Journal of Constructional Steel Research 113 (2015) 234–246

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Ratcheting behaviour of corroded steel tubes under uniaxial cycling: An experimental investigation

M. Zeinoddini [a], M. Peykanu [a], M. Varshosaz [b], M. Ezzati [a,*], S.J. Zakavi [c]

[a] Department of Civil and Environmental Engineering, K.N.Toosi University of Technology, Iran
[b] Department of Geodesy and Geomantic Engineering, K.N.Toosi University of Technology, Iran
[c] Department of Mechanical Engineering, University of Mohaghegh Ardabili, Ardabil, Iran

ARTICLE INFO

Article history:
Received 16 September 2014
Received in revised form 29 May 2015
Accepted 15 June 2015
Available online 30 June 2015

Keywords:
Strain ratcheting
Uniaxial cyclic stressing
Corroded steel pipe
Wrinkling
Defect

ABSTRACT

The influence of corrosion defects on the ratcheting behaviour of steel tubes under uniaxial cyclic loadings has been experimentally investigated. Different material grades, loading protocols and defect geometries have been considered. Surface defects have been found to be more detrimental to the cyclic response of the tubes, as compared to their monotonic uniaxial response. The axisymmetric wrinkling mode of failure in intact tubes changes to non-axisymmetric modes in defective tubes. In a defective tube the strains in the damaged and perfect parts of the tube ratchet at significantly different rates.

1. Introduction

Steel tubulars are used in different industrial applications such as offshore pipelines, offshore platforms and heat exchangers. Axial compression in the tubular members may lead to appreciable plastic strains in the component. Subsequent axial cycling could cause a gradual growth of wrinkling in the member which may eventually result in propagation of plastic strains and failure of the tube. The ratcheting or cyclic creep effects should be addressed in the safety assessment and fatigue life estimation of these components [1].

Strain ratcheting, for example, can be caused by repetitive start-up/shutdown and temperature cycles in unburied offshore pipelines. A submarine pipeline is axially restrained, for instance by the frictions from the pipe bed. As a result, a temperature change, caused by the passage of hot hydrocarbons coupled with high internal pressure, can plastically deform the pipe/tube. In some cases the compression is high enough to initiate axial wrinkling. Imperfections due to small misalignments at girth welds, in heat-affected regions around the welds, hard spots at connections with other equipment, etc. can all accelerate the onset of wrinkling. During its lifetime of around 20–30 years, an offshore pipeline usually experiences several hundred cycles of start-up and shutdown. A question arises as to whether wrinkles formed as a result of such stress rises can grow (ratchet) from the shutdown and start-up cycles and if so what are the consequences [2].

Jiao and Kyriakides [2] investigated whether an intact steel tube that develops small amplitude wrinkles can subsequently lead to total collapse by persistent uniaxial cyclic loads. They then reported experimental and numerical results involving axial cycling of tubes under internal pressure. They showed that axial cyclic loading causes a gradual shortening of the test section (axial strain ratcheting) while the internal pressure induces ratcheting of the hoop strain [3,4].

The ratcheting response of materials is significantly influenced by cyclic loading parameters such as maximum stress, stress amplitude, mean stress, initial axial strain, stress rate and material behaviour such as cyclic hardening/softening. Effects of stress amplitude, mean stress and initial pre-strain on the ratcheting response of intact tubes under uniaxial cyclic loading were investigated by a number of researchers [1,2,5–9]. It was concluded that the ratcheting strain amplitude and ratcheting strain rate increase with increase in the initial pre-strain, stress amplitude or mean stress, correspondingly. Cyclic hardening or softening has been reported to significantly influence ratcheting [10].

Sea water from outside and fluid being conveyed form inside may gradually corrode an offshore pipeline. This type of material loss could appear with different extents and depths on both sides of the pipe wall. The influence of the corrosion defects on the residual strength and local buckling of steel pipes under monotonic loading has received considerable previous attentions in the literature. Netto [11] studied the effect of narrow and long corrosion defects on the monotonic collapse

* Corresponding author at: K.N. Toosi University of Technology, Vali Asr Street, Mirdamad Cross, Tehran, Iran.
E-mail addresses: Zeinoddini@kntu.ac.ir (M. Zeinoddini), Mpeykanu@gmail.com (M. Peykanu), Varshosazm@kntu.ac.ir (M. Varshosaz), Mezzati@sina.kntu.ac.ir (M. Ezzati), Zakavi@uma.ac.ir (S.J. Zakavi).

http://dx.doi.org/10.1016/j.jcsr.2015.06.007
0143-974X/

pressure of offshore pipelines. Results from small-scale experiments and non-linear finite element numerical analyses were reported in these studies. Sakakibara et al. [12] and Netto et al. [13] studied the influence of internal corrosion or erosion defects on the collapse of pipelines under external pressure. Xue [14] presented results from a non-linear finite element analysis for the steady-state buckle propagation phenomenon in subsea corroded pipelines subjected to external hydrostatic pressure. Xue and Fatt [15] derived closed form analytical solutions for this problem.

As it was previously mentioned, the strain ratcheting problem and the corrosion effects on the residual strength of steel tubular have been separately addressed by different researchers. However, the subject of ratcheting, wrinkling and collapse of corroded steel tubes under cyclic uniaxial loadings has not received enough attentions in the literature. The present paper deals with the influence of rectangular corrosion defects on the strain ratcheting behaviour of steel pipelines subjected to uniaxial cyclic loadings. A small scale experimental modelling approach has been chosen. Both monotonic and cyclic uniaxial loading regimes on specimens with and without the corrosion defect have been examined.

2. Experimental set-up and procedures

2.1. Specimens' origin and type

Dimensions and the geometry of tubular specimens considered in the current study were close to those used in cyclic tests carried out on steel tubes by some researchers such as by Jiao and Kyriakides [1,2] and monotonic tests conducted by Paquette and Kyriakides [16]. It should be noted that these researchers employed intact tubes in their experiments.

Test samples in the current study were cut from the ‘as delivered’ lengths of two seamless carbon steel pipes class X42/B and X56 with nominal external diameter and thickness of 59.4 mm and 5 mm, respectively. Mechanical properties of the steel material were determined from standard static tensile coupon tests. For this, four coupon test specimens were prepared using a wire cut machine. The average values obtained from the material tensile tests are presented in Table 1.

The specimens were first cut in 300 mm lengths from the main pipes. This was slightly longer than the final desired length. They were then machined externally and internally in order to eliminate possible existing distortions. Maximum out of straightness in the specimens were kept bellow 0.030 mm, which could be regarded as the pieces' manufacturing error. Final length of the specimens became 280 mm after the two ends were machined at perfect right angles to the specimen axis. Geometrical properties of the specimens are shown in Fig. 1 with the following variations in thickness:

- Two thicker parts at far ends of the specimen (52 mm long), which were left at the as-received diameter.
- The test section in the middle of the specimen (76 mm long), which was machined down to 2 mm wall thickness.
- Two linear tapers (50 mm long), which connected the test section to the thicker end segments.

The tapers were long enough to minimise the thickness discontinuity effects on the axial stresses in the test section. The choice of specimen geometry was based on results of finite element modelling of the test specimen under monotonic uniaxial compression. The taper length was adjusted to minimise any stress risers at the discontinuity and maximise the axial stress consistency along the test section in the middle of the specimen. The thickness of the tube in the test section in the middle of the specimen was chosen based on avoiding local elastic buckling in the tube wall under plastic compressive stressing. Proper selection of the specimen geometry was necessary to ensure that the onset and growth of wrinkling would approach that expected in a long uniform tube [2].

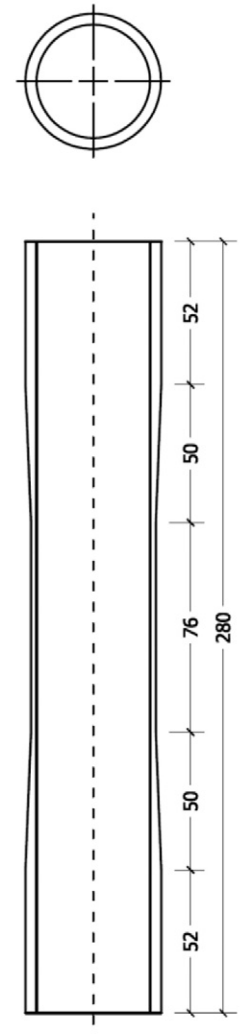

Fig. 1. Geometry of the tested tubular specimens (all dimensions in mm).

Table 1
Mechanical properties of the material from standard tensile tests.

Material type	Yield stress (MPa)	Ultimate stress (MPa)	Strain at rupture
Carbon steel X42/B	297	450	38%
Carbon steel X56	400	550	32%

2.2. Artificial rectangular corrosion defects

The physical shape caused by the metal loss in a corroded tube is irregular in depth and in surface. For engineering purposes, such as the evaluation of the residual strength of a corroded pipeline, it is very common to represent these irregular defects with an equivalent rectangular shape (Fig. 2). The equivalent defect is expected to provide a conservative estimation for the residual strength of a corroded pipeline, as the defect size is larger than that from irregular or parabolic shaped defects. Defect depths greater than 85% of the original wall thickness (i.e., when the remaining ligament is less than 15% of the original wall thickness) are not usually considered in the residual strength evaluation [17]. Corrosion, erosion or wear grooves wider than 60° are not also common in offshore pipelines [12].

In the experiments reported in this paper, similar to the majority of previous studies on corroded tubes (see Section 1), the corrosion defects were simplified by external machine grooves (Fig. 2). They were