ANALYTICAL INVESTIGATIONS ON STIFFENED STEEL AND CARBON FIBRE REINFORCED POLYMER CYLINDRICAL SUBMARINE PRESSURE HULL

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ABSTRACT

A submarine is submersible which operates in deep water for a long period of time and is subjected to a hydrostatic pressure at a specified design depth. Military submarines are exposed to very severe loading conditions due to firing of torpedoes, explosion of mines, etc. The conventional submarines made of high strength steel may adversely affects its performance due to very large dead weight preventing the immediate resurfacing of the submersible under emergency conditions. Carbon Fibre Reinforced Polymer (CFRP) is a very strong light weight material which can be used for constructing submarine pressure hull. In the present work a comparative study of steel and CFRP submarine pressure hull is conducted using Finite Element Analysis. The linear static analysis and buckling analysis is done to study the behaviour of steel and CFRP pressure hull.

Keywords: Stiffened Cylindrical Shell, CFRP, Linear Static Analysis, Buckling Analysis.

1. INTRODUCTION

Submarines are built as an assemblage of several parts namely the hull, ballast tanks, sail, propeller and periscope which are constructed from various combinations of cylinders, cones and domes. The pressure hull is the most important submarine structural component consisting of watertight envelope and it must resist the external water pressure which the submarine is subjected during its operation [1]. The pressure hull is mainly a cylindrical pressure vessel stiffened by inside/outside frames. If thin cylindrical shell is not stiffened, its buckling resistance is very poor and they fail by bifurcation buckling. One method of improving the buckling resistance of such long thin cylindrical shell is to stiffen them using ring stiffeners or stringers. The design of hull structure is complex as the whole submarine has to reach neutral buoyancy. Increase of structural weight is not
an option as it decreases the weight budget of the payload, engine and other performance related features. The use of a lightweight pressure hull opens the door to increased performance. In the search of a lightweight pressure hull, it is found that use of composite materials can be a solution. However, a composite pressure hull design encapsulates the design of the composite itself. For this reason, pressure hull finite element models are created that include the composite related material mechanics [2].

2. GEOMETRIC DESCRIPTION OF MODEL

The structure is modelled in Finite element software ANSYS 14.5. The schematic representation of the model is shown in Fig. 1. The dimensions of the model are given in the TABLE 1.

![Figure 1: Schematic representation of the model](image)

<table>
<thead>
<tr>
<th>Material property</th>
<th>Steel</th>
<th>CFRP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus</td>
<td>210 GPa</td>
<td>270GPA</td>
</tr>
<tr>
<td>Mass Density</td>
<td>7500kg/m³</td>
<td>1760kg/m³</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.3</td>
<td>0.365</td>
</tr>
</tbody>
</table>
2.2 Modeling

The elements used for modeling are, SHELL181 for shell between stiffeners and BEAM 189 for the stiffeners. Fixed boundary condition is applied on either end of the cylinder [3]. The model along with the boundary conditions is shown in Fig. 2.

![Figure 2: Model of the cylindrical shell with boundary conditions](image)

3. LINEAR STATIC ANALYSIS

Linear static analysis determines the displacements stresses, stains and reaction forces under the effect of applied loads. When the loads are applied to a body, it deforms and the effects of loads are transmitted throughout the body. The hydrostatic pressure acting on the submarine for a design depth of 350m is 3.5 N/mm².

3.2 Stress Distribution in Steel and CFRP Pressure Hull

The principle stresses and von Mises stresses are obtained for steel and CFRP pressure hulls by conducting static analysis. The von Mises stress induced in steel and CFRP is shown in Fig. 3 and Fig. 4 respectively. The stress is maximum at the stiffeners and minimum in the shell for steel. But in case of CFRP maximum is induced in shell compared to stiffener. The maximum principle stress obtained for pressure hull made of steel is 312 N/mm² and CFRP is 299N/mm² and is shown in Fig.5.

![Figure 3: von Mises stress distribution in steel](image)
3.3 Deformations in Steel and CFRP pressure hull

The maximum deformation and deformed shaped acquired by the steel and CFRP pressure hull for static analysis is shown in Fig. 6 and Fig. 7 respectively. The deformation in shell is greater than that of stiffener for steel and CFRP and is lower for the latter.
3.4 Comparison of results

The results obtained for stresses and deformation by executing linear static analysis for steel and CFRP is tabulated in TABLE 3 and TABLE 4 respectively.

**Table 3: Deflection and stresses of steel and CFRP pressure hulls**

<table>
<thead>
<tr>
<th>Material</th>
<th>Principal stress (N/mm²)</th>
<th>Von Mises stress (N/mm²)</th>
<th>Von Mises stress (N/mm²)</th>
<th>Yield strength (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Stiffener</td>
<td>Shell</td>
<td>Supports</td>
</tr>
<tr>
<td>Steel</td>
<td>312</td>
<td>327</td>
<td>320</td>
<td>113</td>
</tr>
<tr>
<td>CFRP</td>
<td>299</td>
<td>296</td>
<td>354</td>
<td>164</td>
</tr>
</tbody>
</table>

**Table 4: Deflection and stresses of steel and CFRP pressure hulls**

<table>
<thead>
<tr>
<th>Material</th>
<th>Deflection (mm)</th>
<th>Max. deflection (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Stiffener</td>
<td>Shell</td>
</tr>
<tr>
<td>Steel</td>
<td>8.15</td>
<td>8.25</td>
</tr>
<tr>
<td>CFRP</td>
<td>5.48</td>
<td>7.42</td>
</tr>
</tbody>
</table>

4. LINEAR BUCKLING ANALYSIS

Linear buckling analysis is used to compare the behavior of steel and CFRP submarine at the given design depth of 350m. The model is built in ANSYS and the boundary condition adopted is fixed-fixed. Prestress effect is activated since the Eigen value buckling requires stress stiffness matrices and the extraction method and number of Eigen values to be extracted is specified. The Eigen value calculated from buckling analysis represents load factors and if unit load is specified the load factor will represent the buckling load.
4.2 Analysis of steel pressure hull

The mode shapes for three various modes extracted is shown in Fig. 8 and the critical buckling pressure obtained for \( n=2 \) is 13.84 N/mm\(^2\).

(a) Mode shape and deflection profile for 1\(^{st}\) mode of buckling (\( n=2 \))

(b) Mode shape and deflection profile for 3\(^{rd}\) mode of buckling (\( n=3 \))

(c) Mode shape and deflection profile for 5\(^{th}\) mode of buckling (\( n=6 \))

Figure 8: Mode shapes for three modes extracted
4.3 Analysis of CFRP pressure hull

The mode shapes for three modes extracted for CFRP is shown in Fig. 9 and the critical buckling pressure obtained for \( n=3 \) is 7.10 N/mm\(^2\).

![Mode shapes for three modes extracted](image)

(a) Mode shape and deflection profile for 1\(^{st}\) mode of buckling (\( n=65 \))

(b) Mode shape and deflection profile for 3\(^{rd}\) mode of buckling (\( n=3 \))

(c) Mode shape and deflection profile for 5\(^{th}\) mode of buckling (\( n=2 \))

**Figure 9:** Mode shapes for three modes extracted.
6.4 Comparison of results

The minimum and critical buckling pressure for various modes of buckling for steel and CFRP is charted in TABLE 5.

<table>
<thead>
<tr>
<th>Material</th>
<th>Buckling mode</th>
<th>No of lobes (n)</th>
<th>Buckling pressure (N/mm$^2$)</th>
<th>Critical buckling pressure (N/mm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>1</td>
<td>2</td>
<td>13.84</td>
<td>13.84</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>14.23</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>6</td>
<td>17.60</td>
<td></td>
</tr>
<tr>
<td>CFRP</td>
<td>1</td>
<td>65</td>
<td>5.18</td>
<td>7.10</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>7.10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>2</td>
<td>7.50</td>
<td></td>
</tr>
</tbody>
</table>

5. NONLINEAR BUCKLING ANALYSIS

Nonlinear buckling analysis is more accurate than eigenvalue analysis because it employs nonlinear, large deflection, static analysis to predict buckling loads. Its mode of operation is very simple: it gradually increases the applied load until a load level is found whereby the structure becomes unstable i.e. a very small increase in the load will cause very large deflections [4]. In this problem the loads are subdivided into a series of load increments. The load increments are applied over several load steps. The iterative procedure continues until the problem converges. The analysis is performed for steel and CFRP submarine pressure hull.

5.1 Nonlinear buckling analysis of steel pressure hull

The load deflection response obtained for steel for the fixed boundary condition is shown in Fig. 10. From the graph the nonlinear buckling pressure obtained for steel is 4.25 N/mm$^2$ beyond which the deflection increases tremendously for small increase in load. The value obtained is much less compared to Eigen buckling results.

![Figure 10: Graph showing nonlinear buckling pressure for steel](image-url)
5.2 Nonlinear buckling analysis of CFRP pressure hull

The buckling pressure obtained for CFRP pressure after conducting nonlinear buckling analysis is $3.6 \text{ N/mm}^2$. The load deflection response for CFRP is shown in Fig. 11.

![Graph showing nonlinear buckling pressure for steel](image)

**Fig. 7.2: Graph showing nonlinear buckling pressure for steel**

5.3 Comparison of results

The results obtained for nonlinear bifurcation buckling analysis is shown in TABLE 6. The nonlinear buckling pressures are lower than that obtained for Eigen buckling analysis for both steel and CFRP pressure hull.

<table>
<thead>
<tr>
<th>Material</th>
<th>Nonlinear buckling pressure (N/mm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>4.25</td>
</tr>
<tr>
<td>CFRP</td>
<td>3.6</td>
</tr>
</tbody>
</table>

**Table 3: Comparison of results for nonlinear analysis**

CONCLUSIONS

The stiffened cylindrical submarine pressure hull made of steel and CFRP is modeled and finite element analysis was done using ANSYS 14.5. The main conclusions were:

- The principle stress and von Mises stress obtained for steel and CFRP pressure hull while performing linear static analysis is very much less compared to their respective yield strength of the material which makes the structure safe within the limits and prevents material failure.
- In case of steel, the maximum stress is induced in the stiffener compared to shell whereas in CFRP the maximum stress occurs within the stiffener and this stress induced in stiffener is lesser compared to steel which permits the reduction in area for stiffener leading to overall reduction of dead weight. Hence the payload can be increased for composite submarine.
The buckling pressure obtained for Eigen buckling analysis in steel pressure hull is 48.7% higher than that of CFRP but there is a considerable reduction in buckling pressure for steel in nonlinear buckling analysis which is about 69.3% compared to 49.3% for CFRP. Nonlinear buckling analysis is more accurate than eigenvalue analysis because it employs nonlinear, large deflection, static analysis to predict buckling loads. The buckling pressure of steel and CFRP pressure hull is 4.25 N/mm$^2$ and 3.6 N/mm$^2$ respectively for nonlinear buckling analysis which is within safe limits for design depth adopted.

REFERENCES