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OPTIMISATION OF CONTINUOUS TOW-SHEARED CYLINDERS UNDER UNCERTAINTY

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Summary The sensitivity to geometric imperfections limits the performance of thin-walled cylinders in compression buckling. The present work focuses on reducing the imperfection sensitivity of cylinders by using a novel manufacturing technique for composite materials known as Continuous Tow Shearing (CTS). CTS allows curvilinear steering of carbon fibre tows by shearing the carbon fibre tape, a 50 mm-wide strip of carbon fibre, that is placed via a robot arm. Steering of the carbon fibre tapes by shearing induces a smooth increase in the thickness of the tape and these localised thickness build-ups are used as a symmetry-breaking device to limit the impact of imperfections. The localised thickness build-ups are used to create embedded-stringers and -hoops that tailor the load path within the CTS cylinder. To maximise the effectiveness of the CTS cylinders, an optimisation framework that accounts for uncertainty is used. The results of the optimisation are corroborated with a Monte-Carlo analysis. The first optimisation goal is to maximise the thickness-normalised, mass-normalised buckling load of a CTS cylinder. The second optimisation goal is to minimise mass of a CTS cylinder under a specific load.

INTRODUCTION

The fuel and oxidizer cylindrical tanks of heavy launch vehicles are a large percentage of their total dry mass (60–70%). Using composite materials instead of current generation Li-Al fuel tanks is estimated to save up to 30% in mass and 25% in recurring manufacturing costs [1]. Several research programs have aimed to use composite materials to capitalise on these savings [2, 3] but have used blade-stiffened shells or foam/honeycomb sandwich structures. Few programmes have considered novel monocoque shell architectures due in part to their well-documented geometric imperfection sensitivity when loaded in compression—the design load case of heavy launch vehicles. Typically, the imperfection sensitivity is captured in the design phase using knockdown factors (KDFs), that are applied to the theoretical critical buckling load derived from a linear eigenvalue analysis. The classical KDFs of the NASA SP-8007 [4] guideline are still industry-standard but have been acknowledged to be too conservative for modern materials and manufacturing tolerances. Contemporary knockdown factors have been created that are less conservative [2, 5], but still show the imperfection sensitivity of cylindrical shells.

This paper looks at designing monocoque cylinders that are imperfection *insensitive* by tailoring load paths by using a novel variable-angle composite manufacturing technique, Continuous Tow Shearing (CTS) [6]. Preliminary work has found that CTS cylinders are less imperfection sensitive than straight-fibre cylinders [7, 8, 9]. It has also been shown that the imperfection sensitivity of composite cylinders can be decreased with Automated Fibre Placement (AFP) [10]. However, CTS has several benefits over AFP as a result of shearing the tows instead of bending the tows, *e.g.,* no in-plane bending; no fibre buckling or wrinkling; perfect tessellation of tows; smaller steering radii. In addition to these benefits, the shearing process couples the fibre angle change to the local thickness of the tow, enabling the formation of embedded stringers and hoops perpendicular to the fibre steering direction. Fibre paths are described using the notation $\phi\langle T_0|T_1\rangle^n$, where ϕ is the clockwise angle from the global *x*-axis that defines the refence axis for shearing; T_0 is the initial angle of shearing relative to ϕ; T_1 is shearing angle in the middle of the 'period' relative to ϕ; and n is the periodicity—the frequency of a $T_0 \rightarrow T_1 \rightarrow T_0$ cycle. For the sake of illustration, Figure 1 shows how a $0\langle 20|70\rangle^3$ layer and a $90\langle 0|30\rangle^2$ layer is defined.

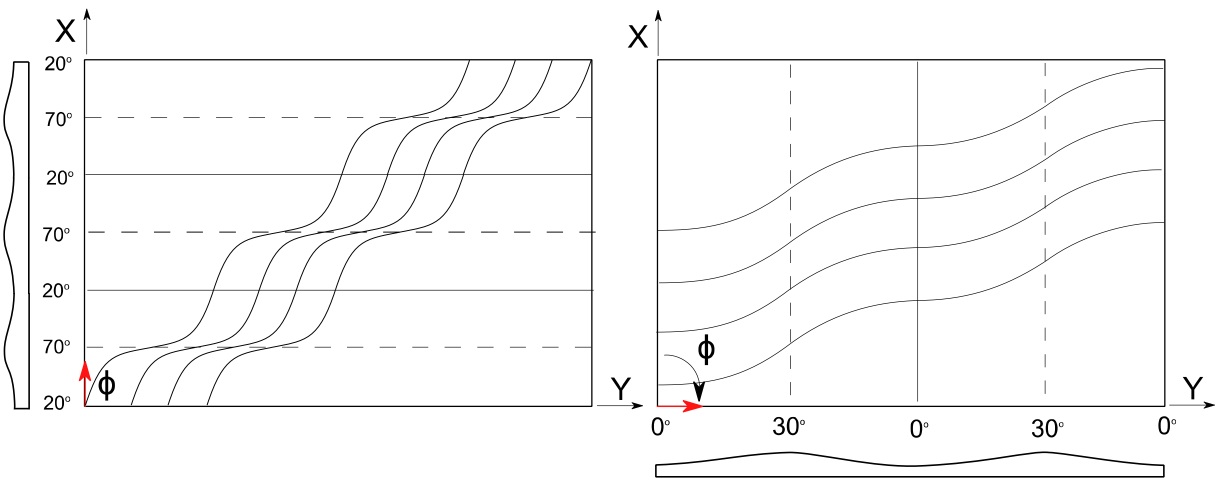

Figure 1 CTS lamina sheared where left is $0\langle 20|70\rangle^3$ and right figure is a $90\langle 0|30\rangle^2$ lamina.

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FUTURE WORK

Two optimisations and a Monte-Carlo analysis will be carried out. The first optimisation will be to maximise the thickness-normalised and mass-normalised buckling load of a CTS cylinder. A by-product of the CTS process (where the local thickness of the tow is increased due to the shearing process) is that the average thickness of a CTS cylinder with shearing is greater than a straight-fibre cylinder. As the buckling load of a cylinder is proportional to t^2 and the mass of a cylinder proportional to t, the mass-normalised specific buckling load of a cylinder is proportional to t. Therefore, to ensure a fair comparison between CTS cylinders and straight-fibre cylinders, a thickness-normalised, mass-normalised buckling load is appropriate if the maximum load carrying capability of a structure is essential. The optimisation will use a reliability-based definition of buckling load. A forward-difference First-Order Second-Moment (FOSM) analysis will be used to calculate a conservative estimate of the buckling load. A realistic data bank of imperfections [11] will be spectrally decomposed into a five principal components that describe the data set. From the principal components, six FEA analyses of the CTS cylinder with different imperfections can approximate a distribution of buckling loads. A buckling load approximately equal to the mean buckling load minus three standard deviations will constitute P_{FOSM}, the buckling load calculated from the FOSM methodology. A Genetic Algorithm (GA) will be the framework in which the FOSM methodology is used to optimise towards maximising the thickness-normalised, mass-normalised P_{FOSM}. To test the robustness of the final result and the assumed distribution, a Monte-Carlo analysis of the converged value will be performed to ensure the assumptions are valid and the result is statistically significant.

As a secondary optimisation, the mass of a CTS cylinder will be optimised. The target function will be to minimise the mass of a CTS cylinder given certain loading criteria. A GA will be used as the optimisation framework. The buckling load will be calculated from the FOSM methodology previously described.

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