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Extension-Torsion Coupling Behavior of Advanced Composite Tilt-Rotor Blades

by

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Helicopter and tilt-rotor blade manufacturers are incorporating fibrous composite materials into their current designs as a means of reducing weight, vibrations, and costs and controlling vibrations. In a very general sense, a composite tilt-rotor blade can be described as an elastic beam that exhibits generally anisotropic behavior, where it's outer shape is generated by rotating a nonhomogeneous irregular cross section about an initial twist axis (see Fig. 1). The line of centroids does not lie on this axis, instead it can be a helix. Thus, the application of a simple extension (centrifugal) load can result in bending and either unwinding or further twisting of the blade section depending upon the definition of the material properties, section profile, and the location of the initial twist axis. NASA engineers are currently trying to exploit this characteristic, by designing blades that will deform (bend and twist) into the optimum aerodynamic shape for each operating condition (take-off, hover, cruise, etc.) by simply changing the rotational speed of the rotor (i.e.; change the centrifugal force distribution).

Previous research studies have only investigated isotropic pretwisted bars with simple (circular or elliptical) cross sections and have used either a three-dimensional elasticity approach or have tried to approximate the coupling effects using simple technical beam theories. The elasticity-based solutions clearly show the need for three displacement functions that describe the local in-plane and out-of-plane deformations of the cross section. Numerical results have shown that the application of an extension (centrifugal) force to a pretwisted bar will untwist the bar if the initial twist axis and centroidal axis are aligned, but if the initial twist axis and centroidal axis are not aligned, then the bar may either untwist or further twist depending upon the initial twist axis location, cross section shape, and Poisson's ratio.

The objective of my summer project was to develop an analytical model to study the extension-bend-twist coupling behavior of an advanced composite helicopter or tilt-rotor blade. The outer surface of the blade is defined by rotating an arbitrary cross section about an initial twist axis. The cross section can be nonhomogeneous and composed of generally anisotropic materials. The model is developed based upon a three dimensional elasticity approach that is recast as a coupled two-dimensional boundary value problem defined in a curvilinear coordinate system. Displacement solutions are written in terms of known functions that represent extension, bending, and twisting and unknown functions for local cross section deformations (generalized warping). The unknown local deformation functions are determined by applying the principle of minimum potential energy to the discretized two-dimensional cross section. This is an application of the Ritz method, where the trial function family is the displacement field associated with a finite element (8-node isoparametric quadrilaterals) representation of the section.

A computer program was written where the cross section is discretized into 8-node quadrilateral subregions. The material properties for each subregion can be generally anisotropic or laminated composite. The linear matrix equations for each subregion are assembled into a complete cross section representation and solved using standard finite element procedures. Solutions for the local deformations are determined for each of the load conditions (extension, torsion, bending) separately. The extension-bend-twist coupling constants are calculated by substituting the displacement solutions into the cross section equations of equilibrium, and performing the necessary numerical integration (Gaussian Quadrature) over the cross section.

Initially the program was verified using previously published results (both three-dimensional elasticity and technical beam theory) for pretwisted isotropic bars with an elliptical cross section. The calculated local section deformation distributions of the pretwisted bar are composed of coupled in-plane and out-of-plane behavior described by combined Poisson-type contractions, anticlastic surfaces, and torsion-type warping. The current model is in excellent agreement with the published solutions showing torsion stiffness increases, extension stiffness decreases, and maximum negative extension-torsion coupling for pretwisted bars where the initial twist axis and the centroidal axis are coincident. As the initial twist axis is offset from the centroid, the coupling changes sign from negative to positive thus the bar undergoes further twisting, instead of untwisting, for applied extension.

In addition, solid and thin-wall multi-cell NACA-0012 airfoil sections were analyzed (Fig. 2) to illustrates the pronounced effects that pretwist, initial twist axis location, and spar location has on coupled behavior. For moderate levels of pretwist, a solid section has decreased extension stiffness and increased torsion stiffness, whereas certain thin-wall configurations undergo a reduction in both extension and torsion stiffness due to in-plane section deformations that reduce the section planform (Figs. 3,4). Locating the initial twist axis at the centroid maximizes both the extension stiffness and the negative extension-torsion coupling, whereas locating the axis near the quarter chord eliminates the coupling and locating it outside of this region introduces positive coupling and further reduces the extension stiffness (Figs. 5,6).

Currently, a series of advanced composite airfoils are being modeled in order to assess how the use of laminated composite materials interacts with pretwist to alter the coupling behavior of the blade. These studies will investigate the use of different ply angle orientations and the use of symmetric versus unsymmetric laminates.

Future issues that need to be addressed and can be studied with this current model include: 1.) improvement of existing technical beam theory approaches by including the local coupled in-plane and out-of-plane section deformations, 2.) assessment of the local deformation behavior on the dynamic characteristics (stability) of the blade, and 3.) Structural and aeroelastic "tailoring" of the blade structural geometry (wall, spar and ply thickness and ply orientation) for "zero coupling" for constant speed rotors and "maximum coupling" for variable speed (tilt-rotors).

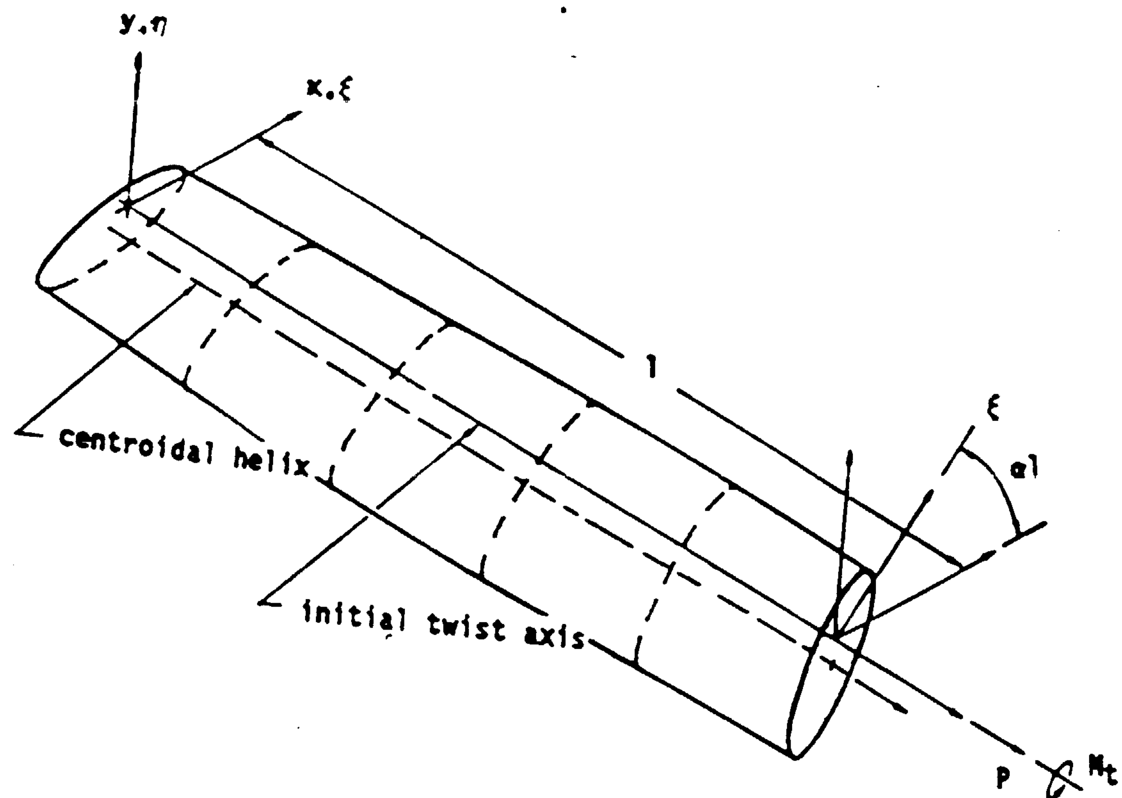

Figure 1 Initially twisted elastic bar with spaced-fixed (x,y,z) and curvilinear (ξ,η,z) coordinate systems and applied extension (P) and torsion (M_t) loads.

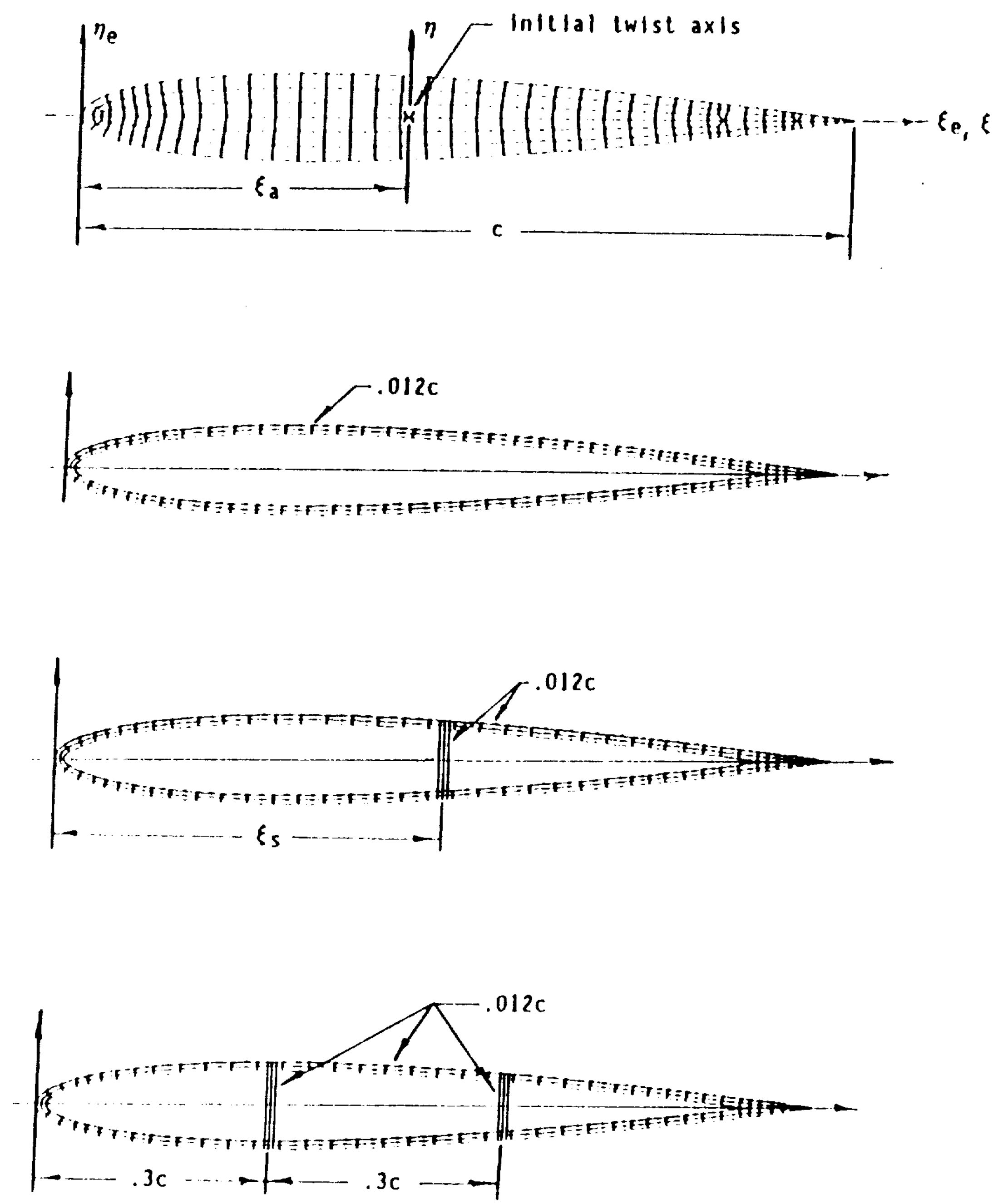

Figure 2 Discretization of four NACA-0012 airfoils with the wall and spar thickness equal to .012c; (a.) solid section using 210 elements, (b.) single cell having 160 elements, (c.) double-cell with 180 elements, and (d.) triple-cell using 200 elements.

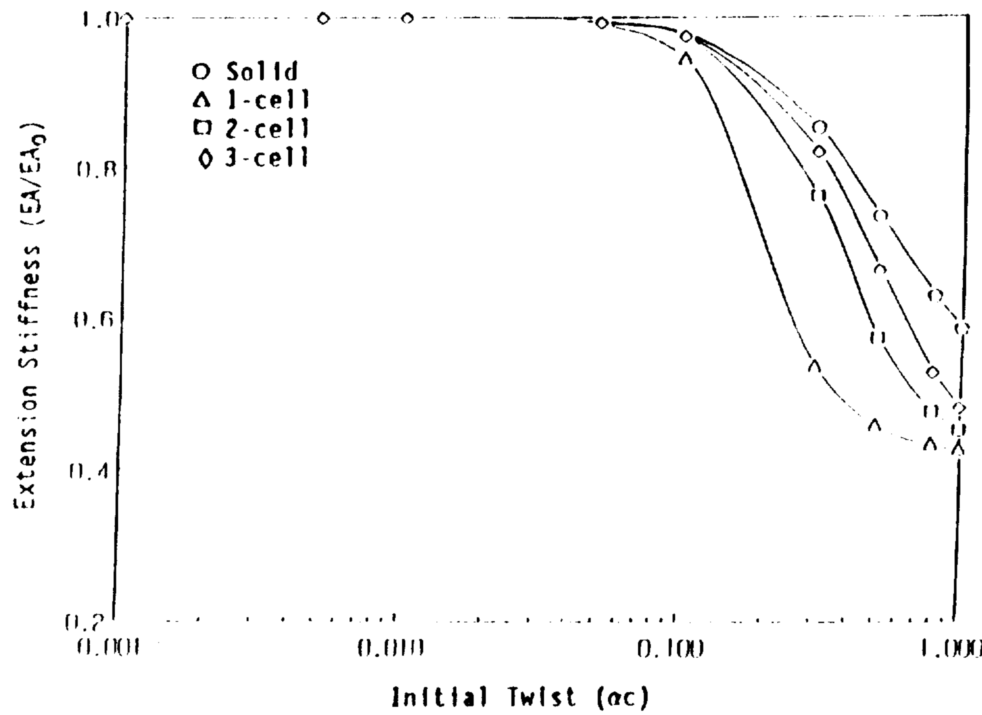

Figure 3 Extension stiffness for pretwisted NACA-0012 airfoil sections with the initial twist axis located at the section centroid.

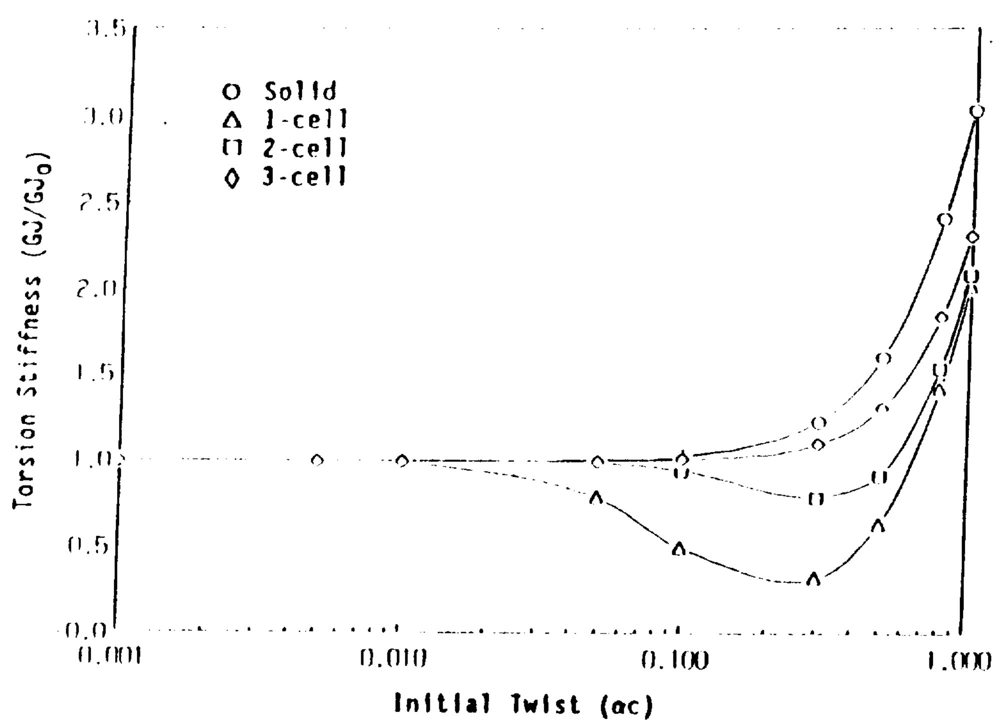

Figure 4 Torsional stiffness for pretwisted NACA-0012 airfoil sections with the initial twist axis located at the section centroid.

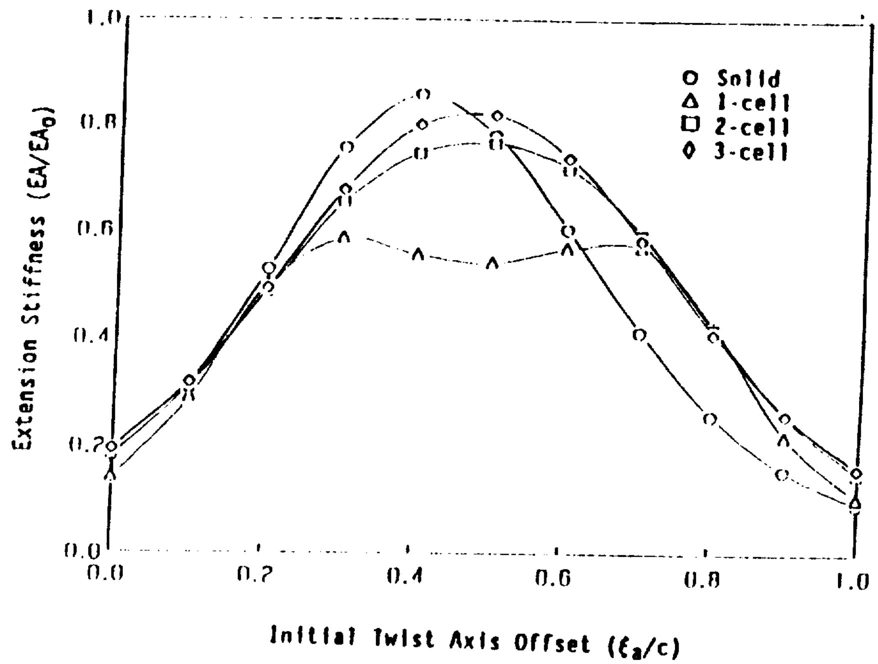

Figure 5 Extension stiffness of a NACA-0012 airfoil section (αc=.30) where the initial twist axis is offset along the chord-wise axis (ξ_a/c).

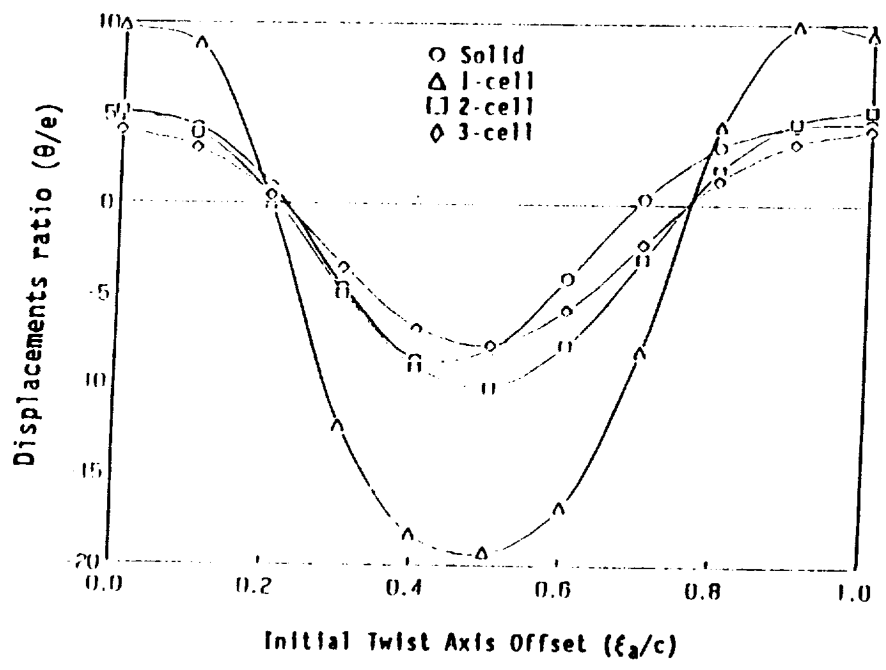

Figure 6 Extension-torsion coupling of a NACA-0012 airfoil section (αc=.30) where the initial twist axis is offset along the chord-wise axis (ξ_a/c).