Probing the stability landscape of thin-walled composite cylinders

R.L. Lincoln[a], C.J. McInnes, M. O'Leary, F. Morabito, A. Pirrera, R.M.J. Groh, S. Akromah, T. Brereton, A. Chen, E. Georgiou, J. Griffith, I. Lee, C. Stewart, M. Veyrat Cruz-Guzman, T. Wilcox, L. Zhu, M.L. Longana

Bristol Composites Institute, University of Bristol, BS8 1QU, UK

[a]reece.lincoln@bristol.ac.uk

Abstract. Thin-walled cylinders under axial compression are prone to buckling at a load lower than classical analysis would predict due to the imperfection sensitivity of such architectures. Accurate prediction of the buckling load typically requires *a priori* knowledge of the specific imperfection signature of the manufactured component. Without knowledge of the as-manufactured imperfection, robust design of axially-compressed thin-walled cylinders relies on conservative knockdown factors or computationally intensive probabilistic analyses. As an alternative experimental approach, the bifurcation load of a manufactured cylinder can be predicted by investigating the stability landscape through a lateral poking force. By increasing the axial load applied to a cylinder and measuring the changing reaction force of a displacement-controlled poker, the maximum load limit can be non-destructively extrapolated. The present work covers the theory and method of implementing the experimental procedure on a thin-walled composite cylinder.

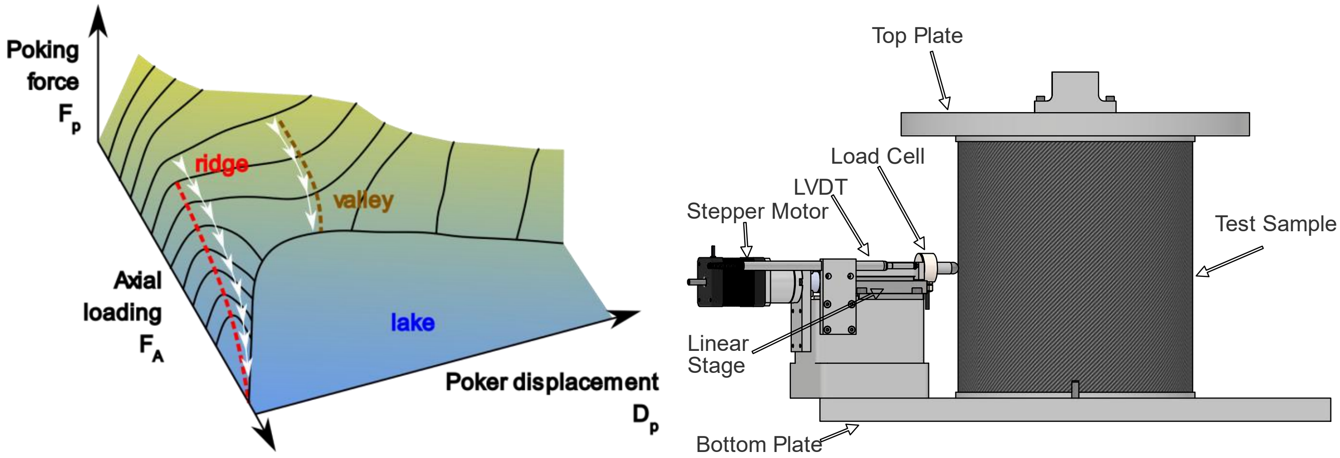
Introduction

Thin-walled cylinders are widely used due to their outstanding load carrying capacity at low weights, their ease of construction and appeal to aesthetics. Classical theory tends to overestimate the buckling load as it is unable to capture the influence of defects. Thin-walled cylinders are sensitive to geometric or loading imperfections. Defects strongly reduce the buckling resistance of these cylinders under axial compression, making the actual buckling load difficult to predict and considerably lower than closed-form solutions. The imperfection sensitivity of cylindrical shells has led to the use of probabilistic descriptions (often requiring manufacturing data) and deterministic knockdown factors (conservative estimates of buckling load). Demand for high-fidelity estimates of the buckling capacity of cylindrical shells has increased due to the renewed interest in thin-walled cylindrical architectures for spaceflight.

Our current research is focused on a non-destructive method of calculating the buckling load. By increasing the axial force to a load below the critical buckling load, keeping this force constant and measuring the reaction force to a lateral probing displacement, the critical buckling load can be extrapolated without the buckling event occurring [1]. The lateral probing method does not necessarily require knowledge of as-manufactured imperfections. If imperfection signature is not known, multiple regions must be probed to find the most compliant location. If the imperfection signature is known, the probing location is informed by Finite Element (FE) analysis. Previous work has implemented the methodology on isotropic cylinders both experimentally and within the FE environment [2–6] but minimal work exists on the use of the lateral perturbation method on composite cylindrical shells. The novelty of this work lies in the realisation of the methodology on a thin-walled composite cylinder, in addition to the full-field metrology of the composite cylinders that will inform the application of lateral force and the in-house custom poking unit that will perform the lateral perturbations.

Theory

The lateral poking method allows for the determination of the buckling load of a cylinder, without the need for destructive testing, by utilising the stability landscape of axially loaded shells [1]. The validity of this method can be understood by considering the physical meaning of the features observed in the stability landscape shown in Fig. 1a. The *lake* is the unstable region protected by an energy barrier; the energy required to cause buckling. When an axial load, F_A, is applied, membrane energy is increased within the system and the *lake* is approached by traversing the F_A axis. Within the landscape there exists a *ridge*, a line that separates a defect insensitive (to the left of the ridge) and defect sensitive region (to the right of the ridge). By increasing the overall energy of the system with an increased axial load and probing the cylinder (thereby traversing along the ridge of the stability landscape), the contours of the ridge can be plotted. By extrapolating down the ridge, we are asymptoting to a zero maximal poker force and as such, identifying the compressive load whereby buckling would occur without the inclusion of any additional lateral displacement. The extrapolated value of zero additional lateral force is the critical buckling load.



(a) **(b)**

Fig. 1. Schematics of **(a)** stability landscape of cylinder shell buckling. The ridge is defined as the region of maximum poker force, leading to the zero maximum poker force giving the spontaneous buckling load. Reproduced from Ref. [4] **(b)** experimental setup for the axial force application and lateral probing.

Experimental campaign

A composite cylinder is manufactured with ThinPreg™ 402 prepreg with nominal radius = 200 mm, length = 226 mm, and thickness = 0.3 mm. Both ends of the cylinder are potted in a depth of 13 mm with Epoxy Prime™ 27 to ensure clamped boundary conditions in the experiment and to evenly load the cylinder. The layup sequence is $[+60_2, -60_2, 0_2]_s$ with the 0° lamina aligned with the axial direction of the cylinder. The laminae are hand-rolled around a cylindrical aluminium tool, vacuum bagged, and cured in an autoclave. Once cured, the cylinder is potted, and CT scanned before testing to measure the imperfection signature. As-manufactured imperfection data are used within the FE model to predict global buckling and estimated lateral perturbation forces required to assess the stability landscape. The data collected from experiment are compared to the FE predictions.

Fig. 1b shows the schematic of the composite cylinder and probing unit within the axial compression testing rig. Data collection is global (the overall cylinder response) and local (data from the probing unit) and both data sets are required to map the stability landscape of the cylinder. Global force displacement and force, D_A and F_A respectively, is output from the 25 kN load cell of the universal testing machine and strain gauges and Linear Variable Differential Transformers (LVDTs) are used to corroborate displacement data. Local force and displacement data from the probe, F_p and D_p respectively, is output to the data collection system attached to the probing unit. The probing unit and data capture system has been designed and manufactured in-house for the specifications set for experimentation. The probing unit is housed on an aluminium block attached to the bottom plate and contains a 2000 N load cell, an LVDT to measure displacement and the probing device. The probing device is a spherical tip attached to a linear stage with 15 mm of travel and is driven by a lead screw attached to a stepper motor. Once the cylinder is held under an axial load by the universal testing machine in the test rig, the probe displacement is increased until the probe load cell shows a decreasing load at which point the probe is removed from the cylinder. The lateral probing process is repeated at increasing levels of axial load until the ridge line can be extrapolated and buckling load predicted.

References

[1] J.M.T. Thompson: *Advances in Shell Buckling: Theory and Experiments*, International Journal of Bifurcation and Chaos (2015) 25:01

[2] A. Abramian, E. Virot, E. Lozano, S.M. Rubinstein and T.M. Schneider, *Non-destructive Prediction of the Buckling Load of Imperfect Shells,* Physical Review Letters 125, (2020)

[3] Yadav, K. K., Cuccia, N. L., Virot, E., Rubinstein, S. M., and Gerasimidis, S: *A Nondestructive Technique for the Evaluation of Thin Cylindrical Shells' Axial Buckling Capacity*. ASME. J. Appl. Mech. (May 2021); 88(5): 051003

[4] E. Virot, T. Kreilos, T.M. Schneider, S.M. Rubinstein: *Stability landscape of shell buckling*, Phys. Rev. Lett. 119 (2017) 1–5

[5] H. Fan, *Critical buckling load prediction of axially compressed cylindrical shell based on non-destructive probing method*, Thin-Walled Structures, 139, (2019) 91-104

[6] P. Jiao, Z. Chen, X. Tang, W. Su, J. Wu, *Design of axially loaded isotropic cylindrical shells using multiple perturbation load approach – Simulation and validation*, Thin-Walled Structures, 133, (2018) 1-16