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Optimizing sandwich foam floats for amphibious aircraft: enhancing performance under water impact

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Improving amphibian aircraft landing performance is the primary goal of this paper, which aims to optimize the design of sandwich aluminum foam (SAF) energy absorbers. To determine how various configurations of the sandwich structure's layers affected landing performance, extensive transient dynamic simulations were used. Using simulation methodologies, the impact performance of the SAF's design parameters was rigorously investigated. The first step of the study was to characterize the SAF as a material for use in impact applications. The three SAF samples were subjected to testing in a water impact environment with a 3.5-ton airplane weight and a landing speed of 76 knots. The core thicknesses of the samples were 3 mm, 5 mm, and 7 mm, respectively. The numerical simulation findings showed that crash behavior indicators like peak crushing force (PCF) and total energy absorption (TEA) are greatly affected by core thickness and material density. Finite element model compares with experiment test, it is found that the differences less than 5%. These meshes are simulated to obtain convergent points of the simulated model mesh size with the error value is 3.08%. Surrogate models based on the Radial Basis Function (RBF) and the Non-dominated Sorting Genetic Algorithm II (NSGA-II) were used in a multi-objective optimization strategy to improve the float's crashworthiness. According to the optimization findings, the SAF float was far more crashproof than the previous float design. These optimal results differ from those derived solely from crushing analyses in prior studies, providing a more robust reference for practical engineering applications.

KEYWORDS

float, optimization, crashworthiness, sandwich aluminium foam, amphibian aircraft

1 Introduction

In recent years, the demand for amphibious aircraft has increased due to their ability to operate on both land and water, making them ideal for remote or coastal regions with limited airport infrastructure. One of the most critical components in these aircraft is the float or pontoon, which ensures buoyancy and absorbs the impact energy during water landings. The floats are equipped with water rudders for navigation and must contain at least four watertight compartments to prevent sinking in case of structural failure. During landing, the float is the first component that comes into contact with the water, and any hydrodynamic interaction leads to significant structural deformation (Carcattera et al., 1999; Yu et al., 2022; Wang and Soares, 2017). The structural integrity of these floats is

determined by their ability to withstand peak hydrodynamic forces, critical stress distributions, and maximum displacement. To study these phenomena, researchers have employed both experimental testing and numerical modeling. While experimental testing offers high accuracy, it is cost-intensive and requires specialized facilities (Hassoon et al., 2017; Judge et al., 2004; Stenius et al., 2013). In contrast, numerical modelling especially with finite element methods, offers a cost-effective alternative, though it demands considerable computational resources (Lu et al., 2000; Engle and Lewis, 2003; dong Xu et al., 2009). For high-fidelity simulations, fluid-structure interaction is often necessary but also computationally expensive. To address this, multi-scale modeling approaches such as complete shell, complete solid, multi-stage, and concurrent multi-scale modeling are employed (Shankar et al., 2020; Curreli et al., 2018; Said et al., 2018; Arai et al., 2015; Narvydas et al., 2021).

Multi-scale modeling increases computational efficiency while preserving accuracy. In multi-stage models, small zones of interest are refined using submodels, while concurrent models dynamically couple macro and micro-scale simulations to capture detailed structural behavior (Sun et al., 2019; He et al., 2020; He et al., 2021; Ali and Shimoda, 2022). For example, in modeling aircraft floats, shell elements can represent the skin, and solid elements can represent internal structures. ABAQUS software is widely used to simulate these configurations, providing tools for mesh refinement, contact interactions, and dynamic explicit analysis (Niknafs et al., 2022). The hydrodynamic impact problem is not limited to amphibious aircraft but also it appears in other sectors such as naval, offshore, and defense engineering (Abraham et al., 2014; Sun et al., 2021; Chen et al., 2023). High-speed water impact can cause severe structural damage, and accurate prediction of these forces is crucial for safety. Numerical methods such as Finite Element Method (FEM) and Smoothed Particle Hydrodynamics (SPH) are often combined for more robust simulations (Fernández et al., 2023; Zhang et al., 2020; Panciroli et al., 2012). Validating these models with experimental data ensures accuracy and enhances prediction capabilities (Engle and Lewis, 2003; Francesconi, 2009; Feng et al., 2021; Yan et al., 2018; Liu et al., 2023; Lu et al., 2000; Xia et al., 2023; Chaudhry et al., 2020; Li et al., 2021; Wu and Earls, 2022).

Given their lightweight and high-strength properties, composite materials especially those with sandwich configurations, are widely used in aerospace applications (Tao et al., 2019; Hernandez et al., 2017; Li et al., 2020). Sandwich panels consist of two stiff face sheets and a lightweight core, typically made from foam, honeycomb, or wood (Banhart and Seeliger, 2012; Banhart and Seeliger, 2008; Harte et al., 2000; Schwingel et al., 2007). Sandwich Aluminum Foam (SAF) structures offer high energy absorption and improved durability, especially when manufactured using integral-forming methods (Xia et al., 2013; Wang et al., 2015; Crupi and Montanini, 2007; Zhang et al., 2022; Xu et al., 2022; Liu et al.,

2022; Yang et al., 2020). Recent studies have focused on optimizing these structures to enhance crashworthiness including marine structures (Catapano and Montemurro, 2014; Brückmann et al., 2017; Klanac et al., 2009; Dayyani et al., 2013) for weight reduction and structural efficiency.

Despite these advances, limited work has been done to optimize sandwich aluminum foam (SAF) structures for amphibious aircraft floats under water impact conditions. Most previous studies have focused on axial or blast impact on dry land (Patel and Patel, 2024; Patel et al., 2023; Sawant and Patel, 2024; Ma et al., 2023; Kumar et al., 2021; Nagarjun et al., 2020; Kumar et al., 2019), lacking a specific investigation into Fluid-Structure Interaction (FSI) during water landings. Additionally, studies on hierarchical and auxetic structures (Fu et al., 2025; Xu et al., 2025; Fu et al., 2024; Guang et al., 2025) show potential for improved energy absorption but have not been fully explored in amphibious applications.

This study aims to fill that gap by investigating the crashworthiness of SAF floats under hydrodynamic impact using ABAQUS simulations. Multi-objective optimization is performed using Non-dominated Sorting Genetic Algorithm II (NSGA-II) and Radial Basis Function (RBF) surrogate modeling to analyze the effects of core thickness and material density on crash parameters such as peak crushing force (PCF) and Specific Energy Absorption (SEA). The goal is to identify the most effective SAF configuration that balances structural integrity, energy absorption, and weight efficiency for real-world amphibious applications.

2 Methods and materials

2.1 Crashworthiness indicator of float impact water

Crashworthiness indicators are critical parameters used to evaluate the ability of a structure to protect its occupants and minimize damage during a crash or impact event. Below are some of the key crashworthiness indicators:

a. Energy Absorption:

- Total Energy Absorption (TEA): The amount of energy a structure can absorb during a crash or impact. A higher value indicates better performance in terms of protecting the occupants by reducing the impact force.

$$TEA = \int_0^{\delta} F(\delta) d\delta \quad (1)$$

- Energy Absorption Efficiency: The amount of energy that a material or structure is able to absorb, as a percentage of the total energy that an impact causes.

b. Peak Crushing Force (PCF):

- The greatest amount of force that a building or its inhabitants may endure in the event of an accident. A lower peak force is preferable as it signifies reduced acceleration and injury risk to the occupants.

c. Crush Force Efficiency (CFE):

Abbreviations: CFE, Crush Force Efficiency; DOE, Design of Experiments; FEA, Finite Element Analysis; FEM, Finite Element Method; FSI, Fluid-Structure Interaction; MOD, Multi-objective Optimization Design; NSGA-II, Non-dominated Sorting Genetic Algorithm II; PCF, peak crushing force; RBF, Radial Basis Function; SAF, Sandwich Aluminum Foam; SEA, Specific Energy Absorption; SPH, Smoothed Particle Hydrodynamics; TEA, Total Energy Absorption.

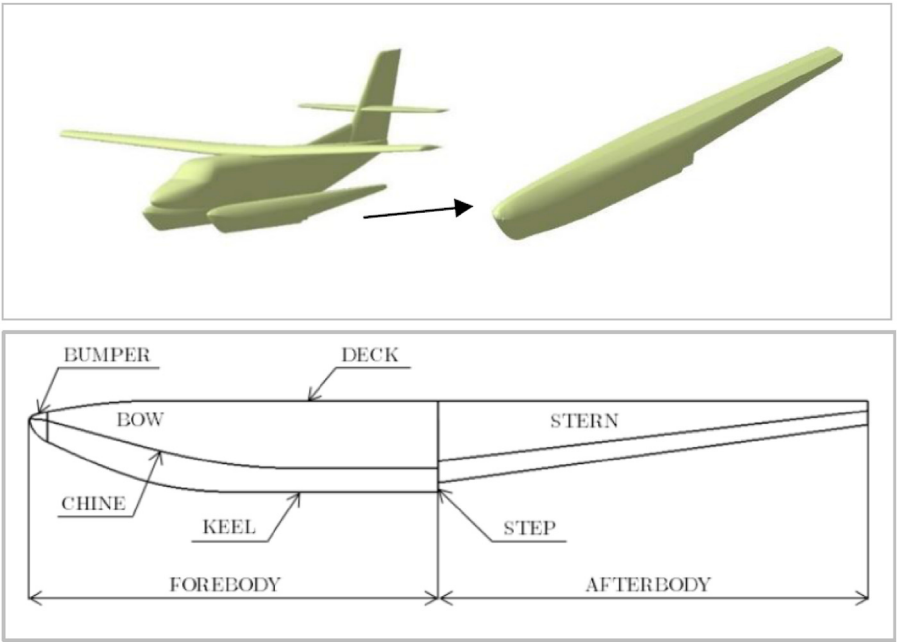


FIGURE 1
Float of amphibious aircraft.

TABLE 1 Float dimension (Shankar et al., 2020).

Parameter	Value
Length (mm)	8.56
Width (mm)	1.20
Height (mm)	1.05
Dead Rise	25°

TABLE 2 Mechanical properties of aluminum 6061 T6 (Dayyani et al., 2013).

Property	Value
Density (kg/m ³)	2700
Young's Modulus (GPa)	68.9
Yield Strength (MPa)	276
Ultimate Tensile Strength (MPa)	310
Poisson's Ratio	0.33

○ A measure of how much energy a building can absorb relative to the force needed to crush it. Higher CFE values indicate a more effective energy absorption capability.

2.2 Finite element models of the float

The amphibian aircraft designed for 19 passengers features twin floats, positioned on either side of the fuselage. The first series of floats for this aircraft is an imported product manufactured by WIPAIRE, Inc., a U.S.-based company specializing in floats for floatplanes and amphibious aircraft (Figure 1). The Twin Otter 300 series (Patel and Patel, 2024) has made use of these aluminum floats, which can sustain loads up to 6.5 tons apiece (see table 1 for dimensions).

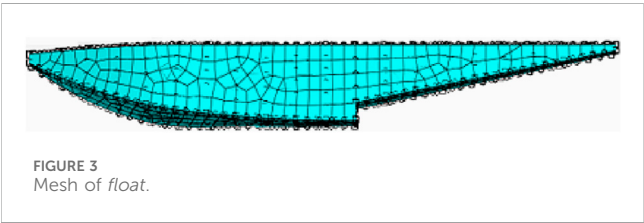
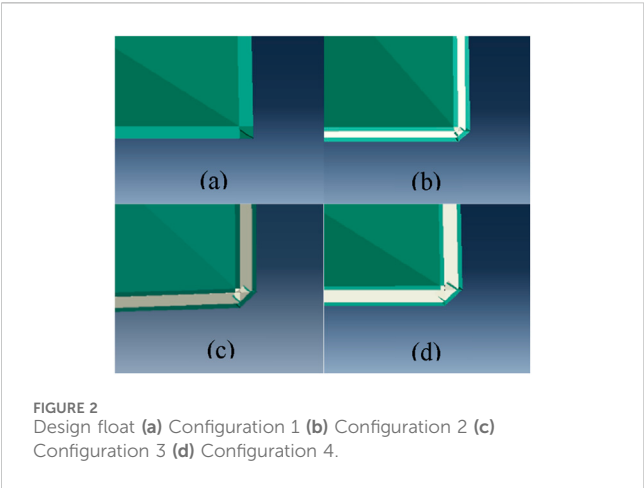
Because of its low weight, high strength-to-weight ratio, and great energy-absorbing qualities, sandwich foam constructions are finding more and more uses in amphibious aircraft. These floats are designed for water impact situations with a lightweight foam core sandwiched between two durable face sheets. They provide structural integrity and buoyancy as needed. Tables 2 and 3 show

TABLE 3 Mechanical properties of aluminum foam (Patel and Patel, 2024).

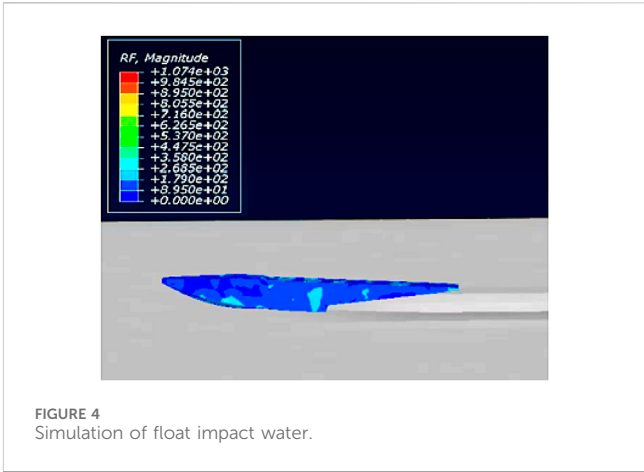
Property	Value
Density (kg/m ³)	710
Young's Modulus (GPa)	2.7
Yield Strength (MPa)	10
Compressive Strength (MPa)	2.53
Poisson's Ratio	0.33

the mechanical characteristics of the core and face sheets used in sandwich foam systems (Dayyani et al., 2013; Patel and Patel, 2024).

The plastic behavior responses of the aluminum core and aluminum face sheet materials used in the sandwich aluminum foam (SAF) structures (Figures 2, 3). The foam core absorbs energy primarily through progressive plastic collapse and aluminum face sheets contribute by plastically deforming under tensile and bending loads. The foam core plays a crucial role in absorbing



impact energy, reducing peak crushing force and maintaining stability during operations. Additionally, the choice of materials and the optimization of parameters such as core density, thickness, and face sheet properties significantly influence the performance of the sandwich structure in crashworthiness and hydrodynamic contexts. The effectiveness and security of amphibious aircraft depend on these specialized sandwich foam floats. The float structure's hydrodynamic influence on the water was simulated in this research using the ABAQUS finite element program. Accurately defining contact interactions such as cohesive or surface-to-surface bonding between dissimilar materials is essential to realistically capture interfacial behavior under dynamic loading. Moreover, the absence of a description of the mesh elements such as solid elements (C3D8R) for foam, shell elements (S4R) for face sheets and Eulerian elements for fluid domains. To ensure realistic simulation of hydrodynamic impact, specific boundary and loading conditions were defined. The float structure was assigned Lagrangian elements to model solid material deformation, while the surrounding water was modeled using Eulerian elements within a predefined Eulerian domain. The loading condition of the float was positioned above the water



surface and then imparted an initial vertical velocity corresponding to 76 knots (approximately 39 m/s), representing the aircraft's typical water landing speed. Gravity was applied as a body force, and no external constraints were applied to the float structure, enabling free-body motion during the initial contact phase. The float's motion and impact behavior were governed by dynamic explicit analysis over a 0.01-s simulation period. The core and face sheet interaction is surface-to-surface contact and frictionless or low-friction contact to simulate realistic test conditions. For this study, there were 3 configuration of SAF and 1 original material in Table 4 and Figure 2.

Figure 4 shows the distribution of 500 data points dispersed uniformly across the course of the simulation, which pertain to speed. The data was taken at four nodes located at the top corners of the base frame.

2.3 Multi-objective optimization

Sectional design parameters such as core thickness (t_c), foam density (σ_y), yield stress of skin (σ_y), and a constant tube length of 120 mm were used in the multi-objective optimization design (MOD) procedure. In order to improve specific energy absorption (SEA) and decrease crush force efficiency (CFE) under transverse impact loads, previous research (Djamaluddin, 2024) investigated two crashworthiness indicators concurrently. Because it may search for a global optimum without ever reaching a local one, the Genetic Algorithm (GA) has become one of the most popular optimization methods (Djamaluddin, 2023b). For ranking solutions, awarding fitness scores, and handling multi-objective issues, the Non-dominated Sorting

TABLE 4 Configuration of SAF.

Configuration	Material	Al thickness (mm)	Foam thickness (mm)
1	Aluminum 6061 T6	4	-
2	Sandwich Aluminum Foam	2	3
3			5
4			7

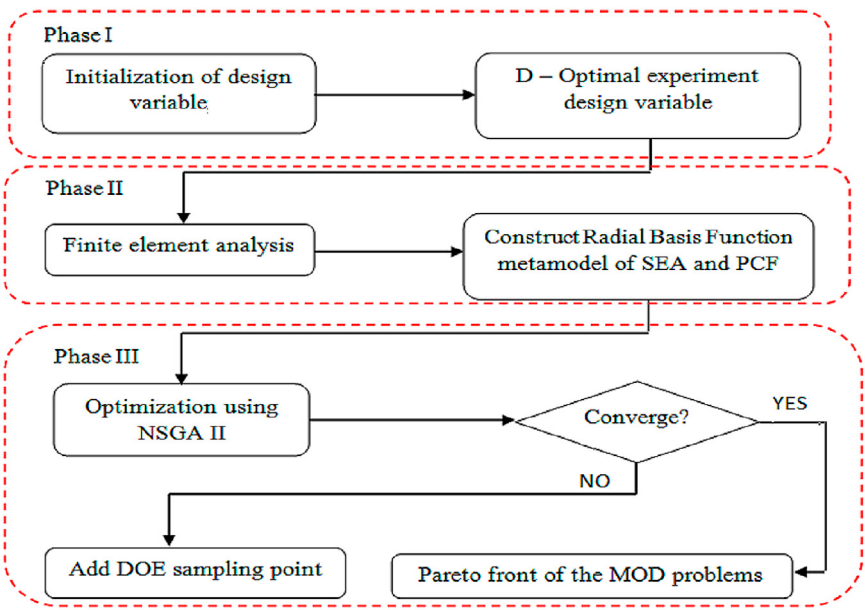


FIGURE 5 Flowchart of crashworthiness multi-objective optimization for tubes (Djamaluddin and Mat, 2023).

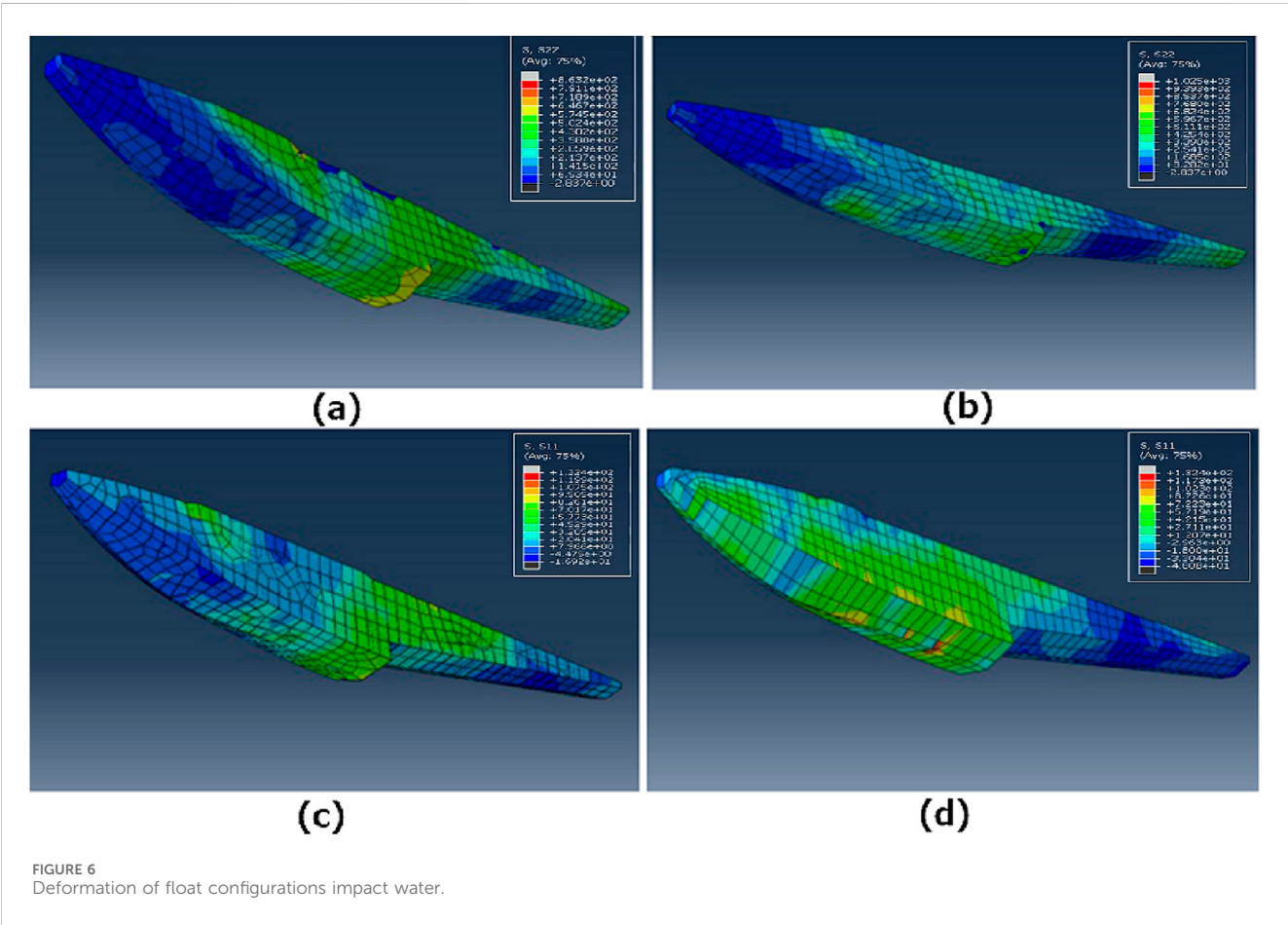
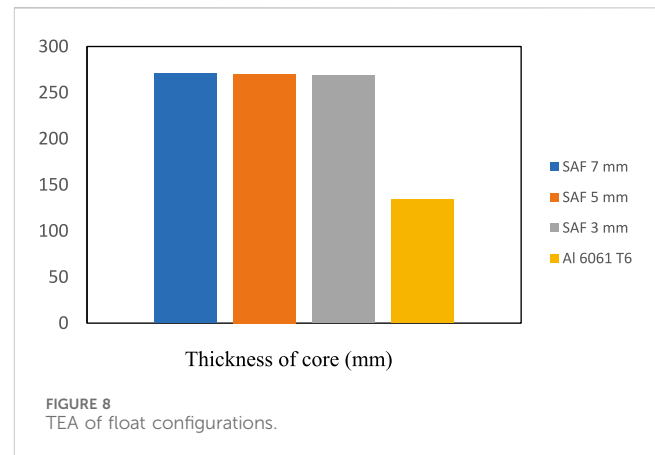
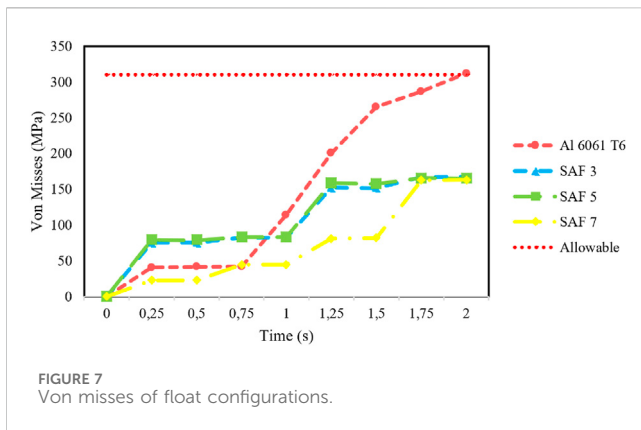


FIGURE 6 Deformation of float configurations impact water.



Genetic Algorithm (NSGA) provides a more effective technique, including versions I and II (Djamaluddin and Mat, 2023; Djamaluddin, 2023a).

Figure 5 shows the procedure for making the double fender more impact resistant. Determining the design space and creating sample sites for different loading angles using the Design of Experiments (DOE) approach were the first steps. Phase two included using Finite Element Analysis (FEA) to find solutions for the design goals' early D-optimal models. Phase three concluded with the determination of Pareto-optimal solutions for stressed systems by the use of the NSGA-II method to maximize performance under varying loads.

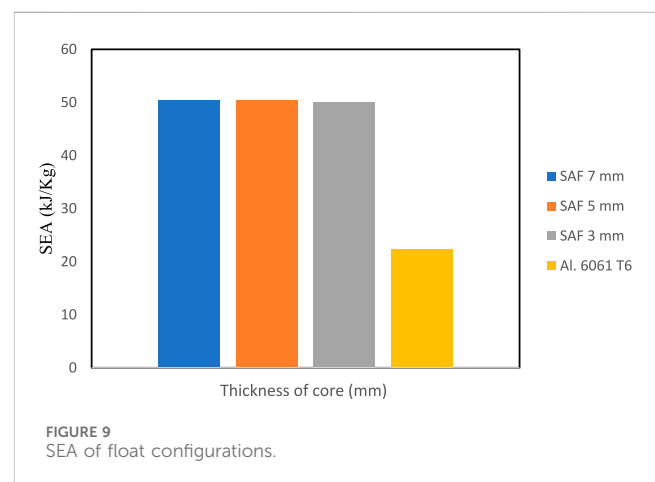
3 Result and discussion

3.1 Finite element analysis of float impact water

The deformation of float configurations during water impact is a critical aspect of evaluating their performance and safety (Figure 6). When the float structure comes into contact with the water surface, a combination of hydrodynamic and structural forces acts on it. The initial impact generates a high-pressure region, causing localized deformation, particularly at the leading edge of the float. This deformation is influenced by the material properties, structural design, and impact velocity.

The foam core in sandwich structures absorbs a significant portion of the impact energy, reducing peak forces transmitted to the aircraft. Simultaneously, the face sheets resist bending and prevent excessive structural collapse. The deformation pattern can vary, ranging from elastic bending to plastic deformation, depending on the float's design and material configuration.

The Von Mises stress distribution in sandwich foam aluminum structures for float configurations is a key indicator of their mechanical performance under load (Figure 7). During water impact, the stress is distributed across the foam core and aluminum face sheets, with the Von Mises criterion used to predict yielding within the material. This analysis is crucial for understanding how the float structure withstands the combined hydrodynamic and structural forces.



In such configurations, the aluminum face sheets typically experience higher Von Mises stresses, especially in regions subjected to bending and direct impact. The foam core, on the other hand, helps to distribute and absorb stresses, preventing localized failure. By examining the Von Mises stress distribution, engineers can identify critical stress points, optimize material thickness, and enhance the overall structural integrity of the float. This ensures the design meets safety standards while maintaining a lightweight and efficient configuration suitable for amphibious aircraft applications.

3.2 Crashworthiness parameters

When it comes to float arrangements, the Total Energy Absorption (TEA) and Specific Energy Absorption (SEA) of sandwich aluminum foam constructions change a lot depending on the thickness of the core. An important factor in a structure's ability to dissipate energy is the thickness of its foam core, as this determines how much material is available to absorb impact forces (Figures 8, 9).

For thinner cores, the TEA and SEA is generally lower because there is less foam material to undergo deformation and dissipate energy during impact. While such configurations may be lighter,

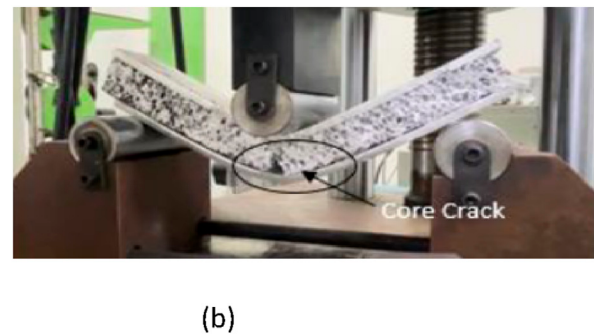
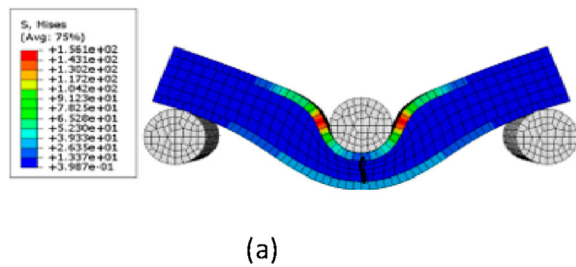


FIGURE 10
Panel deformation (a) simulation result and (b) experiment result.

they often result in higher stress concentrations and reduced crashworthiness. Conversely, increasing the core thickness enhances the TEA, as the additional material allows for more progressive crushing and energy absorption. This reduces the peak forces transmitted to the structure and improves its ability to withstand repeated impacts.

However, excessively thick cores may lead to a significant increase in weight, which can compromise the buoyancy and efficiency of the float. Therefore, optimizing core thickness is essential to achieve a balance between lightweight design and maximum energy absorption. Analyzing TEA for different core thicknesses enables engineers to tailor sandwich aluminum foam configurations for improved safety and performance in amphibious aircraft applications.

3.3 Model verification

In both the experimental setup and the finite element simulation for validation, a three-point bending test configuration was adopted to evaluate the mechanical response of the sandwich aluminum foam (SAF) panel. The specimen dimensions matched those used in the float structure. In the experimental setup, the panel was simply supported at two ends, with a central load applied using a displacement-controlled actuator. The boundary conditions in the experiment replicated simply supported edges and a centrally applied quasi-static load, simulating impact-induced bending.

In the simulation using ABAQUS/Standard, the same boundary conditions were modeled: two ends of the panel were constrained in the vertical direction using pinned supports, while a concentrated vertical displacement load was applied at the mid-span using a reference point connected to a rigid loading surface. The loading rate in the simulation matched the experimental displacement speed to ensure comparability. The face sheet–core interface was modeled with surface-to-surface contact and frictionless behavior to allow delamination, while solid (C3D8R) and shell (S4R) elements were used for the foam and face sheets, respectively. The panel deformation, core crushing, and peak force values were then compared between the simulation and experimental results, with less than 5% deviation, confirming model accuracy. To validate the model, the simulation results were compared with experimental data of foam core sandwich specimens for float in Figure 10.

Figure 10 shows the numerical simulation result showing Von Mises stress distribution in a bending test, and the experimental result where a core crack is visibly initiated under the same loading condition. In Table 5, the small percentage deviations (<5%) confirm that the FEA model accurately captures the mechanical response of the sandwich structure during water impact. These discrepancies because in experimental setups, measurements are subject to uncertainties and calibration limits of sensors and data acquisition systems, particularly in high-speed impact tests. Simulation results can be continued for optimization.

Convergence testing is very important to determine the effect of the number of elements used on the results obtained. In the float analysis, element sizes were tested ranging from 30 to 150 with an increase of 10 in each test (Figure 11). The element size itself is the general length of the element on a surface. The larger the value of the selected element size, the fewer the number of elements will be, and *vice versa*. The convergence investigation found that mesh sizes between 70 and 110 yielded the convergence value. However, when viewed from the error value, as the element size decreases, the error value becomes larger. The error on the graph is the difference in results between the current element measurement and the previous element. Therefore, in this modeling, an element size of 90 is used because it has the smallest error value (Figure 12) (Ardiansyah and Adhitya, 2019).

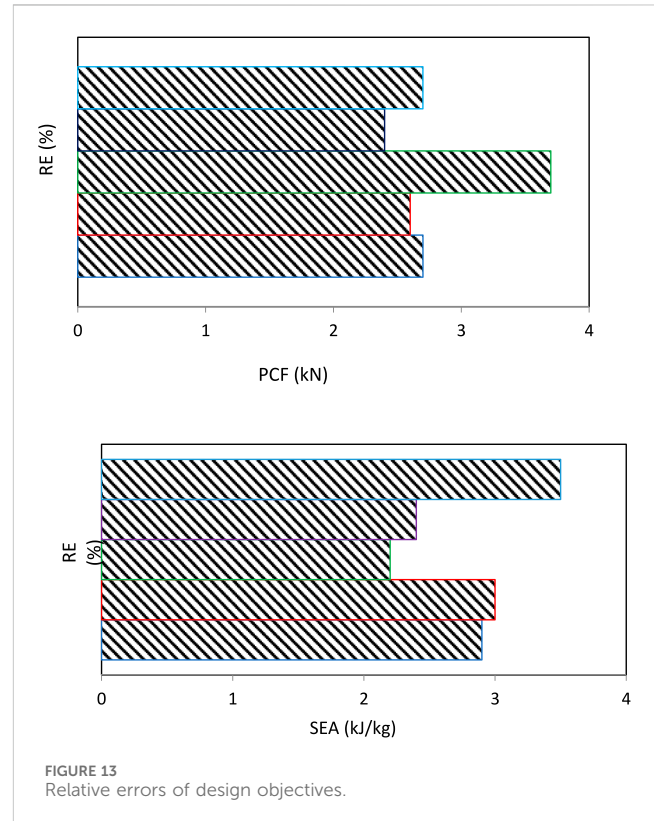
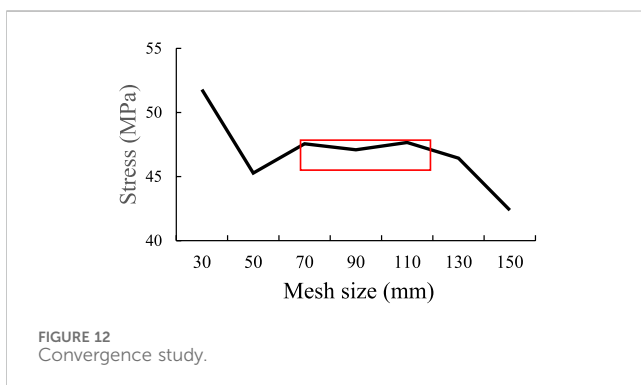
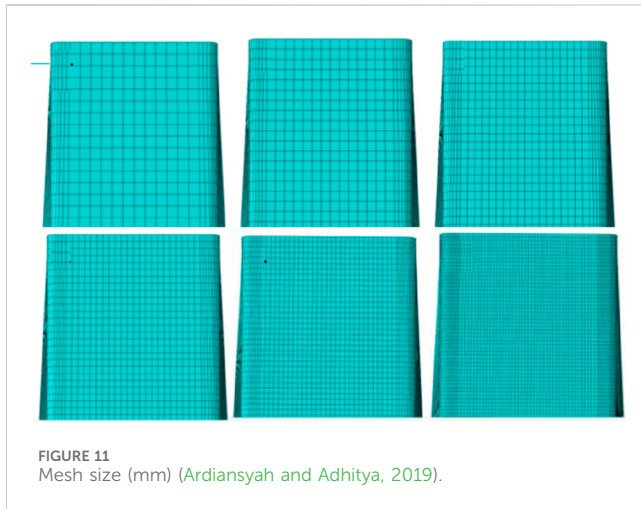
The development of a radial basis function (RBF) meta-model allowed for the precise identification of the sample locations. Also, five additional random locations were produced inside the design area. The cost-effective finite element (FE) and RBF models were validated using the SEA and PCF responses. In order to assess the degree to which the RBF meta-model resembles the outcomes of the finite element analysis (FEA), the following method was used:

$$RE(\%) = \left| \frac{y_i - \hat{y}_i}{y_i} \right| \times 100\% \quad (2)$$

In Figure 13, we can see the five randomly selected starting positions for the FEA and RBF samples. Because the validation values fall below 5% in the SAF float for this RBF meta-model estimate, we may infer that the RBF model achieves an acceptable level of accuracy for optimizing the design with respect to the objective functions (SEA and PCF).

TABLE 5 Differences between simulation and experiment.

Parameter	FEA result	Experimental result	% difference
Peak Impact Force (N)	12,8	13,2	3.03%
Maximum Core Compression (mm)	6.2	6.0	3.3%
Energy Absorbed (J)	85.2	88.1	3.3%



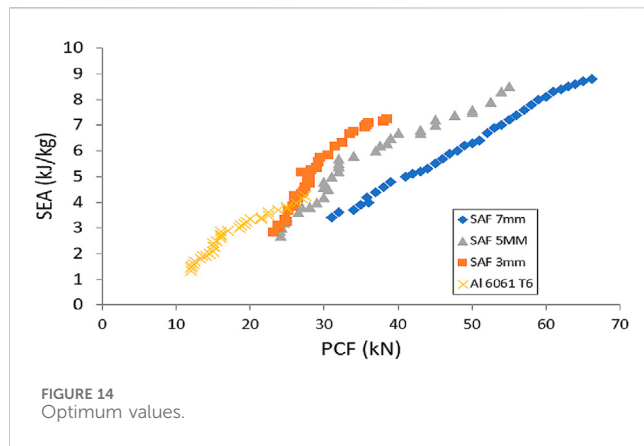
3.4 Crashworthiness optimization design

The SAF float's multi-objective optimization (MOD) equations were developed with the use of several parameters. Addressing trade-offs between conflicting objectives was done via multi-objective optimization. Design characteristics including core thickness (t), foam density (ρ_f), and yield stress (σ_y), were used to develop additional constraint functions and goals for SAF float. Objective functions like Peak Crushing Force (PCF) and Specific Energy Absorption (SEA) were also defined. For MOD equations, the Pareto fronts that were computed are detailed in Equation 3.

$$\left\{ \begin{array}{l} \{SEA(\rho_f, t_c, \sigma_y), PCF(\sigma_f, t_c, \sigma_y)\} \\ 200 \text{ kg/m}^3 \leq \rho_f \leq 700 \text{ kg/m}^3 \\ 235 \text{ MPa} \leq \sigma_y \leq 245 \text{ MPa} \\ 8 \text{ mm} \leq t_f \leq 16 \text{ mm} \end{array} \right. \quad (3)$$

Using the NSGA-II optimization method, the design space was explored using Radial Basis Function (RBF) meta-models. The Design of Experiments (DoE) technique was used to develop a collection of 200 design points for all MOD situations. Next, the SAF 7 mm model's PCF vs. SEA Pareto front graphs were constructed using the NSGA-II approach. These graphs were based on the convergence of optimizations repeated over 20 generations. There was an unintended trade-off between the PCF and SEA criterion, since the data showed that increasing SEA caused PCF to rise.

In order to find inconsistencies between the RBF models and Finite Element Analysis (FEA), multi-objective optimization was used to the section design parameters, which core thickness (t), foam density (ρ_f), and yield stress (σ_y). In Figure 11, we can see that the NSGA-II technique and the RBF methodology were used to produce Pareto fronts using five randomly selected sample points. To test the crashworthiness of fenders with foam fillers, all of them were fine-tuned for transverse loads using the right RBF models and taking MOD into account. From Figure 14, It was observed that increasing core density from 2,700 kg/m³ to 7,100 kg/m³ improved impact resistance by approximately 23%, but at the expense of a 12% increase in total float mass. On the other hand, increasing core



thickness had a more favorable effect, with a 30% increase in thickness resulting in a 27% improvement in energy absorption while only adding 7% to the float mass. It can be concluded that the thickness of the core has a greater influence than increasing the density of the foam (Harte et al., 2000). The SAF 7 mm represent solutions with the highest PCF, reaching up to 65 kN, and correspondingly higher SEA values up to 8 kJ/kg. However, in real-world applications, particularly in vehicle crash scenarios, a very high PCF may transmit excessive force to critical components, which can be unsafe. The SAF 3 mm provide lower PCF (20–35 kN) with moderate to high SEA (up to 7 kJ/kg). These configurations are more suitable for applications where minimizing transmitted force is crucial.

4 Conclusion

This study has demonstrated the effectiveness of sandwich aluminum foam (SAF) structures in enhancing the crashworthiness of amphibious aircraft floats under water impact conditions. Through a combination of material characterization, finite element simulations, and experimental validation, the impact response of various core thickness configurations was thoroughly analyzed. The results highlight that core thickness and material density are critical parameters influencing the Total Energy Absorption (TEA) and peak crushing force (PCF). Among the three tested configurations (3 mm, 5 mm, and 7 mm core thickness), the 7 mm sample exhibited superior energy absorption performance while maintaining acceptable structural integrity.

- Based on simulations, experiments, and multi-objective optimization, the following conclusions can be drawn: The simulation results showed a difference of less than 5% compared to the experimental data.
- Effect of Core Thickness such as the 7 mm core gave the highest SEA (8 kJ/kg) and Peak Crushing Force (PCF) up to 65 kN and the 3 mm core showed lower PCF (20–35 kN) with still good SEA (up to 7 kJ/kg). From optimization results found that increasing foam density from 2,700 to 7,100 kg/m³

improved impact resistance by 23%, but also increased weight by 12%.

- The optimized SAF float is a lightweight, strong, and safe solution for amphibious aircraft. These results provide a strong reference for the development of hybrid marine-aerospace structures and future experimental studies.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

FD: Conceptualization, Investigation, Writing – original draft, Writing – review and editing. ZA: Methodology, Validation, Writing – review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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