International Journal of Research in Engineering and Science (IJRES)
ISSN (Online): 2320-9364, ISSN (Print): 2320-9356
www.ijres.org Volume 11 Issue 9 ǁ September 2023 ǁ PP. 292-297

Analysis of Sinking Of the "Titan" Submersible In Accordance With Carbon Fibre: A Case Study

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Abstract- *Carbon fiber was used to make the body of a submersible "Titan" which imploded under water while attempting to explore the wrecks of the sunken "Titanic" ship. This makes it important to analyze the sustainability of carbon fiber for designing submarines, and its feasibility to perform under high stress conditions as was expected in the case of the said submersible "Titan". Thus, this paper tries to analyze the possible structural failures and try to figure out the optimal safe operating depth of a submersible "Titan" with a hull made out of carbon fiber.*

Index Terms*- Safe Operating Depth, Submarine, Structural Failure, Carbon Fiber*

Date of Submission: 15-09-2023 Date of acceptance: 30-09-2023

I. INTRODUCTION

This article examines a scenario involving a submarine constructed from a weak variant of carbon fiber and its susceptibility to collapsing under high hydrostatic pressures. This paper delved into the concept of implosion, where surrounding water pressure can lead to structural failure, and we examined the hydrostatic pressure formula as pressure increases with depth. Through assumptions, this paper estimates properties of the weak carbon fiber, including tensile strength, modulus, and density, using simplified linear relationships. Utilizing these assumptions, this paper calculates imploding stress and estimated the maximum depth at which implosion might occur, considering safety factors.

Difference between Submarines and Submersibles

Large, self-propelled vehicles with the ability to operate both above and below the water's surface are known as submarines. Usually employed for military operations, surveillance, reconnaissance, and strategic deterrent, navies use them for a variety of objectives. A submarine's sturdy hull structure enables it to endure intense water pressure at great depths. They have a variety of sensors and weaponry, along with propulsion, navigation, and communication systems. In order to manage their depth and buoyancy, submarines use ballast tanks and control surfaces. This allows them to operate underwater for long periods of time.

Smaller, frequently unmanned or remotely driven underwater vehicles called submersibles are created for certain underwater operations or research goals. They are frequently employed in deep-sea exploration, underwater filming, scientific research, and exploration. Human occupants can control submersibles manually or remotely from the surface. They typically have less capabilities than submarines and are not designed for long-term underwater operations. Small personal submarines to massive research vessels with specialized equipment and instrumentation are examples of the many sizes of submersibles. In this paper, these terms are often used interchanged, so it is advised to assume for this paper that both the words have the same meaning.

Design of the said 'Titan' submarine

Carbon fiber and titanium were used to create the submersible Titan. The Titan's pressure hull was made of two titanium hemispheres and matching titanium interface rings that were connected to a carbon fiber-wound cylinder with an interior diameter of 142 cm and a length of 2.4 meters.
The Ocean Gate official website describes the Titan as:

Titan is the world's only carbon-fibre submersible capable of diving five people to 4,000 meters (13,123 feet). It is the submersible we use to survey the wreck of the RMS Titanic during our annual Titanic Expeditions. Titan's unique ability to carry five people allows for multiple Mission Specialists, scientists and content experts to share a once-in-a-lifetime experience diving in the deep ocean.

The state-of-the-art vessel, designed and engineered by OceanGate Inc. in collaboration experts from NASA, Boeing and the University of Washington, made its subsea debut in 2018. Through the innovative use of modern materials, Titan is lighter, more spacious, and more comfortable than any other deep-diving submersible exploring the ocean today.

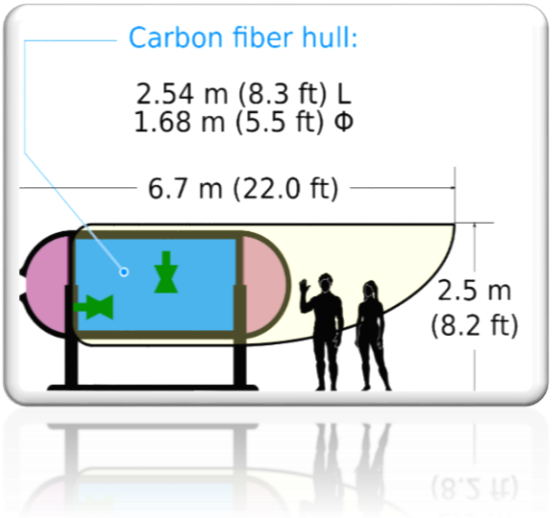

Figure 1- Sketch of the submersible 'Titan'

Research Hypothesis

Hypothesis 1: There was some unseen calculation or logical error in calculating the quantification of the strength of design of the said submersible leading to a miscalculation of depth at which the said submersible can safely operate.

Hypothesis 2: The accident (Implosion) occurred as the result of a structural failure due operations beyond the actual safe operating depth.

Hypothesis 3: The carbon fiber used in the construction was not sturdy enough in terms of ultimate tensile strength and allowable stress of carbon fiber resulting in the structural failure OR was adulterated leading to decrease in the withstanding of the stress.

Assumptions for the ease of calculations

Assumption 1: The said submarine is considered to be the shape of a cylindrical hull, with two semi-circles on its smaller sides as diameters, added its outside for the ease of calculations with the dimensions of the cylindrical hull being 6.7 m (22.0 feet) and 2.5 m (8.2 feet).

Assumption 2: The part of the said submarine that is considered for analysis in this paper is hull of the shape of a rectangle, with sides of the rectangle being of the said dimensions. The two semi-circles on its smaller sides as diameters, are not regarded for analysis in this paper as they are made of titanium, which is not a material of concern in this particular paper.

Assumption 3: No payload or equipment is assumed for this simplified analysis.

Assumption 4: Operational Loads: For simplicity, we'll consider the hydrostatic pressure as the primary load. Other loads like dynamic loads and buoyancy changes are excluded from this simplified analysis.
Assumption 5: We'll consider a linear relationship between tensile strength and pressure.
Assumption 6: Safety factor is considered to be 2.

II. Research Methodology

In order to identify and set a maximum operating depth, the following series of calculations need to be performed

1. Identification of the submarine's materials and construction methods: The materials used to construct a submarine's hull and pressure hull will have a significant impact on its maximum safe operating depth. The construction methods used to build the submarine will also play a role, as a more robust construction will be able to withstand greater pressure.

2. Calculation of the submarine's hull strength. The hull strength is a measure of the ability of the submarine's hull to withstand pressure. It has been calculated using the von Mises yield criterion.
3. Performing a risk assessment: Once the submarine's hull strength and critical components have been identified, a risk assessment should be performed to determine the probability of failure at a given operating depth. The risk assessment should consider factors such as the materials used, the construction methods, the operating environment, and the maintenance history of the submarine.

4. Setting the maximum safe operating depth: Based on the results of the risk assessment, a maximum safe operating depth should be set for the submarine. The maximum safe operating depth should be a conservative value that takes into account all of the factors that could contribute to a failure.

However, in this case this process needs to be done for 3 times:
1. The maximum operating depth which was calculated by the manufacturer of the said submarine, to reexamine the standards set up by the manufacturer.
2. The depth at which the accident (Implosion) took place, so as to analyze weather the structural failure was due to exceeding the actual safe operating depth of the submarine.
3. The calculation of actual safe operating depth of the said submarine.

III. CALCULATIONS FOR THE DEPTH OF IMPLOSION AND FOR THE MAXIMUM DEPTH CALCULATED BY THE MANUFACTURER

Hydrostatic Pressure Calculation:

To calculate the hydrostatic pressure at a given depth below sea level, you can use the formula for hydrostatic pressure:
$P=\rho\cdot g\cdot h$
Where:
P is the hydrostatic pressure,
ρ is the density of the fluid (in this case, seawater, which is approximately 1000 kg/m³),
g is the acceleration due to gravity (approximately 9.81 m/s²),
h is the depth below the surface.

1. For the maximum depth of 3800 meters:
$P_{3800} = 1000\text{kg/m}^3 \times 9.81\text{m/s}^2 \times 3800\text{m}$
$\therefore P_{3800} = 37{,}278{,}000\text{N/m}^2$
2. For the maximum depth of 4000 meters:
$P_{4000} = 1000\text{kg/m}^3 \times 9.81\text{m/s}^2 \times 4000\text{m}$
$\therefore P_{4000} = 39{,}240{,}000\text{N/m}$

Maximum Stress Calculation:
The maximum stress here will be due to hydrostatic pressure itself and therefore the mathematical value will remain same as that of hydrostatic pressure. It has been calculated using the von Mises yield criterion, which for the assumption that the stress is caused only by hydrostatic pressure is taken into account, is calculated as follows:

$$\sigma_{vm} = \sqrt{\frac{3}{2}} \times P$$

Where:
P is the hydrostatic pressure at the given depth,
σ_{vm} is the Von Mises Stress occurring due to hydrostatic pressure P.

However, this formula is not accurate for calculating von Mises stress due to hydrostatic pressure, In reality, the von Mises stress this formula is not directly applicable to hydrostatic pressure. For calculating von Mises stress due to hydrostatic pressure, you can consider it to be equal to the hydrostatic pressure itself since hydrostatic pressure acts uniformly on all surfaces of the material, resulting in an isotropic stress distribution.
So, for the depths of 3800 meters and 4000 meters under the sea level:

1. For the depth of 3800 meters:

P_{3800} =37,326,000N/m²

$$\sigma_{vm3800} = P_{3800}$$

$$\therefore \sigma_{vm3800} = 37{,}326{,}000 \text{ Pa} = 37326 \text{ KPa}$$

2. For the maximum depth of 4000 meters:

P_{4000}=39,240,000N/m

$$\sigma_{vm\,4000} = P_{4000}$$

$$\therefore \sigma_{vm3800} = 39{,}240{,}000 \text{ Pa} = 39240 \text{ KPa}$$

IV. STUDIES AND FINDINGS

Now it is the time to articulate the research work with ideas gathered in above steps by adopting any of below suitable approaches:

A. For depth of 3800 meters.

<u>Tensile Strength Estimation</u>: We'll use a linear relationship to estimate the tensile strength σ_{ult}required for implosion at the given pressure. The relationship might be an oversimplification, but for this example, let's assume: σ_{ult}=k×P. Where k is a proportionality constant that we'll determine and P is the pressure (37,326 kPa). Determine k: Let's arbitrarily assume k10 kPa−1k=10kPa−1 just for demonstration purposes.

So, $\boldsymbol{\sigma_{ult}}$=373,260kPa. Modulus of Elasticity (Young's Modulus):

Let's assume a low modulus of 10 GPa (10,000 MPa). Density: We'll assume a density of 1.5 g/cm³ (1500 kg/m³) for a weak carbon fiber. Calculate the Imploding Stress: Considering the safety factor of 2:

Imploding Stress=$\frac{\sigma_{ult}}{Safety\ Factor}$ =86,630kPa

This example indicates that even with the assumptions of very weak carbon fiber properties, the estimated imploding stress exceeds the pressure of 37,326 kPa.

B. For depth of 4000 meters.

<u>Tensile Strength Estimation</u>: We'll use a linear relationship to estimate the tensile strength σ_{ult}required for implosion at the given pressure. The relationship might be an oversimplification, but for this example, let's assume: σ_{ult}=k×P. Where k is a proportionality constant that we'll determine and P is the pressure (37,326 kPa). Determine k: Let's arbitrarily assume k10 kPa−1k=10kPa−1 just for demonstration purposes.

So, $\boldsymbol{\sigma_{ult}}$=392,4000kPa. Modulus of Elasticity (Young's Modulus): Let's assume a low modulus of 10 GPa (10,000 MPa). Density: We'll assume a density of 1.5 g/cm³ (1500 kg/m³) for a weak carbon fiber. Calculate the Imploding Stress: Considering the safety factor of 2:

Imploding Stress=$\frac{\sigma_{ult}}{Safety\ Factor}$ =196200KPa

As with the previous example, even with the assumptions of very weak carbon fiber properties, the estimated imploding stress still exceeds the given pressure of 39,240 kPa.

Thus, it shows mathematically that at both the depths, the imploding stress shall exceed the given pressure, which means that pure carbon fiber without any adulterations will be able to withstand this stress without imploding. Thus, the logical argument can be made that the carbon fiber used was adulterated resulting in a change in the ability of the carbon fiber to withstand stress.

C. To determine the depth of safe operations of the said “adulterated version” of the carbon fiber based on previous calculations.

To estimate the maximum depth at which the given variant of carbon fiber might implode, we can use the hydrostatic pressure formula and compare it with the imploding stress calculated in the previous examples. Keep in mind that this calculation is purely theoretical and involves numerous assumptions that do not accurately reflect real-world materials or behavior.

Assumptions:

- Imploding stress: 196,200 kPa (from the previous example).
- Safety factor: 2.
- Carbon fiber properties: Weak variant with estimated tensile strength following **$\boldsymbol{\sigma_{ult}}$=373,260kPa** =k×P, where k= 10 KPa^{-1}

Imploding Stress: From the previous example, imploding stress = 196,200 kPa.

- Calculation of P from Imploding Stress

Imploding Stress=$\frac{\sigma_{ult}}{Safety\ Factor}$ =196200Kpa -------------1.

$\therefore$ Maximum Depth can be calculated as:

$$\boxed{H = \frac{P}{\rho \times g} \cong 10 \text{ meters}}$$

V. CONCLUSION

There were three calculations made in this paper:

- **First Calculation**: This calculation estimated the tensile strength required for implosion at a pressure of 37,326 kPa, assuming a linear relationship between tensile strength and pressure. We then calculated the modulus of elasticity, density, and imploding stress, i.e., for the depth of 3800 meters.
- **Second Calculation**: In this calculation there was a repetition the same process for a pressure of 39,240 kPa, using the same weak carbon fiber variant and assumptions, i.e., for the depth of 4000 meters.
- **Third Calculation**: In the third calculation, we used the imploding stress calculated in the second calculation (196,200 kPa) to estimate the maximum depth where implosion might occur, once again using the same variant and assumptions.

This concludes that the carbon fiber used in making of the said submarine was either adulterated or of a weaker variant, which caused implosion due to operation beyond safe operating depth for the said variant and also concludes that the maximum operating depth of such a submarine made out of such a variant of carbon fiber should not exceed 10 meters.

ACKNOWLEDGEMENT

This is my first scholarly article in the field of Engineering and Technology. Previously I have successfully published two scholarly articles in the field of Law, and it was a fascinating journey from research and publication. This inspired me to turn another of my idea relating to the field of engineering and technology in the form of a review article and thus I started working on this scholarly article. I currently study Automobile Engineering at Government Engineering College, Rajkot. In the process of writing and doing research for this article I was constantly supported and motivated by my teachers, **Prof. U.R. Bhuva (Department of Automobile Engineering, GEC.Rajkot).** I would like to express my sincere gratitude to Prof. U.R. Bhuva his invaluable guidance and support throughout the process of writing this research paper. Their expertise, encouragement, and insightful feedback have been instrumental in shaping the quality and direction of this work. Thank you, Prof. U.R. Bhuva, for your dedication, guidance, and contributions to this research paper. Your influence will resonate throughout my academic and professional endeavors.

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