Cellular Compressive Wing (CCW) Architecture for sUAV Applications

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Abstract

Achieving high performance in fixed-wing, unmanned aerial systems necessitates efficient wing assemblies which often entail significant design and production costs. Balancing measures associated with performance, production, reliability, and maintainability adds further complexity to wing design. I present here my current work on the use of Cellular Compressive Wing (CCW) architecture as a viable solution for achieving low structural mass and high flight efficiency while simultaneously enhancing production, maintainability, and reducing costs. To confirm the approach, a wing planform utilizing CCW has been conceptualized based on specific aircraft performance requirements. Computational Fluid Dynamics have been leveraged to generate estimates of dynamic wing loads. These simulation methods have in turn been used to guide the design of the architecture as a whole. Application-specific bench-test and in-flight hardware are currently being constructed and tested for direct experimental validation of dynamic planform and CCW interface loads.

Current Industry Standard

Conventional aircraft wings (Figure 1) are highly complex assemblies integrating many sub-systems necessary for flight. However, this complexity comes at the cost of difficult and/or expensive fabrication, repair, and maintenance.

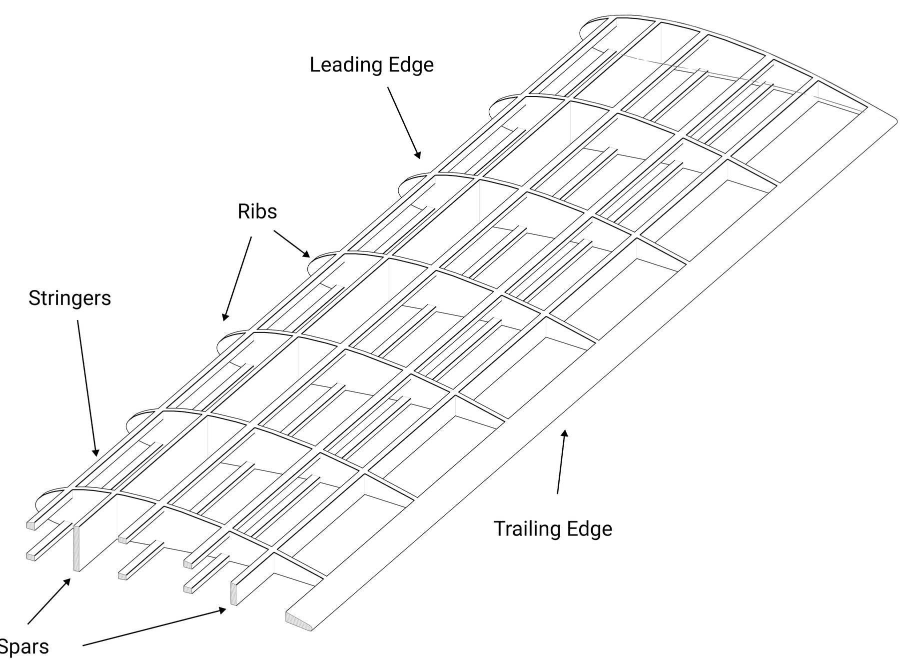

Figure 1. Conventional wing structure

Alternative: The CCW Architecture

The Cellular Compressive Wing (CCW) architecture aims to alleviate design headaches in the realm of manufacturing, assembly, and maintenance, and to increase design flexibility through implementation of a unique modular structure combining these multiple wing sub-assemblies into as few components possible.

Key Points of CCW:

- *Flexibility:* modules with differing capabilities can be hot-swapped (changed on wing while still on aircraft) to quickly reconfigure aircraft.
- *Maintainability:* ease of swapping/replacement of modules in event of wear and/or damage.
- *Modularity:* standardized module architecture increases aircraft design freedom and simplifies manufacturing processes.

CCW Overview

The CCW framework consists of two major classes of components; wing cells, and wing spars.

A wing cell (Figure 2) is a self-contained assembly consisting of wing ribs and a continuous outer skin. Wing spars are of two types; structural and compressive (Figure 3). Structural spars provide rigidity for the wing to resist aerodynamic forces and moments. Compressive spars function as a "binder" for wing cells, hosting fastening hardware which compresses cells into a cohesive structure.

Wing cells are sized in relationship with the overall span b and mean chord $\bar{c}$ of the wing to create a general cell. This "master cell" is then modified as needed to support wing infrastructure, such as control surfaces, motor-mounts, and wing-root units. Wing cells may also be modified to optimize the location of production breaks (especially in adapting to aileron/flap/flaperon placement), but may not extend past $\bar{c}$.

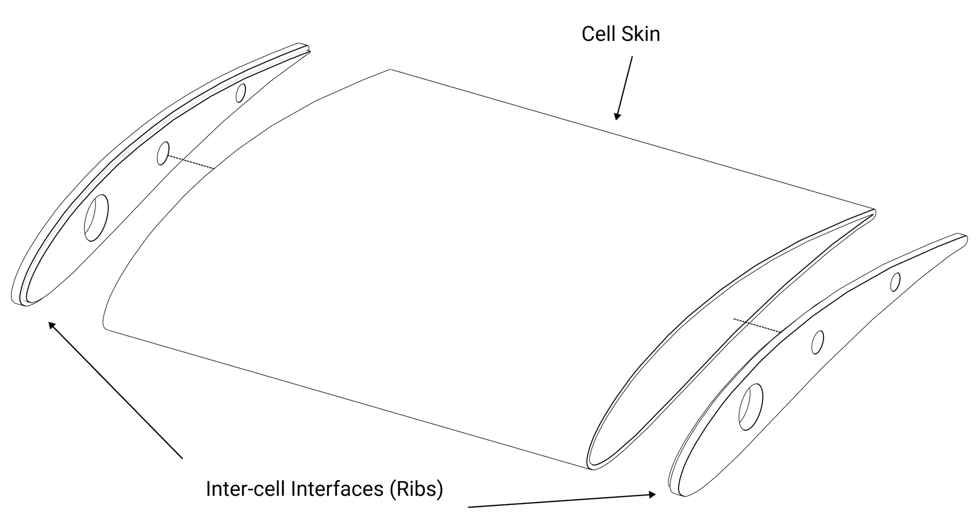

Figure 2. CCW wing cell module.

On each end of a cell a rib serves as both the support for the skin and an interface between other cells. It is fixed to the skin through use of adhesives, and extend slightly into the cell as to form a mating groove to support the cell skin. Use of adhesives allow for a reduced mass of fasteners across the wing assembly.

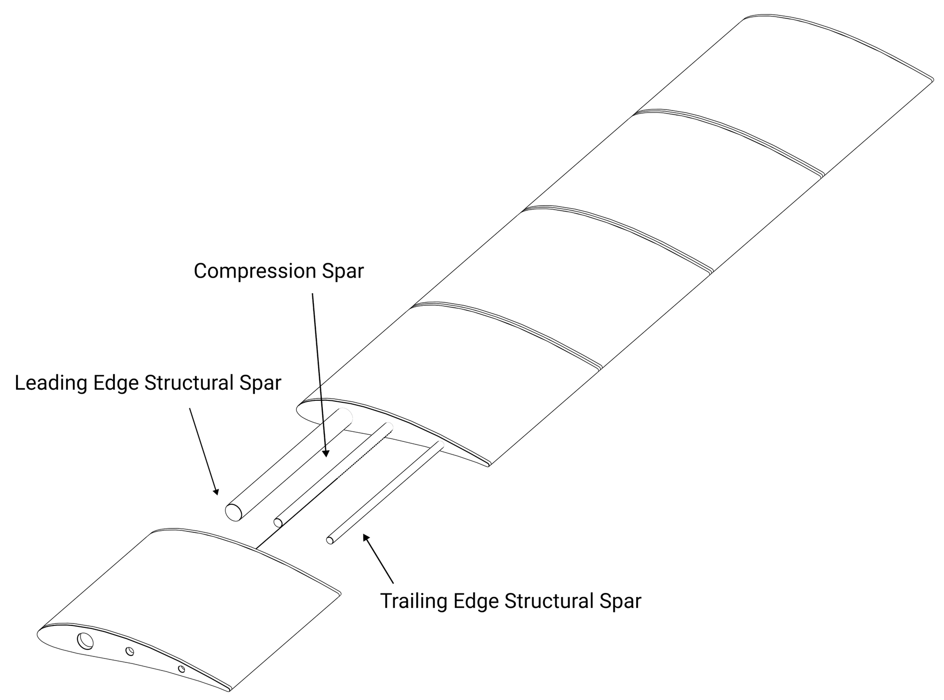

Figure 3. Anatomy of a wing applying the CCW concept.

Application: Demonstrator Aircraft

To demonstrate application of CCW architecture, a small UAV is conceptualized. Designed for take off, simple cruise at medium altitude, and landing with small science payloads, it will highlight the strengths and weaknesses of the CCW independent of other design considerations.

W_{total}	$4kg$
$W_{payload}$	$0.8kg$
$W_{fuel(battery)}$	$1.2kg$
W_{empty}	$2.0kg$
Alt_{cruise}	$5000m$
V_{cruise}	$30m/s$
T_{cruise}	$-17.5C$
$P_{cruise,atmo}$	$79.5MPa$
ρ_{cruise}	$0.7364kg/m^3$
μ_{cruise}	$1.628 \times (10^-5)Ns/m^2$
Re_{cruise}	$108,560.2$

Table 1. UAV design parameters, focusing on cruise characteristics.

Parameters of the mission profile (Table 1) determined the general wing planform (span, chord, geometry) and airfoil cross-section (Figure 4). The wing airfoil was selected as GOE-497. This airfoil is highly efficient at the specific mission parameters. NACA 0012 was selected for elevator/rudder surfaces, as control surfaces generally require a symmetrical airfoil. This specific foil was chosen for favorable stall characteristics.

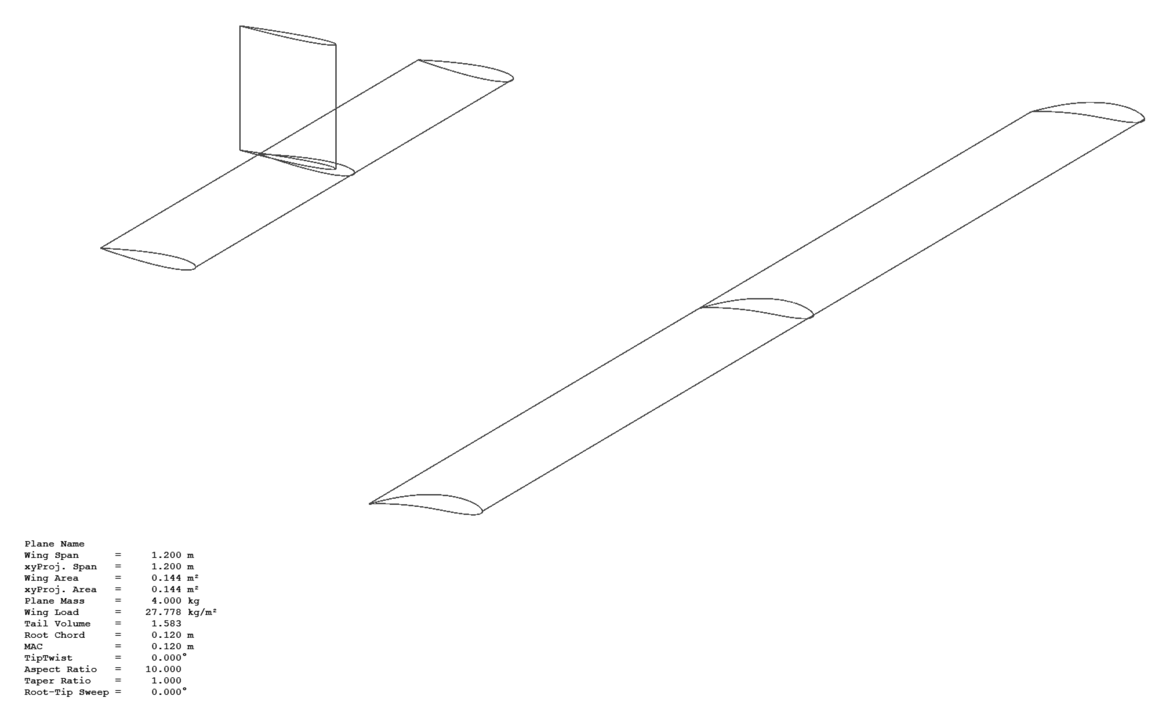

Figure 4. General aircraft wing/tail configuration.
Ailerons exist from 50-90% span, with a hinge at 25% chord, ignoring roll rate considerations. Rear control surfaces are all-moving.

To estimate flight loads, panel theory is applied numerically through the Vortex Lattice Method, or VLM.

The VLM is a computational fluid dynamics method which aims to characterize aerodynamic forces over a wing by simulating the wing as a thin, curved surface sectioned into a matrix of panels. Mathematically, each panel is paired with a "horseshoe vortex", whose properties are influenced by adjacent panels and directly controls aerodynamic forces experienced by the panel.

This mathematical model, once computed, outputs both a force vector and pressure coefficient for each panel. This vector is decomposed into many major aerodynamic forces, including lift, drag, and stream turbulence (Figure 5,6).

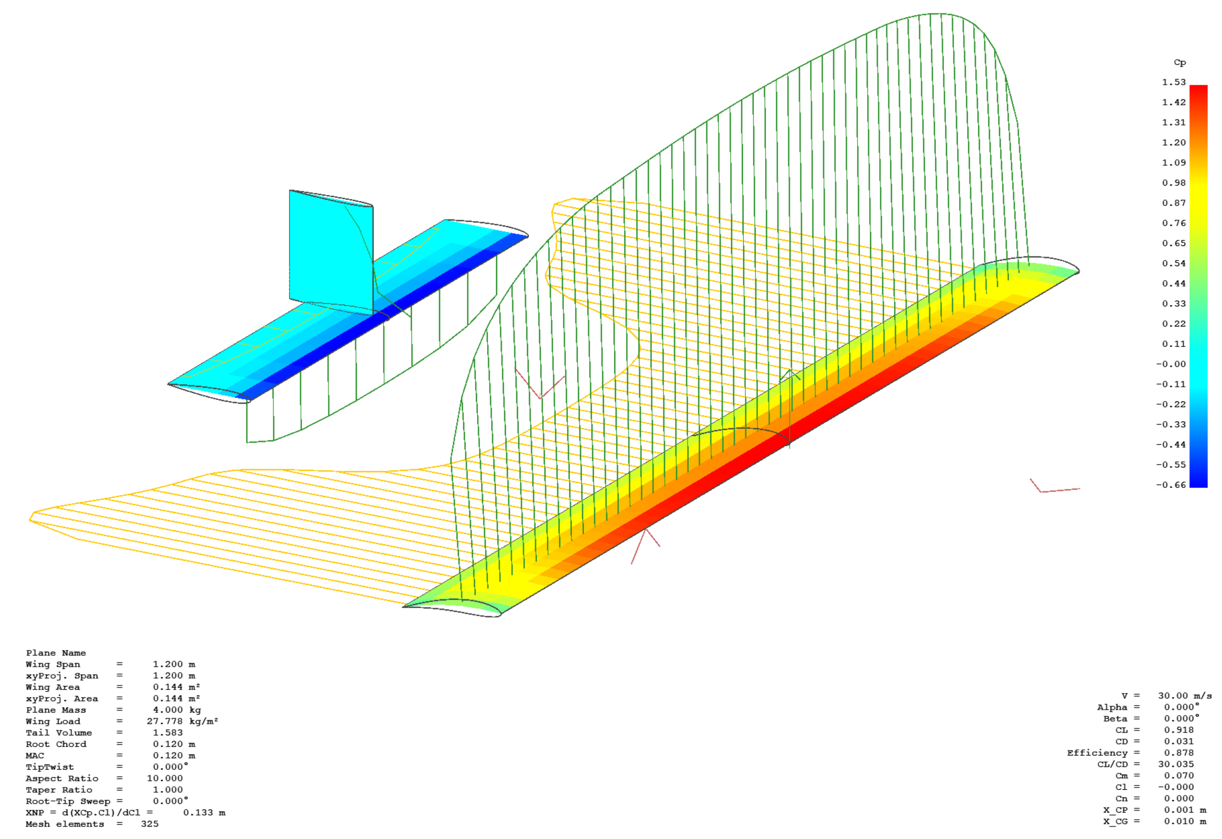

Figure 5. Vortex Lattice Method
Simulation at cruise using the open-source application XFLR5 (v6.61; Deperrois, 2023).

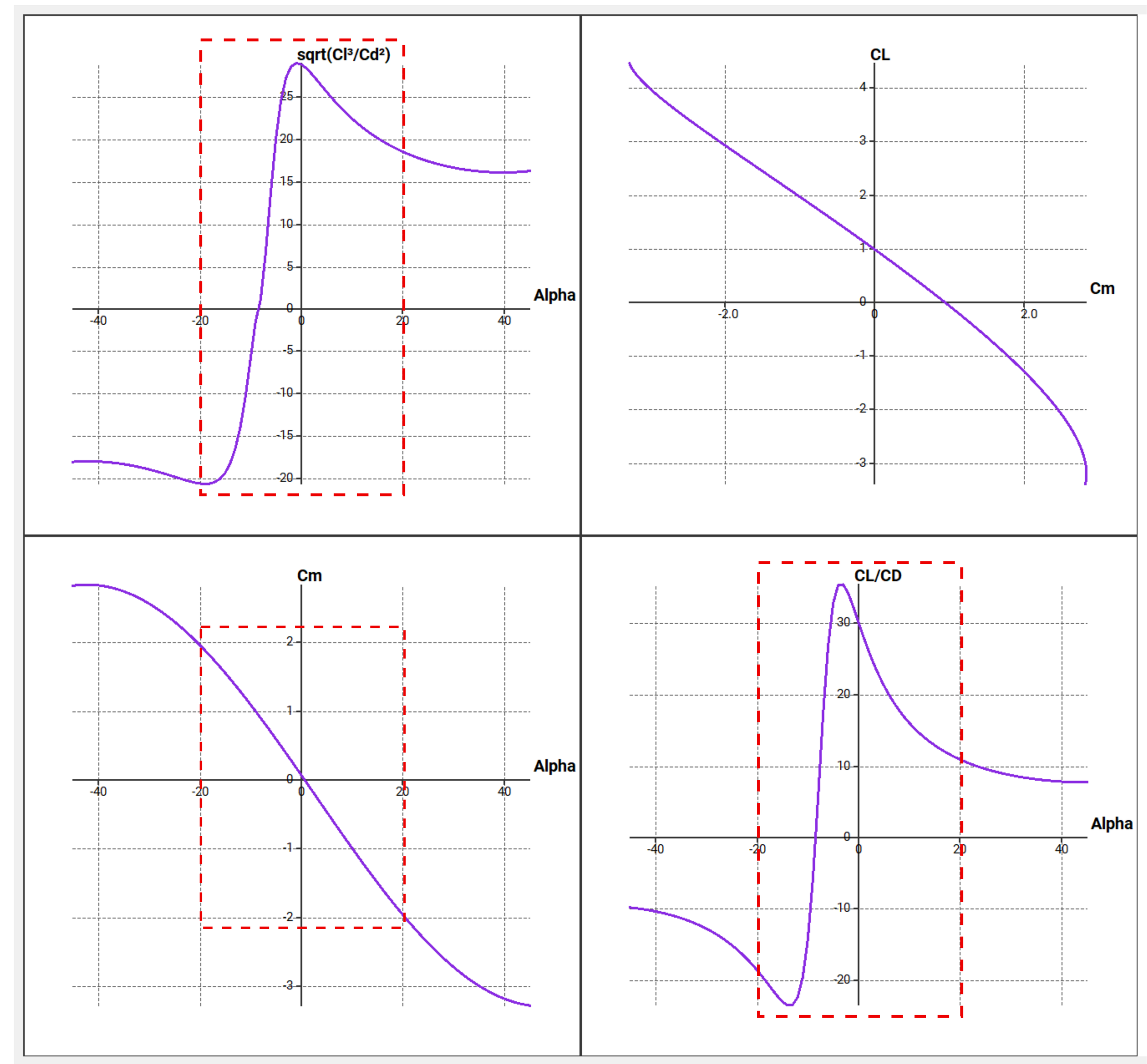

Figure 6. A selection of key wing coefficient data.

With the selected planform and simulation data, the CCW architecture is then applied to create the working concept (Figure 7). Central spars are fastened to a modified cell (wing-root unit), on which the wing is constructed through "stringing" cells together using compression spars along structural spars. The wings are ended with motor-mount cells.

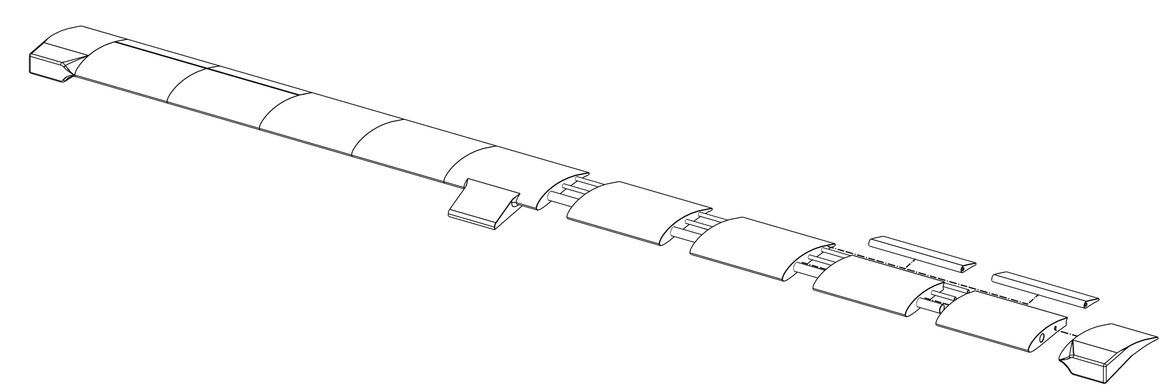

Figure 7. UAV concept wing applying CCW.

With the high-level wing configuration set, simulated loads and assumed cell breaks now inform detailed design of many smaller facets of the wing. These include:

1. Cell-cell interfaces (locking mechanism/compression hardware, internal routing space, electrical contacts).
2. Fuselage integration.
3. Material/manufacturing methods for spars and each component of cells.
4. Control surface integration.

Flight of demonstrator aircraft is anticipated soon.