Non-linear Analysis of Cylindrical Pressure Hull with Functionally Graded Materials

Shilpa SajiKumar and Krupa Mary Varghese

Abstract The pressure hull is one of the main structures of underwater vehicle, mainly designed to withstand the compressive forces associated with hydrostatic pressure. The ring-stiffened cylindrical hulls have better structural performances and are widely used in underwater vehicles and submarines. Functionally Graded Material (FGM) may be characterized by the variation in structure and composition gradually over volume, resulting in corresponding changes in the material properties. FGM found its applications in marine, submarine industry and defence especially for pressure hull and bullet proof underwater vehicle. In this study, non-linear static and dynamic analysis on cylindrical pressure hull with FGM has been done using ANSYS Mechanical APDL. The study included modelling and analysis of cylindrical pressure hull with different materials such as Steel, Titanium, Steel-Aluminium FGM and Titanium-Aluminium FGM with fixed and pinned boundary conditions. Deflection, von-Mises stress and von-Mises strain of different models were compared.

Keywords Submarine · Pressure hull · Functionally graded material · Non-linear analysis

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Fig. 1 Pressure hull

1 Introduction

1.1 Pressure Hull

Pressure hull is the inner hull of submarine designed to use at great depths. The hull structure, which is a very important part of the submarine become more and more important since its strength is the main concern. When submerged, the water pressure on the submarine hull increases and hull surrounding them must be able to withstand high water pressure at the desired depth, usually around 300 m. A thin walled cylindrical shell is used for the submarine as shown in Fig. 1. Ring stiffeners in circumferential and longitudinal directions considerably increase the resistance of the shell. Non-linearity arises when the load displacement graph is non-linear. The cause of non-linearity may be material or geometric. Material non-linearity may be due to the non-linear stress strain relation and geometric non-linearity due to non-linear strain displacement relation. The critical load could not be determined with sufficient accuracy if pre-buckling non-linearity is neglected. Normally the loss of stability occurs at the limit point, rather than at the bifurcation point. In such cases the critical load must be determined through the solution of non-linear system of equations. Geometric non-linearity may be due to the follower force effect of hydrostatic force.

1.2 Functionally Graded Materials

The functionally graded material (FGM) is a two-component composite material characterized by a compositional gradient from one component to the other. In this study mainly two types of Functionally Graded Materials are used such as Titanium-Aluminium FGM and Steel-Aluminium FGM. Steel-Aluminium FGM, in which the hull plates are composed of outer layer fully of Steel and the quantity of Aluminium is increased throughout the thickness. Continuous and layered type FGM are shown in Fig. 2.

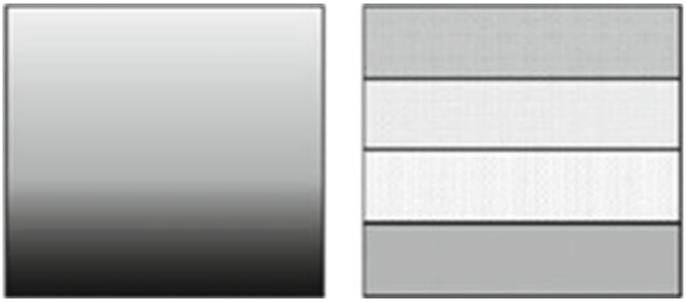


Fig. 2 Continuous and layered type FGM

2 Literature Review

Pandey [1], conducted a study on buckling pressure of moderately thick walled filament-wound carbon–epoxy stiffened composite pressure hull subjected to external hydrostatic pressure through finite element analysis and compare the result with un-stiffened filament-wound carbon or epoxy composite pressure hull. It was observed that the critical buckling pressure of stiffened filament-wound composite cylinder is much higher than to that of carbon or epoxy composite cylinder without stiffener.

Ankit et al. [2], studied about the functionally graded materials (FGMs), types of FGM, manufacturing techniques of FGM different areas of applications of FGM, analytical and experimental solution techniques for FGMs and different stress measuring techniques. Study of stress analysis will continue with changes in the parameters like, effect of stress analysis of FGM plate with isotropic and orthotropic material, change in loading conditions, effects of changes in radius of circular cut-out.

Francoa et al. [3], a parametric study is conducted to find the optimum thickness of pressure hull. Linear buckling analysis was used to predict the feasibility of CFRP submarine pressure hull at deep waters. The design of these pressure vessels is made with reduced thickness walls and ring stiffeners joined to the walls. From the study conducted regarding the weight reduction, it is estimated that replacing steel by CFRP results saves up to 60% in the structural weight.

Bohra et al. [4], presents a complete review of applications of FGM, various processing methods of FGM, developments, different mathematical idealizations of functionally graded materials, modelling techniques, temperature profiles and various solution methods and techniques which are adopted for the vibration analysis of FGM plates. Efforts have been made to focus the discussion on the various research studies conducted until recently for the vibration analysis of FGM plates.

Aileni et al. [5], buckling analysis of ring stiffened circular cylinders subjected to external uniform pressure has been studied by varying radius to thickness ratio, cylinder thickness, ring spacing and stiffener thickness. During the analysis the optimal thickness, loading and boundary conditions are kept constant and the cross-section of the stiffener was varied (Z, square, rectangle, C, I and T sections). It is observed that the buckling pressure decreases as the spacing between ring stiffeners increases for a given radius to shell thickness ratio. The Z section and square section stiffened cylinders have higher buckling pressures and Z section stiffened cylinder has more deformation at buckling initiation.

Asif and Varghese [6], conducted a study to find the best material for the pressure hull according to the Tsai-Wu failure criteria with the optimized values for input and output parameters using response surface optimization technique. Three different composites such as CFRP, BFRP, GFRP were used to analyse the failure criteria to provide the optimum strength. The failure index of the orthotropic composite material should be less than one as per the Tsai-Wu Criteria. The properties of CFRP depend on the layouts of the carbon fibre and the proportion of the carbon fibres relative to the polymer. CFRP have higher tensile strength with lower density comparing with the others. The CFRP fibre shows better results as compared with the GFRP and BFRP fibre in case of failure index.

3 Methodology

- The load, dimensions and various influential factors for the analysis of pressure hull is calculated.
- In accordance with the purpose of hull most appropriate FGM is selected and its properties are calculated.
- Non-linear static and dynamic analysis was done on pressure hull with different materials using ANSYS APDL.
- The deflection, von-Mises stress and von-Mises strain of all hull models were studied and comparisons were made.

4 Modelling of Pressure Hull

For modelling of thin cylindrical stiffened shell eight nodded quadrilateral shell element, SHELL 181 and BEAM188 are used. Pressure hull is modelled using following parameters.

The dimensions of the hull considered in this study are:

- Total Length of Hull = 66 m
- Internal Diameter of the hull = 6 m
- Design depth = 350 m

Materials used are:

- Steel
- Steel FGM: Steel-Aluminium
- Titanium
- Titanium FGM: Titanium-Aluminium

The Steel used for hull is HY 100 grade Steel which has a yield strength of 690 MPa and Grade 19 Titanium plates are used for Titanium models which has yield strength of 1170 MPa.

After several trial and errors of modelling of pressure hulls, an optimum thickness was chosen. A quarter portion of the cylindrical hull is taken and symmetric boundary conditions are provided at the continuous ends and fixed at one end is considered to represent the whole cylinder and corresponding stiffening elements. Inverted T section is used as stiffener and a hydrostatic pressure of 3.5 MPa is applied on the external shell of the hull. Figure 3 shows quarter portion of hull modelled in Ansys APDL. Loading and support conditions are shown in Fig. 4. Figure 5 represent extruded view of pressure hull.

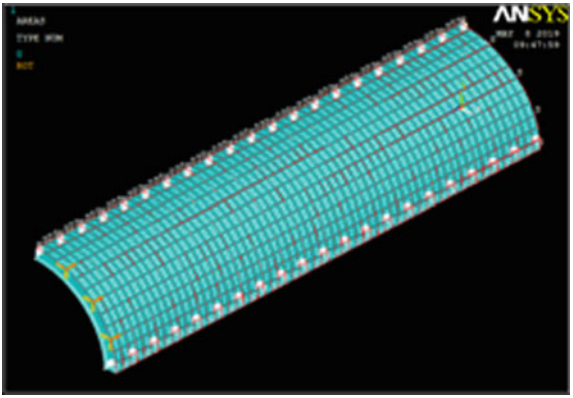


Fig. 3 Quarter portion of hull model

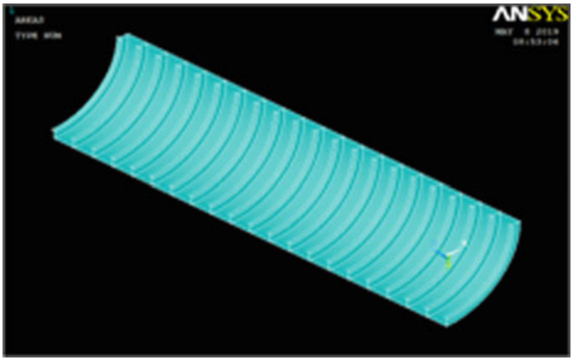


Fig. 4 Loading and support conditions

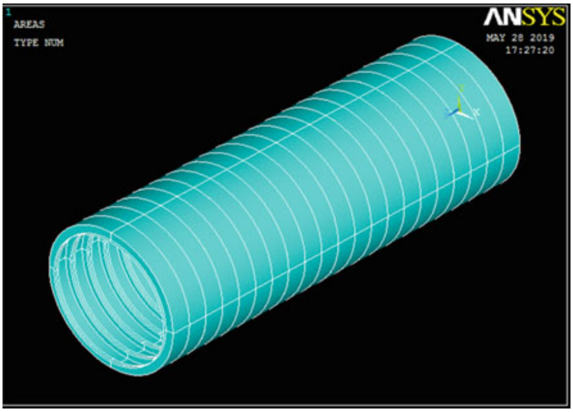


Fig. 5 Extruded view of pressure hull

5 Results and Discussion

5.1 Non-linear Static Analysis Results

Non-linear static analysis on Steel, Steel FGM, Titanium and Titanium FGM hull with fixed support has been done and the results are given in Tables 1 and 2. von-Mises stress and von-Mises strain in Steel, Steel FGM, Titanium, Titanium FGM hull models with fixed supports are shown in Figs. 6, 7, 8, 9, 10, 11, 12 and 13.

Non-linear static analysis on Steel, Steel FGM, Titanium and Titanium FGM hull with pinned support has been done and the results are given in Tables 3 and 4.

Steel hull model shows lower values of deflection, von-Mises stress and von-Mises strain compared to that of Steel-Aluminium FGM and similarly Titanium model shows lower values of deflection, von-Mises stress and von-Mises strain compared to that of Titanium-Aluminium FGM. Steel, Titanium and its FGM models with fixed support shows minimum values of deflection, von-Mises stress and strain compared to that of pinned models. In general, deflection, stress and strain values of FGM models are higher than that of Steel and Titanium Models. Stress and strain in each model are within the yielding limit of corresponding material.

Table 1 von-Mises stress and strain of steel and steel-aluminium FGM with fixed support

Material	Deflection	von-Mises stress (MPa)	von-Mises strain
Steel	4.86	469.17	0.0023
Steel-aluminium FGM	7.077	558.9	0.0028

Table 2 von-Mises stress and strain of titanium and titanium-aluminium FGM with fixed support

Material	Deflection	von-Mises stress (MPa)	von-Mises strain
Titanium	13.06	635	0.0053
Titanium-aluminium FGM	16.09	761.6	0.0069

Fig. 6 von-Mises stress of steel hull

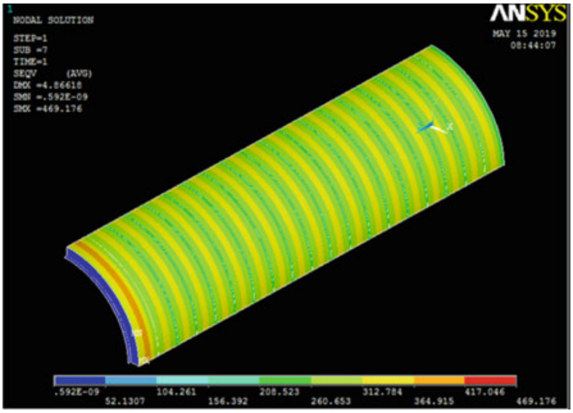


Fig. 7 von-Mises strain of steel hull

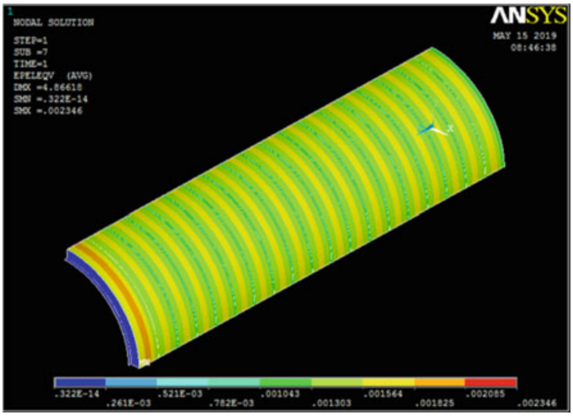


Fig. 8 von-Mises stress of steel FGM hull

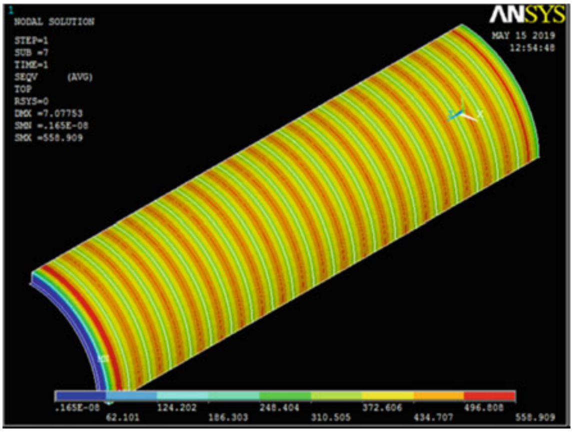


Fig. 9 von-Mises strain of steel FGM hull

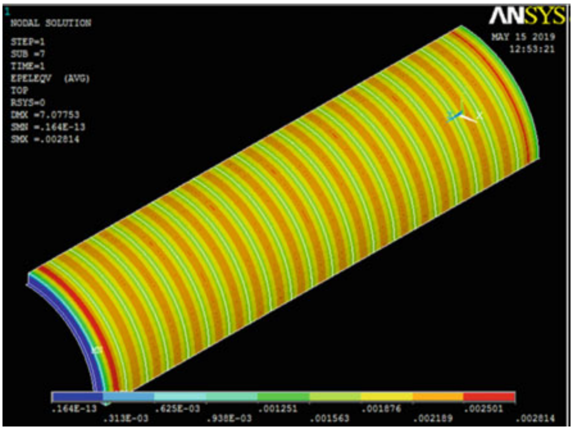


Fig. 10 von-Mises stress of titanium hull

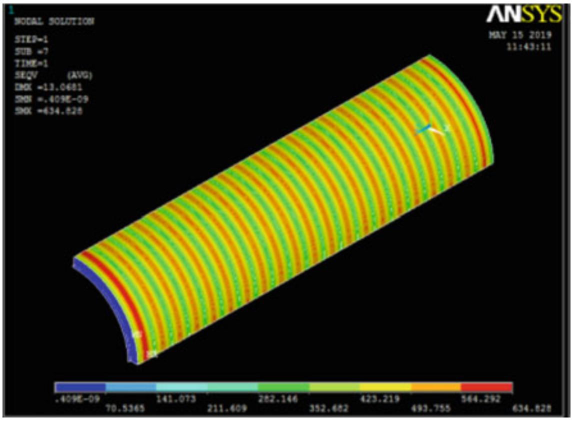
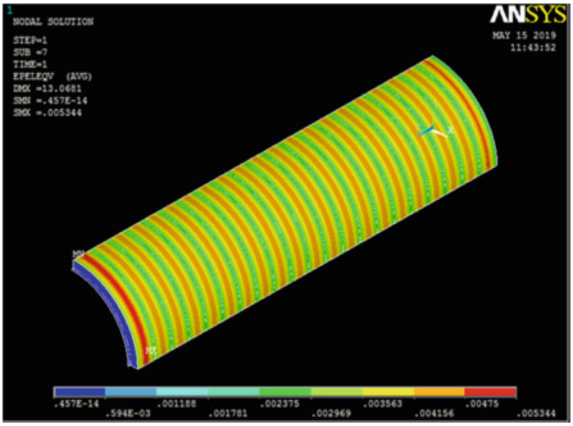


Fig. 11 von-Mises strain of titanium hull



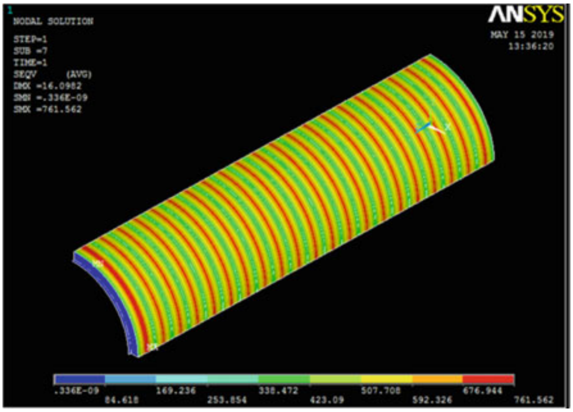


Fig. 12 von-Mises stress of titanium FGM hull

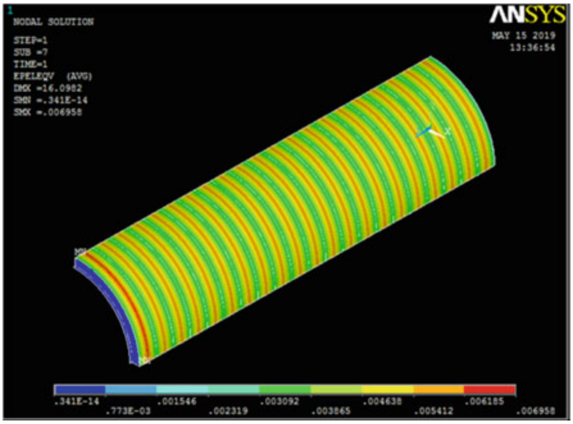


Fig. 13 von-Mises strain of Titanium FGM hull

Table 3 von-Mises stress and strain of steel and steel-aluminium FGM with pinned support

Material	Deflection	von-Mises stress (MPa)	von-Mises strain
Steel	12.89	504.26	0.0025
Steel-aluminium FGM	19.45	615.18	0.00307

Table 4 von-Mises stress and strain of titanium and titanium-aluminium FGM with pinned support

Material	Deflection	von-Mises stress (MPa)	von-Mises strain
Titanium	39.01	815.26	0.0067
Titanium-aluminium FGM	51.92	828.15	0.0087

5.2 Non-linear Dynamic Analysis Results

Non-linear dynamic analysis was performed on quarter portion of cylindrical hull using Steel, Steel-Aluminium FGM, Titanium and Titanium-Aluminium FGM with fixed boundary condition. The dynamic analysis has been carried out on pressure hull models, by varying the hydrostatic loading on the hull at different time corresponding to the different depth of submergence. Graphical comparison of stress and strain values of Steel, Steel FGM, Titanium and Titanium FGM at different depth such as at 87.5, 175, 262.5 and 350 are shown in Figs. 14 and 15, respectively.

For each models von-Mises stress and strain at different depth are studied for dynamic analysis. As the depth increases von-Mises stress and strain of all models are increased but all these values are within the yielding limit of corresponding

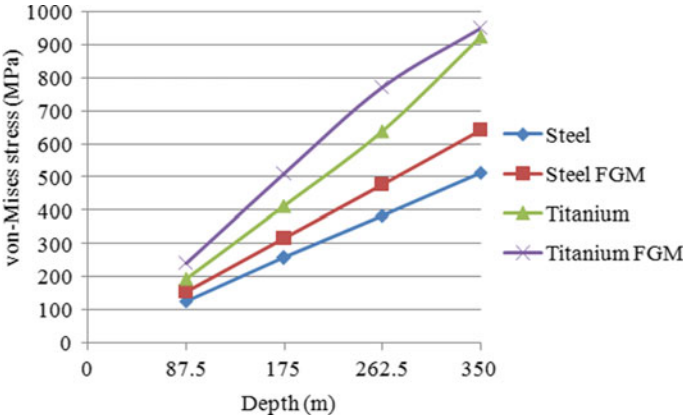


Fig. 14 Graphical comparison of stress values at different depth

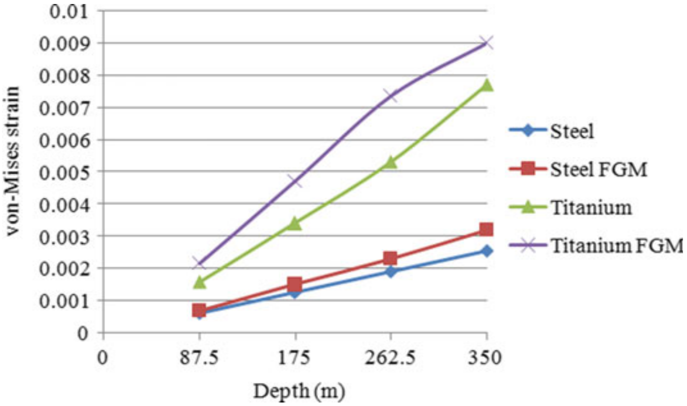


Fig. 15 Graphical comparison of strain values at different depth

materials of hull. Therefore the hull is safe at the design depth. Stress and strain values of FGM models are higher than that of Steel and Titanium Models.

6 Conclusion

Non-linear static and dynamic analysis was done on pressure hull with Steel, Titanium, Steel-Aluminium FGM and Titanium-Aluminium FGM with fixed boundary conditions. The following were concluded from this study.

Steel FGM models were found to give better results as compared to Titanium FGM models. FGM hull models show larger values of deflection, stress and strain compared to that of Steel and Titanium hull models. The stress and strain values of outer layers of FGM models are larger than that of inner layers but, the stresses and strain are found to be slightly increased closer to the inner layers of the hull, this is because the variation of material from FGM to the pure form of metal. Deflection, von-Mises stress and von-Mises strain of all hull models from dynamic analysis are found to be increased with increase in depth of submersion. Titanium models have higher yield strength therefore it helps in reducing thickness of hull and overall weight of hull.

References

1. Pandey (2014) Buckling behaviour of circular ring stiffened filament wound composite pressure hull through finite element analysis. Appl Mech Mat 656
2. Ankit B, Makwana G, Panchal K (2014) A review of stress analysis of functionally graded material plate with cut-out. Int J Eng Res Technol 3(3):2020–2025
3. Francoa J, Corza A, Penab A (2014) Optimization of pressure hulls of composite materials. In: European conference on composite materials
4. Bohra P, Bhandari M, Bohra S, Sharma P (2017) Vibrational analysis of FGM plates a critical review of various solution methods and modelling techniques. Int Res J Eng Technol 4(10):1800–1822
5. Aileni K, Prasanna P, Jain PC (2017) Buckling analysis of ring stiffened circular cylinders using ANSYS. Int J Res Appl Sci Technol 5
6. Asif A, Varghese J (2018) Optimization of submarine ring stiffened composite pressure hull using numerical methods. Int J Innov Sci Eng Technol 5(4):194–199