Ductile Fracture of Pipelines under Energy Limited Severe Loading

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ABSTRACT

Ductile crack initiation under large-scale yielding is more likely to happen under extreme loading with small flaws and tougher materials. This paper discusses the Stress Modified Critical Strain model, and its applications to pipelines subjected to severe loading such as due to geohazards. We explore the relevance of SMCS for judging the loss of containment for nominally flaw-free pipeline, under extreme loads. Experimental and simulation results are presented to demonstrate its applicability.

KEY WORDS: Pipeline, ductile failure, severe loading, Loss of containment, geohazards, Risk mitigation.

INTRODUCTION

Modern performance-based codes (e.g. ISO 92004) require design for two levels of loading combinations associated with different load recurrence intervals. The performance requirement for the upper tier is to prevent the loss of containment, which could lead to loss of lives, injuries and damage to the environment. Whilst the lower tier, using stress-based design, targets business continuity issues and asset protection. The upper performance level aims at containing accidental event and generally the event intensity is chosen to have a very low probability of occurrence, say 10^{-5}/year or less. Such an event, which could cause damage, though being severe but its energy is limited; and its first occurrence, is only of interest. The design goal for the upper tier requires analysis of the “ductile” behaviour of the pipeline. “Ductile fracture” refers to fractures where materials experience large plastic deformation and exhibit high ductility in the region where structural failure would occurs.

Various approaches have been proposed to describe the phenomenon of fracture. Such approaches include the concepts of the stress intensity factor, energy release rate, J-integral, mesoscale void-nucleation-growth-coalescence models and continuum damage mechanics models, etc. Conventional fracture mechanics can be reliably used only to assess brittle fractures, where large scale yielding is absent. Accurate prediction of the fracture is critical for assuring pipeline safety under energy limited severe loads and erring on the either side of reality with large margins is undesirable.

This paper discusses– the Stress Modified Critical Strain (SMCS) model which has its roots in analytical studies of Rice and Tracey (1969). The growth rate of a void in a metallic matrix is influenced by the equivalent plastic strain and the stress triaxility. Our study draws upon prior research where similar models have been proposed and implemented for various materials, e.g., Hancock and Mackenzie (1976), Hancock and Brown (1983), Johnson and Cook (1985), Marini et al (1985), Bandstra and Koss (2004), Benzergera et al (2004) and Panontin et al (1995), Kanvindeh and Deierlein (2005). The approach adopted is to incorporate aspects of the model that captures the most significant features of fracture behaviour while maintaining complexity to a level suitable with their practical application to pipelines design. The distinguishing aspect of this study is to apply the models to steel types and grades used in pipeline engineering. Literature on this subject is growing a few examples are given in the list of references.

This paper presents results of investigation of applicability of the Stress Modified Critical Strain (SMCS) theory to 23 samples taken from an X65 steel pipe and from the Heat Affected Zone (HAZ) as well as its weld. The investigation involves experiments and replication of the experimental results using finite element analyses. Key findings include the accuracy of the model in predicting fracture in X65 steel pipe, under energy limited single load application. The model is also compared with test results available in literature for X65 and similar steels.

MICROVOID GROWTH AND COALESCEENCE

X-65, which is commonly used for pipelines, exhibits ductile fracture accompanied by large scale plasticity, Oh et al. al (2007). The stages observed during this type of fracture are: microvoid nucleation, growth and coalescence, shown schematically in Fig. 1 (Anderson (1995)).

Most steels contain inclusions such as carbides which reside in the steel matrix, around which voids nucleate under stresses. After nucleation, plastic strain and hydrostatic stress cause the voids to grow. As stresses increase, voids grow further, and at some stage interact and eventually coalesce; plastic strain is concentrated along a certain plane of voids. At this stage local necking instabilities cause the voids to grow suddenly forming the macroscopic fracture surface. For X65 pipe, this step