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Damage behaviour of full-scale straight pipes under extreme cyclic bending conditions

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A B S T R A C T

Requirements of industrial piping and pipelines to withstand extreme cyclic loading conditions have been motivating increasing interest on a particular extreme fatigue regime: the ultra-low cycle fatigue (ULCF). This damage domain corresponds to a transition between low-cycle fatigue and monotonic ductile damage. Albeit better understanding of this damage regime is required, very few studies are available covering full-scale testing. This study aims at investigating the performance of X60 and X65 piping steels, subjected to extreme cyclic loading conditions resulting in a reduced number of fatigue cycles ($N_i < 100$). Experimental tests were carried out on full-scale straight pipes subjected to cyclic pure bending, which were performed under the framework of the ULCF RFCS/EU project. Additionally to the large-scale tests, plain material was also tested under monotonic and ULCF conditions, supported by small-scale smooth and notched specimens. Large-scale tests were simulated by means of elastoplastic finite element models in order to reproduce the local plastic instability (buckling) where fatigue cracking was verified. Classical Coffin-Mason relation and a modified Xue relation were calibrated using small-scale testing data, the latter relation accounting for triaxiality and Lode angle stress tensor dependencies. The referred models were applied in the damage prediction of the full-scale pipes and results compared with code based procedures such as the ones proposed in the ASME VIII, Div.2. In general, the incorporation of the stress state parameters in the computation of ULCF damage produced improved predictions with respect to the pure strain range based models as the Coffin-Manson or ASME VIII, Div.2 code.

1. Introduction

Current design procedures associated to available steels for pipelines and general structures avoid brittle failures. High plastic deformation capability is therefore a common characteristic of current steel structures, allowing for significant energy dissipation before failure under either monotonic or cyclic loading. Despite this ductile behaviour, accurate methods to assess the limiting capacity of steel components and in particular pipelines are required to cope with current demands for improved structural integrity and risk assessment methods.

Loading conditions such as those resulting from earthquakes, support settlements, landslides, industrial plant shutdown, pipeline reeling, ocean extreme actions on oil pipelines, accidental loads, among other extreme loadings, may induce significant damage level on pipelines or even exceed the limiting resisting ductility of pipelines leading to their failure. The deformed shape of a pipeline under these extreme conditions is shown in Fig. 1. High intensity bending actions combined with internal pressure can promote the stress and strain concentrations on straight pipes, leading to widespread yielding and damage evolution, often concentrated at plastic instabilities generated at the pipeline components [2].

Among the extreme loading events that pipelines may experience, they can be differentiated into monotonic and cyclic events, since associated damage mechanisms and required models should be different. Damage models for monotonic ductile damage are already at a mature state, with recent approaches for equivalent fracture strains depending on stress triaxiality and Lode angle being considered appropriate [3,4]. Pipeline strain-based design philosophies are already a usual practice in design codes and the dependency of the fracture strain on stress triaxiality is a common approach for monotonic ductile failure assessment [5]. Nevertheless damage under intense cyclic plastic deformations shows distinctive features from that of monotonic ductile damage and low-cycle fatigue (LCF), monotonic and LCF modelling approaches being often extended to the extreme cyclic loading conditions, also commonly named as ultra-low-cycle fatigue (ULCF) conditions, where failure may occur for a very reduced number of load fluctuations

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Fig. 1. Large plastic deformation at the pipeline section [1].

(typically $N_f < 100$ cycles). The availability of specific models for ULCF is limited in the literature [6–13], and their implementation in design codes has not being considered so far by regulation bodies. Design codes do not distinguish ULCF from LCF fatigue regimes and Coffin-Manson rule [14,15] has been selected as the main approach in these codes for LCF/ULCF [16].

A combination of damage features from both monotonic (voids nucleation and growth) and LCF (cracks nucleation and propagation) can be evidenced in damage mechanisms associated to ULCF. Consequently, monotonic ductile damage parameters are often recalled in the formulation of some damage models proposed for ULCF life prediction, such as the stress triaxiality dependency as appears in the Cyclic Void Growth Model proposed by Kanvinde and Deierlein [6] and the monotonic fracture strain, in the Xue model [8,12,17], which is used as a normalization parameter for the plastic strain range. In particular, the last approach has the capability of predicting the failure under both LCF and ULCF domains, which intends to overcome the overestimation limitation of the classical Coffin-Manson relation [14,15], as reported by several authors [7,8,9].

So far ULCF studies have been mostly based on small-scale testing. However tests of small-scale smooth specimens under ULCF loading conditions is very challenging due to the tendency of unstable behaviour under compressive reversals applied to the specimens. Alternatively, notched specimens have been adopted for ULCF testing since they promote the stress and strain concentration at the notches, as reported in [6,10,11], reducing the risks of instabilities. However, the use of notched geometries requires data reduction schemes based on numerical simulation of each tests in order to process the strain histories around the critical locations. Moreover, the notches provide different stress state conditions (triaxialities and Lode angle parameters), which cannot be conveniently modelled using a simplified strain based approach as the one foreseen by the Coffin-Manson relation.

Besides the accumulated equivalent plastic strain, the stress triaxiality parameter has been considered an influent stress parameter on ductile/plastic damage evolution. In particular, the influence of stress triaxiality is evidenced through the ductility curve as proposed by Johnson-Cook [18] which relates the monotonic fracture strain with the stress triaxiality, using an exponential function. However, based on experimental evidences, Clausing [19] postulated that different geometrical conditions could provide distinct ductile fracture behaviors in materials at similar levels of stress triaxiality. McClintock [20] also found that the equivalent plastic strain to failure is lower in torsion than in tension, even if the stress triaxiality in torsion is zero. These hypotheses resulted in the formulation of a ductile failure criterion also dependent on an extra normalized stress parameter related with the third invariant of the stress tensor, besides the stress triaxiality, as originally proposed by Bai and Wierzbicki [3]. This new proposal aimed at covering both shear and hydrostatic failure modes.

Since ULCF shows some damage features similar to what is observed in the monotonic ductile damage, it is expected that the same dependency of the stress triaxiality and Lode angle parameter is observed, and this dependency should be more intense as the ULCF regime approaches the monotonic failure conditions (i.e. cycles to failure approaches 0.5). Therefore a new group of fatigue models for ULCF conditions needs to be developed with dependencies on the second and third invariants of the stress tensor. This could be accomplished with the Xue relation [8], where the normalizing monotonic fracture strain is assumed a function of the stress triaxiality and Lode angle parameters [12].

In this paper a research is conducted on full-scale straight pipes subjected to cyclic bending loading in the ULCF regime. Such kind of tests is unique and valuable to reproduce real operation conditions. Proposed damage models, identified using small-scale testing have the opportunity to be benchmarked using real size components failure prediction.

Two steel grades were selected namely the X60 and X65 piping steels with distinct pipe dimensions. Two straight pipes of each steel grade/size were tested (total of four pipes). The basic material properties were obtained from an experimental program conducted on small-scale tests on same X60 and X65 piping steels and covered both monotonic and fatigue tests. Small-scale data was firstly used in the calibration of the plasticity models necessary to the numerical simulations. Numerical simulations comprised both large and small-scale cyclic tests. Finite element simulations of the small-scale monotonic tensile and fatigue tests allowed the identification of the stress/strain histories located at the critical regions, which is mandatory information for models identification and latter application on large-scale tests damage simulation. Elastoplastic finite element models of the full-scale tests were also developed in order to provide the stress/strain histories at critical locations. Regarding the damage modelling approaches, this paper explores three alternative approaches for the simulation of ULCF damage of the pipelines. The classical Coffin-Manson relation and Xue model are applied with small-scale testing data derived for the materials under analysis; afterwards the ASME Boiler & Pressure Vessel Code, Section VIII, Division 2 S-N curves [16] will be also applied for comparison purposes. The classical Coffin-Manson relation is a well-accepted approach in the LCF literature whereby the assessment of the performance of such model has a practical interest for engineers. A new methodology for the application of Xue model is investigated in this work. In detail, the normalization of the equivalent plastic strain is performed through a fracture strain, which in turn is assumed dependent of triaxiality and Lode angle parameter as demonstrated by [3,21,22]. This was not explored before by Xue since he applied his relation based exclusively on smooth specimens testing data, without considering different triaxialities and lode angle parameters. In addition, ASME design curves are also tested, this option being useful for those lacking small-scale testing data.

2. Small-scale test data and analysis

Two API pipeline steels were investigated in this work, namely the X60 and X65 steel grades that were delivered in the form of straight pipes. The X60 and X65 were delivered in the form of pipes with 16″ outside diameter/9.5 mm wall thickness and 8 5/8″ outside diameter/5.59 mm wall thickness, respectively. The monotonic and cyclic/elastoplastic properties of the base material of the straight pipes were already investigated and characterized in a previous work by authors [2,23]. In addition to the smooth (SP series) and notched

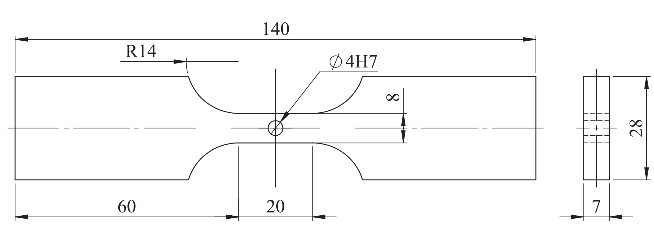

Fig. 2. Notched plane specimen geometry of X60 piping steel, with a circular hole (X60_CHB series).