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Numerical Investigation of a Marine Propeller Blade for Material Effect and Stress Behaviour

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ABSTRACT:

The process of designing a marine propeller for under water applications involves various complex analyses. Analysis is of iterative in nature which makes it cumbersome and inefficient to understand. A part of the research work entitled in this paper is concerned with the material effect and stress behavioural characteristics of a marine propeller blade subjected to cantilever condition. Designing and analysing the behaviour of an anisotropic composite material is one of the most important technologies in the area of marine propulsion. Based on FEM the conventional and composite material marine propeller blades are analysed. To simulate the blade layup and to determine the stress characteristics, ANSYS software with shell 181 elements is taken for reference. A study has also been carried out for determining the stress and deformation pattern arising due to varying ply layup and material. The obtained numerical results are then compared and summarised in. Computational efficiency and integrity of the presently adapted method in this work are determined by several case studies.

KEYWORDS:

Composite; Deformations; Finite elements; Marine; Static analysis; Propeller

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1. Introduction

Thousands of years ago, locomotive device ships were started as simple lugs or bundles of reeds. Today the same has been developed as huge size vessels. During 19^{th} century, the principle of mechanical propulsion was started in ships. The 1^{st} iron hulled ship launched in 1840 by the Great Britain was with the traditional material wood. Later the traditional material was replaced with iron followed by steel and later this technique was gradually employed for manufacturing large ocean going ships. As the geometry of the blade is complex and its boundary conditions are more complicated makes computations more difficult in performing structural analysis. Hence for these complex geometries, the structural analysis can be carried out by relating the classical theory approach applied to a curve beam, plate and shell elements, where propeller blade can be considered as a cantilever beam rigidly fixed to the boss.

2. Literature review

Many of the researchers have used most popular available FEM. As the blade geometry is considered to have an aerofoil cross section with an asymmetric and pre-twisted profile containing taper along its length, a technique named elementary beam theory was first proposed by Taylor [1]. Here a blade is treated as a cantilever attached to the propeller hub and, thereby recommending the stresses are to be calculated for cylindrical blade sections containing a neutral axis parallel to the nose-to-tail (pitch) line of the expanded section. Cantilever beam theories have yielded reasonable estimates of stresses at certain selected points of relatively straight and narrow blades. Some modified forms of beam theory have been proposed for wide-bladed propellers with blade width-to-length ratios of about 1. The shell theory approach was first proposed by Cohen [2]. He has treated a simplified propeller blade model as a helicoidally shell with variable thickness and infinite width. However, when this approach was applied to the problem of a shell of finite width, it was impossible to produce a solution to satisfy the boundary conditions. Later studies included those of Connolly and others [3-4]. Shell-type theories which incorporate broad assumptions do not appear to offer tangible improvement; more-over, they are rather involved for routine design purposes. Analytical methods which was an attempt to predict blade stresses based on conventional mechanics was not a successful one. Considerable efforts have been devoted for measuring blade strains on both the model and prototype propeller blades [3 and 5-7]. Certain cases have fetched good agreement b/w the obtained between beam theory and measured data. However, utmost care must be taken in drawing general conclusions from limited measurements, as large number of factors are involved. The trend in ship building to full after bodies for mammoth tankers and bulk carriers and to higher speeds for modern naval vessels has been accompanied by large irregularities and fluctuations in ship wakes.

As a result, propellers experience increased dynamic excitation and generate severe vibratory forces on ship hulls and propulsion systems. Readers are referred to a SNAME publication for propeller terminology [8]. Propeller-induced vibration is one of the main problems associated with the propulsion of ships by means of screw propellers. The thrust derived from blade-lift force is unsteady when the blades rotate in a non-uniform velocity field behind the ship. The interaction of these unsteady forces-with the hull and appendages causes the excitation of the ship by the propellers. Blade skew, high blade area ratios (that is, wider blades), and a large number of blades per shaft have all been tried to reduce vibration. These innovations of propeller geometry drastically alter blade displacement patterns [9-10] and render the standard methods (for example, beam theory) invalid. If blade design is to have a sound and rational basis, then an effective analytical method is clearly required so that suitable blade strength and stiffness can be determined for a specified ship-operation task.

A finite-element procedure based on a general 3D, formulation [11] will now be used to analyse a screw propeller in its more general form, that of a highly-skewed propeller. The computed results are then compared with measured displacements and stresses under steady pressure loading. This study will provide the basis for further extension of procedure until, it is eventually able to take unsteady stressing and fatigue behaviour into account. In primary research works, the forces acting on the blades and their stress-strain reactions are calculated by using analytical and experimental relations. Sontvedt [16] achieved, using the shell elements, the results for predicting the quasi static and dynamic stresses in marine propeller blades. Young [17] presented a coupled boundary element method (BEM) and finite element method (FEM) for the numerical analysis of flexible composite propellers in uniform flow and wake inflow. This research has been extended for the fluid-structure interaction analysis of flexible, composite marine propellers subjected to hydrodynamic and inertial loads.

The hydrodynamic blade loads, stress distributions, and deflection patterns of flexible composite propellers can be predicted by the method [18]. A coupled structural and fluid flow analysis was performed to assess the hydro-elastic behaviour of a composite marine propeller [19]. A MAU 3-60 propeller was analysed with different stacking sequences of composite layup. The hydro-elastic behaviour of the propeller with balanced and unbalanced stacking sequences were investigated and discussed by Lin et al. [20]. Mulcahy et al [21] carried out a comprehensive work on the hydro-elastic tailoring of the flexible composite propeller. Blade stress-strain relation of the marine propeller was analysed by Chau [22]. Recently, Koronowicz et al [23] has presented a comprehensive computer program to account for the hull-propeller-rudder system in the propeller design process. The program outcome includes the hydrodynamic performance, cavitations effect, and blade strength and efficiency optimization.

The SPD (ship propeller design) software has been recently prepared by Ghassemi et al and applied to various propellers such as propeller-rudder system (PRS) [24], high-skew propeller [25], contra-rotating propeller [26] and surface piercing propeller (SPP) [27]. This software uses the BEM including boundary layer theory to determine the hydrodynamic analysis of marine propeller.

3. Composite as replacement to metallic

The application of composite materials has become more predominant in the field of engineering and technology such as marine, aerospace, wind turbine, automobile, mechanical etc. During 19th century rapid usage of composite materials started as a replacement to base line materials of metallic alloys. New generation heavy sized propeller blades, wing structures; large aircrafts are built up using hybrid composites. The merits of using composite materials lie in high strength to low weight and corrosion resistance. Beyond the above stated advantage of substantial weight reduction over metals, an additional advantage of using composite materials include high service life, ability to maintain more optimum cross section within the service life. Another important advantage is that when a blade is made of composite material, at the time of damage a composite blade can be repaired and returned to its service without adversely affecting the shape of the structure.

4. Materials and methods

In this study a Wageningen-B series, 4 bladed propellers are examined with the specifications as in Table 1. The blade is tested with different isotropic and orthotropic materials. The main objective of the present research work is to study the stress behavioural characteristics in using conventional and composite type of materials.

Table 1: Blade specifications

Type of series	Wageningen B screw series
Delivered power (P_D)	648 kW
Advance speed (V_A)	6.15m/s
Propeller rate of rotation (N)	380 rpm
Propeller diameter (D)	2.12m
Number of blades (Z)	4
Blade area ratio (A_E/A_0)	0.70
P/D Ratio	0.9

4.1. Blade material

In order to evaluate the stress behavioural characteristics, the blade considered for the present study is varied with different materials which are of isotropic and orthotropic. Application of composite materials is more suitable than isotropic materials, which is mainly due to the high strength to weight ratio. In this research paper, different metallic alloys of nickel-aluminium, composite materials of carbon UD and E-glass fibres are investigated. The properties of different materials are described in Table 2 and 3 respectively.

Table 2: Properties of metallic alloys

Material	E_x (GPa)	ν_{xy}	Density (ρ)(kg/m^3)
Cu-Ni Al alloys	122.58	0.33	8530
Cu high tensile brass	102.97	0.35	8300
Ni Al bronze alloy	117	0.34	7600
Ni Mn bronze alloy	105	0.34	8000
Mn Al bronze	125	0.326	7530
Mn bronze	105	0.34	8300

Table 3: Properties of composite materials

Material	Carbon-epoxy	E-glass-epoxy
E_x (GPa)	25.0	46.2
E_y (GPa)	10.0	14.7
ν_{xy}	0.16	0.31
G_{xy} (GPa)	5.20	5.31
ρ (g/cc)	1.60	2.04

4.2. CAD model and numerical simulation

The present study comprises of a hub and blade. In order to reduce the complexity encountered during computation, a single blade was considered in which the mid surface of the blade was extracted and used for analysing its dynamic characteristics. The 3D solid model of the blade was reduced to a single blade and the same is depicted in Fig. 1. And the corresponding load distribution on the same has been depicted in Fig. 2. An efficient numerical and developed numerical approach is used to analyse the stress characteristics of propeller. The method can consider the effects of pre-twist, taper, curvatures associated with geometric non-linearity. A commercial FEM solver ANSYS has been used to solve the dynamic equation. Finite element mesh was created using hexahedral shell (181) elements with each node having 6 degrees of freedom. These elements are well suited for linear, large rotation and large strain nonlinear applications. The blade along was meshed with 10mm element size length and total number of elements are and total degrees of freedom.

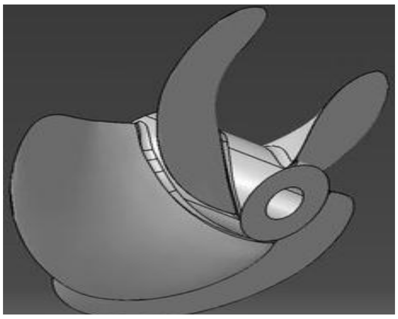

Fig. 1: Solid model four bladed propeller

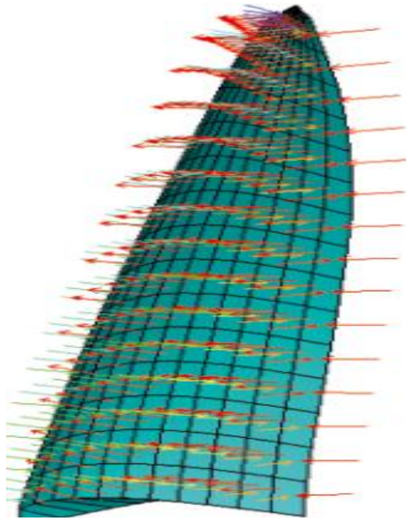

Fig. 2: Single propeller blade with load distribution

5. Results and discussions

Finite element method is taken as the baseline method to find out the stress behavioural characteristics of the metallic and composite propeller. Three sets of balanced sequence with two different materials of the composite are considered. A comparison has been made between metallic and composite propeller for stress analysis.

Table 4: Results-stress analysis

Parameter	NAB	NM_NB	MAB	C-steel	CNA alloy	CHT brass
Deflection (mm)	1.7311	1.994	1.685	1.886	1.724	2.025
Von Mises (MPa)	378.207	378.207	378.095	379.223	378.114	378.367
I-principal (MPa)	404.228	404.228	402.704	404.017	403.134	405.351
II-principal (MPa)	141.637	141.637	135.684	134.762	137.379	145.922
III-principal (MPa)	1.0192	1.0192	1.046	1.0869	1.0388	0.997
X-component (MPa)	85.642	85.642	82.139	85.714	83.137	88.163
Y-component (MPa)	401.441	401.441	399.896	397.171	400.332	402.578
Z-component (MPa)	119.553	119.553	121.573	125.227	121.000	118.087

Table 5: Results-stress analysis 6 layers

Parameter	MAB	CFRP	GFRP	CFRP [(0/90)]	GFRP [090]
Deflection (mm)	1.685	4.298	11.0897	4.519	10.507
I-principal (MPa)	402.704	593.955	525.189	603.214	510.432
II-principal (MPa)	135.684	121.205	99.484	129.13	93.767
III-principal (MPa)	1.046	0.337	0.347	0.362	0313
X-component (MPa)	82.139	47.294	40.294	51.913	39.824
Y-component (MPa)	399.896	584.944	524.963	594.97	510.082
Z-component (MPa)	121.573	161.565	122.570	186.329	105.523

Table 6: Results-stress analysis - 12 layers

Parameter	MAB	CFRP	GFRP	CFRP [(0/90)]	GFRP [(0/90)]
Deflection (mm)	1.685	4.018	11.230	4.829	8.392
I-principal (MPa)	402.704	623.289	571.813	710.721	440.882
II-principal (MPa)	135.684	81.974	88.665	107.301	67.226
III-principal (MPa)	1.046	0.625	0.614	0.566	0.188
X-component (MPa)	82.139	39.868	39.346	46.320	40.281
Y-component (MPa)	399.896	620.817	571.641	707.325	440.746
Z-component (MPa)	121.573	115.823	105.161	147.726	75.189

Table 7: Results-stress analysis - 18 layers

Parameter	MAB	CFRP	GFRP	CFRP [(0/90)]	GFRP [(0/90)]
Deflection (mm)	1.685	3.953	11.305	4.872	7.971
I-principal (MPa)	402.704	663.35	607.83	765.197	445.123
II-principal (MPa)	135.684	85.146	89.718	101.791	65.088
III-principal (MPa)	1.046	0.631	0.608	0.702	0.184
X-component (MPa)	82.139	47.548	51.007	46.193	49.446
Y-component (MPa)	399.896	662.892	607.644	764.696	444.984
Z-component (MPa)	121.573	112.024	102.379	136.11	87.888

Table 8: Results-stress analysis - 25 layers

Parameter	MAB	CFRP	GFRP	CFRP [(0/90)]	GFRP [(0/90)]
Deflection (mm)	1.685	4.024	11.520	4.996	7.984
I-principal (MPa)	402.704	696.671	632.353	819.368	445.281
II-principal (MPa)	135.684	94.453	95.001	107.572	67.006
III-principal (MPa)	1.046	0.688	0.647	0.723	0.187
X-component (MPa)	82.139	50.897	54.477	50.492	49.965
Y-component (MPa)	399.896	696.271	632.164	818.908	445.147
Z-component (MPa)	121.573	114.135	109.277	140.546	91.324

Table 9: Inter laminar stress

Material	6 Layers		12 Layers		18 Layers		25 Layers	
	Min	Max	Min	Max	Min	Max	Min	Max
CFRP	32.986	44.654	21.957	27.729	24.237	29.203	25.104	29.950
GFRP	31.028	38.964	25.451	31.100	25.199	30.649	25.868	34.427
CFRP [(0/90)]	29.651	39.215	23.831	30.882	24.457	30.459	25.528	31.538
GFRP [(0/90)]	32.858	41.426	25.380	35.550	26.123	44.997	26.946	47.955

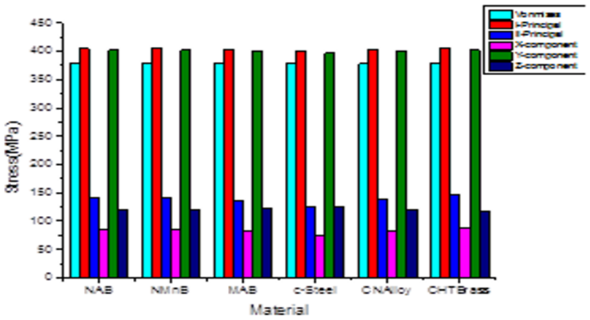

Fig. 3: Stress comparison for conventional materials

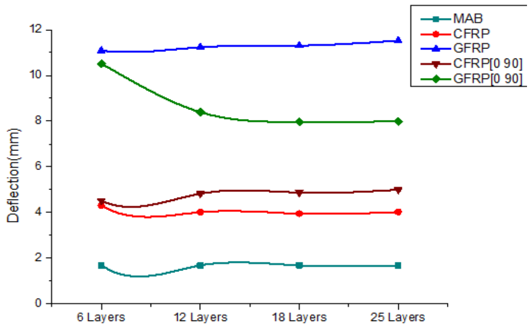

Fig. 5: Deflection comparison MAB vs. Composite materials

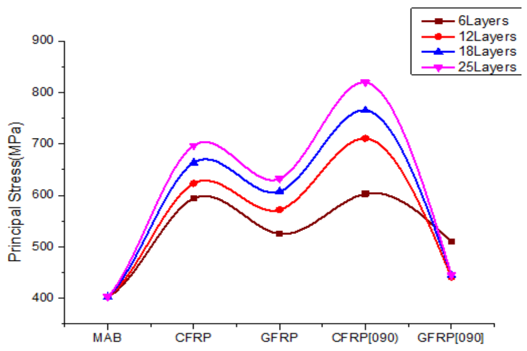

Fig. 4: Principal stress comparison MAB vs. Composite materials

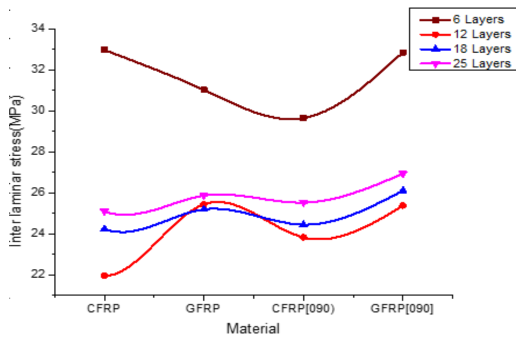

Fig. 6: Minimum inter laminar stress comparison

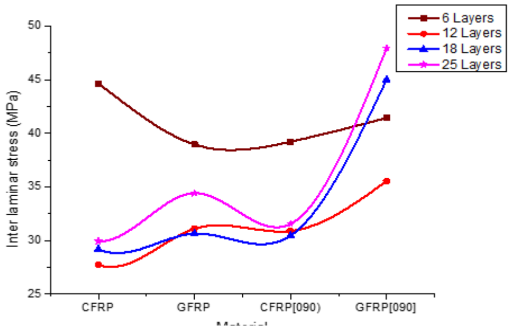

Fig. 7: Maximum inter laminar stress comparison

This paper quantifies the influence of material properties and load uncertainties on the structural response for safe operation and over all reliability of four bladed Wageningen B-series propellers. In addition to above uncertainties related variations in number of plies and ply-stacking sequence for varying number of layers are taken into consideration for both hybrid and non-hybrid composite materials. Based on these parameters strength calculations for both conventional and composites materials are considered. In this study, stress analysis has been carried out for propeller blade with constant element thickness throughout the analysis. The stress analysis of marine propeller blade has been evaluated using ANSYS 15 solver. Mathematical simulation is performed for clamped free condition with root constrained to all degrees of freedom. The corresponding deflection and various stresses for metallic alloys and composite materials are determined and plotted as shown in Figs. 3 to 5. Results have also been tabulated from Tables 4 to 8. The following observations are made:

- From the Table 4, it is understood that the material with lower density (manganese aluminium bronze) has achieved lowest deflection at all materials frequencies, followed by nickel aluminium bronze, copper nickel aluminium alloys carbon steel, etc. The deflection range varies from 1.685 to 2.025mm.
- With MAB considering as the base material for propeller blade the replacement of MAB with composite has been carried out with initially 6 number of plies having stacking sequence [±45/0] From the Table 5, it shows that the CFRP material has attained the least deflection and GFRP has experience very low stress among all other composite materials.
- With increase in number of layers from 6 to 12, the deflection for CFRP is the lowest whereas GFRP tailored with properties of [0/90] will be the lowest. With further increase in number of layers from 12-18, 18-25 CFRP material has attained least deflection and GFRP attained low stress among all other composite materials.
- Considering the inter-laminar stresses for de-bonding the propeller blade with GFRP [0/90] has achieved lower stresses. By varying the number of plies from 12 to 25 the value of inter-laminar stress for CFRP is observed as least in magnitude as observed in Table 8, Figs. 6 and 7.

6. Conclusion

By using FEA based simulation software ANSYS 15, the analysis results are interpreted for the blade subjected under different conditions. The deflection, principal stresses, Von-Misses stress and corresponding XYZ component stress have been calculated by applying fixed free condition. The 3D model is generated using CATIA and finite element model is performed in hyper mesh and transferred to ANSYS. The effects of materials on the propeller blade in terms of its stress behavioural characteristics are differentiated and corresponding graphs are plotted. Finally, a comparison has been made between isotropic and composite. From the results, it can be predicted by proper tailoring composite materials at specified ply angles and varying the number of layers stresses and deflections can be enhanced to cope up with isotropic materials.

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