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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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