International Journal of Offshore and Polar Engineering
Vol. 14, No. 2, June 2004 (ISSN 1053-5381)

Strength Criteria and Analytic Predictions of Failure Pressure in Line Pipes

Xian-Kui Zhu and Brian N. Leis
Battelle Pipeline Technology Center, Columbus, Ohio, USA

ABSTRACT

This paper analytically investigates the failure pressure of line pipes with or without corrosion defects, and focuses on the conditions under which the classic strength criteria are appropriate for predicting failure pressure. Based on finite strain theory, a plastic collapse model is presented for end-capped defect-free pipes in a power-law hardening material. A closed-form solution of the limit pressure is thus formulated as a function of the strain hardening exponent *n*, and an estimation of *n* from the T/Y ratio is developed as well. This plastic instability solution is then extended to predict the failure pressure of corroded line pipes, and is validated using detailed finite element results and the PRCI experimental database. Results show that, when *n* approaches 0.2 or 0, which reflects the practical limits of a high or low hardening material, the plastic instability solution is coincident with that predicted by the Tresca or von Mises criterion, respectively.

INTRODUCTION

The classic strength-failure criteria, i.e. the Tresca criterion and von Mises criterion, are simple and extensively used in engineering structure analysis and design. The Tresca criterion is based on the maximum shear stress, while the von Mises criterion is based on the von Mises effective stress. Consequently, the failure pressure of a line pipe predicted by these strength criteria may differ each from the other even when using the same measure of material strength, such as the ultimate stress. In spite of this, the 2 criteria are still arbitrarily used to estimate the burst pressure of thin-wall pipes. It is useful, then, to establish practical conditions for which strength criterion is appropriate in predicting the failure pressure of a pipe.

The remaining strength of line pipes with corrosion defects is an important subject in the gas and oil pipeline industry, and it has been studied for years, using experimental, numerical, analytic and empirical methods (Kiefner et al., 1973; Mok et al., 1991; Vieth and Kiefner, 1994; Fu and Batt, 1999; Cosham and Kirkwood, 2000; Wilkowski et al., 2000; Cronin and Pick, 2002; Choi et al., 2003). Recently, Fu et al. (2001) presented a good review and comparison of about 10 existing and newly developed methods for assessing corroded pipelines with blunt defects, including ASME B31G (1984), RSTRENG (Kiefner and Vieth, 1989), PCORRC (Stephens et al., 1999), and the BG method (Fu and Batt, 1999), which was incorporated into the DNV guideline RP-F101 (Bjornoy and Marley, 2001). ASME B31G and RSTRENG are semi-empirical criteria based on different definitions of flow stress (Zhu and Leis, 2003b), but they have been widely used for evaluating the remaining strength of corroded pipes. However, many experimental data have shown these 2 criteria can often be overconservative (Fu and Batte, 1999; Cronin and Pick, 2000 and 2002; Choi et al., 2003), with RSTRENG being slightly less conservative than B31G. This may result in unnecessary repair or replacement in practice. To improve these criteria, Leis and Stephens (1997) and Stephens et al. (1999) developed the PCORRC method to predict the remaining strength of corroded pipes based on the maximum principal stress failure criterion (which is equivalent to the Tresca criterion for pressurized pipes—Zhu and Leis, 2003a) and the ultimate tensile stress. Likewise, Fu and Batte (1999) developed the BG method, Choi et al. (2003) proposed a similar method, but both adopted the von Mises failure criterion and ultimate tensile stress.

The early analysis of limit loads ignores the hardening behavior of materials, and the choice of the Tresca or von Mises criterion is usually made on the grounds of convenience (Miller, 1988). Modern pipeline steels such as X70 and X80 with higher tensile strengths have different strain hardening behavior than the traditional lower-strength steels. However, none of the methods noted above effectively considers the effect of material hardening. Stewart et al. (1994) have developed an analytical model for hardening materials, but it is intended only for a long smooth defect. On the other hand, using the Tresca criterion, Leis and Stephens (1997) predicted the limit pressures of corrosion defects with different sizes for X42-X65 steels, but the most predicted results are lower than the experimental data; while using the von Mises criterion, Choi et al. (2003) have demonstrated that the finite element results of limit pressure for X65 corroded pipes overestimate about 10% of experimental data. It is then appropriate to determine under what conditions the Tresca and von Mises criteria should be used for estimating the remaining strength of pipelines with or without corrosion defects.

This paper first presents a plastic collapse model for end-capped, defect-free pipes based on the finite strain theory, and then extends it to line pipes with blunt corrosion defects for power-law hardening materials. A simple estimation of the strain hardening exponent n from the tensile-to-yield strength (T/Y) ratio is developed. By comparing this plastic instability solution with the results predicted by the Tresca and von Mises criteria, the conditions for using the 2 strength criteria are obtained in reference to the strain hardening behavior of pipeline steels. Finally, the present solution is validated by detailed finite element results and the PRCI experimental database.

Received August 21, 2003; revised manuscript received by the editors November 17, 2003. The original version (prior to the final revised manuscript) was presented at the 13th International Offshore and Polar Engineering Conference (ISOPE-2003), Honolulu, Hawaii, USA, May 25–30, 2003.
KEY WORDS: Strength criterion, limit load, corrosion defect, pipeline, strain hardening, plastic instability.