



NABUCCO TAKE-OFF: MULTI-STABLE PANELS FOR AN ADAPTIVE WING

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Abstract

The project NABUCCO (New Adaptive and BUCKling-driven COmposite aerospace structures), funded by the European Union through an ERC Advanced Grant, aims to design new adaptive buckling-driven composite structures for next generation of aircraft configurations. The results of the first year of the project are here summarized, showing the potential impact for reducing weight and increasing efficiency needed for future clean aviation.

Keywords: Composite structures; Buckling and post-buckling; Wingbox; Multi-stable laminates; Gust loads alleviation

1. Introduction

All structural designers know that their structures must satisfy two basic criteria: the strength criterion and the stiffness criterion. In aerospace, most of the components are thin-walled, and compressive or shear stresses may significantly affect the strength or stiffness behavior of the whole structure, or may cause sudden, and often unexpected, partial or total structural failure due to different forms of instabilities. Consequently, in aerospace, next to the two basic criteria, one additional criterion has always been considered in case of thin-walled components subjected to compression or shear stresses: the stability criterion (1).

In the last 70 years theoretical and experimental research programs have been carried out to establish a reliable design basis for buckling-sensitive aerospace structures. Even if there is now a better understanding of the principal factors that must be considered for a reliable prediction of the buckling loads, buckling phenomena are generally avoided in the design of aerospace structures, introducing conservative safety factors that lead to a structural weight increase.

Nowadays, the need to reduce weight, so as to decrease fuel burn, coupled with the use of structural optimization techniques, produces highly stressed thin-walled structures, that require great consideration for the stability criterion in many loading conditions to guarantee safety. At the same time, the increased use of composite materials contributes to the reduction of weight but requires even larger safety factors because it is still difficult to predict damage initiation and progression and collapse mechanisms.

For this reason, in the past years a few projects were funded by the European Commission aiming to develop reliable procedures for the design and analysis of composite structures considering buckling phenomena. POSICOSS project in 2000 - 2004 investigated the post-buckling simulation of composite stiffened structures (2-4); COCOMAT in 2004 - 2008 studied how to increase the safe design of composite airframe structures by accurate collapse simulation (5-7); and MAAXIMUS in 2008 - 2016 demonstrated the fast development and right-first-time validation of a highly optimized composite airframe (8-9).

Even more recently, the capability of composite structures to work safely in the deep post-buckling field with large out-of-plane displacement has been demonstrated in a few projects. Just as an example, thermoplastic composite stiffened panels subjected to compression load were investigated in STUNNING project, a Clean Sky 2 project in 2017 - 2023 (10-11).

In the last years it became evident that a simple evolutionary improvement of aircraft technologies will not be sufficient to fulfil the challenging targets requested in terms of environmental impact reduction, well identified by Flightpath 2050 and Clean Aviation initiatives, among others, with challenging goals set for reductions in CO₂, NO_x and noise by the year 2050 (12-13).

In this perspective, there is more and more interest in admitting buckling in some structural components in a few flight conditions, as in this way a reduction of the structural weight could be easily reached. In a further step, buckling is also explored for innovative applications. Many applications can be found in the field of metamaterials and electronics, while in aeronautics applications using buckling in a favorable way are mainly devoted for the design of energy harvesters or for bistable structures with limited morphing applications [14-16].

The project NABUCCO (New Adaptive and BUCKling-driven COmposite aerospace structures), funded by the European Union through an ERC Advanced Grant, aims to design new adaptive buckling-driven composite structures for next generation of aircraft configurations. In this paper, the results of the first year of the project are summarized.

2. NABUCCO Project

The NABUCCO project is proposing a paradigm shift in aerospace design concepts, considering buckling no longer as a phenomenon to be avoided, but as a favorable behavior to be actively exploited.

The main drawbacks that are commonly seen towards buckling in the design of composite aerospace structures are summarized in Table 1, together with the way they are seen positively in NABUCCO.

Buckling must be avoided because...	Buckling can be exploited because...
Buckling produces stiffness reduction.	The stiffness reduction can be used for shape variation, load redistribution and dynamic response change.
Buckling generates large nonlinear deformations.	The large nonlinear deformations can be exploited to significantly change the structural shape with a minimum amount of provided energy.
The transition from pre- to post-buckling can be instantaneous (snap-through).	The fast structural response can be adopted for passive control of peak loads, such as those due to heavy gust excitation or maneuvers.
Buckling strongly depends on geometrical imperfections, material variability, external loads, boundary conditions.	The potential design space can become very large, allowing for many and unusual combinations of structural configurations to obtain pre-defined shapes.

Table 1 – From drawbacks to advantages of buckling.

The idea of the NABUCCO project is to modify and adapt the aircraft wing shape during the flight mission by the direct use of the buckling phenomena, taking advantage of their typical large nonlinear displacements and stiffness redistribution (Fig. 1).

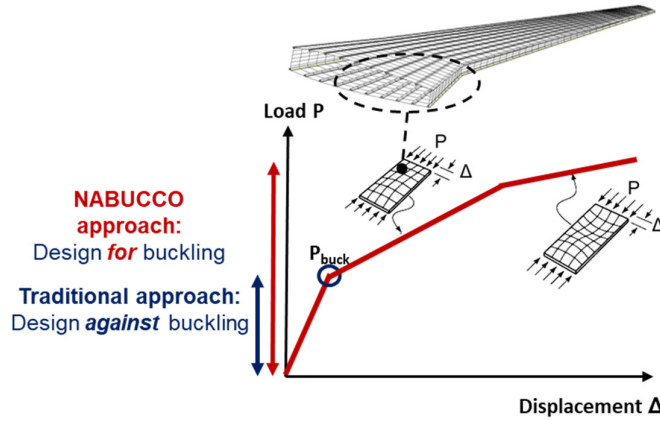


Figure 1 – Approach of NABUCCO project:
Design for buckling of composite aeronautical components.

The methodology adopted in NABUCCO is based on a strongly coupled computational-experimental framework and is applied to three demonstrators of increasing complexity: a panel, a wingbox, and a morphing adaptive wing, as shown in Figure 2.

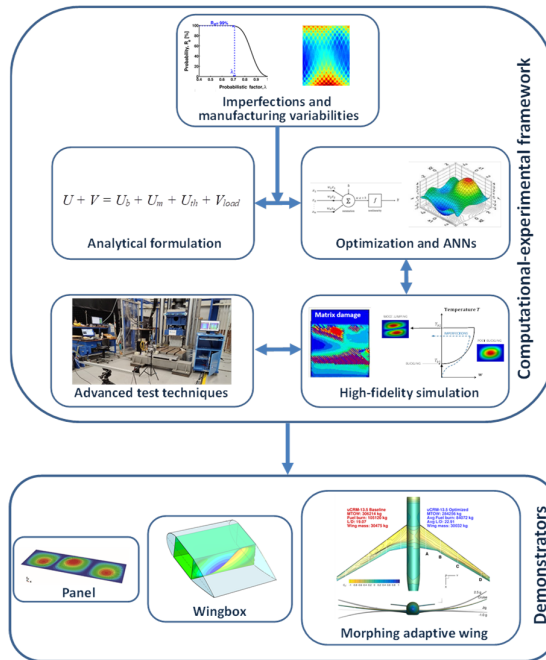


Figure 2 – NABUCCO framework and demonstrators.

3. Different Buckling-driven Structural Concepts

Four different concepts have been explored during the first year to create adaptive configurations using buckling phenomena:

1. Buckling-driven Mechanisms
2. Multi-stiffness Laminates
3. Variable-pressure Panels
4. Magneto-active Elastomer Actuators

All four concepts have been investigated numerically considering panels and a simplified wingbox.

3.1 Buckling-driven Mechanisms

Three buckling-driven mechanisms are investigated to control stiffness changes restraining the out-of-plane buckling deformation using point, area and maximum displacement constraints. In particular, a composite wingbox was analyzed, and the post-buckling behavior of the spar web was controlled by out-of-plane deflection constraints, so that the wing twisting performances were tailored by the relative stiffness of the spar web compared to the rest of the structure.

More details about this approach can be found in a previous feasibility study (17) and in another ICAS paper (18).

3.2 Multi-stiffness Laminates

This concept considers structures divided into areas having different number of plies and different orientations. The orientation and number of plies are optimized to design panels that utilize local buckling of specific zones to modify the axial stiffness (19). This concept is presented in more detail in the following section.

3.3 Variable-pressure Panels

This concept develops a kind of sandwich panel whose stiffness is actively controlled by managing internal pressure. The structure comprises two outer skins and an internal air-filled and pressurized pocket. The variation between internal and external atmospheric pressure determines the alteration in the stiffness of the structure, making it more or less rigid, as required. Furthermore, the internal pressure generates a force that induces deformation in the panel. By controlling the internal pressure, greater or lesser deformations exhibiting morphing properties can be achieved (20).

3.4 Magneto-active Elastomer Actuators

This concept is developed together with colleagues of the Penn State University thanks to an ERC-NSF collaboration. The idea is to develop additively manufactured shape memory polymer and magnetoactive elastomer (MAE) materials to enable adaptive shape changing structures (21). The spatial distribution of magnetic particles is optimally designed to achieve a specified shape change upon application of an external magnetic field (22). The MAE actuation approach offers the advantages of large deflection and force compared to other active materials, without the need for electrodes or wires.

4. Example of Multi-stiffness Laminates Panel Design

An example of the work under development regarding one of the considered concepts, the Multi-stiffness Laminates, is here summarized. The design of a panel to generate adaptability is exploited where changes in stiffness are induced by the evolution of the buckling shape. In particular, the study utilizes composite materials, exploiting freedom in the orientation and number of plies, to design panels that utilize local buckling of specific zones to modify the axial stiffness.

A baseline panel is used as a starting panel to compare the results in terms of pre-buckling stiffness and first buckling load. The baseline panel has dimensions of 900 mm x 300 mm and is made of IM7/8552 carbon fiber composite material. It is composed of 16 plies of quasi-isotropic laminate $[0/45/-45/90]_{2S}$. It is analyzed using the commercial finite element code Abaqus.

The panel is then divided into nine zones as shown in Figure 3, where the thickness and the layup can be varied. The zones are symmetric with respect to the mid-axis aligned with the load, whereas the zones β and η are different to increase the stiffness variability.

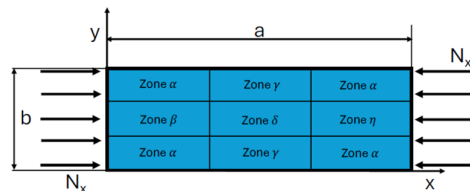


Figure 3 - Multi-stiffness laminate panel.

An optimization of the panel with nine zones is performed to redesign, at a constant weight, the baseline panel maintaining the pre-buckling stiffness with a tolerance of $\pm 5\%$ and increasing the number of different stiffnesses by using local buckling of the β , γ and η zones. For this reason, the thickness of the buckling zones (β , γ and η) is constrained to be at least 12% of the thickness of the no-buckling zones (α and δ). Besides, it is considered that at least 26% of the total number of plies must be distributed in each one of the three sections along the x-axis. The two external plies are constrained to have a 0° orientation in all the zones, to assure a minimum continuity between them, and the resulting laminate must be symmetric. The first buckling load is forced to be a minimum of 20% of the baseline value. Finally, the ratio between the maximum buckling load of the thin zones and the minimum buckling load of the thick zones must be lower than 0.5 to ensure a minimum buckling distance between the zones.

The optimization is performed with the sequential quadratic programming algorithm (SQP), implemented in Matlab, and the objective of the optimization is described using the percentage reduction. The lamination of the optimized panel is reported in Table 2.

Property	Zone α	Zone β	Zone γ	Zone δ	Zone η
N°of plies	25	3	3	32	3
Laminate	$[0/-30/30/-30/30/-60/0/-15/30/-15/15/75/0]_s$	$[0/90]_s$	$[0/-45]_s$	$[0/-45/-60/45/60/60/60/90/-75/-60/60/-45/90/-60/60/15]_s$	$[0/-30]_s$

Table 2 – Optimized multi-stiffness laminate panel.

The load-displacement curve for the optimized panel obtained using a dynamic implicit analysis in Abaqus is reported in Figure 4. Six different linear stiffnesses can be observed and each post-buckling stiffness is associated with a specific deformed shape that induces the stiffness variation. The deformed shapes are reported in Figure 4 with an amplification factor of 30.

Buckling initiates in zone γ , synchronously on both panel sides. The post-buckling stiffness in the (a) segment of the load-displacement curve has a percentage reduction of 16%, with respect to the pre-buckling stiffness. Then, zone η buckles with two half-wave deformed shape and a stiffness reduction in segment (b) of 19%. Then, two sudden buckling phenomena occur in the γ zones at different loads, with two associated stiffness reductions in segments (c) and (d), respectively equal to 25% and 29%. Finally, the buckling of the β zone occurs in segment (e) with a stiffness reduction of 30%.

The optimized panel presents six different stiffnesses and a stiffness reduction, with respect to the pre-buckling one, ranging from 16% to 30%, even if it is important to note that the constraint on the minimum buckling load and the pre-buckling stiffness are not fully satisfied in the finite element results.

This optimized panel, as well as other multi-stiffness panels configurations, are now investigated as a structural component of a simplified composite wingbox. From the preliminary results, the integration of the designed panel within the wingbox confirms the validity of the concept but a reduced magnitude of stiffness variations is achieved.

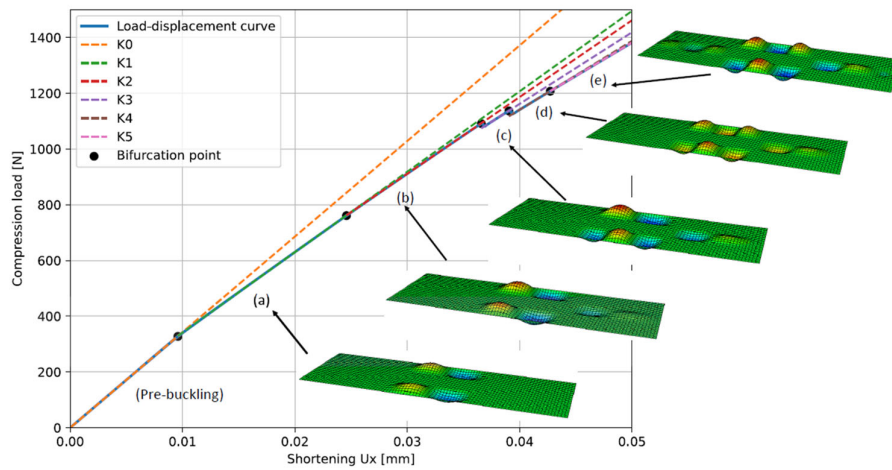


Figure 4 – Load-displacement curve and deformed shapes of the optimized multi-stiffness laminate panel.

5. Damage in Composite Materials and Fatigue Behavior

The explored structural concepts to create adaptive configurations using buckling phenomena need to be properly designed, so that these structures can work in the post-buckling regime and sustain significant loads even if they show a stiffness reduction and large nonlinear deformation. Damage models are considered to determine damage initiation and propagation.

Besides, fatigue models are under development to demonstrate that these structures can undergo repeated loading-unloading-loading cycles and yet remain in the elastic field for all the proposed solutions, and that, if damage does occur, it remains limited and does not lead to structural collapse. Most fatigue models available in literature are demonstrated at the coupon level, while a fatigue model at the structural level is under development starting from a model generated previously (23-25).

The novel aspect of this fatigue model is that non-uniform loading histories are considered. Indeed, using the applied load ratio, as commonly done in most of the models available in literature to calculate damage initiation and growth rate, would result in incorrect predictions. In NABUCCO this is tackled by evaluating the local stress ratio that continues to change due to the changing in the deformed shapes of the different post-buckling equilibrium paths.

6. Induced Buckling to Reduce Wing Gust Loads

The proposed concepts modify the aircraft wing shape, mainly the twist spanwise, tuning the stiffness of the wingbox by controlling the buckling phenomenon of selected structural elements of the wingbox itself. The benefits are mainly due to the possibility to reshape the spanwise load distribution. However, these concepts must be evaluated in an aeroelastic framework to verify the potential impact on the aeroelastic characteristics, to avoid possible instabilities as well as negative impacts on controllability at least at a wing level.

The framework under development helps to understand the impact of the buckling on the aeroelastic response, specifically in the gust response, and is shown in Figure 5. Indeed, gust responses represent a set of critical loads impacting on the structural sizing and, consequently, on the structural weight. The main idea that has been explored aims at reducing the wing root bending moment (WRBM) by inducing a local buckling in specific locations of the wing.

The aeroelastic simulation is performed on a simplified model consisting of stick structures, as a non-linear time marching simulation of a full wing is computationally expensive and cannot be used for trade-off and sensitivity studies. Instead of evaluating the force vs. displacement function as a result of a detailed analysis, it is considered as a bi-linear curve with pre- and post-buckling stiffnesses. The gust analyses are performed using NeoCASS, an aero-servo-elastic simulation tool developed by the Politecnico of Milano (26). It is based on the stick representation for the structural part (beam elements for structural components and concentrated masses for non-structural items) coupled with

a Doublet Lattice Method (DLM) solver for the aerodynamics through a set of splines based on the Radial Basis Functions (RBF) (27).

The aeroelastic simulations provide a correlation map among the stiffness reductions induced by different local buckling phenomena and the potential reduction of WRBM. In this way, the next design steps will be to perform analyses and optimization using higher fidelity models to design a structure that buckles as requested by the most promising cases previously analysed. It is a buckling-driven design because the objective of the high-fidelity optimisation is the buckling behaviour that is identified on a lower fidelity model and computationally cheap aeroelastic framework. After the first set of high-fidelity analyses, the stick model is updated with the buckling behaviour identified, iterating the loop until the convergency is reached.

More details about this approach and the first results applied to an aircraft like the Airbus A321 with an aspect ratio extended to 15 can be found in another ICAS paper (28).

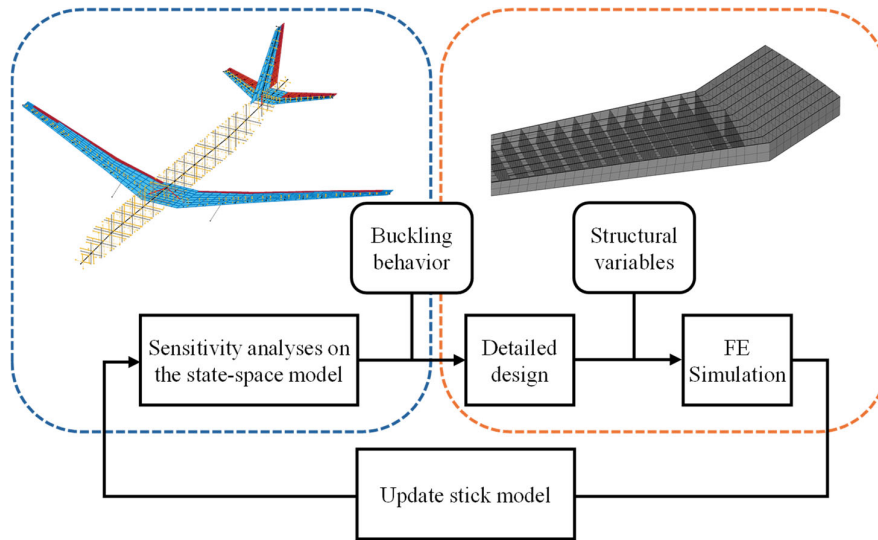


Figure 5 – Aeroelastic framework.

7. Conclusions

The research conducted during the first year of the ERC Advanced Grant NABUCCO has been here summarized. Structures designed to work in the post-buckling field and able to adapt their shape during different flight conditions are under development.

Even if the investigated configurations still require extensive research of feasibility as they need to be validated experimentally, they show the capability of controlling the stiffness changes through the nonlinear post-buckling response and to enhance the adaptivity of the wing structure to meet multi-stable tailorable situations.

The relaxation of some of the established design constraints can contribute to the development of new design philosophies, allowing to realize structural solutions that can act on two of the biggest levers for the future of clean aviation: reduced weight and increased efficiency.

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