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NUMERICAL SIMULATION OF DITCHING DYNAMIC LOADS

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Abstract: Ditching is a planned aircraft event that ends with a controlled emergency landing in water. During the few seconds of the impact phase, large hydrodynamic pressures develop at the interface between the structure and the fluid which in turn may generate damages leading to rupture and cracks on the bottom part of the aircraft fuselage. Ditching is an extreme case of fluid-structure coupling. Currently there are very few available tools to address this problem that is gathering significant attention from public and institutions especially after some recent events with large media coverage (like the ditching on the Hudson River, US Airways Flight 1549, 15 January 2009).

At Airbus DS Military Transport Aircraft Aeroelasticity and Structural Dynamics department ditching has been a topic of continuous research for more than 12 years [1-4]. This interest is also shared by universities, research establishments and industrial partners that have gathered together in the consortium of the European funded research project SMAES (Smart Aircraft in Emergency Situations, 2011-2014).

This paper will focus on explicit Finite Element (FE) numerical simulations to deal with ditching loads and structural response following two different approaches:

- Water is simulated using Smoothed Particle Hydrodynamics (SPH).
- Measured pressures from ditching tests are applied to the FE Model.

The first part of the paper will be devoted to numerical simulation of ditching scenarios of very stiff panels as they has been tested at CNR-INSEAN during SMAES. Magnitudes simulated will be local pressures, forces and strains on the panel. Numerical results will be extensively compared with available ditching test results obtained in SMAES. The study will show a wide variety of sensitivity analysis to different parameters.

The paper will continue with the more challenging task of ditching simulation of flexible panels. Local flexibility affects local pressures which in turn modifies local deformation in a highly coupled fluid-structure interaction phenomena. Comparison of numerical simulations with available SMAES test results will be shown, indicating on one hand what is achievable and on the other, what are the current limitations of the proposed technique for flexible panels. Similitudes and differences between flexible panels and very stiff panels will be highlighted.

The alleviating effect of structural flexibility is one of the most important outcomes of these analyses. It has critical relevance for aircraft ditching certification and it will have a dedicated section in the paper.

Concluding remarks highlight how the SMAES project has allowed a large step forward in the understanding of the complex fluid-structure interaction phenomena that takes place during a ditching scenario. In particular, it has allowed enhancing predictive numerical tools. The paper will end with suggestions for further work in this area.

1 INTRODUCTION

Ditching is an aircraft emergency event that ends with the planned impact of the aircraft against water under controlled conditions. Four main phases have to be analyzed in a ditching event:

- Approach: Characterized by aircraft/environmental conditions before impact
- Impact: Structural response during the impact
- Sliding: Subsequent motion of the aircraft until stoppage
- Floatation: Evacuation of passengers and crew

This scenario is reflected in the Airworthiness Regulations that require the aircraft manufacturer to take all necessary measures to minimize risk during ditching to allow the safe evacuation of the occupants.

This paper is devoted to obtain by numerical simulation the dynamic loads and structural response during the second phase (i.e. the impact with water). During this phase, the high hydrodynamic pressures, derived from the aircraft impact with water, may cause rupture of the structure, which in turn may jeopardize the required safe evacuation of crew and passengers.

Ditching is an extreme case of fluid-structure interaction that constitutes a real challenge. SMAES has devoted part of its activities to perform an experimental ditching test campaign of representative A/C panels at full scale ditching conditions. 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 CNR-INSEAN in Rome [4-6].

2 BRIEF LITERATURE SURVEY

A complete survey of all available literature about ditching is completely out of the scope of this paper. Nevertheless it may be convenient to mention some relevant contributions to provide a perspective to the work presented herein.

Two classical references, [7] and [8], established the basic theory of the vertical impact of a rigid body on water.

Tests in hydrodynamic channels have been needed to understand ditching phenomena in a great variety of geometries. Works [9] and [10] were devoted to rectangular flat plates and arbitrary constant cross section and [11] presented the experimental investigation of the effect of the rear-fuselage shape on ditching behavior.

Investigations about ditching were concentrated between 1930 and 1950 when the basic theoretical developments and experimental techniques were already established. However, during the last decades numerical simulation has experienced a great development, in particular, Smoothed Particle Hydrodynamics (SPH) in combination with Finite Elements (FE) has been used to investigate problems of impact. During the early eighties, the basis of SPH technology was established [12] and [13], and soon it was applied to study free-surface flows, [14] and high velocity impacts [15]. The ditching problem has been studied from a global numerical point of view using SPH in [16] and [17], but showed that this SPH technique needed to be improved to be able to apply it in an industrial environment, when impacts on water with horizontal velocity are considered. These SPH improvements have been one of the focuses of the European funded research project SMAES, [18] and [19].

3 SMAES DITCHING TEST DESCRIPTION

3.1 Ditching test summary

A description of the test and an evaluation of the repeatability of its results are included in reference [4]. A brief summary is introduced herein for completeness.

The SMAES ditching tests are a set of guided impact tests of panels against water at horizontal speeds representative of a real aircraft._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 (30 m/s, 40 m/s, 45 m/s)
- Pitch angle at impact (4°, 6°, 10°)
- Panel curvature (flat, concave, convex)
- Panel stiffness (quasi-rigid, flexible, very flexible)
- Panel material (metal, composite)

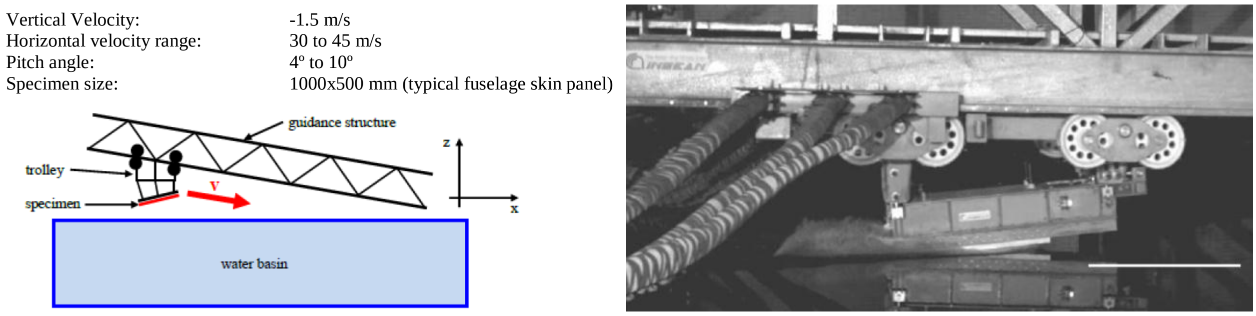

Figure 1: Schematic sketch and exemplary picture of the guided ditching test during impact.

3.2 Ditching test instrumentation

The instrumentation of the guided ditching tests was:

- 18 pressure transducers (18 channels)
- 6 strain gauges – two directions (12 channels)
- Velocity (1 channel)
- 6 accelerometers on the panels (6 channels)
- 6 Load cells to measure forces from the panel to the trolley (5 channels)

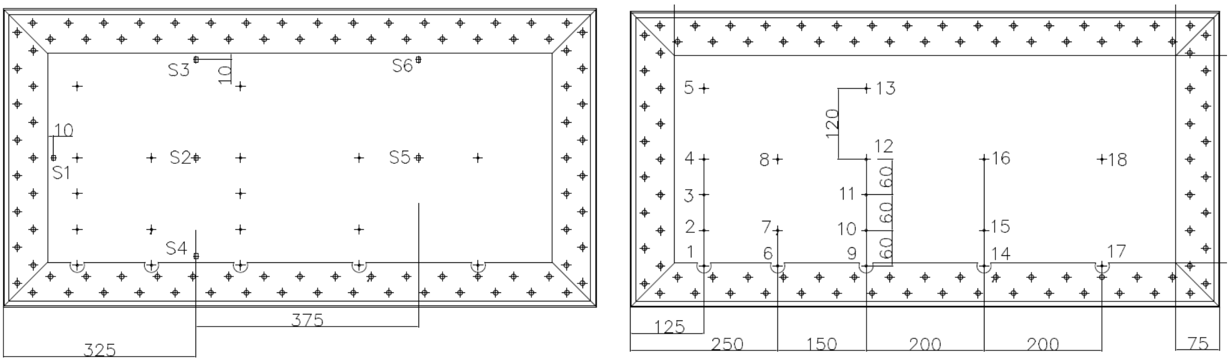

Figure 2: Positions of strain gauges (left) and pressure transducers (right) for quasi-rigid cases.

3.3 Ditching test execution

The specimen, with a size of 1000 x 500 mm (typical fuselage skin panel size), was attached to the guided frame. The frame embedded in a trolley and the trolley guided using an auxiliary structure.

During each test run, six phases could be identified:

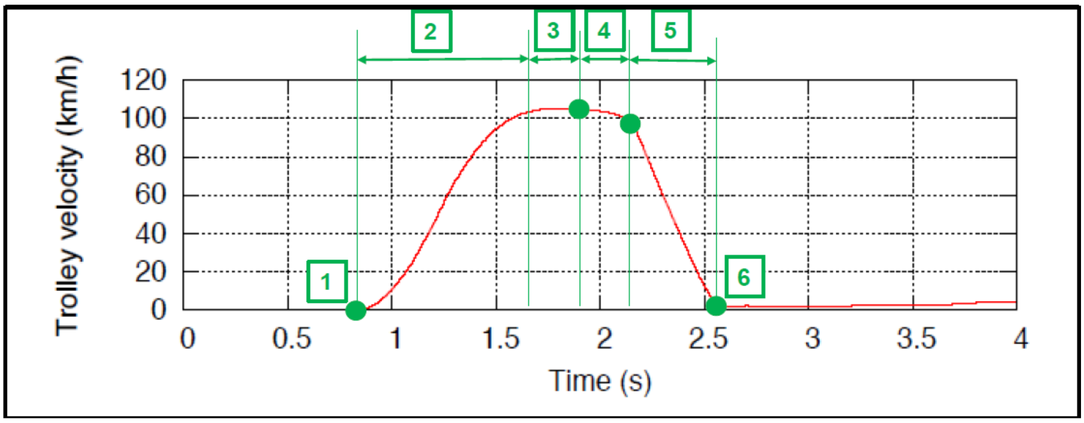

Figure 3: Phases of each ditching test run

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

4 FEM SOLVER FOR DITCHING NUMERICAL SIMULATION

The commercial explicit code Virtual Performance Solution (VPS, formerly PAM-CRASH) provided by the ESI Group has been selected as the software tool kit in the analyses [20].

The water was modeled using Smoothed Particle Hydrodynamics (SPH). SPH is a grid-less computational technique where each SPH particle represents an interpolation point. Particles interact based on a weighted summation of their properties within a zone of influence controlled by the smoothing length.

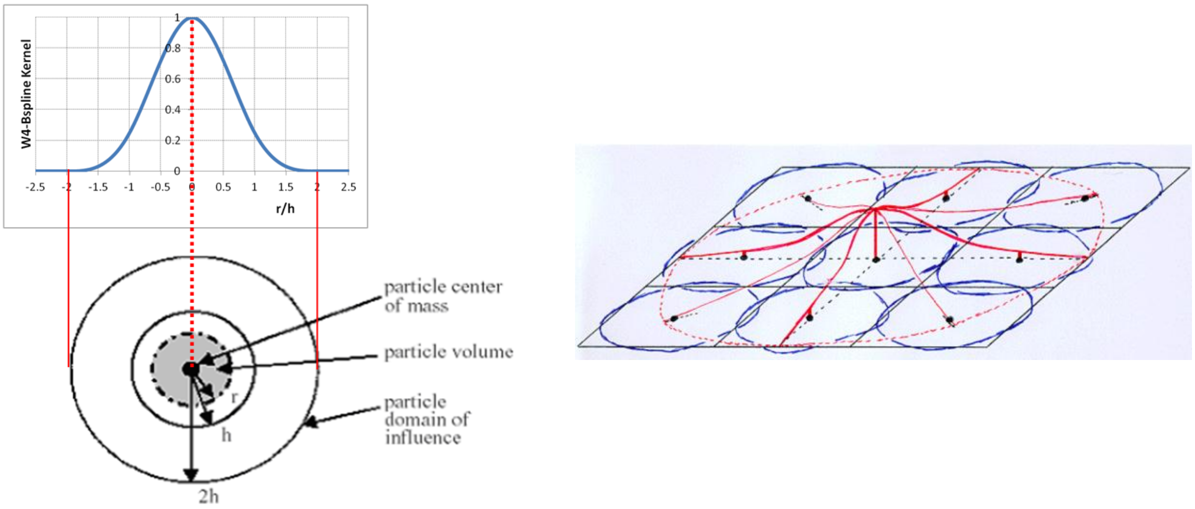

Figure 4: SPH main control parameters [20]

During the SMAES project many efforts have been dedicated to improve simulation techniques in ditching. The Virtual Performance Solution code was enhanced by ESI Group with many features with direct application to ditching [18]. The model includes the following specific SPH relevant features:

- Pressure Correction: The standard weakly compressible SPH method is well known to give poor pressure distributions in terms of high-frequency oscillations (numerical noise) in time and space. This deficiency is counteracted by pressure correction methods which aim to yield a more regular pressure distribution. Various algorithms have been investigated and implemented in the SPH solver of Virtual Performance Solution [18] showing to deliver more accurate flow simulations.
- Periodic boundary conditions and damping: The option of periodic boundaries allows particles leaving a user-defined domain at one side to re-enter the domain at the opposite side with user-defined properties. By default, the position of these boundaries is fixed, but it is possible to link the motion of the boundary to a moving node. This feature allows particles inside the fluid domain to follow the (horizontal) motion of a prescribed node without introduction of velocities. Due to the interaction between nearest neighbor particles that extends on both sides of a periodic boundary, disturbances of conditions at the inflow end may still arise in case the wake at the opposite end is violent. A simple method to reduce these disturb is by defining damping zones in front of these boundaries

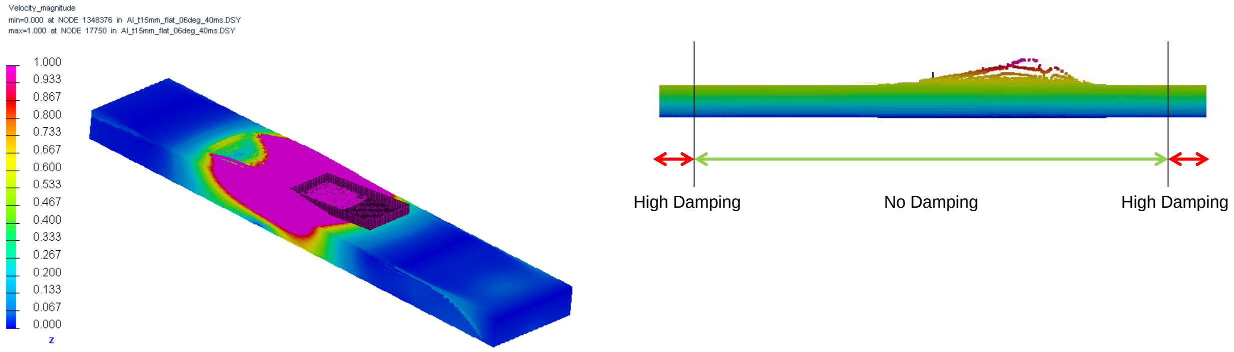

Figure 5: Periodic boundary conditions in ditching simulations: translating domain with undisturbed flow conditions (left). Damping zone example in ditching simulation with high horizontal velocity (right)

- Hydrostatic gravity field initialization: Computer resources may be saved by starting with the correct hydrostatic distribution. It avoids the need to conduct an initialization-simulation to obtain hydrostatic pressure equilibrium dynamically.
- Pressure gauge particles: are SPH particles not ‘visible’ to regular particles but that can probe the properties of the nearby particles within a spherical region with radius equal to twice the smoothing length. For such gauges the pressure is evaluated as the weighted average of all neighbor particles.
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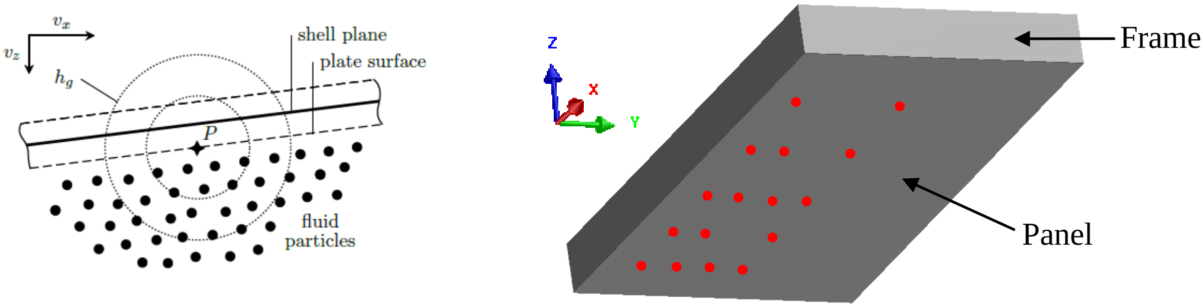

Figure 6: Detailed view on pressure evaluation method: 3D view showing position of pressure gauges (plotted in red) in the numerical model.

5 QUASI-RIGID PANELS DITCHING NUMERICAL SIMULATION USING SPH

5.1 Flat Panel Structural Model

Panel and frame have been modeled using shell elements with aluminum elastic-plastic properties. Both are joined using an elastic bolted junction. The trolley is included as a punctual mass (785 kg) joined to the frame.

The guiding system is modeled as a translation mechanism: there is a driver node that acts like the reference point of the frame outer nodes and the moving water basin. X – Z trajectory is prescribed by the mechanism while Y translation and pitch angle are fully constrained.

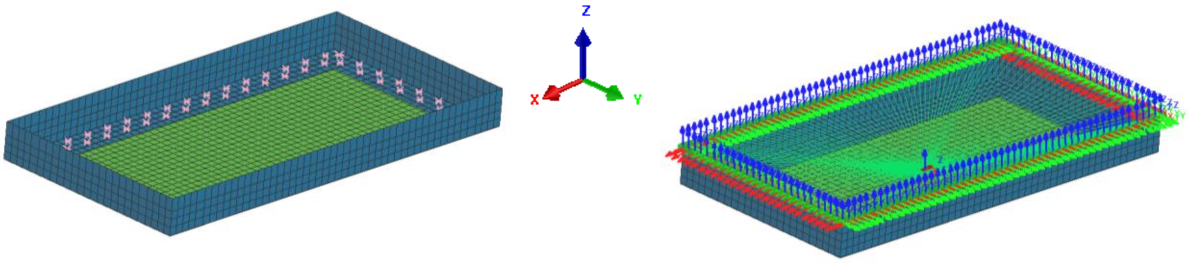

Figure 7: Panel, frame and bolts FE model (left). Detail of the guiding system model (right)

Outputs obtained from the structural model:

- Pressures on the panel are measured at same positions than in the tests using pressure gauges.
- Strains are obtained from the shell elements with closest position to the placement of the strain gauges in the tests.
- Total forces on the panel are measured at the top part of the frame.

5.2 Fluid Model

The water basin has mainly two components:

- Water basin of SPH elements with movable periodic boundaries in X – direction.
- Water basin container of shell elements, acting as supporting structure of the SPH basin in Y and Z directions.

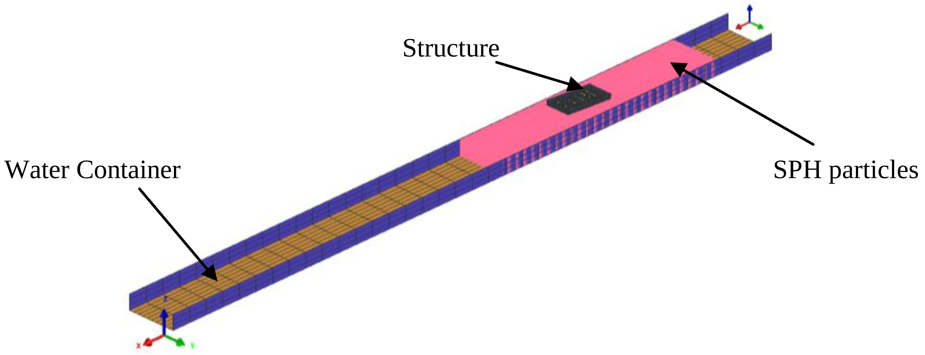

Figure 8: SMAES ditching tests FE model

The water basin is a block of 5 x 1 x 0.3 m filled with 360 000 SPH particles of 16 mm spacing. Water is approximated by a weakly compressible fluid. This material is characterized by Murnaghan equation of state corresponding to material type 28 in Virtual Performance Solution [20]. It leads:

$$p = p_0 + B\left[\left(\frac{\rho}{\rho_0}\right)^{\gamma} - 1\right]$$

where

- B is the Bulk modulus (resistance to uniform compression)
- p_0 is the reference pressure (herein $p_0=0$)
- ρ/ρ_0 is the current over initial density ratio
- γ is the adiabatic exponent set to 7.

5.3 Numerical Simulation results and comparison with Tests

Numerical simulation results and tests have been correlated in terms of pressures and strains along the panel and total forces on the panel. All the numerical simulation results shown in this paper have been filtered using a CFC 600 filter.

Results are shown in figures 9 to 11 for the 15mm quasi-rigid aluminum panel at 40 m/s horizontal speed and pitch of 6 degrees.

Pressures are sharp and the time from leading edge to trailing edge submersion takes approximately 60 ms. Numerical simulations are slightly faster than tests.

The panel deformation pattern is fully captured by the simulations. Areas and time histories of tension and compression are well represented. Maximum values of strains are close to those measured in tests, although the pressure field shows less similarity.

Total forces on the panel obtained from numerical simulation are conservative and follow same evolution than tests.

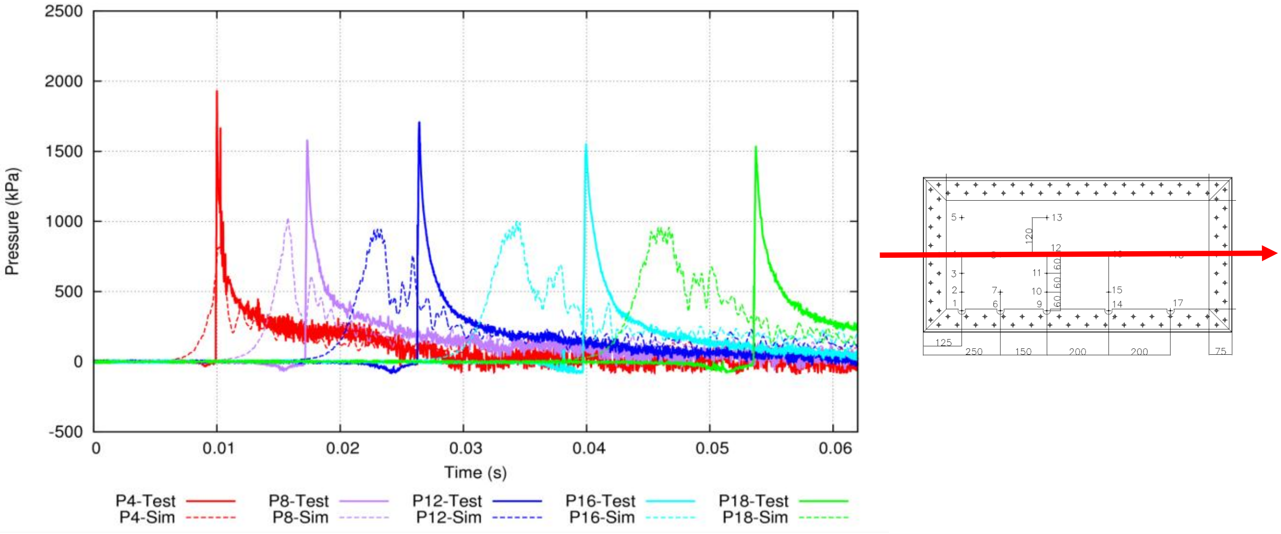

Figure 9: Evolution of pressures along panel symmetry axis. Correlation of test results (solid line) with numerical simulations (dotted lines).

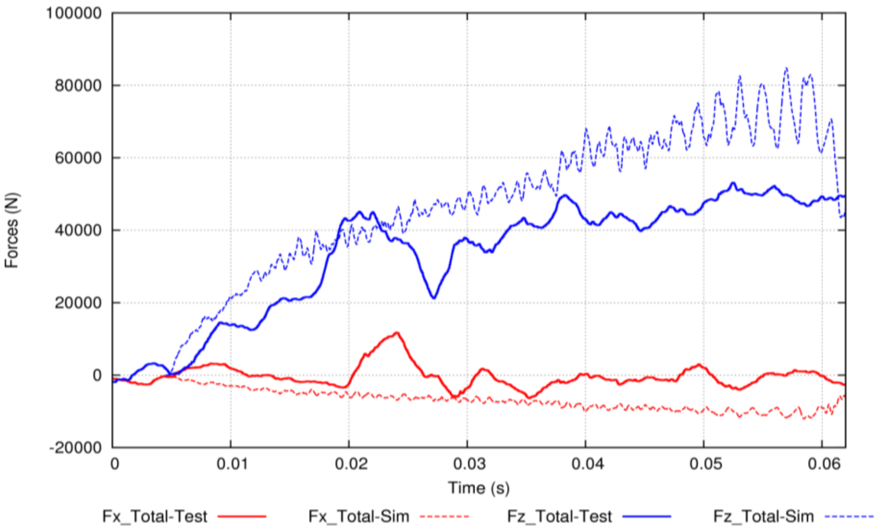

Figure 10: Evolution of total forces on panel. Correlation of test results (solid line) with numerical simulations (dotted lines).

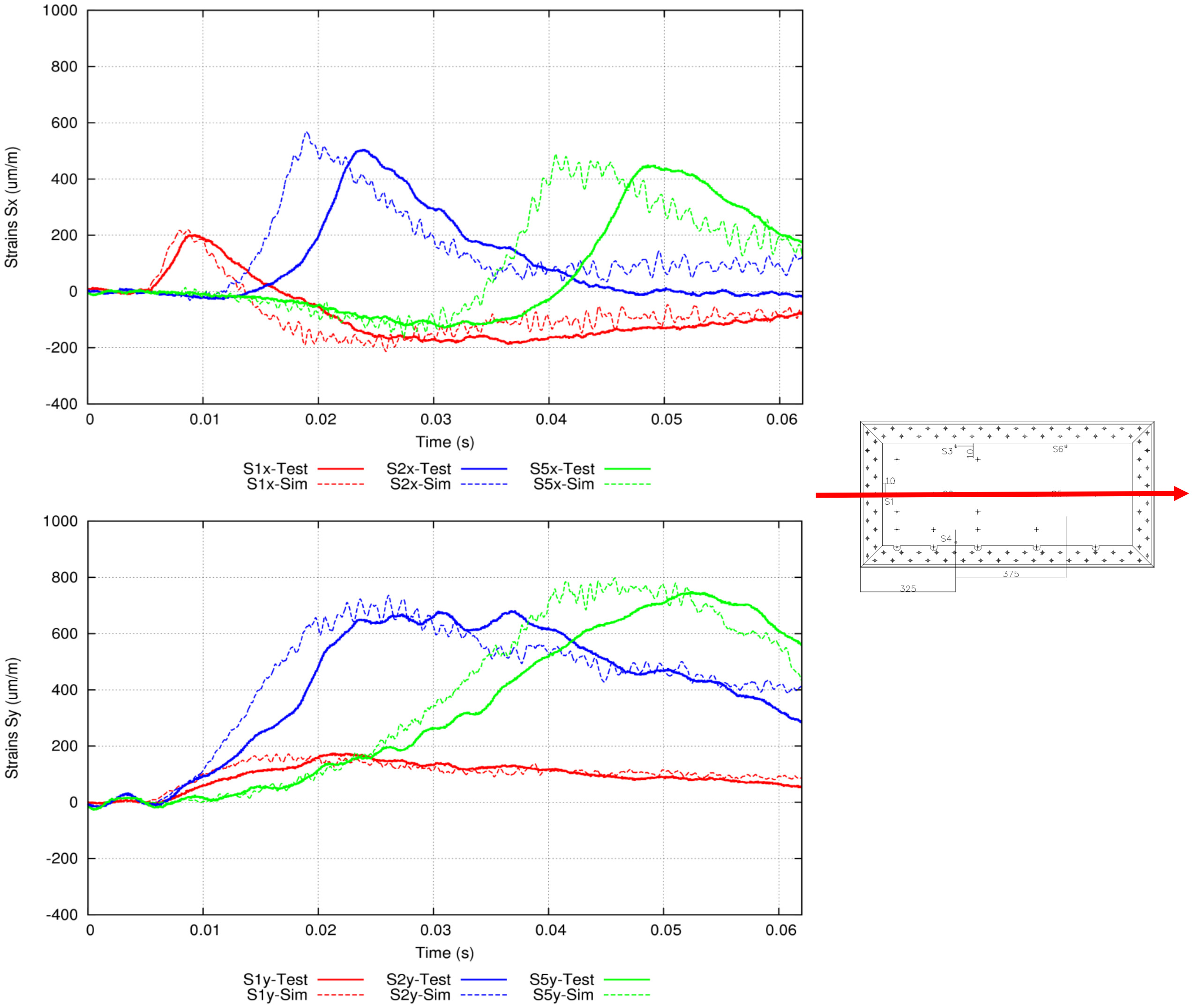

Figure 11: Evolution of strains (x-direction on top, y-direction on bottom) along panel symmetry axis. Correlation of test results (solid line) with numerical simulations (dotted lines).

Although peak pressure values obtained with numerical simulations are not accurately predicted when compared with those obtained in the tests, the total impulse ($\int F \cdot dt$) is fairly well captured leading to the same levels of deformation as shown in Figure 11.

Sensitivity analyses

5.3.1 Sensitivity to horizontal impact speed

Numerical simulations have been performed at different horizontal impact speed in order to study the sensitivity of numerical results to this parameter (Figure 12). Same trends have been found when compared to ditching tests results.

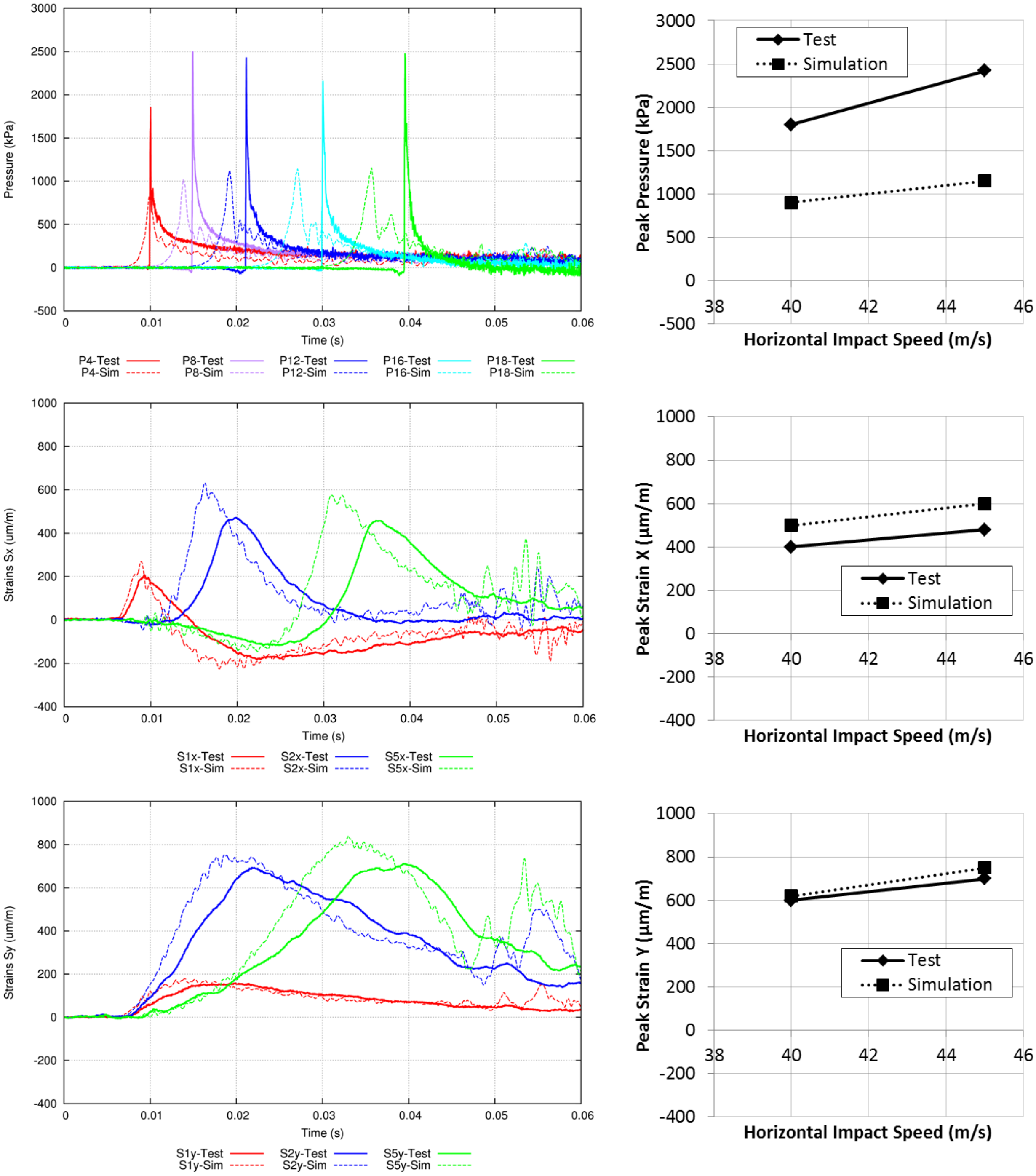

Figure 12: Typical pressure and strain time histories at horizontal impact speed of 45m/s (left). Evolution of peak pressure and strain with horizontal impact speed (right).

5.3.2 Sensitivity to impact angle

VPS simulations have been performed at three different impact angles to investigate the sensitivity (Figure 13). Similar trends are shown when comparing simulation and tests results for peak strains. When comparing peak pressures, there is a decrease trend with impact angle in values from tests while numerical values slightly increase (although this difference found in peak pressures comparison, similar total impulse ($\int F \cdot dt$) increase with angle of impact is obtained for both, numerical simulation and tests, which produces same strain peak levels)

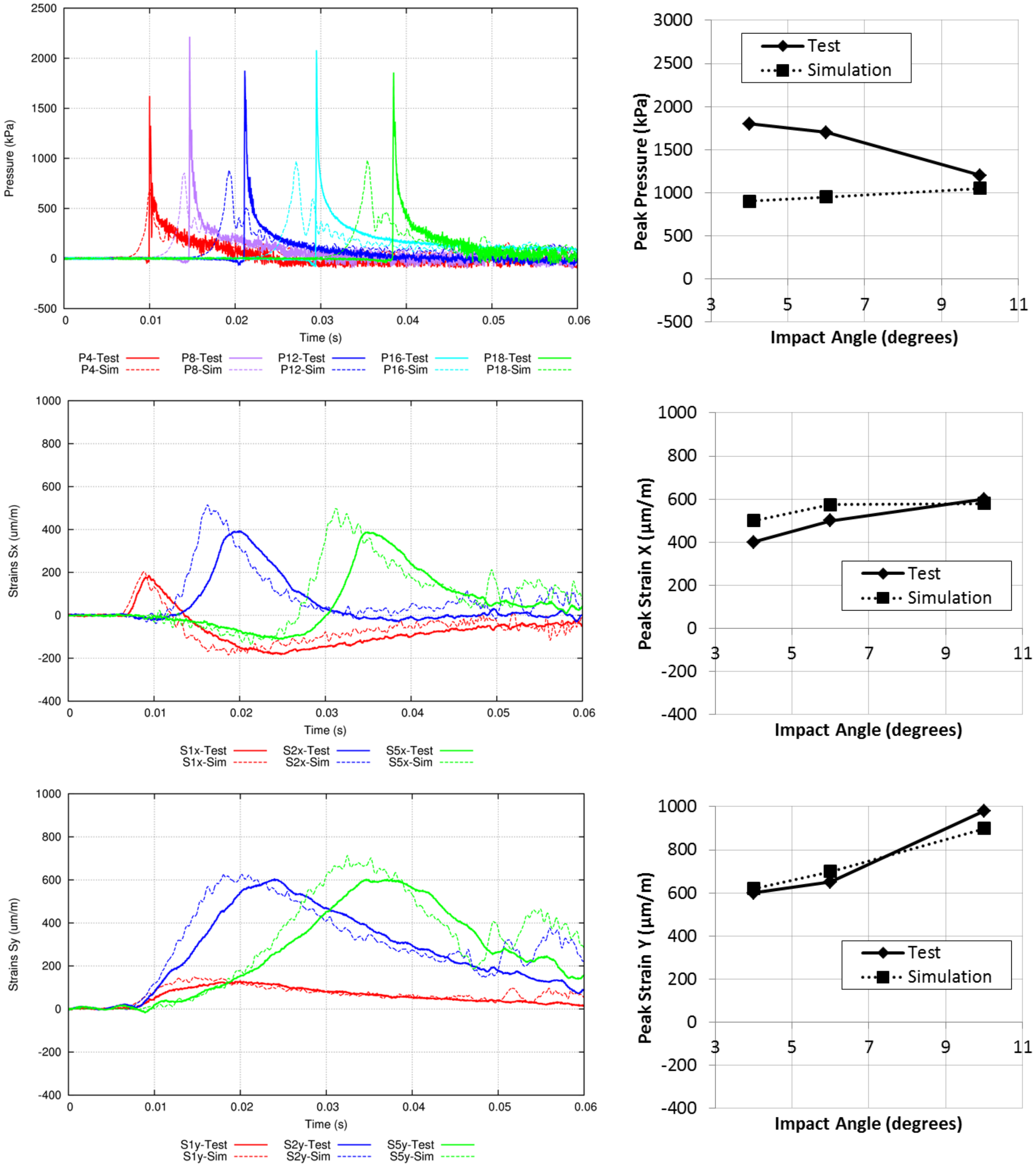

Figure 13: Typical pressure and strain time histories at impact angle of 6 degrees (left). Evolution of peak pressure and strain with impact angle (right).

6 QUASI-RIGID PANELS DITCHING NUMERICAL SIMULATIONS USING MEASURED PRESSURES

6.1 Pressures interpolation process

Another possible approximation to the problem is to apply the pressures obtained from the guided ditching tests [21] directly to the structural model [1]. As SPH is not used with this approach, the CPU cost of the simulation is reduced dramatically. On the other hand, pressures from the tests are obtained at some discrete positions (Figure 2) and an interpolation must be performed to get the evolution of the complete pressure field on the panel.

A MATLAB script has been implemented to perform this interpolation. Using as input the pressures measured in the test and the structural FE model, this MATLAB script generates a file with the pressures time histories applied on every panel shell element that can be used directly as VPS input. Numerical simulation and ditching tests results in terms of strains and forces are then post-processed and compared.

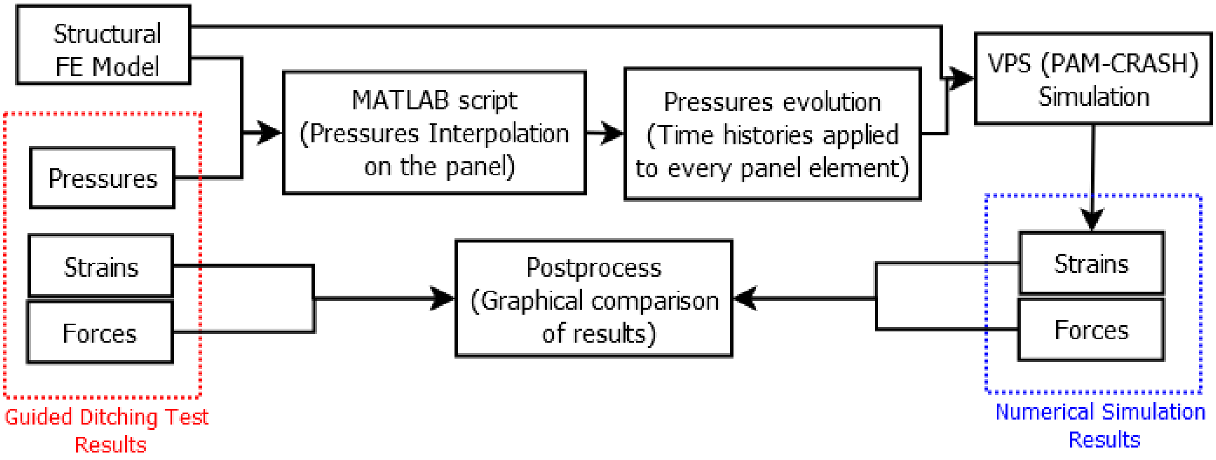

Figure 14: General flowchart of the process.

The MATLAB script performs the following four operations:

1) Adjustment of pressure time history: The MATLAB script reads the pressures time histories from the test data files provided by CNR-INSEAN. For each of the pressure gauges data, the process that is performed is:

    - The starting time and ending time of the pressure pulse is determined.
    - The pressure pulse is fitted to a curve of the type:

$$p(t) = P_F + \frac{P_{SHAPE}}{tg\left(\frac{\pi}{2}t + \varphi\right)}$$

where $\varphi = \varphi(P_{\max}, P_F, P_{SHAPE})$

P_F and P_{SHAPE} are the fitting coefficients, (physical meaning in Figure 15)

$P_{\max}$ is the peak pressure

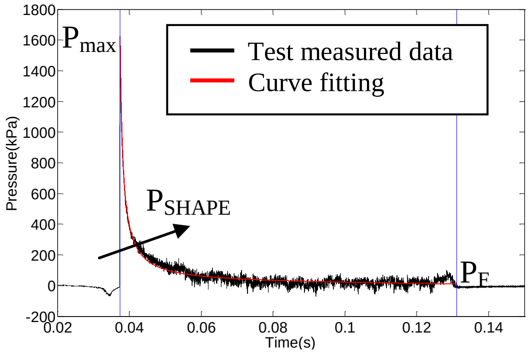

Figure 15: Pressure curve fitting example.

2) Reading VPS Structural FE model: information about the node and element locations is imported into MATLAB.
3) Interpolation of pressures at element positions: interpolation of the fitted curves of the test pressures is performed at the FE model element locations. This interpolation is performed in terms of initial and ending times of the pressure pulse, maximum pressure and A and B coefficients of the curve fitting.

   Figure 16 shows an example of this approximation for two time instants: with 40% of the panel surface wet and at the instant when the water reaches the leading edge.

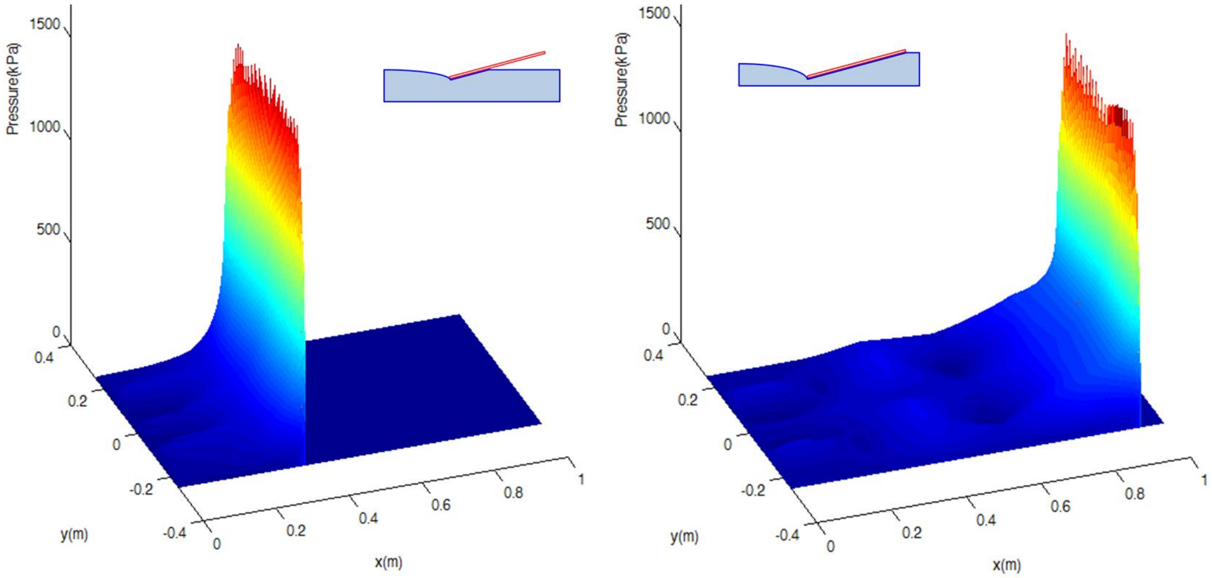

Figure 16: 3D pressure distributions with 40% panel surface wet (left) and with 100% panel surface wet (right).

4) Writing VPS compatible file with pressures time histories input for each FE Model element

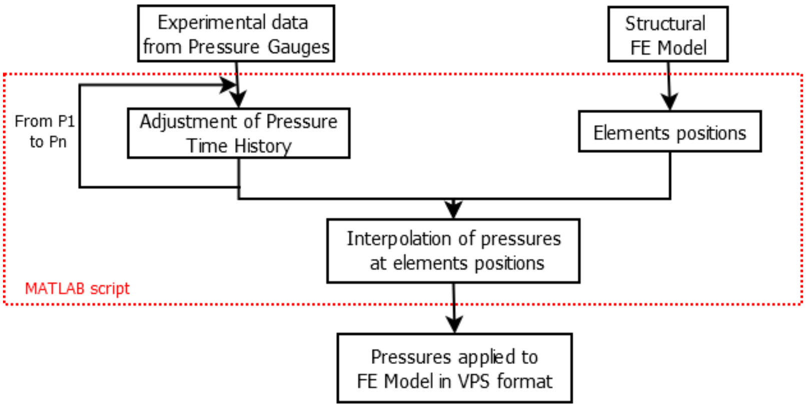

Figure 17: MATLAB script flowchart.

6.2 Numerical results obtained and comparison with tests

Numerical simulation results and tests have been correlated in terms of strains along the panel and total forces on the panel. Results are shown for quasi-rigid aluminum panel at 40 m/s horizontal speed and pitch 4 degrees.

The panel deformation pattern is fully captured by the simulations with measured pressures. Areas and time histories of tension and compression are well represented. Maximum values of strains are close to those measured by tests.

Total forces on the panel are in line with the evolution obtained in the tests.

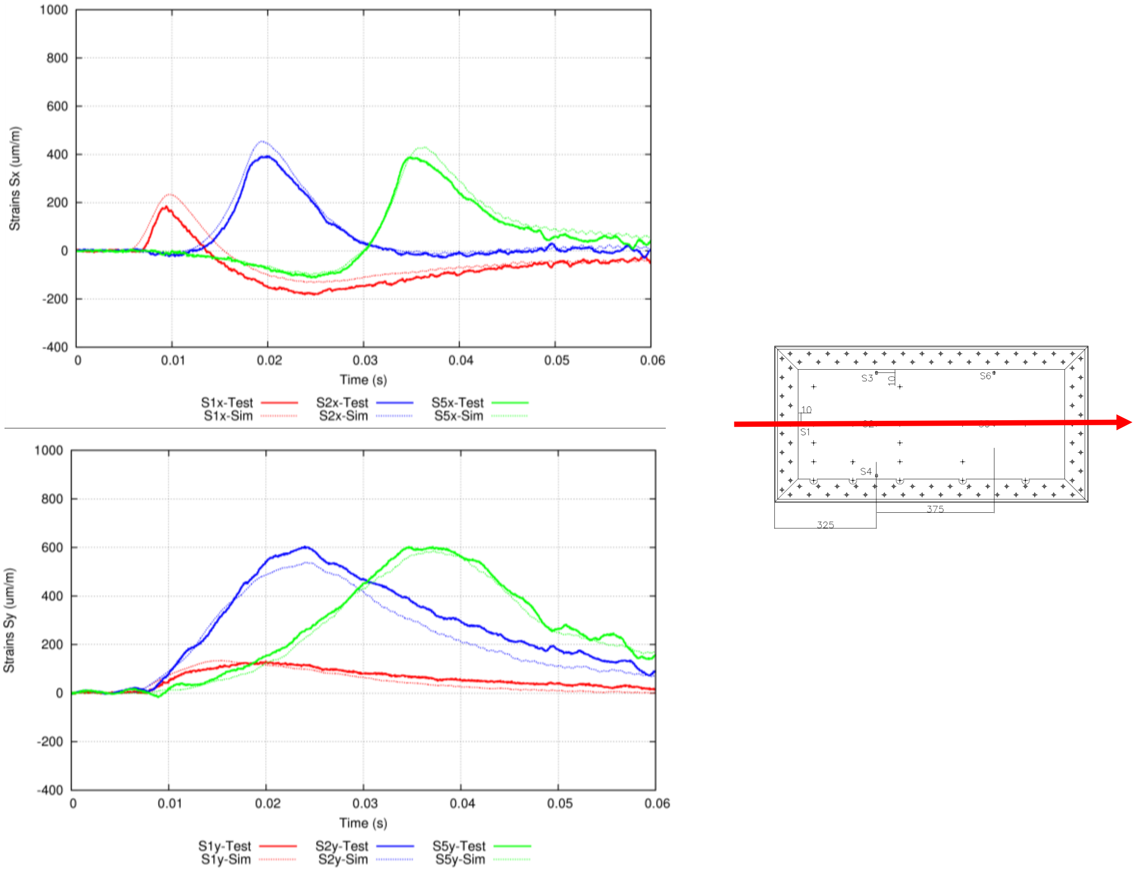

Figure 18: Evolution of strains (x-direction on top, y-direction on bottom) along panel symmetry axis. Correlation of test results (solid line) with numerical simulations (dotted lines).

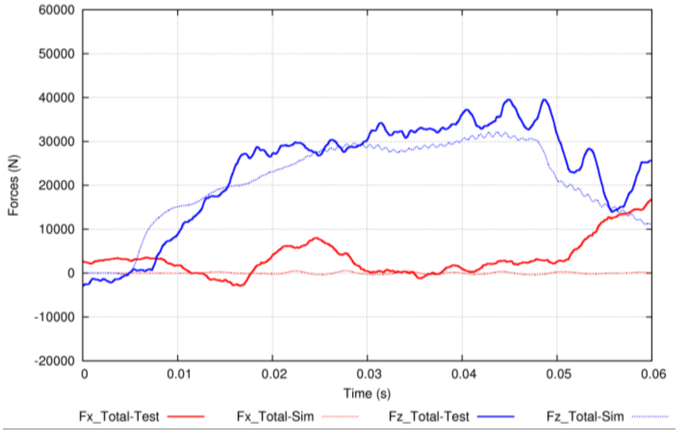

Figure 19: Evolution of total forces on panel. Correlation of test results (solid line) with numerical simulations (dotted lines).

7 FLEXIBILITY EFFECTS

7.1 Flexible panel numerical simulations using SPH

During SMAES ditching tests, the sensitivity to panel stiffness was also studied. Two different flexible panel thicknesses were tested: 3mm and 0.8mm.

As a general conclusion from ditching test data, the flexibility effect is reflected in lower peak pressure (but wider pressure peak) and higher structural response (higher deformations) when compared with quasi-rigid panel results.

The results from SPH simulations show that the maximum values and shapes of strains (in X and Y-directions) are close and conservative when compared to the ones obtained in the tests for flexible panels. Pressure evolution from SPHs simulations match reasonably the pressures measured in tests.

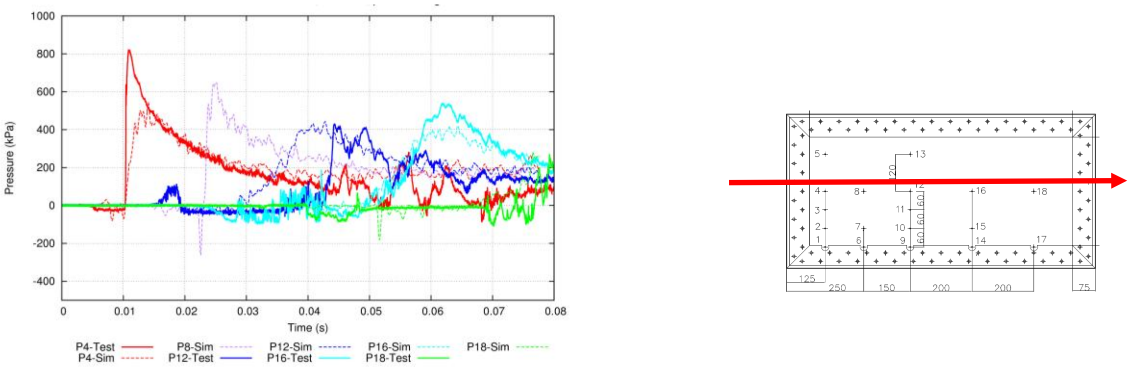

Figure 20: Evolution of pressures along panel symmetry axis for 0.8mm panel. Correlation of test results (solid line) with numerical simulations (dotted lines).

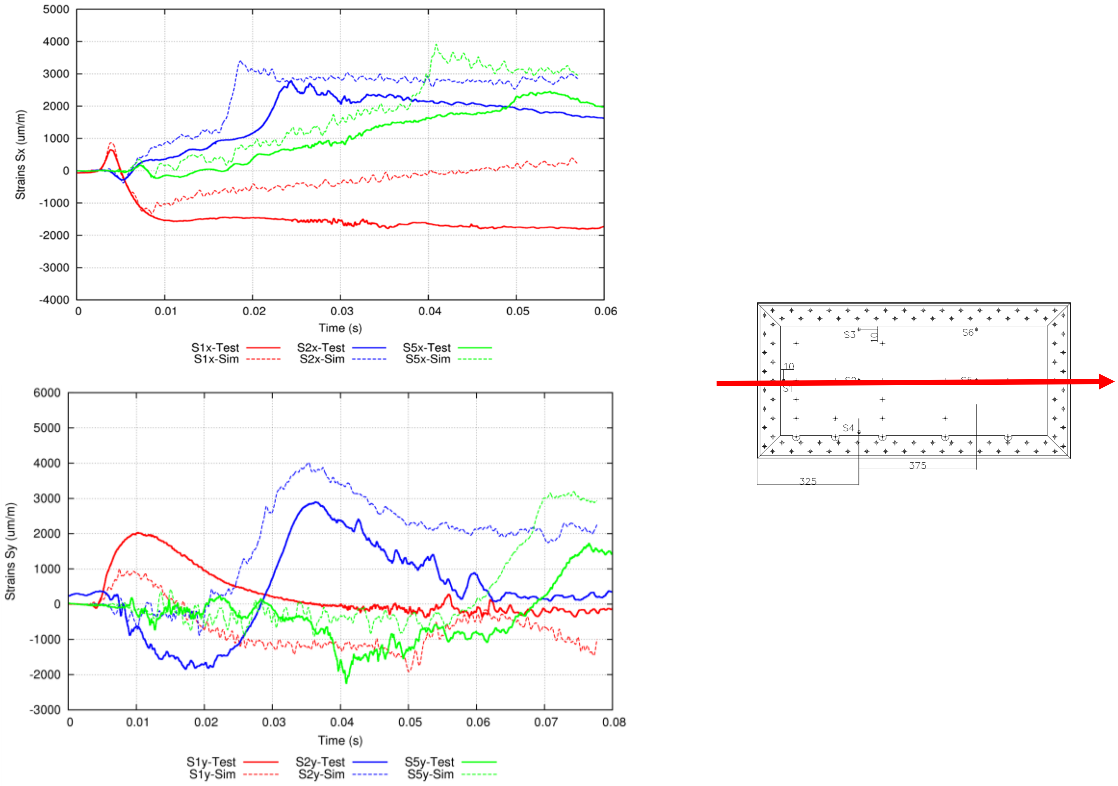

Figure 21: Evolution of strains (x-direction 3mm panel on top, y-direction 0.8 mm panel on bottom) along panel symmetry axis. Correlation of test results (solid line) with numerical simulations (dotted lines).

7.1.1 Influence of SPH particle size on results

A sensitivity study to number of SPH particles included in the simulations (as dimensions of the water are fixed, increasing number of SPH particles means reducing its size) of the different relevant parameters (pressures and strains at panel symmetry axis) has been performed.

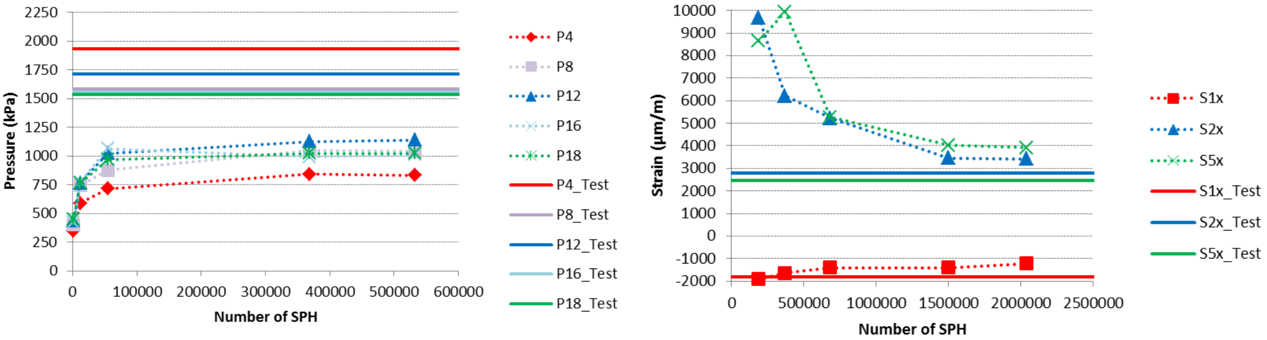

Figure 22: SPH particle size influence on results: quasi-rigid panels (left) and 3 mm flexible panels (right).

As shown in Figure 22, convergence of the results is reached as the number of SPH particles grows. When the stiffness (thickness) of the panel is decreased, the number of SPH particles needed for a converged result is higher (and also the CPU time).

Panel thickness	No. of SPH particles needed for convergence	SPH size (spacing)	CPU time (20 processors)
15 mm	360000	16 mm	9 hours
3 mm	1500000	10 mm	3 days
0.8 mm	10000000	5.3 mm	20 days

Table 1: SPH particle size sensitivity: CPU time needed for converged results.

7.2 Flexible panels numerical simulations using measured pressures

Correlation of flexible panel simulation results using measured pressures and tests results has been studied. Parameters compared are strains along the panel and total forces.

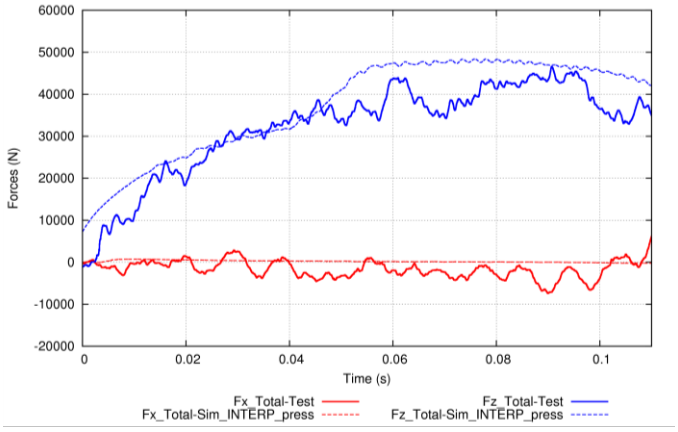

Figure 23: Evolution of total forces on 0.8 mm panel. Correlation of test results (solid line) with numerical simulations (dotted lines)

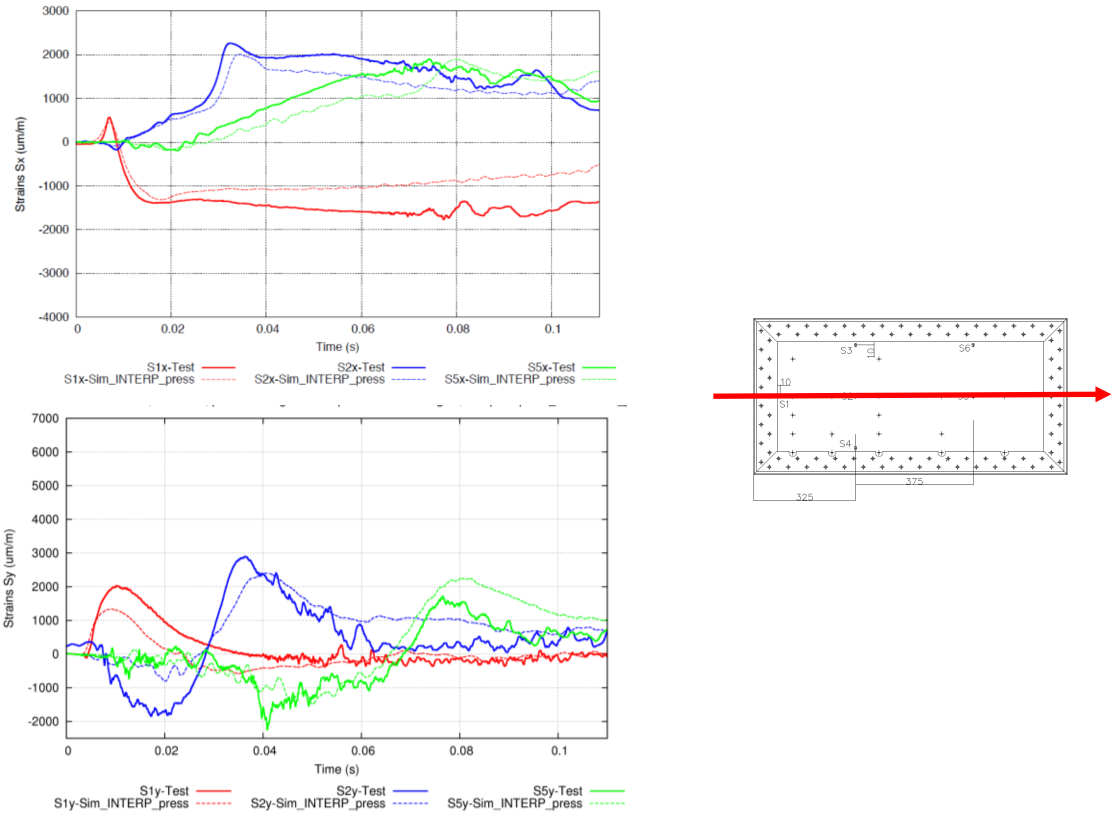

Figure 24: Evolution of strains (x-direction 3 mm panel on top, y-direction 0.8 mm panel on bottom) along panel symmetry axis. Correlation of test results (solid line) with numerical simulations (dotted lines).

The results from measured pressures simulations show very good correlation with test results. As the structural FE Model is exactly the same than that used for SPH simulations, it means that pressures/forces on the panel obtained in SPH simulations are overestimated.

8 CONCLUSIONS AND FUTURE WORKS

The European funded research project SMAES has provided an extensive database of ditching high quality full scale tests where many valuable parameters have been investigated. Treatment and post-processing of these results will help aeronautical industry to understand all the phenomena involved, design with more accurate criteria and fulfill airworthiness requirements

The results shown are a significant step forward towards ditching numerical simulation to perform reliable aircraft ditching loads simulations using SPH – FE codes.

Good correlation of numerical simulations with tests (with sensitivity to different parameters) has been shown in terms of structural response (strains), pressures and forces for quasi-rigid specimens with relatively low number of SPH particles. To ensure convergence in flexible simulations, the number of SPH particles has to be increased (also computational costs) significantly.

Structural response is perfectly captured when measured pressures are applied, which means that SPH water basin modeling requires of further work. First step will be simplifying the model and reducing the computational time of the simulation, which can be done including following VPS features that have been developed during SMAES (and not used in these simulations):

- Possibility of using different sizes of SPH particles in the water model: finer particles mesh close to the impact zone and coarser as distance to this zone increases ("Extended Weighted Voronoi Tesellation" method included in VPS [19] and [22])
- Computer parallelization of the simulations (DMP version of the VPS code)

In the next studies structural response to pressures obtained from heuristic formulas [21] and sensitivity of ditching FE Model results to other parameters included in the guided ditching test (mainly curvature and panel material) will be analyzed and correlation with test results will be established.

The natural way forward of this ditching study will be to perform a full-scale A/C ditching simulation. With this objective, Airbus Defence and Space Military Aircraft have prepared a non-linear explicit numerical model of the CN235 full-scale A/C in VPS. The basis of this model is the official check-stress model used for regular certification justifications but including additional features for impact simulations: refined mesh size, material properties covering plasticity and rupture, element reduced formulation, etc.

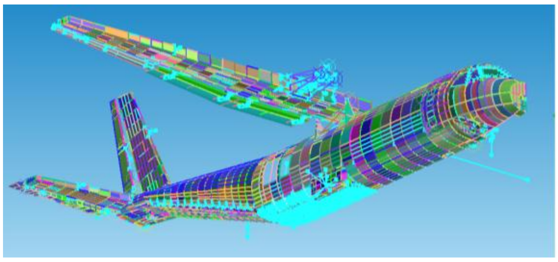

Figure 25: CN235 Explicit FE Model. Half Symmetric Aircraft

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