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Internal material “architecture” for a kink-resistant metal tube

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Abstract

Catastrophic irreversible kink failure of a tubular geometry places considerable constraint on the design of metal structures and forming processes. A solution that postpones or eliminates such failure can be expected to significantly improve performance. The present study presents one possible solution: a tube with an internal “architecture” of alternating material properties along the axial direction. The influence of different geometries and material combinations on bending properties is investigated. Numerical analysis shows that the proposed solution provides better kinking resistance for certain geometries and material combinations. Such improvement is obtained through changes in deformation mechanism where softer regions bulge out during bending and prevent the creation of an inward kink. This allows higher bending curvatures to be reached. A small set of steel tubes was treated by carburization to test the concept. The experiments confirm the potential of the proposed architecture.

Keywords: Finite-element analysis; Continuum mechanics; Composites; Bending test; Metal tube

1. Introduction

It was recently pointed out by Chebab et al. [1] that carburizing offers an effective means to create a variety of spatially varying microstructures. Such variation is frequently employed to create hard outer layers but it can also be exploited to mitigate fracture. In the present study we reveal how a relatively simple spatial variation of the microstructure can retard the development of flow instabilities during plastic deformation. For example, we consider the case of tube kinking.

The tube is one of the most widely used structural components. It combines high stiffness with low weight which makes it an excellent solution in many lightweight structures. However, the tubular geometry has a serious disadvantage which limits its application: its high stiffness can be compromised by kinking. Such catastrophic failure arises from the shell nature of the tubular geometry and its characteristic deformation modes. Despite its geometric simplicity, tube deformation, especially during bending, is rather complex. The problem has been intensively studied [2–14] since the seminal work by St Venant in the 19th century.

The bending performance of the tube (i.e. curvature at the onset of kinking) is determined by the tube geometry and material elastoplastic properties. Tubular geometry gives rise to two characteristic deformations during bending: ovalization and wrinkling. Ovalization is the term used to describe the flattening of the tube cross-section that accompanies increased tube curvature. Once a critical level of ovalization is attained, the tube develops a catastrophic kink [2]. Uniform wrinkling, on the other hand, is related to shell buckling on the compressive side of the tube. Which of these two deformations occurs depends on the ratio between the tube diameter and the wall thickness (D/t) [8]:

- Thick-walled tubes, $D/t < 26$, fail by kinking when ovalization reaches its natural limit. Wrinkling is not pronounced.
- ‘Intermediate’ tubes, $D/t = 26–40$, fail by a combination of both effects. The critical conditions for kink development by ovalization are affected by the wrinkles.

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- Thin-walled tubes, D/t > 40, fail by wrinkling. One wrinkle becomes more pronounced and creates the kink before the natural ovalization limit is reached.

Kinking resistivity can be improved by alternating the tube geometry in order to perturb the deformation mechanisms. This approach leads to the well-known and elegant "fix", which is the introduction of concertina-like hinges (Fig. 1a). The hinges close and stack up on the compressive side of the bend, transferring the deformation to adjacent, less stiff unclosed hinges. The hinges also stiffen against ovalization and collapse is suppressed even at high bending curvatures.

In the present study, we examine another approach. The alternative approach to this problem is based on alternation of the material properties—via the microstructure—along the tube. The aim is to perturb the deformation in such a way to enhance the kinking resistivity. The structure–property relationships between the alternating material "architecture" and the bending properties of the tube is the main objective of the present study. The proposed material architecture consists of a sequence of rings with alternating material properties as shown in Fig. 1b. This means that the scale of such architecture is at the level of the dimensions of the part. After this, an experimental verification of the proposed concept is presented. Finally, the mechanisms at work in our "material" solution are discussed.

2. Finite-element analysis

Finite-element (FE) analysis was performed to determine the potential of different axially varying material architectures to alter the proclivity for kinking. Our initial conception was that alternating bands of plastically soft and hard material would potentially mimic the effect achieved by the concertina geometry shown in Fig. 1a.

2.1. Simulation parameters

FE simulations were performed with the ABAQUS code using the Riks solving method. Initial geometrical perturbations were introduced into the undeformed geometry in order to achieve numerical stability. These perturbations enable the solver to follow one particular deformation path and overcome problems with the bifurcation point of instability. The initial perturbations are in the form of a displacement field produced by an elastic buckling analysis. The buckling analysis calculates the displacement fields for the different buckling modes and the mode corresponding to the lowest eigenvalue, which corresponds to the first buckling mode, is selected. The maximal amplitude of these perturbations is scaled to be 1% of the tube wall thickness. This value aids the numerical solution but does not impact significantly on the final result. This amplitude is rather conservative as, for example, an overall amplitude of ~8% was used in Ref. [14]. The buckling analysis accounts for geometric instability (i.e. wrinkling). Such wrinkling is unaffected by plasticity as it develops from the very beginning of the deformation, while the material is purely elastic. Any instability that is potentially caused by plasticity is a secondary effect and can develop in the simulations during the Riks analysis.

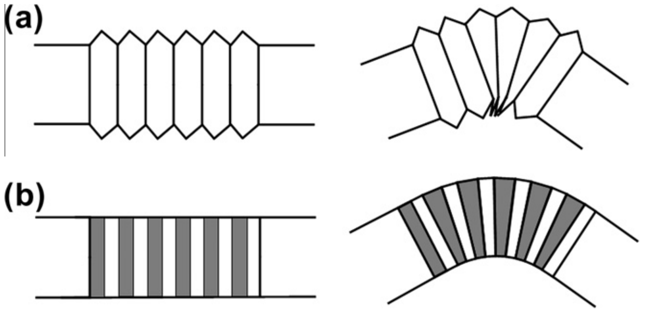

Fig. 1. Concepts of kink-resistant tubes: (a) geometrical solution (articulated straw); (b) material solution (alternating material properties).

The present study considers three different D/t ratios, one from each category defined above. Tube dimensions are summarized in Table 1.

The architecture introduced into the simulations comprises rings of two alternating "materials". The axial length of the rings is varied according to the natural elastic wrinkling wavelength of the tube during bending. These wrinkles appear on the compressive side of the tube and their wavelength depends on the D/t ratio. The definition of wavelength λ is shown in Fig. 2. The wavelength values are obtained using the ABAQUS buckling analysis. The ratio between the wrinkle wavelength and the tube wall thickness (λ/t) takes values of 18.52, 14.94 and 11.40 for $D/t = 50$, 35 and 20, respectively. Thus λ/t is given by approximately two and half times the square root of D/t. The ring lengths are set to $\lambda/2$, λ and 2λ.

The tubular structure was meshed in the simulations using 2-D quadratic shell elements and the mesh density was set by comparison with a semi-analytical model for tube bending, which is described in detail further below.

Table 1
Geometrical dimensions of tubes.

D = 20 mm	D/t = 20	D/t = 35	D/t = 50 mm
t (mm)	1.0	0.57	0.4

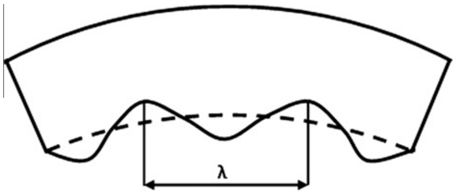

Fig. 2. Definition of the wrinkling wavelength at the compressive side of the tube.