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# Comparison of curvilinear stiffeners and tow steered composites for aeroelastic tailoring of aircraft wings

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ABSTRACT

A series of aeroelastic optimization problems are solved on a high aspect ratio wingbox of the Common Research Model, in an effort to minimize structural mass under coupled stress, buckling, and flutter constraints. Two technologies are of particular interest: tow steered composite laminate skins and curvilinear stiffeners. Both methods are found to afford feasible reductions in mass over their non-curvilinear structural counterparts, through both distinct and shared mechanisms for passively controlling aeroelastic performance. Some degree of diminishing returns are seen when curvilinear stiffeners and curvilinear fiber tow paths are used simultaneously.



## 1. Introduction

The design optimization of flexible wingbox structures via composite laminates affords the optimizer a large design space (relative to metallic components) with which to tune the aeroelastic behavior. The stacking sequence details of each skin panel may be tailored for the desired in-plane properties (***A*** constitutive matrix) and bending properties (***D*** constitutive matrix). The ***A*** matrix of each panel, when assembled into a wingbox structure, govern the global deformation properties of the wing, such as maneuver load response or flutter. The ***D*** matrix of each panel governs the local deformation of that panel, namely the buckling response [1]. Various couplings known to be important for aeroelastic response, such as bend-twist coupling or shear-extension coupling, may be tailored into the structure through various stacking sequence designs. An early well-known paper by Shirk et al. [2] details many of these themes.

There has been recent interest in further expanding the composite design space for wingbox structures through the use of tow steering. Tow steered composites are created with automated fiber placement machines, which can lay fibers along precise curvilinear paths to create variable-stiffness panels [3]. Each layer of a laminate may be steered independently, or the paths of each layer may be linked in order to preserve potentially-desirable laminate features such as balance or symmetry. For a wingbox composed of rib-delineated skin panels, a single steering path may be utilized from root to tip, with plies added or deleted from one panel to the next. Aeroelastic tailoring via tow steered composites is demonstrated in Refs. [4–7], as are benefits to localized skin buckling performance [8], and load paths around cutouts [9].

A second tailoring scheme of interest in this work is curvilinear skin stiffeners: curved metallic subcomponents constructed with additive manufacturing [10]. If metal skins are utilized, the entire stiffened panel may potentially be built as a single piece through the metal deposition process. If, as in the case of this paper, composite skins are used, the metallic curvilinear stiffeners are fastened to the panels. A third possibility is the use of composite stiffeners, but this is not utilized here.

Tailoring of straight stiffener orientation (rotated relative to the spars) has been studied in Refs. [11–13] for a wingbox, while the benefits of using curvilinear stiffeners for panel optimization, driven by buckling and stress metrics, have been demonstrated in Refs. [14,15]. Expanding this curvilinear stiffener framework to an entire wingbox has proven to be a challenge, however, due to the high computational cost of capturing and tracking all of the local buckling modes in between the various curved stiffeners in each panel of the wing, as well as numerous global modes. A simpler industry-standard approach is taken here, by smearing the curved stiffeners into the skin panel [16] for the purposes of computing stiffness properties. These properties (namely the shell's ***A***, ***B***, and ***D*** matrices, where ***B*** represents coupling between in-plane and out-of-plane mechanics) will then spatially vary along the length of the panel in much the same way as for a tow steered

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composite, to account for the spatial variation in stiffener direction and pitch (spacing).

The goals of this work are to demonstrate aeroelastic optimization of a high aspect ratio Common Research Model wingbox using curvilinear stiffeners and/or tow steered composites. The mass of the wing structure is minimized subject to aeroelastic stress, buckling, and flutter constraints, spread across several trimmed maneuver loads. A series of optimization problems are solved with increasingly-complex structural parameterizations:

1. A metallic wingbox with straight stiffeners.
2. A metallic wingbox with curved stiffeners.
3. A composite wingbox with straight stiffeners and straight fibers.
4. A composite wingbox with straight stiffeners and curved fibers.
5. A composite wingbox with curved stiffeners and straight fibers.
6. A composite wingbox with curved stiffeners and curved fibers.

Comparisons between designs 1 and 2 will quantify metallic weight reductions available through curvilinear stiffener design variables. Design 3 similarly serves as a composite baseline for the curvilinear designs 4, 5, and 6. Design 6 is of particular interest, as it will be indicative of any synergistic relationships between tow steered fibers and curvilinear stiffeners, in terms of both the best-available weight reduction and the spatial distribution of stiffness/load.

## 2. Common research model

All of the work in this paper is conducted on a conceptual high aspect ratio Common Research Model (CRM). The 1g outer mold line for a lower aspect ratio (9) CRM is described in Ref. [17], and a jig shape CRM wingbox subsequently developed by Kenway et al. [18]. A span extension of this model increased the aspect ratio from 9 to 13.5; the latter configuration (shown in Fig. 1) is used here. This transonic transport has a wing span of 72 m, a mean aerodynamic chord of 6.3 m, a taper ratio of 0.25, a sweep angle of 35°, and a cruise Mach number of 0.85.

The topology of the wingbox in Fig. 1 consists of 58 ribs, leading and trailing spars, and upper and lower surface skins. The leading spar is straight, and spans between 10% chord at the root and 35% at the tip. The trailing spar has a slight break at 31% of the semi-span (where the planform does as well), and spans between 60% chord at the root, 70% at this break location, and 60% at the tip. All shell members are outfitted with T-shaped stiffeners, where the flange is bonded to the shell members. The thickness of the flange and the web are equal for all cases, as is the width of the flange and the height of the web. The stiffeners are not modeled explicitly, but instead smeared into the shell stiffness properties [16]. The stiffener pitch is equal to 15.1 cm for the skins, 17.6 cm for the spars, and 19.9 cm for the ribs. For the skins, parallel run-out stiffeners are utilized down the span. In the absence of curvilinearity, all skin stiffeners are parallel to the leading spar: curvature design variables will alter this axis, and the local pitch as well.

The wing structure (carry-through plus main wing) is discretized in 21,000 triangular shell finite elements. All nodes along the centerline are given symmetric boundary conditions, and all nodes along the wing root (side-of-body) are pinned, to model the wing-fuselage attachment. Though not shown in Fig. 1, lumped mass representations (attached to the wingbox at rib-spar-skin intersection points with interpolation elements) are used to model control surfaces (4,400 kg), an engine (7,400 kg), and fuel (45,000 kg for full fuel). Non-modeled mass (fuselage, payload, etc.) for the half-vehicle is fixed at 75,000 kg. As will be seen below, typical structural mass values for the wingbox range from 13,000 to 16,000 kg, so the TOGW for the entire vehicle is roughly 290,000 kg.

Aerodynamic paneling for the wing, horizontal tail, vertical tail, fuselage, and engine (the latter two represented as cruciforms) is shown in Fig. 2, with a total of 5,000 panels. For static aeroelastic trim analysis, the entire vehicle representation of Fig. 2 is utilized. For dynamic flutter analysis, only the wing panels are utilized.

## 3. Aeroelastic modeling and sensitivities

### 3.1. Static aeroelastic maneuvers

The shell finite elements used to model the wing structure are defined by a combination of linear strain triangles (LST) and discrete Kirchhoff triangles (DKT) [19]. For static airloads, a linear vortex lattice method [20] is used to model the aerodynamic lifting surfaces. A finite plate spline (FPS) method [21] is used to transfer downwash and pressures between the aerodynamic and structural modules. Only information pertaining to the wing is transferred in this way: the remaining aerodynamic surfaces are not explicitly tied to any structure.

The wingbox structure is sized across three different types of static maneuvers. The first type is a longitudinal maneuver (pull up, push over), where the system is trimmed via the angle of attack, $\alpha$, and the elevator deflection, $\delta$:

$$\begin{bmatrix} \boldsymbol{K} & -q\cdot\boldsymbol{Q} & \boldsymbol{0} & \boldsymbol{0} \\ -\boldsymbol{P} & \boldsymbol{D}_s & -\boldsymbol{L}_\alpha & -\boldsymbol{L}_\delta \\ \boldsymbol{0} & q\cdot\boldsymbol{S}_L^T & 0 & 0 \\ \boldsymbol{0} & q\cdot\boldsymbol{S}_m^T & 0 & 0 \end{bmatrix} \cdot \begin{Bmatrix} \boldsymbol{u} \\ \boldsymbol{C}_p \\ \alpha \\ \delta \end{Bmatrix} = \begin{Bmatrix} N\cdot\boldsymbol{F}_{grav}+\boldsymbol{F}_{thrust} \\ \boldsymbol{L}_{jig} \\ N\cdot W \\ 0 \end{Bmatrix} \tag{1}$$

The first row of Eq. (1) is the finite element analysis: $\boldsymbol{K}$ is the stiffness matrix, and $\boldsymbol{u}$ is the displacement vector. Forcing functions include self-weight inertial loading, $\boldsymbol{F}_{grav}$ (scaled by the load factor $N$), thrust loading, $\boldsymbol{F}_{thrust}$, from the engine, and aerodynamic forces. Aerodynamic forces are written as $q\cdot\boldsymbol{Q}\cdot\boldsymbol{C}_p$, where $\boldsymbol{C}_p$ is a vector of differential pressure coefficients acting on each panel, $\boldsymbol{Q}$ is an interpolation function derived from FPS, and $q$ is the dynamic pressure.

The second row of Eq. (1) is the aerodynamic analysis, where $\boldsymbol{D}_s$ is the matrix of aerodynamic influence coefficients (AIC) and the subscript indicates a symmetric aerodynamic condition about the centerline of the airplane in Fig. 2. This equation is driven by downwash due to angle of attack, $\boldsymbol{L}_\alpha\cdot\alpha$ (where $\boldsymbol{L}_\alpha$ is a linear operator that converts the scalar angle of attack into a downwash at each panel), elevator deflection, $\boldsymbol{L}_\delta\cdot\delta$, built in camber/twist of the wing and tail jig shapes, $\boldsymbol{L}_{jig}$, and downwash induced by structural wing deformation. This latter term is written as $\boldsymbol{P}\cdot\boldsymbol{u}$, where $\boldsymbol{P}$ is a second interpolation function, also derived from FPS-based methods.

Trim equations are written in the 3rd and 4th rows of Eq. (1): $q\cdot\boldsymbol{S}_L$ and $q\cdot\boldsymbol{S}_m$ convert the differential pressure vector, $\boldsymbol{C}_p$, into a total aerodynamic lift and aerodynamic pitching moment (about the aircraft center of gravity). Lift must offset the total weight of the vehicle ($N\cdot W$), and the pitching moment must be zero.

A second type of static maneuver considered here is a rolling trim analysis Eq. (2), where the deflection, $\beta$, of an outboard wing aileron is found such that a constant specified non-dimensional roll rate, $p\cdot L/U$, is maintained, with no rolling acceleration. In this analysis, $p$ is the dimensional roll rate, $L$ is the semi-span, $U$ is the flight speed, and the aileron is placed between 70% and 90% of the semi-span, with a hinge line at 71% of the local chord. The system is simultaneously trimmed longitudinally for steady level flight ($N = 1$) with the angle of attack, $\alpha$. The rolling analysis requires an anti-symmetric condition about the centerline of the airplane; the longitudinal analysis uses a symmetric condition: