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Enhancing Safety and Reliability of Marine Airbags for Ship Launching:

Failure Analysis and Mitigation Strategies

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Abstract

Marine airbags are widely used in ship launching operations, but they are prone to various failure modes that can compromise their safety and reliability. This research paper provides a comprehensive analysis of the failure modes of marine airbags used in such and proposes practical mitigation strategies to enhance their safety and reliability. The paper examines the effects of applied force, internal pressure, material properties, and environmental factors on the stress distribution and deformation of marine airbags. The paper also presents numerical methods to evaluate the performance and failure mechanisms of marine airbags under different loading conditions. Based on the results, the paper suggests some recommendations for improving the design, fabrication, installation, operation, and maintenance of marine airbags for ship launching. This study contributes to the ongoing research to ensure the safe and reliable use of marine airbags in ship launching operations.

Keywords—Ship Launching; Marine Airbag; Pressure; Stress; Force; Failure Mode

I. INTRODUCTION

Ship launching, the pivotal transition of vessels from land to water, embodies the essence of maritime innovation. Amidst the array of methods available, airbag deployment stands as a prominent and efficacious technique. Marine Airbag launching method in Fig. 1 shows the use of a series of large inflatable bags to support the weight of the ship. Marine airbags, often referred to as ship launching airbags, inflatable marine airbags, or even roller bags, encapsulate this transformative technology. Marine airbags are made of synthetic-tire-cord layers and rubber layers that can withstand high pressure and provide support to the hull of the ship [1]. The size, model, and bearing capacity of marine airbags depend on the dimensions and weight of the ship to be launched [2].

Safety remains paramount in this aspect of ship launching for reliability and efficiency, Airbag quality assurance is the basis for safe launching of ships. The impact of bad marine airbags goes beyond mere inefficiency. These jeopardize the entire ship launching operation, risking the integrity of the ship and the safety and lives of the operating employees [4]. Marine airbags are designed for specific load capacities, requiring a delicate balance over risking failure [4]. Precise calculations and selection of airbags based on the ship's weight and dimensions are essential to ensure safe and successful launching. External factors such as wind, waves, and tides can affect the stability and control of the ship during launching with airbags. These factors must be properly evaluated and mitigated to ensure smooth and safe operations.

During ship launching using marine airbags, several potential failure modes can occur, leading to accidents and risks to personnel and the ship. The potential failure modes include airbag bursting, inadequate load-bearing capacity, loss of buoyancy, insufficient water level, and launch ramp and holding system failure. Liang *et al*; conducted an exhaustive exploration of marine airbag failure modes during ship launching and concluded that insufficient load-bearing capacity can precipitate airbag bursting or deflation, leading to accidents and endangering operational safety [5].

One of the major factors that lead to potential failure mode is loss of buoyancy which occurs when the airbag is not properly inflated or when it loses air pressure during ship launching. Sunarso *et al;* analysed the economic and technical aspects of launching a ship using the slipway and airbag method [3], with an emphasis on determining the appropriate water level prior to the launching operation, which is important to successful deployment and effective operation of marine airbags during launching. Insufficient water level during ship launching is termed as another major key factor that can cause the marine airbag to be overloaded up to five times the normal or designed pressure, leading to airbag explosion. Liang *et al;* examined the failure modes of marine airbags and pointed out the importance of a robust launch ramp and holding system to ensure the safe and successful launching of ships [5]. Preventing potential failure, proper design, manufacturing, and quality control processes, regular maintenance, inspection, and testing procedures, proper delivery of airbags, and adherence to existing safety measures and regulations are crucial.

Another major cause of marine airbag failures is related to material properties, structural design, operational conditions, and environmental factors [3]. Failures in material properties, such as inadequate tensile strength or poor tear resistance, can lead to airbag rupture or damage [6]. Structural design flaws, like weak seams or insufficient reinforcement, may result in airbag failure during inflation or deflation processes. Operational conditions, such as improper handling or overloading of the airbags, can cause them to burst or deflate prematurely. Environmental factors like exposure to extreme temperatures, humidity levels, or chemical substances can also contribute to airbag failures [2].

Ren *et al;* research highlights the importance of selecting materials with appropriate tensile strength, tear resistance, and durability for marine airbag's safety and reliability [1]. The authors also suggest that improved manufacturing techniques, including proper bonding methods, stringent quality control measures, and minimizing manufacturing defects, can enhance the structural integrity of airbags.

Fig. 1. Marine Airbag ship launching

II. FAILURE CRITERIA ANALYSIS

The failure criteria used in determining the pressure analysis of marine airbags play a crucial role in ensuring the safety and structural integrity of the airbags during ship launching or other applications. These failure criteria help identify potential failure modes and predict the conditions under which the airbags may fail [7].

Fibre reinforced composites have several failure criteria for forecasting lamina failure, these criteria can be classified into two types: those not related to failure modes and those associated with failure modes. Marine airbag material failure criteria in ship launching have been extensively studied [8][9], with Tsai-Wu, Tsai-Hill, maximum stress, and maximum strain being suitable for burst failure finite element analysis.

By subjecting marine airbags made of synthetic fibre-reinforced rubber to rigorous simulations and real-world testing, which can be used to ascertain the critical stress and strain thresholds. The results obtained indicate the material's limits under different operational conditions, reflecting the point at which structural integrity is compromised. To predict the reliability and undertake mitigation studies in ship launching, the application of failure analysis and criteria becomes imperative, several criteria can be applied based on different theories and methods.

One common failure criterion is the maximum principal stress theory. This theory states that failure occurs when the maximum principal stress in the material exceeds the material's ultimate tensile strength.

The maximum principal stress can be calculated using the following equation (1).

$$\sigma_1 = \frac{\sigma_x + \sigma_y + \sigma_z}{3} - \frac{\left(\sigma_x - \sigma_y\right)^2}{2 \times \sigma_y} \tag{1}$$

where:

σ_1 is the maximum principal stress
σ_x is the stress in the x-direction
σ_y is the stress in the y-direction
σ_z is the stress in the z-direction

The ultimate tensile strength of the fibre-reinforced rubber material can be determined from a tensile test. In a tensile test, a specimen of the material is subjected to a tensile load until it breaks. The ultimate tensile strength is the maximum stress that the material can withstand before it breaks.

If the maximum principal stress in the airbag exceeds the ultimate tensile strength of the material, then the airbag is considered to have failed.

In addition to the maximum principal stress theory and the maximum shear stress theory, a variety of other failure criteria can be used to assess the potential for failure of marine airbags.

The Mooney-Rivlin criterion is a material model commonly used to describe the stress-strain behaviour of synthetic rubber materials, including those used in marine airbags [11]. It provides a mathematical representation of the material's response to deformation and is particularly useful for finite element analysis and other numerical simulations. The Mooney-Rivlin model is an extension of the simpler Neo-Hookean model, allowing for more accurate representation of nonlinear material behaviour. The Mooney-Rivlin model is expressed in equation (2).

$$W = C_1\left(I_1 - 3\right) + C_2\left(I_2 - 3\right) \tag{2}$$

For in-compressible materials like rubber, the second invariant (I_2) is zero, simplifying the equation to (3).

$$W = C_1\left(I_1 - 3\right) \tag{3}$$

The first invariant (I_1) is related to the principal stretches (λ_1, λ_2, λ_3) of the material as shown in equation (4).

$$I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2 \tag{4}$$

The material constants C_1 and C_2 are determined through experimental testing, such as uniaxial tension or compression tests, where the stress-strain behaviour of the material is measured under different loading conditions.

III. MATERIAL PRPOERTIES AND METHOD

The airbags have nonlinear, viscoelastic, heterogeneous and anisotropic properties. Generally, the cord layer consists of axial and radial cords, which can be regarded as linear elastic materials. Their mechanical properties are determined by the mechanical and geometric characteristics of each layer of cords. The rubber material has a much larger bulk modulus than its elastic modulus, so it is an isotropic incompressible hyper elastic material. During the deformation process, the stress is a nonlinear function of the instantaneous strain. In this paper, to simplify the rubber material model, it is assumed that the rubber material is isotropic, incompressible and hyper elastic, and only considers the nonlinearity of rubber, not its viscoelasticity. Its mechanical properties can be described by the Mooney-Rivlin model strain energy density function.

According to [10], airbag fabrics exhibit deformational shear behaviour under quasi-static loading, and their stress-strain behaviour is affected by the material properties of the fabric. [6] also notes that a constitutive model for an airbag membrane with reinforcement was established through uniaxial tensile tests and numerical simulations. These findings suggest that the deformation and stress behaviour of marine airbags can be influenced by their material properties, including the membrane and reinforcement.[6] provides a mathematical model of deformation, bearing force, and inner air pressure of a loaded airbag, which can be used to assess the ultimate bearing capacity of marine airbags. The membrane material property was determined by the model, indicating the importance of material properties in determining the behaviour of marine airbags under pressure.

A. Ship Main Parameters

Defining ship parameters is a pivotal step in the accurate design and implementation of the airbag system. These parameters offer essential insights into the vessel's dimensions, weight, and characteristics, directly impacting the selection and configuration of marine airbags. Precise knowledge of these parameters facilitates the calculation of load distribution, supports suitable airbag selection, and optimizes the ship launching process for success. The Ro-Ro ferry's specifications used is outlined in Table 1.

TABLE 1 SHIP PARAMETERS

Vessel type	**Ro-Ro Ferry**	
Hull type	Ro-Ro	
Parameter of Ship	**Dimensions**	**Units**
Length (L deck)	52.0	m
Length (L pp)	42.50	m
Breadth (B deck)	12.50	m
Depth main deck	3.00	m
Draft max	1.228	m
Block coefficient	0.55	
displacement	440	tons

B. Marine Airbag Calculations

Number of Airbags required

Amount of need for airbags must be calculated using the formula in equation (5).

$$N = K_1 Q \times \frac{G}{C_B} \times R \times L_D + N_1 \tag{5}$$

where;
N is the quantity of airbags used for ship launching;
K_1 is a coefficient, in general, $K_1 \geq 1.2$
Q is the weight of the ship (ton), = 375 tons;
g is acceleration of gravity (m/s^2), g = 9.8;
C_b is block coefficient of ship = 0.55;
R is the allowable unit bearing capacity = 62.88 (kN/m);
L_d is the contact (m), = 10 m;
N_1 is Number of airbags replaced continuously, = 2;

$$N = \frac{1.2 \times 375 \times 9.8}{0.55 \times 62.88 \times 10} + 2 = 14 \text{ Airbags}$$

For the distance between airbags must not exceed 6 m. which can be calculated and checked using equations (6) and (7).

$$\frac{L}{N} - 1 \leq 6 \tag{6}$$

which was estimated to be = 3.2 m

Equation (7) is to analyze the marine airbag vulnerability to rupture, or failure.

$$P = \frac{F}{A} \tag{7}$$

where;

P is the load received;
F is the force exerted;
A is the contact area;

In order to calculate the airbag load distribution during the launching operation, the average load of airbag acting on the ramp per unit length (q), was estimated from equation (8).

$$q = \frac{p}{s} \tag{8}$$

Front loading, (qd), was calculated from equation (9).

$$qd = 2q\frac{(3x - s)}{s} \tag{9}$$

While rear loading (qb), was estimated using equation (10).

$$qb = 2q\frac{(2s - 3x)}{s} \tag{10}$$

C. Finite Element Analysis

The generation of CAD models for simulation purposes was executed using the geometry workbench of ANSYS Mechanical version 2023 R1. The three-dimensional representation of the airbag was then meticulously constructed through the extrusion of this base sketch. The resulting model captured the essence of a cylindrical airbag, with dimensions mirroring real-world specifications.

The model consists of a cylindrical body, spanning a length of 10 meters and boasting a diameter of 1 meter. Notably, the conical ends of the airbag adhere to standardized dimensions, each measuring 0.866 meters in diameter as shown in Fig. 2.

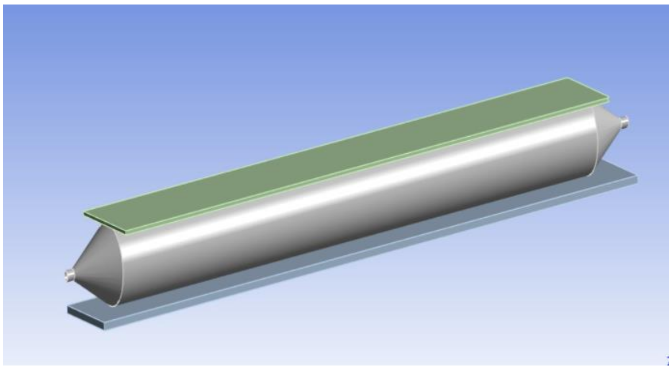

Fig. 2. Airbag Geometry

D. *Meshing*

The mesh generation method for marine airbag geometry in ANSYS static structural is based on the following steps. First, the geometry of the airbag is imported from a CAD file and assigned a material property. Second, the geometry is divided into several parts according to the inflation pressure and the contact regions. Third, the mesh size and type are specified for each part, and the mesh is generated using the sweep method. Fourth, the mesh quality is checked and improved by adjusting the mesh parameters or refining the mesh locally. Fig. 3 shows the final mesh which has 58070 nodes and 29235 elements, and it conforms to the geometry and boundary conditions of the airbag.

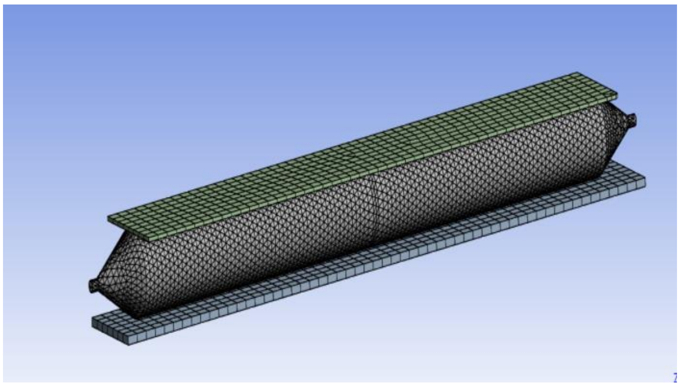

Fig. 3. Airbag Mesh

E. *Boundary Conditions*

The simulations conducted within this study encompassed a comprehensive array of parameters critically required to understanding the pressure effects on the airbags during ship launching. These parameters comprised pressure, force, stress, deformation, strain, and safety factor.

Assumptions were meticulously formulated to mirror the real-life conditions observed during ship launching operations.

a. The physics model replicates real-life conditions of the ship launching operation.
b. The ship is assumed to be in direct contact with the airbag on the launching ramp.
c. The airbag is inflated to specified pressure values for the simulations.
d. Maximum stress and strain criteria were used for safety limit analysis.
e. The applied load is based on the weight of the vessel being launched.

Loading conditions for the simulation are established based on the vessel's weight and relevant parameters. This involves factoring in the ship's weight distribution, positioning of airbags, and their interaction with the ship hull during the launching procedure. Throughout the simulation, a meticulous analysis of pressure distribution within the airbags takes place. This analysis provides valuable insights into how pressure is distributed along the airbag’s length and circumference. These pressure patterns play a crucial role in influencing airbag deformation and interaction with the ship hull.

F. *Pressure and Force load Magnitudes*

The study also selects force loads, which play a crucial role in determining the interaction between marine airbags and the ship hull during launching. Force loads of 30 kN represents the average load (q) of the airbag acting on the ramp, 143 kN,is the bearing load capacity (qbc) and 195 kN is the load at the rear of the ship (qb) which is the largest load magnitude acting on the airbag, the force loads represent a range of realistic scenarios, encompassing both standard and non-standard launching conditions. These force loads evaluate how varying pressures interact with different ship sizes and weights, providing a comprehensive understanding of the airbag system's performance.

The pressure values of 0.11 MPa which represents the working pressure and 0.33 MPa is that of the burst pressure limits were selected. These values correspond to the lower and upper bounds of ISO-standard [12] pressures for airbags used in ship launching scenarios. By encompassing this range, the airbag system's performance across typical operational pressures, allowing for a comprehensive evaluation of its behaviour.

IV. RESULTS AND DISCUSSIONS

The study analyzes pressure on marine airbags during ship launching operations to determine the structural integrity and safety. Deformation and stress areas were examined to ensuring even pressure distribution. The analysis also helps calculate safety factors by comparing maximum pressure to rated limits. The study also evaluates the airbag material's performance, assessing its ability to withstand pressure without excessive deformation or stress.

A. Total Deformation

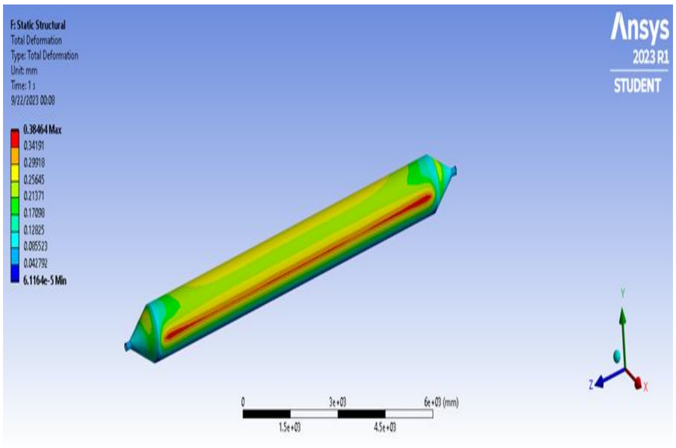

Fig. 4. Deformation at 0.11 MPa

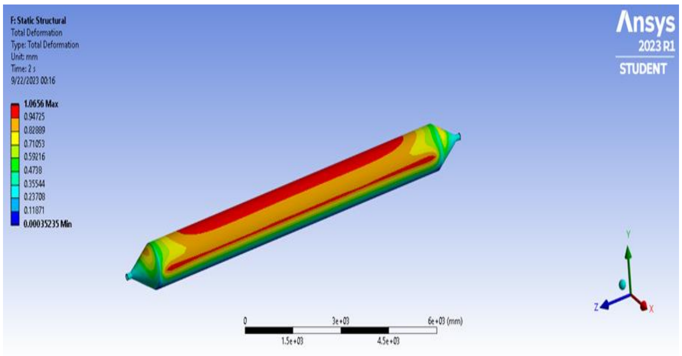

Fig. 5. Deformation 0.33 MPa

Condition 1: Load = 143 kN, Pressure = 0.11 MPa, Deformation = 0.38464 mm

Condition 2: Load = 143 kN, Pressure = 0.33 MPa, Deformation = 1.0656 mm

In Condition 2, the working pressure is higher at 0.33 MPa compared to 0.11 MPa in Condition 1. The increase in pressure by almost three times can significantly impact the behavior and response of the airbag.

The applied load is the same in both conditions, with a force of 145 kN acting on the airbag. Therefore, the load remains constant for the comparison.

In Condition 2 as the working pressure is higher at 0.33 MPa compared to 0.11 MPa in Condition 1. The increase in pressure by almost four times can significantly impact the behavior and response of the airbag.

The deformation of the airbag is significantly different between the two conditions of the on simulation of the airbag. The airbag experiences a total deformation of 0.38464 mm as shown in Fig. 4 which indicates the highest points of deformation under a pressure load of 0.11MPa, while in Condition 2, the deformation increases to 1.0656 mm as shown in Fig. 5

Comparing the deformation values, we observe that the higher working pressure in Condition 2 leads to a more pronounced deformation of the airbag. The increase in pressure results in a greater displacement or strain within the airbag structure, as evident from the larger deformation value in Condition 2.

In Fig. 6 the Pressure to deformation Chart suggests that higher pressures can induce larger deformations in the marine airbag, indicating a higher level of strain and potential structural changes which can lead to potential rupture or failure.

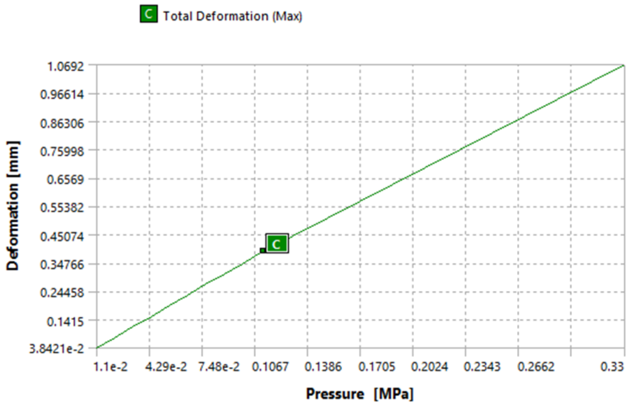

Fig. 6. Pressure vs Deformation Chart

B. Equivalent Stress

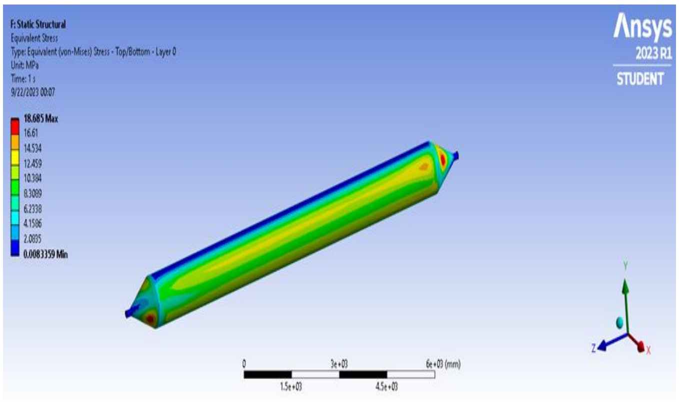

Fig. 7 stress at 0.11MPa

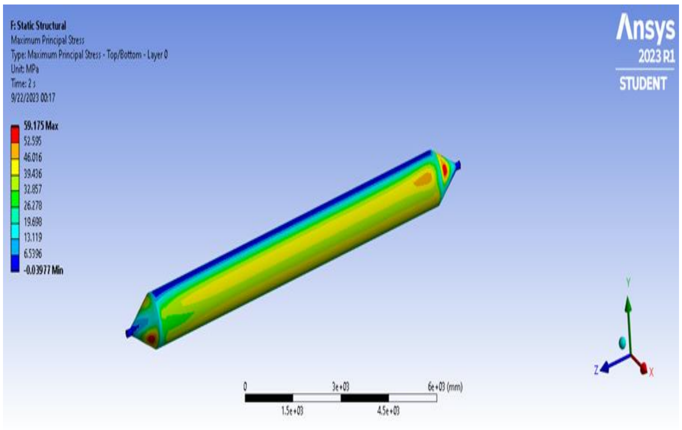

Fig. 8 stress at 0.33 MPa

Condition 1: Load = 143 kN, Pressure = 0.11 MPa, Equivalent (Von-Mises) Stress = 18.685 MPa.

Condition 2: Load = 143 kN, Pressure = 0.33 MPa, Equivalent (Von-Mises) Stress = 56.628 MPa

The equivalent stress experienced by the airbag is substantially different between the two conditions. In Fig. 7, the stress is 18.685 MPa, while in Fig. 8, it increases to 56.628 MPa. The contour plots in the Fig.s show the stress concentration areas where the airbags will potentially fail.

Comparing the equivalent stress values, there is a significant increase in the stress level when the working pressure is increased from 0.11 MPa to 0.33 MPa while maintaining the same applied load. The higher pressure in Condition 2 leads to a higher stress concentration within the airbag structure.

The pressure to Stress chart in Fig. 9 suggests that the airbag experiences a more substantial level of stress, potentially approaching its material's yield strength or failure criteria, when subjected to the higher pressure in Condition 2. The increased equivalent stress value implies a higher potential for plastic deformation, yielding, or even structural failure of the airbag under these conditions.

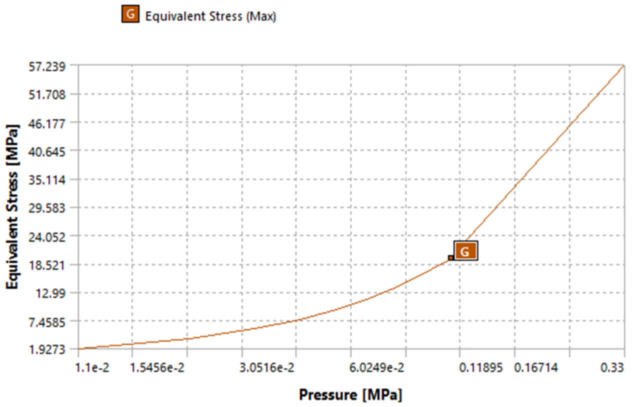

Fig. 9. Pressure vs Stress Chart

C. *Equivalent Strain*

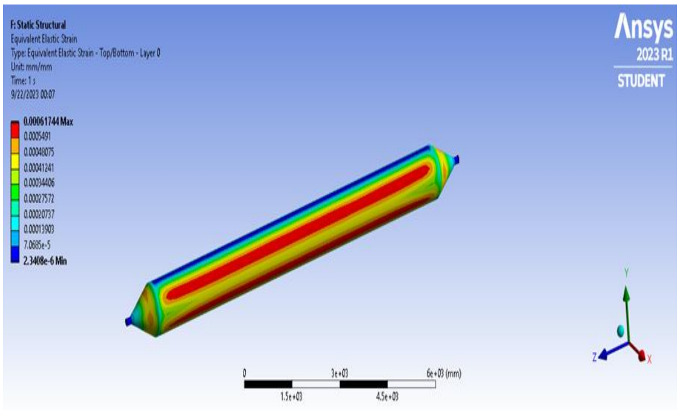

Fig. 10. Strain at 0.11MPa

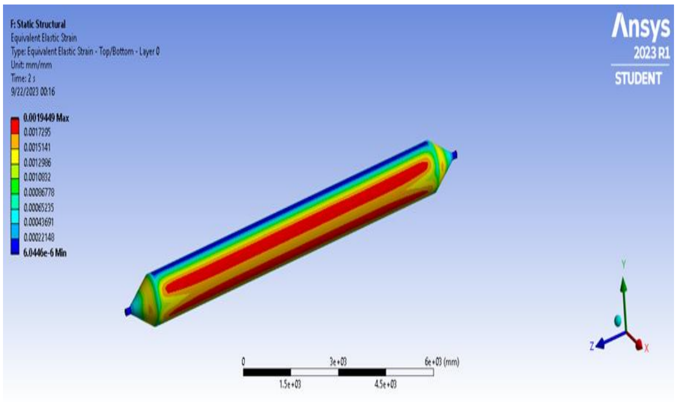

Fig. 11. Strain at 0.33MPa

Condition 1: Load = 143 kN, Pressure = 0.11 MPa, Equivalent total strain = 0.0006174 mm/mm

Condition 2: Load = 143 kN, Pressure = 0.33 MPa, Equivalent total strain = 0.001944 mm/mm

In Fig. 10, with a working pressure of 0.11 MPa, the airbag experiences an equivalent total strain of 0.0006174 mm/mm. The strain is relatively small, indicating a minor deformation of the airbag under the applied load. This suggests that the airbag is able to withstand the load with minimal strain and remains within its elastic limit.

In Fig. 11, with a higher working pressure of 0.33 MPa, the airbag experiences an equivalent total strain of 0.001944 mm/mm. The strain is larger compared to Condition 1, indicating a more significant deformation of the airbag under the same load. This suggests that the higher pressure leads to a greater strain in the airbag material, potentially pushing it closer to or beyond its elastic limit.

The pressure to strain chart in Fig. 13 shows a notable increase in the equivalent total strain in Condition 2 compared to Condition 1. This suggests that higher working pressures can lead to greater deformation of the airbag material, potentially compromising its structural integrity or longevity.

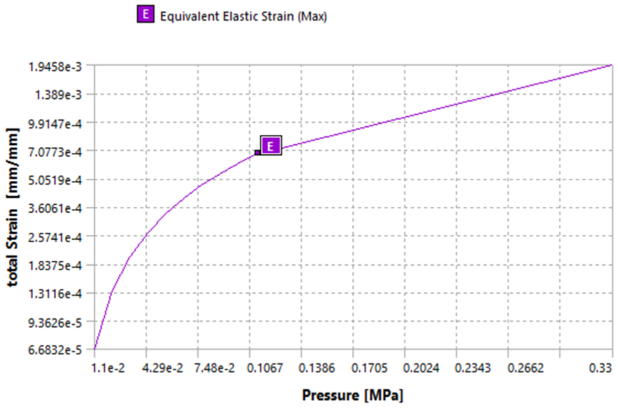

Fig. 13. Pressure vs Strain Chart

D. *Safety Factor*

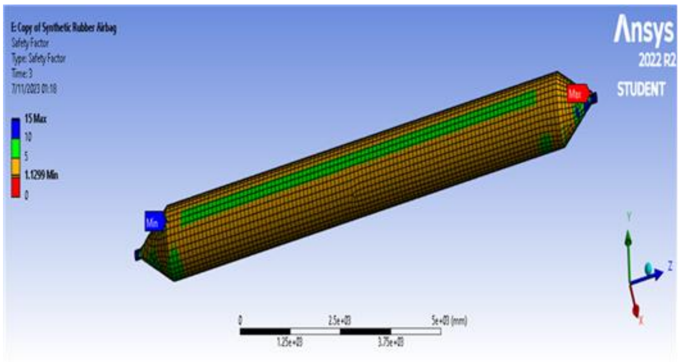

Fig. 14. Safety Factor at 0.11

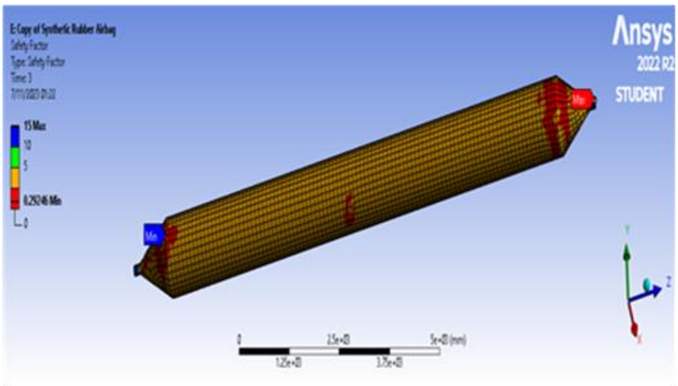

Fig. 15. Safety Factor at 0.33

The safety factor is a measure of how close a structure or component is to its failure point. A safety factor of 8.1166 in Fig. 14 suggests that the applied load of pressure 0.1MPa is within the safe zone limit capacity of the airbag.

In this case, the weight of the vessel is applied to the airbag with an internal pressure of 0.33 MPa. The safety factor of 0.29246 in Fig. 15 indicates that the airbag is experiencing a load that is higher than its capacity, which is a critical situation. This suggests that the airbag is likely to rupture or fail under this excessive pressure load.

When an airbag ruptures, it means that it cannot withstand the applied load and loses its ability to support the weight or pressure effectively. This can result in a sudden loss of support, potential damage to the vessel or surrounding structures, and pose safety risks.

Based on the safety factor analysis result, it is recommended to reconsider the factors and configuration of the airbag system, either by increasing the number of airbags, enhancing the material properties, or adjusting the load distribution to ensure a higher safety margin and avoid the risk of rupture. It is crucial to ensure that the airbag system can adequately withstand the applied loads and provide the necessary support and safety during ship launching operations.

V. CONCLUSIONS

This research paper analyses the failure modes of marine airbags used in ship launching and proposes mitigation strategies to improve their safety and reliability. It highlights the correlation between applied force and stress experienced by the airbag system, emphasizing the need for precise force control. The study also confirms that heightened internal pressure increases stress on airbag materials, emphasizing the importance of monitoring and controlling internal pressure. Excessive deformation, especially under high-pressure conditions, is identified as a potential risk factor, emphasizing the need for a delicate balance between operational loads and structural resilience.

Further research and development in this area are encouraged to continually improve the safety and reliability of marine airbags for ship launching applications.

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