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On the effect of Lüders bands on the bending of steel tubes. Part I: Experiments

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ABSTRACT

In several practical applications hot-finished steel pipe that exhibits Lüders bands is bent to strains of 2–3%. Lüders banding is a material instability that leads to inhomogeneous plastic deformation in the range of 1–4%. This work investigates the influence of Lüders banding on the inelastic response and stability of tubes under rotation controlled pure bending. Part I presents the results of an experimental study involving tubes of several diameter-to-thickness ratios in the range of 33.2–14.7 and Lüders strains of 1.8–2.7%. In all cases the initial elastic regime terminates at a local moment maximum and the local nucleation of narrow angled Lüders bands of higher strain on the tension and compression sides of the tube. As the rotation continues the bands multiply and spread axially causing the affected zone to bend to a higher curvature while the rest of the tube is still at the curvature corresponding to the initial moment maximum. With further rotation of the ends the higher curvature zone(s) gradually spreads while the moment remains essentially unchanged. For relatively low D/t tubes and/or short Lüders strains, the whole tube eventually is deformed to the higher curvature entering the usual hardening regime. Subsequently it continues to deform uniformly until the usual limit moment instability is reached. For high D/t tubes and/or materials with longer Lüders strains, the propagation of the larger curvature is interrupted by collapse when a critical length is Lüders deformed leaving behind part of the structure essentially undeformed. The higher the D/t and/or the longer the Lüders strain is, the shorter the critical length. Part II presents a numerical modeling framework for simulating this behavior.

1. Introduction

Seamless steel pipe used in offshore operations and more generally seamless tubes used in aerospace, automotive, power generation and other industries, often must be cold bent to strains of 2–3%. It is well known that plastic bending of circular tubes is limited by structural instabilities that are governed by the tube D/t and the stress-strain response of the material. Briefly, bending ovalizes the tube cross section (Brazier, 1927) gradually reducing its bending rigidity and leads to a limit load instability that is followed by localized deformation and local collapse. Wrinkling on the compressed side is a second type of instability, which for higher D/t tubes leads to collapse by local kinking (e.g., see Ju and Kyriakides (1991, 1992), Kyriakides and Ju (1992), Corona et al. (2006), Kyriakides and Corona (2007)).

Plastic bending of tubes is further complicated when the steel exhibits Lüders banding, a material instability associated with unpinning of dislocations from nitrogen and carbon atmospheres (see Cottrell and Bilby (1949), Johnston and Gilman (1959), Hall (1970)). Lüders banding takes place during the initial part of the plastic regime of the material and results in macroscopic localized deformation. For example, in a uniaxial test on a strip it manifests as inclined bands of plasticized material that propagate from one end of the strip to the other while the stress remains nearly constant (e.g., Hall (1970), Kyriakides and Miller (2000)). Material behind such fronts is deformed to strains of 1–3% while ahead of them it is still elastic. When the whole specimen is consumed by Lüders deformation, the response starts to harden and the deformation becomes homogeneous once more. This two-part series of papers examines how this material instability affects the response and stability of tubes in bending. Of particular interest is the complex interaction of Lüders bands with the prevalent nonlinearities of ovalization and wrinkling.

Kyriakides et al. (2008) showed that for a relatively thick tube (D/t = 18.7) under pure bending the interaction with Lüders strain of about 1.8% resulted in an extended moment plateau. As the plateau was being traced two curvature regimes co-existed, one approximately corresponding to the strain at the end of the stress plateau and the second to that at the beginning of the plateau. Under rotation-controlled bending, the larger curvature regime gradually propagated until the whole length of the tube was consumed. Subsequently, the moment increased monotonically and the structure resumed homogeneous bending deformation. In an earlier study Aguirre et al. (2004) investigated the interaction of

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wrinkling and Lüders banding in higher D/t tubes (27.2). A similar moment plateau was traced during which pockets of inclined Lüders bands were found to emanate from peaks of wrinkles. Here we present a continuation of these studies by examining in detail the effect of the tube D/t and of the extent of the Lüders strain on the observed behavior and the extent to which the tubes can be safely bent. The problems are studied using a combination of experiment and analyses. Part I presents representative results from an extensive study that involved tubes of several D/t values in the range of 33.2–14.7 and Lüders strains of 1.8–2.7%. The tubes are tested to failure under rotation controlled pure bending. Part II presents numerical simulations of these experiments followed by an extensive parametric study of the problem.

2. Experimental facilities and procedures

The experiments were conducted on carbon steel (CS) 1020 tubes with nominal diameters (D) of 1.25 and 1.375 in (32 and 35 mm) and D/t values in the range of 14.7–33.2. The tubes used are cold formed, and consequently in the as-received state have a monotonic stress–strain response (continuous hardening). They were thus heat-treated in a vacuum furnace in order for Lüders bands to reappear (700 °C vacuum temper for 40 min followed by quenching). Following the heat treatment they developed Lüders strains in the range of about 1.8–2.7% and yield (plateau) stresses in the range of 32–52 ksi (220–358 MPa, e.g., see Fig. 1).

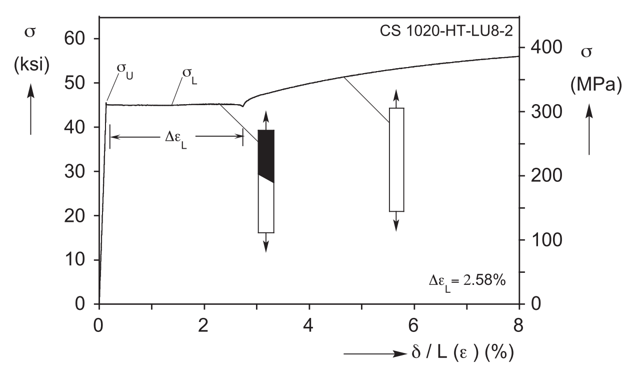

Fig. 1. Stress-elongation response of a carbon steel exhibiting Lüders deformation of 2.58% followed by hardening.

The heat-treated tubes were bent to collapse in the custom four-point bending facility shown in Fig. 2a (see Corona and Kyriakides (1988), Kyriakides and Corona (2007)). The bending machine consists of two free-turning sprockets mounted on two stiff support beams. Heavy chains run around the sprockets and are connected to two actuators and in-line load cells to form a closed loop. Solid steel extension rods are closely fitted into each end of the tube and the assembly is mounted onto the bending machine. The solid rods engage smooth rollers housed in each sprocket assembly as shown in the figure. The machine is activated by simultaneously contracting one of the cylinders and extending the other, in the process rotating the sprockets and the solid rods. The roller arrangement allows an essentially four-point bending loading of the tube and the required inward translation of the rods. The bending machine is operated by a closed-loop, servo-controlled system, shown schematically in Fig. 2b, that can be run under either moment or rotation control (Corona and Kyriakides, 1991). The present experiments were run under rotation control at a rate that corresponds to a maximum bending strain rate of $10^{-4}\ s^{-1}$ (for uniform deformation, this strain rate corresponds to that of the tensile tests).

The applied moment (M) is monitored by the in-line load cells shown in Fig. 2a, and rotary transducers (RVDTs) record the rotation of the sprockets ($\theta_\alpha, \alpha = 1,2$). While the deformation of the tube is uniform, its curvature (κ) is proportional to the sum of the angles of rotation of the two sprockets. The transducer signals $\{M, \theta_1, \theta_2\}$ are monitored through a computer-operated data acquisition system. The global deformation of the deforming tube was also monitored and recorded using a high-resolution digital video camera running at 2 frames/s.

In their numerical simulations of Lüders deformation in tubes under bending, Aguirre et al. (2004) and Hallai and Kyriakides (2010) reported systematic initiation and propagation of angled, localized deformation bands on the tensile and compressive sides

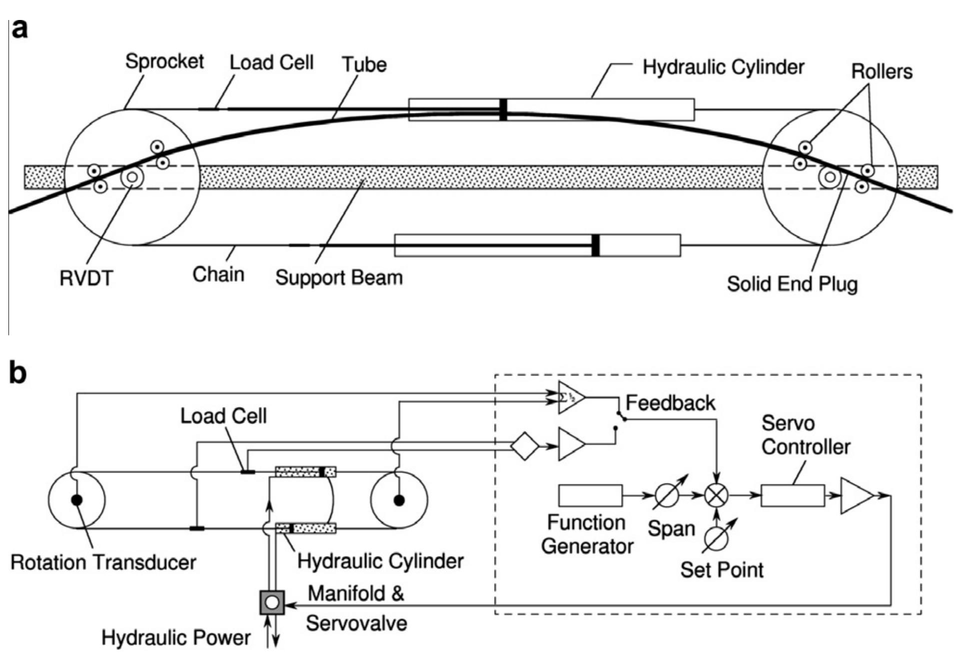

Fig. 2. Schematics showing the pure bending testing facility used in the experiments. (a) Bending machine and (b) closed-loop controller of the bending machine operating in rotation control.