A Numerical-Experimental Investigations on Crash Behaviour of Skin Panels during a Water Impact Comparing ALE and SPH Approaches

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Summary:

Water landings in emergency are likely to have tragic consequences for helicopters. Most of the safety devices developed to enhance helicopter crashworthiness have been designed referring to ground impacts and they might be not effective in case of water landings. At LAST, the crash labs of Politecnico di Milano, water impact drop tests were carried out to deepen the knowledge of the event dynamics and to collect reliable data to validate numerical models. The water impact behaviour of skin panels made of aluminium alloy was investigated, in particular the panel failure due to water impact pressure. Drop tests with several drop heights and different impacting masses were performed measuring accelerations of the test article. In the second part of the research, the tests were numerically reproduced adopting ALE and SPH approaches to model the fluid region. The numerical results were compared both ones to the others and to the experimental tests in terms of impact dynamics and data acquired. As a result, a satisfactory correlation was achieved and guidelines to model fluid regions adopting ALE and SPH approaches were drawn.

Keywords:

Water impact, Drop tests, Fluid-Structure Interaction, Smoothed Particle Hydrodynamics, Arbitrary Lagrangian Eulerian.

1 Introduction

Water landings in emergency are likely to have tragic consequences for helicopters. According to statistics, the 10% of accidents in Civil General Aviation and the 33% in Military Air-Force involve water impacts and, most of the times, the consequences are fatal for cabin crew [1], [2]. Moreover the percentage grows up to 40% when considering only military rotorcraft accidents.
Most of the safety devices realized to enhance helicopter crashworthiness have been developed referring to ground impacts [3], [4] and therefore it often happens that the mentioned devices are not effective in case of water landings [3], [5].
Indeed, during a water impact, loads on structures do not reach the high values typical of a ground impact, but the impact duration is longer and the load distribution is not constant in time and not uniform in space. Thus, it is not unlikely that a water impact causes more severe consequences than a ground impact at the same conditions (velocity and attitude).

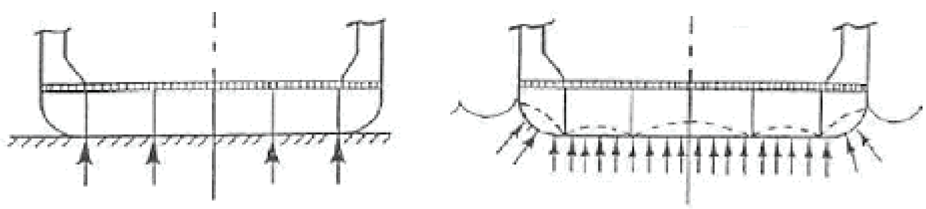

Figure 1: Load distribution on subfloor [4]

Since the lack of experimental data to validate numerical models, at LaST, the Laboratory for Safety in Transports of Politecnico di Milano, water impact drop tests on deformable and rigid structures have been carried out.
These tests aimed to deepen the knowledge of the event dynamics and to collect experimental reliable data focusing on water modelling and fluid-structure interaction.
The goal of these researches is to validate numerical models for developing design-by-analysis methodologies to realize crashworthy structures in case of water landing.
Recently, moving from the outcome of previous researches [6], a dedicated test device (Fig. 1) was used to investigate the water impact behaviour of skin panels made of aluminium alloy.

In the first part of the research an intense test campaign was carried out. Drop tests were performed to investigate the water impact behaviour of aluminium alloy skin panels with different thicknesses (0.3 mm and 0.45 mm).
During the tests, accelerations of the test article were measured and structural failure was studied considering the thinner panel. The event dynamics was captured using a high-speed camera (Fig. 2).
Drop-tests with several drop heights (from 0.1 m to 3.0 m) and different impacting masses were performed to highlight the load variations due to these parameters.
In the second part of the research, the tests were numerically reproduced using LSTC/LS-Dyna 971 [7]. The fluid region was modelled adopting the Arbitrary Lagrangian Eulerian and the Smoothed Particle Hydrodynamics [8] approaches.
When investigating a water impact, in effort to model the fluid region Eulerian approach is usually preferred to Lagrangian formulation because it allows handling severe deformations in the fluid region. Nevertheless, the known drawbacks in the use of Eulerian approach stimulate research on alternative approaches such as SPH Method.
Despite the number of its applications is increasing, it has been widely recognized that the use of SPH approach to water impact is not straightforward because of stability problems of simulations and treatment of boundary conditions when dealing with unbounded large fluid regions.
Moreover, finding the appropriate number of SPH particles to achieve a close correlation with experimental data is not trivial.
These difficulties were kept into account in developing the numerical models of the tests. The results obtained were compared to the experimental tests in terms of impact dynamics, post-failure deformation and data collected during the tests. Besides, assets and drawbacks of both approaches were considered.
As a result, a satisfactory correlation was achieved for both the approaches and guidelines to model fluid regions adopting ALE and SPH approaches and to obtain accurate results were drawn.

2 Water impact drop tests

In the first part of the research an intense test campaign was carried out performing water impact drop tests on two aeronautical aluminium alloy skin panels and measuring impact accelerations.
Besides, high velocity movies of the tests were recorded to study the impact dynamics of the event.

2.1 Test panels

Two 400x400 mm aluminium alloy panels were tested during the experimental phase of the research. Al 6082-Ta16 panels with different thicknesses (0.3 mm and 0.45 mm) were used. The thinner panel was used to study the structural failure and the consequent water inrush. To achieve the repeatability of the measurements, a number of tests were performed and, as a consequence, since after each tests the panels were deformed or failed, it was necessary to use several panels. One of the tested panels is shown in Figure 2.

2.2 Test article

The test article (Figure 3) consisted of a massive base frame, four lateral flat aluminium alloy panels and four L-shaped corner stiffeners. The base frame was a 400x400 mm, 40-mm height Al 6082-Ta16 plate, machined to have a square hole of 320x320 mm. The test article was properly sealed to avoid water inrush. The height of the test article was 500 mm and its mass was 16 Kg. Each panel was bolted on the base frame so that the actual panel impact region corresponded to the hole dimensions.
Most of the weight of the test article was due to the frame (massive and little deformable) so that the centre of gravity was located at the bottom of the test article. 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 aluminium alloy frame allowed to test panels of different materials and thicknesses and to focus the analysis only on the panel behaviour. Water impact drop tests to evaluate the behaviour of skin panels to improve aircraft water impact crashworthiness are still quite rare and in this way this research was pioneering.

2.3 Test facilities

The test article dimensions allowed to perform the experimental activity using the indoor facilities of LaST. A 3,000 ton bridge crane was used as hoisting system while a 1.5-m diameter and 1.4-m depth PVC round pool filled with water was the impact region. The test article was hanged to a quick-release system and four steel cables were used to guide the article during the fall and to maintain the impact incidence within acceptable limits (i.e. smaller than 3 deg). The test facilities are shown in Figure 4.

2.4 Measuring instruments

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

2.4.1 Accelerometers

Eight mono-axial ENTRAN D-0-500 accelerometers were used to measure impact decelerations. The accelerometers were fixed on the midpoints of the base frame sides.
Since the needing to evaluate the test article impact attitude, four accelerometers were used to measure the vertical accelerations and the others were used to measure the lateral accelerations. The number and pattern allowed a sufficient redundancy of the measurements and the capability to evaluate the impact incidence of the test article evaluating the time difference between acceleration peaks.

2.4.2 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 attitude of the test article.

2.4.3 Acquisition system

The transducers were connected to a Power-DAQ 14 bit/16 channels data acquisition system. Signals were acquired at 15,000 Hz to avoid aliasing and to guarantee a sufficient 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 accelerometer pulses to estimate the test article attitude.

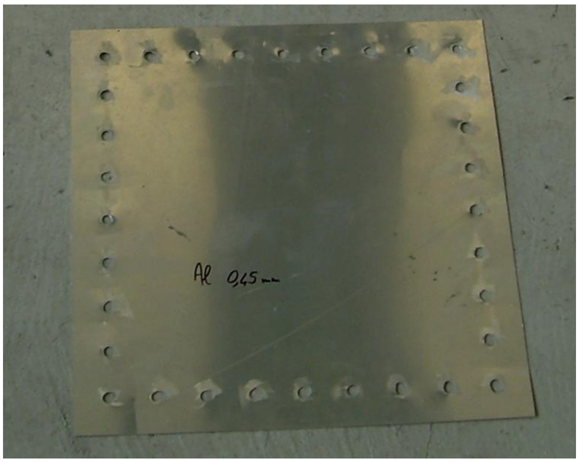

Figure 2: The 0.45-mm aluminium test panel

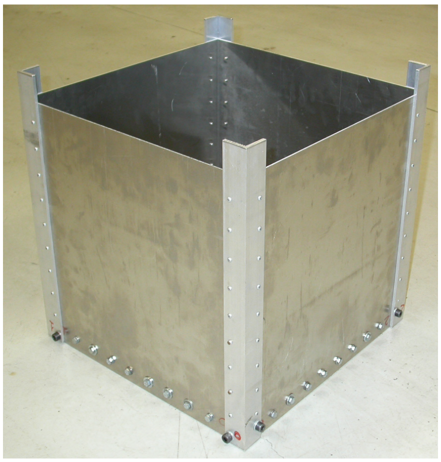

Figure 3: The test article

Figure 4: The test facilities

2.5 Carried out tests

The experimental campaign was carried out releasing the test article from several prescribed heights. The facilities used in the tests allowed a maximum drop-height of 3.0 m.

Both of the aluminium alloy panels were tested from the maximum height but also from 0.1 m and 0.2 m to concurrently evaluate the acceleration trend with respect to drop height and to avoid panel plasticity. Moreover some ballasts were applied on the test frame to highlight the mass addition influence on impact decelerations.

Measured impact velocities and analytical predictions based on weight drop showed that the influence of the friction between the test article and the steel cables was negligible (the difference was smaller than 3%).

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

The test article impact attitude was evaluated on the basis of both high speed movies (Figure 7) and differences in acquired accelerations (pulse values and time delays). Only the tests with an impact incidence smaller than 3 deg were considered acceptable.

2.6 Data collected

The impact deceleration time history for the 3.0-m drop height tests on the 0.3-mm panel is plotted in Figure 8. The dotted curves refer to tests where the panel failure occurred whilst the solid lines refer to tests where the panels showed only plastic deformations without collapsing. Figure 5 and Figure 6 show the post-impact conditions respectively of the 0.45-mm and of the 0.3-mm aluminium panels.
Inspecting Figure 8, it was possible to infer the general trend of acceleration: a first peak and following oscillations due to the test article dynamic response.

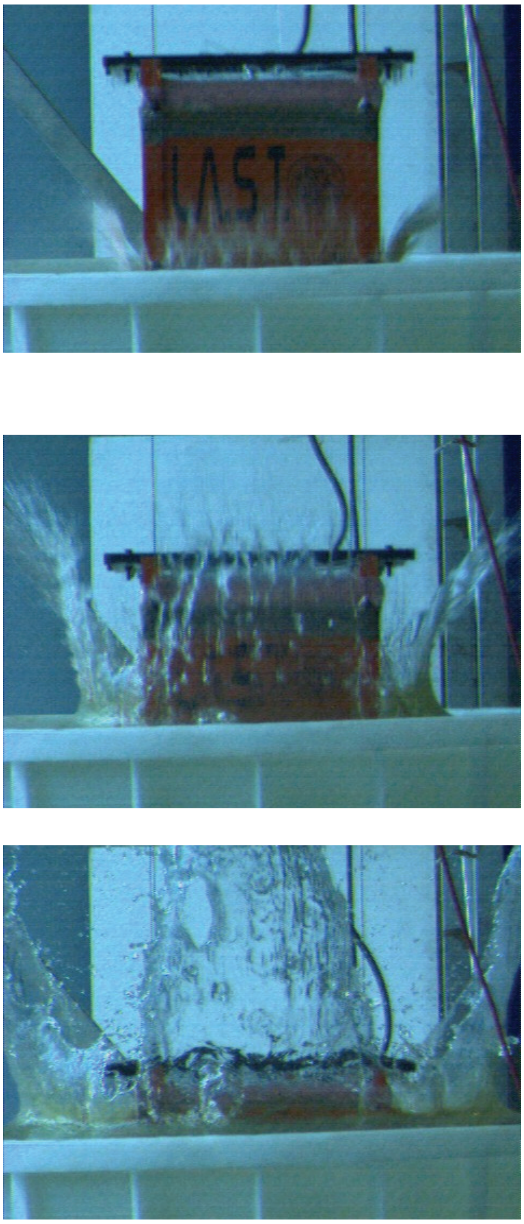

Figure 7: Frames from a high-speed movie

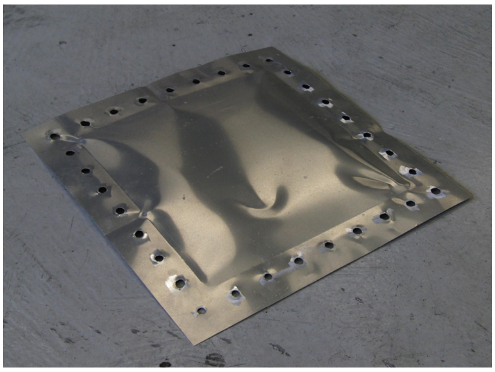

Figure 5: Post-impact conditions of the 0.45-mm aluminium panel

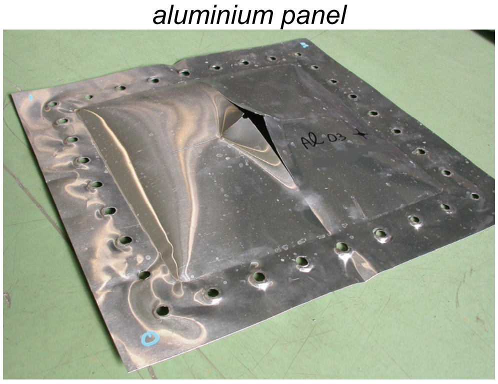

Figure 6: Structural failure of the 0.3-mm aluminium panel

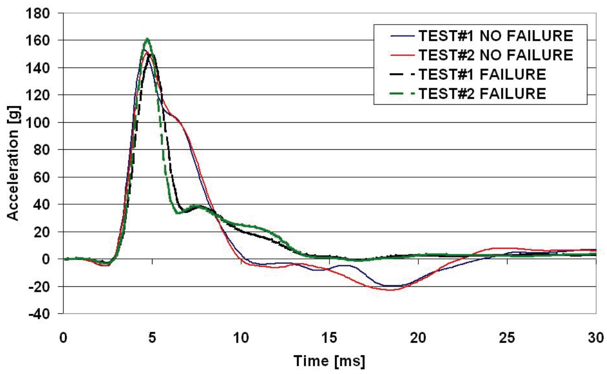

Figure 8: Impact decelerations of the 0.3-mm aluminium panel

2.7 Discussion

After analyzing the obtained results, it was possible to draw some conclusions about the experimental phase of the research. The repeatability of the measurements was achieved guaranteeing the same initial conditions in terms of impact attitude, impact velocity and water conditions during the tests from each drop height.
Since the tests were performed using the indoor facilities and a low-mass test frame, the impact energy was not enough to make the panels fail. As a consequence it was necessary to perform a little cross-cut in the centre of the panel to allow it to fail.

The failure, as shown in Figure 6, mainly spread along one direction because it was difficult to exactly reproduce symmetrical impact conditions. However this result was judged satisfactory for a numerical-experimental comparison on panel failure and water inrush.
Observing Figure 8, where the acceleration were compared, it was possible to highlight the difference in energy absorption capability in case of failure or not. Peak values are similar but when failure occurs the acceleration has a sudden variation and, as a consequence, the deceleration pulse is shorter.
According to [8] the measurements were made dimensionless. If test article behaviour is rigid-like the accelerations were linear with respect to drop height [9] and the dimensionless curves identical. In this case, i.e. increasing impact velocity, the dimensionless peaks decreased.
Globally, the experimental results were satisfactory and allowed to make some interesting observations on flat plate water impacts. The experimental set-up was numerically reproduced in the second phase of the research.

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 and the fluid region was modelled adopting both ALE and SPH approaches.
Despite its known drawbacks, Eulerian approach is usually preferred in fluid modelling to Lagrangian one because it allows handling severe deformations without significant accuracy reduction. The drawbacks in the use of Eulerian formulation stimulate researches on different solutions such as meshless methods based on Lagrangian approach. SPH [12] is a genuinely meshless method initially introduced in astrophysics and subsequently applied to a number of Continuum Mechanics problems such as events involving fluid-structure interaction or high-velocity impacts.
To correctly represent the structural failure it was necessary to model the whole test article to reproduce the tests on the thinner panel since it was not possible to reduce the required computational resources applying symmetry conditions. The numerical simulations were performed using LSTC/LS-Dyna [11] a proven non-linear finite element code that implements an effective SPH solver.

3.1 Panel finite element model

The geometry of the panels was simple and hence it was possible to build an uniform mesh consisting of 6400 four-node shell elements. The chosen reference length (5 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. In a second phase, in order to more accurately represent the failure the element reference length was halved and, as a consequence, the element number became 12800.
The elastic piecewise linear plasticity material model was adopted to model the aluminium panels and the structural failure was considered defining a criterion based on the maximum effective strain.
Bolts were not modelled and every panel was linked to the test frame using a tied contact [11]. Cowper-Symonds' coefficients were finally introduced to represent the strain-rate dependency of the panels deformation.

3.2 Test article finite element model

The test article geometry was simple and it was possible to build a rather regular mesh. A slightly higher element reference length than the one used for the base panels was decided. The riveted and bolted joints were not modelled since it was observed that the benefits of representing in details the joints were not such to justify the increased 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 accelerometers were modelled using specific elements that allow to accurately measure accelerations in local axis. Overall, 33892 elements were used to model the test article: 26880 eight-node solid elements for the base frame, 6856 four-node shell elements for the lateral panels and the stiffeners, 148 point masses and 8 dedicated discrete elements type accelerometer [11]. The elastic piecewise linear plasticity material model was adopted.
The test article was placed over the fluid surface with an initial velocity equal to the one measured during the tests.

3.3 Numerical models of the fluid region

The water basin 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 modelled as 1600x1600x600 mm side box. Reflected waves were avoided imposing non-reflecting silent boundary conditions.

The water behaviour was reproduced using a previously validated [7] isotropic material characterized by a linear equation of state. A pressure cut-off was defined to roughly model the cavitation in the water region.

The ALE mesh consisted of 384,000 eight-node solid elements. The mesh was refined below the test article, where the elements belonging to the fluid region have about four times the reference length of the elements of the impacting panels. Moving along the depth towards the bottom, the mesh of the water region becomes progressively coarser. An initial surrounding void region, where the fluid could flow after the impact, was modelled. An automatic mesh 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 structure had approximately the same reference length, one point over each coupled Lagrangian surface segment was used. Defining a higher number of points would have improved the coupling constraint accuracy but also it would have increased the coupling interface stiffness. 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 SPH model consisted of 144,000 particles. The accuracy of the SPH model depends on regularity of the particles layout; hence a uniform layout was created. The distance between the particles was 22 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 [11]: a set of ghost particles was automatically created by reflecting the particles closest to the boundaries.

4 Numerical-experimental correlation

Numerical results were compared with experimental evidence referring both to the impact dynamics captured by the high-speed movies, the acquired impact measurements and the post-crash deformation of the aluminium panels.

4.1 Impact dynamics

The numerical behaviour of both the test article and the fluid region was similar to the one captured by the high-speed movie (Figure 9, Figure 10). The ALE and SPH models described accurately the behaviour of the fluid in terms of water mass motion. The SPH model showed clearly the spreading of the water particles while the ALE mesh was not particularly refined and the water sprays could not be visualized.

A finer ALE mesh was not considered because it would have meant larger computational resources without improving the numerical-experimental correlation with respect to the measurements.

Figure 12 shows the post-impact conditions of the 0.3-mm aluminium panel. It was possible to notice that the panel failure is similar to the one obtained during the tests. In particular the failure stopped near the lower bolts both in the numerical and in the experimental cases.

4.2 Impact deceleration

The impact deceleration of the test article was accurately reproduced by each model realized: both the peak value and the event duration were quite close to the experimental measurements.

In Table 1 the numerical-experimental correlation for both the model is computed with respect to pulse value and duration. In Figure 13 the numerical curves are compared with the experimentally measured ones.

4.3 Required CPU-time

CPU-time is a central parameter for any design-by-analysis procedure. The first 30 ms of the event were simulated using an Intel Core 2 Quad CPU, 2.40 GHz – 4 GB RAM PC.

The average required CPU-time is listed in Table 1.The CPU-time was computed in CPU hours for every hundredth of second simulated.

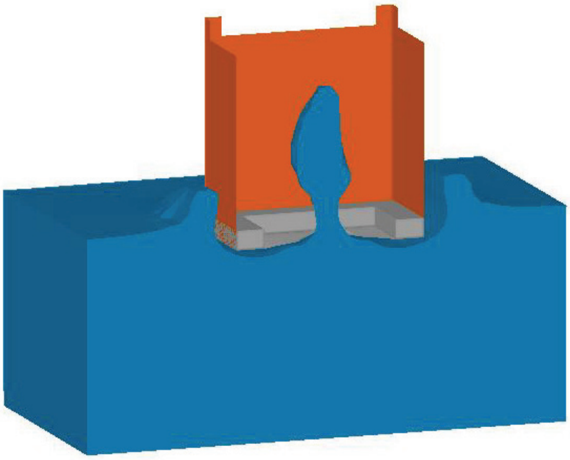

Figure 9: ALE numerical simulation

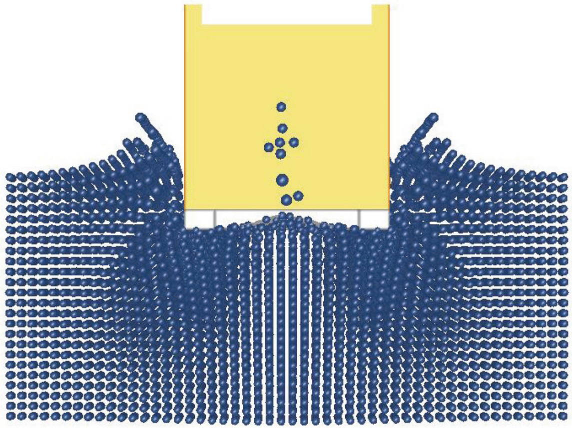

Figure 10: SPH numerical simulation

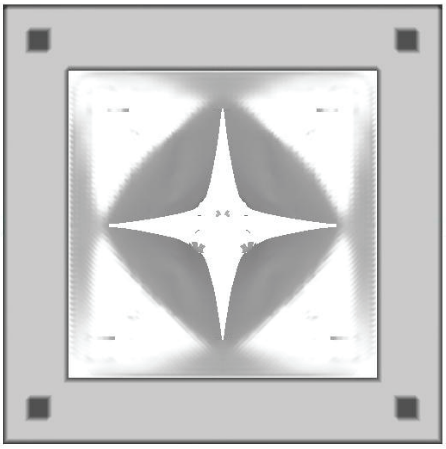

Figure 11: Numerical failure of the panel (ALE)

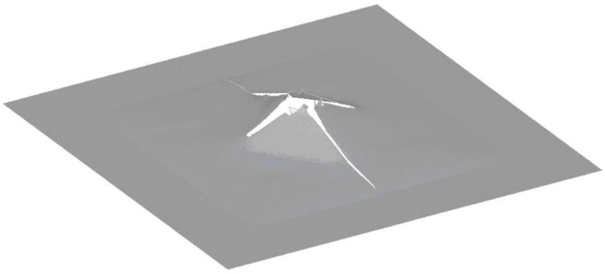

Figure 12: Numerical failure of the panel (SPH)

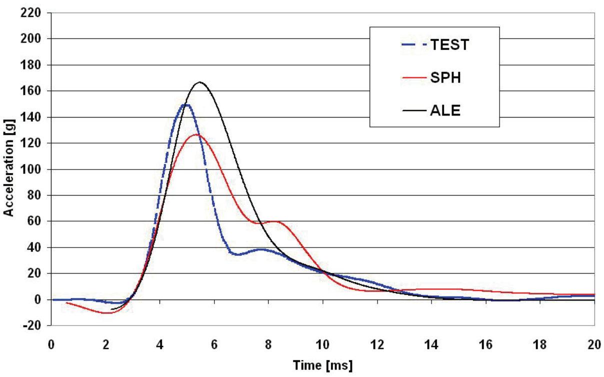

Figure 13: Numerical-experimental correlation on acceleration

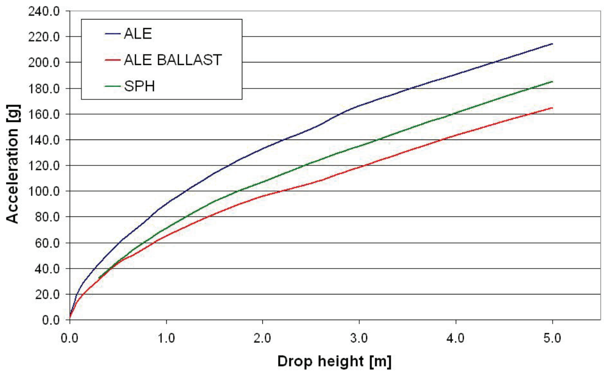

Figure 14: Impact deceleration vs drop height

	Acceleration		CPU-time
	Pulse Value	*Pulse Duration*	
SPH	84%	75%	3.1
ALE	90%	63%	5.2

Table 1: Numerical-experimental correlation

4.4 Discussion

The numerical-experimental correlation was globally satisfactory for each model realized. Considering the SPH model a better correlation was obtained with a coarser model with respect to the ALE one. Nevertheless increasing the number of SPH particles does not guarantee an improvement of results.
Hence finding the more appropriate number of SPH particles and parameters is not trivial but allows to relevantly reduce the CPU-time required. High computational resources are one of the main drawbacks of ALE approach.
Comparing ALE and SPH approaches in terms of model accuracy with respect to CPU-time required, SPH seems more convenient for design analyses even if ALE approach is in general more accurate.
When considering the failure dynamics of the panel, both the approaches led to feasible results. Nevertheless, only during these simulations, base panel shell elements suffered from hourglass.
An hourglass control was not sufficient to avoid an excessive zero-energy mode numerical deformation which would have relevantly affected the failure dynamics and it was necessary to use the full integration formulation for shell elements.
After setting the proper shell formulation and observing Figure 13, the ALE model (black curve) did not show the second acceleration peak.
The first peak is due to the panel failure along one direction of the cross-cut and the second peak corresponds to panel failure along the other direction that subsequently starts.
Even after a panel mesh refinement and variations of coupling parameters, the failure due to the ALE water region model showed the absence of the second peak although the failure first started only along one direction.
The results obtained with the SPH and ALE models are quite accurate in terms of acceleration peak and slightly overestimated with respect to pulse duration.
The SPH model provided satisfactory results in terms of impact dynamics, numerical-experimental correlation and post-failure residual deformation but, since the reduced number of particles and consequently their large mass, the water inrush was not accurately described. On the other hand the ALE approach showed feasible results with regard to water inrush.
Finally the quadratic dependency of the impact deceleration to the drop height was numerically proved as shown in Figure 14, where the results of a ballasted test article are also plotted (red curve). According to [9], the mass addition led to a reduction of deceleration, even if the trend is slightly different since the impact body was deformable whilst in [9] only rigid bodies were studied.

5 Conclusions

Water impacts of helicopters are rather likely to turn into tragic events. 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) of Politecnico di Milano is here presented. The research consisted of an experimental and a numerical phase.
In the experimental phase, water impact drop tests were carried out and impact decelerations of two aluminium panels were acquired. Tests on a 0.3-mm aluminium panel also allowed to study the structural failure and the water inrush.
The tests aimed at collecting reliable data to develop and validate numerical models focusing on impact dynamics and fluid-structure interaction.
The dynamics of the event was captured using a high-speed camera. The experimental activity also allowed to draw some interesting on differences in energy absorption capability between panels with an without failure.
In the numerical phase, the tests were reproduced adopting two approaches to model the fluid region: ALE and SPH.
The results obtained with each approach were compared ones to the others and numerical-experimental correlation was considered also simulating the failure of the thinner aluminium panel and the consequent water inrush.
Finally, assets and drawbacks of each approach, findings and guidelines for further investigations and to study more complex events were obtained.
In particular, the ALE approach is satisfactory in terms of agreement with experimental measurements; the CPU-time is acceptable but higher than SPH.
Moreover the ALE effectiveness related to other similar events has to be proved, since its low sensitivity to mesh refinement and the difficulties in tuning the coupling parameters.
On the other hand 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 simulations on panel failure showed interests results in terms of limitations of the numerical approaches considered. SPH also proved to be the best approach when considering agreement with experimental measurements but the water inrush was not described in detail.
The ALE model was accurate in terms of impact dynamics but the correlation with experimental data has to be further improved.
In this paper an overview of recent water impact activities carried out at Politecnico di Milano has been presented. After having obtained a close agreement between experimental data and numerical results for what concerns water impact of rigid and deformable bodies of different materials, the next step of the research will be the development of helicopter subfloor devices to absorb impact energy and to prevent skin panel failure.

6 Acknowledgements

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