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Plastic buckling of circular tubes under axial compression—part I: Experiments

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Abstract

Elastic buckling of cylindrical shells due to axial compression results in sudden and catastrophic failure. By contrast, for thicker shells that buckle in the plastic range, failure is preceded by a cascade of events, where the first instability and failure can be separated by strains of 1–5%. The first instability is uniform axisymmetric wrinkling that is typically treated as a plastic bifurcation. The wrinkle amplitude gradually grows and, in the process, reduces the axial rigidity of the shell. This eventually leads to a limit load instability, beyond which the cylinder fails by localized collapse. For some combinations of geometric and material characteristics, this limit load can be preceded by a second bifurcation that involves a non-axisymmetric mode of deformation. Again, this buckling mode localizes resulting in failure.

The problem is revisited using a combination of experiments and analysis. In Part I, we present the results of an experimental study involving stainless steel specimens with diameter-to-thickness ratios between 23 and 52. Fifteen specimens were designed and machined to achieve uniform loading conditions in the test section. They were subsequently compressed to failure under displacement control. Along the way, the evolution of wrinkles was monitored using a special surface-scanning device. Bifurcation buckling based on the J_2 deformation theory of plasticity was used to establish the onset of wrinkling. Comparison of measured and calculated results revealed that the wrinkle wavelength was significantly overpredicted. The cause of the discrepancy is shown to be anisotropy present in the tubes used. Modeling of the postbuckling response and the prediction of the limit load instability follows in Part II.

Keywords: Circular tubes; Circular cylindrical shells; Axial compression; Plastic buckling; Collapse

1. Introduction

Long, relatively thick tubes and line pipe used to transport fluids experience axial, shell-type buckling mainly when restrained from lateral movement. This, for example, is the case for a pipeline buried in a trench or resting on a deformable foundation. In offshore operations, compression can be caused by the passage of hot hydrocarbons carried from the well to a central gathering point by buried flowlines [1]. Motion of the foundation caused by fault movement, landslides, ground subsidence, permafrost melting, or soil liquefaction, can also result in severe compression of the lines [2–5]. Both loading scenaria can impose compressive strains high enough to result in axial buckling. In most onshore and offshore pipeline operations, diameter-to-thickness ratios (D/t) and steel grades are such that buckling occurs in the plastic range.

Unlike elastic shell buckling, in which collapse is sudden and catastrophic, plastic buckling failure is preceded by a cascade of events, where the first instability and collapse can be separated by average strains of 1–5%. The behavior is summarized schematically in the axial stress-shortening response of a long tube shown in Fig. 1. Initially, the tube deforms uniformly (OA). At some strain level indicated by "↓" on the response, axisymmetric wrinkling becomes preferred. The wrinkles, initially small in amplitude, gradually grow (AB) as illustrated in Fig. 2. In the process, the axial rigidity of the shell gets reduced. For thicker shells, this eventually leads to a limit load instability (indicated by "∧") that can be considered as the limit state of the structure. Under displacement controlled loading,

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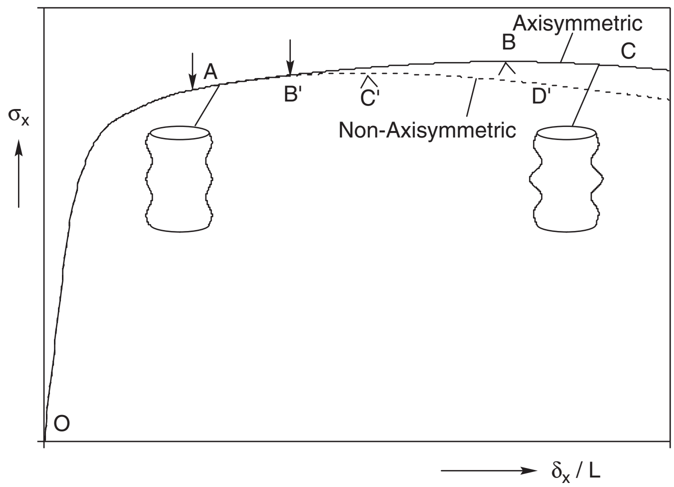

Fig. 1. Stress-shortening responses expected in a compression test of an inelastic circular cylinder. Shown are the onset of wrinkling (A) followed by axisymmetric collapse (B) or non-axisymmetric collapse (C′).

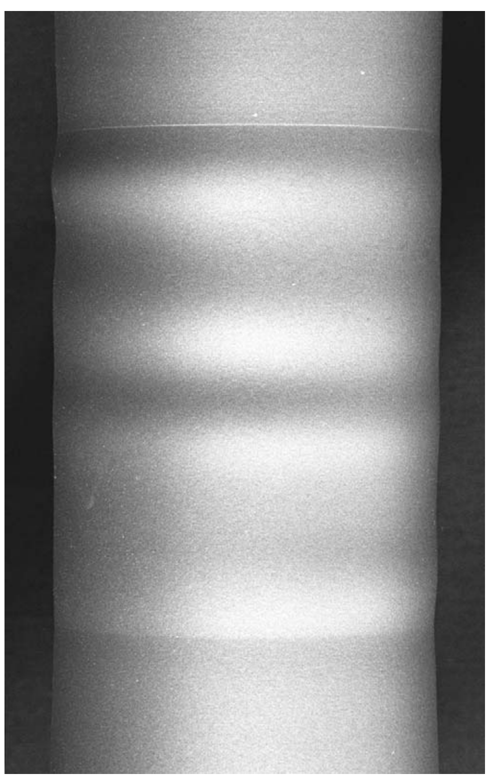

Fig. 2. Specimen winkled under axial compression ($D/t = 28.97$).

deformation localizes with the load dropping (BC). The localized deformation is in the form of one axisymmetric lobe that grows until its folded walls come into contact. The process can subsequently be repeated, resulting in concertina folding, as illustrated in Fig. 3a [6]. Alternatively, a non-axisymmetric mode with 2, 3 or more circumferential waves develops in the zone of localization. Under persistent compression, this can again be repeated as demonstrated in Figs. 3b and 3c.

For thinner shells, the non-axisymmetric mode develops before the limit load associated with the purely axisymmetric deformation (e.g., point B′). This results in additional softening of the response (dashed line) (B′C′) that causes a limit load to occur earlier (C′). Beyond this limit load, the non-axisymmetric deformation localizes (C′D′), followed by folding similar to what was described above. Which of the two paths is followed by a given cylinder depends on D/t and the material stress–strain response.

The main experimental data for axial buckling quoted in the literature are those of Lee [7] and Batterman [8]. Lee tested ten Al-3003-0 tubes. This is a relatively soft alloy with yield stress $\sigma_o = 6\,\text{ksi}$ (41.4 MPa) and significant hardening. The tubes had diameter-to-thickness ratios (D/t) of 20, 40, 59.7 and 93 and length-to-diameter ratios (L/D) between about 2 and 5. The cylinders were clamped at the ends and, as a result, edge bulges developed and dominated the recorded response. Because of this, no "bifurcation" stress or wrinkle wavelength was reported although axial waves were observed in the test section. The three lower D/t tubes developed limit loads, some due to axisymmetric collapse. $D/t = 93$ tubes developed non-axisymmetric buckling modes. The paper reports only the limit stresses.

Batterman tested 16 Al-2024-T4 ($\sigma_o = 56.5\,\text{ksi}$—390 MPa) shells of D/t values between about 20 and 180. The shells had L/D ratios between about 1.5 and 0.18. The specimens were compressed between lubricated rigid platens. Axisymmetric modes are reported for tubes with lower D/t values. Once again the only "buckling" variable quoted is the maximum stress. In this case, end effects may have had less influence, but the relatively short length of most of the shells must have affected the results. In some cases, the length was insufficient for even two axial waves to develop.

Regrettably, both Lee and subsequent workers compared the measured limit stresses with calculated axisymmetric wrinkling bifurcation stresses. As a result, they found the predictions lower than measured limit stresses, by itself a rather unorthodox result for buckling. A comparison of the corresponding strains would have demonstrated a considerable difference between the two and the inappropriateness of this comparison (as realized in a later paper by Murphy and Lee [9]). Batterman conducted a similar comparison between his experiments and predictions of the onset of buckling. Since his experimental collapse stresses were influenced by length effects, his conclusions are somewhat suspect.

A more correct experimental or analytical investigation of the problem must recognize and follow the progression of events associated with Fig. 1. First establish the onset of axisymmetric wrinkling, then allow the wrinkles to grow and finally establish the limit load. Along the way, search for a possible second bifurcation into a non-axisymmetric mode. If such a bifurcation occurs before the axisymmetric wrinkling limit load, follow this alternate