

# **Flexible Structures Response to Ditching Loads**

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This paper addresses local structural flexibility aspects on the impact of an aircraft against water during a ditching event (aircraft emergency condition that ends with the planned landing of the aircraft in water). This impact of the sliding aircraft with water is an extreme case of fluid-structure coupling where high pressures may develop, causing cracks and/or ruptures of the structure of, mainly, the lower rear fuselage, and 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 and describes the future ditching tests to be performed within the European funded research project SARA on flexible structures. SMAES 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 SMAES 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.

Keywords: structural dynamics; dynamic loads; ditching loads.

## **Introduction**

January 15th 2009 in New York City: at 15:25h in La Guardia airport, the breaks of the Airbus A320 piloted by Chesley “Sully” Sullenberger were released. Exactly 208 seconds later he landed in the cold waters of the Hudson River. All, crew and passengers (a total of 155), survived the ditching that day.

Ditching is a planned aircraft event that ends with controlled impact of the aircraft against water. 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. A ditching event is normally divided in four main phases:

- (1) Approach: Characterized by aircraft/environment conditions before impact.
- (2) Impact: Fluid-structure interaction during the impact (Structural response).
- (3) Landing: Sliding motion of the aircraft until stoppage.
- (4) Floatation: Evacuation of passengers and crew.

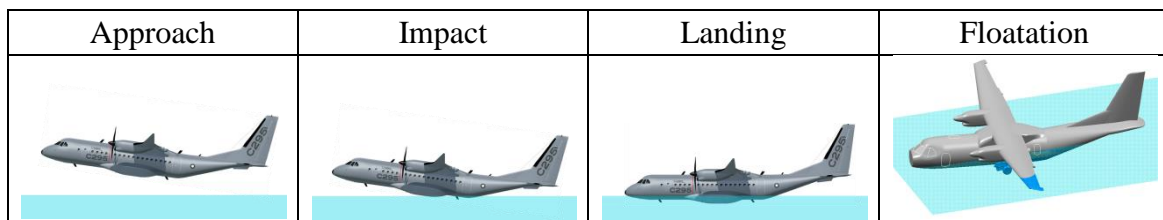


Figure 1: Ditching Phases

At Airbus DS Military Transport Aircraft Aeroelasticity and Structural Dynamics department, ditching has been a topic of continuous research for more than 12 years [1-7]. This interest is also shared by universities, research laboratories and industrial partners that have gathered together in the consortia of two European funded research projects: SMAES (Smart Aircraft in Emergency Situation, 2011-2014) and, currently, in the SARA project (Increased Safety and Robust Certification for Ditching of Aircrafts and Helicopters, 2016-2019). SMAES project 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 behaviour during ditching. The tests were performed at the CNR-INSEAN institute in Rome (Italy).

The paper briefly describes the SMAES 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 (panel stiffness, curvature, material, pitch angle and horizontal speed). Test measurements include accelerations, strains, pressures and forces on the panel.

The two papers presented at ASIDIC 2015 [6, 7] described respectively experimental ditching loads on rigid plates and numerical simulation of structural response. Present paper on ASIDIC 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 [6] 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 formulation. 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 current European project SARAH.

## **SMAES ditching test summary**

### ***Ditching test configurations***

The SMAES ditching tests were a set of guided impact tests of panels against water at horizontal speeds representative for aircrafts. The objective of the tests was measuring 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 deg., 6 deg., 10 deg.)
- Panel curvature (flat, concave, convex)
- Panel thickness (rigid  $t=15\text{mm}$ , flexible  $t=3\text{mm}$ , very flexible  $t=0.8\text{mm}$ )
- Panel material (metal –Al2024-T351–, composite)

Vertical Velocity: -1.5 m/s  
Horizontal velocity range: 30 to 45 m/s  
Pitch angle: 4° to 10°  
Specimen size: 1000x500 mm (typical fuselage skin panel)

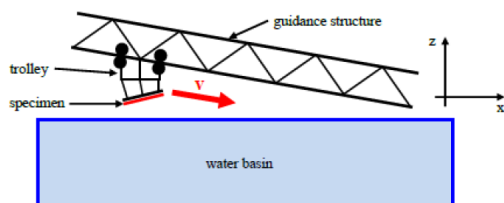


Figure 2: Schematic sketch of the guided ditching test setup

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.

### ***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.

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

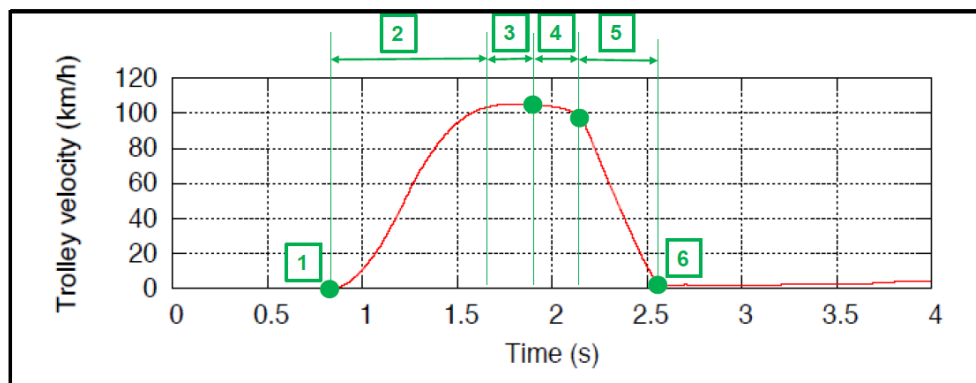


Figure 3: Phases of each ditching test run

- (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

### ***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 flexible 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)

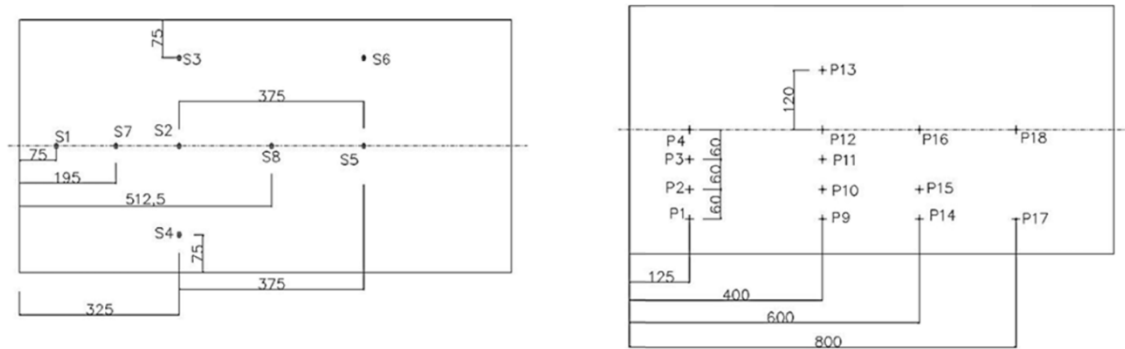


Figure 4: Positions of strain gauges (left) and pressure transducers (right) for flexible plates.

### ***Ditching test results***

From the structure point of view, all the relevant phenomena occur during test impact phase 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.

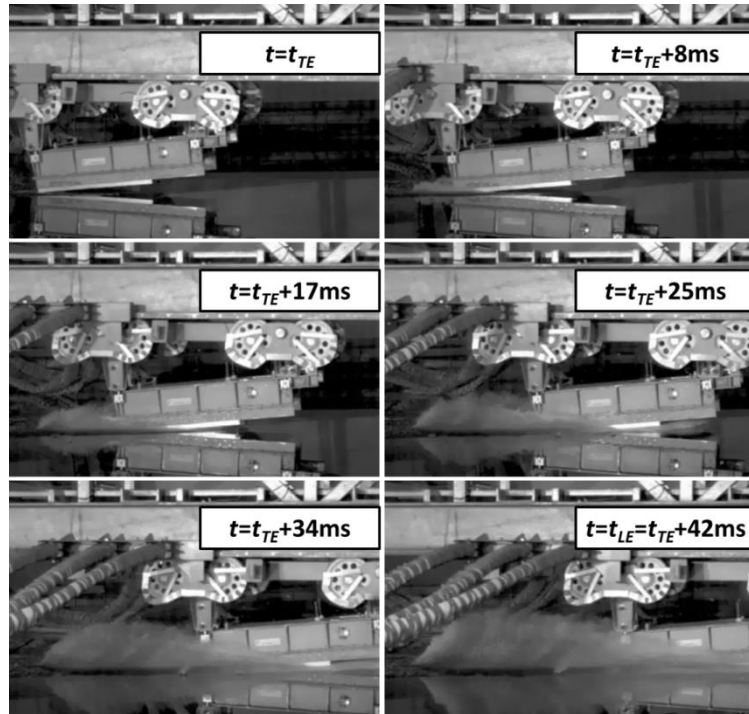


Figure 5: Photos illustrating the guiding structure, the trolley and the specimen at impact phase.

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:

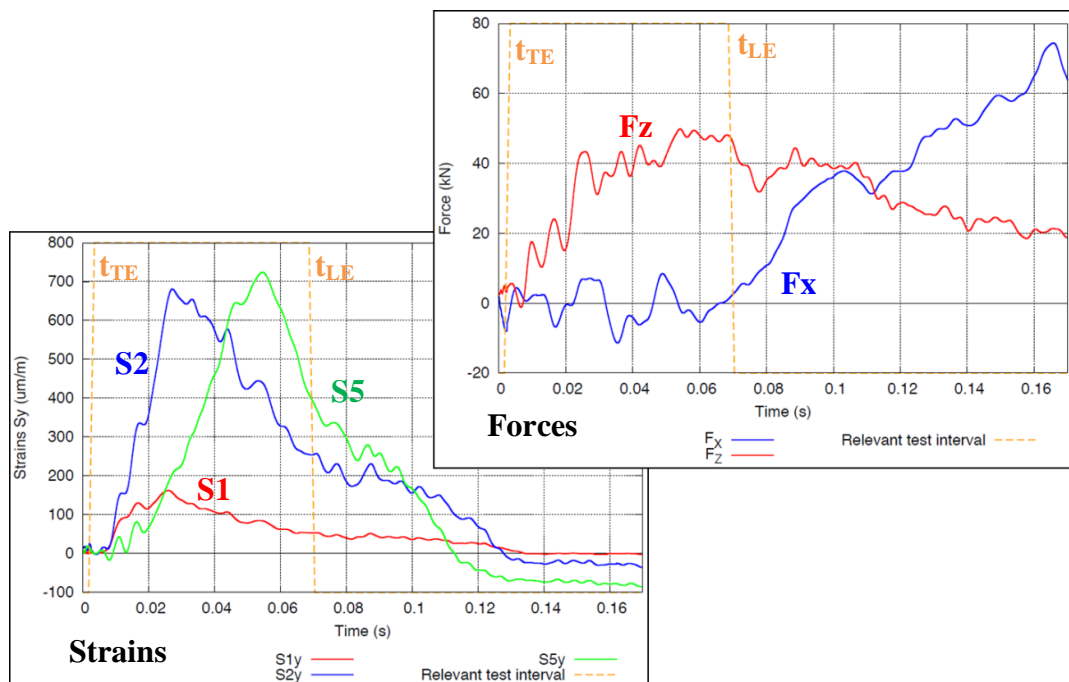


Figure 6: Typical time histories of forces and strains

## Synthetic pressures expression obtained from flat rigid panels measurements

Figure 7 shows the shape of the measured pressures with 40% of the panel surface wet and at the instant when the water reaches the flat panel leading edge.

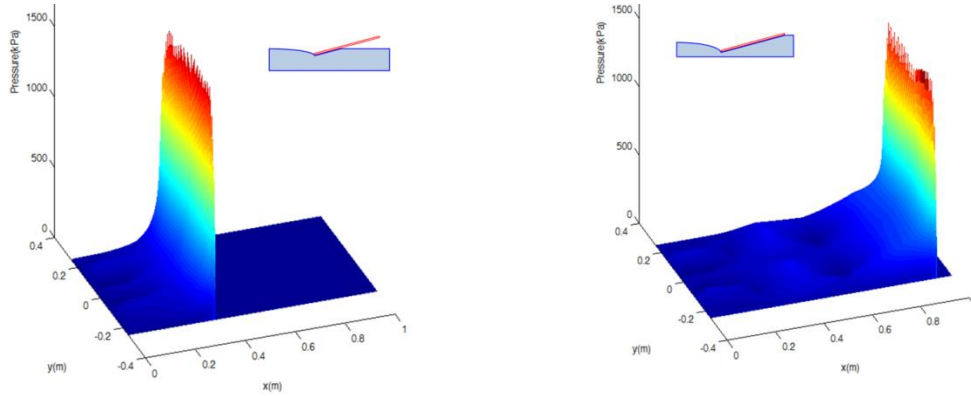


Figure 7: 3D pressure distributions with 40% panel surface wet (left) and with 100% panel surface wet (right)

In light of the test results, the expression (1) plotted in Figure 9 seems appropriate to approximate analytically the pressure time histories obtained experimentally for a flat quasi-rigid panel ditching. In a general way, the pressure time history can be expressed as a function of the position in the panel and the initial conditions described in Figure 8.

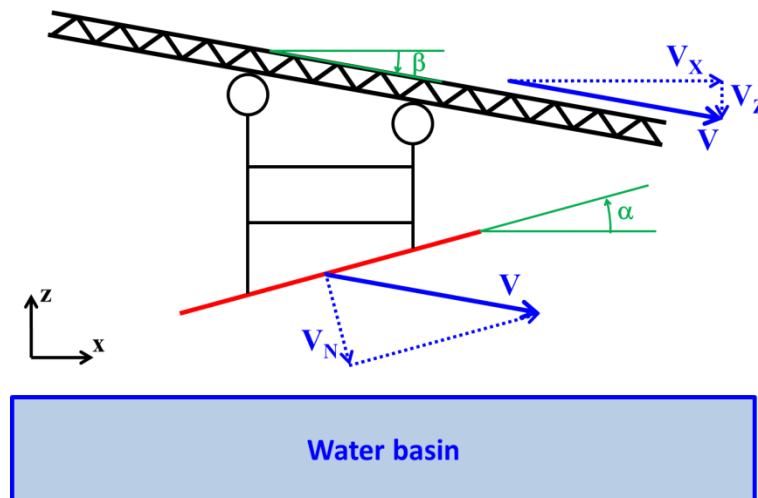


Figure 8: Initial ditching conditions sketch

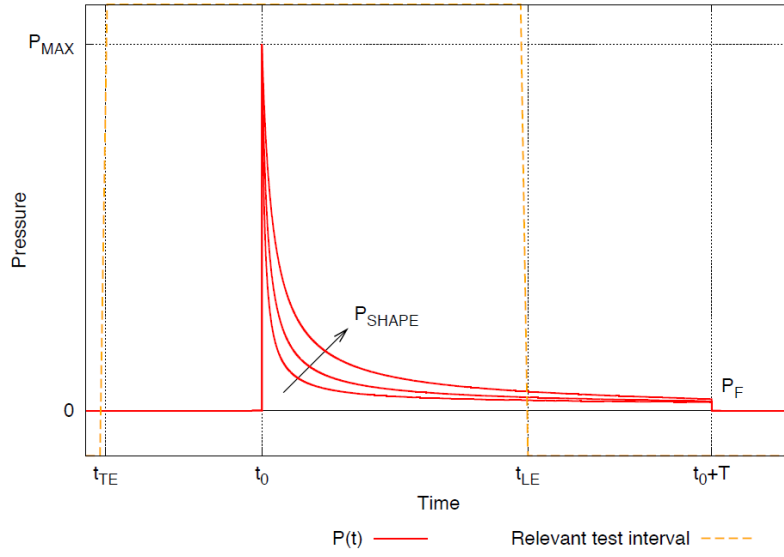


Figure 9: Analytical approximation for the pressure time histories

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

Where:

$V_X, V_Z, \alpha$  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

## Application of synthetic “rigid” pressures to flexible plates

### *Comparison in positions close to the frame (small deformation expected)*

Figure 10 compares test and simulation deformations for the case  $V_x=46$  m/s and Pitch=10 deg. The deformations in the simulations for positions close to the frame are slightly larger, but the good agreement of shapes and time of peaks occurrence is remarkable.

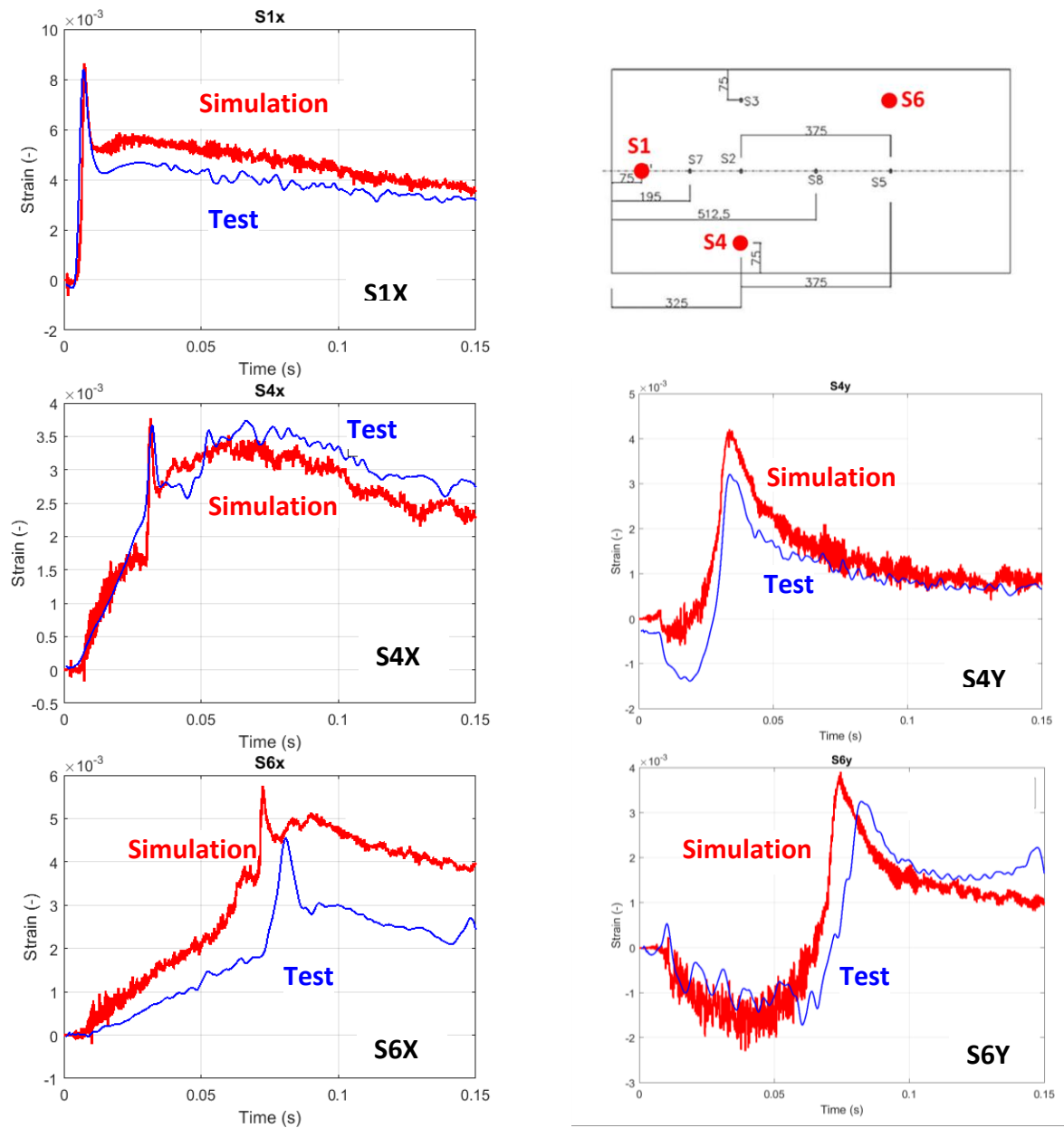


Figure 10: Deformations on a Flexible Plate: numerical simulations using synthetic pressures vs. test results – Close to frame positions

### *Comparison in positions at symmetry axis (large deformation expected)*

Figure 11 compares test and simulation deformations for the case  $V_x=46$  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.

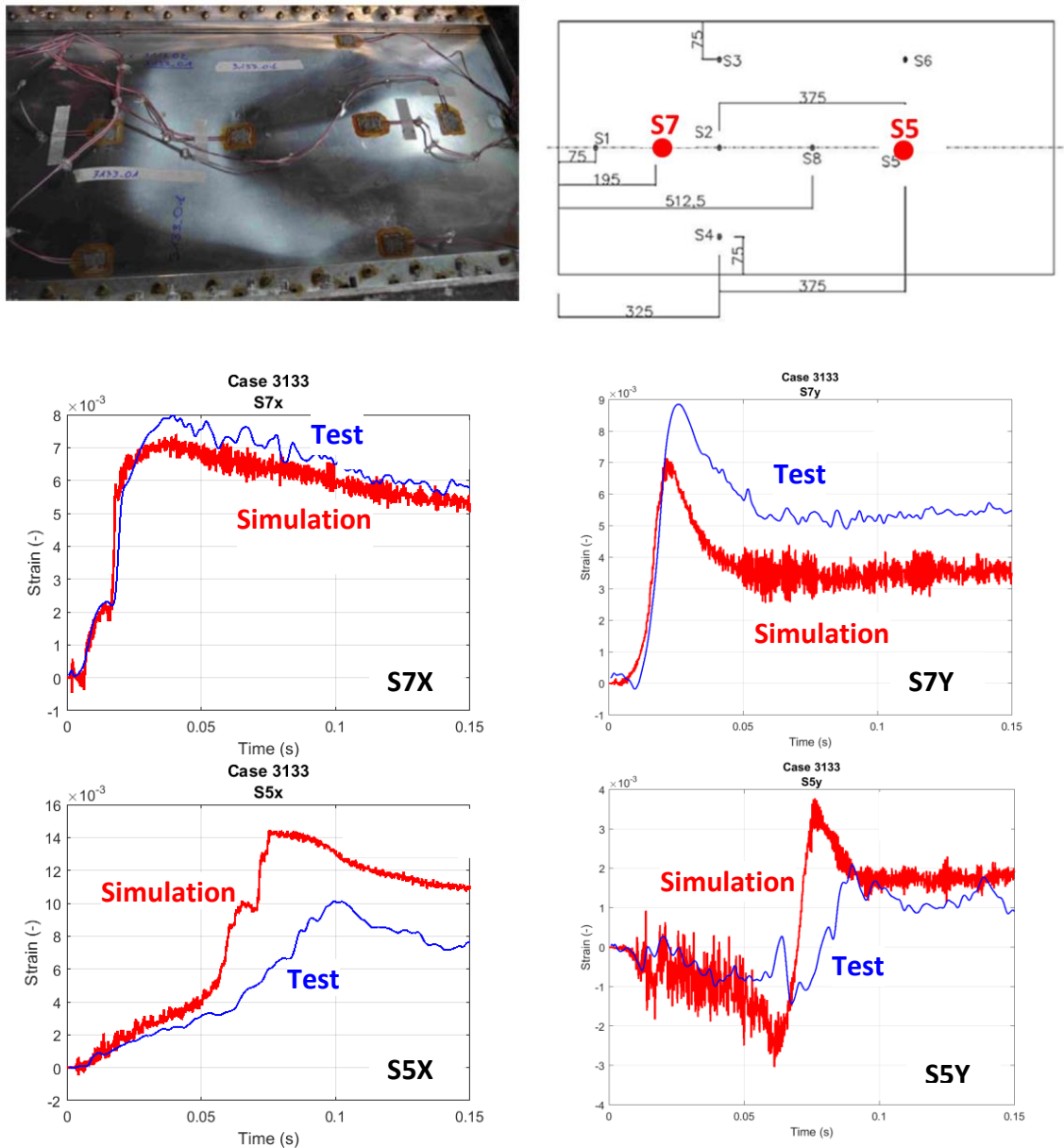


Figure 11: Deformations on a Flexible Plate: numerical simulations using synthetic pressures vs. test results – Symmetry axis positions

## Plate Flexibility effect on ditching pressures

### *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 ( $t=15\text{mm}$ ;  $t=3\text{ mm}$ ;  $t=0.8\text{ mm}$ ) on ditching pressures for  $V=30\text{ m/s}$  and  $\text{Pitch}=10\text{ deg}$ . Figure 12 show the evolution of the pressures time histories in different pick-ups for the 3 plates.

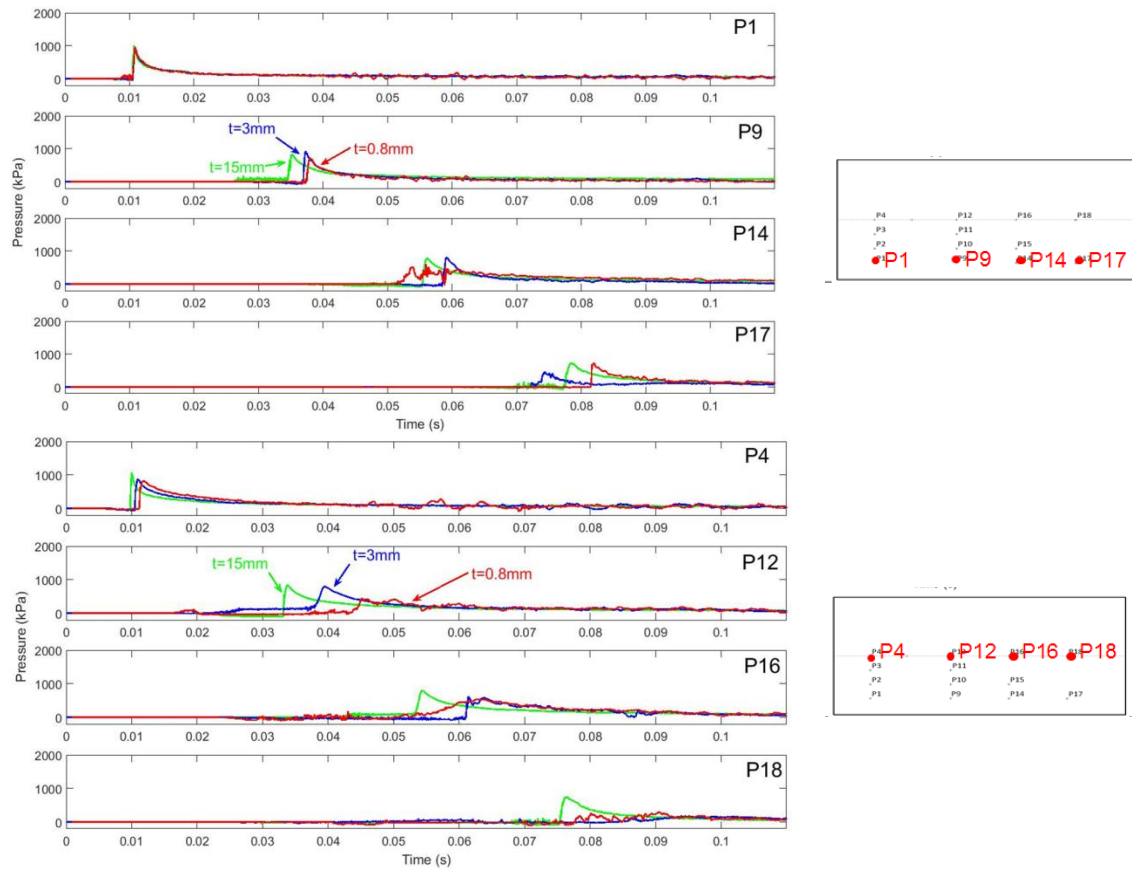


Figure 12: Comparison of measured ditching pressures at  $V=30\text{ m/s}$  and  $\text{PITCH}=10\text{ deg}$  for three plates of  $t=15\text{ mm}$ ;  $t= 3\text{mm}$ ;  $t=0.8\text{ mm}$ .

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.  $P_{\text{MAX}}$  is lower)

- The larger the flexibility, the larger the time-duration of the pressures time histories. (i.e PSHAPE 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.

### ***Strategy to correct synthetic pressures using local flexibility***

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

- The main effect of the deformation local height ( $\Delta z$ ) is introducing a time delay on how the water front advances along the plate.
- The deformation local pitch angle ( $\Delta\alpha$ ) will modify pressure parameters ( $P_{MAX}$ ,  $P_{SHAPE}$ ).

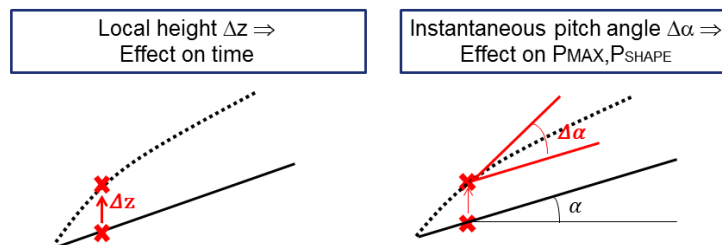


Figure 13: Description of Local Deformation Effects to be used in the strategy of ditching loads alleviation due to flexibility effects

By using the information of local deformation ( $\Delta z$ ,  $\Delta\alpha$ ) 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:

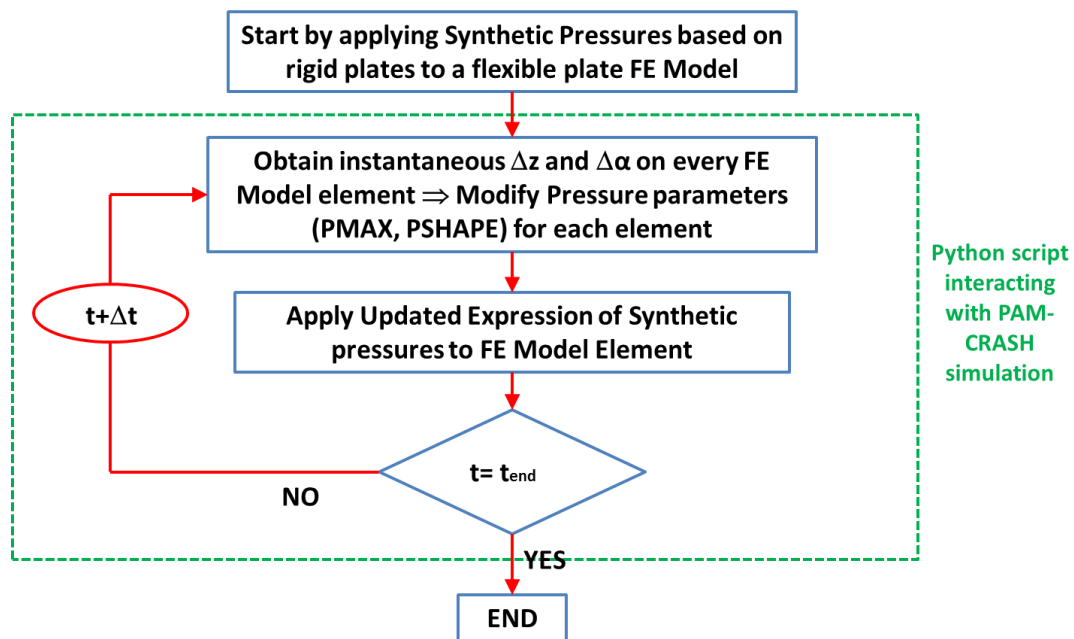


Figure 14: Flowchart highlighting the Strategy to Correct Synthetic Pressures Using Local Deformations on Flexible Plates

### *Effect of local height $\Delta z$*

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  $\Delta z$  is basically a delay on when the water front reaches the deformed point. The larger is the deformation  $\Delta z$ , the larger is 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.

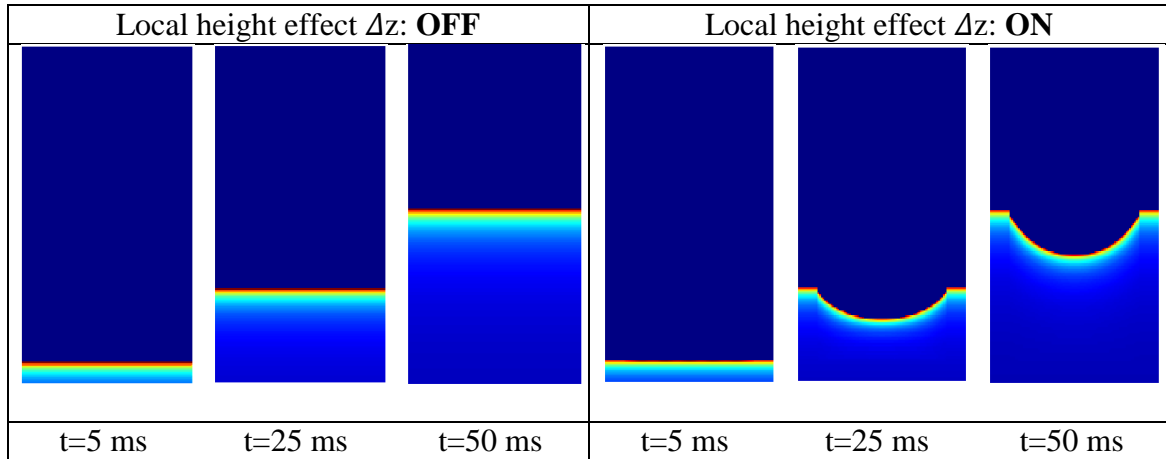


Figure 15: Water Front Shape for Rigid  $t=15$  mm (Left) and Flexible  $t=0.8$  mm (Right) Plates.

### *Effect of local pitch angle $\Delta\alpha$*

Next plot shows the  $\Delta\alpha$  found by the pressure front due to deformation of a flexible  $t=0.8$  mm panel after applying the synthetic pressures (without correction yet). The trends are as expected:

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

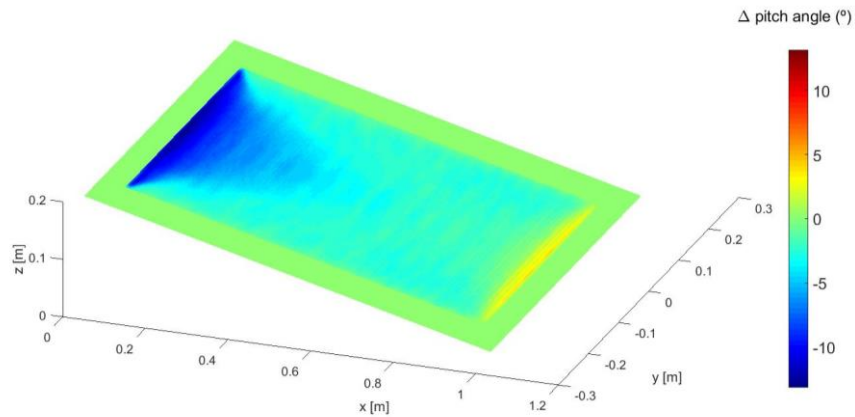


Figure 16:  $\Delta\alpha$  calculated on the FE Model after applying synthetic pressures.

This correction is intended to modify Synthetic Pressures main parameters (PMAX, PSHAPE) with respect to the local pitch angle. In order to do that, experimental values of these parameters in rigid and flexible plates at 30 m/s and pitch 10° have been used (the only set of comparable data available from the tests).

The ratio between experimental flexible plate parameters and experimental rigid plate ones have been obtained for each pressure transducer of the plate and plotted against the  $\Delta\alpha$  obtained from the numerical simulation. Linear regression has been used to set the magnitude of the correction for each of the pressures parameters.

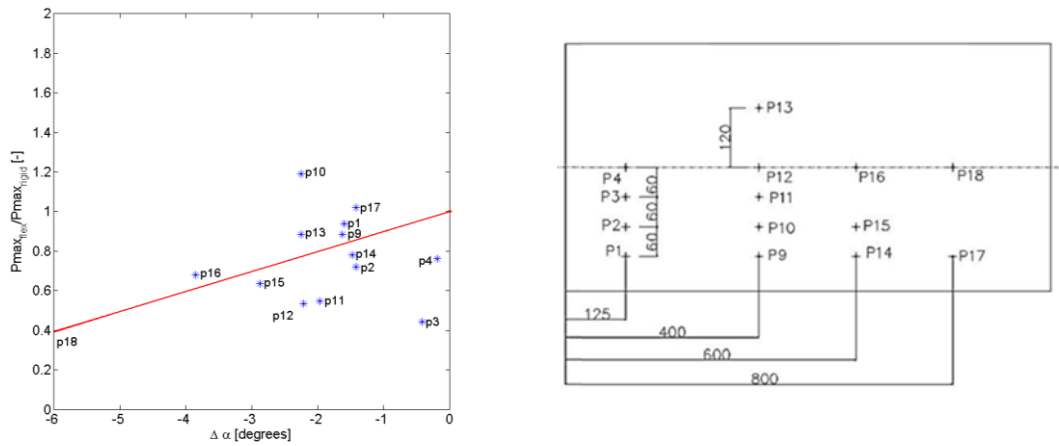


Figure 17: PMAX parameter proposed correction versus pitch angle

## Results incorporating flexibility corrections

Next figure shows the results of the numerical simulation of the case  $V=46$  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:  $\Delta z$ -only correction (green curves) and  $\Delta z + \Delta\alpha$  corrections (red curves).

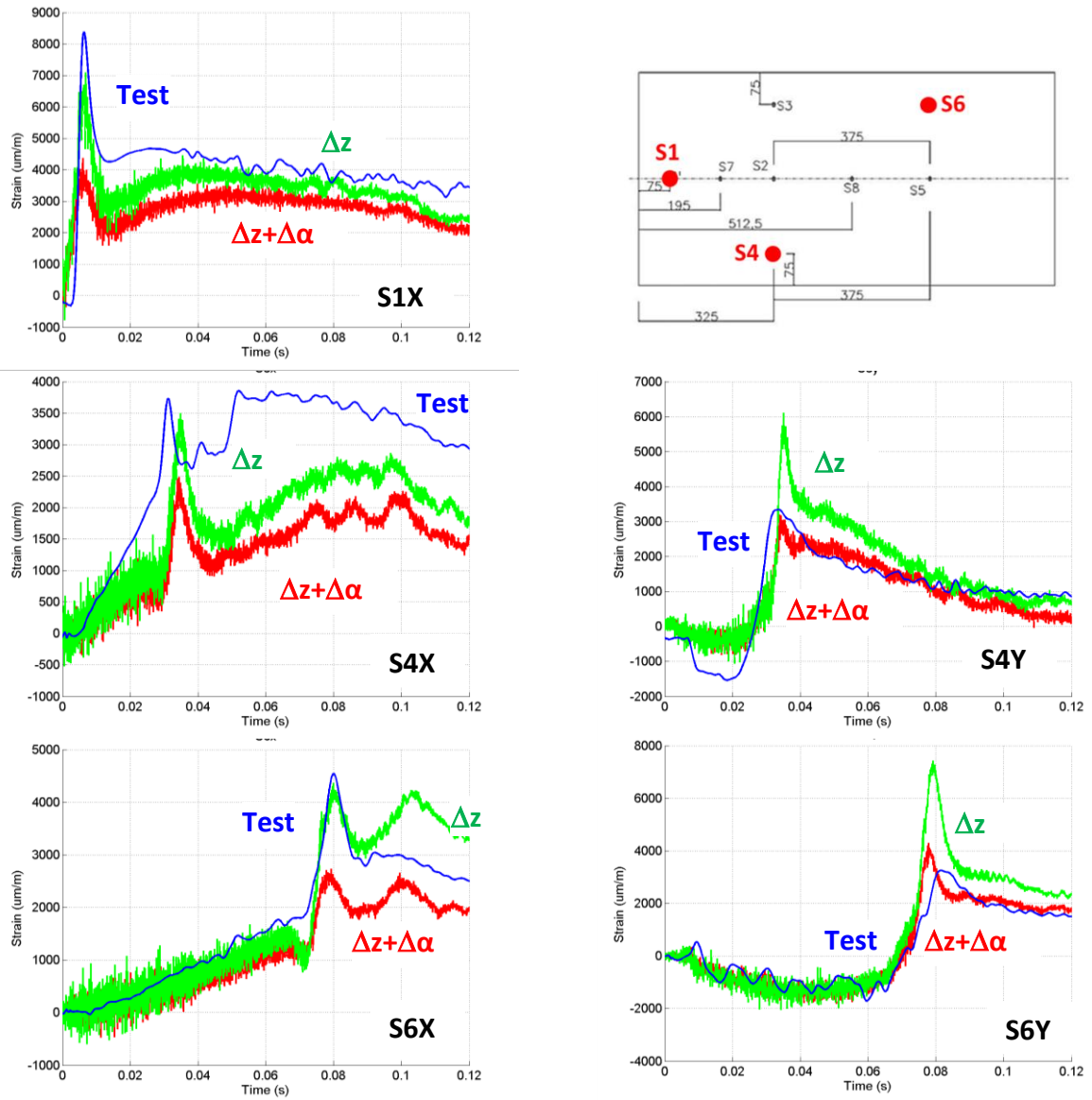


Figure 18: Deformations on a Flexible Plate: numerical simulations using corrected synthetic pressures vs. test results – Close to frame positions

The corrections worked relatively well in trying to reproduce (for the same plate and simulation conditions) the 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, S4, S6) the numerical simulation is able to capture the shape, the instant of the peak deformation and very closely (although not entirely conservative for X-direction when both corrections are applied) the peak level of the deformation.

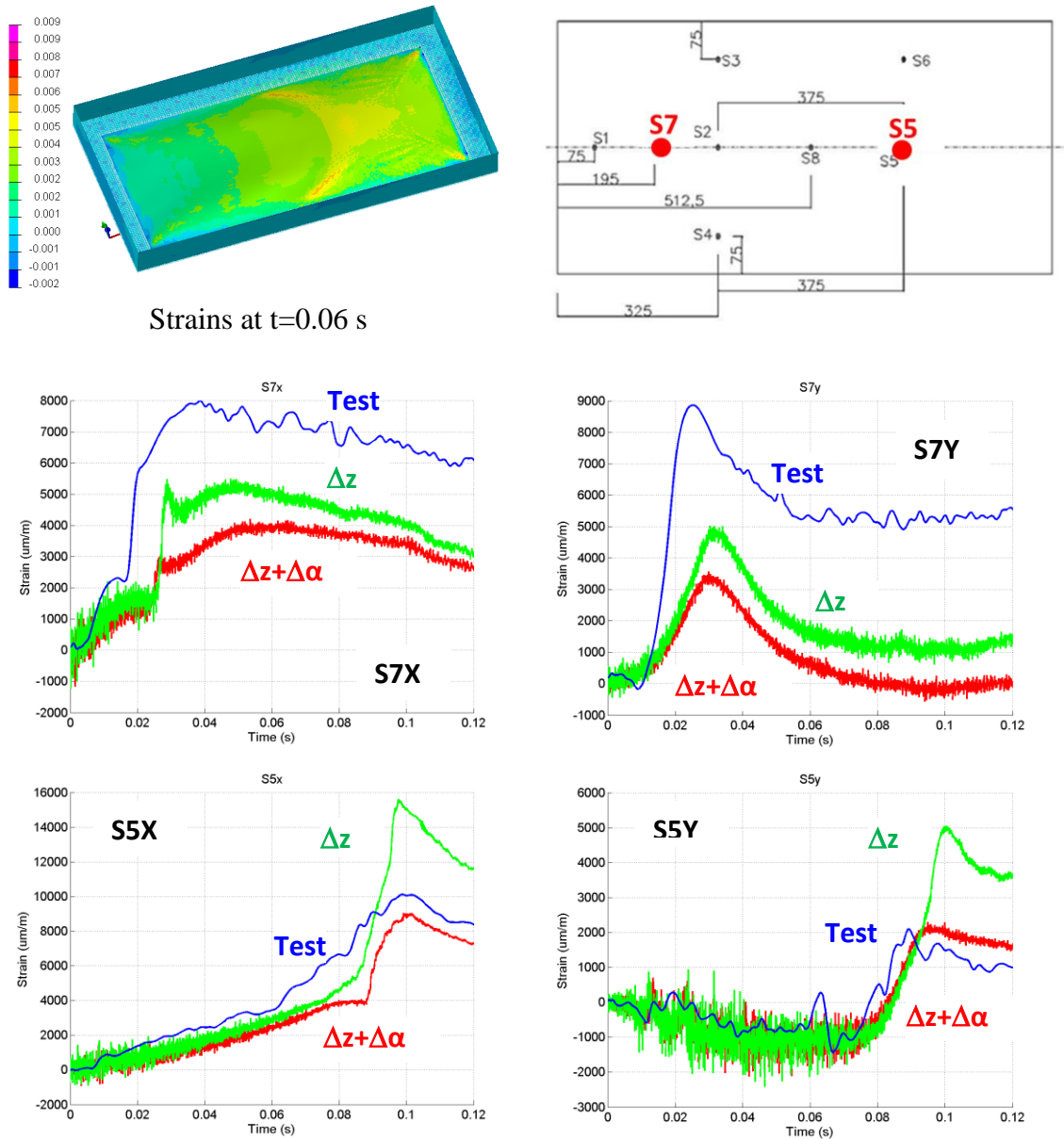


Figure 19: Deformations on a Flexible Plate: numerical simulations using synthetic pressures vs. test results – Symmetry axis positions

- For the positions with larger expected deformations (pick-ups S7, S5), the numerical simulation also is able to capture the shape and the time instant of the peak:
  - For S5 pick-up, the corrections with  $\Delta z + \Delta \alpha$  follow very closely the shape and levels of the test measurements.  $\Delta z$ -only correction seems to lead to conservative results.

- For S7 pick-up, both corrections follow the shape and peak time occurrence from the tests, but the peak level of the deformation is about 40% apart (lower) in the numerical simulation with respect to the test results. This type of simulation would have been non-conservative (even worse when both corrections are applied).

As a summary: this attempt to incorporate flexibility corrections in the ditching simulations is promising. For most of the pick-ups (i.e all except S7) the results are relatively good in terms of shapes and time of occurrence of peaks and slightly non-conservative.

## **Concluding remarks and future activities**

### ***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)

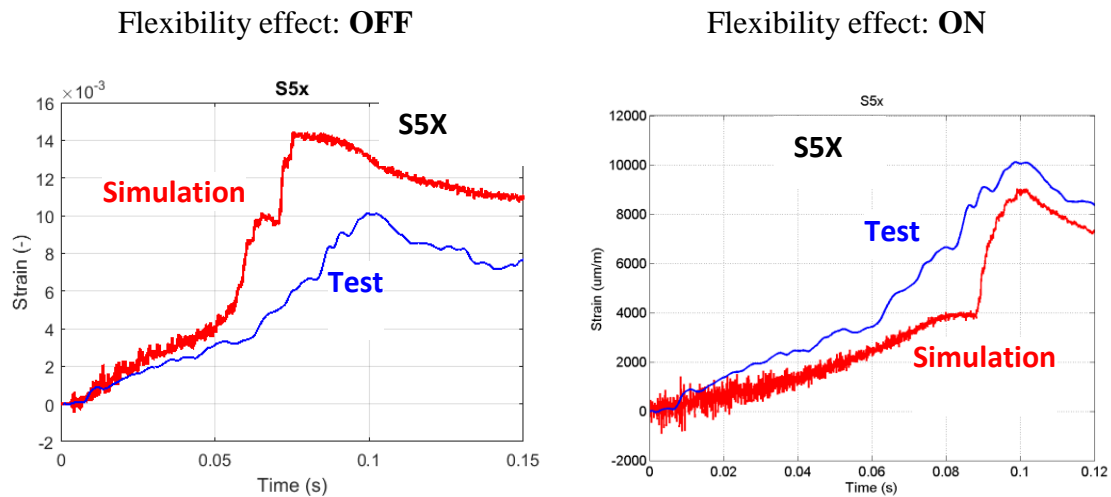


Figure 20: Comparison of deformations at S5X position with flexibility effect ON and OFF. Results for  $V_x=46\text{m/s}$  and pitch 10 deg.

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
- 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)

### ***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.

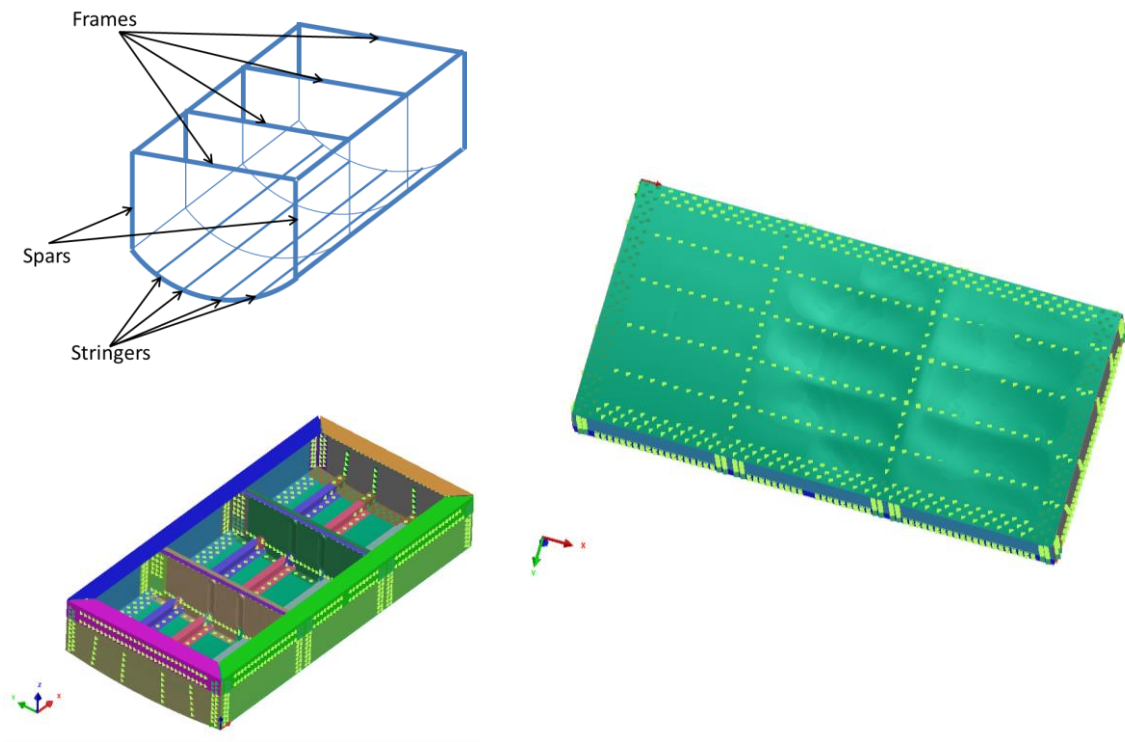


Figure 21: SARAH fuselage-like tests specimen scheme, FE Model and Skin deformed shape with Synthetic Pressures applied ( $V_x=46\text{m/s}$ , Pitch 6 deg,  $t=0.05\text{s}$ )

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 SARAHE (including elasticity effects obtained from SARAHE 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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