Modeling and Failure Analysis of Multi-Layered Sandwich Pressure Vessels for Autonomous Underwater Vehicles (AUVs)

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Abstract

Autonomous Underwater Vehicles (AUVs) represent an essential class of unmanned undersea systems designed to execute deep-ocean exploration, pipeline mapping, and defense missions without real-time human intervention. Because these submersibles operate under extreme hydrostatic pressures, their primary cylindrical pressure hulls are highly susceptible to buckling collapse and catastrophic failure prior to reaching material yield limits. This paper evaluates an innovative structural design concept using multi-layered sandwich configurations combined with sliding internal stiffeners to maximize buckling resistance while preserving vital payload volume. Utilizing computer-aided three-dimensional interactive application (CATIA V5) for high-precision parametric geometric modeling and ANSYS Workbench for finite element analysis (FEA), a series of robust simulations were executed. Four explicit sandwich beam structural core layer configurations were investigated: Case 1 (2mm C40 Steel + 2mm Rubber + 2mm C40 Steel), Case 2 (2.5mm C40 Steel + 1mm Rubber + 2.5mm C40 Steel), Case 3 (2mm Ti-6Al-4V + 2mm Rubber + 2mm Ti-6Al-4V), and Case 4 (2.5mm Ti-6Al-4V + 1mm Rubber + 2.5mm Ti-6Al-4V). The pressure hulls were subjected to a critical operational hydrostatic radial pressure of 65 Bar (6.5 MPa). High-fidelity static structural and dynamic modal analyses were conducted to compare Von-Mises stress distribution, structural deformation fields, elastic strain values, and shear stress compliance. Additionally, dynamic frequencies and corresponding mode shapes were extracted up to the 300 Hz operating range. The empirical simulation results conclusively demonstrate that the Ti-6Al-4V titanium alloy configuration combined with a 2mm elastomeric core layer (Case 3) exhibits superior stress mitigation, optimal strain fields, minimal deformation, and exceptionally stable dynamic withstand capability, confirming its mechanical suitability for deep-sea deep-submergence pressure hulls.

Keywords: Autonomous Underwater Vehicles (AUV), Pressure Hull, Sandwich Beam Structure, Finite Element Analysis (FEA), Von-Mises Stress, Modal Resonant Vibration.

1. Introduction

Autonomous Underwater Vehicles (AUVs) are highly advanced programmable, robotic submersibles capable of navigating ocean depths, gathering scientific data, and mapping seafloor topography independently without real-time interaction or control tether lines from human operators. Depending on their dedicated design architecture, these vehicles can drift, actively drive, or glide through underwater currents while communicating periodically or continuously with surface research vessels via advanced satellite telemetry or underwater acoustic transponder beacons. This technological autonomy permits oceanographers and marine scientists to optimize operational timelines, executing secondary shipboard scientific experiments while the autonomous asset maps deep-ocean trenches or monitors delicate marine ecosystems elsewhere.

In terms of structural hull anatomy, submersibles utilize a distinct dual-classification terminology: the light hull (or outer casing) and the primary pressure hull. The light hull functions as an outer hydrodynamically streamlined shield, containing complex equipment that operates at ambient sea-level parameters and experiencing zero net differential pressure loading across its boundary. Conversely, the inner pressure hull serves as the primary load-bearing citadel designed to withstand profound compressive hydrostatic forces while safely maintaining normal standard atmospheric internal pressure environments for vulnerable embedded electronic control modules, sensor boards, and heavy lithium battery packs.

Engineering a robust deep-sea pressure vessel represents a complex structural challenge due to the immense hydrostatic gradient that escalates at a predictable rate of approximately 1 atmosphere (0.101 MPa) for every 10 meters of depth progression. Consequently, an unshielded structural envelope diving into deep regions encounters tremendous multi-axial crushing forces capable of immediate catastrophic destruction. To prevent electrical short-circuiting or component fracture due to water intrusion, solid pressure vessels with perfectly circular cross-sections are mandatory. Circular geometry is highly efficient at distributing compressive stresses symmetrically; however, manufacturing geometric imperfections or localized structural non-roundness drastically down-rates the buckling threshold. Standard structural calculations establish that even a minor cross-sectional roundness deviation of 1 inch (25 mm) triggers a severe 30 percent degradation in structural load carrying capability. Traditional heavy naval vessels combat this via internal ring stiffeners directly welded to the inner shell face. However, for compact micro-AUVs, permanently welded structural stiffeners reduce invaluable internal volume, trap thermal dissipation, and introduce detrimental metallurgical residual stresses during fabrication. This limitation underlines the critical need for advanced lightweight, non-corrosive multi-layered composite sandwich structures to maximize structural integrity without weight penalties.

2. Literature Review

The engineering fundamentals, design paradigms, and failure analysis methodologies regarding underwater vessels have been extensively evaluated across key historical milestones. Arentzen and Mandel presented comprehensive technical foundations demonstrating that single-hull structures provide optimal design efficiency for small-scale submersibles and research vehicles, whereas complex massive military submarines frequently separate into heavy multi-compartment double-hull configurations to increase redundant internal protection reserves. Modern engineering requires that when an asset resides fully submerged, the surrounding hydrostatic force field increases exponentially, demanding exact calculation of buckling thresholds versus ultimate material yield strengths.

Further research by McDaniel and John R. MacKay into the structural analysis and future design trends of thin-walled pressure hulls emphasized that thin curved shells are inherently critical under buckling scenarios. They identified that cross-domain design methodologies sharing clear commonalities with advanced aerospace shells and offshore civil structures provide valuable modern non-linear numerical prediction tools. Historically, linear analytical rules enforced an overly conservative safety margin.

Incorporating reliable non-linear computational finite element formulations provides engineers a clear, optimized pathway to accurately simulate true collapse mechanisms.

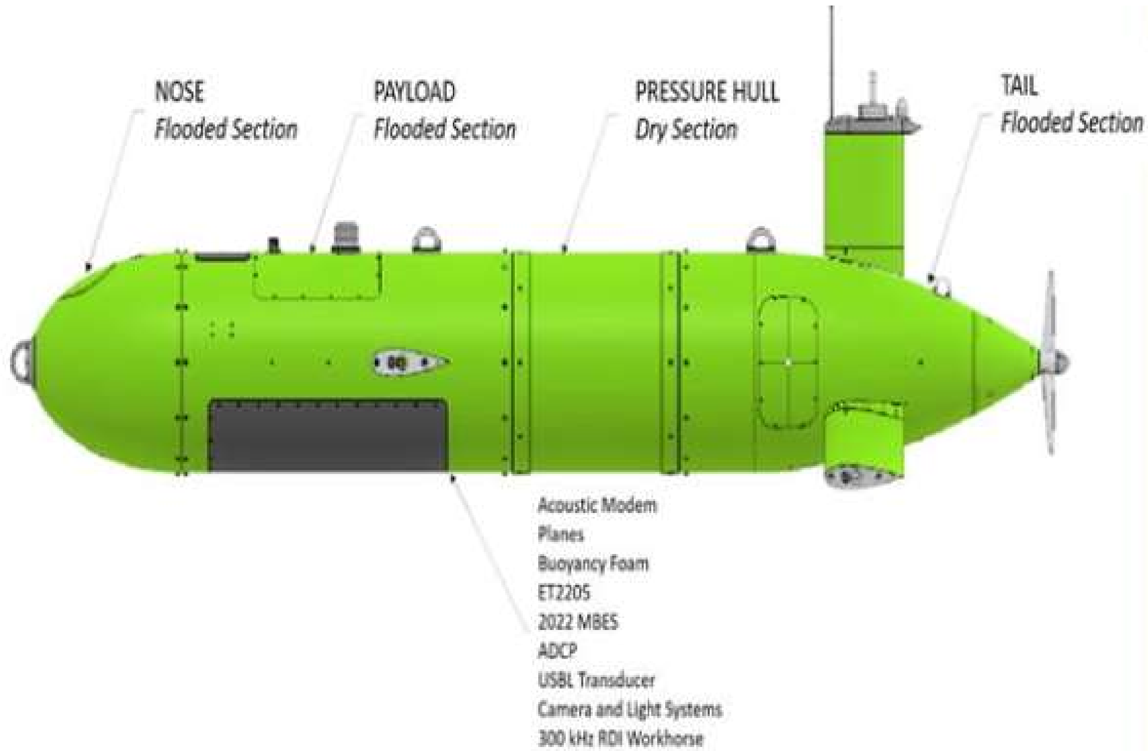

Figure 1 :Outer part of AUV

The physical influence of fabrication processes on pressure hull stability was thoroughly investigated by Liam Gannon. His specialized research evaluated how cold-bending operations used to shape thick shell plating and heavy internal frames introduce high internal residual stresses that reduce overall structural collapse pressure values. Comparative evaluations of empirical modeling equations, finite difference programs, and high-fidelity FEA codes demonstrated that leveraging specialized effective stress-strain curves inside finite element models provides an accurate methodology to capture manufacturing stress records. This prevents unsafe over-estimation of the pressure hull's true structural buckling limit. Additionally, specialized sandwich panels and core material formulations studied by researchers like Swathi, Khatua, and Frosting proved that introducing structural decoupling layers effectively mitigates localized strain concentrations and provides superior flexural rigidity, making sandwich design ideal for high-pressure deep-sea exploration.

3. Problem Identification and Research Methodology

Improper selection of structural materials or un-optimized thickness combinations can lead to sudden, catastrophic structural buckling collapse under heavy deep-sea service loads. This research addresses structural optimization by analyzing a micro-AUV cylindrical pressure hull under an operational hydrostatic loading of 65 Bar (6.5 MPa), which corresponds to an exploration depth of approximately 650 meters. The engineering objective is to systematically analyze four unique material layer configurations utilizing the sandwich beam concept to achieve minimum deformation, low shear stress development, and robust dynamic behavior inside the 0-300 Hz vibrational frequency operating envelope.

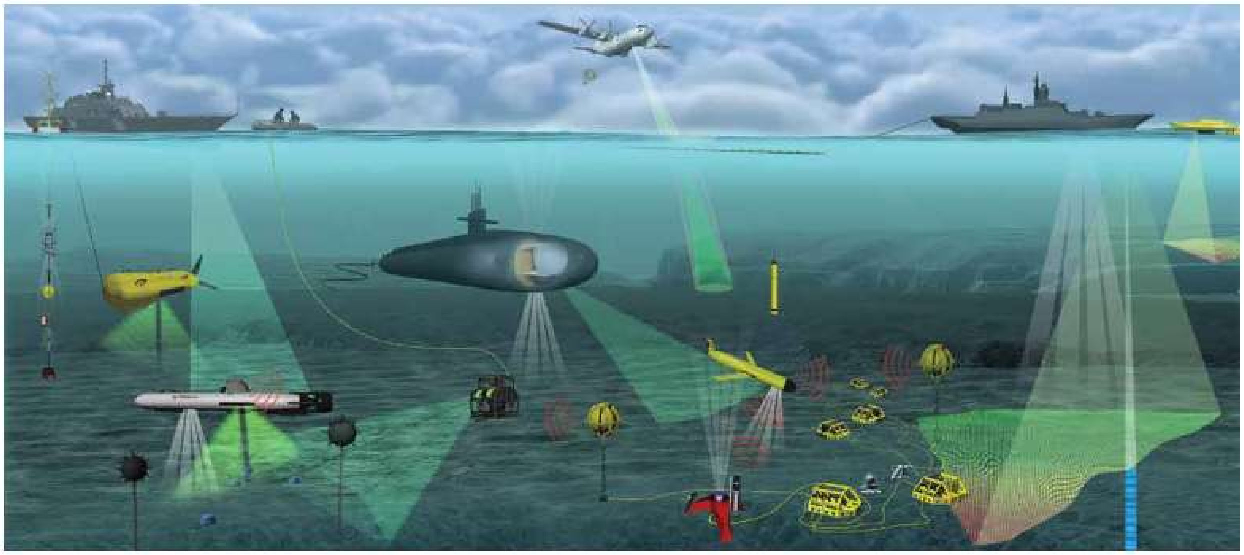

Figure 2 :Various applications of Autonomous Under water vehicle

3.1 Geometric Configuration and Material Specifications

To ensure experimental control, all finite element models maintain a constant overall length of 1000 mm, an outer cylindrical diameter of 0.4 meters, and a fixed combined multi-layer total structural wall thickness of 6.0 mm. Symmetrical rigid disk bulkheads seal both terminal ends of the cylinder. The primary sandwich beam concept relies on two high-strength thin metallic skin layers separated by a thick, resilient elastomeric rubber core layer. The underlying mechanics mirror an structural I-beam: the high-modulus outer skin sheets absorb primary axial and hoop tensile-compressive forces, while the inner core increases the cross-sectional moment of inertia, significantly limiting transverse shear deformation.

Material Designation	Density (g/cm³)	Poisson's Ratio (μ)	Young's Modulus (GPa)
Titanium Alloy (Ti-6Al-4V)	4.429	0.30	206.0
Medium Carbon Steel (C40)	7.800	0.29	200.0
Elastomeric Rubber Core	1.100	0.48	0.2

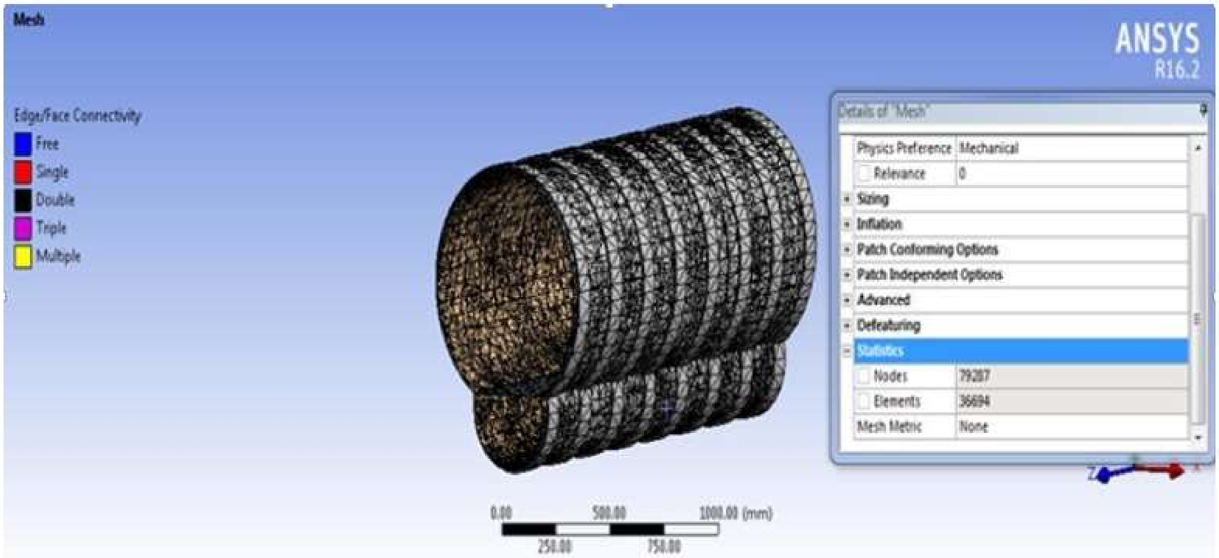

FIGURE 03: MESH IN ANSYS WORKBENCH NODES:79287, ELEMENTS:36694

To determine the mechanical performance under high hydrostatic loading, four distinct structural layout cases were established for comparative numerical evaluation:

- Case 1: 2.0 mm C40 Steel Skin + 2.0 mm Rubber Core + 2.0 mm C40 Steel Skin
- Case 2: 2.5 mm C40 Steel Skin + 1.0 mm Rubber Core + 2.5 mm C40 Steel Skin
- Case 3: 2.0 mm Ti-6Al-4V Skin + 2.0 mm Rubber Core + 2.0 mm Ti-6Al-4V Skin
- Case 4: 2.5 mm Ti-6Al-4V Skin + 1.0 mm Rubber Core + 2.5 mm Ti-6Al-4V Skin

4. Finite Element Modeling and Simulation Setup

The 3D parametric geometry was modeled using CATIA V5, utilizing the dedicated Part Design and Assembly Design workbenches to construct independent layer interfaces with precise concentric constraints. The geometric assembly was subsequently exported as a high-fidelity neutral file and imported into the ANSYS Workbench simulation package. The physical mesh was generated using higher-order 3D SOLID45 brick elements, characterized by eight nodes featuring three independent translational degrees of freedom (x, y, and z) at each nodal vertex. This element configuration supports large deflection, plasticity, hyper-elastic core modeling, and precise strain tracking across multi-layered interfaces. The final mesh convergence achieved a high-density discretization comprising 79,287 nodes and 36,694 continuum elements.

Boundary conditions were applied to represent operational deep-sea conditions. Symmetrical boundary constraints fixed both circular flat end caps of the cylinder in all degrees of freedom ($u_x = u_y = u_z = 0$) to capture rigid bulkhead support. An external uniform hydrostatic pressure of 65 Bar (6.5 MPa) was applied normal to the outer surface shell face. Static structural solver routines executed the principal stress vectors, deformation fields, and multi-axial strains. Following the static structural evaluation, a block-Lanczos numerical routine was triggered to perform dynamic modal analysis, successfully solving for the fundamental natural frequencies and corresponding three-dimensional mode shapes up to the targeted 300 Hz operational vibration threshold.

5. Results and Discussion

The comparative analysis between the four multi-layered sandwich pressure vessel configurations revealed critical insights into stress distribution, structural compliance, and dynamic behavioral characteristics under identical external loading conditions.

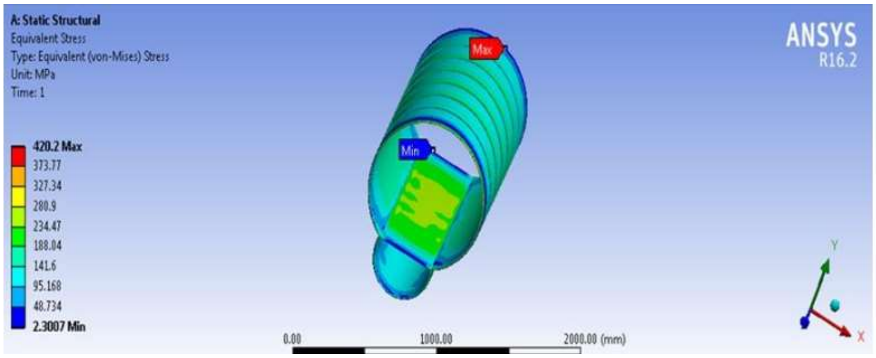

FIGURE 04: VON-MISSES STRESS OF C40 STEEEL+1MM RUBBER+2MM C40 STEEL MATERIAL

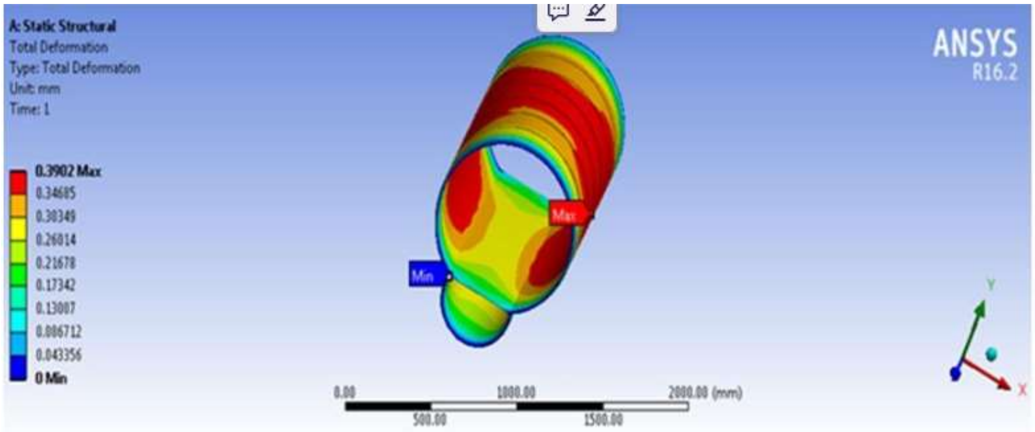

FIGURE 05: TOTAL DEFORMATION OF C40 STEEEL+1MM RUBBER+2MM C40 STEEL MATERIAL

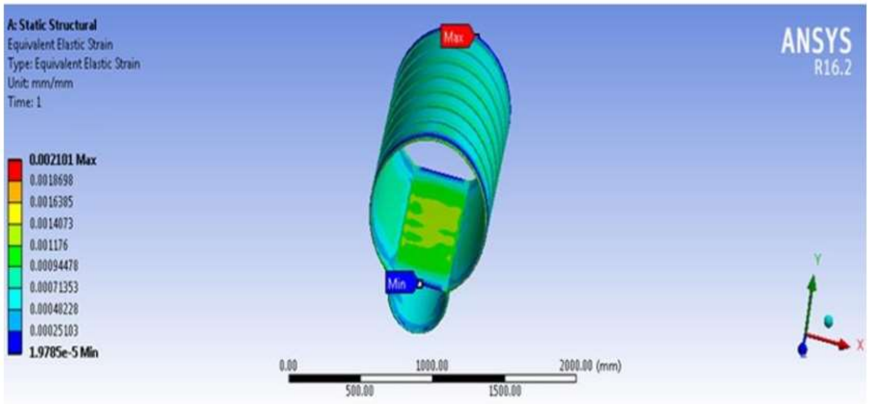

FIGURE 06: STRAIN OF C40 STEEL+1MM RUBBER+2MM C40 STEEL MATERIAL

Simulation Configuration	Max Von-Mises Stress (MPa)	Max Total Deformation (mm)	Max Equivalent Strain	Max Shear Stress (MPa)
Case 1: 2mm Steel + 2mm Rub + 2mm Steel	418.4	0.288	0.00209	100.10
Case 2: 2.5mm Steel + 1mm Rub + 2.5mm Steel	420.2	0.345	0.00198	100.50
Case 3: 2mm Ti64 + 2mm Rub + 2mm Ti64	414.5	0.241	0.00207	99.15
Case 4: 2.5mm Ti64 + 1mm Rub + 2.5mm Ti64	416.5	0.249	0.00207	99.60

The static structural calculations demonstrate that Case 3 (utilizing 2.0 mm Ti-6Al-4V titanium alloy outer skin sheets in combination with a 2.0 mm hyper-elastic core) minimizes stress concentrations, yielding a peak Von-Mises stress value of 414.5 MPa. This represents a significant performance improvement compared to the corresponding 2.5 mm steel configuration (Case 2), which exhibited an elevated peak stress value of 420.2 MPa. More importantly, Case 3 restricted the total structural deformation to an optimal value of 0.241 mm. In comparison, the steel sandwich layout under identical thickness boundaries deflected significantly up to 0.345 mm, indicating lower structural stiffness under heavy pressure fields. The high shear stress compliance of Case 3 (99.15 MPa) prevents mid-layer delamination, confirming strong interfacial load transfer across the core boundaries.

5.2 Dynamic Vibration and Modal Characteristics

The dynamic block-Lanczos solver successfully captured the primary resonance modes within the targeted operational testing frequency spectrum. For Case 3 (2mm Ti-6Al-4V + 2mm Rubber + 2mm Ti-6Al-4V), Mode 1 occurred at 248.5 Hz with an internal deformation amplitude of 3.648 mm. Mode 2 shifted safely to 264.2 Hz with a deformation shape of 3.877 mm, and Mode 3 occurred at 287.6 Hz with a total deformation peak of 4.126 mm. Conversely, the alternative configuration utilizing carbon steel skins coupled with a 2.0 mm rubber core (Case 1) exhibited lower fundamental frequencies due to its higher material density: Mode 1 emerged at 221.4 Hz (Deformation: 4.825 mm), Mode 2 at 234.6 Hz (Deformation: 4.862 mm), and Mode 3 at 243.8 Hz (Deformation: 4.913 mm).

This shift in natural frequencies confirms that the higher specific strength and optimal mass-to-stiffness ratio of the titanium-based sandwich hull effectively raises the fundamental resonance threshold. This frequency shifting prevents structural lock-in with low-frequency acoustic vibrations and propulsion motor excitation frequencies, minimizing the risk of resonance-induced fatigue failure.

6. Conclusion

This research presents a comprehensive numerical simulation and structural optimization of an Autonomous Underwater Vehicle (AUV) multi-layered sandwich pressure vessel operating under an extreme hydrostatic environment of 65 Bar (6.5 MPa). Symmetrical finite element evaluations using CATIA V5 and ANSYS Workbench conclusively show that material selection and core thickness combinations significantly dictate the pressure vessel's structural withstand capability. The comparative engineering results show that Case 3 (comprising a 2.0 mm Ti-6Al-4V titanium alloy skin combined with a 2.0 mm elastomeric core) delivers superior performance. This configuration minimized peak Von-Mises stress concentrations to 414.5 MPa and minimized external structural deformation fields to 0.241 mm. Furthermore, dynamic modal extraction confirmed that the high specific strength of the titanium-elastomer sandwich configuration successfully shifts natural frequencies into higher ranges, preventing structural resonance inside the 0-300 Hz operating envelope. Consequently, this multi-layered design represents an optimized, high-performance structural solution for deep-submergence pressure hulls.

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