EXPERIMENTAL DITCHING LOADS ON AERONAUTICAL FLEXIBLE STRUCTURES

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Keywords: structural dynamics, dynamic loads, ditching loads.

Abstract: Ditching is an aircraft emergency condition that ends with the planned impact of the aircraft against water. Four main phases may be considered in a ditching event: Approach, Impact, Landing and Floatation

This paper addresses some aspects of the second phase, an extreme case of fluid-structure coupling were high pressures may be developed during the impact of the sliding aircraft with water, which in turn may cause rupture of the structure, jeopardizing the required safe evacuation of crew and passengers.

For completeness, the paper recalls a description of the ditching tests performed within the European funded research project SMAES. These tests were first used to derive a synthetic expression of the ditching loads based on rigid plates measurements.

For flexible plates, these synthetic pressures are in turn corrected using local deformation (in terms of local delta-pitch and local delta-z deformation) in an iterative process. When comparing the deformations obtained using Finite Element Method simulation and the corrected synthetic pressures versus deformation measurements, the results show very good comparison of deformation shape time histories, good comparison of time of occurrence of peak deformation in each pick-up and only fair comparison in terms of deformation levels.

1 INTRODUCTION

January 15th 2009 was a cold winter day in New York City. At 15:25 in La Guardia airport, Chesly “Sully” Sullenberger released the breaks of the Airbus A320 he was piloting bounded to Charlotte (NC). Just 208 seconds later he landed in the chilly waters of the Hudson River. All, crew and passengers up to a tally of 155, survived the ditching that day.

Ditching is a planned aircraft event that ends with controlled emergency landing in water. Four main phases may be considered in a ditching event:

- Approach: Characterized by aircraft/environment conditions before impact.
- Impact: Structural response during the impact (fluid-structure interaction).
- Landing: Subsequent motion of the aircraft until stoppage.
- Floatation: evacuation of passengers and crew.

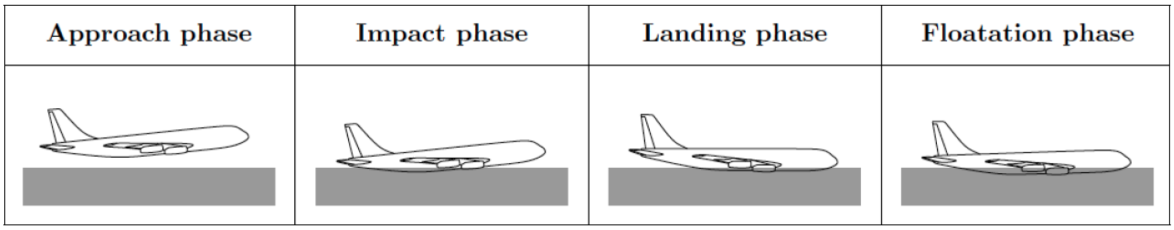

Figure 1: The Four Ditching Phases

This scenario is reflected in the Airworthiness Regulations that requires the aircraft manufacturer to take all necessary measures to minimize risk during ditching to allow the crew and passengers to evacuate the cabin safely.

At Airbus DS Military Transport Aircraft Aeroelasticity and Structural Dynamics department ditching has been a topic of continuous research for more than 12 years [1-5]. This interest is also shared by universities, research laboratories and industrial partners that have gathered together in the consortia of the European funded research project SMAES (Smart Aircraft in Emergency Situation). SMAES has devoted part of its activities to perform experimental ditching test. Data obtained from these tests can be used both, directly or indirectly to validate numerical tools / analytical theories for solving the fluid-structure behavior during ditching. The tests were performed at the Italian INSEAN institute in Rome.

The paper briefly describes the tests set up and execution. The tests consist on impact of plates against water at a similar horizontal speed than it could be expected in a real aircraft ditching event. 64 runs were performed covering a wide variety of parameters:

- Rigid and flexible plates with different stiffness,
- Flat plates, positive and negative curvature plates,
- Metal and composite,
- Pitch angles, horizontal speeds, etc.

Test measurements include accelerations, strains, pressures, forces etc.

The two papers presented at IFASD 2015 [4, 5] described respectively experimental ditching loads on rigid plates and numerical simulation of structural response. Present paper on IFASD 2017 is devoted to experimental ditching loads on flexible plates. From the structural dynamics standpoint, one of the most relevant parameters is the structural flexibility: it affects the local pressures distribution and in turn strains and loads. The alleviating effect of flexibility is one of the most important outcomes of the ditching test campaign and it has critical relevance for aircraft ditching certification.

The paper will show an analytical expression for the ditching pressures that will account for flexibility effects and that is function of 3 parameters:

- PMAX is the maximum peak pressure
- PSHAPE is a parameter that determines the shape of the decaying pressure from the peak PMAX. Thin shapes correspond to rigid plates. The larger the flexibility, the “thicker” the shape of the pressure function.
- PF is the final pressure at the end of the time history

Paper [4] showed how these three parameters on the ditching pressures synthetic expression (PMAX; PSHAPE ; PF) can be determined based on the aircraft input conditions (horizontal speed, vertical speed, pitch angle…). Present paper will introduce the local deformation effect to modify the synthetic pressures. This is the novelty of the present paper.

Concluding remarks will highlight how these results constitute a significant step forward in the understanding of the complex fluid-structure phenomena that takes place during a ditching. The paper will end with suggestions for further work in this area, with a specific mention to the just-started European project SARAH.

2 SMAES DITCHING TEST DESCRIPTION

2.1 Ditching test summary

The SMAES ditching tests are set of guided impact tests of panels against water at horizontal speeds representative of aircraft skins. The objective was to measure the pressures acting on the panel and the structural deformation during the impact. To provide with a complete database, the most relevant parameters were varied during the test:

— Horizontal speed (30m/s, 40m/s, 50m/s)

— Pitch angle at impact (4°, 6°, 10°)

— Panel curvature (flat, concave, convex)

— Panel stiffness (rigid, flexible, very flexible)

— Panel material (metal –Al2024-T351–, composite)

Vertical speed:	-1.5 m/s
Total guidance structure length:	64 m
Trolley mass:	~ 600 Kg
Trolley + specimen mass:	~ 800 Kg

The trolley is accelerated by a catapult composed by a total of 8 elastic cords

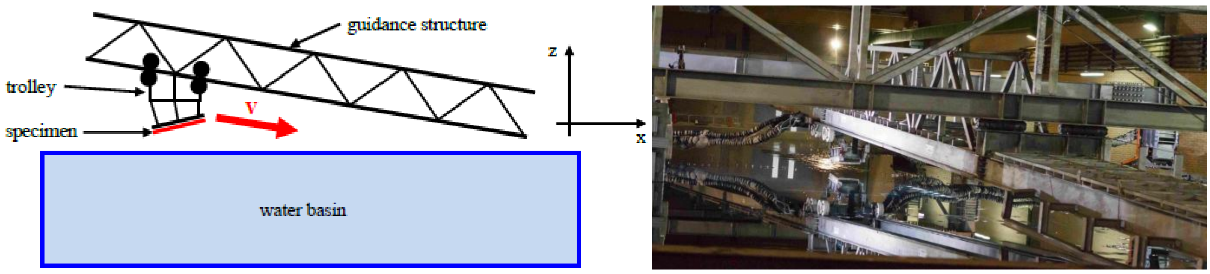

Figure 2: Schematic sketch of the guided ditching test setup

2.2 Ditching test instrumentation

The instrumentation of the guided ditching tests was very complete and differs slightly depending on the specimen and the test conditions. The typical set of instrumentation for deformable plates would be:

— 14 pressure transducers (14 channels)

— 8 strain gauges – two directions (16 channels)

— Velocity (1 channel)

— 2 biaxial and 2 single axis accelerometers on the panels (6 channels)

— 6 load cells to measure forces from the panel to the trolley (4 channels)

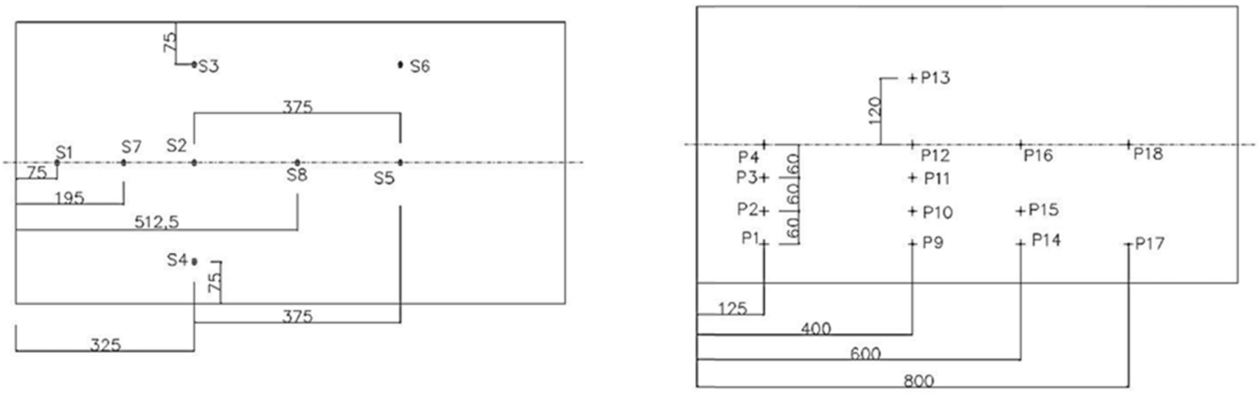

Figure 3: Positions of strain gauges (left) and pressure transducers (right) for deformable plates.

2.3 Ditching test execution

The panel specimen, with a size of 1000 x 500 mm (typical fuselage skin panel size), was installed in a frame. The frame embedded in a trolley and the trolley guided using an auxiliary structure up to reaching the desired test conditions at the impact.

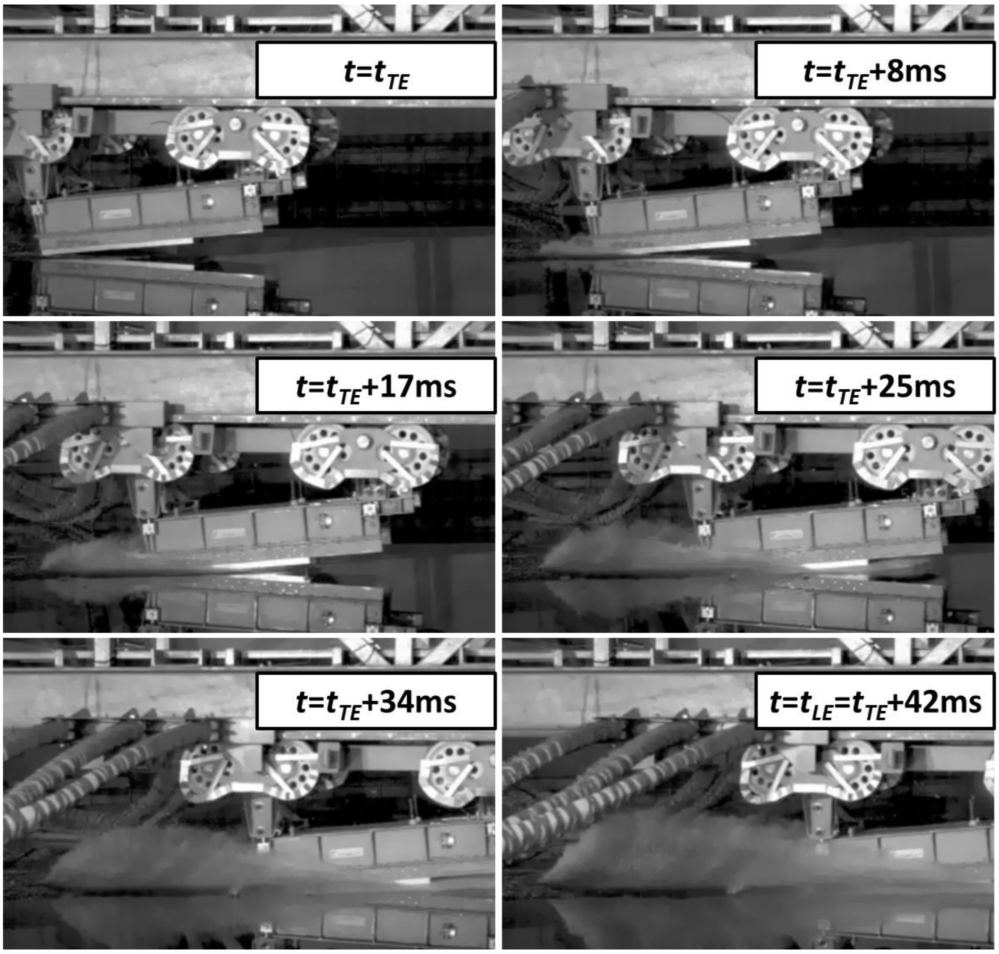

Figure 4: Pictures illustrating the guiding structure, the trolley and the specimen at impact phase

During the complete execution of each run test, six phases could be identified

1) Release
2) Acceleration: 1.00 s approximately
3) Constant velocity: 0.20 s approximately
4) Impact and natural deceleration: 0.30 s approximately
5) Forced breaking: 0.44 s approximately
6) Stop

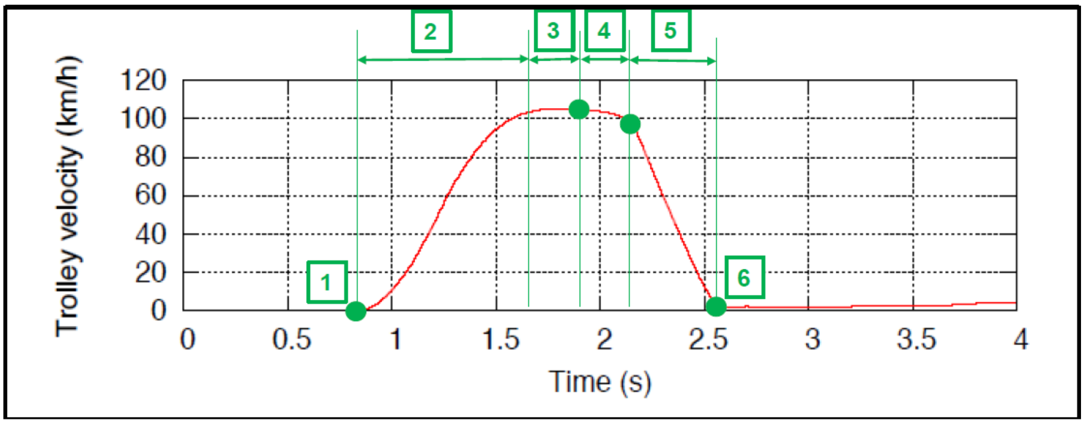

Figure 5: Phases of each ditching test run

2.4 Ditching test typical results

From the structure point of view, all the relevant phenomena occur during phase 4 in a time interval starting when the panel trailing edge gets in contact with the water surface (t_{TE}) and ending when the panel gets fully submerged (t_{LE}). The test results after t_{LE} are not considered representative of a ditching event in an aircraft, so they have not been taken into account for the analysis.

Figure 6 shows the typical behaviour of the overall forces acting over the panel and the strains produced in the transversal direction along the panel symmetry axis:

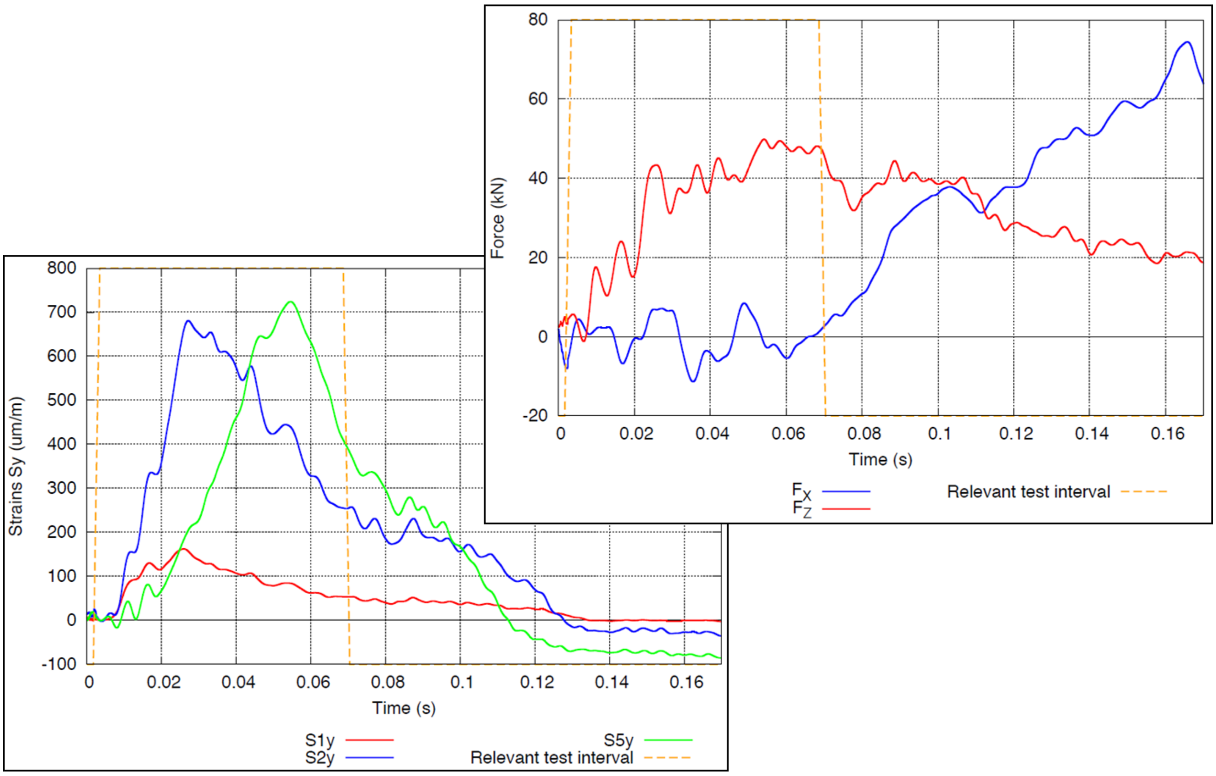

Figure 6: Typical time histories of forces and strains

Most part of the paper is devoted to present and discuss the behaviour of the pressures acting over the panel. Typical time histories for the pressures are presented in Section 3.

2.5 Test data accuracy and repeatability

As discussed in Section 2.1, a large amount of parametric variations have been performed in order to obtain a wide database with different initial conditions. To guarantee the accuracy of the test results and the independency of the environment conditions, several runs have been performed for each set of initial conditions.

3 TIME HISTORIES OF SYNTHETIC DITCHING PRESSURES OBTAINED FROM FLAT RIGID PANELS MEASUREMENTS

In a general way, the pressure time history can be expressed as a function of the (x, y) position in the panel and the initial conditions described in Figure 7.

In light of the test results, the expression (1) plotted in Figure 8 seems appropriate to approximate analytically the pressure time histories obtained experimentally for a flat quasi-rigid panel ditching.

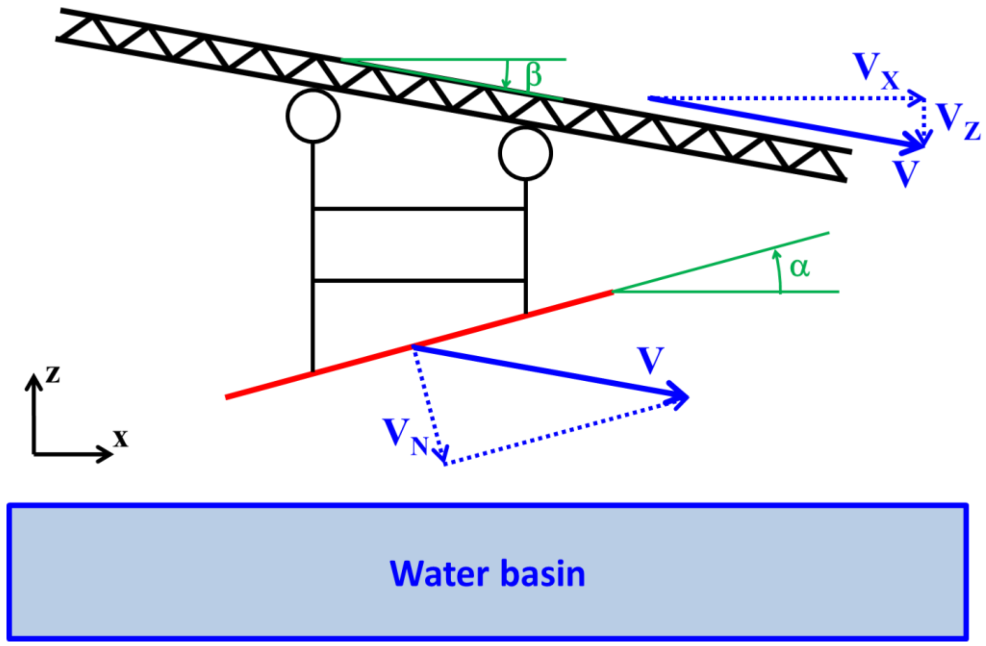

Figure 7: Initial ditching conditions sketch

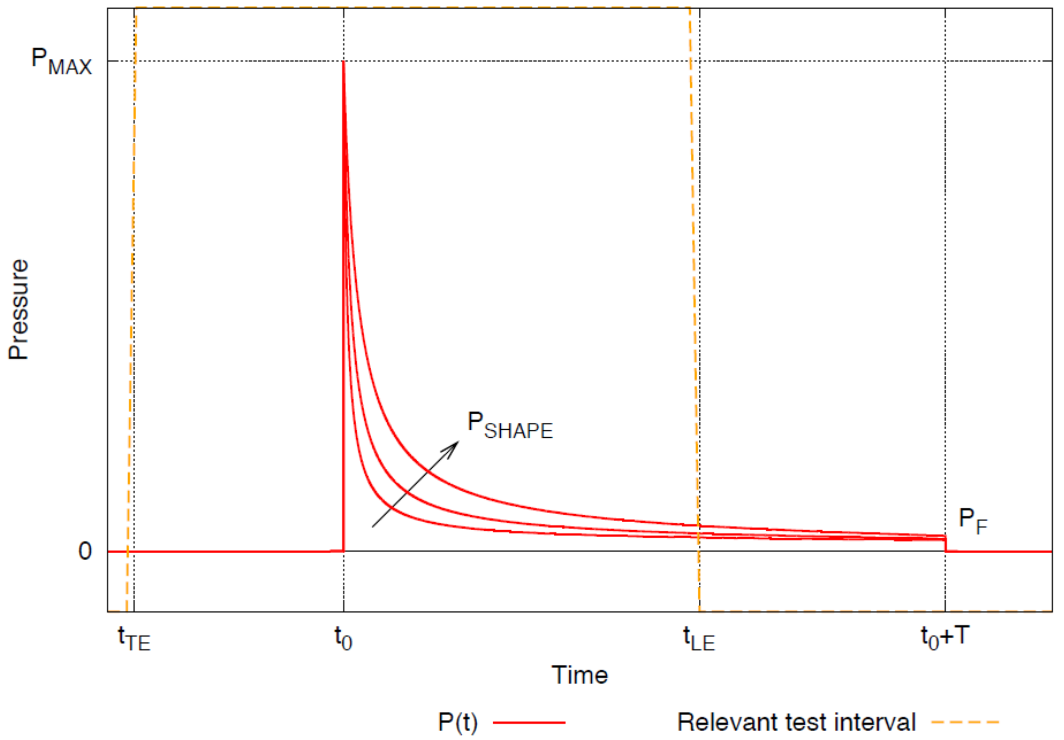

Figure 8: Analytical approximation for the pressure time histories

$$P(V_X, V_Z, \alpha, x, t) = \begin{cases} P_F + \dfrac{P_{SHAPE}}{\tan\left[\dfrac{t-t_0}{T}\dfrac{\pi}{2} + \arctan\left(\dfrac{P_{SHAPE}}{P_{MAX} - P_F}\right)\right]} & , \quad t_0 \le t \le t_0 + T \\ 0 & , \quad t < t_0 \ \& \ t > t_0 + T \end{cases} \tag{1}$$

Where:

V_X, V_Z, α are the initial ditching conditions: horizontal speed, vertical speed and pitch angle

(x, y) are the panel coordinates, with the origin in the central point of the trailing edge, x positive towards the direction of motion and y positive to port

t is the time

$t_0 \equiv t_0(V_Z, \alpha, x)$ is the time instant for which $P = P_{MAX}$

$P_{MAX} \equiv P_{MAX}(V_X, V_Z, \alpha, x)$ is the peak value of the pressure time history

$P_{SHAPE} \equiv P_{SHAPE}(V_X, V_Z, \alpha, x)$ is a shape factor that determines the decay rate of the pressure time history

$P_F \equiv P_F(V_X, V_Z, \alpha, x)$ is the final pressure value at $t = T + t_0$

$T \equiv T(V_Z, \alpha)$ is an arbitrary but sufficiently large time as to make sure that the pressure time history has become almost flat

Figure 9 shows the shape of these synthetic pressures with 40% of the panel surface wet and at the instant when the water reaches the flat panel leading edge.

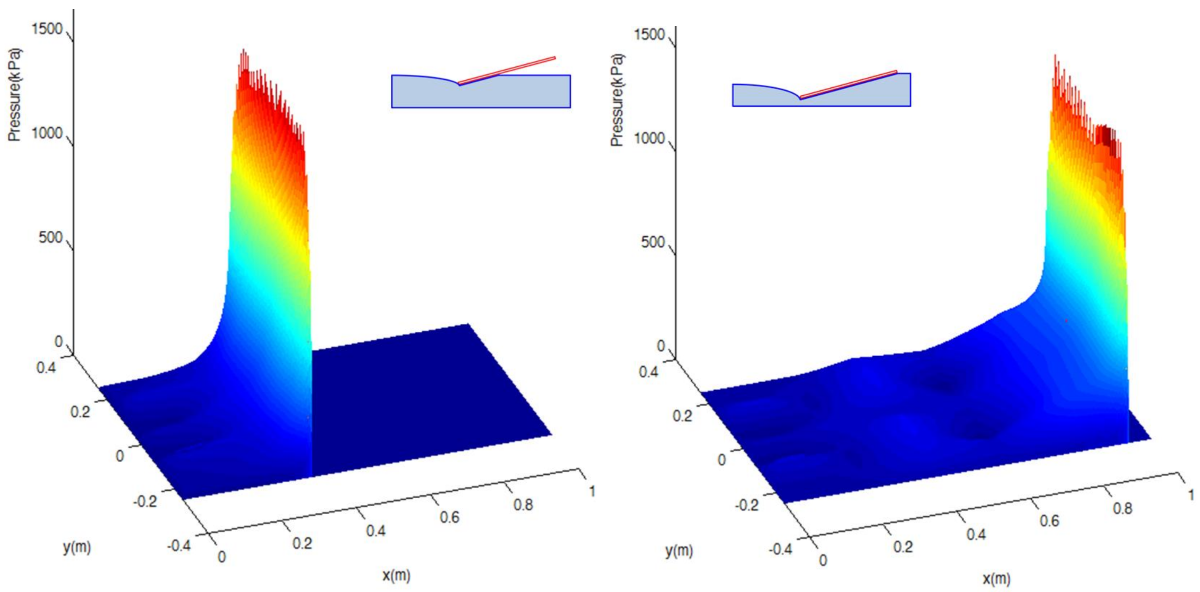

Figure 9: 3D pressure distributions with 40% panel surface wet (left) and with 100% panel surface wet (right)

4 APPLICATION OF SYNTHETIC PRESSURES TO FLEXIBLE PLATES

4.1 Synthetic Rigid Pressure Applied to a Flexible Plate. Comparison in positions with expected small deformation.

Next step is to verify whether the synthetic pressures obtained from pressure measurements on rigid plates are applicable or not to flexible plates. Figure 10 compares test and simulation deformations for the case Vx=46 m/s and Pitch=10 deg. Comparison shows larger deformations in the simulations for positions close to the frame (positions with small expected deformation). It is remarkable the good agreement of shapes and time of peaks occurrence.

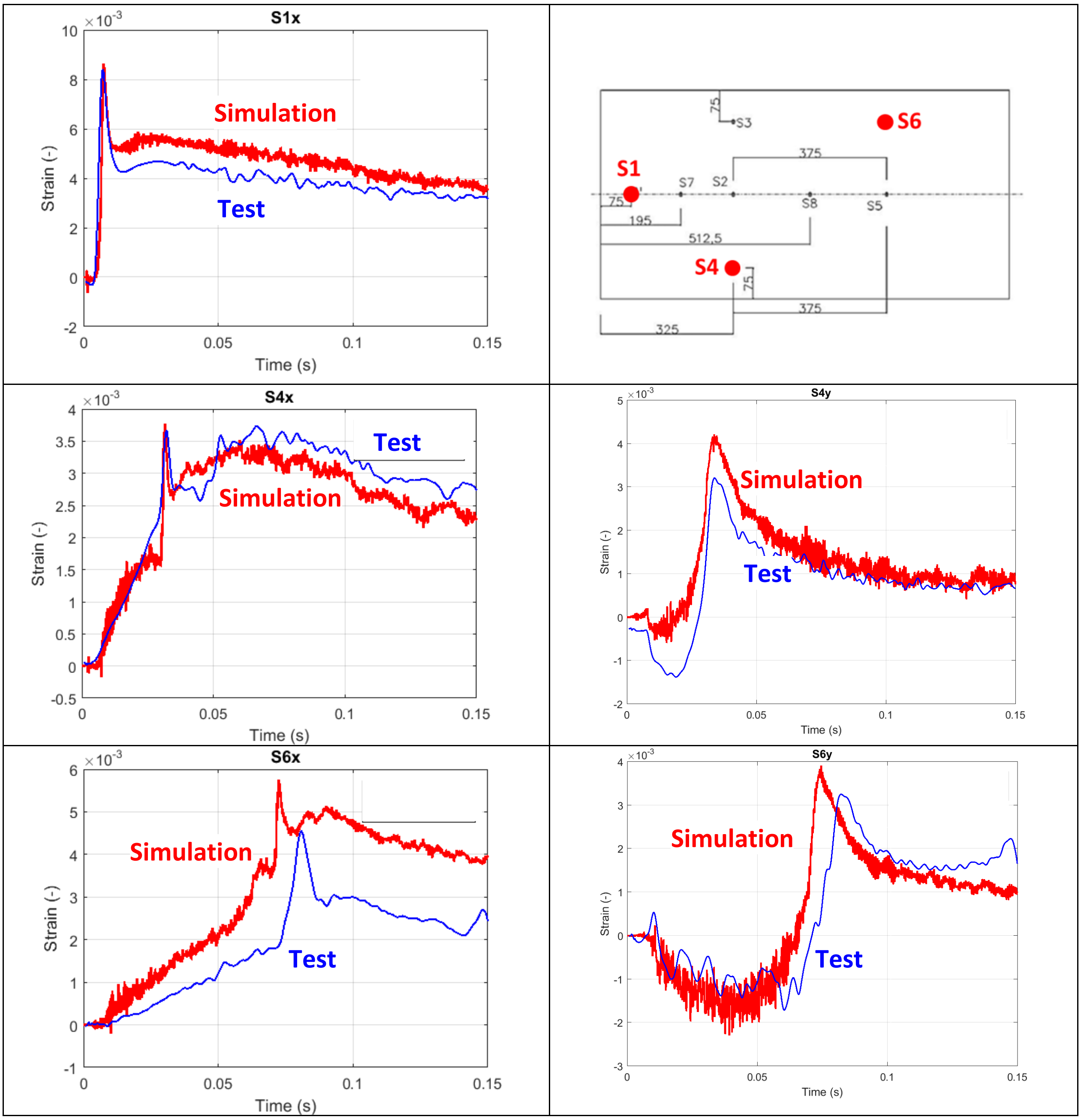

Figure 10: Comparison of Time Histories of Deformations on a Flexible Plate between Numerical Simulations using synthetic pressures and test results – Positions with expected small deformation

4.2 Synthetic Rigid Pressures Applied to a Flexible Plate. Comparison in positions with expected large deformation

Figure 11 compares test and simulation deformations for the case Vx=46 m/s and Pitch=10 degrees for positions with large expected deformation. For S7 position simulation shows slightly lower deformations versus the tests. For S5 position, with the largest deformations of the entire panel, simulations are 40% conservative compared with tests. Again, it is remarkable the good agreement of shapes and time of peaks occurrence.

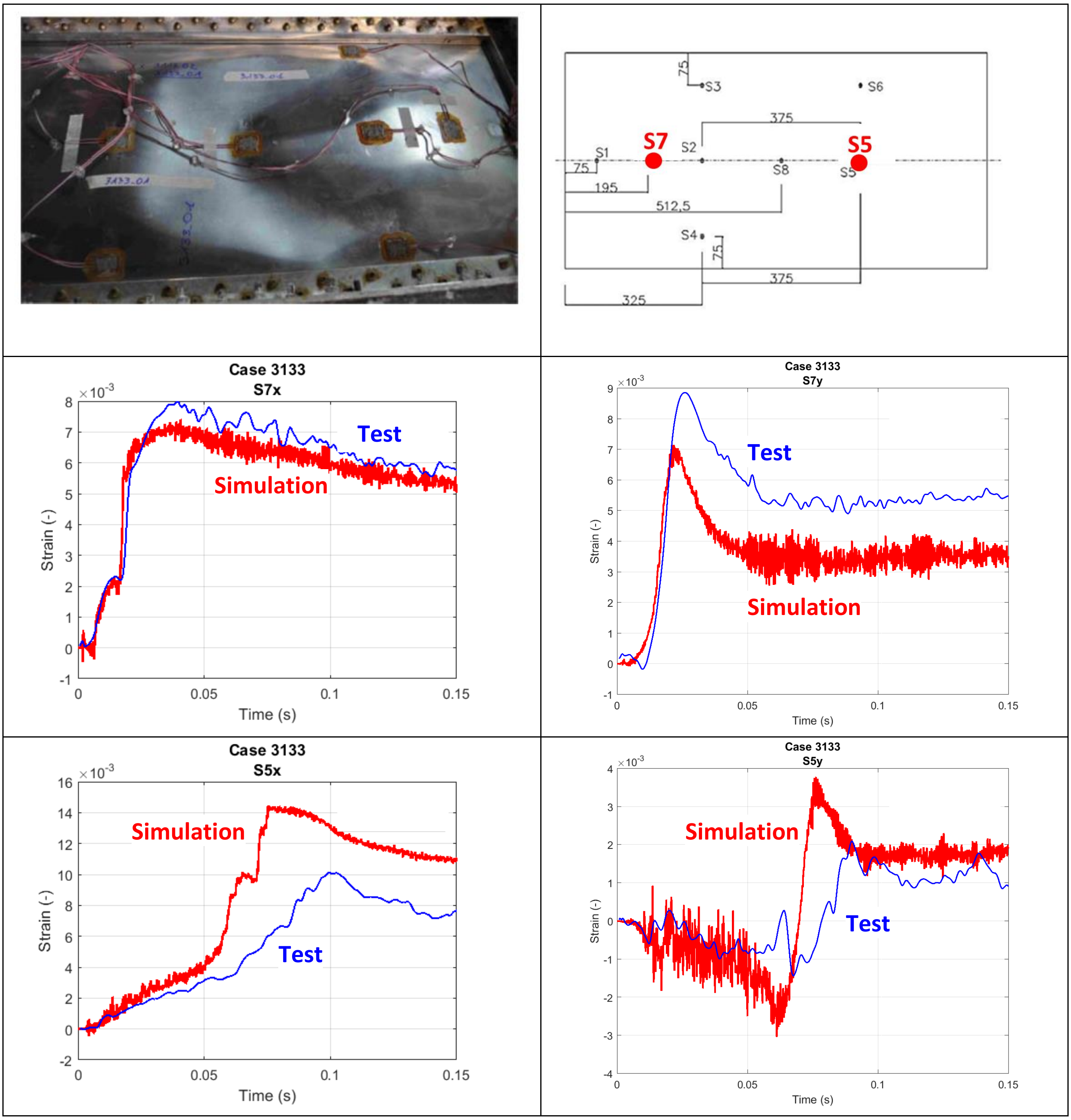

Figure 11: Comparison of Time Histories of Deformations on a Flexible Plate between Numerical Simulations using synthetic pressures and test results – Positions with large deformation

5 TIME HISTORIES OF DITCHING PRESSURES ON FLEXIBLE PANELS

5.1 SMAES Pressures Results as Function of Flexibility

In the SMAES research project there was only one set of test conditions in which we could compare the effect of the 3 panel thickness (t=15mm; t=3 mm; t=0.8 mm) **on ditching pressures.** These test conditions were for V=30 m/s and Pitch=10 deg. Next plots show the evolution of the pressures time histories in different pick-ups for the 3 plates.

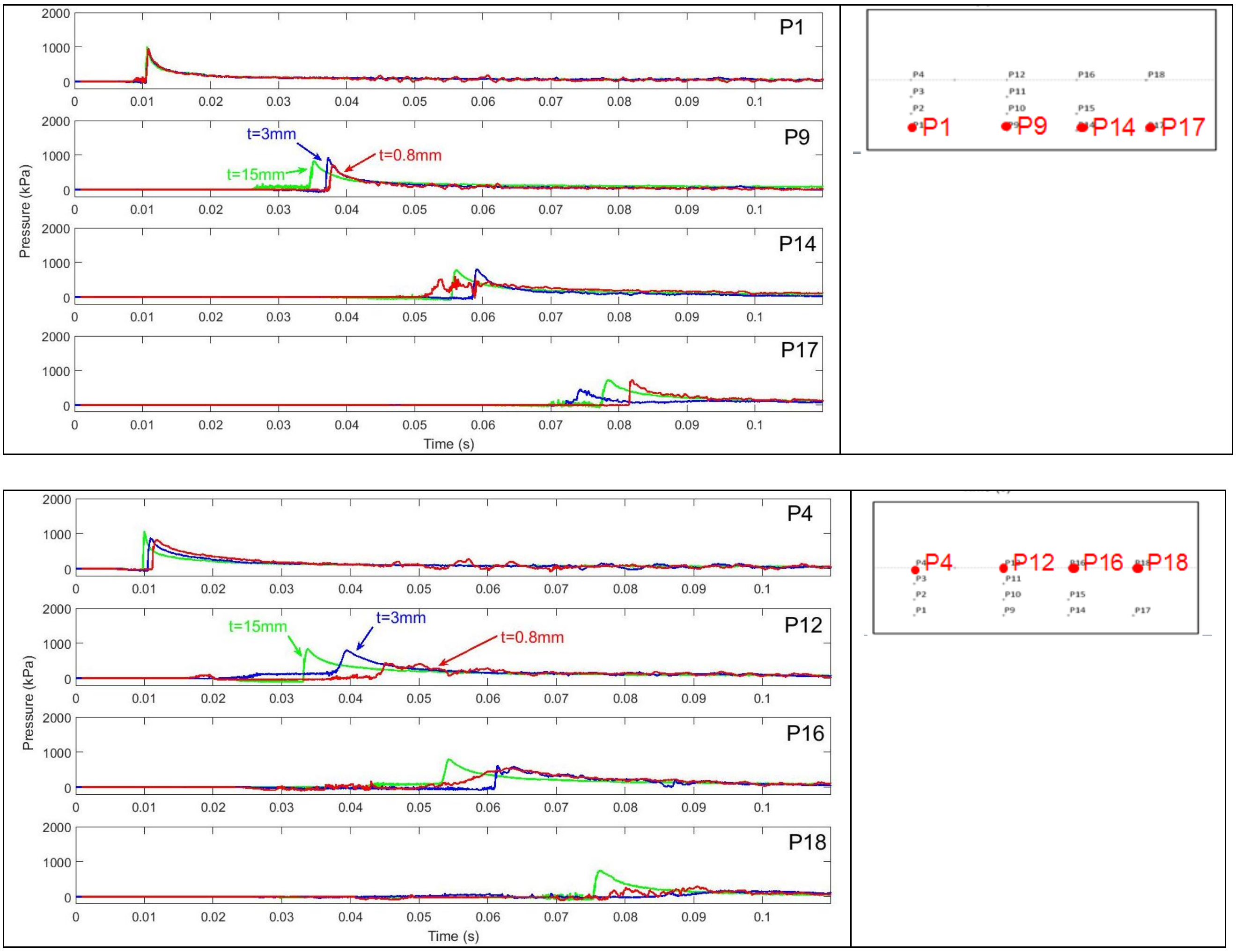

Figure 12: Comparison of measured ditching pressures at V=30 m/s and PITCH=10 deg
for three plates of t=15 mm; t= 3mm; t=0.8 mm.

Comparison of the pressures measured among the 3 plates shows:

- The peak value of the pressures is always lower for flexible plates than for rigid plates (i.e. P_{MAX} is lower)
- The larger the flexibility, the larger the time-duration of the pressures time histories. (i.e P_{SHAPE} increases)

In general terms, by scrolling the different pressure transducers, it is envisaged that there is an alleviating effect of the flexibility on measured pressures.

5.2 Strategy to correct synthetic pressures using local flexibility deformations

The deformation of a plate in a ditching guided test will have two effects:

- The deformation local height (ΔZ) introduces a time delay on when the water front reaches the plate.
- The deformation local pitch angle (Δα) will modify P_{MAX} and P_{SHAPE}.

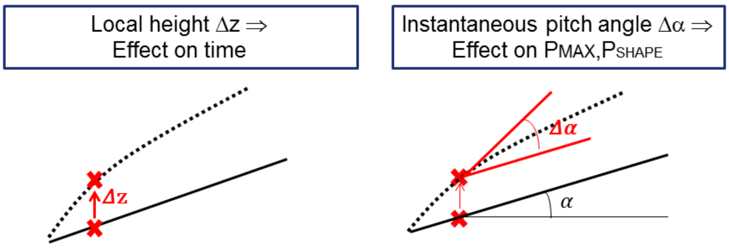

Figure 13: Description of Local Deformation Effects to be used in the strategy of ditching loads alleviation due to flexibility effects

By using the information of local deformation (ΔZ, Δα) in the FE model the synthetic pressures could be updated and in turn applied in the next time step to the FE model as shown in next flowchart:

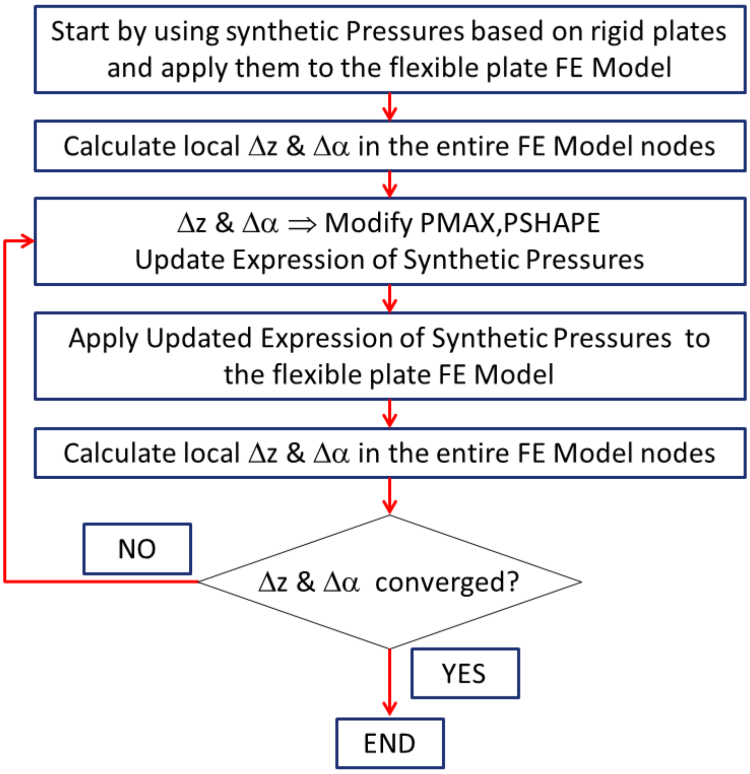

Figure 14: Flowchart highlighting the Strategy to Correct Synthetic Pressures Using Local Deformations on Flexible Plates

5.3 Effect of Local Height Δz

For rigid plates, the water front in contact with the plate is basically a straight line. This water front reaches all points with the same x coordinate at the same time.

For flexible plates, the effect of local height Δz is basically a delay on when the water front reaches the deformed point. The larger the deformation Δz; the larger the delay. As a corollary, the water front is no longer a straight line; it becomes a curved water front as shown in Figure 15.

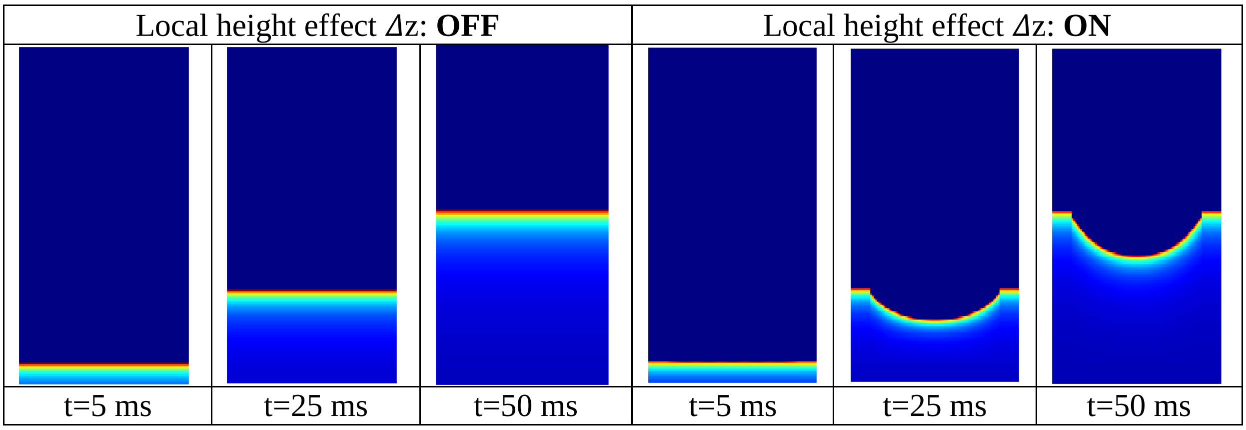

Figure 15: Water Front Shape for Rigid t=15 mm (Left) and Flexible t=0.8 mm (Right) Plates.

5.4 Effect of Local Pitch Angle Δα

Next plot shows the Δα due to deformation of a flexible t=0.8 mm panel after applying the synthetic pressures (without correction yet). The trends are as expected:

- Δα is positive at the entrance of the panel with the water reaching peaks in the order of 4 degrees (yellow colour)
- Δα is negative at the final part reaching peaks in the order of -12 degrees (dark blue colour)

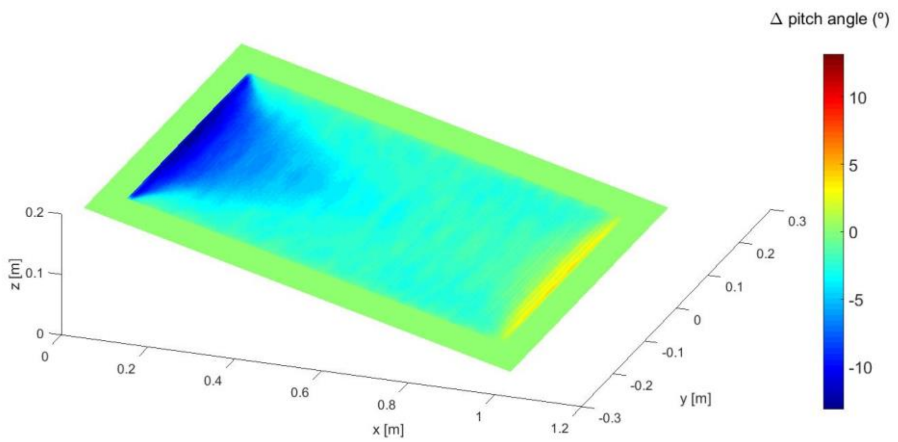

Figure 16: $\Delta\alpha$ calculated on the FE Model after applying synthetic pressures.

Next plot shows the sensitivity of the Peak Pressure versus the pitch angle <u>for rigid plates</u> and for the 18 pressure transducers used in the SMAES project. Plot shows a clear negative trend: the larger the pitch angle, the lower the peak pressure. As a first attempt to consider the alleviation effect of the flexibility on ditching loads, exactly the same trend has been incorporated in the correction of the synthetic pressures due to local delta-pitch deformation.

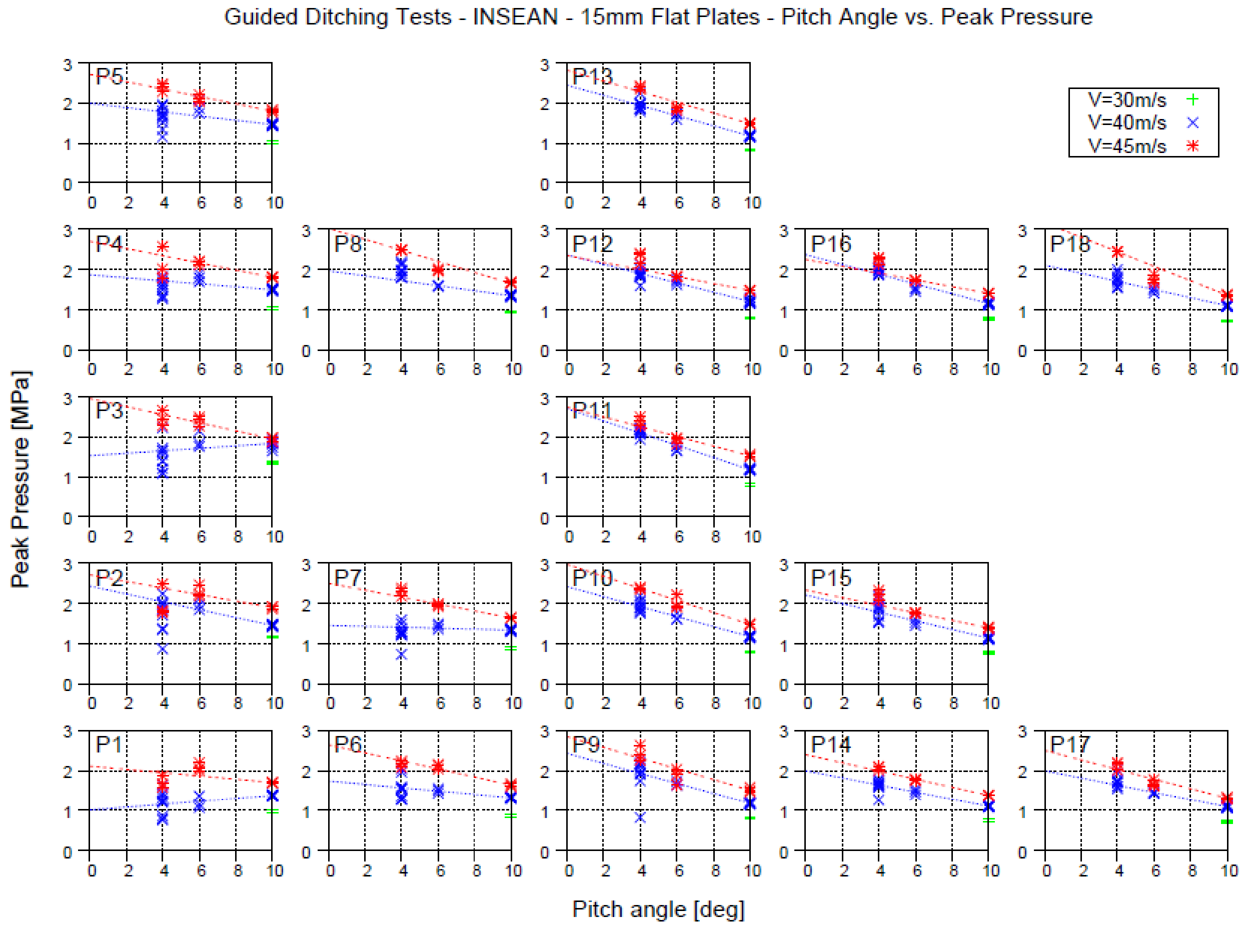

Figure 17: Sensitivity of peak pressure versus pitch angle for 18 pressure transducers used in the SMAES project

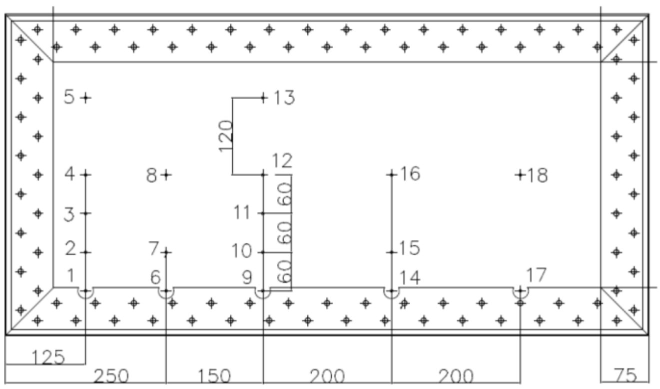

Figure 18: Pressure transducers position in SMAES quasi-rigid (15 mm) flat plates.

6 RESULTS INCORPORATING FLEXIBILITY CORRECTIONS

Next figure shows the results of the numerical simulation of the case V=30 m/s and Pitch=10 deg. using the flexibility corrections strategy described in previous section.

The numerical simulation results are compared with the SMAES measured strain test results (blue curves). Numerical simulations are, in turn split into two cases: Δα-only correction (green curves) and Δα+Δz corrections (red curves).

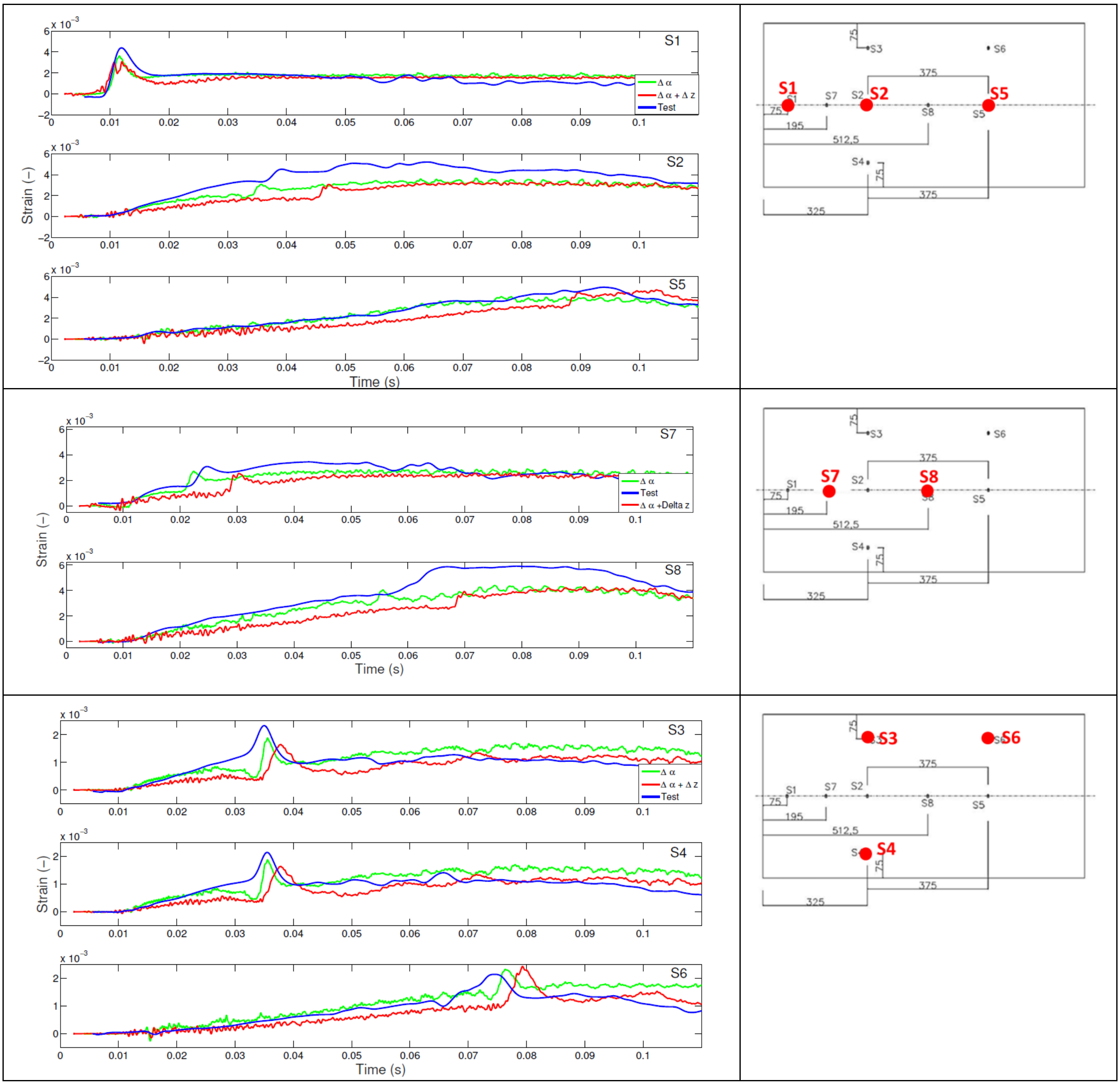

Figure 19: Comparison of deformations in three pick-ups between the test results and the numerical simulations using the strategy shown in this paper

The corrections worked relatively well in trying to reproduce (for the same plate and simulation conditions) three quite different shapes and levels of deformations.

- For the positions with small expected deformation (i.e. close to the border of the plate, **pick-ups S1, S3, S6, S4**) the numerical simulation is able to capture the shape (kind of (1-cos)), the instant of the peak deformation and very closely (although not entirely conservative) the peak level of the deformation (difference in the order of 15%)

- For the positions with intermediate expected deformation (**pick-ups S7, S2**), the numerical simulation also is able to capture the shape (kind of ramp-step-long-plateau). Nevertheless, the time instant of the step is not entirely captured:

  - with **$\Delta\alpha$-only** correction the step is slightly ahead in time than the in the test
  - with **$\Delta\alpha+\Delta z$** correction the step time occurs later in time than in the test demonstrating that the main effect of the **Δz** correction is to introduce a time delay on when the water front reaches each point, especially in the center line of the plate that is where the pick-ups S7 and S2 are located.

  On the other hand, the peak level of the deformation is 50% apart (lower) in the numerical simulation with respect to the test results for S2 and around 30% lower for S7. This type of simulation would have been non-conservative.

- For the positions with larger expected deformations (pick-ups S8 and S5), located in the center line, one in the center of the plate (S8) and the other in the rearward part of the plate (S5) the results are different one with respect to the other:

  - For S5 pick-up, the corrections with $\Delta\alpha$-only follow very closely the shape (a kind of continuously-increasing-ramp) and levels of the test measurements. It is important to note that $\Delta\alpha$-only correction seems to behave better that the $\Delta\alpha+\Delta z$ correction.

  - The S8 pick-up measures the largest strains in this case (6000 μdeformations). The numerical simulation with $\Delta\alpha$-only correction follows the shape of measurements during the first part but then departs from measurements when reaching a plateau around 4000 μdeformations. Comparison does not improve with $\Delta\alpha+\Delta z$ correction.

As a summary: this first attempt to incorporate flexibility corrections in the ditching simulations is promising. For most of the pick-ups (i.e all except S8) the results are relatively good in terms of shapes and time of occurrence of peaks and slightly non-conservative.

7 CONCLUDING REMARKS AND FUTURE ACTIVITIES

7.1 Concluding Remarks

The paper has presented a first attempt to include flexibility effects on ditching loads.

The starting point has been the synthetic pressures obtained using SMAES test results on rigid plates. A correction strategy using local deformation (in the FE model) has been introduced to account for flexibility effects.

The strategy has proven quite successful in reproduce the shape of the different pick-ups. Time of occurrence is also well reproduced in general terms but sometimes the levels of deformation have resulted not conservative, an indication that this correction may have been gone too far in introducing the alleviating effect of flexibility (see figure 20)

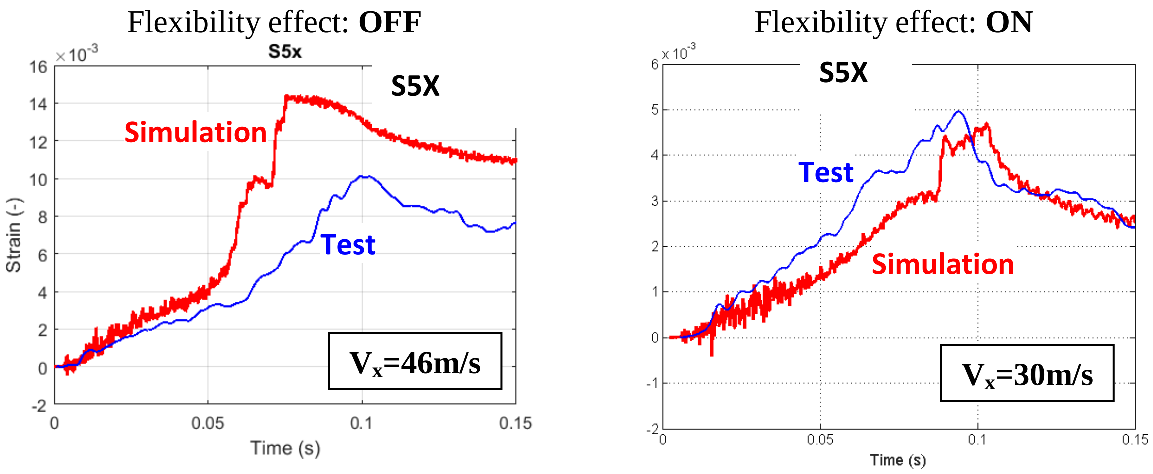

Figure 20: Comparison of deformations at S5X position with flexibility effect ON and OFF.

Therefore, further work is still required. Next steps will include:

- Refinement of the flexibility correction technique by revisiting the coefficients used in the flexibility correction
- Introduce the loop of corrections inside a single run in the explicit FE simulation by using a subroutine that interacts with the explicit FE code in such a way that the pressures adjust at each Δt.
- Increase the fidelity representation of SMAES test results by including also the FE model of the trolley
- Increase the data base of ditching tests in the European funded research project SARAH (see next section)

7.2 The European Funded Research Project SARAH

The European Funded Research Project SARAH (Increased SAfety and Robust certification for ditching of Aircrafts and Helicopters, European Union Horizon 2020 research and innovation programme under grant agreement No 724139) is concerned with establishing novel holistic, simulation-based approaches for the analysis of aircraft and helicopter ditching. SARAH project will tackle the following objectives:

- Improve aircraft/ helicopter certification tools in order to deliver accurate loads to safely design aircrafts/ helicopters and deliver input on how ditching needs to be simulated in order to obtain robust, safe and accurate loading information
- Derive a robust way to safely design new configurations (for which no engineering experience is available) w.r.t. ditching
- Use methods obtained to analyse and optimise approach, landing and impact phases to supporting the pilot in water-landing scenarios

SARAH project is composed from a consortium of 12 partners including experts from OEM industries, experienced suppliers of simulation technologies, established academic and research institution and supported by representatives of the certification authorities.

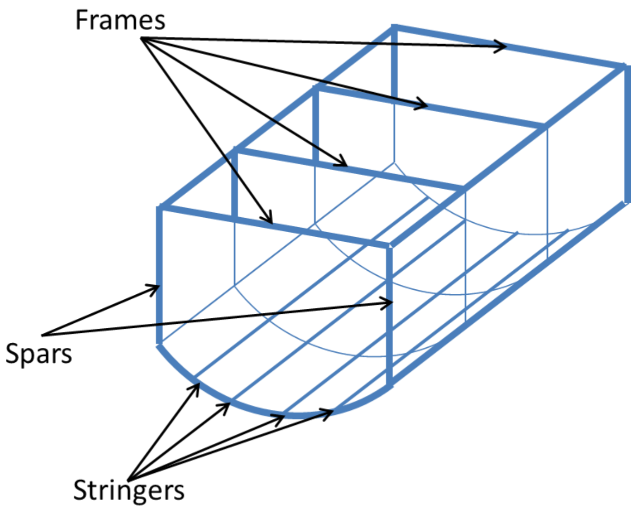

Figure 21: SARAH fuselage-like tests specimen scheme

At Airbus Defence and Space, the specific challenge for the design of airborne vehicles is to minimize the risk of injury to persons on board during the whole water landing and to give chance for safe evacuation of the occupants. The developments within SARAH (including elasticity effects obtained from SARAH test campaign) will help with a deeper knowledge of the two-way interaction between structural deformation and hydrodynamic loads, in the way that ditching loading can be properly regarded. One of the cornerstones of the project will be the ditching test at real speeds of a fuselage-like component as shown in Figure 21.

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9 ACKNOWLEDGEMENTS

Part of the work leading to the results presented has received funding from the European Commission’s Seventh Framework Programme under grant agreement no FP7- 266172 and was performed within the project SMAES — SMart Aircraft in Emergency Situations.

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