Numerical simulation of different aircraft sub-floor structures during ditching

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Abstract

To enhance the impact resistance capacity and ensure the floatability of aircraft after ditching, the slamming response of three types of aircraft sub-floor structures are investigated including the flat, cylindrical, and ellipsoidal under floor. A coupled Finite Element-Smooth Particle Hydrodynamic (FE-SPH) method is employed with focus on non-linear structural collapse in fluid-structure interaction. The material is defined by bilinear elastic plastic law and the strain rate effect is taken into account. Further, comparison and analyses are performed in terms of acceleration, local pressure and strains at different speeds. Results show that conventional flat sub floor structures perform poorly during ditching due to excessive peak acceleration and pressure. By contrast, the peak acceleration of ellipsoidal under floor is lower at all measured speeds and the pressure on the sides is reduced. Moreover, the ellipsoidal sub-floor with bi-directional curvature generates smaller plastic strain and deflection of skin, demonstrating better mechanical properties in water impact scenarios.

Keywords: Ditching; Aircraft skin; Crashworthiness; Smoothed Particle Hydrodynamics

Nomenclature

FE	Finite Element
SPH	Smooth Particle Hydrodynamic
CFC	SAE Channel Filter Class
EOS	equation of state
ACC	accelerometer
P	pressure transducer
E_i	linear in internal energy

C_i	material constant
r	position
m	mass
p	pressure
v	velocity
ρ	density
μ	volumetric strain

1. Introduction

Ditching is the emergency procedure for landing aircraft on water, which must be taken into account by the aircraft manufacturers of all countries in the certification process. The ditching process of an aircraft can be divided into four stages: approach, impact, landing, and floatation [1,2]. The impact stage is crucial for the success of ditching. During the impact stage, the aircraft is subjected to extreme overloads. There is a huge impact on the fuselage belly which lead to structural deformation or damage. Moreover, excessive deformation and rupture of the fuselage will affect the floatability of the aircraft and the safe egressing of passengers.

The issue of structures impacting water surfaces is first addressed by Karman, who developed the physical concept of the problem in 1929 [3]. Some researchers conducted extensive theoretical studies on the vertical water entry problem for two-dimensional objects. With zero gravity and a constant entry velocity, significant progress is made with both linear theories and the theories of treating the free surface conditions exactly [4,5]. Researchers agree that the impact processes involved in a fluid-structure interaction are extremely complex, with the influence of water kinetics and the underlying physics still not properly understood [6,7]. Furthermore, for the complex aircraft structure, the theoretical research is difficult to analyze in a comprehensive and in-depth manner [8]. Hughes conducted experimental studies on the impact resistance of metal helicopter under floor structures when hitting the water [9]. Furthermore, he discussed the recommendations for design changes that could improve the level of crashworthiness and summarized the advancements and achievements in the experimental aspects of aircraft water impact resistance since the 1980s [10]. In order to get a more realistic data of the aircraft impact water, a full-scale WG30 helicopter test is performed, and discussed challenges in predicting measured acceleration and pressure peaks using numerical modelling methods [11]. The crucial vertical drop tests were conducted comparing rigid surfaces and water surfaces, providing valuable reference data for analyzing such problems [12,13]. These research studies identified the classification of failure and damage on soft and hard surfaces, providing a framework and catalyst for the development of numerical methods.

With advancements in computing power and simulation tools, numerical modeling techniques have provided satisfactory solutions for predicting the nonlinear hydrodynamic response of aircraft during ditching[14-17]. Smoothed Particle Hydrodynamics, as a numerical method, can easily handle distortions and complex boundaries, and its stable results make it widely applicable to large-scale fluid-structure coupling simulations [18-20]. From 2000 to 2003, the CAST project, Crashworthiness of Helicopter on Water: Design of Structures using Advanced Simulation Tools, examined various techniques for simulating helicopter ditching, including the application of SPH [21,22]. This research is extended through the GARTEUR HC/AG-15 project [23], focusing on enhancing SPH methods for helicopter ditching applications [24]. The subsequent program, Smart Aircraft in Emergency Situations (SMAES), continued this investigation from 2011 to 2014 [25]. Woodgate quantified the impact of numerical parameters in SPH, including the boundary conditions between water and solid, as well as the influence of the number and type of smoothed particles for ditching [26]. Furthermore, a weakly compressible SPH method is developed to investigate the hydrodynamic and dynamic behavior of a helicopter ditching [27]. The simulation model is established for an AW159 helicopter ditching based on SPH method, the cases of a vertical drop of the helicopter at no sea-state and on the crew of a wave were simulated [30]. These studies used numerical simulation methods to investigate landing angle problems and sea state problems during ditching. However, the problem of entering water with multiple shapes has been confined to the investigations of two-dimensional objects. Currently, there have been limited studies of different shapes of three-dimensional aircraft sub-floor during ditching.

The present work addresses the water slamming response of three types of sub-floor structure using the FE-SPH method, organized as follows. In Section 2, the principles of the SPH method are briefly described and the loads of an aircraft landing versus water landing are analyzed. In Section 3, the accuracy of the numerical method is verified by vertical water impact experiments of a semi-cylindrical steel structure conducted in the Italian Laboratory for Impact Tests on Aerospace Structures (LISA). The acceleration values and three pressure values at a variety of speeds are compared separately. Furthermore, the structural deformation of the steel skin is evaluated. In Section 4, three shapes of sub-floor structures are built, including a flat without curvature, a cylindrical surface with single curvature and an ellipsoidal surface with double curvature. Several parameters are compared to analyze the loading of the three structures at different speeds during impacting water, including acceleration, local pressure, skin deflection and plastic strain. the better shape of the sub-floor structure for aircraft is investigated by assessing the effects of curvature of the sub-floor shape during ditching.

2. Numerical Model

SPH is a mesh-free method originally proposed by Lucy, Gingold, and Monaghan in 1977 [31][32]. It accurately and stably solves a set of partial differential equations without the need for any grid connecting the particles. The SPH method employs a discrete set of smooth particles with position, velocity, and mass attributes to approximate the values and derivatives of continuous variables. Subsequently, it calculates the weighted averages of all neighboring particles. A simplified overview of the SPH method is depicted in the Fig 1. In SPH, fluid is treated as a collection of particles, each possessing associated physical properties such as position $r(t)$, mass $m(t)$, density $\rho(t)$, pressure $p(t)$, and velocity $v(t)$. The computational domain is then discretized into spatial bins of size 2h, and particles within the particle's own space and adjacent spaces are identified. For a given particle, only interactions with neighboring particles within a distance less than 2h are considered. The interactions are computed for the given particle and the selected neighboring particles by solving the following NS equations:

$$\frac{dv_i}{dt} = -\sum_j m_j \left(\frac{p_i}{\rho_i^2} + \frac{p_j}{\rho_j^2} + \Pi_{ij} \right) \nabla_i W_{ij} + F_i \tag{1.1}$$

$$\frac{d\rho_i}{dt} = \sum_j m_j \left(v_i - v_j \right) \nabla_i W_{ij} \tag{1.2}$$

The position and velocity of the particle for the next time step are then updated based on the results of the following calculation. Fig 2 illustrates the detailed calculation cycle.

$$r_i\left(t+\Delta t\right) = r_i\left(t\right) + \Delta t v_i\left(t\right) \tag{1.3}$$

$$v_i\left(t+\Delta t\right) = v_i\left(t\right) + \Delta t a_i\left(t\right) \tag{1.4}$$

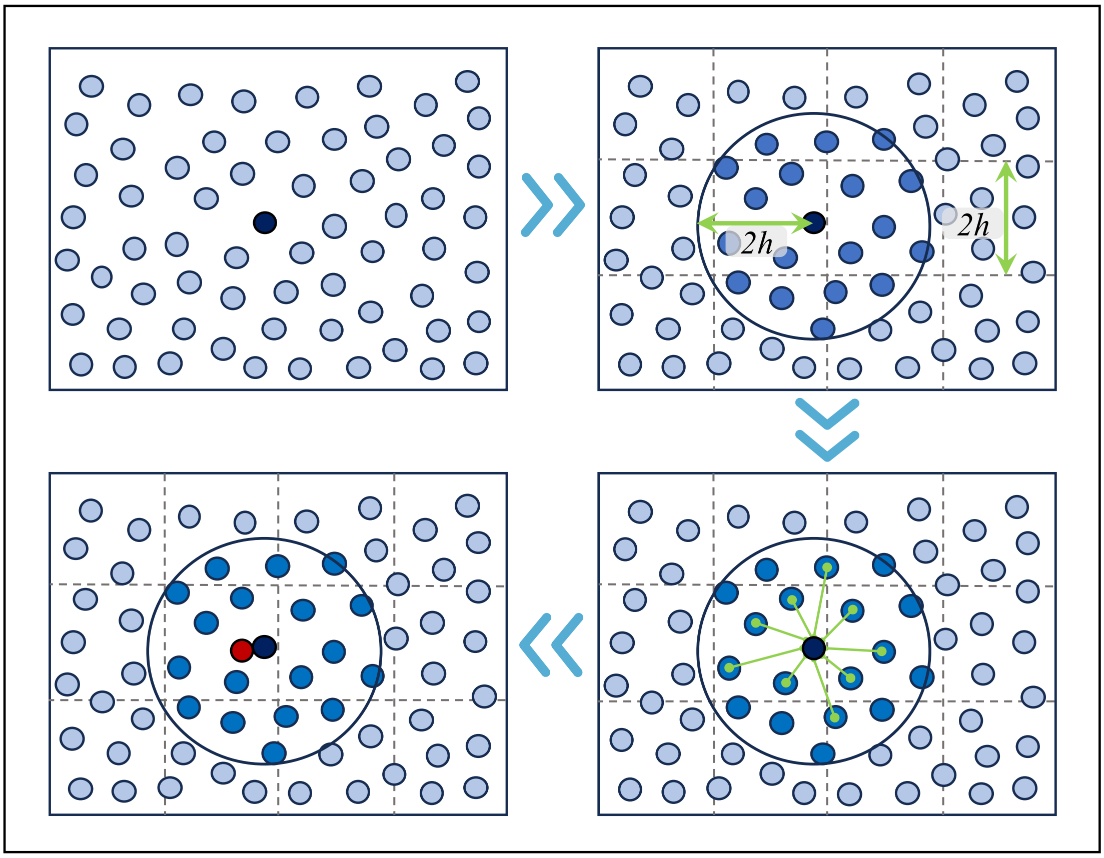


Fig. 1 Brief overview of SPH method

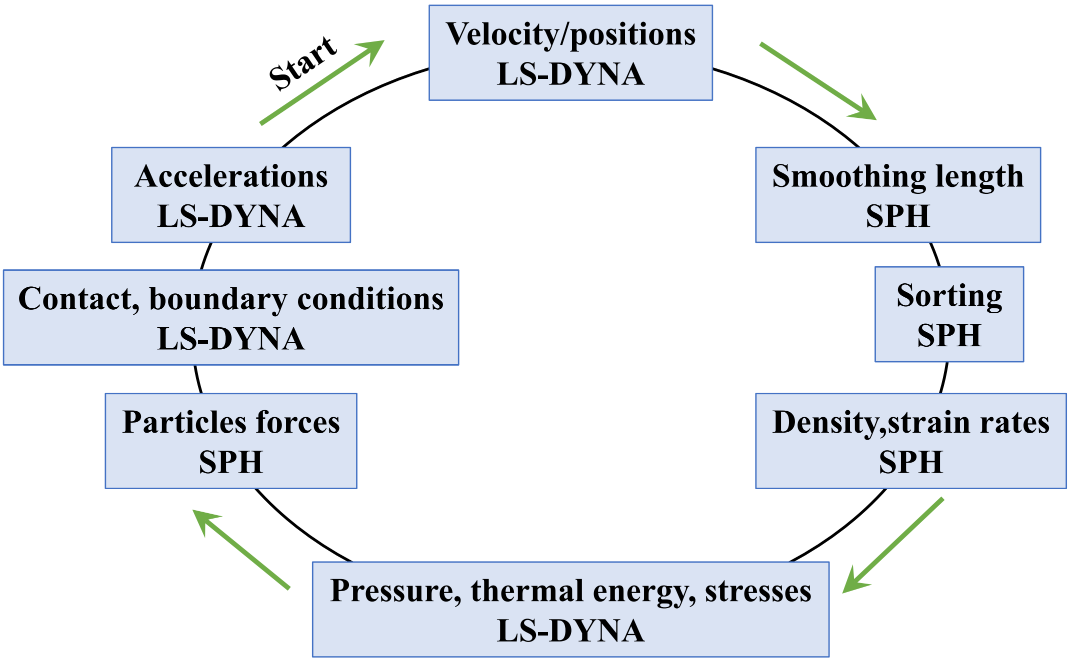
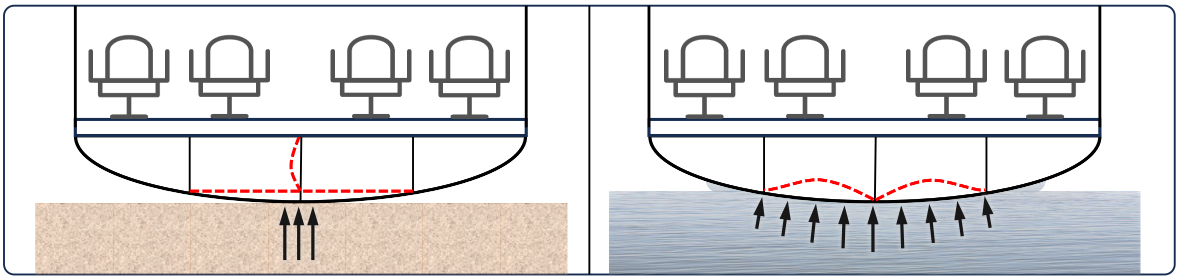


Fig. 2 The calculation cycle of SPH method

It is widely recognized that structural loading for water impact is significantly different to hard surfaces [33]. As shown in Fig. 3, the aircraft's kinetic energy is absorbed by the plastic deformation of the metal structure during impact on a hard surface, reducing the impact load and acceleration to survivable levels. However, in the case of water impact, the landing gear and conventional flat under floor structures perform poorly in absorbing impact energy [34,35]. The impact load is distributed along the skin, and energy absorption depends primarily on bending behavior of the skin as well as the limited plastic collapse of supporting frames [36,37]. In severe cases, aircraft skin rupture or inability to transmit impact loads could significantly reduce the efficiency of sub-floor structural energy absorption. Internal structures may also suffer secondary damage due to water ingress [38]. Therefore, it is imperative to investigate the effects of water impact on different structures to enhance the survivability of passengers during aircraft emergency water landing.



(a) Impacting on land (b) Impacting on water

Fig. 3 Comparison between impact on a rigid floor and on water

Numerous accident cases have demonstrated that the aircraft skin rupture during ditching is the main reason affecting passenger survival rates [39,40]. To investigate the aircraft under floors impacting water surfaces and analyze the load on aircraft skin during water impact, the Italian Center of Aerospace Research (CIRA) conducted a water entry impact experiment at the Laboratory for Impact Tests on Aerospace Structures [41]. The test specimen of steel structure is dropped into the water at different velocities to generate an experimental database for validating numerical models. The test specimen is a semi-cylindrical aircraft skin reinforced with three frames positioned symmetrically on both sides and at the center of the skin. To secure the structure on the drop tower trolley, L-shaped and U-shaped steels are mounted above the structure. Both the skin and frames are constructed using 2 mm thick hot-rolled steel (DD11). The material is defined by bilinear elastic plastic law and takes into account the strain rate effect by adding the stress-plastic strain curve. As the experimental impact velocities are not sufficient to cause damage to the material, the material model does not need to consider material failure. The structure had a length of 1200 mm, a cross-sectional radius of 475 mm, a central circular hole with a diameter of 150 mm in the frames, a specimen weight of 66.4 kg, and the trolley weight of 174 kg.

The structural model employed shell elements with a total of 7592 elements. All shell elements are implemented in the Belytschko-Tsay format, and the selected thicknesses are consistent with the experimental setup. As there is no structural failure observed in the experiments, interconnection between models is established through merged nodes. The material model for the drop tower trolley utilized the rigid model, with the addition of mass points at the center to simulate the actual trolley weight. To align with experimental constraints, only the vertical degrees of freedom for the trolley are retained.

The water model is structured using the SPH algorithm. The water domain consists of a cubic shape measuring 2000mm × 1600mm × 800mm, composed of 40,000 particles. The Particle Approximation Theory employs an enhanced fluid formulation. The equation of state (EOS) is linear in internal energy (E_i) and it defines the pressure-volume relationship as:

$$\rho = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + \left(C_4 + C_5\mu^2 + C_6\mu^3\right)E_i \tag{1.5}$$

where in this case μ is the volumetric strain defined as:

$$\mu = \frac{\rho}{\rho_0} - 1 \tag{1.6}$$

ρ is the current density, ρ_0 is the reference water density and C_i (i=1, 2, …, 6) are material constants. The following values are used: C_1=2.723 GPa, C_2=7.727 GPa, C_3=14.66 GPa, $C_0 = C_4 = C_5 = C_6 = 0$ [42].

The penalty methods are implemented with the contact interaction between the structural model and the water model, and the soft constraint mode is activated. The soft constraint option's force scaling factor is set to 0.5. In the soft constraint option, the interface stiffness is based on the nodal mass and the global time step size. This method of calculating interface stiffness will typically give a much higher stiffness value than would be obtained using the bulk modulus. Therefore, this method is the preferred approach when water interacts with metals. Moreover, self-contact is enabled for the skin to prevent penetration. The structural model is initialized with impact velocities identical to those in the experiments, and gravitational effects are taken into account. Acceleration data are collected at the top plate of the model, representing the average acceleration at various points on the plate. Pressure values obtained by dividing the collected force by the corresponding area. The experiments involve drop tests with velocities of 3 m/s, 8 m/s, and 10 m/s, and the overall simulation model are depicted in Fig 4.

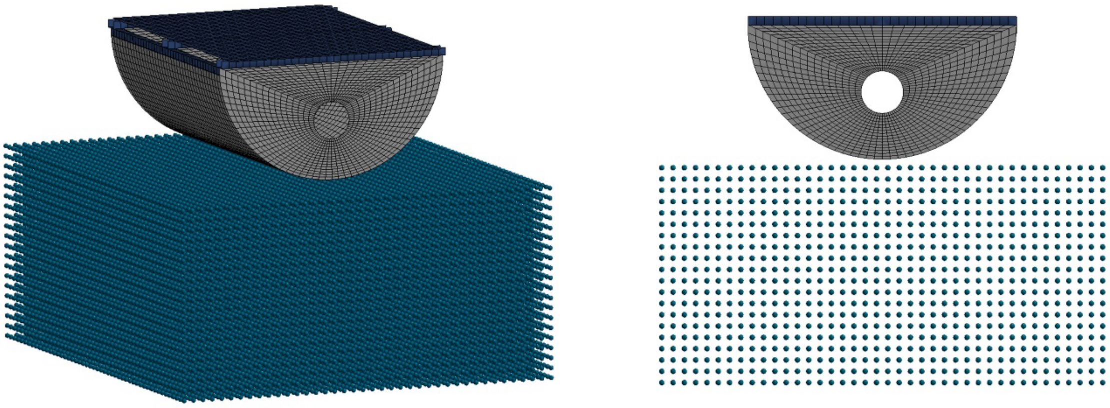
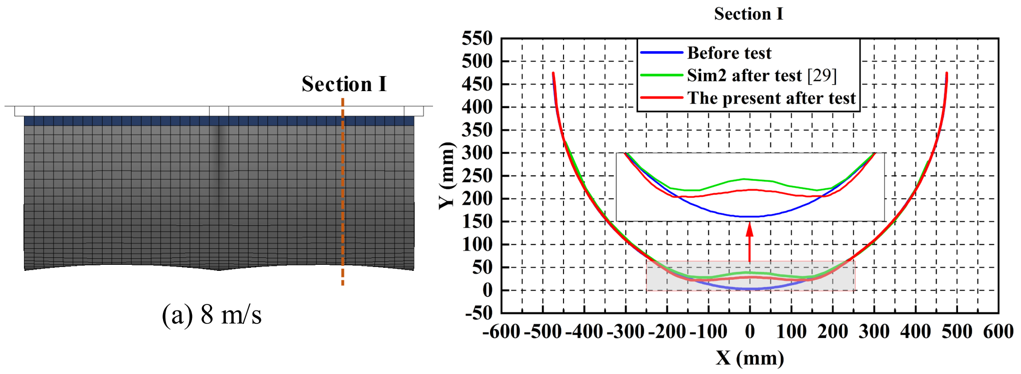


Fig. 4 Steel structure finite element model and water particle model

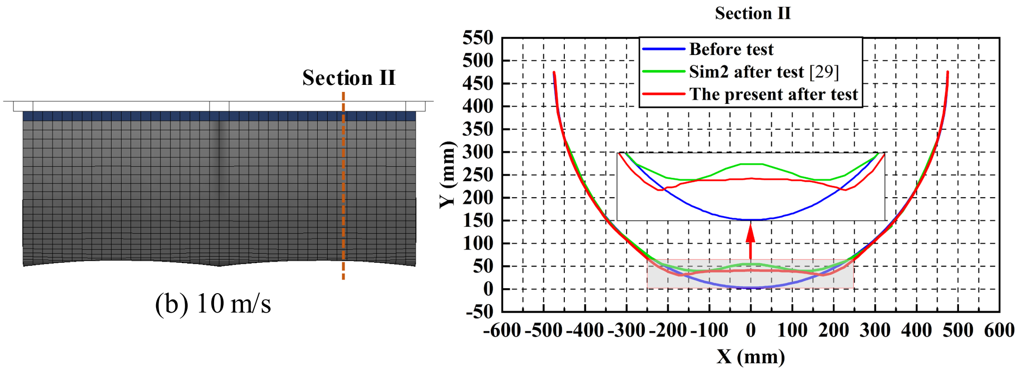
3. Numerical Simulation Results

3.1Skin deformation

To analyze the impact behaviors of the aircraft skin structure by simulation, the experimental and numerical results obtained from Borrelli and Grimaldi are used to validate the devised numerical model [28,29]. The measured deformation sections are illustrated in Fig 5. In Fig 5(a), for an entry velocity of 8 m/s, the maximum relative displacement at Skin Section I is 31 millimeters. In Fig 5(b), with an entry velocity of 10 m/s, the maximum relative displacement at Skin Section II is 45 millimeters. As shown in Fig 5, there is a strong correlation between the experimental results and the present. Both values exhibit an error within 10% when compared to the experimental measurements obtained from the specimen post-impact. In the present results, the side of the skin is deformed outwards by the bending moment generated by the bottom deformation. This trend of the predicted displacements is closer to the experimental results and is not found in previous results. The symmetry of the deformation on both sides of the skin at different velocities aligns closely with the experimental findings, providing further evidence of the accuracy of the simulations.



(a) 8 m/s



(b) 10 m/s

Fig. 5 Shape of the skin and measurement of deformation of section[29]

3.2Acceleration and Pressure

The positions for the accelerometer (ACC1, ACC2, ACC3, and ACC4) and pressure transducer (P1, P2, P4, P6, and P7) are illustrated in Fig 6. Due to symmetry considerations, three locations on the skin are designated as pressure sensor locations in the simulation.

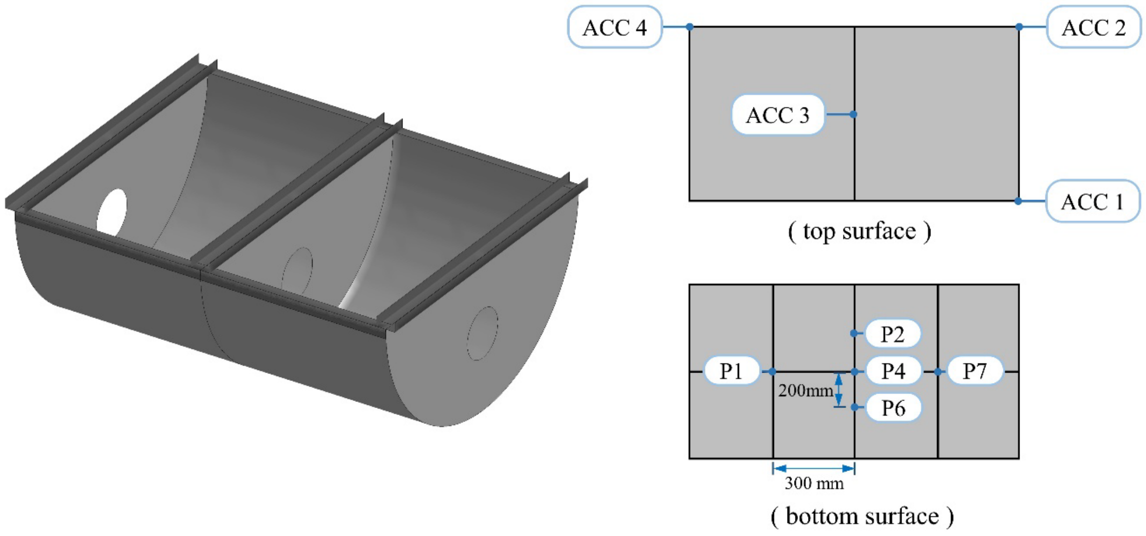


Fig. 6 Transducer deployment location[28]

The acceleration-time histories and pressure-time histories at different velocities are depicted in Fig 7, Fig 8 and Fig 9. Sim1 represents the simulation results from Borrelli, Sim2 from Grimaldi and Sim1 employs filtering with SAE Channel Filter Class (CFC) 60, and Sim2 uses CFC180 for filtering. The water model of Sim1 utilizes a mixed SPH-FE approach and Sim2 used the SPH method to model. In present simulation, both experimental and simulated data are subjected to filtering with the SAE Channel Filter Class (CFC) 60Hz [43]. In order to facilitate comparison, all the numerical curves are adjusted on the time scale to fit the experimental curves.

As depicted in Fig 8(a) and Fig 9(a), Sim1 and Sim2 demonstrate a strong correlation in peak accelerations at impact velocities of 8 m/s and 10 m/s. However, as depicted in Fig 7(a), at an impact velocity of 3 m/s, the water models of Sim1 and Sim2 exhibit excessive rigidity resulting in an overestimation of the acceleration peak. The results show that the water model fails due to excessive rigidity when the impact velocity is insufficient to induce plastic deformation in the specimen. With regards to pressure, accurate predictions are observed in soft areas (bays), while overestimations are evident in stiff areas (under the frames).

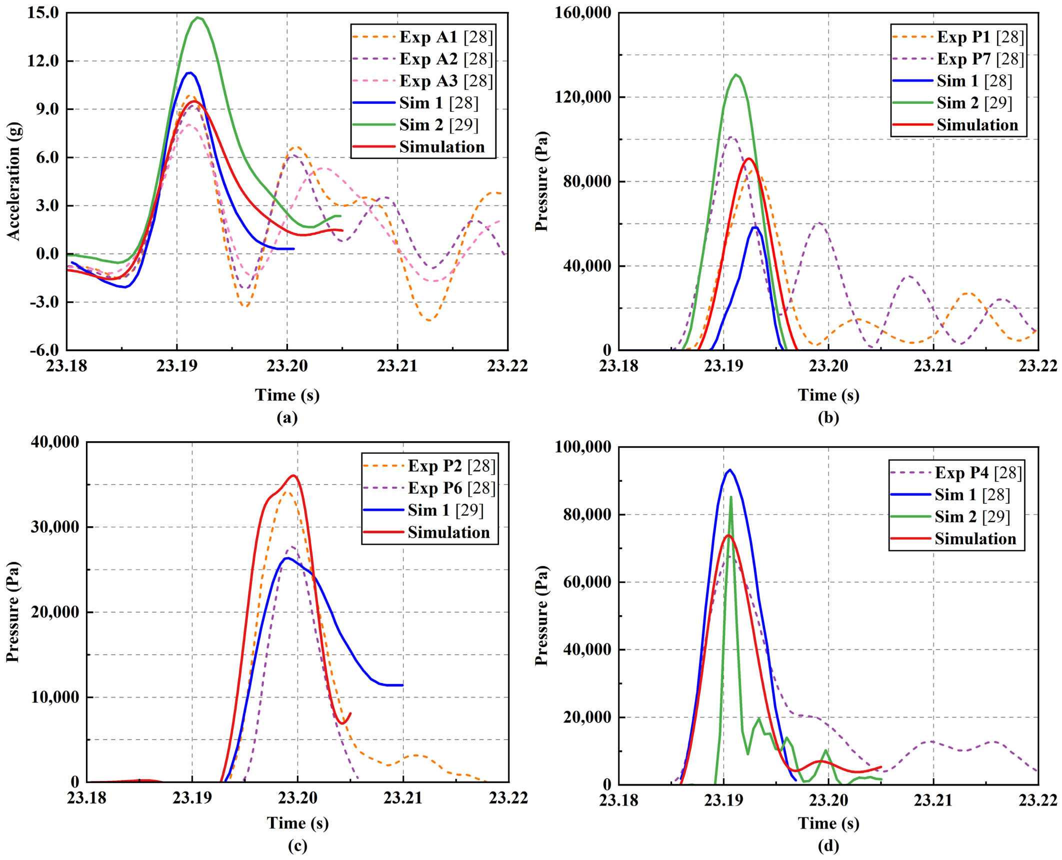
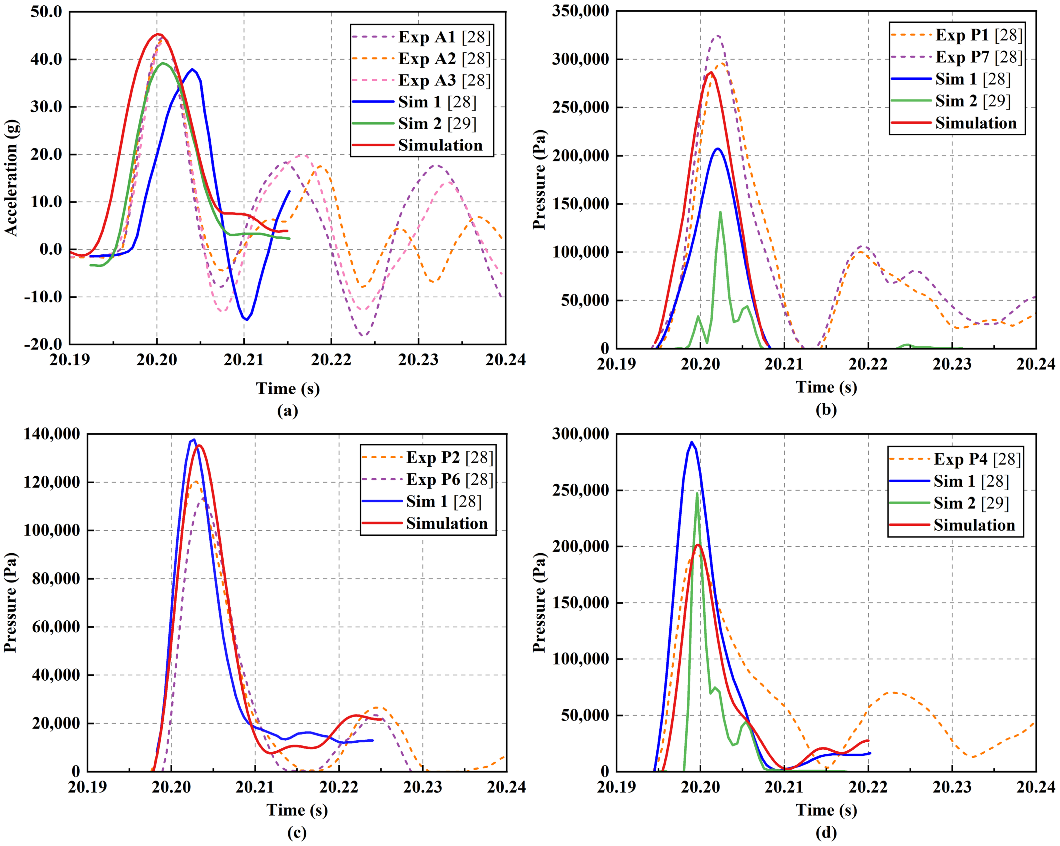
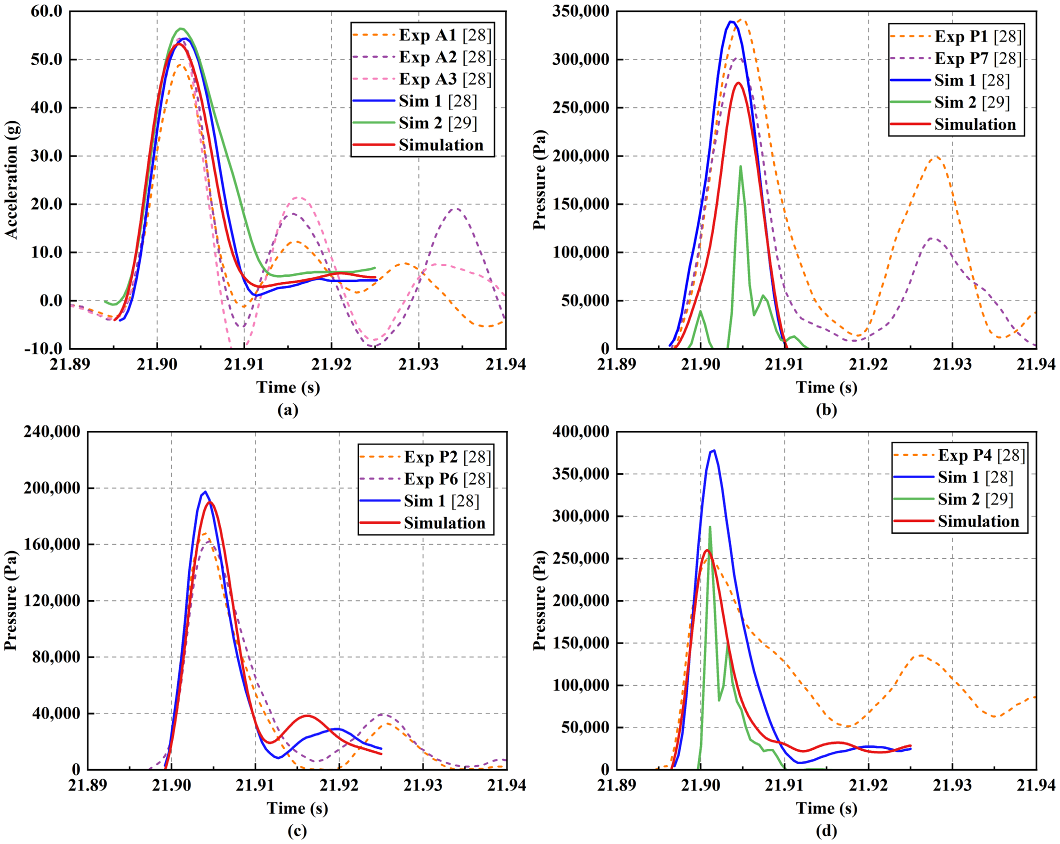


Fig. 7 At 3 m/s, time histories of acceleration and pressures[28][29]



(a) (b) (c) (d)

Fig. 8 At 8 m/s, time histories of acceleration and pressure[28][29]



(a) (b) (c) (d)

Fig. 9 At 10 m/s, time histories of acceleration and pressure[28][29]

Building upon the findings of previous research, this study further refined the model parameters. The entire water pool model is represented using a particle-based approach. The particle spacing of the present simulation is chosen taking into account calculation accuracy and computational cost. To enhance stability in contact calculations, merged node connections are established between various models. The soft constraint formulation is implemented, and the scale factor for constraint forces of the soft constraint option is set to 0.5. The correlation between numerical and experimental peak accelerations at different velocities is significantly improved, with errors kept within 5%. Pressure values is the most challenging to measure. Beneath the stiff areas, the optimization of the parameters demonstrated noticeable improvement, with errors controlled within 10%. In the soft areas, the predicted values aligned closely with experimental results when no plastic deformation occurred in the material. While there are still some errors in the predicted values at the lateral positions beneath the stiff areas, notable progress is observed compared to previous results. All errors of simulation are within 20%, with six peak data errors below 5%, showcasing strong correlations. Particularly, peak accelerations exhibit excellent agreement with experimental values across different impact velocities.

4. Simulation of Different Sub-floor Shapes

Three different shapes of helicopter sub-floor structures are established, as shown in Fig 10. The sub-floor shapes include the flat, the cylindrical surface with transverse curvature, and the ellipsoid with double curvature. A coupled FE-SPH method is employed, which is not only capable of predicting non-linear structural collapse, but also represents the underlying kinematics of water and pressure transmissibility. As the weight of the floor structure is primarily concentrated on the trolley, weight variations among the models are less than 1% of the overall weight. Therefore, the impact of weight variation on the results can be disregarded. The impact velocities are 3 m/s, 8 m/s and 10 m/s, respectively.

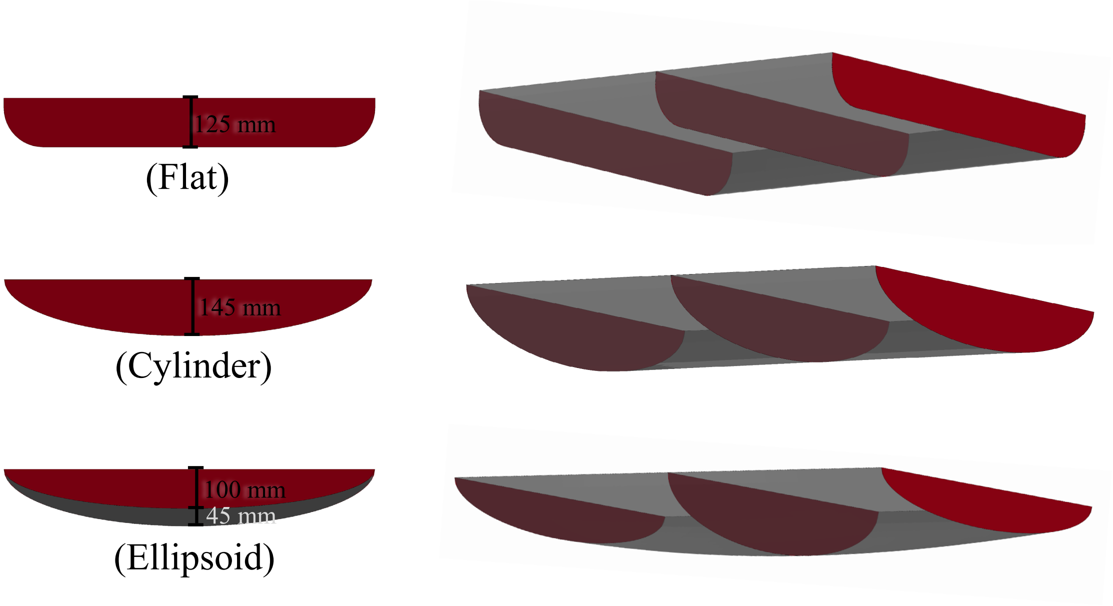
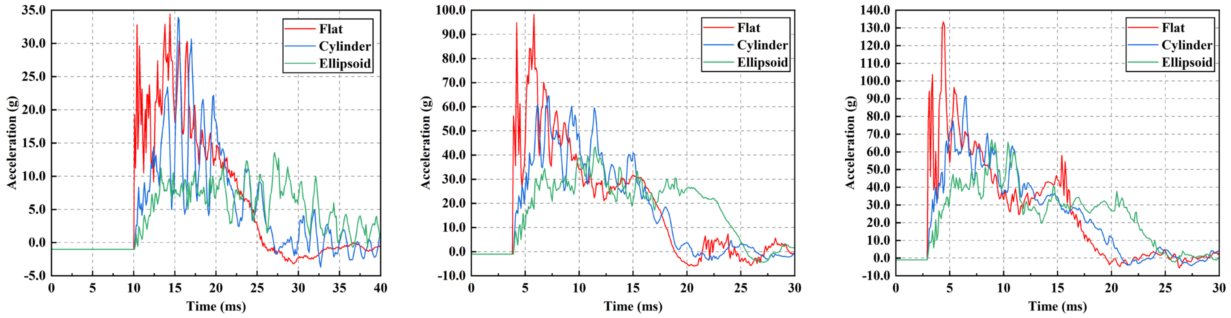


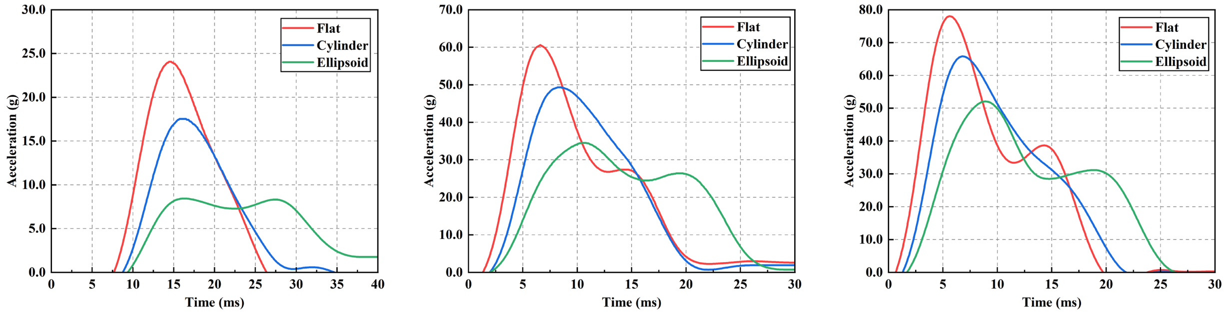
Fig. 10 Under floor models

Acceleration data are collected from the top plate, and the values represent the average acceleration at various points on the plate. As depicted in Fig 11, the peak acceleration upon water impact exhibits a gradient distribution among the flat, cylinder, and ellipsoid shapes. the flat surface experiences the highest impact acceleration, while the ellipsoid surface encounters the lowest. Experimental results demonstrate that appropriately shaped surfaces can effectively mitigate the impact during structural water entry. With increasing velocity, the deceleration effect persists, although its efficacy diminishes gradually. In short, at different speeds, the ellipsoid is the best of the three shapes.



3 m/s 8 m/s 10 m/s

(a) Acceleration-Simulation

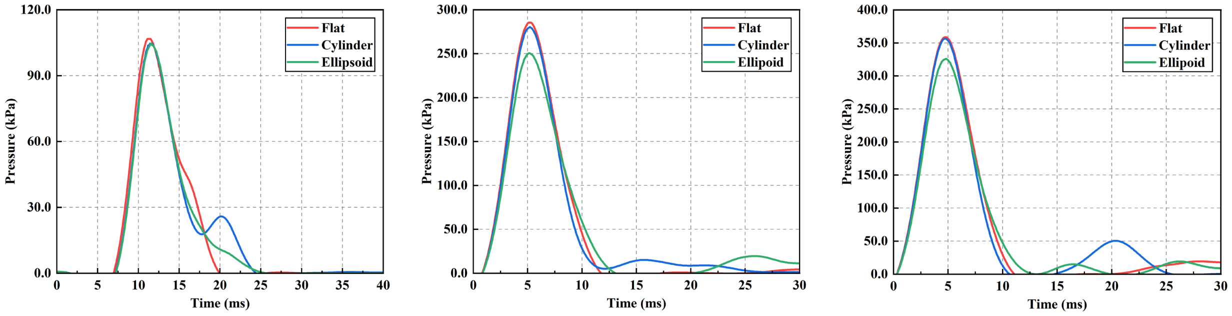


(a) 3 m/s (b) 8 m/s (c) 10 m/s

(b) Acceleration-Simulation CFC_60

Fig. 11 Time history of acceleration

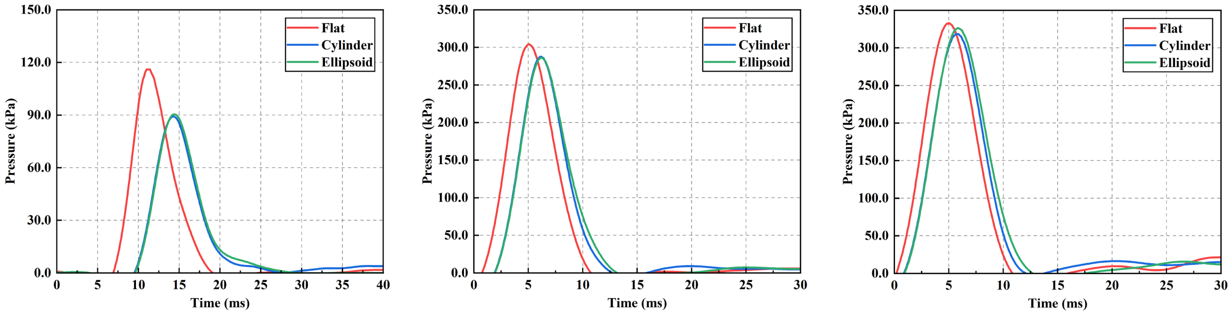
The P4 pressure sensor is positioned at the central location of the under floor. And it is the initial contact point with water after the descent of all structures. The pressure-time history of P4 is illustrated in Fig 12. As the structure enters the water at 3 m/s, the peak pressures at different locations on various under floor structures are nearly identical. With an increase in velocity, the pressure levels on the flat and cylinder surfaces remain consistent, while the advantage of the ellipsoid shape becomes apparent, displaying significantly lower pressures on its skin surface compared to the other two structures.



(a) 3 m/s (b) 8 m/s (c) 10 m/s

Fig. 12 Time history of pressure P4

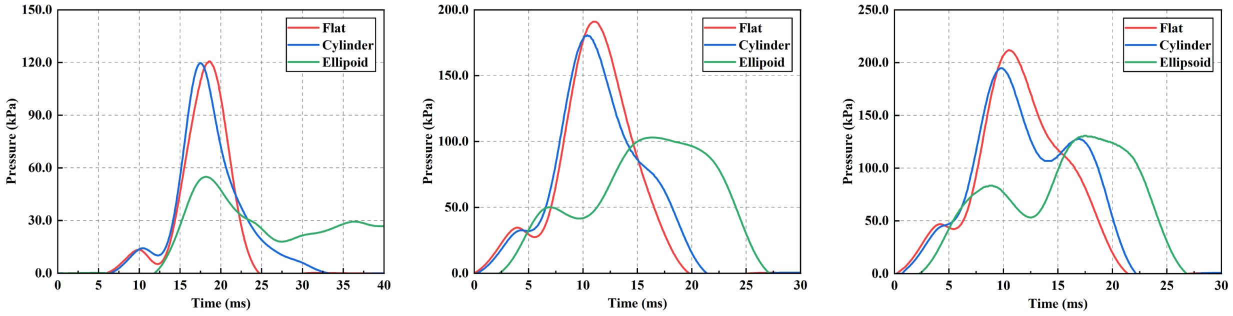
The pressure-time curve for P1 is depicted in Fig 13. As the structure enters the water at 3 m/s, the pressure at P1 on the flat surface is significantly higher than on the curved surface. With an increase in velocity, the difference between the two gradually diminishes. The pressures at P1 for the cylinder and ellipsoid surfaces are nearly identical, and at a velocity of 10 m/s, the slightly smaller peak pressure on the ellipsoidal surface compared to the cylinder.



(a) 3 m/s (b) 8 m/s (c) 10 m/s

Fig. 13 Time history of pressure P1

From Fig 14, it can be observed that, due to the curvature of the ellipsoid surface deflecting the water flow radially, the surface deformation changes relatively little, thereby minimizing the loads at these locations. At 3 m/s, the pressure at P2 on the ellipsoid surface is comparable to that on the flat surface, as the curvature of the ellipsoidal surface is relatively small. With an increase in velocity, the superior structural resistance of the cylinder surface over the flat surface gradually becomes apparent. In general, the ellipsoidal sub-floor reduces pressures at the side observably due to the bi-directional curvature.



(a) 3 m/s (b) 8 m/s (c) 10 m/s

Fig. 14 Time history of pressure P2

Fig 15 illustrates the plastic strain nephogram at various time for different models when the velocity is 8 m/s. The distribution of plastic strain on the ellipsoid surface is more uniform, with severe plastic deformations not extensively concentrated. The ellipsoid under floor has a significant inward deflection either side of the frame. It is able to better transfer the load from the skin to the frame, so the main energy absorbing components are utilized in an efficient manner.

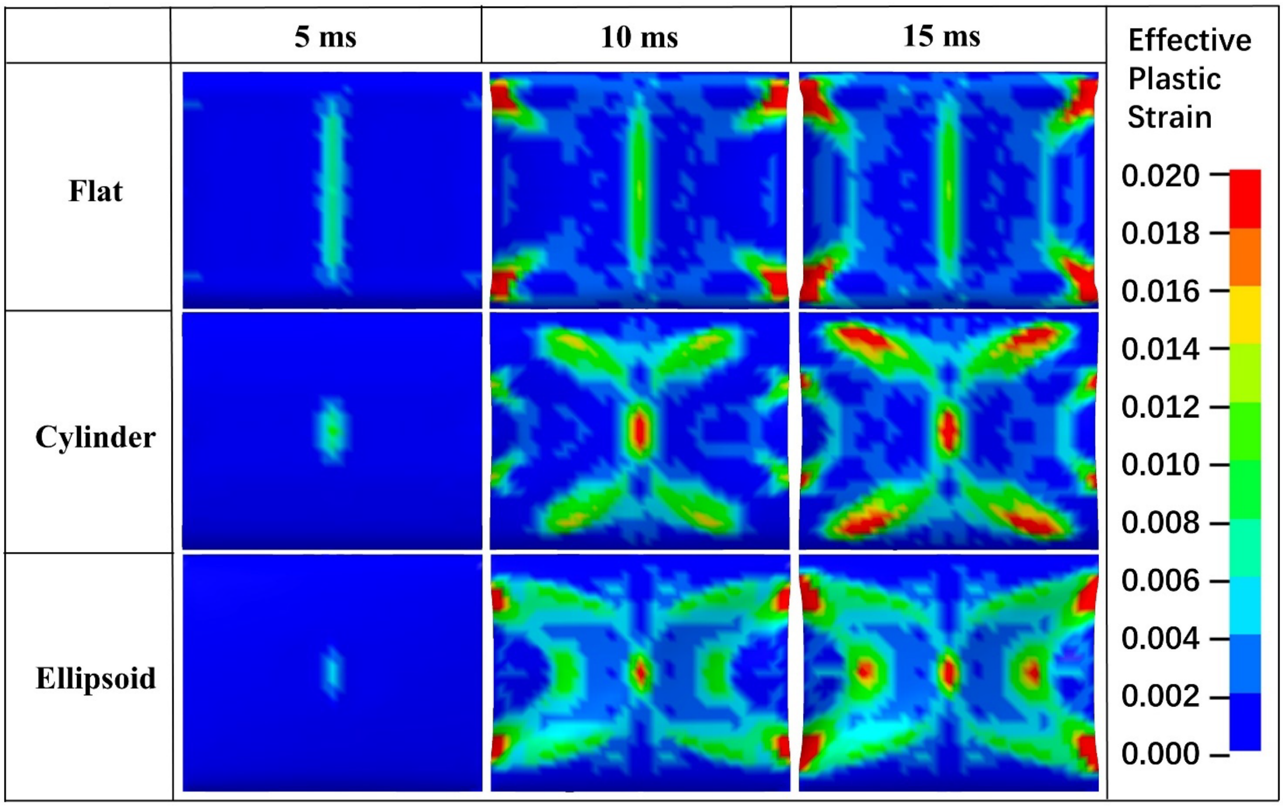


Fig. 15 Time histories of effective plastic strain at 8 m/s

The deformation of the skin during ditching is investigated. Considering that the mechanical properties of the aircraft floor frame are much better than the skin, it is worthwhile to set the frame as a rigid body to compare the changes in skin deflection. In addition, a longitudinal stiffener was installed at the longitudinal centerline of the new set of models, aiming to analyze the influence of longitudinal stiffeners on skin deflection during water impact. Fig 16 shows the vertical displacement contour map when the skin undergoes maximum deformation. When there is no longitudinal stiffener, the maximum deformation positions of the skin are all on the centerline. On this line, the midpoint is supported by the frame and no deformation occurs. The location of maximum deformation of the skin is not right in the middle of the two frames, but more towards the edge frames. The area of deformation of the flat floor is the largest, and the deflection value is also the largest, at 21.2 mm. The maximum deflection of the cylindrical floor is 18.3 mm. The deformation area of the ellipsoidal floor is the smallest, and the maximum deflection value is also the smallest, at 16.6 mm. After installing a longitudinal stiffener, the original maximum deformation positions are supported by the stiffener, and the deflection of all skins are greatly reduced, as shown in Fig 17. The maximum deflection of the flat, elliptical, and ellipsoidal floors decreases by 35.8%, 41.5% and 72.9% respectively. The maximum deflection of the ellipsoidal floor with a longitudinal stiffener is only 4.5 mm. The results indicate that under water impact conditions, the longitudinal stiffener can significantly reduce skin deformation, and the elliptical floor has better mechanical performance than flat and cylindrical floors.

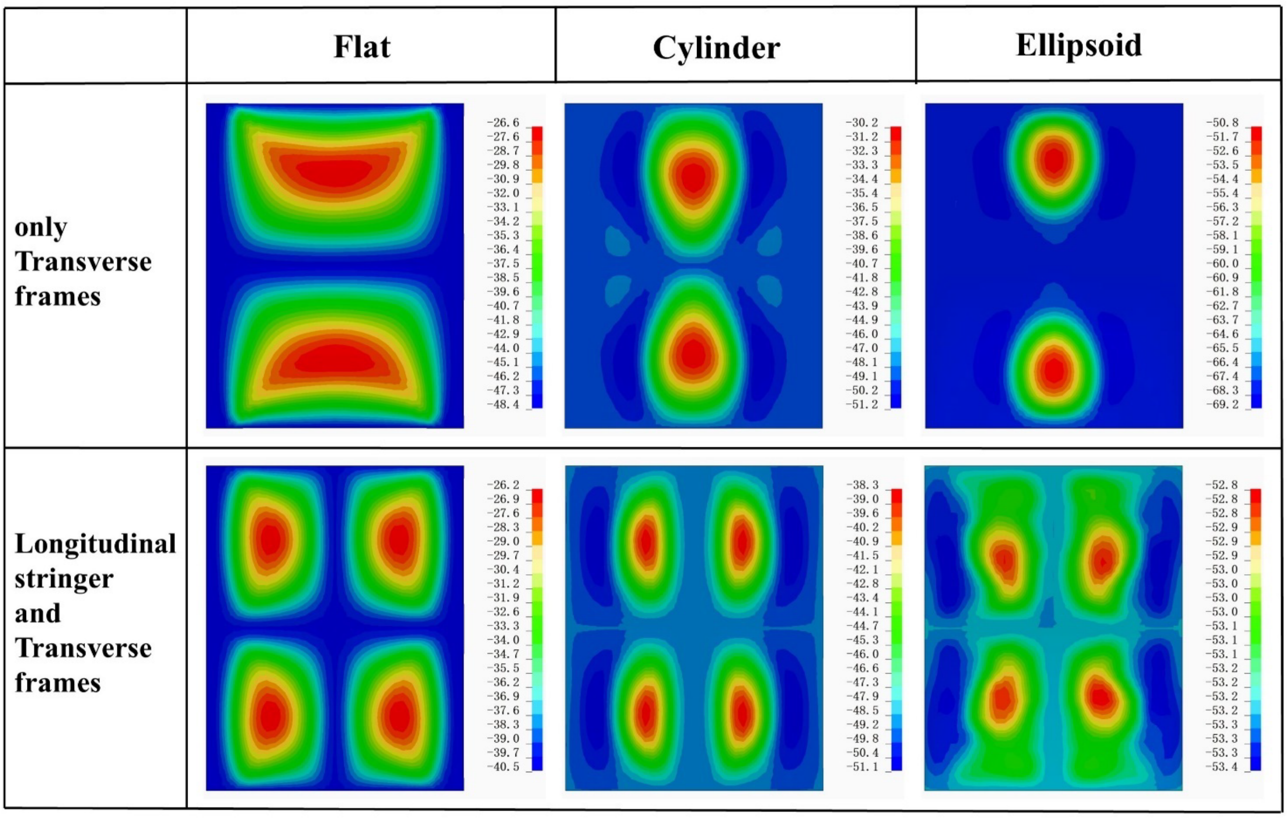


Fig. 16 The vertical displacement of the skin at 3 m/s

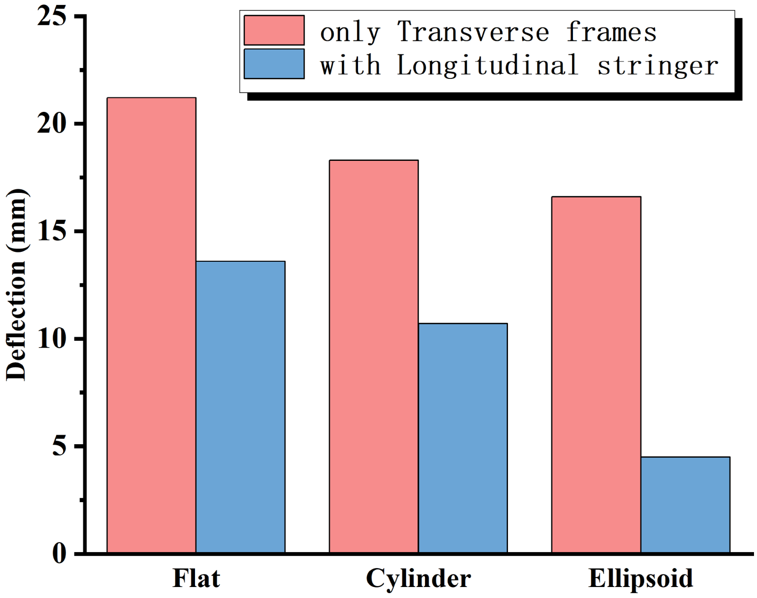


Fig. 17 Maximum deflection value of the skin at 3 m/s

Conclusions and Future Works

A numerical simulation of the structures impact water is presented based on a coupled FE-SPH method. Numerical model validation is conducted with the experiment in the SPLASH project at the Laboratory for Impact Tests on Aerospace Structures. The peak acceleration and peak pressure at different locations on the under floor during water impact are investigated. The model is refined by adjusting contact parameters and particle density, resulting in simulation outcomes that closely align with experimental values.

Furthermore, the better shape of aircraft sub-floor structure is investigated in the case of ditching. This work proposes three types of aircraft sub-floor structures, including the flat under floor, the cylindrical under floor, and the ellipsoidal under floor, designed to enhance impact resistance capacity to ensure skin integrity after water impact. The results show that the ellipsoidal under floor experiences lower peak acceleration during ditching compared to other shapes, effectively mitigating the impact forces on the structure. The curvature of the ellipsoidal surface diverts the water flow decreasing pressure loads at the sides. Additionally, the effect of the longitudinal stiffener on skin deflection during water impact was investigated. After the installation of longitudinal stiffeners, the deflection values of all skins decreased significantly. The maximum deflection of the ellipsoidal hull at 3 m/s is only 4.5 mm, much lower than the other shapes. And the plastic strain distribution on the ellipsoidal sub-floor is more uniform, improving resistance to rupture. Therefore, the ellipsoidal floor structure had better mechanical properties than the flat and cylindrical floor structures in the case of water impact.

In the roadmap of ditching for future development, a major challenge in predicting ditching loads is the inclusion of the effects of high velocity water flow on airframe loads, including effects such as cavitation, suction and aeration. To achieve the following objectives, it is necessary to investigate numerical methods and simulation, as well as experimental testing. Firstly, the methods should be demonstrated on representative aircrafts that use metallic, composite, and composite-metallic hybrid structures. Secondly, there is a significant difference in load between aircraft with horizontal speed and a helicopter during ditching. New experimental facilities need to be developed for in-water impact testing of structural components at horizontal velocities of 50-80 m/s to provide more realistic experimental data. Thirdly, to improve cavitation modelling, it is necessary to develop new models that consider the evolution of void fraction and the changing vapor and liquid during cavitation.

Acknowledgments

The present work is supported by the financial support from the National Natural Science Foundation of China (No. 52172356) and Hunan Provincial Natural Science Foundation of China (No. 2022JJ10012).

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