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Design and Analysis of a Composite Semi-Submersible Propeller (With MARC & AUTOCAD 3D)

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Abstract: Marine Propellers of different types have been used in vessel propulsion systems. Surface Piercing Propeller or Semi submerged propellers (SPP) are today used for high-speed crafts. These propellers operate at the surface of the water for a superior performance, and thus they are subjected to severe hydrodynamic pressure. SPPs are commonly made of stainless steel materials having the required stiffness and strength to withstand the applied loads. Designing a novel composite SPP is the basic purpose of our investigation for its lower friction, no corrosion, and low detestability. The mechanical loads considered in our work are the hydrodynamic pressure, the centrifugal force, and the gravity. Through a boundary element analysis of the unsteady flow characteristics, we obtained the non-uniform distribution of the hydrodynamic pressure on the surface of the blades. The fluid dynamic analysis has been performed in an apart-related investigation, which only was presented and used its result as the input to the structural analysis of our work. In order to have a basis for the comparison, we analyzed a stainless steel propeller in addition to the composite one.
Keywords: Semi-Submersible Propeller, Composite, MARC, AUTOCAD

1. Introduction

The three dimensional finite element models for the metal propeller have been constructed by using tetrahedral soiled elements while we made up the model for the composite propeller of quadrilateral shell elements [1]. Large strain elastoplastic analysis using Ludwig strain hardening for the steel propeller was performed to determine the permanent deformation during each loading and unloading process. On the other hand, we carried nonlinear Progressive failure analysis using Tsai-Wu and maximum stress failure theory put for carbon/epoxy laminated propeller, in order to consider stiffness degradation process. The results show that the maximum stresses occur along the leading and the trailing edges of the blade where the failure is observed.

As mentioned above, we have analyzed a SPP; these kinds have generally high skew angle [2]. Trailing edge has large thickness, which causes resistance against corrosion, and erosion, but the leading edge is so sharp in order to dominate the water velocity easily [3]. The common range of Rake angle is between 0 and 150 degree. These propellers have usually 4 or 5 blades, because the more the number of blades, the less will be the axial vibrations range [4]. Sometimes their numbers may increase up to 8. One sample of these kinds is shown in below figure

As before said, one composite propeller modeling has been applied too, therefor some of its superiority to the steel one is explained. Steel propellers are prone to corrosion, cavitation, destruction, and fraction due to fatigue [5]. They are not also strong enough to control the noise, which causes vibration in the structure; therefore, today's increasing tendency is to use the composite propellers as substitutes of steel ones [6]. Composite material has the high strength, and hardness to weight ratio, which result in significant weight loss in propellers, and also one of its important factor is the low maintenance cost during the use [7].

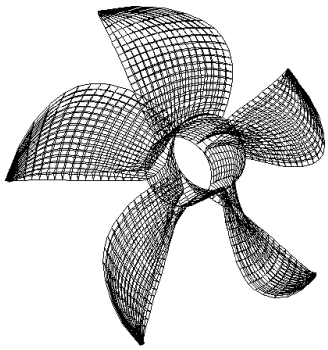
2. Methodology

Entering the main part of our project, we studied past until now research of structural strength of propellers. Blades of propeller are under high hydrodynamic pressure, and in each water cycle, water affects the

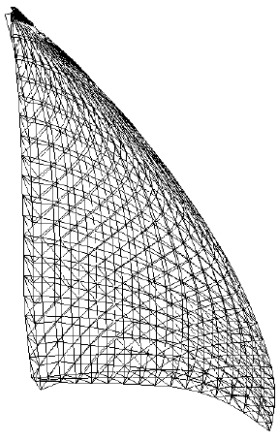
blades for twice which causes significant twisting and bending deformation in them. Moreover, while the propeller rotates in water, blades are also under the centrifugal force, hence these blades must have sufficient strength bearing these heavy loadings. Stress, strain, and structural design technique determination of propellers was stable until 1970s which named Cantilever beam method. While the propellers geometry got complicated, numerical and finite element methods have been substituted in which shell and solid elements are used to obtain stress and strain distribution in all directions. Moreover, by this method many calculations of non-isotropic composite propellers can be obtained easily.

The propeller that was chosen for structural analysis and determining the stress and strain is the HqSPD-5.D

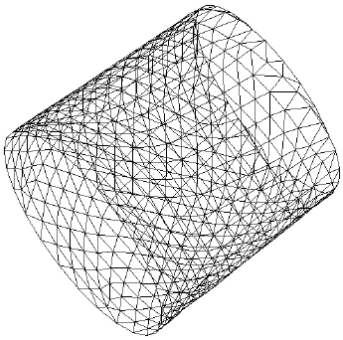
With 5 blades that is shown below



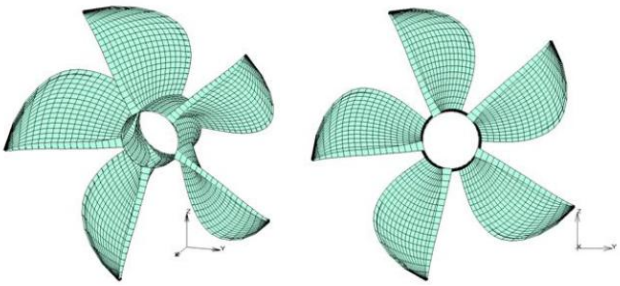
Construction and sections of this model is shown below



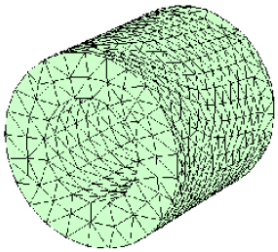
Geometric sketch of our propeller's hub is shown below



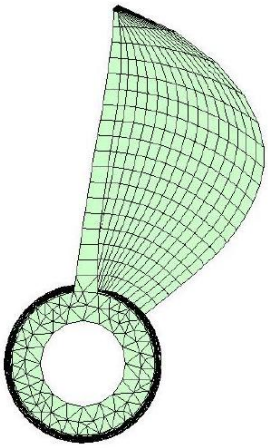
Initially we designed a 5-blade shell including the hub in 3D AUTOCAD. Then did the mesh with quadrilateral elements in order to analyze the model with finite element model, and it is shown below.



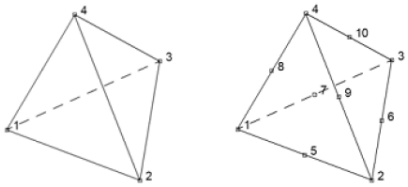
Moreover, we designed the hub in shell element with an appropriate thickness compared to its real sample, and we blocked the open areas in the model by triangle elements, which is shown below



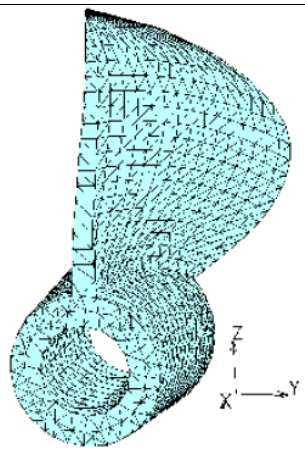
After that, we modified the designated model in Ms.c MARC finite element software. Our reason for choosing the software is its ability to analyze nonlinear composite material, theories, and failure criteria related. To structurally analyze our submersible propeller and to calculate related stress and strain, we considered only one blade (with hub) which is under the worst condition, and the others are ignored. The mentioned blade is under the maximum hydrodynamic pressure; gravity and centrifugal forces are in the same direction in the blade. Consequently, while preserving the main loading section's geometry, large amounts of calculation, elements, and nodes are reduced. The model is shown in below



Steel propellers are completely solid. Therefore, to analyze our model, surface elements must convert to solid elements which have shell model in outside but completely solid in inside. This was somehow a complicated process in which we converted every quadrilateral surface element to two triangle surface element. Then surface elements were converted to tetrahedral tetragonal pyramid solid elements in order to fill the whole blade and hub. 10 node tetrahedral elements have been chosen in this model to gain the nonlinear stress and strain distribution which is needed to bending loading and elastoplastic analysis. These sample elements are shown below



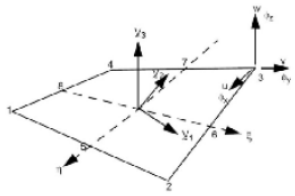
Our Blade and hub mesh model with triangle surface elements is shown below



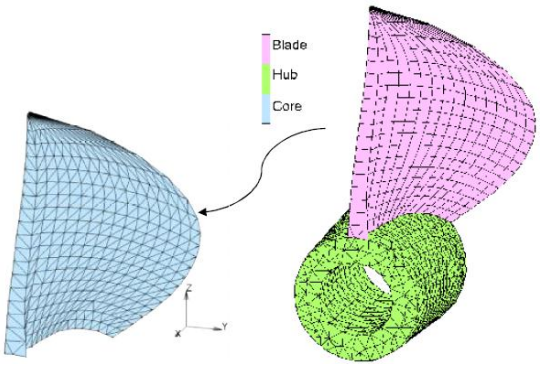
To model our composite propeller we used the initial AUTOCAD model of the steel one, and likewise that we chose the blade that is under the maximum hydrodynamic pressure.

Commonly, composite structures have shell construction unlike the steel ones that are solid. The reason is difficulties in construction of composite components. They are made from thermoset resins like polyester and in the process of polymerization great thermal stress is produced which is very destructive for the composite product. Hence, choosing the shell structure for composite must be taken into consideration. Inside of the blade must be filled with various special foams in order to avoid buckling. We designed hub elements with triangle surface elements, and for filling it, we used the 10 nodes tetrahedral solid elements like the steel one. Main part of our modeling was the core of blade. To do this, we filled the space between the shell with elements, which were triangle surface elements in outside and solid tetrahedral elements inside. Crust of blade is composite and we modeled it by 8 node quadrilateral shell elements. In this element distribution of stress and strain is nonlinear and Timoshenko Bending Theory is used meaning that shear force in bending deformation of shell (which is ignored in Euler Bending Theory) is formulated along with bending torque effect. This element is for modeling the whole isotropic, non-isotropic, and composite material.

One sample of 8 node shell elements is shown below



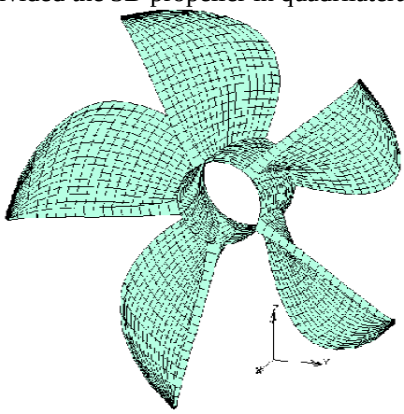
The stainless steel for the hub was chosen and it is attached to blade model and foam. Practically to build a propeller a layer of composite that is attached to blade must be installed to steel hub, but this composite layer does not have that much effect on structural calculation. In the figure below our model is shown, in which shell elements of blade and solid elements of hub are shown with different colors. It should be noted that foam solid elements are inside the blade space, and hence, cannot be seen in the figure.



To analyze loads on our propeller, the various types of them when the propeller is rotating and moving are explained:

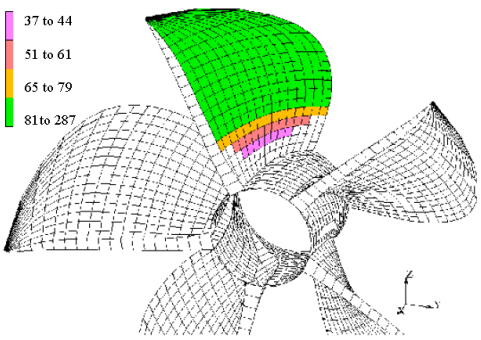
- Hydrodynamic pressure on active area of blade (which is gained through Boundary Element Method)
- Centrifugal force on whole elements of propeller
- Gravity force of propeller on total elements

Many parameters are involved in hydrodynamic pressure on propellers like diameter, pitch to diameter ratio, shape of blade, shaft axial slope, immersion height, free surface effect, Froude Number, and Reynolds Number. To analyze our model, we divided the 3D propeller in quadrilateral surface elements (as shown below)

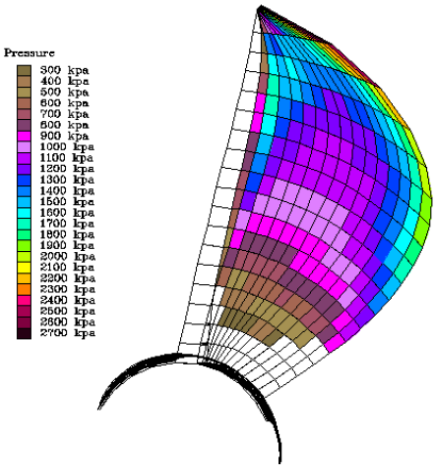


Then we applied Green Integral Equation in every element, and calculated matrix effective coefficients. After solving the essential equations, we calculated Potential Function in every element. Then by derivation of the Potential Function, we could determine velocity, pressure, and as a result forces and hydrodynamic torque of the propeller. We used this method for calculation of our propeller, and result of determined Thrust coefficients, torque, and efficiency showed that boundary element method has satisfactory results compared with experimental one.

To analyze our propeller structurally, we considered the case that maximum hydrodynamic pressure is applied to the blade (while it is at the lowest point of its traveling route and is completely immersed). Namely, in figure below, element locations of 37 to 44, 51 to 61, and 65 to 79 are shown.



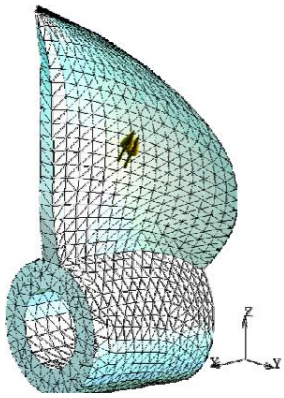
In the figure below pressure level on the elements are shown



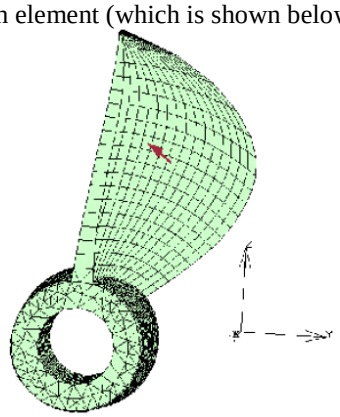
Some samples of hydrodynamic pressure distribution on our propeller's elements in most critical situation is presented in the table below

$\frac{r}{R} = 0.50167$		$\frac{r}{R} = 0.545$		$\frac{r}{R} = 0.58833$		$\frac{r}{R} = 0.63167$	
Element No.	Pressure [kPa]	Element No.	Pressure [kPa]	Element No.	Pressure [kPa]	Element No.	Pressure [kPa]
97	1284.335	113	1429.958	129	1573.295	145	1725.539
98	1126.488	114	1265.701	130	1396.514	146	1517.007
99	1012.467	115	1144.337	131	1261.55	147	1352.362
100	972.9607	116	1090.79	132	1191.204	148	1261.626
101	952.8227	117	1053.531	133	1131.878	149	1183.788
102	932.0361	118	1017.357	134	1078.555	150	1122.06
103	912.0338	119	983.3059	135	1039.241	151	1087.151
104	901.4478	120	972.5155	136	1030.344	152	1079.085
105	881.9905	121	960.862	137	1026.908	153	1078.433
106	851.5055	122	931.4824	138	1006.063	154	1070.534
107	849.2867	123	933.2187	139	1009.043	155	1082.302
108	854.4325	124	949.4696	140	1025.439	156	1098.377
109	850.2198	125	955.8524	141	1040.324	157	1125.009
110	948.3163	126	1093.667	142	1224.653	158	1342.3
111	516.9023	127	610.8605	143	701.5079	159	769.0499

It must be mentioned the problems encountered in finite element analysis when the pressure was applied to the elements. Pressure hydrodynamics which were gained by boundary element method were for quadrilateral surface elements, but as we said before, elements of steel propeller are pyramid volume ones, and this cause the difference between number and position of elements. To solve the problem, in finite element analysis, we applied the pressure vertically on two triangle elements (which is corresponded to one quadrilateral element), and it is shown below

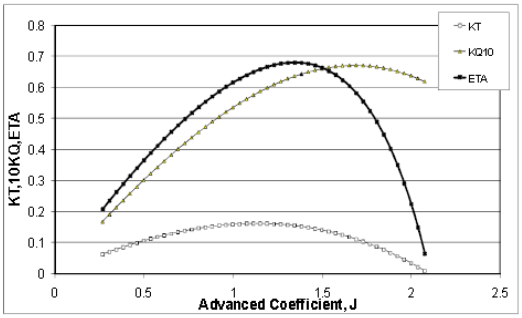


But in our composite propeller, elements of finite element and boundary element are similar and the corresponded pressure is applied on each element (which is shown below)



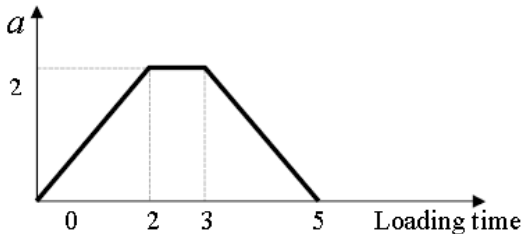
Hydrodynamic specification of our propeller like efficiency (ETA), thrust coefficient (Kt), torque coefficient (Kq) in different advance coefficient (J) are given in the table and figure shown below

J	KT	10KQ	ETA	J	KT	10KQ	ETA
0.26923	0.06278	0.16813	0.20802	1.19231	0.16147	0.59841	0.66564
0.30769	0.07075	0.19118	0.23558	1.23077	0.16059	0.6089	0.67161
0.34615	0.07843	0.21394	0.26257	1.26923	0.15925	0.61863	0.676
0.38462	0.08584	0.23636	0.28899	1.30769	0.15743	0.62759	0.6787
0.42308	0.09295	0.25845	0.31481	1.34615	0.15513	0.63576	0.67959
0.46154	0.09976	0.28016	0.34003	1.38462	0.15233	0.64313	0.67856
0.5	0.10626	0.3015	0.36462	1.42308	0.14904	0.64967	0.67546
0.53846	0.11245	0.32243	0.38855	1.46154	0.14524	0.65536	0.67014
0.57692	0.11831	0.34294	0.41182	1.5	0.14092	0.6602	0.66245
0.61538	0.12384	0.363	0.43439	1.53846	0.13608	0.66416	0.6522
0.65385	0.12904	0.38261	0.45624	1.57692	0.13071	0.66723	0.63918
0.69231	0.13388	0.40174	0.47734	1.61538	0.12481	0.66938	0.62316
0.73077	0.13836	0.42037	0.49766	1.65385	0.11835	0.67061	0.60391
0.76923	0.14248	0.43849	0.51716	1.69231	0.11135	0.67089	0.58112
0.80769	0.14623	0.45607	0.53582	1.73077	0.10378	0.6702	0.5545
0.84615	0.1496	0.4731	0.5536	1.76923	0.09564	0.66854	0.52367
0.88462	0.15258	0.48955	0.57044	1.80769	0.08692	0.66588	0.48824
0.92308	0.15516	0.50542	0.58632	1.84615	0.07763	0.66221	0.44775
0.96154	0.15734	0.52068	0.60118	1.88462	0.06773	0.65752	0.40169
1	0.15911	0.53531	0.61496	1.92308	0.05724	0.65177	0.34945
1.03846	0.16045	0.54929	0.62761	1.96154	0.04615	0.64498	0.29036
1.07692	0.16137	0.56261	0.63908	2	0.03452	0.63753	0.22407
1.11538	0.16185	0.57525	0.64929	2.03846	0.0222	0.62864	0.14896
1.15385	0.16188	0.58719	0.65817	2.07692	0.00927	0.61871	0.06436



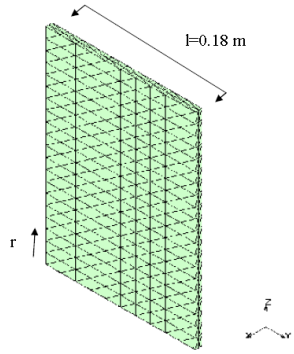
As the steel propeller is modeled based on elastoplastic behavior, total pressures applied gradually on elements till arriving the intended pressure and even multiple, in order to gain the elastic and plastic deformation response of structure. However, in our composite propeller which is analyzed on elastic and progressive failure behavior hydrodynamic pressure is applied gradually till the equivalent one; if the failure occurs in one point of the propeller layer, failure index will be 1 at that point and layer.

To apply the pressure changes in steel propeller, we nominated a pressure coefficient called "a" which increases from 0 to 2 and decreases to 0 (shown below). By multiplying this coefficient to the hydrodynamic quantity in each element, we gained the intended pressure change.



Submersible propellers have relatively a high rotational velocity, and rotating propeller in this condition can cause significant stress. On the other hand, centrifugal force distribution of the blade is not uniform and by increasing distance from the center of blade, this force diminishes. Our propeller working velocity is equivalent to 2400 rpm, and we modeled a filled shell in Ms.c MARC in order to calculate the

centrifugal force. Our shell dimension was 0.18 × 0.25 m² and 0.008 m thickness. Kind of this shell elements is analyzable like the steel propeller. Material of the shell is a stainless steel with 7900 kg/m3 and the rotational velocity is ω = 40 rev/s and our model is shown below

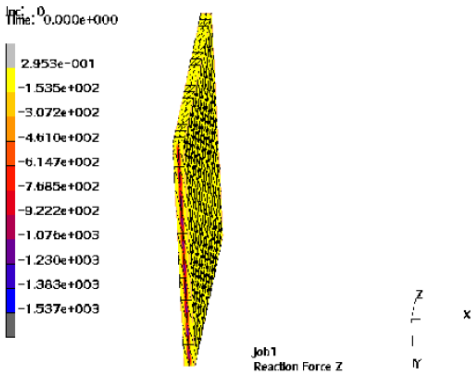


We calculated the centrifugal force on the following process:

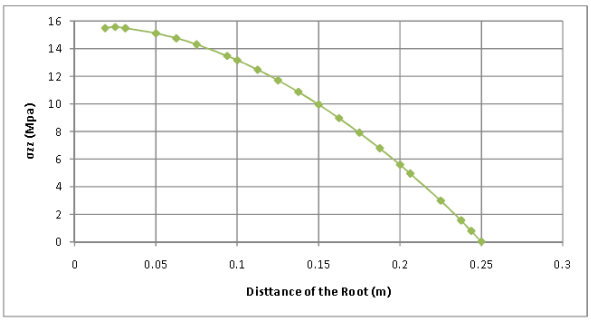
The centrifugal force on each element is f = m (mass) × r (distance from the rotation center) × ω^2 (angular velocity)

F = $\int_0^R df = \frac{\rho\omega^2 lb}{2}(R^2)$ and the stress along the z-z axis is $\sigma_{zz} = \frac{F}{lb} = \frac{\rho\omega^2}{2}(R^2)$ and for our propeller dimension and the rotating velocity F = 22.46 KN & σ = 15.597 Mpa

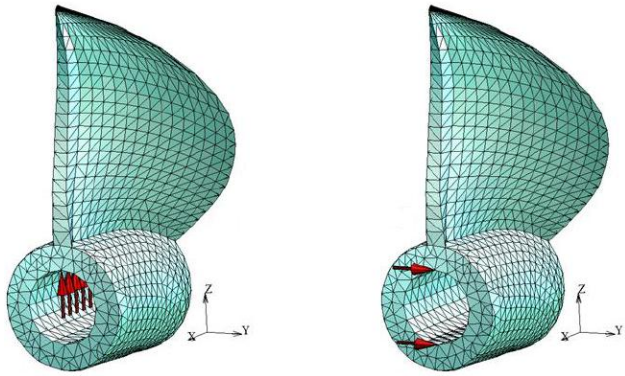
Support reaction force at the bottom of shell is shown below



The mentioned stress from the shell root to its head is shown below



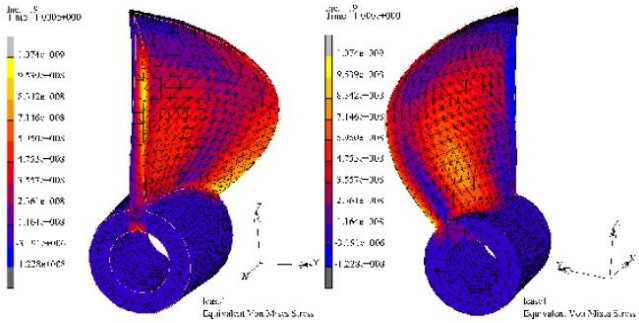
Like the centrifugal force, the gravity force must be applied non-uniformly on all the elements. Thus, when the blade is at its lowest point of moving, and maximum hydrodynamic pressure is applied on that simultaneously, centrifugal and gravity force, both on same direction, are imposed on the blade to put it on its most crucial loading condition. After the loading part, we explain about boundary and support condition. We considered the support condition of the propeller shaft. Because of the hub being on the X-axis, all the displacements along the Y and Z for the nodes up and down this axis is to be zero. Consequently, only one node along the X-axis has the zero displacement. The related figure is shown below



As we said, our main purpose of our project was to analyze the elastoplastic behavior of the submersible propeller in its function and possibility of failure in loading and unloading process. To structurally analyze the propeller after modeling and applying the forces, we used finite element method to solve large strain equations. Firstly, we calculated all components of displacement, strain, and stress on the forward and back surface of our propeller in a case that hydraulic pressure is totally applied on that. In this situation, pressure index is equal to one. After that we analyze the propeller under the double hydraulic pressure (pressure index is equal to two). In the second stage, we used these equations to gain displacement, strain and stress components in unloading case. Analyzing the propeller condition after unloading is of high priority, because applying the hydrodynamic pressure the stress goes beyond the yield stress which causes permanent deformation in the blade. On the other hand, cause to permanent deformation and deletion of elastic deformation in some sections, residual stresses will form in the blade. We considered the unloading case in two situations too like the loading case (pressure index one and two).

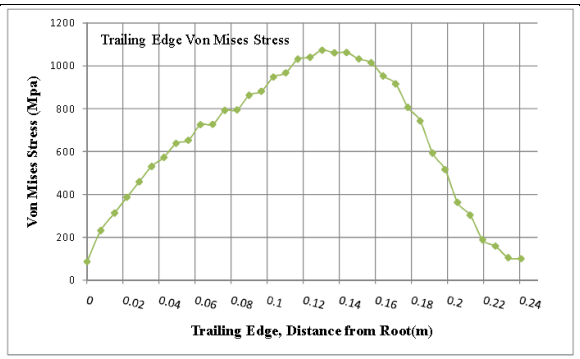
3. Results and Discussions

One of the yield stress criteria in steels is Von Mises criterion that is based on the root of square tension's sum in three directions. In the figure below Von Mises stress distribution of forward and back of the blade in case of complete hydraulic pressure (Time:1.0 means hydrodynamic pressure index 1)

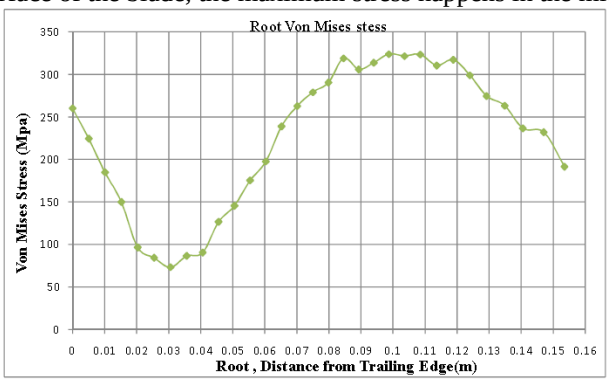


As seen in the figure maximum Von Mises tension is equal to 1074 Mpa, and we had that on both blade's edge. Moreover, this stress is more than the steel yield stress (980 Mpa). It is also seen that alongside the blade spin on back, mid and forward surface, stress is more. Stress distribution in the radial direction from tip to root of the blade increase.

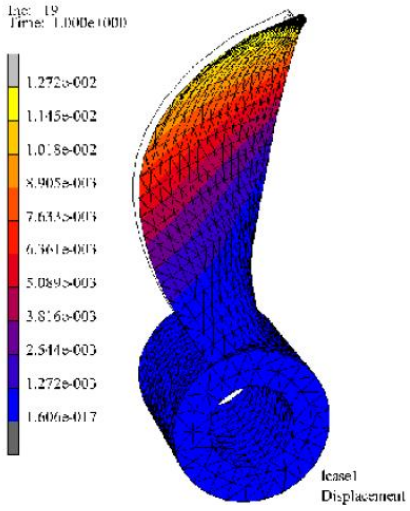
Namely, Von Mises stress on Trailing edge on a=1 is shown below.



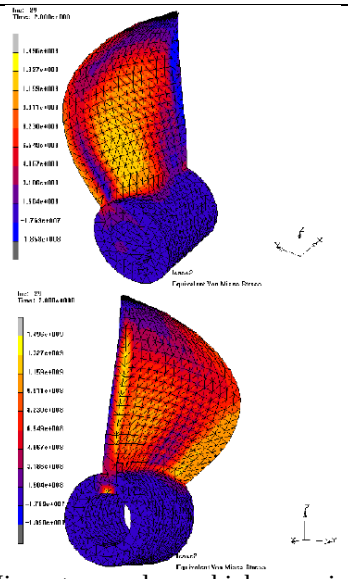
Considering the hub and creating the model, we provided conditions in which stress and deformation could be analyzable. In figure below results we gained through Von Mises stress in the blade root (connection place to the hub) in back surface is shown. As we got closer to the leading edge in the forward blade root stress got more, but in the back surface of the blade, the maximum stress happens in the mid-section of the blade.



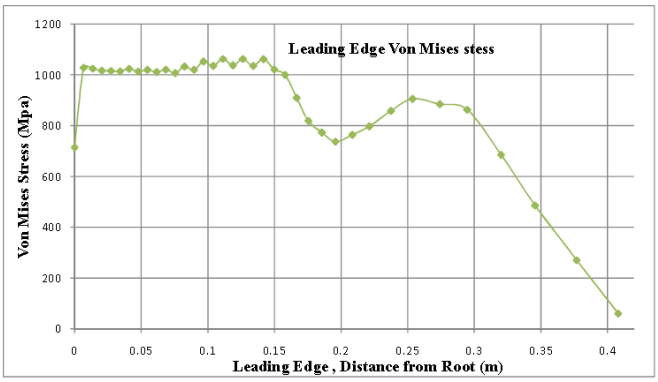
Due to the loading, strain and deformation happen in every blade that has effects in in hydrodynamic operation of the propeller. To analyze this effect we considered the displacement distribution on the blade geometry which shown in below, and as it is clear maximum displacement happens in the leading edge of the tip whereas it is 1.272 cm under the hydrodynamic pressure.



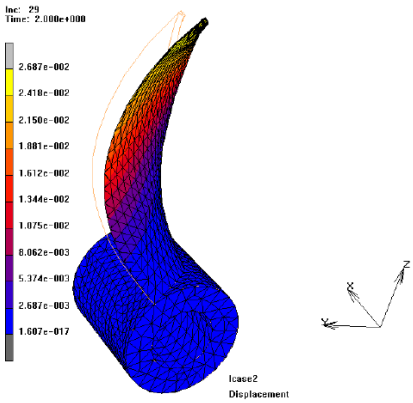
After applying the total hydraulic pressure on the blade, we analyzed the maximum force (Time:2.0) and result of Von Mises stress on the forward and the back is shown below (as seen, maximum value of Von Mises stress is 1496 Mpa)



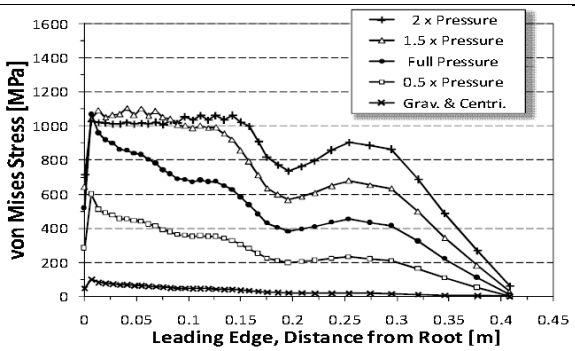
And in the graph below Von Mises stress values which we gained on leading edge is shown. The graph may have irregular behavior in the middle of blade but the total conduct has not changed.



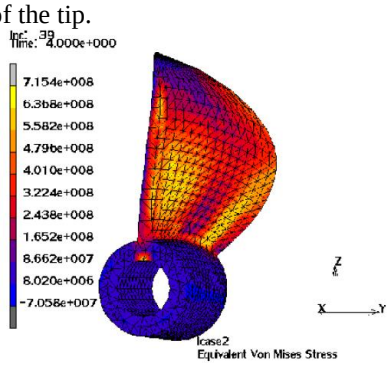
Stress and deformation under this pressure is shown below (maximum displacement value is 2.687 cm), and as the previous loading, the maximum happens at the leading edge of the tip



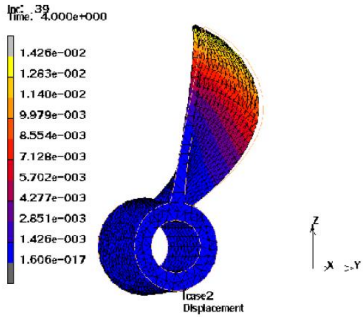
As the previous, we analyzed the stress and deformation value in this case too and as a sample we show the Von Mises stress distribution on the trailing here, and as it is seen, the minimum stress is in the case that the pressure on the blade is zero and only gravity and centrifugal ones are applied.



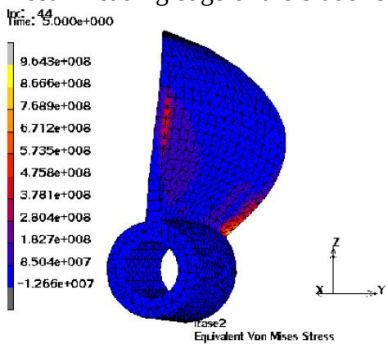
Due to the importance of unloading and permanent deformation in blade, we analyzed stress and deformation in two cases. In the first stage, blade is under the pressure equivalent to hydrodynamic one. In the figure below when the Von Mises stress gained the maximum pressure (equivalent to double hydrodynamic pressure) and pressure equivalent to hydrodynamic one unloaded is shown (Time:4.0 means coefficient 1 to hydrodynamic pressure on the blade). Maximum value of Von Mises is 715.4 in this case and it happens on the back of the blade in middle and near of the tip.



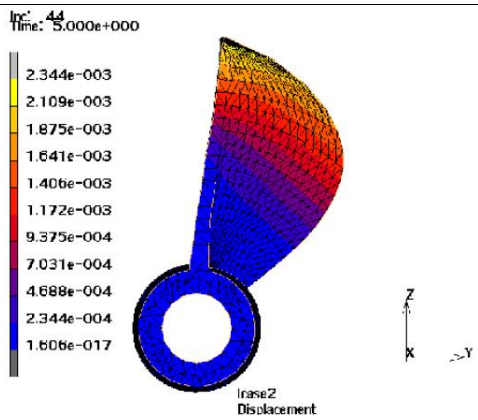
The figure below show our analysis on the residual displacement on the blade in this case (tip of the blade had the displacement equivalent to 14.26 mm)



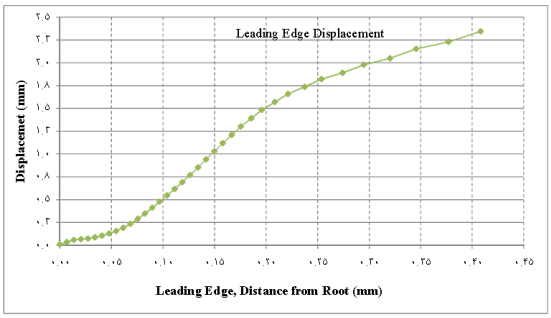
We unloaded the whole pressure on the blade (equivalent to double hydrodynamic pressure), and the Von Mises stress distribution is shown below (Time: 5.0 mean the pressure index of zero). Maximum residual stress is 964.3 Mpa which happened almost in leading edge of the blade root, and middle of trailing edge.

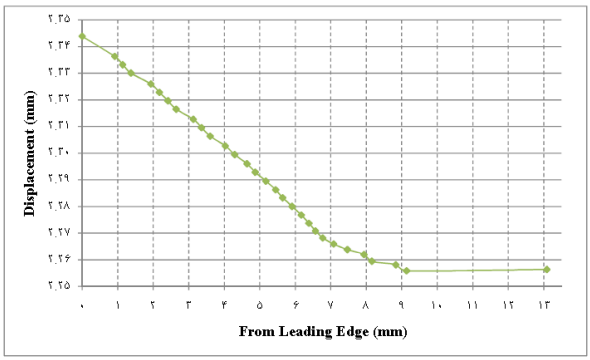


In this case, permanent displacement of blade tip is 2.344 mm that is too much and is completely effective in hydrodynamic operation of the blade (figure shown below)

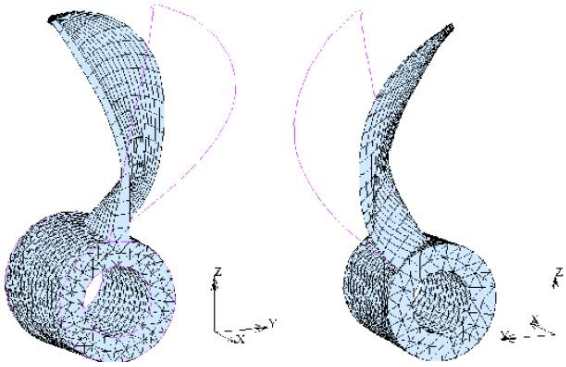


In three figures below, we gained the residual displacement after the complete unloading in the leading edge and in the tip.

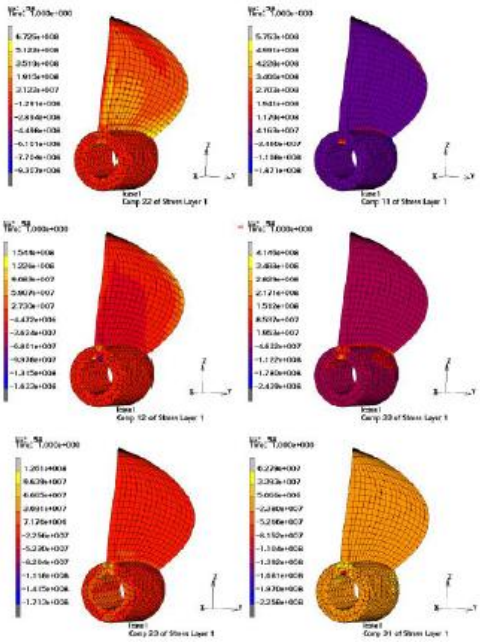




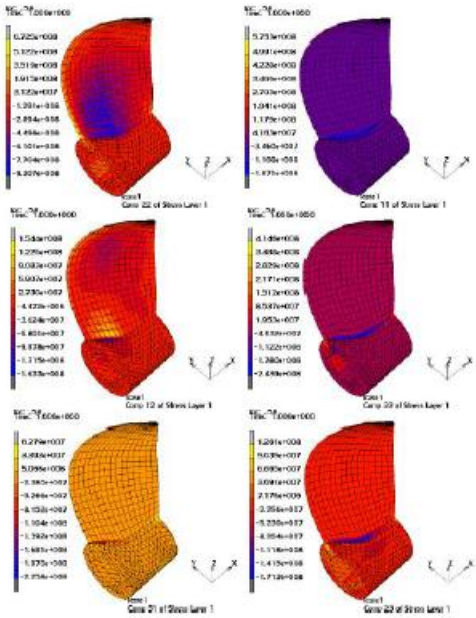
For now we want to discuss our analysis on the failure possibility of our composite propeller. To structurally analysis of the propeller, after modeling and applying the forces, we used progressive failure method to modeling laminated stiffness degradation, and ultimately we analyzed the laminated layer failure, and the maximum tension with Tsai-Wu criteria. Buckling of our coreless blade in two views is shown below, and as it seems deformation in the back area was so great due to excessive pressure and it fails because of buckling (due to bending forces behind the blade shell). To prevent the buckling, we should have filled the blade, which we used the typical foams, which have high modulus and strength to be chosen as the core.



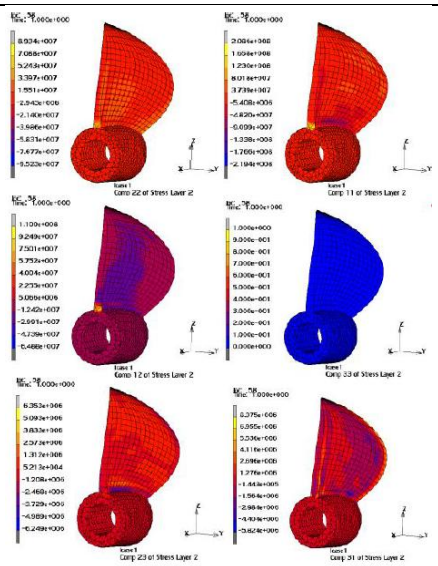
After filling the blade, we calculated all displacement, strain, and stress components in all the layers on the forward and the back of the blade in a case that the hydraulic pressure in completely applied on the blade. To analyze the stress in the composite blade, we should have taken into consideration stress along the fiber, vertical to fiber, and the shear stress in all the layers. The figure below shows the stress components in the forward area of the blade, layer 1.



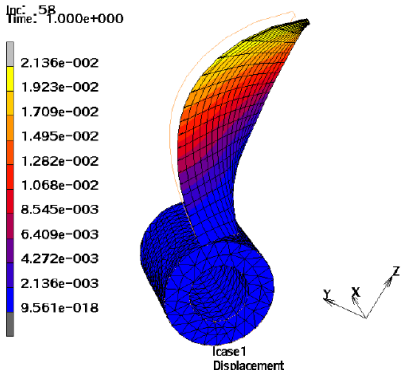
The figure below shows stress components of our model in the back area.



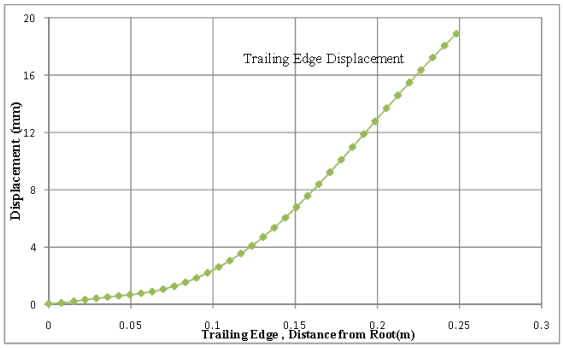
In figure below stress components of one sample of the layers 2 to 8 is shown in forward and back area of the blade, and its result shows that shear tensions are less, and maximum stresses are in middle of trailing edge and in the root of the leading edge.

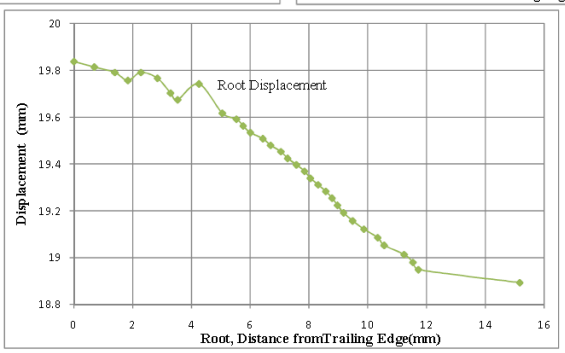


We calculated the blade displacement that the maximum amount in the blade tip is 2.136 cm which is greater than the number gained in the steel propeller of blade tip (shown below).

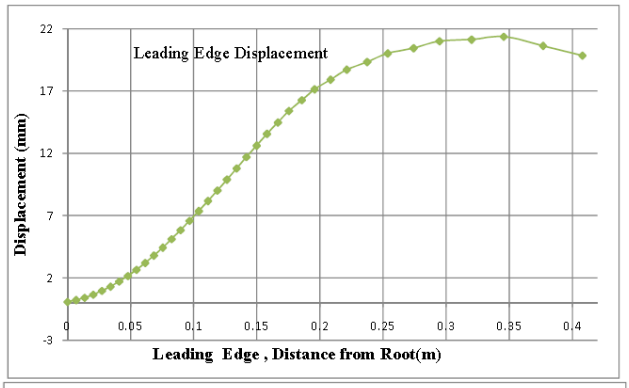


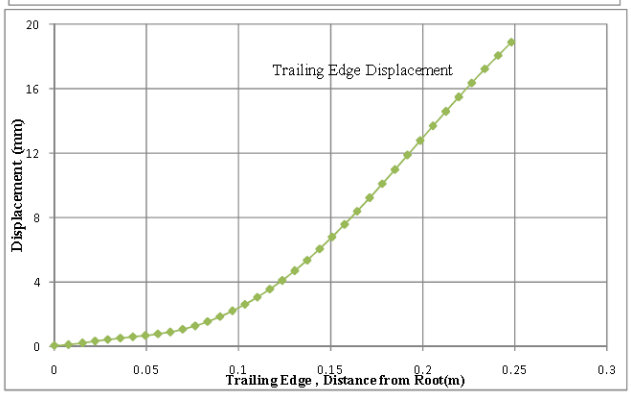
Displacement distribution in trailing edge, leading edge, and the blade tip are shown below respectively.

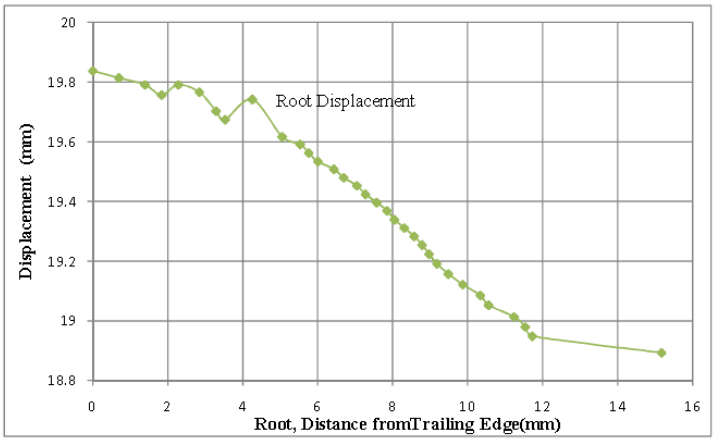


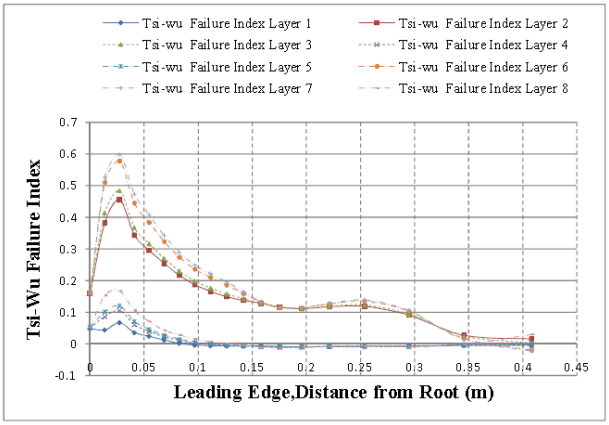


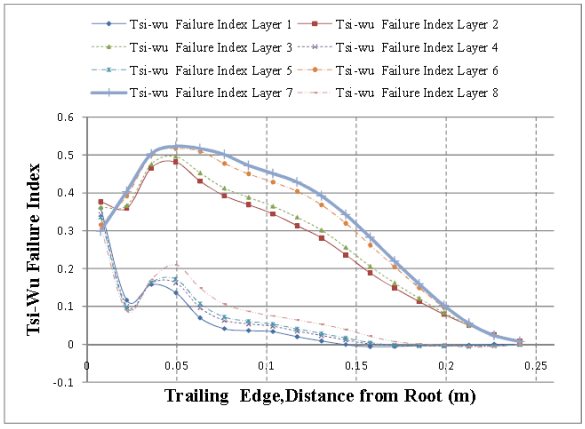
In the figures below failure index of trailing and leading edge is shown based on Tsai-Wu and in pressure coefficient 1.



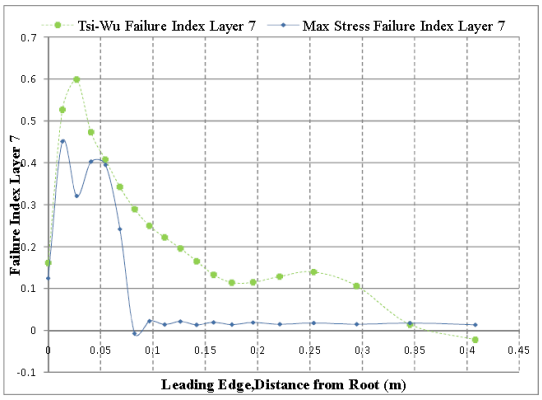








As it seems, failure index of 0 degree layers are similar to each other and so are failure index of 90 degree layers, and also we should mention that the maximum failure index is in 90 degree layers especially the 7th layer, because in 90 degree layers, forces are vertical to fiber direction where force tolerance is less compared to forces along the fiber direction. Failure index of 7th layer comes with maximum stress theory and Tsai-Wu is shown below



Mechanical characteristics of the foam we used is brought below

Elastic Constants for a Foam		
E [MPa]	ν	[Kg/m^3]
2100	0.4	100

4. Conclusion

The object of our research was to achieve a new design for a marine propeller. We designed steel and a composite submersible propeller under the hydrodynamic pressure loading, centrifugal and gravity force, and we analyzed it in finite element method. Among all our analysis and results gained, we mention the below parts as the most significant summarized ones:

1) To finite element analyze of our steel propeller that had the loadings including bending, torsional, and tensional, 10noded tetrahedral solid elements were a good choice and gave me reliable results in calculations. On the other hand, 4noded tetrahedral element choices were completely improper.
2) Applying the centrifugal and gravity forces simultaneously, without the hydrodynamic pressure causes Von Mises stresses in the blade that the maximum amount of them is about 10% of the steel yield strength.
3) While hydrodynamic pressure, centrifugal and gravity forces were applied on the blade simultaneously, maximum amounts of Von Mises stress is provided on the trailing and leading edges. Therefore, it is expected that the failure begin in these areas.
4) By applying the hydrodynamic pressure gradually, along with the centrifugal and gravity forces, it was observed that in the pressure equivalent to 90% of the hydrodynamic pressure, first points on the leading and trailing edge have reached the yield strength. By increasing the pressure till 100% of the hydrodynamic pressure, more areas on edges yield and permanent deformation grow in these areas. This means the hydrodynamic pressure that we calculated by finite element method is so much great that causes the steel propeller to yield and permanently deform in edge areas. It must be considered that hydrodynamic pressure distribution happens in the most critical pressure loading, and the propeller is under this extent loading only once in its every cycle. Occurrence of permanent strain in the mentioned areas does not mean the total failure of the propeller but to mean that after the loadings applied in different cycles, fatigue failure of the propeller begins from the stress concentration areas.
5) After the hydrodynamic pressure decreases from the maximum to the zero amounts, permanent displacement in the blade, residual stress, and permanent strain are considerable.
6) Regarding to polymerization process of composite material, composite propeller blade must be designed and modeled in shell type, and modeling it into solid is pointless. As the blade thickness is narrow in the leading edge region, thickness of composite shell encounters limitations.
7) We could not use the laminate including fiberglass (Class E) with polyester resin due to its cheap combination, because its mechanical properties, namely elastic modulus and strength are too low.
8) Using laminate consisting of carbon fiber along with epoxy resin whereas the blade shell is empty and under the loading, causes the pressure stress in the back area of blade that results in buckling and great deformation, so we must have used foams inside the composite shell

9) Maximum failure index in composite blades happens in layers near to the shell surface, because in there fiber direction is perpendicular to bending caused stress direction where tensional strength is so much low in there. Moreover, maximum failure index points occurrence differs in different composite layers.
10) Displacements in steel and composite blade tip under maximum hydrodynamic pressure are respectively 12.7 and 21 mm. this affects the hydrodynamic performance. After unloading the blade, permanent displacements in steel and composite blade tip are respectively about 0.8 and 0.4 mm and the reasons are plastic deformation in steel propeller, and partial failure in some layers of composite propeller.
11) We observed that by applying the hydrodynamic pressure gradually to its maximum, maximum amount of failure index on blade tip and in different epoxy/carbon laminate layers is about 0.7 (which does not reach to 1). Therefore, it is concluded that using the proper material that has stiffness of about 2 Gpa (which helps preventing the buckling) put the mentioned laminate as a great choice of having the proper strength to bear the loading.

Our only suggestion in this research is to do vibration analysis of submersible composite propeller and comparing to steel propeller vibration.

5. References

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[5] Lin ching-chieh, Lee Ya-Jung, Hung Chu-Sung, "Optimization and experiment of composite marine propeller" , Composite Structure,2008
[6] Young L.Y. ,"Time – dependent hydro elastic analysis of cavitating propulsions", J. Fluid and Structure, 2007: PP 269-295
[7] Ghassemi H., Ghiasi M., "Hydrodynamic Characteristics of the Surface Piercing Propeller (SPP) by Using Special Practical and Numerical Approach", 8th Int. conf. on hydrodynamics (ICHD2008), France