of the X70 material (87.2 ksi). Figure 6 shows that the difference in failure pressure for the three materials is fairly constant across the range of defect sizes, indicating that there is little interaction between these material properties and defect size. The results show, however, that the failure pressure of defects in X65 material is predicted to be higher than that in the X70 material because the ultimate tensile strength is higher. These results indicate that yield strength, flow stress, strain hardening and material plasticity are much less important than ultimate tensile strength to defects which fail by plastic collapse.

DEVELOPMENT OF THE PCORRC SIMPLIFIED CRITERION

The results of the parametric investigation demonstrate that a number of variables can influence the remaining strength of blunt corrosion defects that *fail by plastic collapse*, each to a differing degree. The results suggest that the variables can be ranked on the basis of their relative contribution to remaining strength of these defects in the following order:

- Internal pressure
- Pipe diameter
- Wall thickness/defect depth
- Ultimate tensile strength
- Defect length
- Defect shape characteristics
- Yield strength/strain hardening characteristics
- Defect width
- Fracture (Charpy) toughness.

Note that toughness is last on this list because, as long as toughness is sufficient to ensure plastic collapse, its has little additional influence on failure pressure for this class of defects. This, of course, is not true for toughness controlled defects in low toughness materials.

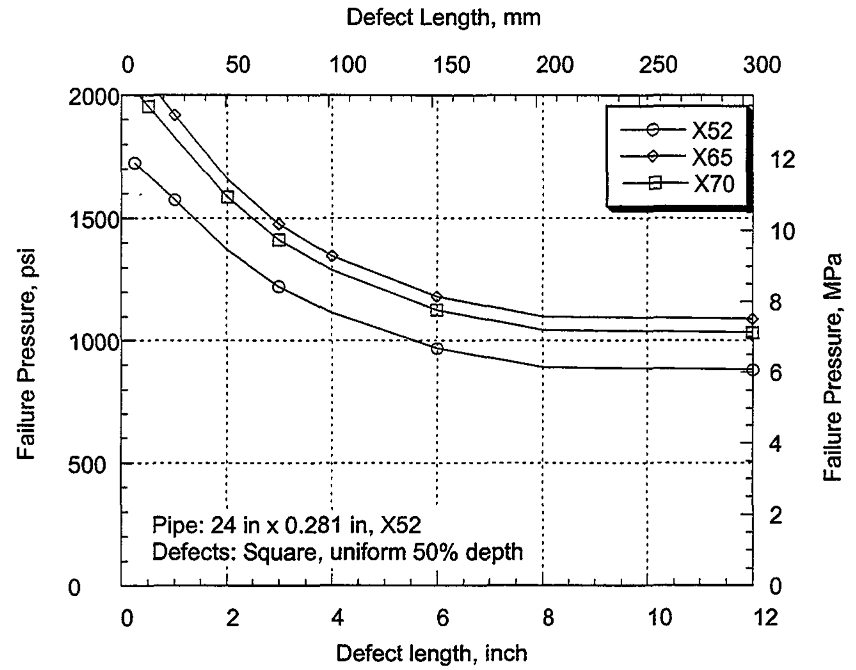

Figure 6. Comparison of failure pressures for three different pipeline steels.

Material Resistance to Failure

In developing a simplified criterion, consider first the two limiting cases of very small defects and very large areal defects. A sufficiently small defect does not appreciably influence burst conditions. Hence, the upper limit on failure is the failure pressure of unflawed pipe. As described in Reference 5, this failure pressure occurs at a nominal hoop stress level typically 2 to 6 percent greater than the ultimate tensile strength of the pipe. For the purposes of a simplified criterion, then, we recognize that the controlling limit is the ultimate strength, and we adopt it as the failure reference stress. Recognize also that the lower limit on failure pressure of a defect of depth d is the failure of a large areal patch whose failure pressure is proportional to the remaining wall thickness t* given by

$$P_{LL} = P_P \frac{t^*}{t} = P_P\left(1-\frac{d}{t}\right) = \sigma_u \frac{2t}{D}\left(1-\frac{d}{t}\right) \qquad (1)$$

In this case, the defect is sufficiently large that it behaves as if it were a pipe of thinner wall. The evaluations of defect depth in Figure 3 and of shape in Figure 5 suggest this is true for defects of length greater than $6\sqrt{Rt}$.

Modeling of the Fundamental Driving Forces

Obviously, corrosion defects come in all sizes and are not limited to the very large or infinitesimally small. Figures 3 through 6 suggest that the failure pressure of defects which fail by plastic collapse in moderate-to-high toughness pipe, P_d, can be written in an expression of the general form:

$$\begin{aligned} P_d &= P_P\left(1-\frac{d}{t} f\,(\text{geometry}, \text{material})\right) \\ &= \sigma_u \frac{2t}{D}\left(1-\frac{d}{t} f\,(\text{geometry}, \text{material})\right) \end{aligned} \qquad (2)$$

Here *f(geometry, material)* is a function of the geometry and material variables that define the failure characteristics of small to medium defects. These include the remaining variables in the list above such as defect length, shape, yield, strain hardening, width, and fracture toughness.

Many investigators have adopted simplified geometry and material models from this point to define the geometry and material function. The current investigation, however, has demonstrated that the interactions of the variables are sufficiently complex that simplified models are not adequate to define this relationship *a priori*. In this investigation, the

PCORR analytical model is used to define the basic form of the complex expression.

Defect length dominates the remaining geometry and material variables. Hence, for this effort, length is the primary variable, and reasonable assumptions are made for the remaining terms. Figure 7 shows the results of a series of analyses using PCORR with the assumptions that

- Defect width equals half its length
- Defect cross-section is elliptic
- Material yield and ultimate tensile strength are the minimum specified values for X52 pipe
- Charpy energy is 45 ft-lb.

Most investigators have adopted the conventional shell parameter $L/\sqrt{Rt}$ to nondimensionalize length where R is pipe radius. However, in this formulation we recognize that the behavior of a defect will be dominated more by its local wall thickness than the global pipe wall thickness. Consequently, we adopt the dimensionless length parameter $L/\sqrt{Rt^*}$ where $t^* = t - d$ is the remaining ligament thickness of the defect.

From inspection of the PCORR results in Figure 7, we adopt an expression for the geometry and material function of the form:

$$\begin{aligned} f\,(\text{geometry}, \text{material}) &\approx f\,(\text{geometry}) \\ &\approx 1-\exp\left(C\frac{L}{\sqrt{Rt^*}}\right) \end{aligned} \qquad (3)$$

Here *C* is a curve fit constant. This expression does not fit the results over the entire range of defect lengths, but it does capture the global behavior of the defect failure relationship. Regression analysis yields the value for *C* = *-0.157*. The complete expression for the simplified criterion is then given by:

$$P_d = \sigma_u \frac{2t}{D}\left(1-\frac{d}{t}\left(1-\exp\left(-0.157\frac{L}{\sqrt{Rt^*}}\right)\right)\right) \qquad (4)$$

This expression, dubbed PCORRC for ***P****ipeline* ***CORR****osion* ***C****riterion*, is simpler in overall form than the conventional ASME B31G and has a number of unique features that result from its fundamental basis.

Limitations and Restrictions on Application of PCORRC

The PCORRC expression given in Equation 4 is an analytically based criterion for estimating the remaining strength of blunt corrosion defects in moderate- to high-toughness pipe that fail by the plastic collapse mechanism. While PCORRC is not a replacement for the existing RSTRENG and ASME B31G criteria, it is a complementary criterion for moderate- to high-toughness pipe. It can be nonconservative if incorrectly applied to lower-toughness materials or materials operating below their ductile-to-brittle transition temperature. As described in Reference 5, the PCORRC remaining strength criterion is applicable to

- blunt defects whose local width is greater than their local depth
- defects less than two pipe diameters in length

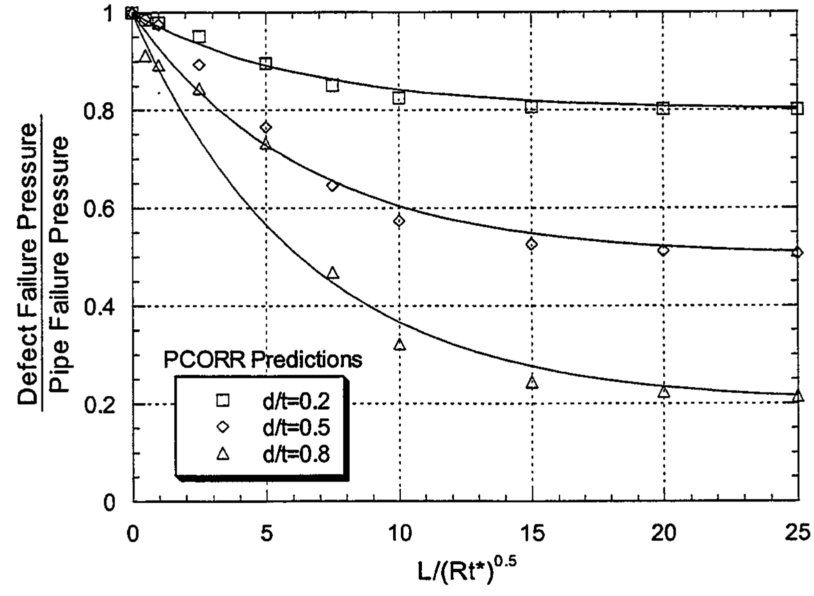

Figure 7. Fit of geometry function to PCORR finite element analysis results.

- pipe operating above its ductile-to-brittle transition temperature (85 percent shear area)
- pipe operating at full-thickness Charpy energy of 45 ft-lb or greater at the at the lowest expected temperature of operation.

As shown in the experimental validation, actual measured ultimate tensile strength is used in PCORRC for prediction of actual failure pressure. The *specified minimum ultimate tensile strength* of the materials as given by API 5L [9] should be used for conservative evaluation of the suitability of defects to remain in service.

These guidelines for the use of PCORRC are intended to be conservative and may be refined as new analyses and data defining a lower bound for plastic collapse behavior becomes available.

EXPERIMENTAL VALIDATION

A number of assumptions were made in the establishment of the PCORRC equation, and the expression must compare reliably against an experimental database to be validated. To this end, Figure 8 shows a comparison of failure pressures predicted by the PCORRC expression (using measured ultimate tensile strength) and actual failure pressures for isolated defects in "X" grades of pipe in the PRC*I* experimental database[5,10]. These defects in X grade pipe were all assumed to be of sufficient toughness that they likely failed by plastic collapse. The results in the figure demonstrate a consistent and reliable prediction capability by this equation for these defects. The average ratio of predicted to actual failure pressure is 0.97, and the standard deviation of the ratio is 0.098. These results also show that, although simplifying assumptions were made, the PCORR analytical model and parametric investigations yielded a simplified criterion with excellent predictive capabilities.

PCORRC has been further validated in Reference 11. This report compares PCORRC and other criteria to new recently developed experimental database of blunt defects in high toughness pipe developed in Europe. This data was not available during the development of PCORRC and the comparison further demonstrates its validity in predicting failure of defects in pipe which fail by plastic collapse.

Conservative Criterion for Field Application

In practical applications, the actual ultimate tensile strength of the joint of pipe with a defect will not be available. For field applications it is desirable to have a criterion that is based upon minimum properties and is conservative, but with minimal scatter. Figure 9 shows a comparison of predicted versus actual failure pressure of defects from the PRC*I* database, using the minimum ultimate tensile strength. There are many more data points in Figure 9 than in Figure 8, because the grade and

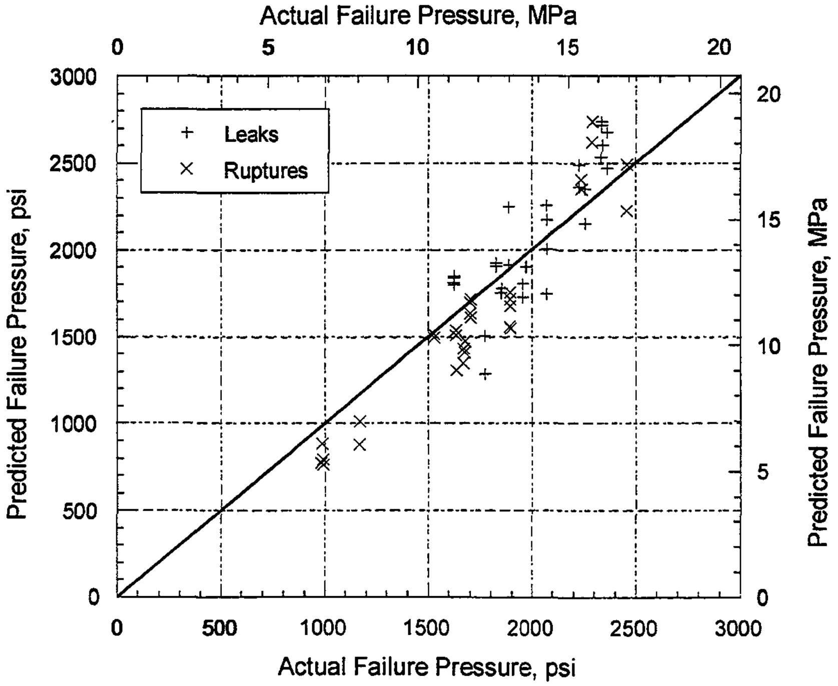

Figure 8. Comparison of failure pressures predicted by PCORRC equation using actual ultimate tensile strength properties to actual failure pressures for corrosion defects in X grade pipe in the database, all assumed to be of sufficient toughness to have failed by plastic collapse.

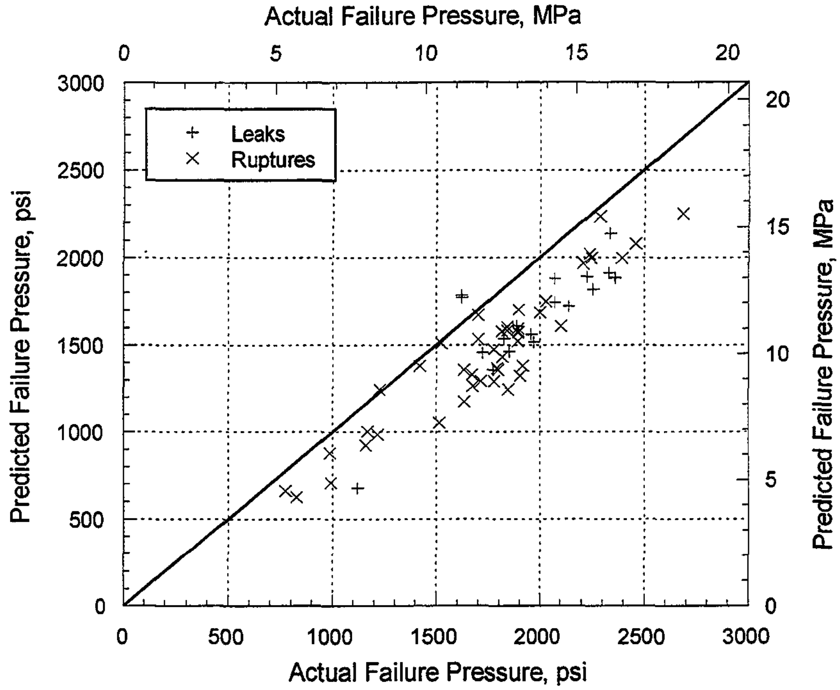

Figure 9. Comparison of failure pressures predicted by PCORRC using minimum ultimate tensile strength properties to actual failure pressures for corrosion defects in X grade in the database, all of which were assumed to be of sufficient toughness to have failed by plastic collapse.

minimum ultimate tensile strength was available for all defects, but the actual ultimate tensile strength was not recorded in many cases.

The comparison in Figure 9 shows that the accuracy of predictions does not change appreciably when predictions are based upon minimum properties rather than actual properties. The ratio of predicted to measured failure pressure in this case is 0.834 with a standard deviation of 0.093. Predictions based upon minimum properties are conservative in all but two cases, both of which were leaks. RSTRENG is similarly nonconservative in predicting failure of these same two defects and their validity has been called into question by the originators of the database. These results and comparisons in Reference 10 and 11 suggest PCORRC predictions based upon minimum pipe properties are conservative for moderate- to high-toughness pipe in the database with less scatter than existing criteria.

APPLICATION OF THE PCORRC CRITERION

To demonstrate the benefits of PCORRC, Figure 10 compares the maximum acceptable size of defects for X52 pipe predicted using the ASME B31G, RSTRENG 0.85 (Modified B31G) and PCORRC equations. Here the RSTRENG 0.85 criterion is expected to yield results comparable to those of RSTRENG. The comparison shows that in all cases, PCORRC allows a longer maximum acceptable defect length than ASME B31G or RSTRENG 0.85. For a defect 80 percent of the wall thickness in depth, PCORRC's acceptable defect length is 53 percent greater than the RSTRENG 0.85. For 50 percent deep defects, PCORRC's allowable length is 229 percent greater than RSTRENG 0.85. For longer defects, PCORRC predicts an acceptable depth of more than 28 percent of the wall thickness, compared to an acceptable depth of approximately 21 percent predicted by RSTRENG 0.85.[2]

This comparison suggests that PCORRC has the potential to reduce the number of unnecessary repairs in moderate to high toughness pipe. Further evidence of this observation is given in Reference 10, which suggests that PCORRC has the potential to reduce unnecessary repairs in some cases by more than 50 percent.

CLOSURE

This paper summarizes the results of an investigation performed under the sponsorship of PRC*I*, on development of a simplified criterion for the predicting remaining strength of

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[2] Actual corrosion defects longer than two pipe diameters in length are often dominated by pits or subfeatures with a long general corrosion. PCORRC may be excessively conservative for these cases and, consequently, it is not considered applicable.

corrosion defects under internal pressure with minimal excess conservatism. The value of PCORRC is demonstrated in comparisons that show it capable of reducing excess conservatism significantly in the class of defects that fail by plastic collapse, potentially resulting in significant reductions in pipeline maintenance and repair costs. The investigation shows that the first priority for future work is the development of a comprehensive definition for the lower bound for the plastic collapse failure of corrosion defects. PCORRC has the potential to simplify defect assessment for this class of defects and to reduce the number of unnecessary cutouts and repairs.

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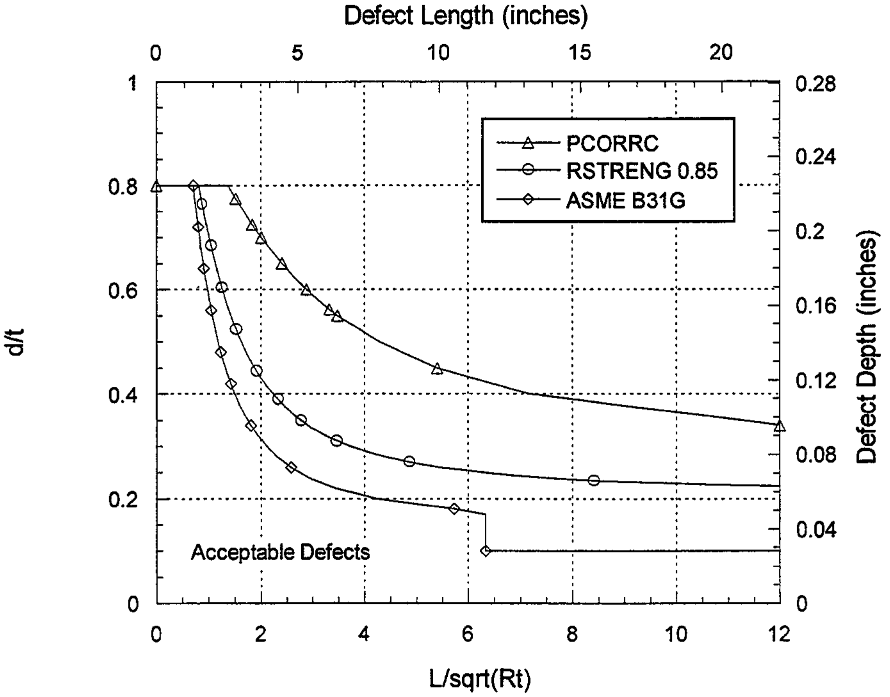

Figure 10. Comparison of maximum defect dimensions permitted by PCORRC, RSTRENG 0.85 and ASME B31G for X52 pipe (yield/tensile=0.79) (Upper and right axes represent acceptable defect dimensions for example of 24 inch diameter, 0.281 inch wall thickness pipe)

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