The Twist-Bending Behavior of Forward Swept Wings: A Case Study of a Glass/Carbon Hybrid Composite Structure

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Summary: The behavior of the wing of an aircraft is characterized by the complex interaction among dynamic (distribution of the masses), elastic (ownership of the materials) and aerodynamic (shapes, forces and moments) phenomena. As a rule it is expected from us that the aerodynamic actions damp the oscillations (natural or forced) of the wing. However, above given speeds a lot of undesired aero-elastic phenomena, among which the divergence of the wings, occur and became of considerable importance in view of safety. To potentially prevent dangerous situations, generally the speed of the aircraft is limited; a possible alternative is to endow the "system wing" of proper devices (passive or active, i.e. controls) in order to prevent that the energy transfer of aerodynamic actions amplifies its instability. The forward swept wings are extremely efficient in terms of aerodynamics performance (stall and supersonic behavior) and therefore of maneuverability of the aircraft, even if, unfortunately, they are extremely critic under the profile of the aero-elastic stability. The solution of the technical-scientific and technological problems associated with the use of innovative configurations of wings prefigures a meaningful breakthrough in the international aerospace sector. Within this work the authors aim to determine a particular configuration of composite material for the realization of a forward swept wing in such a way that, under the action of the effective aerodynamic loads, the wings structural response provides a coupled bending-torsion deformations with stability effects. It will be shown that by using a recursive analysis of the composite lay-up one can tailor the overall bending/torsion deformation ratio value.

Keywords: composites; computer modeling

Introduction

Analyzing in short the history of aviation, three basic milestones, corresponding to the most dramatic growth of aircraft overall performance, can be easily found. Such development stages were all mainly characterized by the introduction of new families of materials, able to maximize strength-to-weight and stiffness-to-weight ratios. In the early times of aircraft evolution, wood was the material with highest specific moduli and consequently represented the only reasonable choice. Surprisingly, this first material employed in aeronautics was already nonisotropic, and this circumstance led the first and somewhat empirical attempts to study and adapt wood directional properties to the demanding aeronautical requirements. The resulting structural layout was the well-known multi-wing architecture based on wooden

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ribs and frames covered by cloth, arranged in a bracing structure with solid wooden push-rods and steel wire pull-rods. After more than twenty years of this primeval formula, a quantum leap in aircraft structure was determined by availability on a large scale of aluminum light alloys. Since the 1930s, thin-walled metal structures, i.e. fuselage and wing box with stiffened stressed skin, changed completely the aircraft layout. Cantilever-wing in monoplane configuration allowed a huge increase of wing loading, stiffness and aerodynamic efficiency with a subsequent enormous improvement of flight performance. This structural formula has proved such a great effectiveness to be still applied in modern aircraft nowadays.

In most recent past the introduction of fiber-reinforced composite materials has further on increased structural capability. This solution in some respects is still a challenge for designers and researchers, as it requires more accurate analysis of the load path and some specific optimization procedures to capitalize the great advantages offered in terms of strength, stiffness and reduced weight.

Specifically, the intrinsic nonisotropic properties of fibrous materials can be successfully exploited not only to increase aircraft performance, but also to make feasible some other architectural configurations that are much attractive from an aerodynamic point of view, but characterized by a very poor aeroelastic behavior.

A typical example is the forward (or negative) swept wing (FSW) architecture. Sweep angle Λ is an important geometric parameter that characterizes wing design. Conventionally, for a linearly tapered wing, the sweep angle is measured between the line that connects every point at one-quarter of aerodynamic chords, and the reference y axis normal to the aircraft symmetry plane.

The introduction of the rearward (or positive) swept wing (RSW) can historically be brought back to the middle 1940s, almost contemporaneously to the introduction of first jet-engines. Approaching the divergence Mach number, corresponding to supersonic conditions on the wing, a sudden increase of wave drag occurs. The presence of a positive or negative sweep angle delays these highly undesirable effects, because only the component of velocity normal to the leading edge is effective for compressibility.[1] Basically, the tangential component of velocity makes only a transverse slip flow which direction depends on the sweep angle sign. For rearward swept wings the flow is directed from the root to the tip; this direction is reversed for negative swept wings. In Figure 1A–B a simplified sketch of both RSW and FSW is represented with grey arrows showing slip flows. Although irrespective about compressibility, these slipping phenomena have a considerable consequence on the stall path. In particular, the classical rearward swept wing experiences critical lateral controllability at low speed and limited aerodynamic efficiency. On the contrary, the forward swept wing exhibits great maneuverability also at high angles of attack and a lower stall speed. This interesting behavior was already clear in the early studies of swept wings; unfortunately the forward swept configuration greatly reduces the divergence speed as consequence of geometrically coupled flexural-torsional effects.

Divergence is a static aeroelastic phenomenon that involves every elastic wing (or lifting surface) independently from the presence of a sweep angle. It identifies a critical speed, called the divergence speed, which corresponds to an unstable equilibrium between the torsional moment of the aerodynamic forces and the torsional rigidity of the wing. In these conditions, every occasional torsional perturbation causes large rotations along the elastic axis with consequent structural failure. Bending of straight wings has no effect on divergence, this being only dependent on twisting about the flexural axis. The sweep angle modifies this basic behaviour. Figure 1A–B also shows how differently RSW and FSW behave. For a RWS the points C and D disposed along a generic aerodynamic chord receive a different amount of dis-

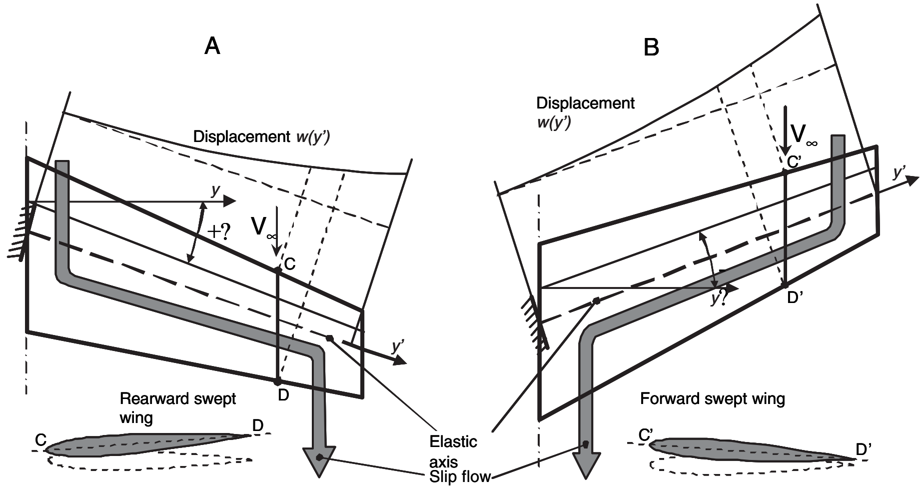

Figure 1.
A–B: Geometric layout and flexural-torsional coupling effect of RSW and FSW.

placement w(y′) that reduces the airfoil incidence. As consequence, a much higher divergence speed than straight wing occurs. The opposite is for FSW; the bending displacement causes an increase of incidence that destabilizes the torsional equilibrium causing a very low divergence speed. For this reason the forward swept wing was an impracticable solution for a long time. A renewed interest for this formula took place in the 1970s with some studies at General Dynamics about filamentary composite materials for supercritical wing design.[2] The TSO project, developed in the same years, produced a computer program for aeroelastic tailoring as synthesis of some early research works.[3–7] Further studies, due to Krone, demonstrated composite laminates capability to approach successfully the FSW design.[8,9] Most recently, HiMat project[10,11] and Grumman X-29 demonstrator provided a flying platform for an high performance, FSW aircraft.[12]

Starting from this framework, in the present paper a feasibility study for the aeroelastic tailoring of the wing-box of an high-performance, FSW uninhabited aircraft vehicle (UAV) is presented. The proposed wing-box is based on unbalanced, hybrid glass-carbon/epoxy composite material, and advanced filament-winding manufacturing. The composite wing is tailored in such a way to counteract the side-effects of forward sweep angle on divergence. In the next paragraphs a parametric model of the wing and a plausible geometric lay-out is illustrated first. Subsequently, a reference flight condition is considered and the related aerodynamic loads are evaluated in order to perform one-way, fluid-structure interaction FEM analysis. An iterative procedure is then performed to optimize composition, orientation and staking sequence of the composite material.

Wing Parametric Model

For both structural and configuration analysis purposes, a detailed parametric FEM model of the wing has been preliminary developed in the Ansys environment via an APDL procedure.[13,14] For the sake of simplicity, wing section geometry is provided with a parametric four-digit NACA airfoil. Although simplified, this design is adequate for aeroelastic simulation; a more sophisticated, and perhaps more useful, transonic/supercritic airfoil geometry could be anyway adopted simply replacing the related sub-procedure. Besides airfoil, wing section is fully characterised as concerns geometry and topology, having defined the box extension, the number of cells and the number and type of stiffeners (if any). Wing plan includes two regions separated by a kink section, each one with its own wing span, taper ratio, sweep angle, number and spacing of ribs. In Figure 2 the wing geometric/topologic lay-out, combined with some sketch examples, is shown.

To analyze the flexural-torsional behavior, a reference multi-box structural configuration, integrating the leading-edge without stiffeners has been considered. In Figure 3 a dimensional sketch of the wing is reported.

For aerodynamic integration purposes, the root region has neither sweep angle nor taper ratio. In both wing regions an uniform web spacing has been adopted. Wing-box components, i.e. upper skin, lower skin, spars and webs, have been finally provided with parametric layered materials, as required by aeroelastic tailoring.

Loads Estimation

An aerodynamic analysis has been previously performed in order to evaluate the pressure field (i.e. the aerodynamic loads) over the entire wing surface. Starting from Ansys geometric data, 3D wing span load distribution has been estimated by means of CMARC software.[15] CMARC is a fluid flow analysis program of the type known as a low-order panel method: this means that calculated pressure coefficient for each panel is applied uniformly over the entire panel. Flow is assumed to be incompressible, irrotational and inviscid. Such a type of panel methods are able to provide the same level of accuracy as higher-order methods in which pressure gradients are calculated within panels, so long as the meshing of the model is sufficiently dense, particularly in areas of rapidly changing pressure coefficient.

First of all, the three-dimensional model to be analyzed must be divided into a large number of generally rectangular panels and then a distribution of aerodynamic singularities (sources and doublets) can be applied over all the panels. As already said, CMARC is a low order panel method, so that constant strengths for sources and doublets are assumed over each panel. The problem is modeled by means of a linear equations system solved iteratively by CMARC for the unknown doublet strengths. Once the doublet strengths have been obtained, singularities on all panels are known, and it is possible to evaluate velocity and then pressure coefficient at the control points (centroids) of each panel.

Figure 4 shows the three dimensional model of the right-half wing used to estimate the loads distribution.

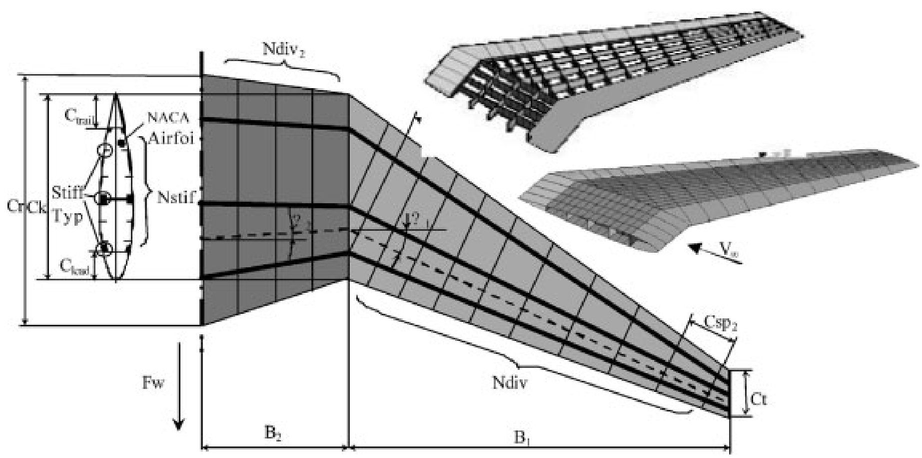

Figure 2.
Wing parametric lay-out and sketch examples (stiffeners not shown for the sake of clarity).

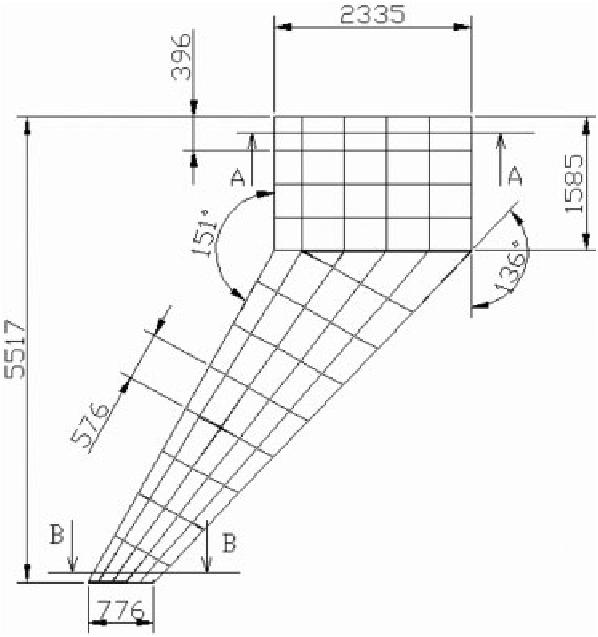

Figure 3.
Dimensional sketch of the considered wing.

Before starting CMARC analysis, the following flight condition has been selected:

- Speed = 110 m/s (396 km/h) or M = 0.323 at sea level
- Angle of attack = 2 degree

Figure 5 shows the related pressure coefficient (Cp) distribution over the right-half wing.

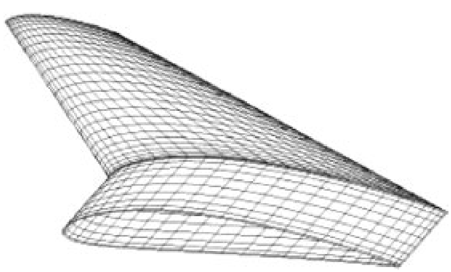

Figure 4.
Right-half wing 3D model for loads estimate on. A total number of 1750 panels have been used.

Material Configuration Premise
As stated above in an aircraft wing the "*structure*" should be able to resist a different bending moment along the axis of the wing than twisting moment about the axis of the wing. In metallic structures the capability of carrying loads in different directions is achieved by using different stiffeners in different directions while laminated composite structures can be tailored taking into account the direction from which the load comes. At the laminate level, tailoring is achieved by simply changing the laminate stacking sequence and, eventually, taking advantage of the best possible performance of a very high-modulus fibers. The analysis reported below is substantially a methodological path that follows the above consideration. Thus far, choosing a given wing configuration with given aerodynamic loads represents just the initial stage of the design process in airplane structures, where the design of a structural component necessarily requires iterative procedures that may,

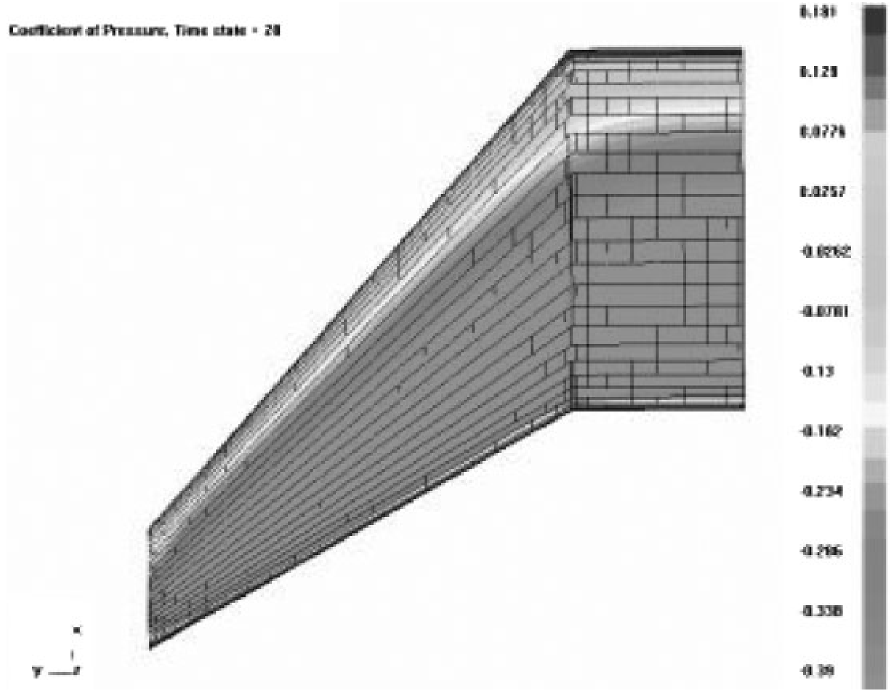

Figure 5.
Pressure coefficient (Cp) distribution over wing upper surface.

actually, drive to change the structure configuration and consequently the aerodynamic loads.

FE Parametric Study

The parametric study starts by assuming a quasi-isotropic laminate lay-up (historically developed for the wing skin of fighter aircraft) to build the wing box. This allows, first of all, imparting the global stiffness to the wing with typical mass reductions of order of 25–30% with respect to metal structures. The composite lay-up consists of an hybrid quasi-isotropic stacking of carbon and glass fibres plies $[0_{Gr}/90_{Gr}/0_G/90_G/\pm45_G/\pm45_{Gr}]_S$.

However, it can be easily shown that, with a different lay-up, satisfactory torsion and bending stiffness can be achieved on the same wing box geometry. The substantial point is that whatever the configuration, the quasi isotropic in-plane properties of the laminates of the wing box is unable to counterbalance the intrinsic instability of a FSW. Here we attempt to realize a structure that under the aerodynamic loads of the kind calculated in the above section exhibits a bending displacement that causes a decrease of the incidence in order to stabilize the torsional equilibrium that, finally, allows reaching higher divergence speeds.

The logical path generating the above solution starts from very simple considerations: if some $\pm\theta$ layers exist in a laminate and if the number of pairs of $\pm\theta$ is increased, then the bend-twist coupling stiffness will tend toward zero as the number of pairs increases. Instead, the coupling is highly enhanced on unbalanced and symmetric laminates.[16] In this case the relation between the moments per unit length (M_x, M_y, M_{xy}) and the curvature of the middle plane (k_x, k_y, k_{xy}) is

$$\begin{bmatrix} M_x \\ M_y \\ M_{xy} \end{bmatrix} = \begin{bmatrix} D_{11} & D_{12} & D_{16} \\ D_{12} & D_{22} & D_{26} \\ D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{bmatrix} k_x \\ k_y \\ k_{xy} \end{bmatrix}$$

the bending-extension coupling stifnesses B_{ij} being equal to zero.

Under these circumstances the governing stiffness are D_{16} and D_{26}, while their relation with the other components of the bend-twist matrix, **D**, and the structure configuration determine the bend-twist response of the wing.

In particular the term D_{26} takes into account the coupling between twist and bending around x (the bending axis is y). In other terms the twist curvature of the middle surface, k_{xy}, depends on M_y through D_{26} and the bending curvature of the middle surface around x, k_y, depends on M_{xy} through D_{26}. D_{26} can be expressed as:

$$D_{26} = \sum_{k=1}^{N} \overline{Q}_{26}^{k} \left(t_k \overline{z}_k^2 + \frac{t_k^3}{12} \right)$$

Where t_k is the thickness of the k^{th} layer, $\overline{z}_k$ is the z-coordinate of the middle surface of the k^{th} layer and $\overline{Q}_{26}^{k}$ is the term 26 of the stiffness matrix of the k^{th} layer in the global coordinate system as defined in Figure 6.

$\overline{Q}_{26}^{k}$ is equal to zero for layers at 0 and 90° (the principal material directions coincide with the axis of the global coordinate system), and is a constant for layers at 45°. So that the θ dependence of D_{26} is contained in the θ dependence of $\overline{Q}_{26}^{k}$ for the carbon-epoxy layer. In the next figure we report the term $\overline{Q}_{26}^{k}$ for the carbon-epoxy layer.

From these arguments, with reference to the Figure 3, representing the selected geometrical configuration of the analyzed wing box, a parametric FE study has been developed by considering as parameters the two angles, θ_1 and θ_2, defined in Figure 6. θ_1 and θ are the angles of the carbon fibers, versus the y-axis, on the upper and on the lower skin surfaces of the wing box. The schematic view of Figure 6 allow us to prefigure as conceivable the filament winding process[17] through which one can suitably obtain the ''winding angles'' defined above. However this is a matter of a different subject and will be bypassed at this stage. The aim of the parametric study was the search of the minimum twist deformation as function of both θ_1 and θ_2.

The FE study has been developed by following two different phases.

At first, fixing the value of the angle between the carbon fibers and the y-axis on the upper skin surface of the wing box, θ_1, the value of the angle on the lower skin surface, θ_2, has been varied between 0° and 180°. In Figure 8 the twist angle β versus the θ_2 angle is reported; it is shown that the minimum of the twist angle can been obtained for $\theta_1 = \theta_2$. Similar results have been obtained for different fixed values of the θ_1 angle.

Further, fixing $\theta_1 = \theta_2 = \theta$, and varying θ in the range 0–180° a minimum value of the bend-twist deformation ratio was calcu-

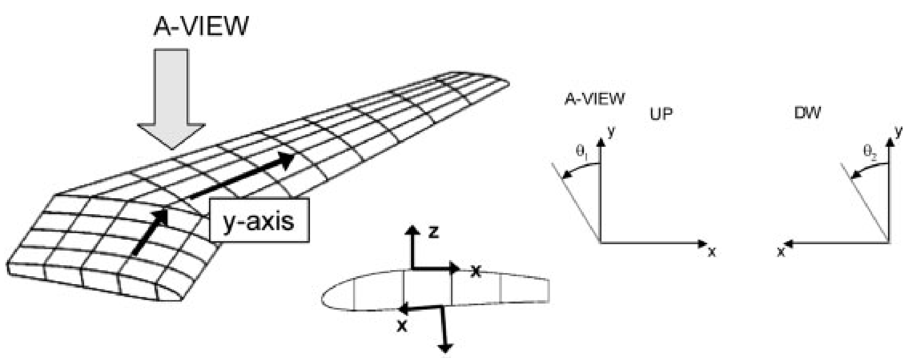

Figure 6.
carbon fiber direction on the upper and on the lower surfaces of the wing box.

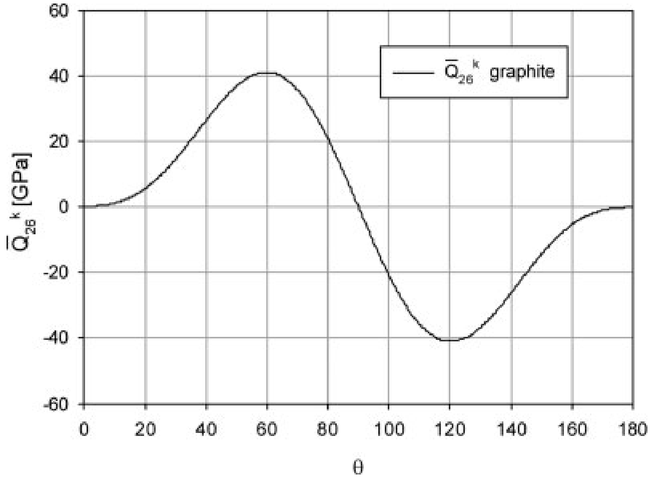

Figure 7.
The angular dependence of $\overline{Q}_{26}^{k}$.

lated: the minimum value has been obtained for θ about equal to 70° (see lay-up 1 in the graph of Figure 9). More importantly, the bend/twist ratio assumed a negative value.

Then, a rough sensitivity study of the influence of the number of the 0°/90° glass-epoxy layers on the global behavior of the composite has been performed. The results are still reported in Figure 9 as the twist-bending deformation ratio vs. the carbon fibers angle, θ, for two different composite lay-up configurations (namely, lay-up 2 and lay-up 3) where layers of glass-epoxy have been added to the laminate lay-up.

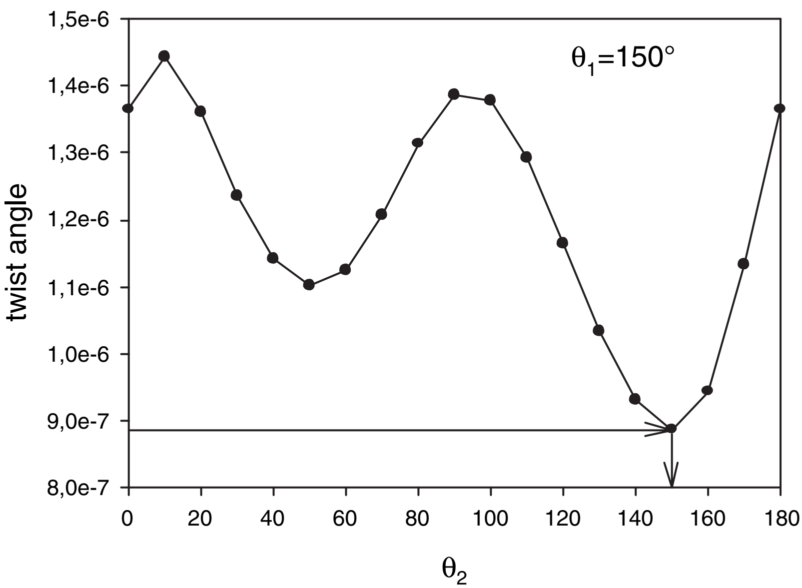

Figure 8.
results of the parametric FE study.

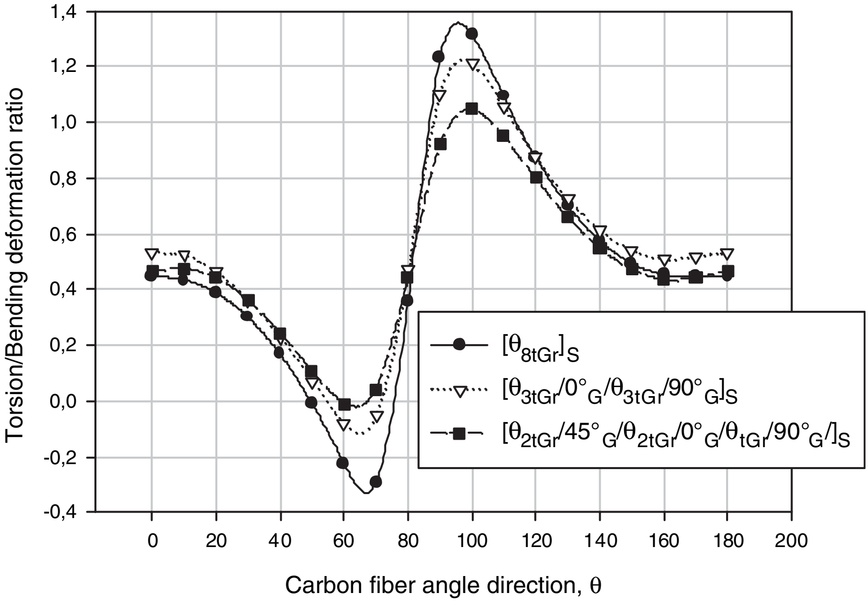

Figure 9.
The structural twist-bending deformation ratio.

From Figure 9 it can be observed the dramatic influence of the glass-epoxy layers on the value of the minimum bend-twist deformation ratio. As expected, since lay –up becomes less unbalanced and less symmetric (actually the level of the in-plane anisotropy is reduced) the "structure" bend/twist ratio increases. Meanwhile it can be readily observed that the minima shift towards slightly lower "winding" angles, θ.

Conclusions

A typical wing box configuration has been considered in this study with an attempt to investigate on the possibilities to find a global composite lay-up configuration that fulfills the requirements of a FSW.

The selected structural and geometrical configuration has been verified to be able to sustain the typical considered load conditions. This configuration might be very crude, but constitutes a start to the *necessarily iterative process*. It is a matter of fact, however, that once we have the initial configuration, some knowledge of the loads, and some idea of what materials we might like to use, then we can begin the actual structural design process.

Thus, more detailed investigation can be developed on the structural and geometrical configuration by acting on the wing section geometrical properties.

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[1] N. B. Pamadi, *"Performance, Stability, Dynamics and Control of Airplanes"*, AIAA, 1801 Alexander Bell Drive, Reston VA 20191, **1998**.
[2] M. E Waddoups, C. B. Smith, and R. W. McMickle, Composite Wing for Transonic Improvement, Composite Wing Aeroelastic Response Study **1972**, AFFDL-TR-71-24, 1.
[3] S. B. Dong, R. B. Matthiesen, K. S. Pister, and R. L. Taylor, Analysis of structural Laminates Aeronautical Research Laboratory, University of California, Los Angeles, Rept. 76, **1961**.
[4] D. Young, *Journal of Applied Mechanics*, **l950**, *17*, 448.
[5] M. V. Barton, Vibration of Rectangular and Skew Cantilever Plates Representing Idealized Missile Fins

Defense Research Laboratory, University of Texas, Austin, Rept. 222, Dec. **l949**.
[6] M. E. Waddoups and L. A. McCullers, Structural Synthesis of Anisotropic Plates AIAA/ASME Structures, Structural Dynamics and Marterial Conference April **1970**.
[7] J. E. Ashton and M. E. Waddoups, *Journal of Composite Materials*, **l969**, *3*, 148.
[8] N. J. Jr. Krone, Divergence Elimination with Advanced Composites Ph.D. Thesis, University of Maryland, College Park, MD, Dec. **1974**.
[9] N. J. Jr. Krone, Divergence Elimination with Advanced Composites AIAA Paper 75-1009, **1975**.
[10] M. A. Prince, HIMAT Structural Development Design Methodology NASA CR-144886, **1979**.
[11] W. Lokos, HiMAT Aeroelastic Analysis, Research and Tecnology Annual Report 1983, NASA TM-85865, **1983**.
[12] N. J. Jr. Krone, Forward Swept Wing Flight Demonstrator AIAA Paper 80-1882, **1980**.
[13] Swanson Analysis Systems INC. ''Ansys user's manual Rev. 5.5'' Vol. I, II, III, **1998**.
[14] Swanson Analysis Systems INC. ''Ansys Programmer's guide Rev. 5.5'' **1998**.
[15] AeroLogic, CMARC release 5.0 User manual, **2003**.
[16] R. J. Jones, ''*Mechanics of Composite Materials*'', Taylor & Francis, Inc. **1999**.
[17] A. D'Amore, M. Zarrelli, ''*Polymer Matrix Composites*'' The 3rd edition of Encyclopedia of Polymer Science and Technology, John Wiley & Sons, NJ **2004**.

