3D MODELLING AND STRUCTURAL ANALYSIS OF AN UNMANNED UNDERWATER VEHICLE: UNSTIFFENED AND FLAT RING STIFFENED STRUCTURE CONFIGURATION

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ABSTRACT

The structural integrity of unmanned underwater vehicle (UUV) hulls under high external hydrostatic pressure is paramount for reliable deep-sea operations. This study presents a comprehensive finite element analysis (FEA) evaluating the performance of unstiffened versus flat ring stiffened hull configurations. Three-dimensional models were developed and analyzed using ANSYS to investigate critical parameters including stress distribution, deformation characteristics, and buckling stability. Aluminium Alloy AA7068 was selected as the structural material owing to its superior strength-to-weight ratio and compatibility with marine environments. Additionally, the effects of Retrogression and Re-Aging (RRA) heat treatment on corrosion resistance and overall durability were incorporated into the analysis. Results demonstrate that the incorporation of flat ring stiffeners significantly enhances the structural response when compared to unstiffened hulls, primarily by mitigating deformation and increasing load-bearing capacity. Nonetheless, localized stress concentrations were identified near stiffener junctions, indicating potential areas for further design optimization. The numerical findings exhibit strong correlation with analytical estimations, thereby validating the employed modeling approach. This investigation confirms that flat ring stiffening offers a practical and efficient method to improve the structural performance of UUV hulls while preserving design simplicity, thereby supporting their application in demanding underwater environments.

KEY WORDS: *Underwater vehicle, Design, Stiffeners, Hydrostatic pressure, Static structural, Buckling factor*

1. INTRODUCTION

Unmanned underwater vehicles (UUVs) play a vital role in modern marine applications such as ocean exploration, surveillance, environmental monitoring, and offshore operations. These vehicles are required to operate under severe hydrostatic pressure conditions, especially in deep-sea environments, where structural integrity becomes a primary design concern. The external pressure acting on the hull can lead to excessive deformation, material yielding, or even catastrophic buckling failure if not properly addressed during the design stage. Traditionally, cylindrical pressure hulls are widely adopted for UUVs due to their geometric efficiency in withstanding external pressure. However, unstiffened cylindrical shells are highly susceptible to buckling, even under relatively moderate pressure levels. To overcome this limitation, stiffening techniques are introduced to enhance the load-carrying capacity and structural stability of the hull. Among various stiffening methods, flat ring stiffeners are commonly used due to their simplicity in design and compatibility with cylindrical geometries.

The present study focuses on the integrated 3D modelling and structural analysis of an unmanned underwater vehicle hull by comparing unstiffened and flat ring stiffened configurations. Finite Element Analysis (FEA) is employed using ANSYS to evaluate critical parameters such as stress distribution, deformation, and buckling behaviour under external pressure loading. Aluminium Alloy AA7068 is selected as the structural material due to its high strength-to-weight ratio, making it suitable for lightweight yet robust marine structures. Additionally, the influence of Retrogression and Re-Aging (RRA) heat treatment is considered to improve corrosion resistance and mechanical performance. The objective of this work is to assess the effectiveness of flat ring stiffeners in enhancing structural performance compared to an unstiffened hull. By analysing and comparing both configurations, the study aims to provide insights into optimized structural design strategies for underwater vehicles operating in high-pressure environments.

2. LITERATURE REVIEW

i. S. Margonis
Focused on multi-objective optimization in AUV design, useful for selecting optimal dimensions (L/D ratio), weight, and performance trade-offs in your UUV.

ii. T.-H. Joung, K. Sammut, F. He, S.-K. Lee Applied CFD-based shape optimization, helping improve hydrodynamic efficiency and reduce drag in your vehicle design.

iii. Z. Sun, G. Hu, X. Nie, J. Sun
Provides detailed buckling analysis of cylindrical shells, directly relevant for evaluating pressure hull stability under external hydrostatic pressure.

iv. M. W. Temme
Compares analytical and numerical failure methods, supporting validation of your ANSYS results with theoretical approaches.

v. S. Timoshenko, S. Woinowsky-Krieger Fundamental theory of plates and shells; essential for deriving stress, deformation, and buckling equations used in your design.

vi. P. A. Rometsch et al.
Explains heat treatment of 7xxx aluminium alloys, useful for understanding strength enhancement of AA7068 material used in your hull.

vii. J. Osten et al.
Focuses on precipitation behavior of AA7068, helping justify material selection based on high strength and corrosion resistance.

viii. E. H. Baker et al. (NASA Shell Analysis Manual)
Provides standard procedures for shell stress and buckling analysis, supporting your structural calculations and validation.

ix. N. Wakita et al.
Describes deep-sea AUV development, useful for understanding real-world design constraints and pressure resistance requirements.

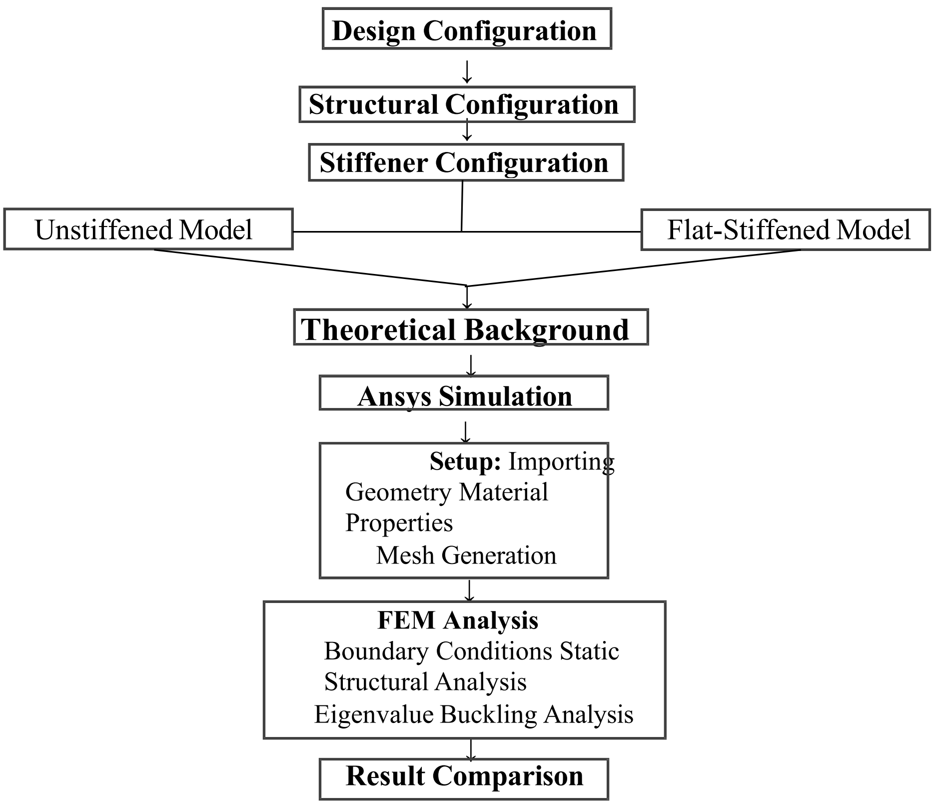
x. E. H. Baker et al. (NASA CR-912)
Extended shell analysis reference, helpful for advanced failure prediction and design safety factors.

xi. Y. Nie et al.
Discusses motion performance in turbulent conditions, useful for stability and control considerations of your UUV.

xii. M. Helal et al.
Covers buoyancy optimization of pressure hulls, directly applicable for balancing weight and displacement in your design.

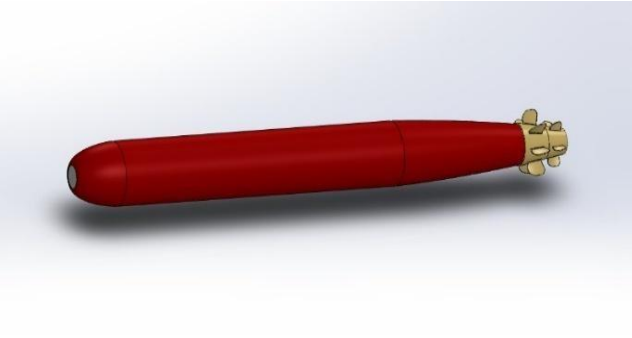
xiii. D. Padhi et al.
Provides design and structural analysis of submarine shells, supporting your overall methodology and validation approach.

3. METHODOLOGY



4. STRUCTURAL CONFIGURATION

Unmanned Underwater Vehicle



The unmanned underwater vehicle (UUV) in this study comprises three main structural components: the forward section, cylindrical shell, and tail section. These form the load-bearing framework designed to withstand hydrostatic pressure at 1500 meters depth. The cylindrical shell acts as the primary pressure-resistant body, while the forward and tail sections ensure smooth transitions and uniform load distribution, balancing strength, stability, and hydrodynamic performance

Forward Section

The forward section features a streamlined conical shape to reduce hydrodynamic resistance and promote efficient fluid flow. Its smooth curvature aids in uniform pressure distribution, minimizing localized stress concentrations. Additionally, it ensures structural continuity between the front end and cylindrical shell, enhancing overall integrity under external loads.

Cylindrical Shell

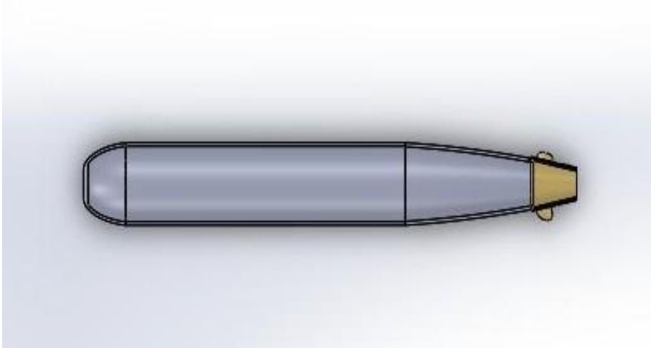
The cylindrical shell is the primary structural element, designed to withstand most of the external hydrostatic pressure. Its geometry efficiently distributes compressive stresses, ideal for deep-sea use. This study evaluates both unstiffened and stiffened configurations, with stiffeners notably increasing rigidity, reducing deformation, and enhancing buckling resistance under high pressure.

Tail Section

The tail section, with its tapered conical shape, provides a smooth transition from the cylindrical shell, enhancing hydrodynamic efficiency by reducing drag and flow separation. Structurally, it supports load transfer and maintains structural continuity, while accommodating propulsion and control system integration.

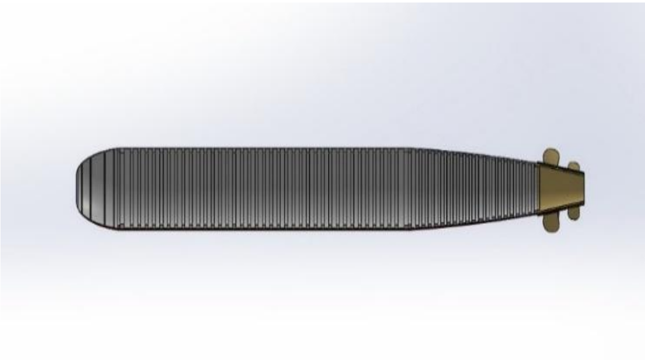
5. STIFFINEER CONFIGURATIONS

Unstiffened Model



The unstiffened configuration serves as the baseline model to assess inherent structural behavior without reinforcement. The forward section is modeled with its natural conical geometry, reflecting load distribution under external pressure. The cylindrical shell, treated as a thin-walled structure, allows evaluation of stiffness, deformation, and instability. The tail section extends the shell with a tapered design to ensure smooth load transfer and structural continuity.

Flat-Stiffened Model



The flat-stiffened configuration is introduced to evaluate stiffness and stability improvements from moderate reinforcement, serving as an intermediate case between unstiffened and advanced stiffened models. The forward section remains unchanged, interacting structurally with the reinforced shell. Flat ring stiffeners are added along the cylindrical shell to increase the moment of inertia, enhancing deformation resistance and stability under compression. The tail section connects to the stiffened shell, ensuring effective load transfer and uniform stiffness distribution.

6. THEORETICAL BACKGROUND

Stress Analysis Using Von Mises Yield Criterion

a) The forward section is modelled as a **closed conical shell** subjected to external hydrostatic pressure.

The equivalent Von Mises stress is expressed as:

$$= \frac{\sqrt{3}}{2} \cdot \frac{r}{h\sin}$$

b) The cylindrical shell is analysed using thin shell theory under external pressure, where hoop and longitudinal stresses dominate.

Hoop stress $= \; = \frac{}{2h}$

Axial stress $= \; = \frac{}{4h}$

The equivalent Von Mises stress is given by:

$$= \frac{}{\sqrt{3}} \cdot \frac{4h}{}$$

c) The tail section is treated as an **inclined open conical shell**, For analytical validation, a modified Von Mises expression is used:

$$= \sqrt{3} \cdot \frac{}{4h\cos}$$

Buckling Assessment Based on Stress Ratio

Buckling is the primary failure mode for thin-walled pressure hulls under external pressure. In this study, the buckling factor (λ) is assessed using a simplified stress- based approach, defined as the ratio of material yield strength (σyt) to the induced Von Mises stress (Syt):

$$= \; /$$

Interpretation of λ values is as follows: λ >

1: Structure is safe

λ ≈ 1: Critical condition

λ < 1: Failure likely due to buckling

For the forward and tail sections, the Von Mises stresses from analysis are used to calculate λ, providing a rapid and effective means for design validation and buckling resistance estimation.

Buckling Analysis of Stiffened Cylindrical Shell

For the stiffener-reinforced cylindrical shell, buckling behavior is more complex and occurs in distinct modes. Analytical methods are utilized to assess these various instability conditions.

I-Stiffener Shell Buckling Analysis

1. Axisymmetric Buckling

$$_A = \frac{3}{12(1 - {}^2)^3} \left(\frac{22}{2} \right) + \frac{A\ h^2}{3} -$$

- → Deformation is uniform along the circumference
- → No wave formation around the shell
- → Represents global collapse mode
- → Dominant when stiffeners provide strong circumferential rigidity

2. Asymmetric Buckling

$$= \frac{3}{12(1 - {}^2)^3} \left(\frac{22}{2} \quad + \frac{}{2} \right) + \frac{A\ h^2}{3}$$

- → Characterized by circumferential wave patterns
- → Localized deformation occurs between stiffeners
- → More critical for thin shells with wider stiffener spacing

3. General Instability

$$_G = \frac{2}{\sqrt{3(1 - {}^2)}} \left(- \right)^3 + \frac{A\ h^2}{3} -$$

- → Combined effect of:
  - Shell deformation
  - Stiffener deformation
- → Represents interaction between local and global modes
- → Considered the most realistic failure condition

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7. ANALYSIS

Geometry Import

The three-dimensional geometry of the pressure hull, including the forward section, cylindrical shell, tail section, and flat ring stiffeners, was developed using CAD software and imported into ANSYS Workbench for analysis. Standard file formats such as STEP, IGES, and Parasolid were used to ensure seamless compatibility. After import, the geometry was thoroughly verified to eliminate gaps, overlaps, and missing surfaces. Proper connectivity between the shell and flat ring stiffeners was carefully ensured to maintain structural continuity. Minor geometric inconsistencies were corrected, and unnecessary features were simplified to reduce computational effort without compromising accuracy. Additionally, the geometry was checked for proper alignment and orientation to ensure accurate application of boundary conditions and loading. This step is essential, as a clean and well-defined geometry significantly influences solution convergence and overall simulation accuracy.

Material Selection

Aluminium alloy AA7068 was selected as the structural material due to its high strength-to-weight ratio and excellent mechanical properties. The material offers high yield strength, adequate stiffness, and low density, making it highly suitable for underwater applications where both strength and weight efficiency are crucial. It also exhibits good corrosion resistance, which is essential for long-term operation in marine environments. To further enhance performance, Retrogression and Re-Aging (RRA) heat treatment is considered, improving resistance to stress corrosion and increasing durability under high external pressure conditions. The material also provides good machinability, allowing efficient fabrication of cylindrical shells and flat ring stiffeners. Its proven use in aerospace and high-performance engineering applications further supports its suitability for reliable and safe underwater structural components.

Mesh Generation

Mesh generation plays a vital role in finite element analysis, where the geometry is discretized into smaller elements for numerical evaluation. In this study, predominantly tetrahedral elements were used due to the complex geometry of the pressure hull and the inclusion of flat ring stiffeners. Automatic meshing with default body sizing was adopted to maintain a balance between computational efficiency and result accuracy. Mesh quality was assessed using parameters such as skewness, element distortion, and smooth transition across adjacent elements. Special attention was given to regions near the stiffener connections to accurately capture stress concentrations. Mesh refinement was applied in critical regions to improve result precision. Additionally, mesh independence was ensured to confirm that further refinement does not significantly affect the results. A high-quality mesh ensures better convergence, numerical stability, and reliable simulation outcomes.

8. MODEL WITH BOUNDARY CONDITIONS AND LOADS

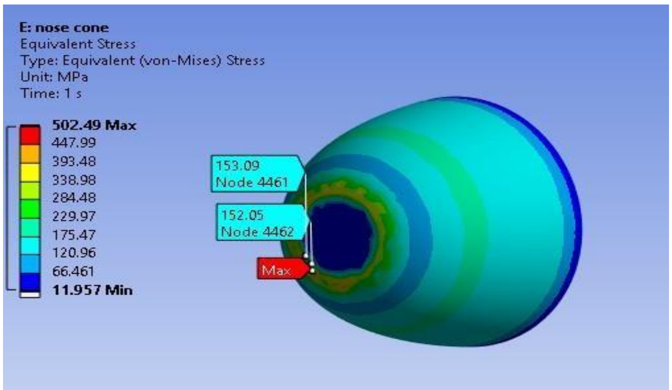
$= \; = \; = 0$ at Front End And $= \; = 0$ at Rear End External Pressure P = 15 Mpa is applied to the model surface

$= 1.3 \times 10^{7}$ at Rear End for Axial Compressive Force (SHELL)

$= 2.9 \times 10^{5}$ at Rear End for Axial Compressive Force (Forward & TAIL SECTION)

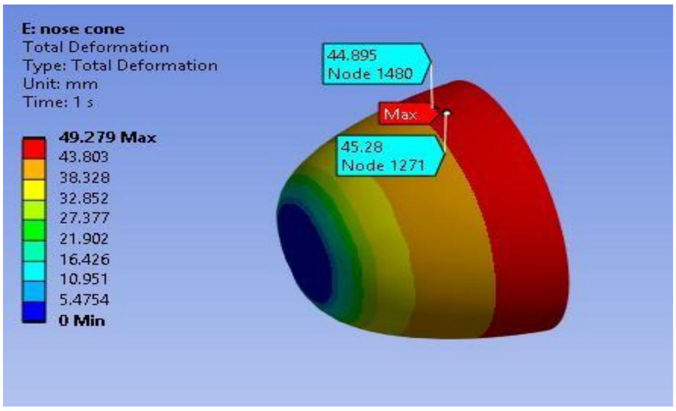
9. FEM ANALYSIS OF UNSTIFFENED MODEL

Forward Section

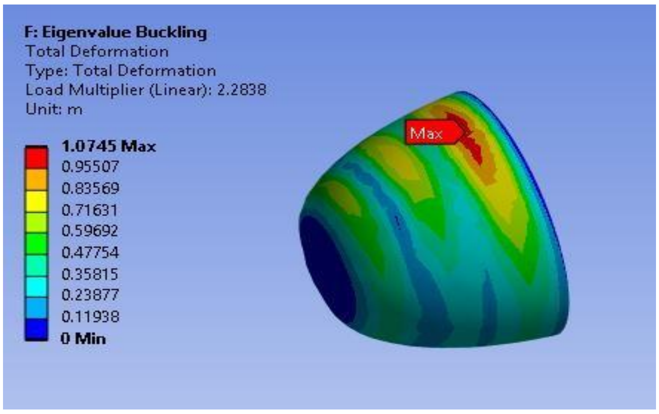


Maximum Equivalent Stress

153.09 Mpa

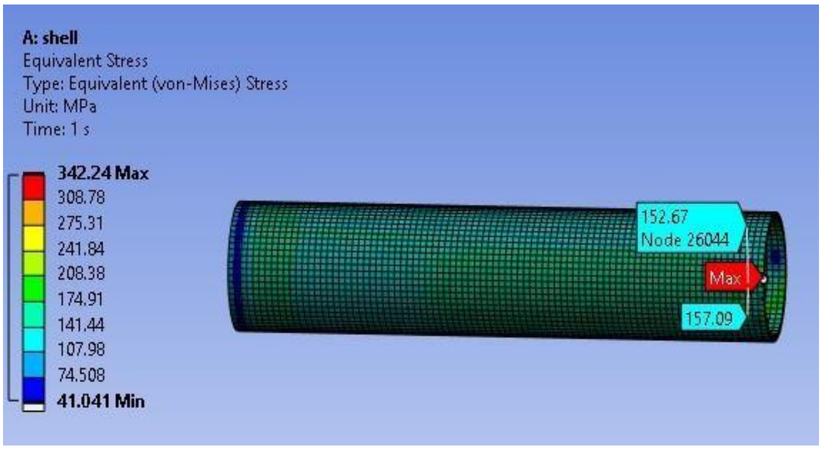


Maximum Deformation
45.28 mm

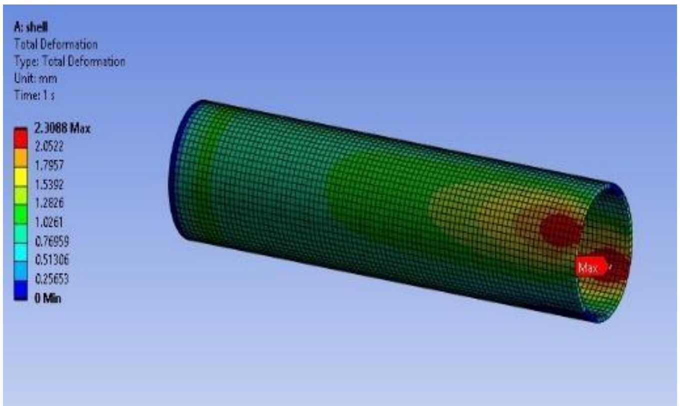


Minimum Buckling Factor 2.2

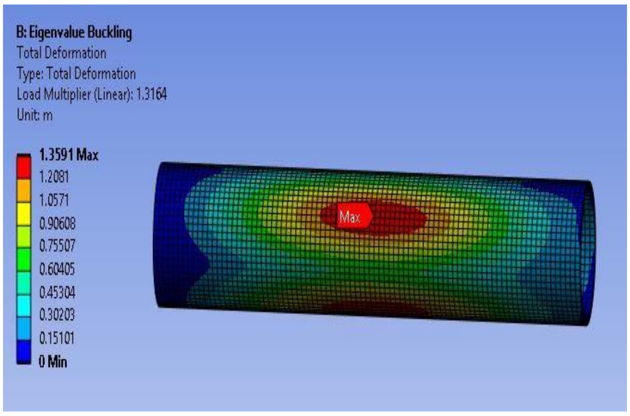
Cylindrical Shell



Maximum Equivalent Stress
157.09 Mpa

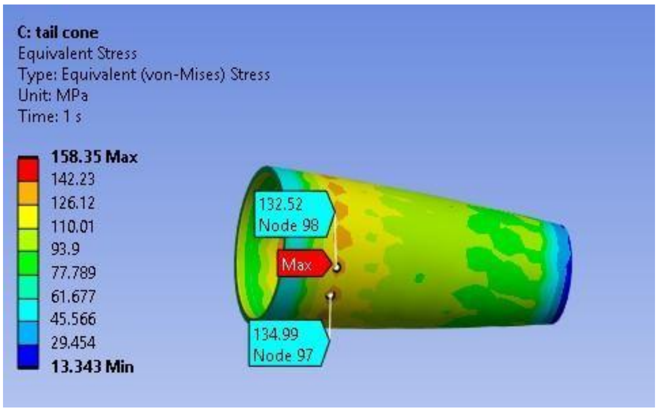


Maximum Deformation
2.3 mm

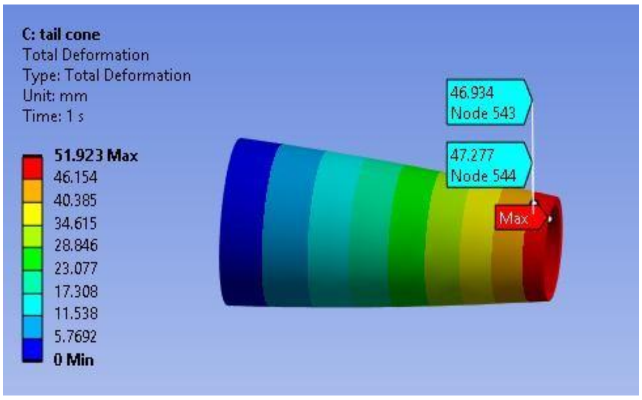


Minimum Buckling Factor
1.3

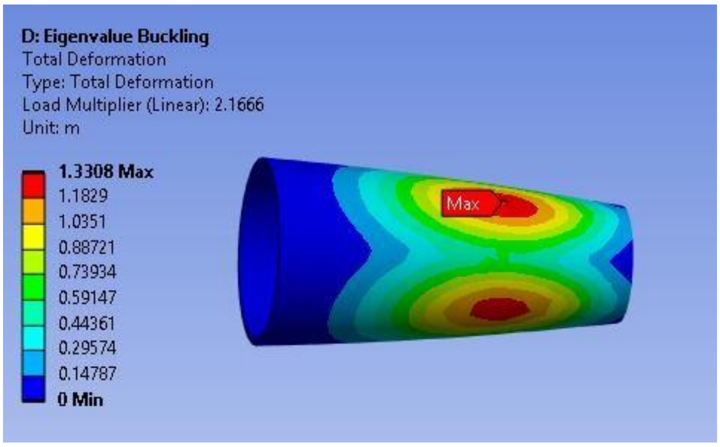
Tail section



Maximum Equivalent Stress
134.99 Mpa



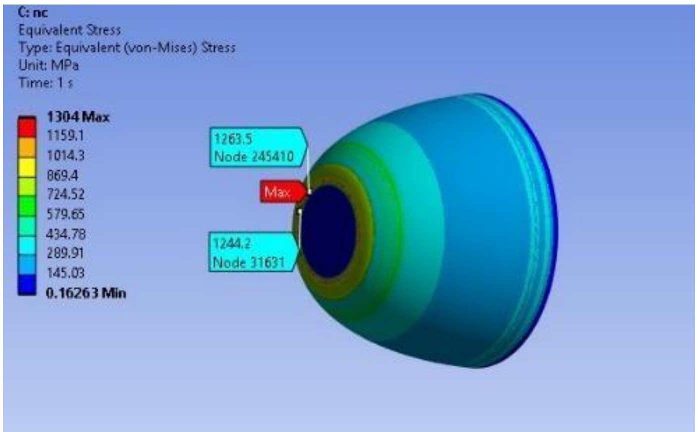
Maximum Deformation
47.27 mm



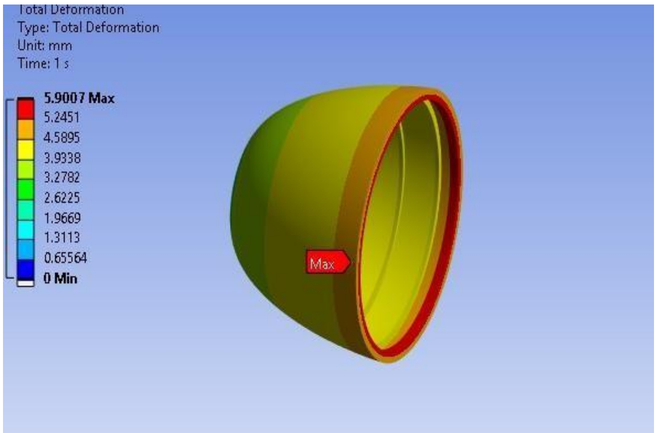
Minimum Buckling Factor 2.1

10. Fem Analysis of Flat stiffened Model

Forward Section



Maximum Equivalent Stress
1263.5 Mpa



Maximum Deformation
5.90 mm

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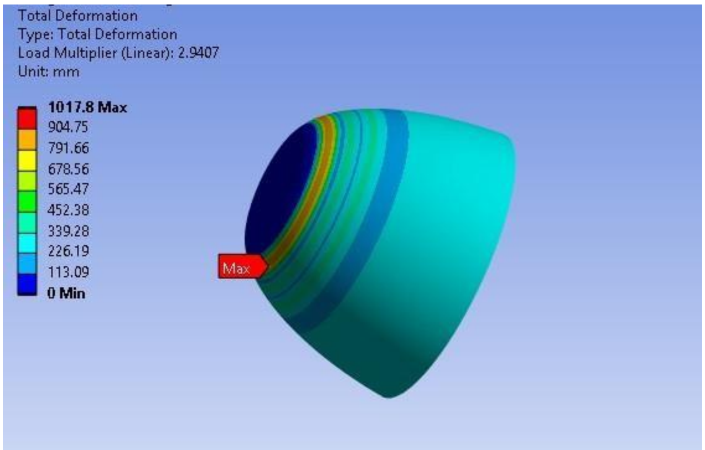
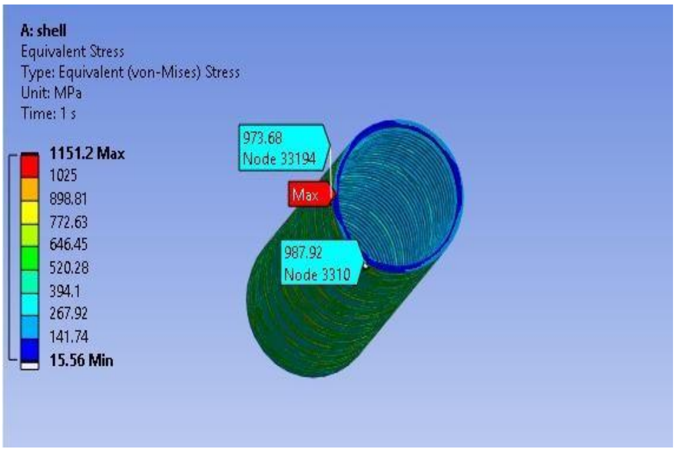
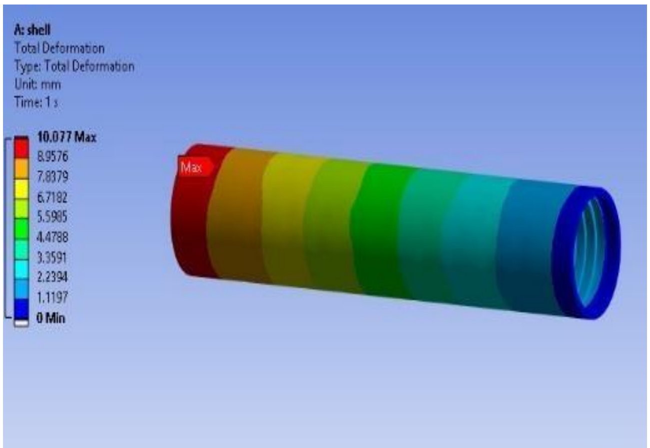


Minimum Buckling Factor 2.23

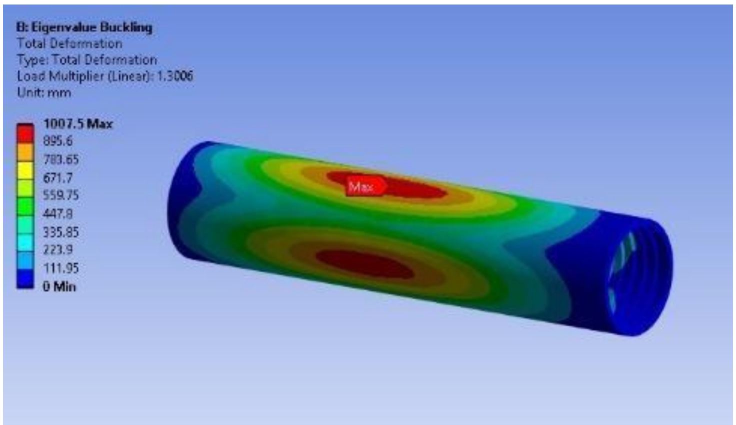
Cylindrical Shell



Maximum Equivalent Stress
987.92 Mpa



Maximum Deformation
10.07 mm



Minimum Buckling Factor 1.3

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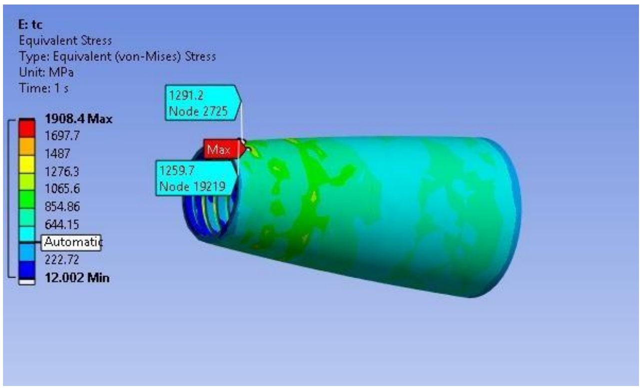
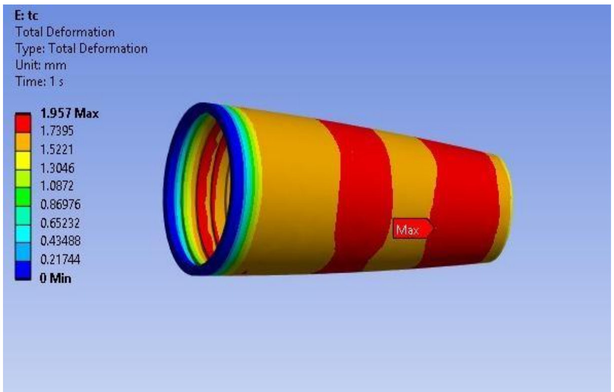
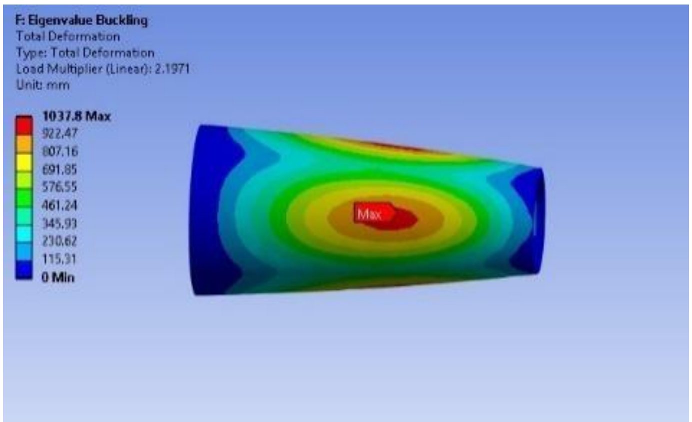
Tail section



Maximum Equivalent Stress
1291.2 Mpa

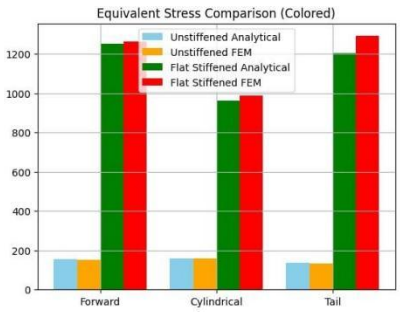


Maximum Deformation
1.95 mm

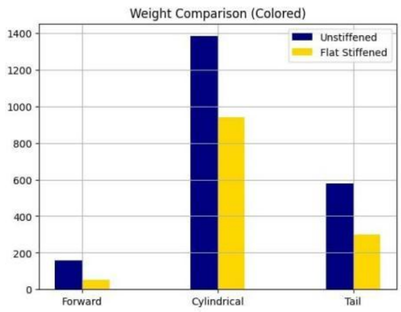


Minimum Buckling Factor 2.1

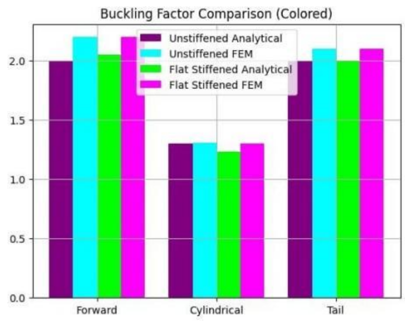
GRAPHICAL REPRESENTATION



STRESSES



WEIGHT OPTIMIZATION



BUCKLING FACTOR

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RESULT

1) Comparison Of Equivalent Stresses (Von-Mises)

MODEL	PARTS	STRESSES (Mpa)	
		ANALYTICAL	FEM
UNSTIFFENED	Forward section	156.4	153.09
	Cylindrical shell	157.09	157.09
	Tail section	134.99	134.9
FLAT STIFFENED	Forward section	1251.3	1263.5
	Cylindrical shell	962.5	987.92
	Tail section	1203.1	1291.2

2) Comparison Of Buckling Factor

MODEL	PARTS	BUCKLING FACTOR	
		ANALYTICAL	FEM
UNSTIFFENED	Forward section	2	2.2
	Cylindrical shell	1.3	1.31
	Tail section	2	2.1
FLAT STIFFENED	Forward section	2.05	2.2
	Cylindrical shell	AXISYMMETRIC 1.23	1.3
		ASYMMETRIC 1.31	
		GENERAL INSTABILITY 1.16	
	Tail section	2	2.1

3) COMPARISON of WEIGHT OPTIMIZATION

TOTAL WEIGHT OPTIMIZATION (%)		
PART	REDUCTION OF WEIGHT FROM UNSTIFFENED MODEL	FLAT STIFFENED (% REDUCED)
Forward section	159 > 54	66%
Cylindrical shell	1383 > 940	32%
Tail section	580 > 301	48%

MODEL	PARTS	WEIGHT OPTIMIZATION (kg)
UNSTIFFENED	Forward section	159
	Cylindrical shell	1383
	Tail section	580
FLAT STIFFENED	Forward section	54
	Cylindrical shell	940
	Tail section	301

CONCLUSION

This study evaluated the structural performance of an unmanned underwater vehicle pressure hull by comparing unstiffened and flat ring stiffened configurations through finite element analysis. Results reveal that the unstiffened model exhibits higher deformation and lower resistance to external hydrostatic pressure, limiting its suitability for deep-sea use. Incorporation of flat ring stiffeners significantly enhances stiffness and reduces deformation, though improvements are moderate and localized stress concentrations persist near stiffener connections. While stiffeners increase load-carrying capacity and delay buckling onset, they do not entirely eliminate structural instability risks at higher pressures. Numerical findings closely align with theoretical predictions, validating the modeling approach. Overall, flat ring stiffening offers a practical, effective solution to improve structural performance while preserving design simplicity and manufacturability, making it suitable for moderate- depth underwater applications where performance, cost, and fabrication considerations are balanced..

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