Buckling and post-buckling response of curved, composite, stiffened panels under combined loads including pressurization

Luisa Boni[1,a*], Daniele Fanteria[1,b*], Tommaso Lucchesi[1]

[1]Department of Civil and Industrial Engineering – Aerospace division, University of Pisa, via G. Caruso, 8, Pisa, Italy

[a]luisa.boni@unipi.it, [b]daniele.fanteria@unipi.it

Keywords: Post-Buckling, Curved Composite Stiffened Panel, Finite Element Analysis, Combined Loads

Abstract. In recent years, metal stiffened shells for aerospace applications have been gradually replaced by composite shells, which are widely used in fuselage, tail, and wing structures due to their advantageous properties. Under operating conditions, stiffened panels are subjected to different types of loads, combined in various ways, which can lead to instability. Like their metallic counterparts, allowing post-buckling within the operational envelope could lead to significant weight reductions for composite structures, but unlike the metal case, their response in this state is not fully understood and the potential of composites is not fully exploited. In this context, the main objective of the present work is to investigate the buckling and post-buckling behavior of composite curved panels subjected to combined loads. The buckling behavior of a representative stiffened curved panel has been simulated by non-linear finite element analyses, from the simplest pure compression and pure shear cases to the final analysis of the panel subjected to pressurization, shear, and compression simultaneously. The results of this study quantify the reduction of the critical compression and shear loads due to their simultaneous action, as well as the effect of the pressurization load, which was generally beneficial, but remarkably so in the case of pure shear.

Introduction

Over the years, the use of composite materials has gradually increased, reaching levels of up to 50% of the structural weight of new generation aircraft such as the Airbus A350 or Boeing B787. In this context, metal stiffened shells, either flat or curved, have been replaced by their composite counterparts. Regardless of their constituent materials, stiffened panels must withstand a variety of complex loading conditions, any of which could cause the panel to buckle. Therefore, it is of paramount importance to establish methods that can effectively predict the structural behavior of composite panels beyond the first occurrence of instability in order to exploit their post-buckling capabilities. In the present work, the Finite Element Method (FEM) has been chosen as the main analysis tool. Indeed, the FEM has proven to be a valuable tool for investigating the structural response of stiffened panels [1].

Particular attention has been paid to the realistic modelling of geometry, loading and boundary conditions, avoiding the oversimplifications commonly found in the literature. The commercial software ABAQUS 2022 [2] was used to perform all the FE analyses. The modelling and simulation strategies are preliminarily validated on a metal panel whose data are available in the literature, as well as experimental and numerical results detailing its critical and post-critical behavior.

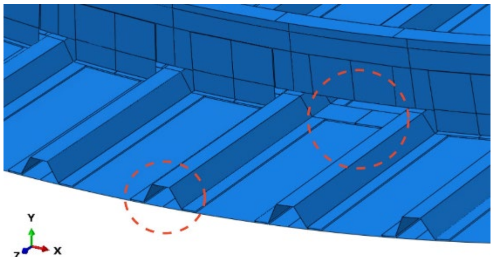
For this the lower fuselage panel studied by Rouse et alii in [3] was selected. Considerable effort has been made to apply realistic boundary conditions to the panel under analysis to avoid the D - BOX modelling used in [3] but not described in detail. The reference metal panel model was loaded with pure compression only. A composite version of the panel was then developed to investigate its stability under combined loading.

Reference panel and development of the composite version

The reference panel is made of aluminium alloy and consists of a curved skin stiffened by fifteen hat-section stringers and four zee-section frames. An aluminium tear strip is bonded to the skin underneath all the stiffening elements. While the stringers are attached directly to the skin, the frames are attached to the skin by shear clips and to the stringers by tension ties.

Quadrilateral, 4-node, stress/displacement shell elements with reduced integration and a large strain formulation (S4R) [2] were used to model all panel components. The tear strip was modelled implicitly by increasing the thickness of the skin under the stiffening elements and the connections between adjacent members were modelled using TIE constraints.

The eigenvectors provided by a preliminary linear buckling analysis were assigned as initial imperfections to a non-linear analysis to determine the pure compression buckling load of the structure. The loading and Boundary Conditions (BC) were assigned according to a typical experimental setup: one of the curved edges was fixed and the other was compressed by a concentrated axial force applied to the reference node, which shares its d.o.f. with all edge nodes. The analysis yielded a buckling load substantially in agreement with that reported in [3], thus qualifying the metal model as a reference to develop of the composite version.



	Ply n.	CPT [mm]	Stacking sequence
Skin	14	1.75	$[+45/-45/90/+45/-45/0/0]_S$
Stringer	16	2	$[+45/-45/90/+45/-45/0/90/0]_S$
Frame	48	6	$[+45/-45/90/+45/-45/0/90/0]_{3S}$
Shear Clip	32	4	$[+45/-45/90/+45/-45/0/90/0]_{2S}$

Fig. 1 – Composite panel architecture and layup.

The composite panel has "omega" section stringers (15 as a reference, with the same spacing) as shown in Fig. 1. The attached flanges of adjacent stringers are extended to form a pad-up under the shear clips (see Fig. 1). The width of the shear clips has been increased while maintaining sufficient clearance for the stringers to pass through ('mouse holes'); the tension straps have been eliminated. All components are thin laminates of carbon-epoxy prepreg and have a symmetrical and balanced stacking sequence to avoid couplings (see Fig. 1).

Tab. 1 – Stiffness properties of the composite panel compared to the reference.

	Skin		
Material	**AA Alloy**	**CFRP**	
Thick. [mm]	1.6	1.75	
Esten. Stiff. [kN/mm]	$Et/(1-v^2)$	A_{11}	A_{22}
	131.2	109.4 (-16.6%)	77.6 (-40.9%)
Flex. Stiff. [kN*mm]	$Et^3/12(1-v^2)$	D_{11}	D_{22}
	28.0	16.4 (-41.4%)	25.2 (-10.0%)

	Stringer	
Material	**AA Alloy**	**CFRP**
Cross section	**Hat**	**"Omega"**
Cross Sect. Area [mm^2]	249.5	248.8 (-0.3%)
Axial Stiff. (EA) [KN]	17895	12560 (-29.8%)
Bend. Stiff. (EI$_{yy}$) [KNm^2]	2.61	1.34 (-48.7%)

The composite stringers are designed to have the same cross-sectional area as their metallic counterparts, and the composite skin has a thickness comparable to the metallic reference.

The frames and shear clips were dimensioned to carry the combined loads without causing instability problems. The stiffness properties of the composite panel are shown in Tab. 1. Overall, the reference panel has stiffer elements than the composite panel.

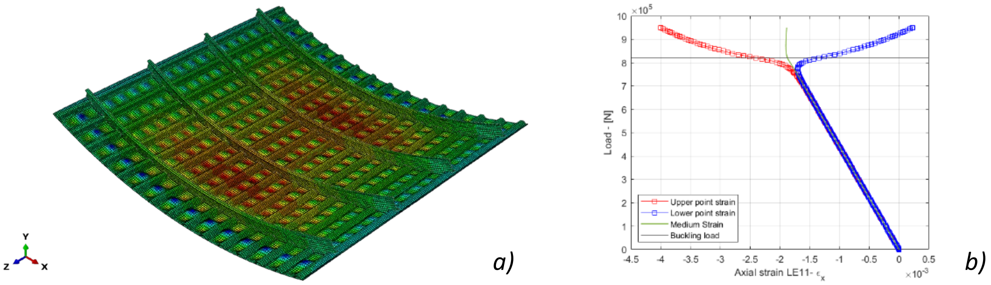


Fig. 2 – Compression buckling: radial displacement a) and load-strain diagram b)

The analyses on the composite panel were carried out using a mean element size close to that used for the reference panel, which was selected through a sensitivity analysis. Despite the lower stiffness, the compression buckling load of the composite panel is 820 KN (deformed shape in Fig. 2), significantly higher than that of the metal panel (570 KN).

The composite design was then frozen and used for all subsequent analyses.

Compression and Shear Buckling

The same procedure as for compression was used to calculate shear buckling: the eigenmodes of the linear analyses were used to perturb the geometry in the non-linear analyses. Again, using an experimental setup as a reference to enforce BC, one curved edge was fixed and the other was loaded by a pure torque (acting around the axis of the cylinder defined by the skin).

The strain analysis confirmed that the structure had been subjected to pure shear, as the longitudinal and transverse strains were zero prior to the instability, which manifested itself with skin buckles following patterns like those of metal panels. The skin between the stiffeners develops diagonal buckles at an angle of about 30°, as shown in Fig. 3a.

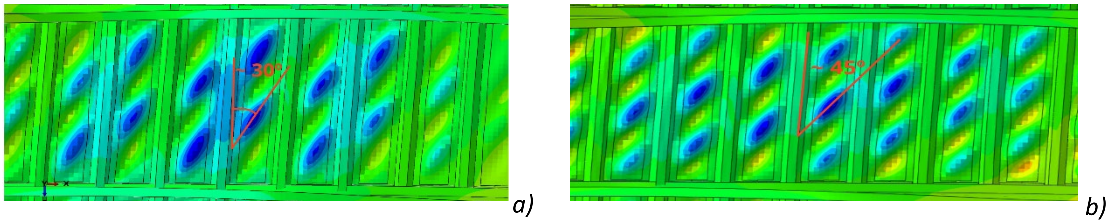


Fig.3 - Waves orientation for a) pure shear and b) shear and compression

The post-buckling configuration and stress state meet the *Incomplete Diagonal Tension Theory* formulated by Khun [4], widely accepted as the reference theory about shear buckling. The effect of restrained warping was also investigated and a strong reduction in buckling torque, quantifiable to about 50%, was found when warping is allowed. Eventually, an analysis was then carried out under the simultaneous action of compression and shear, with restrained warping. The effect of the compression is to increase the effectiveness of the shear loads in inducing the diagonal tension field; this synergy reduces the combined buckling load by about 40% with respect to the compression alone. Furthermore, in accordance with the reference theory, the angle of inclination of the buckles increased up to 45°, as shown in Fig. 3b.

The Effects of Pressurisation

The pressure was applied in advance to obtain realistic conditions: the radial displacement was left free, the symmetry is imposed along straight edges and the longitudinal stress that occurs in the real fuselage is introduced as an imposed displacement, evaluated through an ad hoc analysis.

In a second step, an increasing external compressive or shear load was applied to reach the buckling condition and to study the behavior of the panel in the post-buckling regime. The results of these analyses show that pressurization increases the buckling load significantly - 1540 KN vs. 821 KN for compression only (more than 85% increase) - or even remarkably: 3110 KNm vs. 1430 KNm for shear only (more than 115% increase).

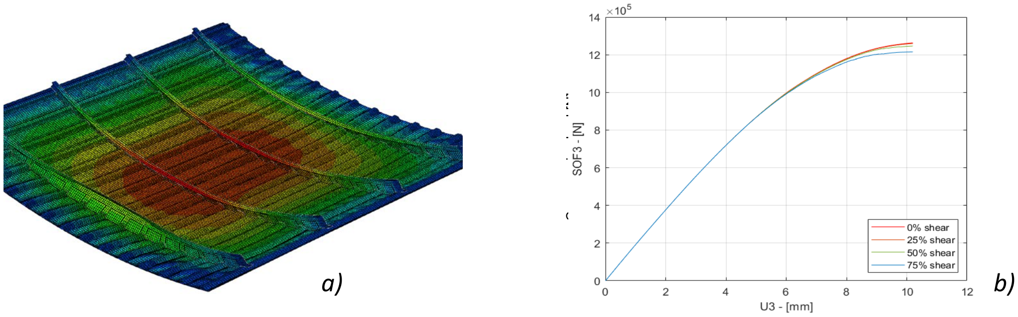


Fig.4 – Simultaneous application of pressurization, compression, and shear: a) Radial displacement, b) Longitudinal load-displacement curve.

Finally, some compression analyses were carried out at a given level of pressurisation with a constant shear load applied (increasing percentages of the pure shear buckling load were considered). For each value of the shear load, the deformed shape shown in Figure 4a is very different from those relevant to individual load cases (see Figures 2 and 3). The influence of the different shear levels on the longitudinal load-displacement curve is shown in Figure 4b. The buckling load is insensitive to the shear that slightly affects the post-buckling phase.

Conclusions

The study allowed the development of buckling and post-buckling modelling and analysis strategies under single and combined loading. Results relevant representative stiffened composite curved panel show that the buckling and post-buckling behavior in shear is consistent with the incomplete diagonal tension theory developed for metal structures.

The reduction in buckling load under simultaneous compression and shear loads is quantified and the effect of pressurisation is evaluated. Pressurisation is found to be remarkably beneficial in the case of pure compression; when shear is also present, it slightly affects the post-buckling phase, while the buckling load remains the same.

References

[1] L. Boni, D. Fanteria, and A. Lanciotti, Post-buckling behaviour of flat stiffened composite panels: Experiments vs. analysis, Composite Structures. (2012), pp. 3421 – 3433. https://doi.org/10.1016/j.compstruct.2012.06.005

[2] ABAQUS 2022 User's Manual, Dassault Systèmes Simulia Corp., Providence, USA (2022).

[3] M. Rouse, R. Young, and R. Gehrki, Structural stability of a stiffened aluminum fuselage panel subjected to combined mechanical and internal pressure loads, 44th AIAA/ASME/ ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference. (2003). https://doi.org/10.2514/6.2003-1423

[4] P. Kuhn, J.P. Peterson, and L.R. Levin, A summary of diagonal tension Part I: methods of analysis, NACA TN 2661. (1952).