

Post-Buckling Behaviour of a Multi-Stable Composite Stiffened Specimen under Low-Cycle Fatigue – A Preliminary Study

Xi LI^{1,a*} and Chiara BISAGNI^{1,b}

¹Department of Aerospace Science and Technology, Politecnico di Milano, Milano, Italy

^axi.li@polimi.it, ^bchiara.bisagni@polimi.it

Keywords: Buckling Mode-Switching, Composite Laminates, Compression, Digital Image Correlation

Abstract. This study experimentally investigates the effect of low-cycle fatigue loading on the evolution of buckling modes in a specimen consisting of a composite skin and four metallic stringers. The specimen was designed to achieve multiple stable configurations under compression through a tailored lay-up configuration that enables buckling to initiate in the thinner region and subsequently expand to the thicker region. The results indicate that the designed specimen was able of switching among different buckling modes under low-cycle fatigue loading. However, the skin-stringer separation was observed during high-amplitude fatigue loading.

Introduction

To meet the ambitious targets for clean aviation, weight reduction and efficiency increase are essential in structural design. Fibre reinforced composite materials are used in thin-walled aeronautical structures like wings and fuselages due to their light weight. By nature, they are susceptible to buckle under in-service loads, which can induce significant non-linear deformation and potentially complex failure mechanisms [1]. Consequently, a conservative no-buckling approach is often considered in the design phase. However, if buckling and post-buckling behaviour are allowed, provided they remain controlled, predictable, and confined to the elastic region, significant weight reduction can be achieved, even under fatigue loading. Furthermore, the potential to switch among different buckling modes could enable multiple stable configurations in aeronautical structures. Currently, there is a limited understanding on how aeronautical composite structures behave under fatigue loading with repeated buckling mode switches.

Buckling-driven composite design concepts for structural multi-stability are investigated in the NABUCCO project [2]. Studies to support such design concepts have been reported: Zhang and Bisagni [3] applied local displacement constraints to a simplified wing box, achieving changes in stiffness and buckling modes with redistributed load for twisting control; Gutiérrez Álvarez and Bisagni [4] combined mechanical and thermal loading in a flat, four-edge-clamped panel, which enabled buckling and subsequent mode switching under compression and heating; Bisagni and Gigliotti [2,5] designed multi-stiffness laminates with different number of plies and varying layups in local regions, which achieves changes in axial stiffness through local buckling at specific locations.

To further explore whether structural multi-stability induced by buckling can be controlled within the elastic region during repeated mode switching, this study investigates the post-buckling behaviour of a multi-stable stiffened specimen, achieved through a tailored layup configuration, under low-cycle fatigue loading.

Design, manufacturing and testing

As a preliminary study, the multi-stable design should be capable of switching among different buckling modes under compression and be suitable for easy hand laminating. To this end, a panel was designed from IM7/8552 material, incorporating four metallic stringers to create three distinct



regions. The geometry of the design is detailed in Fig. 1. The central region (Region 1) is stacked in a sequence of $[0/90/0]$, while the layup of the two lateral regions (Region 2) is $[0/90/0/90/0]$. The composite plate has a ply thickness of 0.125 mm, and the stringers are 1.5 mm thick. Buckling is expected to firstly occur in the thin region and subsequently expand to the thick region, enabling mode switching as the compressive load increases. Four aluminium 6061 T6 stringers were bonded to the composite plate. The top and bottom of the specimen were potted in metal-filled casting resin tabs.

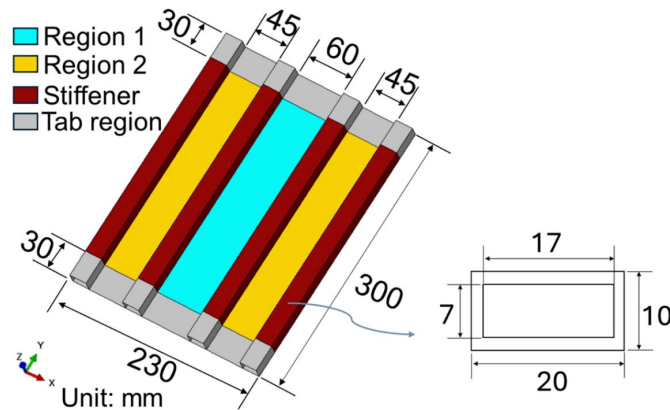


Fig. 1 Geometry of the multi-stable stiffened specimen.

A series of static tests were conducted to establish a baseline for the buckling and post-buckling behaviour of the specimen prior to fatigue testing. The tests were performed to different maximum loads, ranging from 3 kN to ~46 kN. During these tests, two digital cameras were positioned in front of the specimen to measure full-field deformation using digital image correlation (DIC) techniques, as shown in Fig. 2. The surface of the composite specimen was painted with a speckled pattern to assist DIC measurements. Then, a fatigue load profile was applied with a frequency of 1 Hz and a load ratio of 0.1. Each loading block consisted of approximately 10000 cycles at a constant amplitude. In total, four load blocks were applied with increasing maximum cyclic loads: Load Block 1 - 10 kN, Load Block 2 - 20 kN, Load Block 3 - 30 kN, Load Block 4 - 40 kN. To enable DIC image acquisition, the fatigue loading was interrupted every 1000 cycles to perform a static test at a loading rate of 10 kN/min.

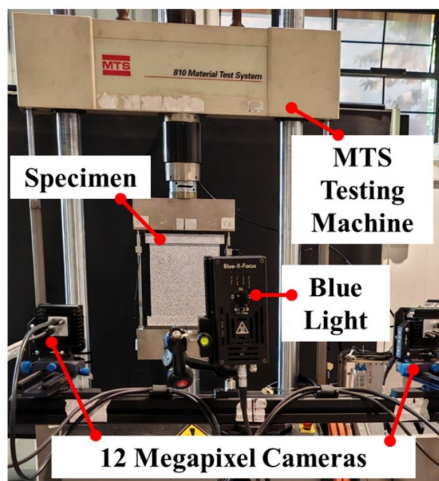


Fig. 2 Experimental set-up.

Results

The designed specimen exhibited a linear force-displacement relationship in the post-buckling regime under static loading, as shown in Fig. 3(a), which represents the final static test conducted prior to fatigue loading. The evolution of the buckling modes began in Region 1 with three half-waves and subsequently expanded to Region 2, forming a six half-wave pattern (Fig. 3(b)). As the applied force increased from 20 kN to 30 kN, the number of half-waves in the central region transitioned from three to four (Fig. 3(b)).

Fig. 4 presents the out-of-plane deformation fields of the specimen under a static load equivalent to the maximum cyclic load, both initially (0 cycle) and after 10000 cycles of Load Blocks 1-3. During Load Block 1, buckling primarily occurred in the central region with three half-waves, similar to the static baseline shown in Fig. 3. The low-cycle fatigue loading up to 10000 cycles evidently has a negligible effect on the post-buckling behaviour at this low load amplitude. When the maximum cyclic load was increased to 20 kN in Load Block 2, the buckling mode in the central region switched from three to four half-waves. This mode transition occurred at a static load higher than 20 kN. In Load Block 3, the buckling mode frequently changed between four and five half-waves in the central region. Meanwhile, visible local debonding between the composite skin and the stringers was observed at the top of the specimen. At the early stage of Load Block 4, local debonding propagated across the entire width of the specimen.

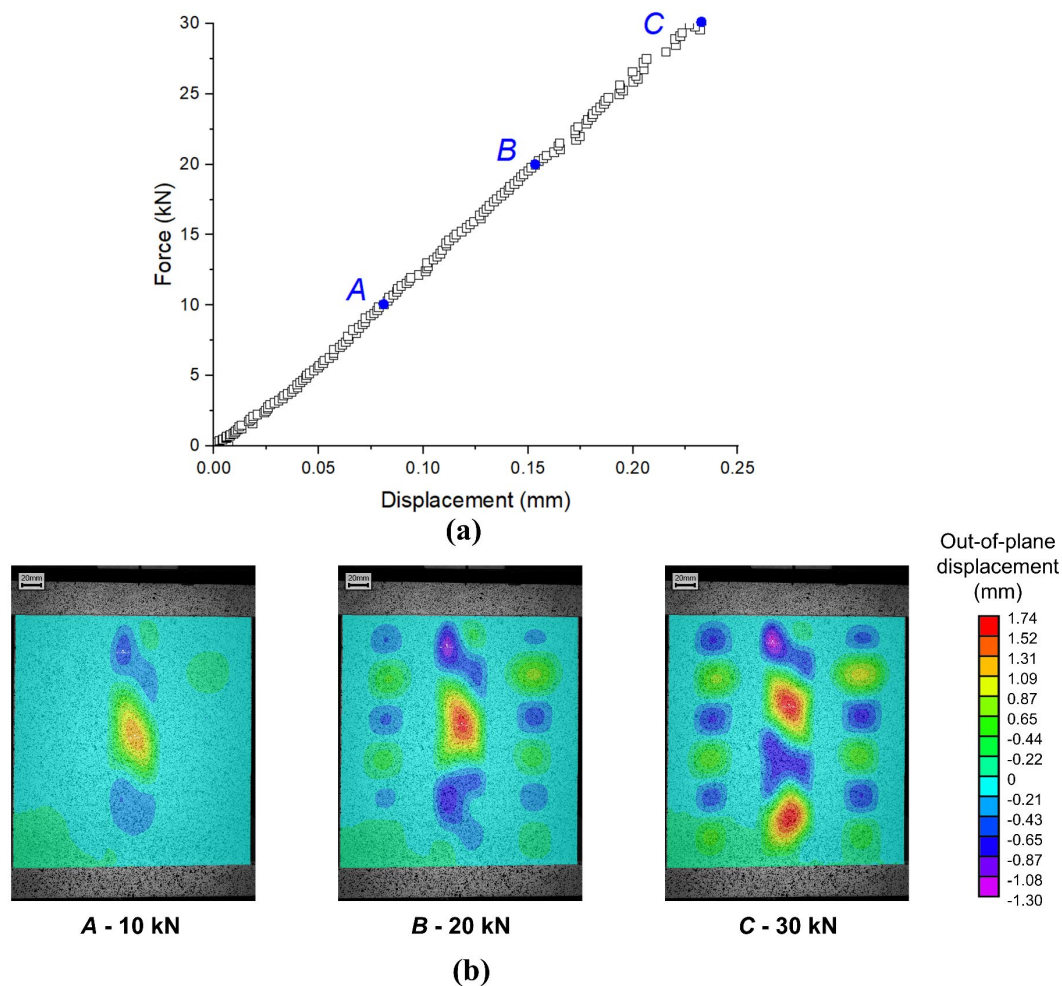


Fig. 3 Force-displacement response of the static test up to 30 kN (a), and evolution of buckling modes (b).

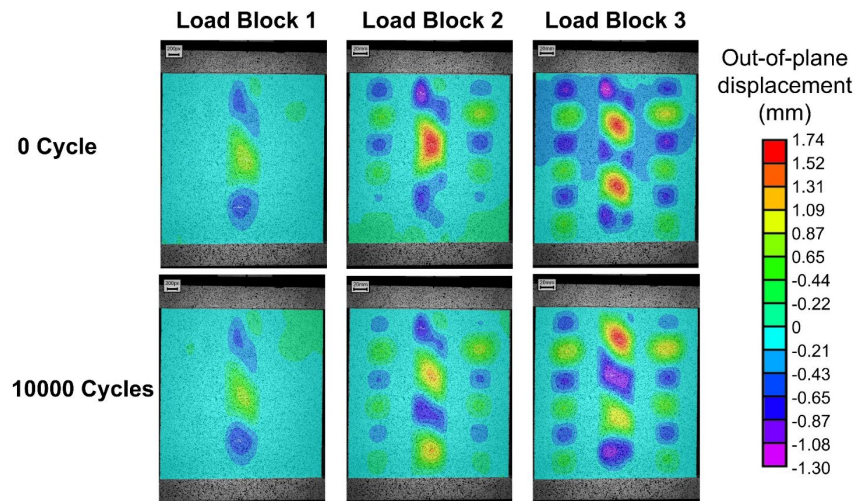


Fig. 4 Post-buckling mode at the maximum load of Blocks 1-3 at 0 and 10000 cycles.

Summary

Experimental work was carried out to design, manufacture and test a stiffened specimen with composite skin and metallic stringers under both static and fatigue loading conditions. The specimen was designed with variations in skin thickness, enabling to switch among different buckling modes as compressive load increases. Under low-cycle fatigue loading, the buckling mode in the central region changed as the load amplitude increased: it remained unchanged during the fatigue with 10 kN maximum load, transitioned from three to four half-waves during fatigue up to 20 kN, and switched frequently between four and five half-waves during fatigue up to 30 kN. Furthermore, local debonding between the composite skin and the stringers was observed under high-amplitude fatigue loading.

Acknowledgements

This study is partially funded by the European Union (ERC Advanced Grant, NABUCCO, project number 101053309). Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or the European Research Council Executive Agency. Neither the European Union nor the granting authority can be held responsible for them. The first author would like to acknowledge the funding from the Italian Ministry of University and Research for young researchers, financed under the National Recovery and Resilience Plan as part of the European Union's NextGenerationEU program.

References

- [1] J. Paz, A. Raimondo, and C. Bisagni, Experimental study of post-buckled single-stringer composite specimens under fatigue loads with different load levels and load ratios, *Compos. Part B Eng.*, (2023) 255:110606. <https://doi.org/10.1016/j.compositesb.2023.110606>
- [2] C. Bisagni, Nabucco take-off: multi-stable panels for an adaptive wing, in *ICAS Proceedings*, (2024) 1–9.
- [3] J. Zhang and C. Bisagni, Buckling-driven mechanisms for twisting control in adaptive composite wings, *Aerosp. Sci. Technol.*, (2021) 118: 107006. <https://doi.org/10.1016/j.ast.2021.107006>
- [4] J. G. Álvarez and C. Bisagni, Investigation on buckling and mode jumping of composite plates under thermomechanical loads, *Int. J. Non. Linear. Mech.*, (2021) 138:103837. <https://doi.org/10.1016/j.ijnonlinmec.2021.103837>
- [5] G. Gigliotti, Design and analysis of buckling driven multi-stiffness panels for adaptive composite structures, Master thesis, Politecnico di Milano, (2024).