SURVEY OF FEASIBLE NUMERICAL APPROACHES TO ANALYSE THE BEHAVIOUR OF A COMPOSITE SKIN PANEL DURING A WATER IMPACT

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Abstract

Water impacts are likely to have tragic consequences for the passengers of helicopters. Most of the passive safety devices developed for helicopter crashworthiness are designed for ground impact. When impacting a solid or a soft surface, impact loads are rather different and therefore energy absorption devices developed for ground impact are not effective during a water impact.
In order to collect reliable data for numerical model validation, water impact drop tests were carried out: a Carbon Fiber Reinforced Plastic panel, similar to modern aircraft skin panels, was mounted on a specific test device and tested. Impact decelerations and deformations of the panels were measured.
Afterwards, numerical models of the tests were created. Finite element and meshless approaches were used to model the water region. Eventually, a close experimental-numerical correlation was obtained for each model in terms of impact dynamics, decelerations and deformations. The main features of the event and the differences between the four numerical approaches were discussed. Guidelines for further investigations were also drawn.

1 Introduction

Water impact is a topic that is increasingly gathering interest in crashworthiness design of helicopters. Accordingly with recent statistics [1], the 11% of civil aircraft accidents involves water impact and the percentage rises to the 20% for military aircraft accidents.

When considering only US civil helicopter accidents [2], over the 40% of the accidents involves ground or water impact and over 10% is fatal for the helicopter occupants. Remarkable progresses in crashworthiness design have been achieved recently even if most of the passive safety devices have been developed considering ground impacts [3]. The structural response and the loads transferred during a water impact and a ground impact are rather different. Therefore, it is not unusual that energy absorption devices developed for ground impact are not effective during a water impact.

Impact loads during a water impact are not as high as during a ground impact, but the impact duration is longer, the distribution of the forces is different and involves parts of the structure that are not designed to carry impact loads [4]. Furthermore, during a ground impact, load transfer depends only on the structure behavior whilst, when impacting a fluid surface, loads transfer depend also on structural response and on fluid-structure interaction.

During a ground impact (Fig. 1-A), the subfloor structure of a helicopter (frames and spars) absorbs the impact energy by progressively deforming and guaranteeing smooth deceleration profiles whilst the skin panels are not involved. On the contrary, during a water landing (Fig. 1-B), the water pressure insists on the skin panels which are not meant to carry such a large load and hence skin panels collapse.
Consequently, the load transfer mechanism from skin panels to spar fails, the loads are not longer redistributed on the spars and the subfloor structure is not more capable to absorb the impact energy.

The failure of skin panels leads to two potentially critical consequences: reduction of the energy absorption capability of subfloor (as the load path changes) and water inrush into the subfloor with consequent various types of malfunctioning (such as cabin flood and reduction of helicopter floating time).

Fluid-structure interaction is a complicated event to model and its numerical investigation is extremely difficult to perform. Therefore experimental water impact tests are mandatory. Nevertheless, water impact tests are often not repeatable, expensive and difficult to perform.

Researches aiming at deepening the knowledge of the event are fundamental to develop efficient numerical tools to reduce the number of tests and to design high efficiency water impact worthy structures. The research carried out at the Laboratory for Safety in Transports (LAST), Politecnico di Milano, was focused on fluid-structure interaction between the water and a composite Carbon Fiber Reinforced Plastic (CFRP) skin panel.

In detail, the research consisted of two phases: experimental phase and numerical phase. In the experimental phase, an intense test campaign was carried out and impact decelerations and deformations of the panel were acquired. A number of water impact drop tests were carried out using a specimen representative of typical skin panel of modern aircrafts. A CFRP flat panel, 400x400mm, was mounted on a test frame built on purpose to test panels and dropped on water. The tests aimed at collecting reliable experimental data to develop and validate numerical models. In the numerical phase, the tests were reproduced adopting two finite elements approaches - Lagrangian and ALE - and two *meshless* formulations - SPH and EFG - to model the fluid region. The results obtained with each of these approaches were compared ones with each other and numerical-experimental correlation was considered also referring to the failure of the CFRP panel and the consequent water inrush. In view of that pros and cons of each model were discussed and *rules of thumb* were drawn.

Finally, findings and guidelines for further investigations and to study more complex events were obtained.

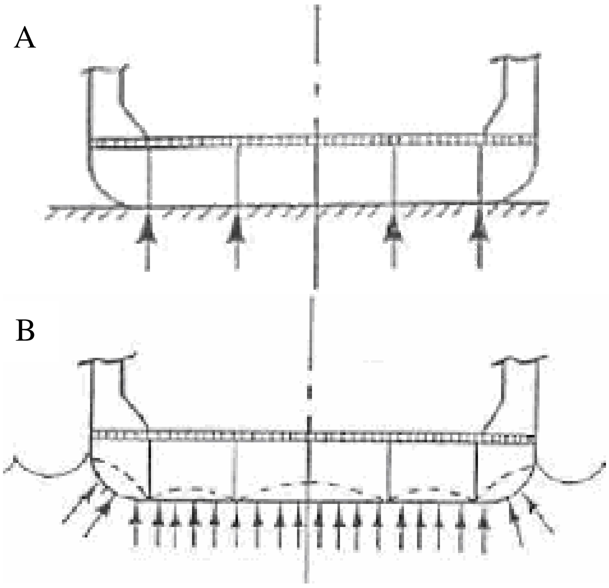

Fig. 1. Loads distribution on an helicopter subfloor [3]

2 Experimental Water Impact Drop Tests

The intense test campaign carried out in the first part of the research consisted in performing water impact drop tests using a CFRP skin panel.

A solid test frame was built to investigate the impact behavior of the panel. During the tests impact decelerations and deformations were acquired.

Besides, high velocity movies of the tests were recorded to evaluate the impact dynamics of the event.

2.1 The specimen

The specimen (Fig. 2) was a flat 400x400 mm CFRP panel. The thickness of the panel was 2.00 mm. Material VICOTEX and a staking sequence $[90°, 45°, 0°, -45°]_{SYM}$ typical of aircraft skin panel were used.

2.2 Test article

The test article (Fig. 3) consisted of a massive base frame, four lateral flat Aluminium alloy panels and L-shaped corner stiffeners. The base frame, in particular, was a 400x400 mm, 40-mm height Al 6082-Ta16 plate machined to have a square hole of 320x320 mm. The CFRP panel was bolted on the base frame so that the actual impact region was 320x320 mm.

The test article was provided with a cap to avoid water inrush. The global dimensions of the test article were 400x400x500 mm and the mass was 16 Kg. Most of the weight of the test article was due to the frame (massive and little deformable) so that the centre of mass was located at the bottom of the test frame. The lateral panels and the stiffeners (introduced to avoid sinking and to guide the test article during the fall) were rather stiff but lighter than the frame. The test frame allowed to test panels of different materials and thicknesses and to focus the analysis only on the panel behavior. Water impact drop tests to evaluate the behavior of skin panels to improve aircraft water crashworthiness are still quite rare and in this way this research is pioneering.

2.3 Test facility

The dimensions of the test article allowed performing the drop tests using the indoor facilities of LAST. A 3,000 t bridge crane was used as hoisting system and a 1.5-m diameter and 1.4-m depth PVC round pool was used as water basin.

The test article was hanged to a quick-release system and four steel cables were used to guide the test article during the fall and to maintain the impact incidence of the test article within acceptable limits (i.e. smaller than 3 deg). The test facility is shown in Fig. 4.

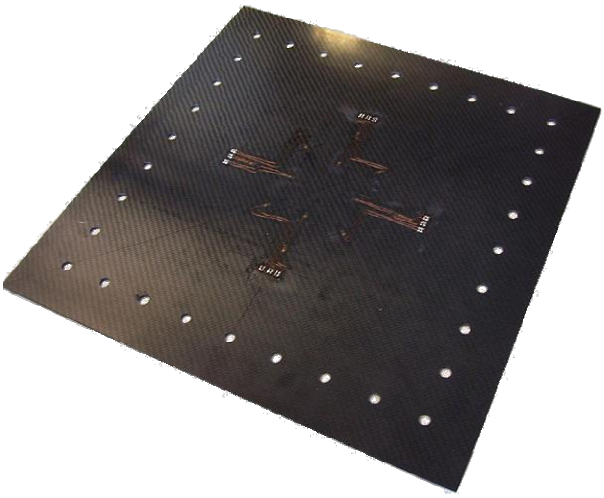

Fig. 2. The CFRP skin panel

Fig. 3. The test frame

Fig. 4. The test facility

2.4 Measuring instruments

Impact decelerations and deformations were measured during the tests because they are quantities of paramount interest in designing structures safe in water landing.

2.4.1 Accelerometers

Four ENTRAN D-0-500 accelerometers were used to measure impact decelerations. The accelerometers were fixed in the midpoints of the sides of the base frame (Fig. 5). The number and the pattern of the accelerometers allowed a sufficient redundancy of the measurements and the possibility to evaluate the impact incidence of the test article.

2.4.2 Strain gage

Twelve OMEGA KFG-5-120 strain gauges were installed on the skin panels to measure impact deformations. The strain gauges were placed on three circumferences of radius respectively of 30 mm, 50 mm and 70 mm – as shown in Fig. 5. The number and the placement of the strain gauges allowed to have redundancy in the measurements and to evaluate the deformation in different points of the panel accordingly with the shape of the deformation of the panel itself. The strain gauges were sealed to avoid contact with water.

2.4.3 High speed camera

The tests were filmed using a high speed camera to capture the impact dynamics of the event and to have a deeper insight in it. Besides, the movies were also used to estimate the impact velocity and the incidence of the test article.

2.4.4 Data acquisition system

The accelerometers and the strain gauges were connected to a Power-DAQ 14 bit/16 channels data acquisition system. Signals were acquired at 20,000 Hz to avoid aliasing and to guarantee a large number of sample points during the initial phase of the impact, when the quantities of interest had a sudden growth. The value of the sampling rate was also decided in view of evaluating the delay between the accelerometers pulses.

2.5 Carried out tests

The water impact tests were carried out releasing the test article from several prescribed heights. The facility used in the tests allows a maximum drop-height of 3.0 m. Nevertheless, to avoid delaminations or cracks of the skin panel under investigation, the maximum drop-height was limited to 1.50 m.

Measured impact velocities and analytical predictions based on weight drop showed that the influence of the friction of the guides was negligible (the difference was smaller than 3%). Carried out tests and measured impact velocities are listed in Tab. 1.

For every height, the tests were repeated at least five times to ensure the accuracy of the measures and to verify the repeatability of the data acquired.

The impact incidence of the test article was evaluated on the basis of both high speed movies (Fig. 6) and differences in acquired decelerations (pulse values and time delays). Only the tests with an impact incidence smaller than 3 deg were considered acceptable and therefore the number of tests carried out was larger than the one suggested from Tab. 1.

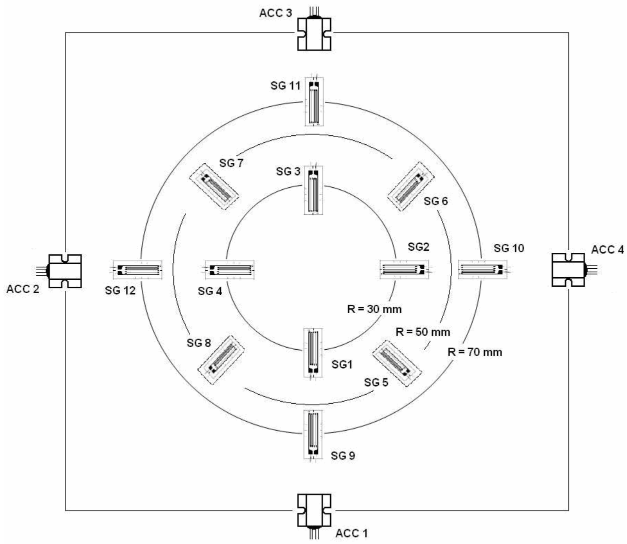

Fig. 5. The transducers configuration

2.6 Data collected

The impact deceleration time history for three reference drop-heights is plotted in Fig. 7. Inspecting Fig. 7, it is possible to infer the general trend of the decelerations: a first peak and the following oscillations due to the test article dynamic response.

The deformation time history of the CFRP skin panel for three reference drop-heights is plotted in Fig. 8.

Inspecting Fig. 8, it is possible to observe the general trend of the deformations: a first peak and the following oscillations due to the base panel vibrations.

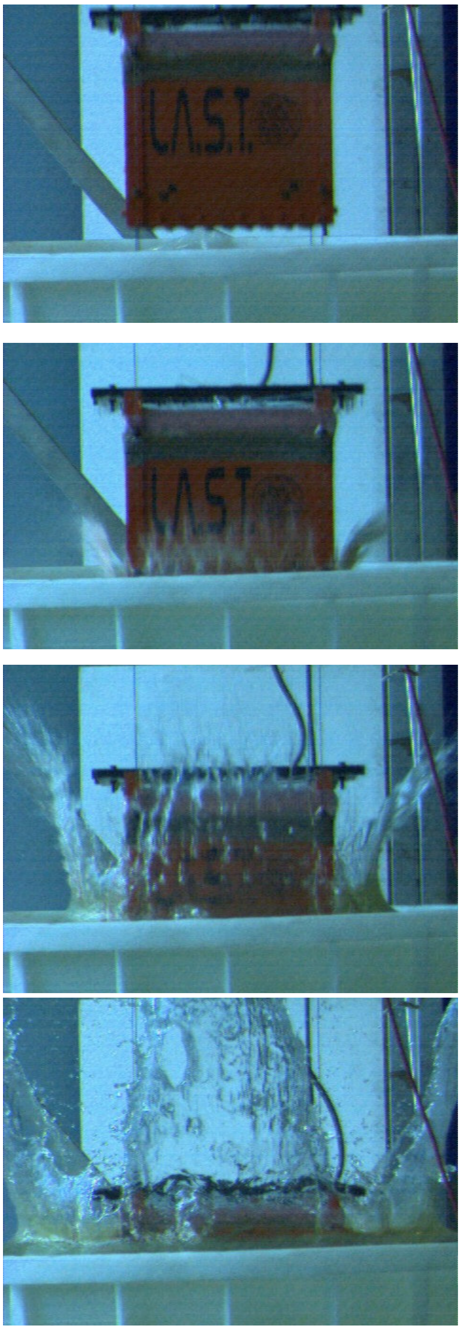

Fig. 6. Frames from a high-speed movie

Test #	Drop Height [m]	Impact velocity [m/s]
1	0.10	1.29
2	0.30	2.29
3	0.50	3.12
4	0.70	3.67
5	1.00	4.35
6	1.30	4.96
7	1.50	5.32

Tab. 1. Tests carried out

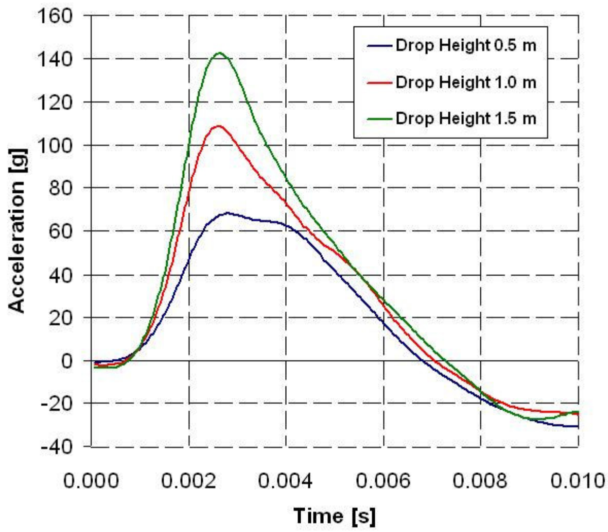

Fig. 7. Impact decelerations

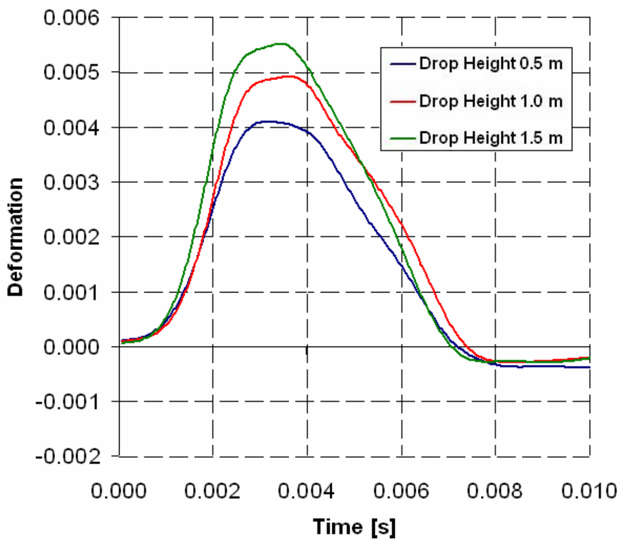

Fig. 8. Impact deformations

2.7 Discussion

The repeatability of the tests in terms of collected data indicate the reliability of the carried out tests. In effort to compare the mean measurements obtained in the tests from different drop heights, the acquired data were also made dimensionless [5]. The mean values of the decelerations and deformations are shown in Fig. 7 and Fig. 8: the standard deviation from the mean values is negligible for all the tests carried out in the two campaigns.

The impact decelerations and deformations for different drop heights were compared all together observing a linear trend with respect to the impact velocity.

As a consequence, the dimensionless peaks decreased with the drop height. Comparing the measured impact decelerations and deformations with the ones collected during tests performed with a stiffer base panel [6], it was possible to notice that a more deformable panel leads to lower decelerations and higher deformations, with a structural damping depending on the mechanical properties of the panels.

3 Numerical Simulations

The second phase of the research was devoted to develop and validate reliable numerical models of the carried out tests. The Lagrangian FE approach was adopted to model the test article whilst the fluid region was modeled adopting four different approaches: Lagrangian FE, ALE, SPH and EFG. Despite its known drawbacks, the Eulerian approach is usually preferred in fluid modeling to the Lagrangian FE one because it allows handling severe deformations without significant accuracy reduction. The drawbacks in the use of the Eulerian formulation stimulate researches on different solutions of the problem such as meshless methods based on the Lagrangian approach. SPH is a genuinely meshless method initially introduced in astrophysics [7] and subsequently applied to a number of Continuum Mechanics problems such as events involving fluid-structure interaction or high-velocity impacts. EFG method was first introduced to study crack propagations [8] and its applications to fluid-structure interaction are still quite rare. The feasibility of each model was investigated and the accuracy quantitatively evaluated referring to the data collected in the tests (i.e. test article decelerations and base panel deformations). In the model realized the double symmetry of the problem was exploited and only a quarter of both the test article and the fluid region were modeled. Proper symmetry constraints were applied both to the Lagrangian model and the water region. The numerical simulations were performed using LSTC/LS-Dyna [9], a proven non-linear finite element code that implements effective Eulerian, SPH and EFG solvers.

3.1 Finite element model of the specimen

The skin panel was a square flat panel and hence it was possible to build a regular and uniform mesh consisting of 3600 four-node shell elements. The chosen reference length (about 6.6 mm) was a trade-off between accuracy and CPU-time required by the simulations and strictly depends on the typical dimension of the fluid region elements.

The CFRP panel was modeled as a laminate accordingly with the *Lamination Theory* which allows modeling the stacking sequence and the fiber orientations of each lamina. One integration point for each lamina was defined. The composite material was modeled using a constitutive law based on the *Damage Mechanics* for which it is assumed that the deformations introduce micro-cracks and cavities into the material which cause stiffness degradation. The failure criteria are loading criteria and represent threshold variables in the damage model. Non-smooth failure surface allows uncoupled failure.

3.2 Finite element model of the test article

The geometry of the test article was simple and hence it was possible to build a rather regular mesh. The same reference length defined for the base panel was used.

The riveted and bolted joints were not modeled since it was observed that the benefits of modeling in details the joints were not such to justify the increased model complexity and the required CPU-time. Point masses were introduced in place of rivets and bolts in effort to reproduce the correct mass distribution. The overall weight of rivets and bolts becomes not negligible when considering all the rivets and bolts together.

The accelerometers were modeled using specific accelerometer elements that allow to measure with accuracy the accelerations in local axis. Overall, 8471 elements were used to model the test article: 6720 eight-node solid elements for the base frame, 1714 four-node shell elements for the lateral panels and the stiffeners, 37 point masses and 4 dedicated discrete elements type accelerometer [7].

The elastic piecewise linear plasticity material model was adopted to represent the Aluminium alloy behavior. The test article and the skin panel were placed over the fluid surface and the initial velocity equal to the one measured during the test from 0.7 m was imposed to them.

3.3 Numerical models of the fluid region

The water basin in the tests was a 1.5-m diameter *pool*. In effort to limit required CPU-time, memory allocation and to avoid rigid motion of the water, the dimensions of the fluid region in the numerical simulations were smaller than the actual one: the fluid region was modeled as 650x650x800 mm sides box. Reflected waves were avoided imposing *non-reflecting* silent boundary conditions. The water behavior was reproduced using a previously validated [10] isotropic material characterized by a linear equation of state. A pressure cut-off was defined to roughly model the effect cavitation in the water region.

The first water region models were built using the same numbers of nodes for each approach then, after observing the correlation with experimental data, improvements of the models were introduced according to the peculiarity of each formulation.

3.3.1 Lagrangian FE model

The first Lagrangian FE model consisted of 172,970 eight-node solid elements. The mesh was refined below the test article, where the elements belonging to the fluid region have about the same reference length of the elements of the skin panel. Moving along the depth towards the bottom the mesh of the water region becomes progressively coarser.

The interaction between fluid and structure was reproduced via contact algorithm: in particular, it was defined a bidirectional contact based on *penalty method* – recommended when the parts in contact have different mechanical properties.

Observing the first simulation results it was decided to refine the water region mesh to improve the numerical-experimental correlation. A new model consisted of 892,080 eight-node solid elements with a reference length reduced to about 4 mm was realized.

3.3.2 ALE model

The ALE mesh consisted of 250,985 eight-node solid elements. The fluid mesh was the same of the Lagrangian model but it was necessary to model a initial *surrounding* void region where the fluid after the impact could flow. Hence the number of elements is larger. An automatic motion following mass weighted average velocity was imposed to the ALE mesh.

The interaction between fluid and structure was reproduced via *coupling algorithm*. Since the mesh of the fluid region and the mesh of structure had the same reference length, one point over each coupled Lagrangian surface segment was used. Defining a higher number of points improves the accuracy of the coupling constraint but also increases the stiffness of the coupling interface. A normal direction compression only coupling for shell (without erosion) was defined. The damping factor, which is typical for event involving rigid bodies, was not defined for the penalty coupling, but a coupling leakage control and a mass-based penalty stiffness factor were introduced.

The first simulation results were satisfactory. However it was decide to refine the mesh to improve the correlation of panel deformation. The new model consisted of 973,504 elements.

3.3.3 SPH model

The first SPH model consisted of 163,863 particles. The accuracy of the SPH model depends on regularity of the particles layout; hence a uniform was created. The distance between the particles was 12.5 mm. The fluid-structure interaction was reproduced using a node to surface contact, based on *penalty method*, between the SPH particles and the test article. The boundary conditions were imposed using a special treatment implemented in LSTC/LS-Dyna [9]. A set of *ghost particles* was automatically created by reflecting the particles closest to the boundaries. After observing the first results it was decide to reduce the number of particles and to increase their smoothing length. This solution allows a *harder* impact of the particles on the panel. The new model consisted of a uniform grid of 36,000 particles with a 22 mm spacing.

3.3.4 EFG model

The first EFG model consisted of 36,518 nodes and 166,500 four-node solid elements. The tetrahedral background elements are the only solid elements available for EFG in LSTC/LS-Dyna, hence the distance between the nodes is higher than in the previous models: 12 mm in the impact region and 35 mm near the boundaries.

The fluid-structure interaction was defined with a nodal contact based on penalty method. The new model was obviously refined: 89,964 nodes were used to model the water region. The characteristic length was reduced to 7 mm in the impact region.

4 Numerical-experimental correlation

Numerical results were compared with experimental evidence referring both to the impact dynamics captured by the high-speed movies and the acquired impact decelerations and deformations.

4.1 Impact dynamics

The behavior of both the test article and the fluid region is alike the one captured in the high-speed movie for each model realized (Fig. 10). The Lagrangian FE and the ALE models described accurately the behavior of the fluid in terms of water mass motion but not the spray. On the other hand the SPH and the EFG models also showed clearly the spreading of the water particles.

4.2 Impact decelerations and deformations

The impact deceleration of the test article and the CFRP panel deformation were accurately reproduced by each model used: both the peak value and the event duration were closer to the experimental measurements.

In Tab. 2 and Tab. 3 every column has two values: the first is relative to the initial water region models whilst the second is related to the new ones.

In Fig. 9 the numerical curves are compared with the experimentally measured ones.

4.3 Required CPU-time

CPU-time is central for any design-by-analysis procedure. The first 20 ms of the event were simulated using an Intel Core 2 Quad CPU, 2.40 GHz – 6 GB RAM PC. The same simulation was run five times and the average required CPU-time is listed in Tab. 2. The CPU-time was computed in CPU hours for every hundredth of second simulated.

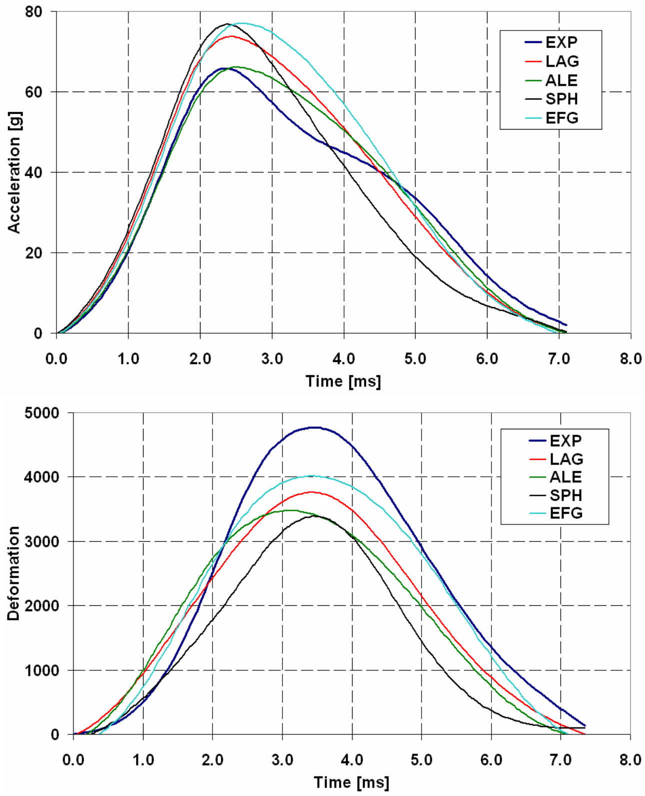

Fig. 9. Numerical-experimental correlation

Model	Peak Value	Peak Duration	CPU-time
LAG	89%- 64%	98%- 95%	0.5 – 7.8
ALE	99% - 95%	100% - 93%	2.5 – 5.5
SPH	94% - 86%	65% - 82%	4.0 - 2.0
EFG	69% - 85%	95% - 100%	3.5 – 37.5

Tab. 2. Num-exp. correlation (Acceleration)

Model	Peak Value	Peak Duration
LAG	79%- 81%	85% - 93%
ALE	73% - 72%	88% - 93%
SPH	20% - 71%	11% - 83%
EFG	71% - 84%	59% - 97%

Tab. 3. Num-exp. correlation (Deformation)

4.4 Panel failure and water inrush

In effort to evaluate the behavior of the composite panel after a structural failure, a water impact at 15 m/s was simulated. Since the failure could be not exactly symmetric it was necessary to model the whole fluid region. In Fig. 11 the results of the simulation are shown. The failure was localized in the centre part of the panel, where the deformations were larger and propagates from there along the panel.
The Lagrangian FE model provided a widespread collapse of the panel due not to the effective load transferred to the panel but to the element hourglass. On the other hand the ALE model result seemed more realistic and the failure is localized in the centre of the panel. Considering the SPH model, the small deformations obtained produced only a negligible fracture in the centre of the CFRP panel. The improved EFG model simulation did not run because of the excessive memory requirement, hence the first model was used and then the failure of the panel was not realistic and close to the base frame of the test article.

4.6 Discussion

The numerical-experimental correlation was globally satisfactory for each model realized both for the acceleration and the deformation. It is relevant to notice the differences between the first and the improved models. Except for the ALE model, each approach shown different results. The first Lagrangian FE model was more accurate than the refined one just because the large deformations of the water elements cause difficulties in tuning the hourglass coefficients but when the CPU time becomes higher, performing several analyses is not convenient. On the other hand the ALE models provided accurate results for any mesh but, because of the limitations in setting the coupling parameters, it was not possible to further improve the correlation on the deformation. Considering the SPH model a better correlation was obtained with the coarser model. Indeed increasing the number of SPH particles does not guarantee an improvement of results. Hence finding the more appropriate number of particles and SPH parameters is not trivial.

Referring to the EFG models, only the finer model provided satisfactory results but the CPU time was extremely high and the required memory very large. Finally, when considering the failure of the panel, only the ALE approach seemed to provide feasible results and it is consequently necessary to deepen the analysis of this event.

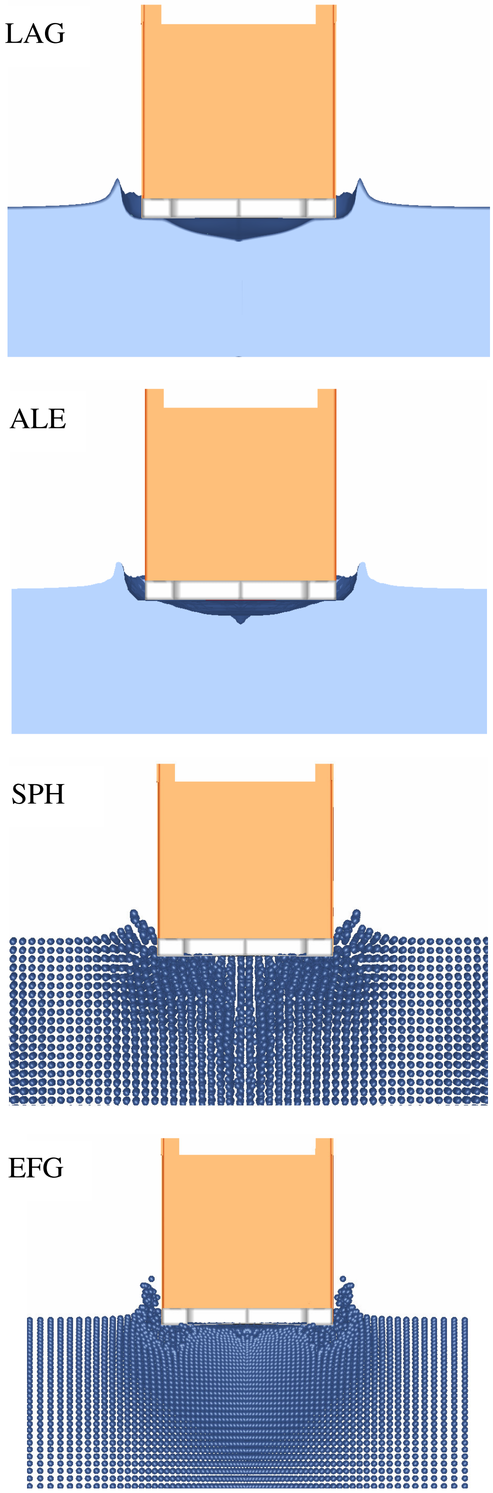

Fig. 10. Frames from the numerical simulations

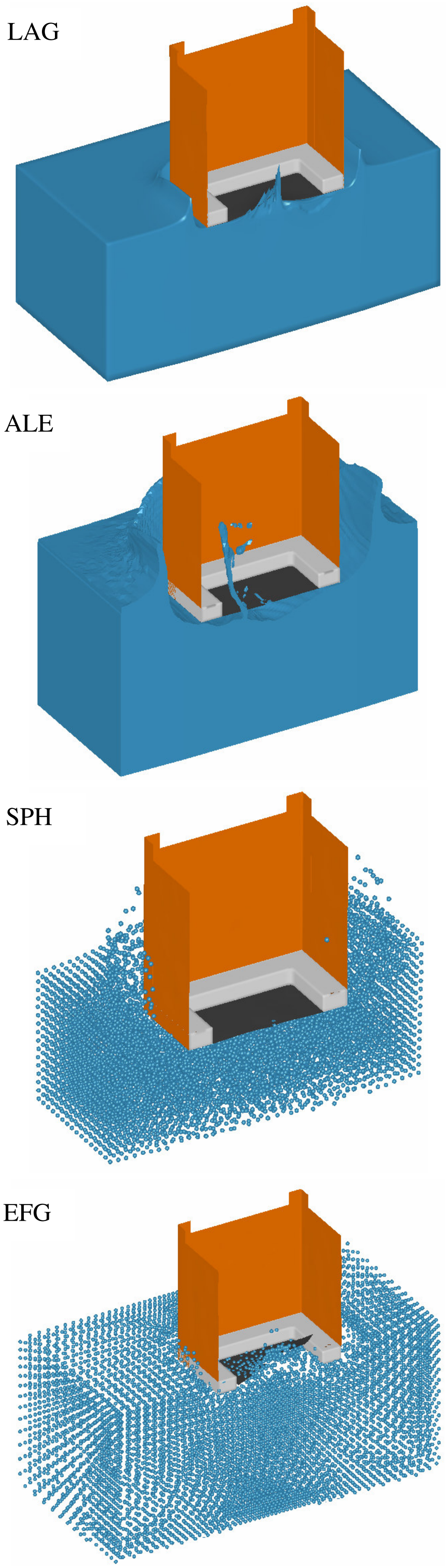

Fig. 11. Frames from the high impact velocity simulations

5 Conclusions

Water impacts of aircrafts are rather likely to turn into a tragic event. In view of that, it is crucial to develop numerical tools to design safer helicopter structures.

The outcomes of a research carried out at the Laboratory for Safety in Transports (LAST), Politecnico di Milano is here presented The research consisted of two phases: an experimental phase and a numerical phase.

In the experimental phase, water impact drop tests were carried out and impact decelerations and deformations of a CFRP panel were acquired. The tests aimed at collecting reliable data to develop and validate numerical models focusing on impact dynamic and fluid-structure interaction. The dynamics of the event was captured using a high-speed camera.

In the numerical phase, the tests were reproduced adopting two finite elements approaches - Lagrangian and ALE - and two *meshless* formulations - SPH and EFG - to model the fluid region.

The results obtained with each approach were compared ones to each other and numerical-experimental correlation was considered also simulating the failure of the CFRP panel and the consequent water inrush.

Finally, pros and cons of each approach, findings and guidelines for further investigations and to study more complex events were obtained.

In particular the Lagrangian modeling of the fluid allows fast simulations and model creation but accurate results only when the fluid deformations are small.

The ALE approach is satisfactory, the CPU-time acceptable but its effectiveness related to other similar events has to be proved, since it is difficult to tune the coupling parameters.

The SPH approach provided the best results with respect to the CPU-time but the difficulty in finding the correct number of particles makes realizing the model not immediate.

The EFG approach provided very accurate results considering both the dynamics and the correlation with the measurements but the CPU-time is still too elevate.

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