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AEROELASTIC AIRFOIL SMART SPAR

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SUMMARY

Aircraft wings and rotor-blades are subject to undesirable bending and twisting excursions that arise from unsteady ærodynamic forces during high speed flight, abrupt maneuvers or hard landings. These bending excursions can range in amplitude from wing-tip flutter to failure. A continuous-filament construction "smart" laminated composite box-beam spar is described which corrects itself when subject to undesirable bending excursions or flutter. The load-bearing spar is constructed so that any tendency for the wing or rotor-blade to bend from its normal position is met by opposite twisting of the spar to restore the wing to its normal position. Experimental and theoretical characterization of these spars was made to evaluate the torsion-flexure coupling associated with symmetric lay-ups. The materials used in this study were uniweave AS-4 graphite and a matrix comprised of Shell 8132 resin and U-40 hardener. Experimental tests were conducted on five spars to determine spar twist and bend as a function of load for 0°, 17°, 30°, 45° and 60° fiber angle lay-ups. Symmetric fiber layups do exhibit torsion-flexure couplings. Predictions of the twist and bend versus load were made for different fiber orientations in laminated spars using a spline function structural analysis. The analytical results were compared with experimental results for validation. Excellent correlation between experimental and analytical values was found.

INTRODUCTION

Cantilevered airfoils with high aspect ratios such as wings or rotor blades are generally soft in flexure. The presence of unsteady ærodynamic forces and a lack of flexural stiffness can lead to airfoil oscillations in bending and twist. The magnitudes of such instabilities depend both on æroelastic and ærodynamic factors, and can range from the imperceptible to the destructive.

Rotor blades of helicopters in forward flight are subject to periodic ærodynamic forces that are required for lift, thrust and control. However these periodic forces can induce fluctuating bending loads and twisting moments on the blades not associated with flight requirements. If the resultant bending excursions through an angle Δ are ærodynamically imposed so that a twisting moment though an angle α results which tends to increase the magnitude of the excursion then the effect is divergence ($d\alpha/d\Delta>0$) with respect to such oscillations. It follows therefore that an upwards bending accompanied by a decreasing pitch angle should lead to convergence ($d\alpha/d\Delta<0$) and static stability, and could improve dynamic stability, depending on the frequency and amplitude of the oscillations.

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A common form of such instabilities is flutter which primarily manifests itself as rotor tip oscillations. In terms of æroelastic factors, the amplitude of such bending excursions is inversely proportional to airfoil stiffness in torsion and flexure. Considering ærodynamic factors, the amplitude is dependent on airfoil section, thickness ratio and pitch angle. Moreover, the amplitude increases with increasing helicopter flight speed, becoming pronounced as advancing and retreating blades approach the limiting extent of their normal lift behavior at the onset of compressibility and stall effects, respectively.

With conventional blade construction bending and twisting excursions are uncoupled ($da/d\Delta \approx 0$). Accordingly no ærodynamic constraints are present to damp the extent of any bending excursion, although rotor blades are subject to unsteady ærodynamic loading.

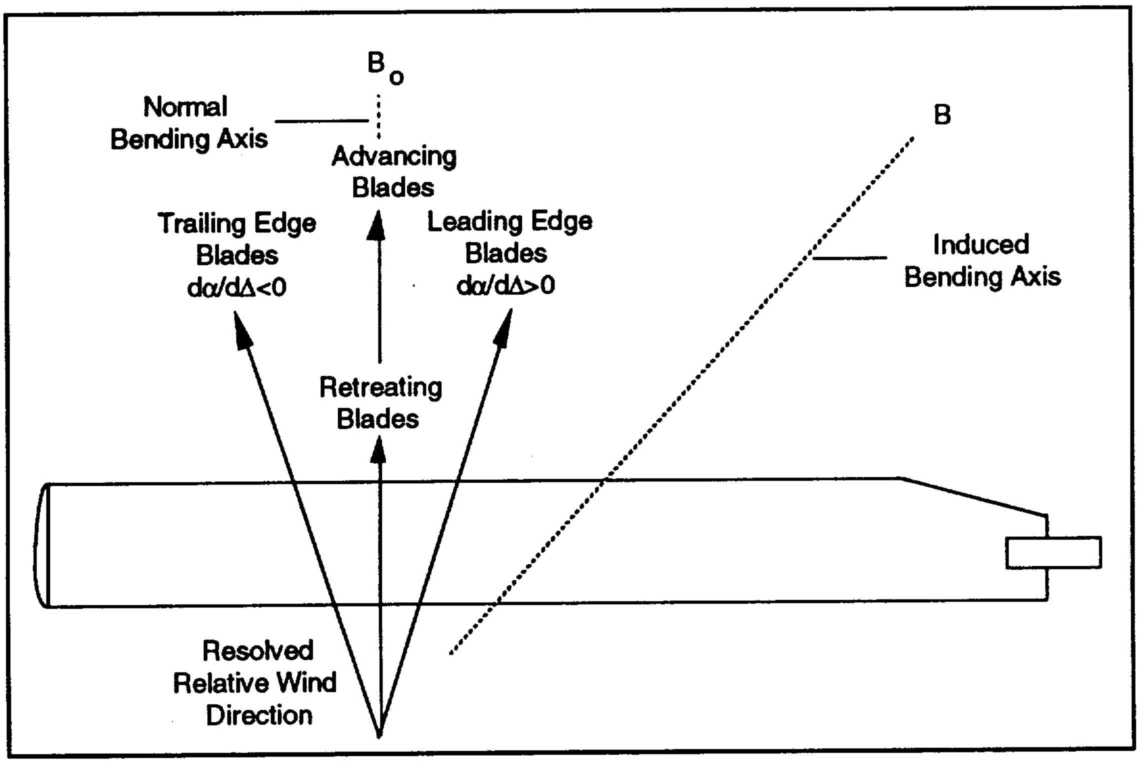

Figure 1. Rotor Blade Resolved Wind

The varying loads to which rotor blades are subject arise from unsteady air forces which have an in-plane component and a normal component relative to the rotor disc. In forward flight the rotor disc can be divided roughly into four azimuth sectors: a trailing blade sector, an advancing blade sector, a leading blade sector, and a retreating blade sector.

In all of these sectors the blades are subject to both the relative wind arising from forward flight and that from blade rotation. When resolved, the relative in-plane wind to which the blades are subject intersects the blade at various angles. In the trailing blade sector the blade is swept backward relative to the wind, and in the leading blade sector it is swept forward. The former condition is stabilizing in regard to flutter (effective $da/d\Delta<0$) as in the case of swept-back wings, and the latter condition is destabilizing in regard to flutter (effective $da/d\Delta>0$) as in the case of swept-forward wings [1,2].

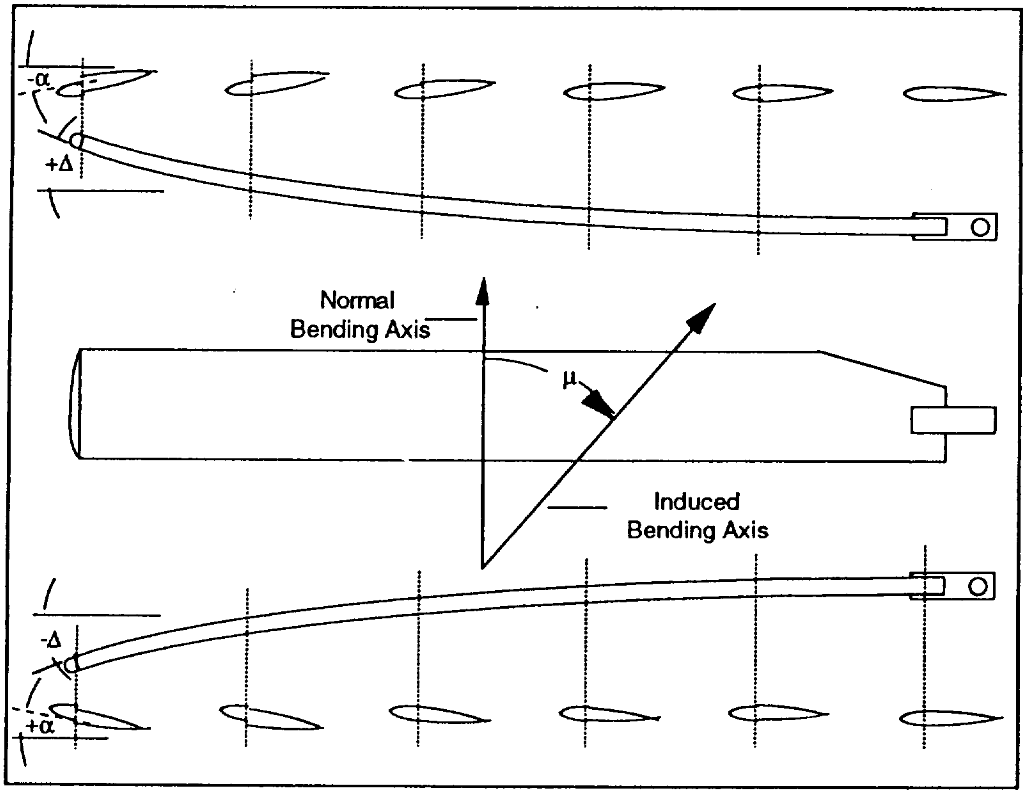

Figure 2a. Effect of Beneficial bend-twist coupling

In the advancing sector the resolved wind is essentially the sum of the rotational wind and the flight wind while in the retreating sector the resolved wind is essentially the difference between the rotational wind and the flight wind. Hence the resolved wind changes both in velocity and direction relative to the normal bending axis of the blades as the blades pass through the azimuth sectors, as shown in Figure 1. With conventional blade construction the normal bending axis B is normal to blade span so that effectively $da/d\Delta=0$, resulting in no beneficial coupling.

Further complicating the ærodynamic loading, because the blades are twisted, the outboard section of the advancing blade can be subject to an updraft while the in-board section is subject to the downwash. Moreover, compressibility in the advancing blade and stall in the retreating blade can directly lead to blade flutter.

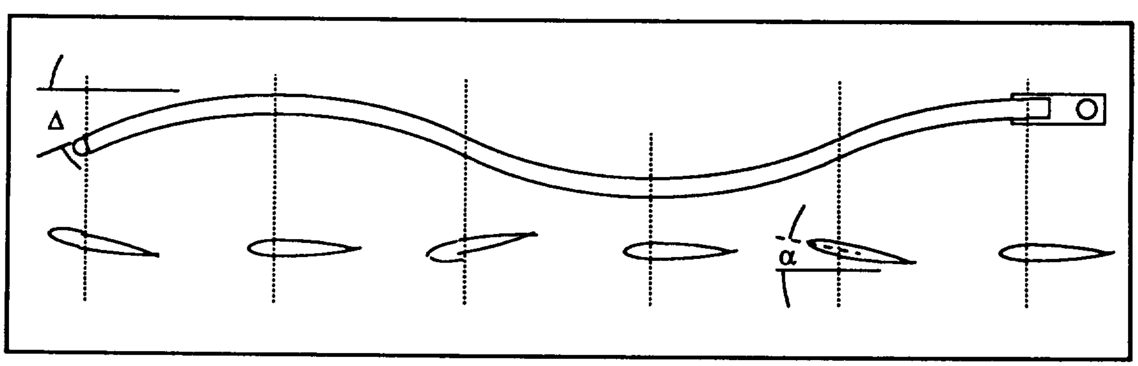

Figure 2b. Effect of Beneficial bend-twist coupling

Furthermore, rotor blades can also be subject to significant bending loads and twisting moments which do not depend on sector. Gust loading can subject rotor blades to high loads at high flight speeds which can result in significant bending excursions. Ice accumulation can so distort the airfoil section that flutter can be induced. Abrupt maneuvers can cause a rotor blade root to contact its flapping stops, as can hard landings. Resulting blade bending can bring a blade in contact with portions of the fuselage.

Essentially, the highly unsteady ærodynamic forces to which rotor blades are subject arise from these diverse sources and lead to blade flutter and even possibly dangerous blade bending excursions. Because in normal blade construction $da/d\Delta=0$, little damping is available.

It is evident that the amelioration of the effects of these fluctuating ærodynamic forces on blade bending and twisting beyond those required for lift, thrust and control would improve helicopter safety and reliability. One means is to employ æroelastic constraint wherein the blades are made sufficiently stiff to largely resist such bending and twisting or to significantly increase blade flapping-hinge offset. However this brute strength approach results in excessive blade weight and might raise rotor hub stress levels beyond safe limits.

An alternative means is to employ ærodynamic constraint wherein convergent torsional-flexural coupling would diminish the amplitude of fluctuating blade bending and twisting, particularly at high flight speeds, and might result in a noticeable reduction in fuselage vibration.

Accordingly, if an airfoil could be so constructed that a bending excursion through section angle $d\Delta$ structurally induces a twisting moment through section angle $d\alpha$ then the airfoil exhibits torsional-flexural coupling: $d\alpha/d\Delta\neq0$. Furthermore, if $d\alpha/d\Delta<0$ a rotor blade would exhibit convergent behavior with upwards bending ($+d\Delta$) accompanied by decreasing pitch angle ($-d\alpha$) and vice versa, which denotes beneficial torsional-flexural coupling. Such beneficial coupling could be induced in a rotor blade if the normal bending axis were skewed through an angle μ. Such an induced bending axis is also shown in Figure 1.

Considerable work has been done on developing spars which impose a beneficial coupling on rotor blades, thereby improving the performance of helicopter rotors under extreme flight conditions, particularly abrupt maneuvers [3,4,5,6].

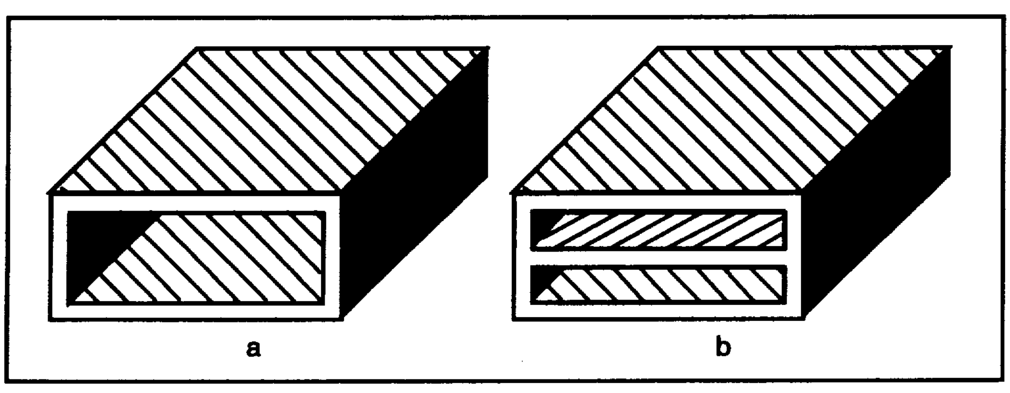

Figure 3. Alternative symmetric laminate construction

The effect of torsion-flexure convergence on a blade subject to first order bending is shown in Figure 2a for any azimuth sector. Hence a bending excursion always results in twisting so as to oppose the bending: $d\alpha/d\Delta<0$. The possible effect of beneficial torsion-flexure coupling on higher orders of bending is shown in Figure 2b.

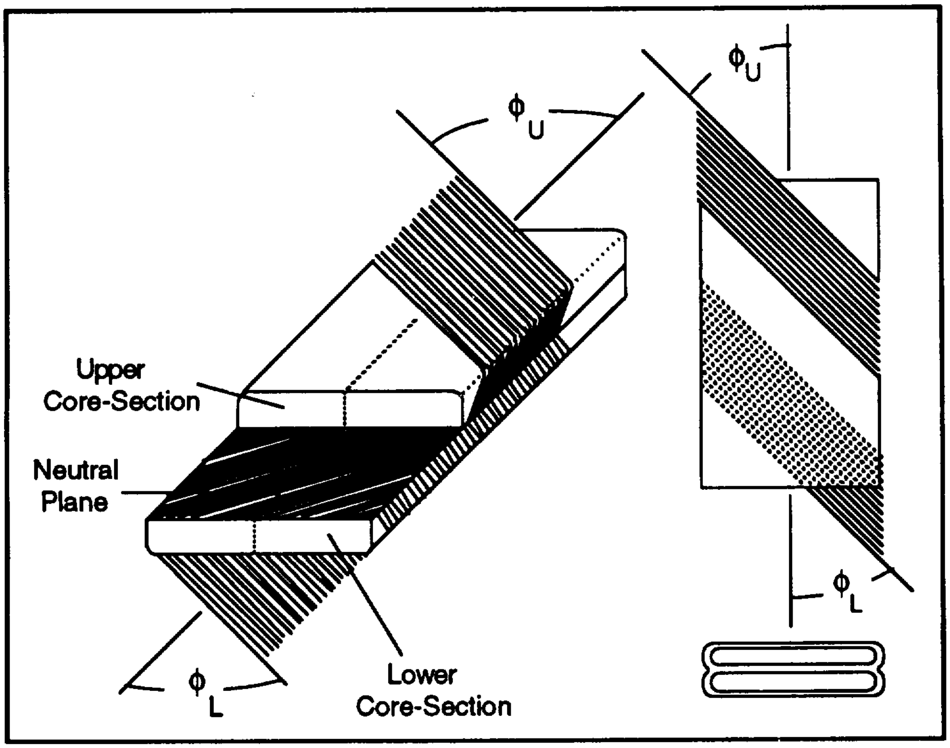

Figure 4. Sectored-core spar

EXPERIMENTAL RESULTS

To construct a rotor blade whose actual bending axis is skewed from its normal bending axis requires a spar construction in which the flexural modulus of the spar can be controlled in different directions relative to the longitudinal axis of the spar, characterized as aeroelastic tailoring [7].

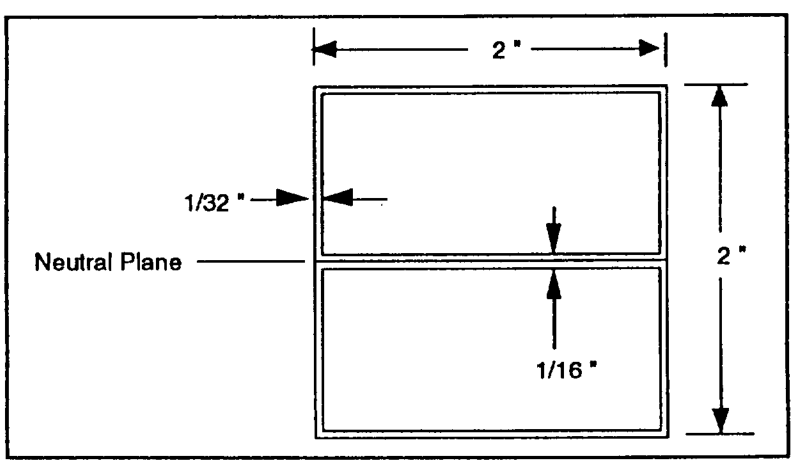

Figure 5. Box-beam cross-section

This behavior can be induced in the spar through an unbalanced symmetric sandwich laminate, such as [q/core/q] as shown in Figure 3a. However, this lay-up sequence cannot be achieved through continuous filament winding processes [8,9].

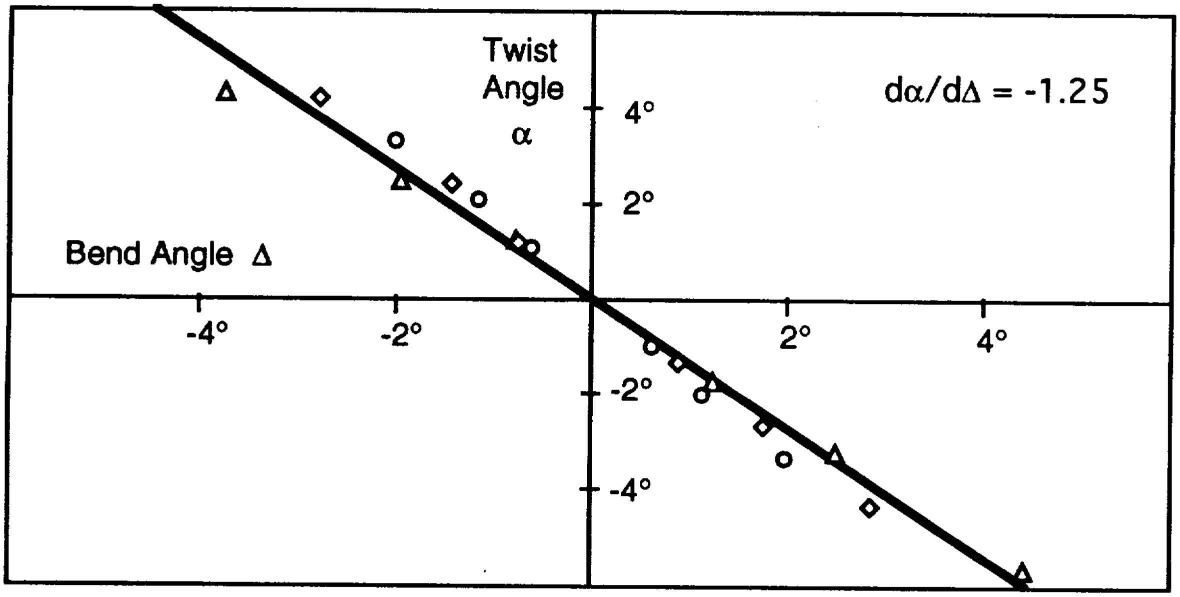

Figure 6. Coupling behavior of a ϕ=45° sectored-core symmetrical wound spar

This shortcoming is circumvented by forming the spar of two box-beams joined at the center as shown in Figure 3b. The individual box elements are wound in opposite directions and joined as shown in Figure 4. The resulting sectored-core lamination sequence formed by this process is $[q/core/-q/core/q]_S$. The central –q ply sequence does not detract significantly from the bending-torsion coupling [10].

A series of prototype spars were fabricated with this construction to demonstrate the behavior. The spars were fabricated using continuous uniweave carbon (<1% 90° glass) and Shell 828 Resin with V-40 curing agent. A single ply was wound about each 36 inch long core at ϕ angles of 0, 17, 30, 45, 60° and then joined to form a box-beam as shown in Figure 5.

The uni-weave material is primarily unidirectional carbon fiber with a small (<2%) amount of glass running in the 90° direction to maintain fabric stability. Winding the fabric onto the cores was a relatively simple matter.

As is evident from the twisting-bending behavior exhibited by the prototype smart spar as illustrated in Figure 6, beneficial torsional-flexural coupling can be realized using sectored-core symmetrical sequence construction and conventional continuous-filament fabrication techniques. The torsion-flexure coupling associated with spars formed from a ϕ=45° winding is illustrated.

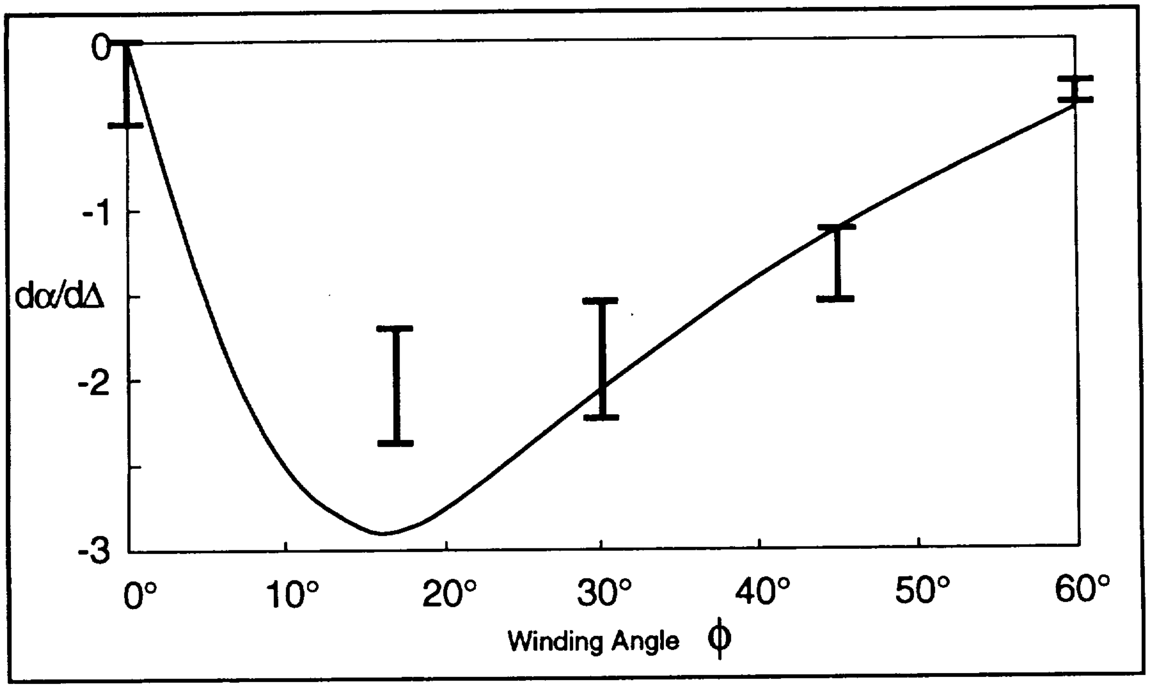

Figure 7. Coupling behavior of the sectored-core wound spars examined

A spline-function aided structural analysis has been developed expressly for the study of composite materials by accounting for the physical material inhomogeneities between plies. Initial efforts of applying this model to prototype spars with ply orientations ranging from 0° to 60° shows promising results, as illustrated in Figure 7.

The solid line in Figure 7 indicates the predicted results. Although the $\phi \approx 45°$ winding showed the greatest twist per unit of bending load, the peak coupling $d\alpha/d\Delta \approx 2$ occurs at $\phi \approx 17°$ for the configuration shown in Figure 5.

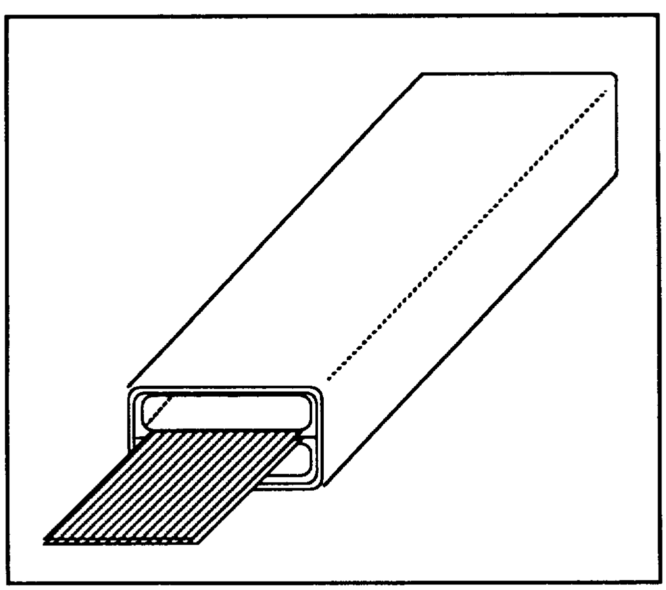

Figure 8. Placement of longitudinal yarns

In actual service rotor blade spars are subject to high centrifugal loading, a condition that must be accounted for by longitudinal yarn layups. To account for this spanwise loading on the spars longitudinal yarns can be inserted adjacent to the neutral plane, as shown in Figure 8. With longitudinal yarns it is expected that the winding angle ϕ which corresponds to the maximal torsion-flexure coupling will be displaced to higher values.

CONCLUSION

A continuous-filament construction "smart" laminated composite box-beam spar for helicopter rotor blades is described which corrects itself when subject to undesirable bending excursions or flutter. Experimental and theoretical characterization of these spars was made to evaluate the torsion-flexure coupling associated with symmetric lay-ups.

Five laminated composite box spars were constructed from a uniweave graphite fiber and epoxy matrix. The spars were made with 0°, 17°, 30°, 45°, and 60° fiber orientation angles with respect to the longitudinal axis. The analytical modeling involved spline function displacement approximations to predict the deformation properties of laminated spars.

From the results of the analytical work, stresses and relevant deflections were found and compared to the test results conducted. Correlations were determined and plotted for each case tested. The greatest twist per unit bending load was found at ϕ=45° and maximum tension-flexure coupling at ϕ=17°.

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