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NUMERICAL SIMULATION AND EXPERIMENTAL VALIDATION OF GUIDED DITCHING TESTS

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Abstract. The oblique water entry of structures with high horizontal speed is investigated in this work. First, the necessity of aircraft ditching analysis as well as the requirements for numerical tools to simulate aircraft ditching are described. The paper provides a brief explanation of an extensive experimental campaign of guided ditching tests carried out in the SMAES project. These tests are then simulated using a hybrid Smoothed Particle Hydrodynamics – Finite Elements modeling approach. Most recent advances done in computational modeling are presented and applied to the guided ditching simulation model. Comparison with experimental data in terms of force and strain results is established with the aim to validate the numerical model. Good correlation could be proven for test cases with purely elastic as well as deformable aluminum panels.

1 INTRODUCTION

The activities are motivated by the necessity to improve understanding of the critical processes during ditching which refers to an emergency landing of an aircraft on water. This is of special interest to the aircraft industry, who must prove compliance to specific ditching paragraphs of the airworthiness regulations as part of the aircraft certification process. In order to assess ditching capabilities of an aircraft, simulation tools which can model this fluid-structure interaction may be used. However, existing simulation tools commonly display strong limitations in the accurate description of the event and need to be improved.

The ditching problem is complex, both from the computational and the experimental viewpoint, due to several reasons: it is characterized by sharp gradients with extremely small time and spatial scales, such as highly localized pressure distributions, which make it — even more than in other water entry problems — extremely challenging to capture them. This is further complicated by the requirement to capture non-linear structural deformation, including potential failure, together with the description of the flow features. Moreover, due to the high speed involved and depending on the shape of the body, hydrodynamic phenomena like hydroelastic coupling, suction, ventilation, air cushioning and cavitation are likely to occur and affect the fluid-structure interaction [1, 3, 24].

Hence, two key components are needed: (1) reliable experimental data which enhance the understanding of the involved physical phenomena and support the validation of the computational models and (2) development and improvement of appropriate numerical simulation tools over the state of the art which help to overcome current limitations.

2 EXPERIMENTAL CAMPAIGN

In order to support the development of appropriate computational models, detailed experimental data is needed for validation. The only results available in this context date back to the 1950s [22]. Although very important for that period, the available data is not adequate to support code development, as there is no information about the structural deformation and global loads. Moreover, the time resolution seems poor compared to today's state of the art. The absences of suitable data lead to the requirement for a new experimental campaign of guided ditching tests to provide test data at representative impact conditions.

2.1 Test facility and setup

As part of the EC-funded research project SMAES [2], a large high speed ditching facility has been designed, built and installed at the end of towing tank #1 of the CNR-INSEAN site in Rome, Italy. The chosen test setup aims to be as realistic as possible by using quasi full scale velocities and typical aircraft structures, i. e. a skin panel riveted to a frame. The test specimen impact guided (fixed pitch angle and flight path) representing the high aircraft inertia which may be assumed to prohibit rotation (pitching) in the short duration regarded.

The new experimental facility consists of a guide track and a catapult system which accelerates the trolley holding the test specimen to horizontal impact velocities in the $30 - 45\,m/s$ range (see figure 1). Parameters that are varied include approach and pitch angle, shape of the structural panel, panel thickness and material, leading to a total of 65 tests. All test specimen measure $1000 \times 500\,mm$ and are equipped with up to 44 sensors measuring velocities, accelerations, forces, strains and pressures. The on-board acquisition system records data at a sampling rate of $200\,kHz$ (pressure and synchronization) and $20\,kHz$ (other) during the test. [12]

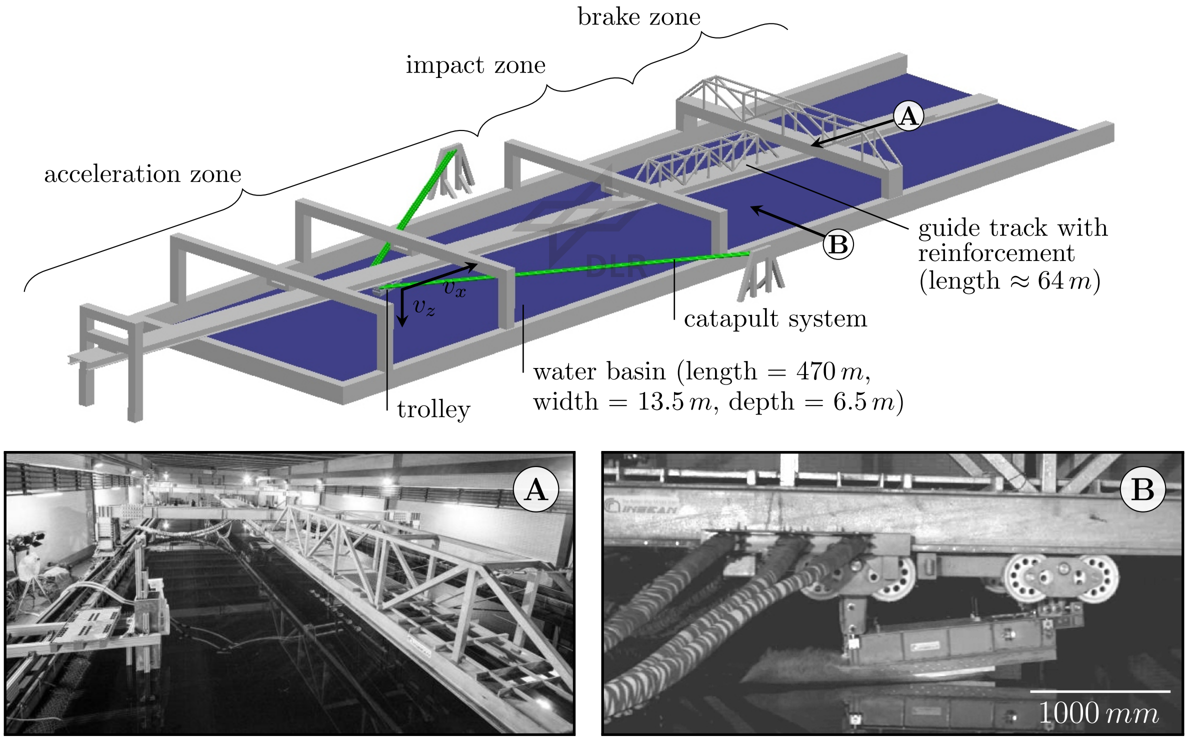


Figure 1: Schematic overview of guided ditching experimental facility (top), photograph of impact zone seen from A (left) and observation during impact stage using an external high-speed camera seen from B (right).

In addition to a lateral high-speed camera, an underwater camera system was installed to record high-speed movies of the impact seen from below. These recordings are beneficial to help understanding measurements in detail as they reveal the occurrence of hydrodynamic phenomena such as air entrapment or cavitation but also the propagation of structural deformations.

2.2 Test program and results

One main concern prior to the experimental campaign was the test-to-test dispersion, as throughout the test program it was not feasible to repeat each test condition more than three times which required a certain level of confidence. Two series of test-to-test dispersion experiments ($v_{x,0} = 40\,m/s, v_{z,0} = -1.5\,m/s, \alpha = 4$ and 10°) with ten repeats each were conducted. A high level of repeatability could be proven based on Pearson correlation coefficients while the highest repeatability was observed at 10° pitch angle. A followup analysis of the underwater high-speed recordings allowed to attribute this to entrapped air in the 4° tests which is responsible for larger oscillations in pressure results.

So-called purely elastic test cases focus on the analysis of flow related results, such as pressure distributions, whereas deformable test cases are conducted with the focus on the structural behavior under water pressure loading. The detailed evaluation of all experimental results would exceed the focus of this paper where test results are mainly used for validation of computational models (section 4). Nevertheless, initial, more detailed analysis of test results can be found in [13, 14]. Further investigation is ongoing and findings are to be published in related journals as well as international conferences.

3 NUMERICAL MODELING APPRAOCH

Simulating ditching involves large deformations and complex free surface geometries. In general, mesh-based Lagrangian methods like finite elements (FE) are not most suitable to accurately describe such interfaces as they may suffer from mesh distortion. Mesh-free particle methods, e. g. the Smoothed Particle Hydrodynamics (SPH) method, provide a more natural methodology to handle such cases.

The present modeling approach uses SPH to represent the fluid domain while FE is used to discretize the structures. Note that the air phase is not explicitly modeled because it would significantly increase the computational effort while only having small influence on results for regarded cases in this work. Nevertheless, when the angle between impacting structure and water surface is small, an air cushioning effect may affect results [6].

Presented results are generated using the commercial explicit finite element software package VPS/PAM-CRASH (ESI Group, www.esi-group.com) with embedded SPH solver. The guided ditching simulation model shown in figure 2 will be described in the following.

3.1 Structural modeling

In order to analyze structural loads in simulations, structural models are composed of classic finite elements, i. e. beam and shell elements. For the guided ditching simulations, elastic-plastic material models are used to allow for structural deformations including rupture. Structural details such as rivets are modeled using point link elements in order to represent realistic boundary conditions in reference to the experiments. Load cells are explicitly modeled (discretized with beam elements) for direct comparison to test results. The movement is prescribed by an initial velocity $\mathbf{v}_0$ equal to the target velocity of the experiment. Moreover, the mass of the trolley model is adapted to the real trolley mass.

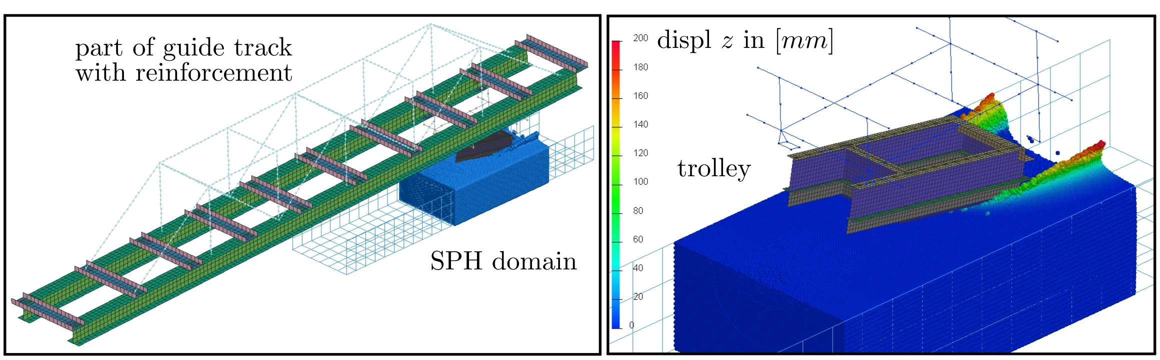


Figure 2: Guided ditching simulation model and zoom on trolley with SPH domain.

The coupling of SPH and FE is achieved using node-to-segment penalty contacts between structure and particles. Both methods are Lagrangian which facilitates their use within one code.

3.2 SPH method

Initially proposed independently by Gingold & Monaghan [5] and Lucy [15] for astrophysics in 1977, SPH has become popular in the field of free-surface flow starting in 1994 [17]. Nowadays, the SPH method is a versatile mesh-free method which is well suited to solve fluid-structure interaction problems.

The basic equations of the weakly compressible (WC)-SPH method to be solved for fluid dynamic problems are mass conservation, Euler equations (momentum conservation) and energy conservation as in (1).

$$\frac{d\rho}{dt} = -\rho\nabla\cdot\mathbf{v} \qquad \frac{d\mathbf{v}}{dt} = -\frac{1}{\rho}\nabla p \qquad \frac{du}{dt} = -\frac{p}{\rho}\nabla\cdot\mathbf{v} \tag{1}$$

Above symbols refer to: density ρ, time t, velocity $\mathbf{v}$, pressure p and specific internal energy u. The above system of differential equations comprises five equations but has six unknowns which requires one further equation to close the system. This is achieved by adding an equation of state (EOS) relating pressure to density. The frequently used Tait EOS (eqn. 2) [23] with reference pressure p_0, speed of sound c_0, ratio of current over initial mass density ρ/ρ_0 and adiabatic exponent γ of the fluid is used.

$$p(\rho) \;=\; p_0 + \frac{c_0^2\,\rho_0}{\gamma}\left[\left(\frac{\rho}{\rho_0}\right)^{\gamma} - 1\right] \tag{2}$$

The Tait EOS allows representing a fluid with artificially increased compressibility. This approach is feasible for cases where flow velocities $\mathbf{v}$ remain well below the corresponding speed of sound (satisfying $c_0 \geq 10\,max(\mathbf{v})$) and hence compressibility effects are insignificant [17, 18].

A quintic Wendland kernel with radius $2h$ is used because it was found to reduce or even alleviate the problem of standard SPH where particles tend to coincide. Numerical stability is treated by adding the Monaghan-Gingold artificial viscosity term [10, 16] to the momentum and the energy equation.

For more detailed reviews on the fundamentals and the development of the SPH method the reader is referred to publications by Monaghan [19] and Randles & Libersky [20].

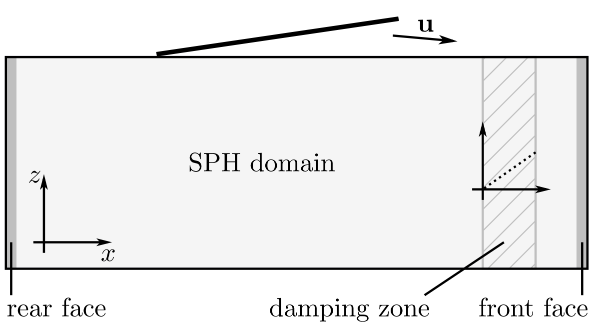
3.3 Enhanced SPH method

Simulating (aircraft) ditching required a list of improvements over the state of the art to enhance the accuracy and efficiency of existing numerical tools. Recent advances are summarized below.

Particle regularization techniques – Due to the violent nature of the regarded fluid-structure interaction, the particle distribution may become irregular over time. Additionally, standard SPH may suffer from unphysical clumping which is well known to be one reason for inaccuracies of the method. Particle regularization methods aim to alleviate these problems by locally redistributing particles (distortion smoothing). Three methods, namely diffusion smoothing, color gradient smoothing and the particle packing algorithm, were analyzed and found to improve results [8, 9].

Pressure correction methods – Furthermore, standard WC-SPH is known to produce a high level of noise in pressure results. This deficiency may be counteracted by application of pressure correction methods which aim to yield a more regular pressure distribution. Two methods, the density re-initialization by Shepard filtering and the Rusanov flux, were investigated. Fundaments and numerical observations of these two correction methods are documented in [9, 21]. It should be noted that these corrections give superior results and hence they are essential for the regarded application.

Translating periodic boundary conditions – The ditching event is computationally challenging because it requires a fine particle resolution but also a large fluid domain. This combination leads to large amounts of particles which drive the computational time excessively. To deal with this, the amount of particles used for the simulation must be significantly reduced in order to allow for efficient computation. One method to accomplish this is the use of translating periodic boundary conditions [7, 9]. The main idea is to model particles only where needed. Hence a much smaller domain of particles is constrained to move along with the structure, i. e. the aircraft or a panel of the guided ditching test. Particles leaving this domain through the rear face re-enter at the front face restoring their initial positions for directions other than that of translation. A special damping algorithm (linear interpolation over defined zone) is used in the proximity of the front face in order to avoid disturbances initiated by particle interactions across the periodic boundary. A schematic illustration is given in figure 3 (left).



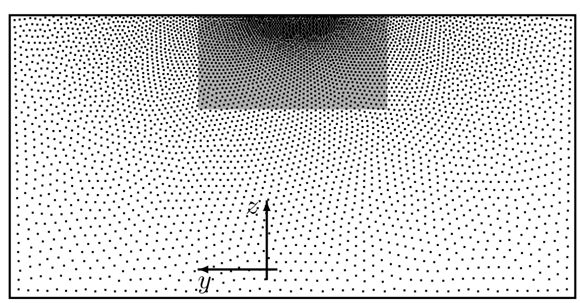


Figure 3: Enhancements of SPH model: schematic view on translating periodic boundary condition with special damping zone (left) and initial non-uniform particle distribution generated using extended weighted Voronoi tessellation starting from a simple rectangular patch of uniformly spaced particles occupying only 1/9 (shaded) of the final volume (right).

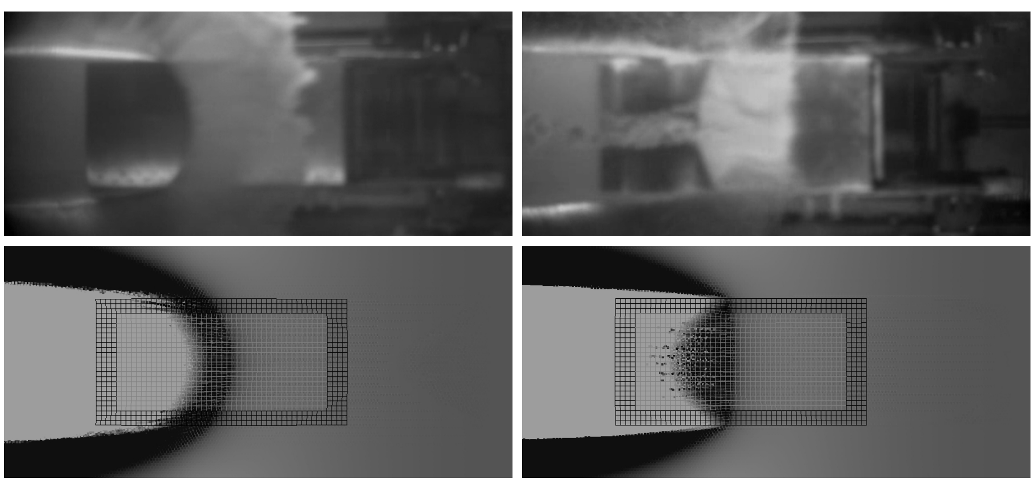
Initial non-uniform particle distributions – In addition, recent work concentrated on the use of non-uniform initial particle distributions aiming for further reduction of the amount of particles. This approach funds on the concept of using fine particles in areas where fluid-structure interaction requires a high resolution and larger particles towards the boundaries. The approach seems to be in conflict with the SPH method which requires uniform/regular spacing. Therefore, it has to be ensured to generate a distribution which is globally non-uniform but locally quasi-uniform. One means to generate such a distribution is given by the extended weighted Voronoi tessellation (EWVT) developed by Groenenboom [10, 11] which is based on a technique published by Diehl et al. [4]. Figure 3 (right) shows a cross section of such a distribution which was generated from a simple rectangular patch of uniformly spaced particles occupying only 1/9 of the final volume.

4 NUMERICAL RESULTS AND VALIDATION

In this section comparison of numerical and experimental results is established with the aim of validating the developed model. Note that only exemplary results are presented in this work due to the large extent of the experimental campaign which would exceed this paper. Nevertheless, presented comparisons will allow analyzing the influence of certain test parameters, i. e. the impact velocity and the curvature of the structure.

4.1 Purely elastic panels

A qualitative comparison of experimental underwater images with numerical results shows similar behavior in terms of bow wave formation and shape; see figure 4 for exemplary test cases with 15 mm thick, convex (left) and concave (right) aluminum panels.



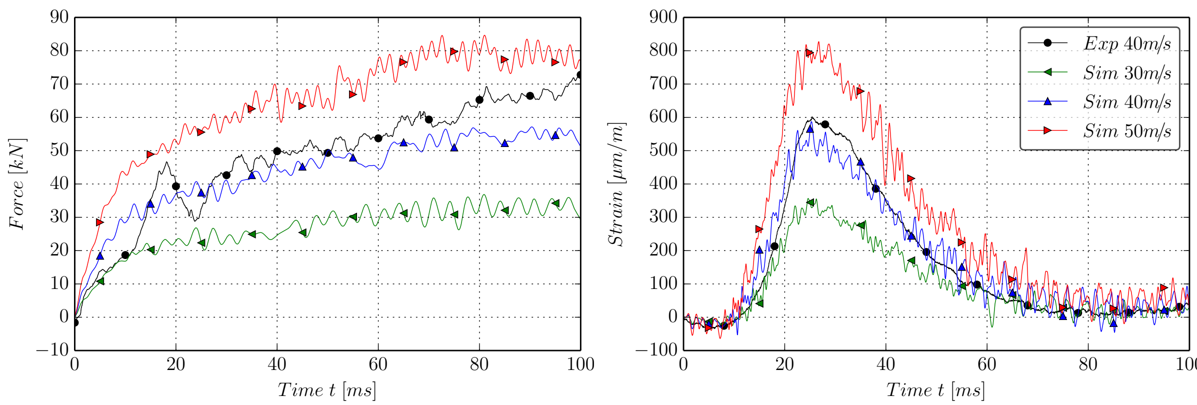
(a) Convex panel

(b) Concave panel

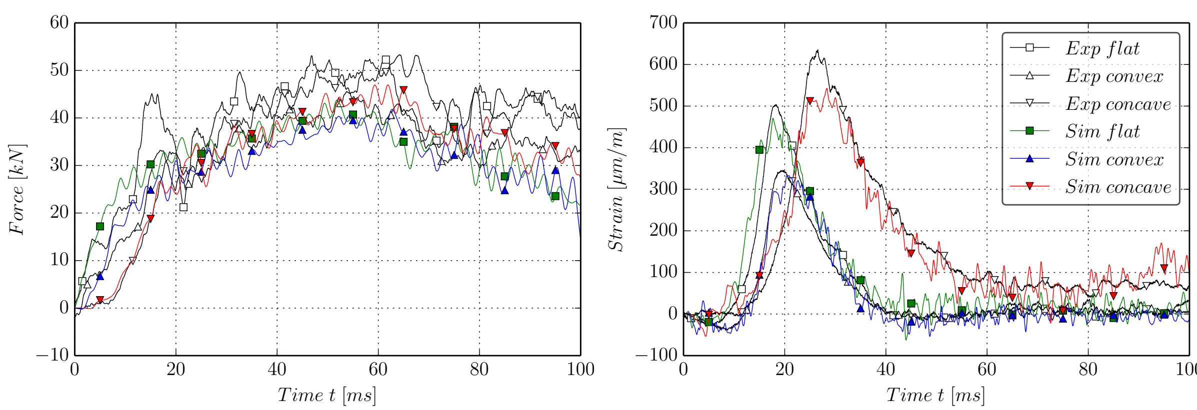
Figure 4: Comparison of underwater images of experiment (top) with numerical results (bottom) at a time approx. 30 ms after first impact. Test cases with purely elastic, 15 mm thick aluminum panels, 6° pitch angle and 40 m/s horizontal impact velocity.

Depending on the panel shape, the bow wave is curved positive or negative. This three-dimensional nature of the flow is stronger for larger pitch angles (not shown here) because the fluid is less constrained underneath the impacting structure. In the experiment a stripe of bubbles can be observed in the center of the concave panel (figure 4 top right) which points at air being entrained due to the shape of the panel.

Quantitative comparison in figure 5 shows very good correlation both for force and especially for strain results. Forces in the computational model are extracted using numerical load cells at the same positions as in the experiment. Summed maximum force values in z-direction of the panel increase considerably with the regarded impact velocities. Strain results show a similar increase with the impact velocity but they remain still well within the purely elastic range. As anticipated, loads and strains are slightly higher for concave cases compared to convex cases due to the additional constraint the fluid is facing; see figure 5 (bottom).



(a) Variation of impact velocity of flat panel at 10° pitch angle.



(b) Variation of panel shape at 6° pitch angle and 40 m/s horizontal impact velocity.

Figure 5: Summed force-time history of load cells in z-direction of the panel (left) and strain-time history for gauge in x-direction on the center line of the panel (right). Purely elastic test case using 15 mm thick aluminum panel with variation of impact velocities (top) and panel shape (bottom).

Despite very good agreement of force and strain results, the pressure-time histories are still suffering from considerable oscillations. In a simplified two-dimensional model this could be overcome by refining the particle distribution. At this time, it is intended to govern this issue by application of non-uniform particle distributions with appropriate refinement in the proximity of the panel as discussed in section 3.3.

4.2 Deformable panels

After numerical results using purely elastic panels showed good correlation with experimental ones, the next step was to correctly simulate the behavior of deformable aluminum panels. New challenges arise as, for instance, correctly reproducing deformations requires a finer discretization of the structure which reduces the critical time step of the simulation. This emphasizes once more the necessity of efficient numerical modeling.

Figure 6 (top) illustrates experimental as well as numerical force- and strain-time histories of deformable test cases using panel thicknesses of 0.8 and 3.0 mm. In comparison to purely elastic cases, loads in deformable cases increase with reduced panel thickness be-

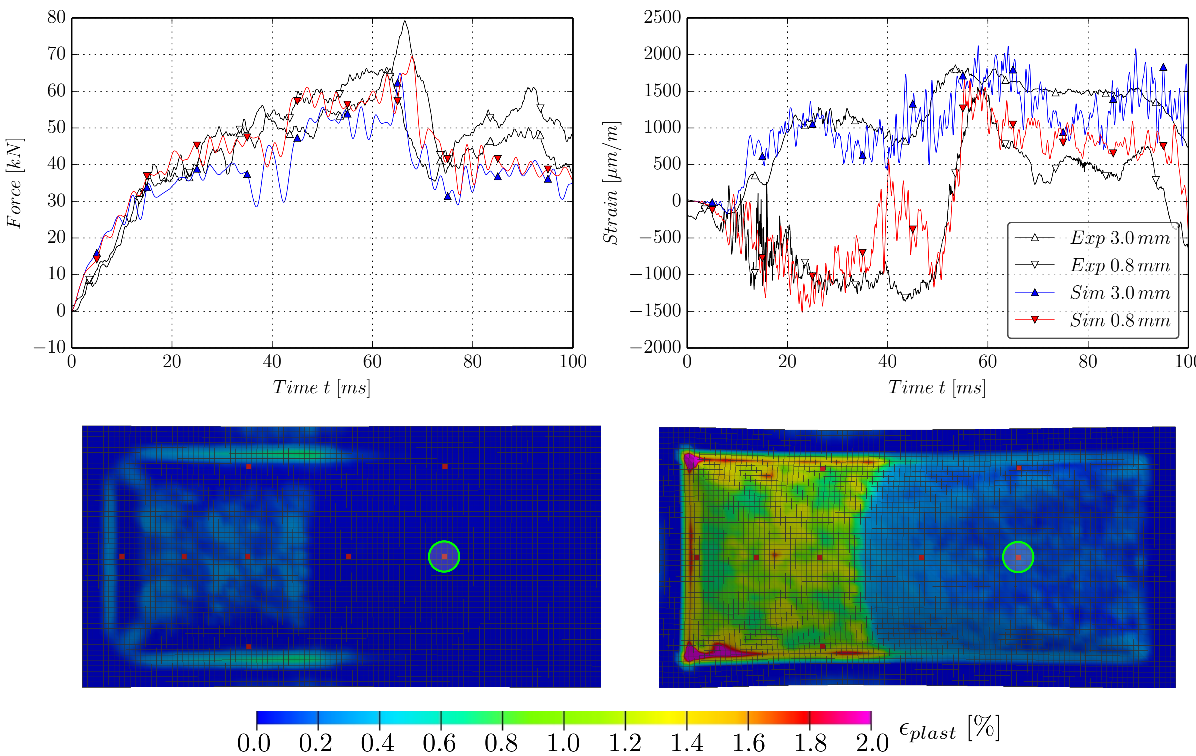


Figure 6: Experimental and numerical results of deformable test cases using thin flat aluminum panels at 40 m/s horizontal impact velocity and 6° pitch angle. Summed force-time history of load cells in z-direction of the panel (top left) and strain-time history for gauge in y-direction on the center line of the panel (top right). Contour plots of maximum plastic strain over thickness for test cases using 3.0 mm (bottom left) and 0.8 mm (bottom right) thin aluminum panels at $t \approx 30\,ms$. Strain gauge positions used for time history plot are encircled in green color; others are highlighted in red color.

cause of the inherent increasing deformation into a concave shape (regarding the studied thickness range and recalling that rupture occurred neither in experiments nor in simulations). Measured strain values are in the elastic regime; however, experiments as well as simulations show permanent deformation. The apparent discrepancy is due to the fact that highest strains are found in the proximity of the inner edge of the frame which holds the panels. This could be justified by analyzing strain contour plots of the simulations as shown at the bottom of figure 6. The high strain zones are very local and do not coincide with the strain gauge positions in the experiments.

Overall, force and strain results compare well between experiments and simulations which allows validating the chosen simulation approach for deformable and purely elastic metallic panels.

5 CONCLUSION

The paper emphasizes the necessity as well as the requirements for numerical tools to successfully simulate aircraft ditching especially when local deformations shall be considered and the risk of panel rupture has to be assessed. A brief introduction to the experimental campaign of guided ditching tests was given. Due to the number and complexity of the physical processes relevant for ditching, achieved full-scale experimental results provide a significant step forward for the investigation of the phenomena involved. Moreover, a hybrid modeling approach utilizing SPH to represent the fluid and FE to model structures was presented. Most recent enhancements of the SPH method applied to the guided ditching simulation model were discussed. Guided ditching tests could successfully be modeled using this coupled SPH-FE approach wherein the enhancements of the SPH method are key to success. Comparison of strain and force results for purely elastic as well as deformable test cases shows good agreement. However, numerical pressure results in the proximity of the impacting structure are still challenging to capture due to the extremely small temporal and spacial scales of present pressure peaks.

In the next step of validation, experimental and numerical results of CFRP panels are to be compared in order to fully validate the simulation model. Future work will further address non-uniform initial particle distributions with the aim of (1) further reduction of computational effort and (2) improvement of pressure results. Therein, the ease of use is an important objective. Moreover, the inclusion of a model for the suction effect and other hydrodynamic phenomena will be pursued. The long term objective is a full-scale deformable aircraft ditching simulation.

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