

ANALYSIS AND PREDICTION OF TRANSITION LENGTH IN CIRCULAR THIN SHELL DEPLOYABLE BOOMS

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Abstract

Coilable thin shell booms are components of deployable space structures, where the transition from a locally flattened state to the recovered circular cross section governs the extent of geometric disturbance along the boom. This study investigates the transition length of circular thin shell booms using finite element modelling, experimental validation and analytical prediction. Numerical models were developed in Abaqus to examine the influence of boom length, radius and wall thickness. Experimental tests using UPVC tubes showed good agreement with the predicted cross-sectional deformation profiles. The results indicate that transition length becomes independent of boom length once sufficient length is available for complete recovery, while increasing radius increases transition length and increasing wall thickness reduces it. A reduced analytical model based on ovalisation, membrane stretching and circumferential bending was developed and reproduced the observed geometric trends. The proposed model provides a basis for estimating transition length in circular deployable booms.

Keywords: Thin shells, Deployable booms, Coiling, Transition region, Ovalisation

1. Introduction

Coilable thin-shell booms are widely used in deployable space structures because of their compact stowage and ability to recover their deployed shape [1]. During deployment, a transition region forms between the flattened and recovered cross-sections, where significant geometric and curvature changes occur. Although transition behaviour has been widely studied for open-section tape springs, closed-section configurations remain less explored. Practical deployable booms are commonly manufactured from orthotropic composite laminates [1], whereas the present analytical model and UPVC validation are isotropic. This study investigates transition length using finite element modelling, experiments and analytical prediction, considering the effects of boom length, radius and wall thickness.

2. Numerical and Experimental Investigation

Circular cylindrical booms were modelled using Abaqus with one end locally flattened. The variation of the cross section along the boom was quantified using the ratio between the two principal axes, where a ratio of unity represents the original circular cross section. An initial study considered 46 numerical models with a radius of 20 mm and boom lengths ranging from 200 mm to 4400 mm. The results showed that the cross section initially recovered towards the circular configuration, passed through the original shape and then gradually approached the undeformed state. For sufficiently long booms, the transition profile and the distance required for recovery remained almost unchanged with further increases in boom length.

Experimental validation was carried out using UPVC tubes with a diameter of 63 mm, an average thickness of 1.075 mm, an elastic modulus of 3000 MPa and a Poisson's ratio of 0.38. Specimen lengths of 260, 450, 650, 950 and 1450 mm were tested. One end of each tube was flattened using wedge clamps, while longer specimens were supported at the free end to minimise deformation due to self-weight. The measured cross-sectional deformation profiles showed good agreement with the numerical results as shown in Figure 1.

The influence of boom length showed that shorter specimens deviate near the free end because they do not contain sufficient length for complete recovery. In longer booms, the deformation profiles were almost identical, indicating that transition length is primarily governed by local shell geometry rather than total boom length.

Boom diameter had a strong effect on transition length. Models with diameters from 32 mm to 110 mm showed that the transition length increased as the diameter increased. Smaller-diameter booms experienced larger changes in transverse curvature and steeper variations in longitudinal slope, allowing the cross section to recover over a shorter axial distance.

Wall thickness showed the opposite behaviour. For a 63 mm diameter boom, increasing the thickness from 1 mm to 5 mm reduced the distance required for cross-sectional recovery. For thicker shells, shear deformation also became increasingly significant near the flattened region, causing the deformation to become more localised.

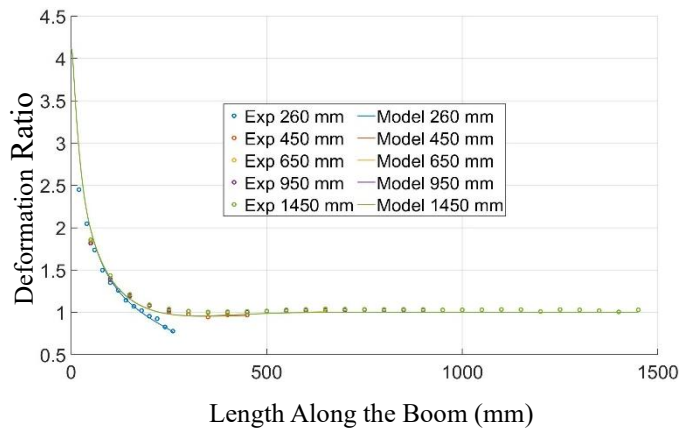


Figure 1: Comparison between experimental and numerical deformation profiles.

3. Analytical Model

A reduced analytical model was developed for a circular cylindrical shell with radius R , thickness t , Young's modulus E and Poisson's ratio ν . The transition was assumed to be dominated by the $n = 2$ ovalisation mode, with radial displacement expressed as

$$w(x, \theta) = W(x) \cos(2\theta) \text{ ----(1)}$$

The shell was assumed to be thin and isotropic, with negligible circumferential strain and in-plane shear strain. Only axial membrane stretching and circumferential bending energies were retained [2]. Minimisation of the total strain energy using the Euler–Lagrange equation gives

$$W'''' + \frac{12t^2}{R^6} W = 0 \text{ -----(2)}$$

The bounded solution for the ovalisation amplitude is

$$W(x) = A_2 e^{-qx} [\cos(qx) + \sin(qx)] \text{ -----(3)}$$

where, $q = 3^{1/4} \frac{\sqrt{t}}{R^{3/2}}$ and A_2 is maximum radial displacement at clamped end

This predicts an oscillatory recovery with an exponentially decaying amplitude, consistent with the numerical response.

The resulting transition length is

$$L^{\text{transition}} = \frac{(3 + \ln A_2) R^{3/2}}{3^{1/4} \sqrt{t}} \text{ ----- (4)}$$

This predicts longer transition lengths for larger radii and shorter lengths for greater thicknesses. The analytical model overpredicts the FEM results, with maximum discrepancies of 32.4% for varying radius and 38.1% for varying thickness. The differences mainly arise because only the $n = 2$ ovalisation mode is represented, whereas the strongly flattened region can contain higher circumferential modes captured by FEM. In addition, axial and twisting curvature energies are neglected; although small in the outer transition region, they may influence the response near the imposed flattening. Despite these simplifications, the model captures the dominant geometric trends observed numerically over the range of parameters

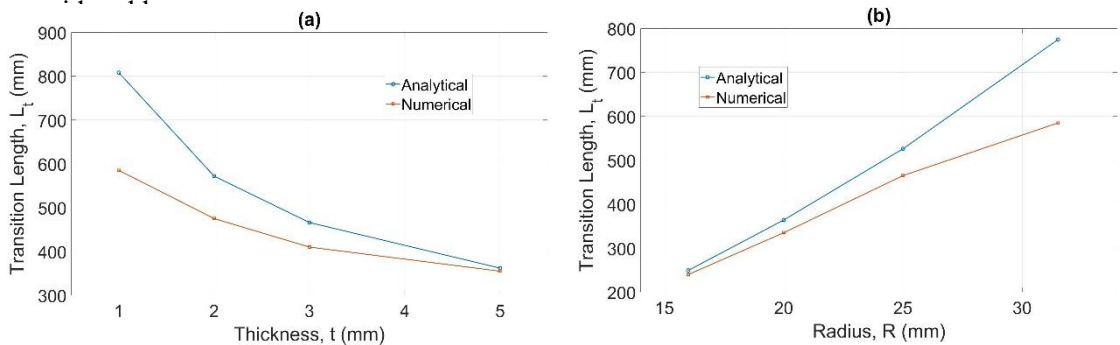


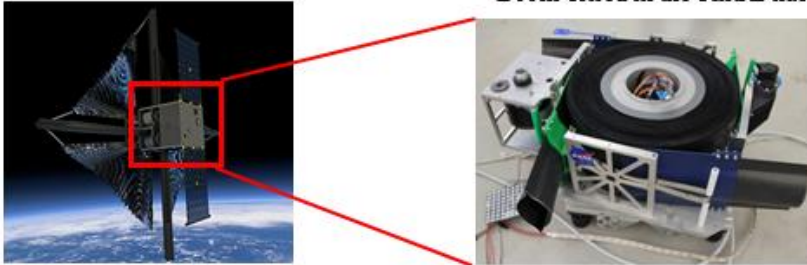
Figure 2: Comparison of analytical and numerical transition lengths: (a) varying thickness; (b) varying radius.

References

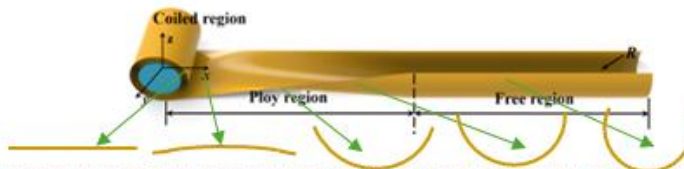
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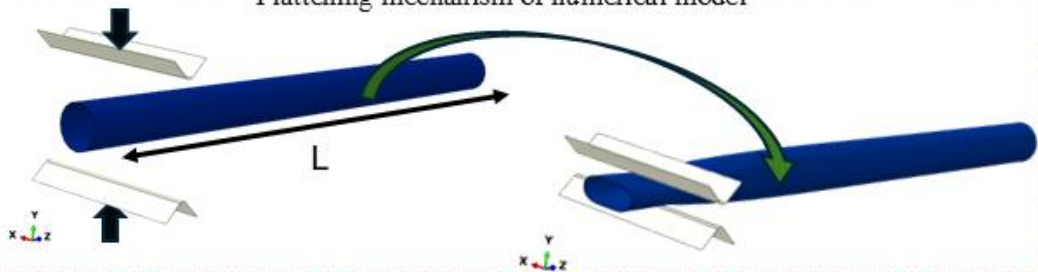
Deployment of space structures using coiled deployable booms
Boom coiled in the central hub



Transition region between coiled and deployed region



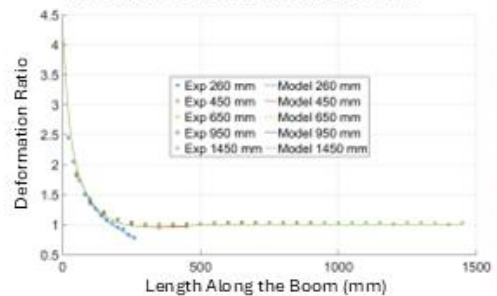
Flattening mechanism of numerical model



Experimental setup

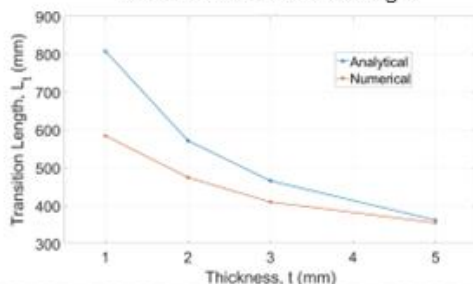


Validation of numerical model



Comparison between analytical and numerical model

thickness vs transition length



radius vs transition length

