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Composite Propellers for Naval Vessels

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Abstract

There are a number of issues with current Nickel Aluminum Bronze (NAB) submarine propellers including cavitation and vibration, electric signature, and possibly excess weight. A possible solution to all of these is to fabricate the entire propeller (or a significant portion) out of composite materials such as carbon fibre. For naval applications, propellers fabricated of composites could reduce/eliminate electric signatures and the need for corrosion protection. Furthermore, a lighter propeller would result in a potential improvement in draft or loading capacity while reducing bearing loads, and would also allow for thicker blade sections which may end up improving cavitation performance. The Royal Canadian Navy (RCN) has an interest to investigate the design/analysis of various composite propeller configurations in order to achieve the required strength, vibration, weight, and other performance criteria. Due to the complexity of naval propeller geometric configurations, RCN has, in collaboration with Lloyd's Register ATG, developed the PVAST software tool to facilitate the development of propeller finite element models for use with the Trident FEA solver.

The developed tool was used to model and evaluate a number of composite propeller configurations against a legacy NAB propeller on a naval research vessel. The materials considered included glass-fibre reinforced plastic (GFRP), carbon-fibre reinforced plastic (CFRP), and very high modulus (VHM) CFRP. Finite element models of these composite propeller configurations were developed and used for the assessment. The in-air and in-water natural frequency and static stress responses of the composite and NAB propeller configurations were computed. The natural frequencies of the composite propeller blades were generally lower than those of the NAB propeller. The maximum blade deflection of the CFRP and GFRP blades were both significantly higher than of the NAB blade. It was shown that the use of a sandwich composite blade construction, with reinforcing fibres in the through-thickness direction, can be used to reduce the maximum tip deflections to the same order as the NAB blade deflections.

Introduction

Nickel Aluminum Bronze (NAB) is currently the standard material of choice for naval ship and submarine propellers. NAB has high strength and stiffness; however, problems have been encountered with NAB propellers including vibration, electric signature, and possibly excess weight. A possible solution to all of these is to fabricate the entire propeller (or a significant portion of it) using fibre-reinforced polymer (FRP) composite materials, due to the advantages these materials offer, such as corrosion resistance, tailorability of material properties, low electric signature and acoustic properties [1]. FRP composites have the potential of reducing the weight of naval ship and submarine propellers. In addition, designers can take advantage of the bending-extension coupling of FRP composites to modify the deformations of the propeller under load [2]. An initial survey undertaken by the authors highlighted several successful projects in which FRP composites have been used in the fabrication of submarine propellers [3]. As follow-on work to that study, upgrades were implemented in the propeller analysis software, PVAST (Propeller Vibration and Strength) developed jointly by Defence Research and Development Canada (DRDC) Atlantic and Lloyd's Register ATG. These upgrades allow for the efficient analysis of FRP composite propellers using finite element methods.

PVAST Program Description

The finite element method provides an accurate and efficient tool for determining the static response and natural frequencies of structural components. Due to the complex geometry of naval ship and submarine propellers, each element has a different thickness and highly curved geometry. For isotropic blades, this does not pose a problem when computing the element stiffness. For propellers made from FRP composite materials, however, each element must be assigned the correct lamination sequence and the fibre orientation [4]. To reduce the pre-processing effort required by the user, PVAST automatically assigns each element a unique material property based on the element geometry and location. The user specifies so-called "master-laminate" material properties and the desired mapping of the different master-laminates on the propeller blade geometry along the chordwise and radial directions. The mapping of the material properties is performed using a rectangular grid defined by chordwise and radial fractions, such as the one shown in Figure 1. This allows the modeling of composite propellers blades where, for example, the leading edge is made of a metallic material (e.g., NAB), and the composite portion can be assigned different master-laminates, as necessary.

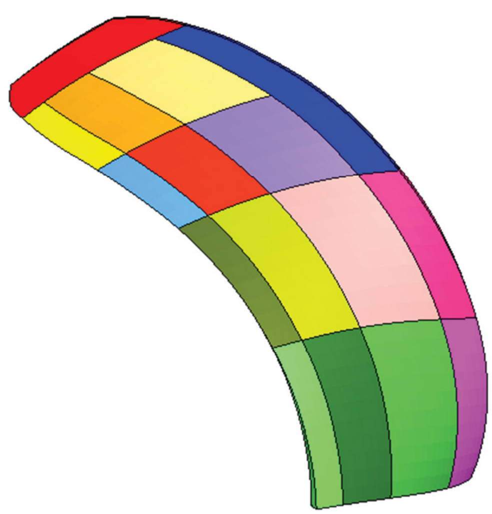


Figure 1: Definition of Material Property Mapping Regions in Chordwise and Radial Directions.

PVAST can generate the propeller finite element model using the higher-order 20-node solid (brick) or 16-node solid-type shell elements with full-integration. In the 16-node shell element, the element stiffness is computed in the same manner as an 8-node shell element, but the element geometry is captured using 16 nodes to better capture the curvature of the element. For each element, PVAST determines the appropriate lamination sequence by trimming the master laminate to fit within the actual element thickness. This approach is fundamentally different from the typical approach used in most general purpose finite element codes, which squeeze the composite laminas, or plies, to fit within the element thickness. It is believed that the approach used by PVAST is more representative of the true blade material. PVAST provides the user the ability to control the master laminate trimming method to reflect the construction of the propeller blade, and applies to both single-skin and sandwich constructions.

In order to correctly capture the anisotropic behaviour of the FRP composite blade, PVAST allows for defining the orientation of the reinforcing fibers locally and individually for each element based on the nodal coordinates. In this case, the fiber orientation can be specified with respect to the chordwise or radial directions. Alternatively, the orientation of the reinforcing fibers can be defined in terms of the global coordinate system, if deemed appropriate by the user.

Verification of PVAST

Before using PVAST in the modeling of naval ship and submarine propellers, a series of verification tests were performed to ensure the composite element formulations converged under axial and bending loading conditions. Subsequently, verification tests were performed on the composite elements capabilities in PVAST aimed at verifying the convergence of the model mass and stiffness with increasing mesh refinement of propeller model. For stiffness calculations, the composite element thickness is averaged at the nodes, and this averaging introduces errors that decrease with increasing mesh refinement. For the purposes of this check, the research ship propeller (P5363) blade [3] was modeled using the layered composite formulation, as well as the currently available isotropic formulation, using elastic properties of steel, as summarized in Table 1. The selection of the isotropic material properties was meant to verify the accuracy of the layered element formulation before anisotropic properties are introduced to the model.

Table 1: Mechanical Properties of Propeller Blade for Convergence Analysis

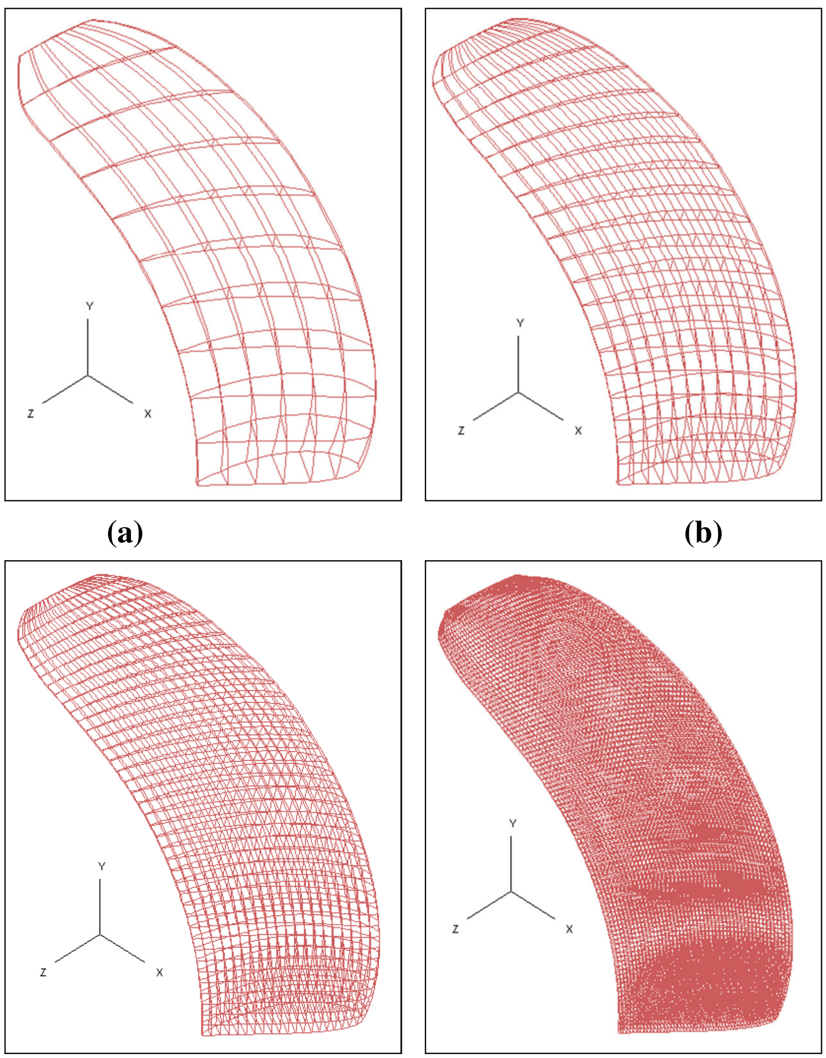
Elastic Modulus (GPa)	207
Poisson Ratio	0.30
Density (kg/m^3)	7,900

Four different mesh densities were considered, as summarized in Table 2 and shown in Figure 2. With increasing mesh refinement, the layered composite and isotropic element formulations show excellent agreement in natural frequency and model total mass. Even with a relatively coarse mesh, the layered composite formulation yielded results that were very close to results obtained using a very fine mesh. Mesh convergence was verified for both 20-node solid and 16-node shell element formulations.

Table 2: Summary of Convergence Analysis Results

Model	Very Coarse FE Mesh (a)		Coarse FE Mesh (b)		Fine FE Mesh (c)		Very Fine FE Mesh (d)	
Mesh Density (radial x chordwise)	10 x 6 elements		20 x 12 elements		40 x 20 elements		100 x 50 elements	
Formulation	Iso.[1]	Lyr.[2]	Iso.	Lyr.	Iso.	Lyr.	Iso.	Lyr.
Mode 1 (Hz)	50	49.1	49.5	49.6	49.5	50	50.3	50.2
Mode 2 (Hz)	110	103	108	104	108	105	106	106
Mode 3 (Hz)	197	181	193	182	194	183	184	184
Mode 4 (Hz)	247	221	232	217	233	218	220	219
Mode 5 (Hz)	356	329	337	319	337	321	323	323
Blade Mass (tonnes)	0.255	0.249	0.248	0.249	0.249	0.248	0.249	0.249

1. Iso. = current isotropic formulation in PVAST; 2. Lyr. = Layered material formulation.



(a) **(b)**

(c) **(d)**

Figure 2: Finite Element Model of Propeller Blade Used in Convergence Analysis.

Analysis of FRP Composite Propeller Blade

The composite modeling capabilities introduced to PVAST were used to analyse the performance of composite propeller blades based on the P5363 blade geometry. The mechanical properties of the different composite materials used in the natural frequency and static analyses are summarized in Table 3. The blade geometry was also analysed using NAB material to provide a baseline against which the composite blade performance is compared.

Table 3: Mechanical Properties Used in Composite Propeller Analysis

Property	Woven Roving GFRP	Woven Roving CFRP	Woven Roving VHM Graphite	NAB
E_{11} (GPa)	20	60	120	125
E_{22} (GPa)	20	60	120	125
E_{33} (GPa)	4	4	8	125
G_{12} (GPa)	3	4	110	47.35
G_{23} (GPa)	3	4	110	47.35
G_{13} (GPa)	1.5	1.5	2.3	47.35
ν_{12}	0.3	0.3	0.3	0.32
ν_{23}	0.06	0.02	0.02	0.32
ν_{13}	0.06	0.02	0.02	0.32
Density (kg/m^3)	1900	1600	1600	7900

Natural Frequency Analysis

The first five natural frequencies of the P5363 blade were obtained using GFRP, CFRP and NAB materials. The finite element model used in the analysis is shown in Figure 3 where the base of the blade was constrained against translation in all directions.

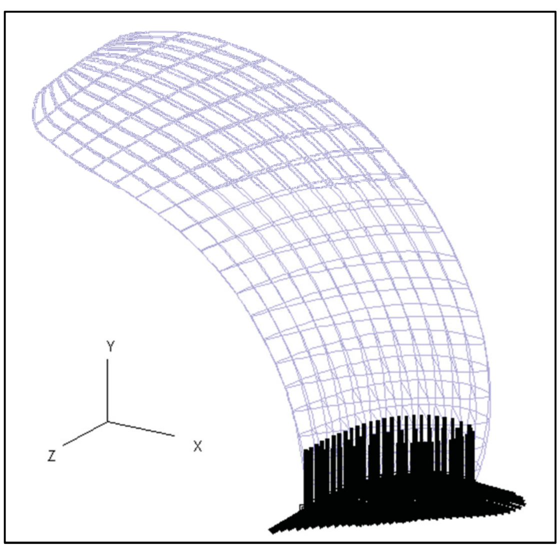


Figure 3: Finite Element Model Showing Displacement Boundary Conditions.

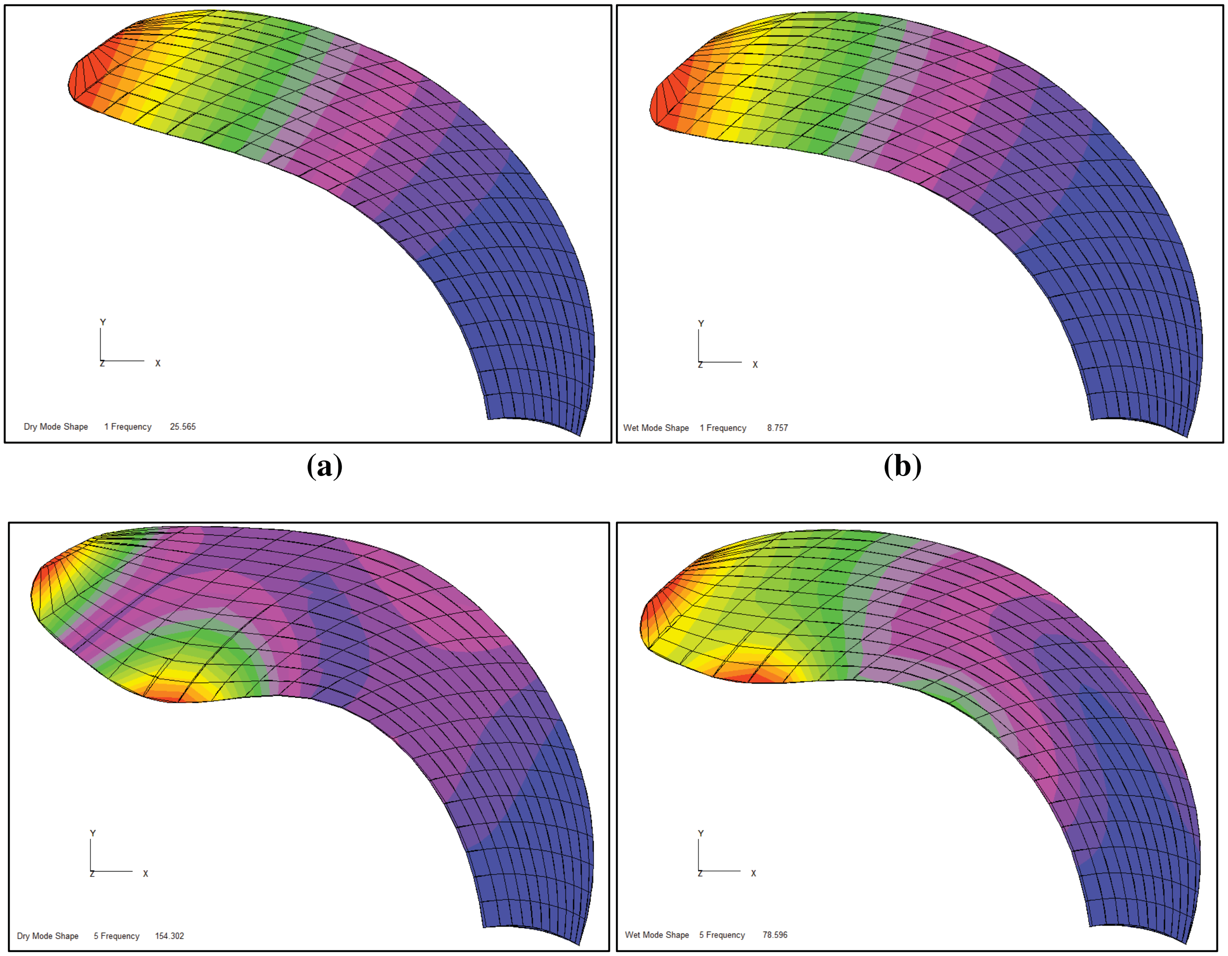
The natural frequencies were computed using dry (in-air) and wet (in-water) conditions as summarized in Table 4. Typical deformation contours representing the first five natural frequencies are shown in Figure 4 for the GFRP propeller. Similar deformation contours were observed for the CFRP blade. The results presented in Table 4 were obtained from the 20-node solid element models, and similar results were obtained using the 16-node shell element formulation.

Table 4: Summary of Natural Frequency Results

Analysis Type	Mode No.	NAB	GFRP	CFRP
		Frequency (Hz)		
Dry (in-air)	1	36.4	25.6	41.5
	2	79.3	54.5	91.7
	3	135	86	132
	4	162	117	201
	5	232	154	243
Wet (in-water)	1	21.9	8.7	12.9
	2	58.7	26.5	41.1
	3	103	49.0	77.2
	4	124	58.8	92.9
	5	169	78.6	118

For the dry model, the natural frequencies of the CFRP propeller were generally higher than those of the NAB propeller. Modes 1 and 2 were about 15% higher for the CFRP propeller, mode 4 is 24% higher, and modes 2 and 5 were within 5% of the corresponding natural frequencies of the NAB propeller. These results indicate that the lower stiffness of the CFRP material is offset by the low density of the material, thus providing natural frequencies higher than those of the denser and stiffer NAB propeller. The GFRP propeller dry natural frequencies were 28% to 36% lower than those of the NAB propeller. It is worth noting that the CFRP material has the highest stiffness-to-density ratio, while GFRP has the lowest.

All five wet (in-water) natural frequencies of the composite propellers were lower than those of the NAB propeller. The CFRP propeller wet natural frequencies were observed to be 25% to 41% lower than the corresponding wet natural frequencies of the NAB propeller, while the GFRP propeller wet natural frequencies were 52% to 60% lower than those of the NAB propeller. It is worth noting that the decrease in the natural frequency from dry to wet conditions was in the range of 23% to 40% for the NAB propeller, 43% to 66% for the GFRP propeller and 42% to 69% for the CFRP propeller.

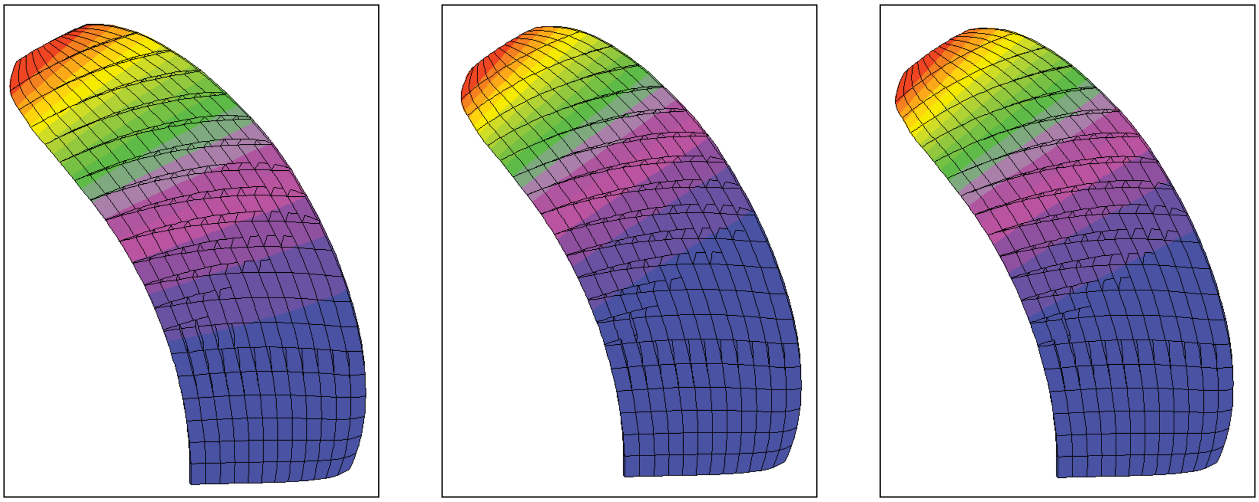


(a) **(b)** **(c)** **(d)**

Figure 4: Deformation Contours for GFRP Propeller
(a) Mode 1 (dry); (b) Mode 1 (wet); (c) Mode 5 (dry); and (d) Mode 5 (wet).

Static Analysis Results

The performance of the composite propeller blade was investigated in PVAST under quasi-static loading conditions. The blade design pressures and drag forces were applied as surface pressure loads to the finite element model, and the base of the propeller was restrained against translation as shown earlier in Figure 3. The deformation contours of the CFRP, GFRP and NAB propellers are shown in Figure 5. The contour ranges in Figure 5 vary linearly from zero at the base of the propeller to a maximum at the tip of the blade. The maximum deflection at the tip of the NAB propeller shown in Figure 5(a) was 16.7 mm, while the maximum tip deflections at the tips of the CFRP and GFRP propellers, shown in Figures 5(b) and 5(c), respectively, were 43.0 mm and 46.1 mm, respectively, significantly greater than that observed for the NAB blade. The large propeller blade deflections observed are in agreement with findings of Lin [5].



(a) **(b)** **(c)**

Figure 5: Displacement Contour Results of Propeller Finite Element Model:
(a) NAB; (b) CFRP; and (c) GFRP.

It is worth noting that maximum blade deflection of the CFRP and GFRP propeller blades are not significantly different from each other, and both are significantly higher than those observed for the NAB blade. The significant increase in the blade deflection cannot be explained only by the decrease in the material elastic moduli in the radial and chordwise directions. Instead, it is evident that the low through-thickness elastic modulus and the low shear stiffness of the composite material contribute to increasing the overall blade deflection significantly. To alleviate this problem, a sandwich composite blade construction can be used to increase the blade shear stiffness and introduce reinforcing fibres to the through-thickness direction. To illustrate the benefits of the sandwich construction, the P5363 blade was modeled using CFRP skins and a sandwich core constructed from very high modulus (VHM) graphite. The orientation of the reinforcing fibres in the core is aligned with propeller radial and through-thickness directions, in an effort to increase the through-thickness properties of the propeller. The deflection contours for the sandwich composite propeller are shown in Figure 6, with a maximum tip deflection of 25.1 mm, which represents a 41.6% reduction compared to the CFRP propeller model. However, a strength check performed on the sandwich propeller shows a significant drop in strength in the chordwise direction and does not pass the Tsai-Wu criteria. Therefore, a more detailed study will be required to optimize the composite material layup to balance the strength and stiffness requirements for the propeller.

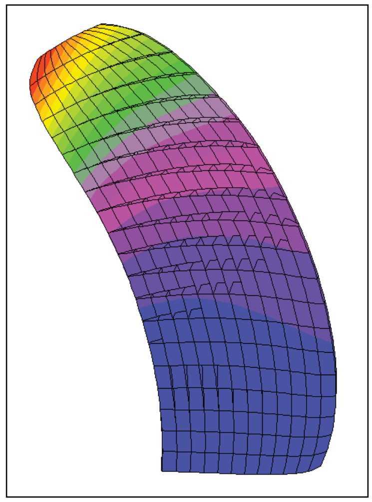


Figure 6: Displacement Results of Sandwich Composite Propeller.

CONCLUSION

Modifications implemented in the PVAST software to allow modeling and analysis of ship and naval composite propellers were presented. Using the developed capabilities, users of PVAST can construct finite element models of laminated composite propellers using the same pre- and post-processing tools available for isotropic propeller blades. The current work also investigated the use of the modified PVAST software to perform a preliminary design study of a naval composite propeller. The geometry of the research ship propeller (P5363) blade made of NAB material was used to investigate the composite propeller capability. Results of natural frequency analysis show that dry (in-air) natural frequencies of CFRP propellers are generally higher than those of NAB propellers while the dry natural frequencies of GFRP propellers are lower. Wet (in-water) natural frequencies of CFRP and GFRP propellers are significantly lower than those of NAB propellers.

Static stress responses of composite propeller blades constructed of woven roving glass-fibre reinforced polymer (GFRP) and carbon-fibre reinforced polymer (CFRP) were compared to the response of the baseline isotropic NAB propeller blade. The maximum blade deflection of the CFRP and GFRP blades were similar and significantly higher than that of the NAB blade. It was shown that the use of a sandwich composite blade construction, with reinforcing fibres in the through-thickness direction, can be used to reduce the maximum tip deflections the same order as the NAB blade deflections. Further investigation is required to develop a composite propeller design that would meet the DRDC propeller blade performance requirements. Plans are also underway to validate the new capabilities experimentally.

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