WATER IMPACT OF METALLIC AND COMPOSITE MATERIAL STRUCTURES
EXPERIMENTAL TESTS AND NUMERICAL SIMULATIONS ADOPTING THE ALE APPROACH

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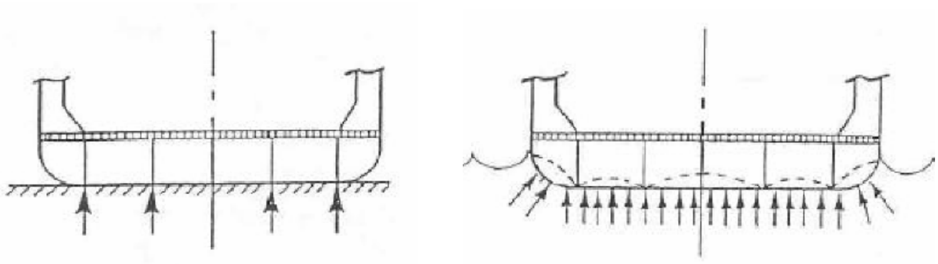
Abstract: Water impacts in emergency are likely to have tragic consequences for the passengers of helicopters. Most of the passive safety devices developed for helicopter crashworthiness are designed for ground impact. When impacting a solid or a soft surface, impact loads are rather different and therefore energy absorption devices developed for ground impact are not effective during a water impact. In order to collect reliable data for numerical models validation, water impact drop tests were carried out: an Aluminium alloy and a Carbon Fibre Reinforced Plastic panel, similar to modern aircraft skin panels, were mounted on a specific test device and tested. Impact decelerations and deformations of the panels were measured. Afterwards, a numerical model of the tests was worked out. The Arbitrary Lagrangian Eulerian approach was adopted to model the fluid region. Eventually, a close experimental-numerical correlation was obtained for both the panels in terms of impact dynamics, decelerations and deformations. The main features of the event and the differences between the impact behaviour of the two panels are discussed and failure of the composite panel was investigated. Guidelines for further investigations are also drawn.

INTRODUCTION

Water impact is a topic which 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.
Even if most of the passive safety devices have been developed considering ground impacts [3], remarkable progresses in crashworthiness design have been achieved recently. 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, loads transfer depend only on the structure whilst, when impacting a fluid surface, loads transfer depend *also* on structural response and on fluid-structure interaction.
During a ground impact (Figure 1-LHS), 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 (Figure 1-RHS), the water pressure insists on the skin panels which are not meant to carry such a large loads 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: the vanishing of the energy absorption attitude of subfloor (as the loads path changes) and water inrush into the subfloor with consequent various types of malfunctioning (cabin flood and reduction of helicopter floating time).
Fluid-structure interaction is a complicated event 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.



GROUND IMPACT WATER IMPACT

Figure 1: Loads distribution on an aircraft subfloor [4]

Researches aiming at deepening the knowledge of the event are fundamental to develop efficient numerical tools which will allow to reduce the number of tests and to design higher 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 and on the difference between metallic and composite skin panels. Two typical materials used in aircraft constructions were chosen: Aluminium alloy and Carbon Fibre Reinforced Plastic (CFRP) woven. 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 panels were acquired. A number of water impact drop tests were carried out using specimens which are representative of typical skin panels of modern aircraft. Flat panels, 400x400mm, were mounted on a test article developed on purpose 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 the ALE approach to model the fluid region. The feasibility of a model including the attitude of the ALE approach to reproduce water inrush after skin panel failure were investigated. Numerical-experimental correlation was considered and, in view of that, findings, guidelines for further investigations were obtained.

1. EXPERIMENTAL WATER IMPACT DROP TESTS

The intense test campaign carried out in the first part of the research here introduced was divided into two stages: tests on an Aluminium alloy skin panel and tests on a CFRP skin panel.
A solid test article was built to test the impact behaviour of the two panels. Impact decelerations and deformations were acquired. Besides, high velocity movies of the tests were recorded to evaluate the impact dynamics of the event.

1.1. The specimens

Aluminium alloy panel
The first tested specimen (Figure 2) was a flat 400x400 mm Al 6082-Ta16 skin panel. The thickness of the panel was 4.00 mm. Typical aeronautic Aluminium alloy skin panels are usually thinner: 0.75 mm to 1.25 mm. However, it was assumed that using a thicker panel would have not remarkably altered the results of the tests but, on the contrary, it would have guaranteed to avoid local plasticity or failures.

CFRP panel
The second tested specimen (Figure 3) was a flat 400x400 mm CFRP panel. The thickness of the panel was 2.00 mm. Material VICOTEX and staking sequence $[90°, 45°, 0°, -45°]_{SYM}$ typical of aircraft skin panel were used.

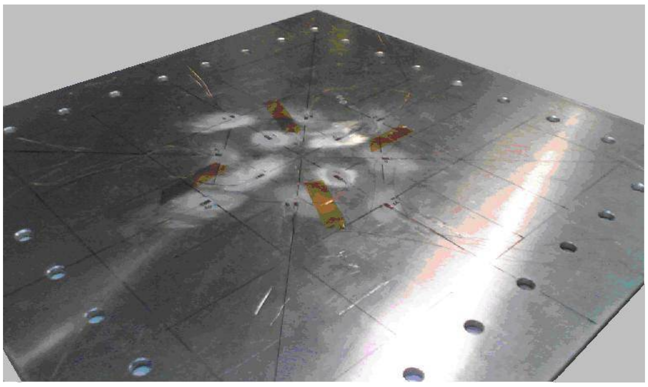


Figure 2: The Aluminium alloy skin panel

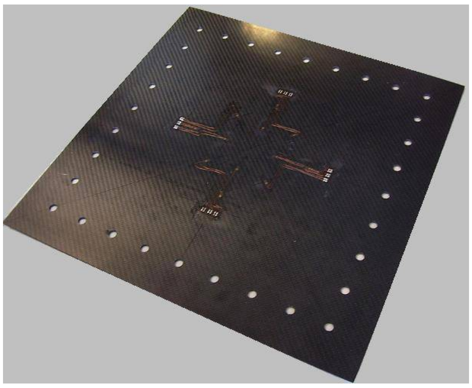


Figure 3: The CFRP skin panel

1.2. Test article

The test article (Figure 5-A) consisted of a massive base frame, four lateral flat Aluminium alloy panels and L-shaped corner beam. The base frame in particular was a 400 x 400 mm, 40-mm height Al 6082-Ta16 plate machined to have a square hole 320 x 320 mm. The Aluminium alloy and the CFRP panels were bolted on the base frame so that the actual impact region was a 320 x 320 mm surface. The test article was provided with a cap to avoid water inrush. The global dimensions of the test article were 400x400x500mm 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 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 test article allowed to mount different kind of panels (i.e. 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 panel to improve aircraft water crashworthiness are rather unusual and in this way this research is pioneering.

1.3. Test facility

The dimensions of the test article allowed performing the drop tests using the indoor facilities of LAST Crash Labs. 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 indoor test facility is shown in Figure 4.

1.4. Measuring instruments and data acquisition system

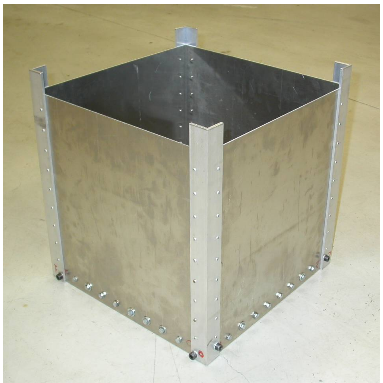
Impact decelerations and deformations are quantities of paramount interest in designing structures safe in water landing and hence were measured.

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 (Figure 5-B).
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.

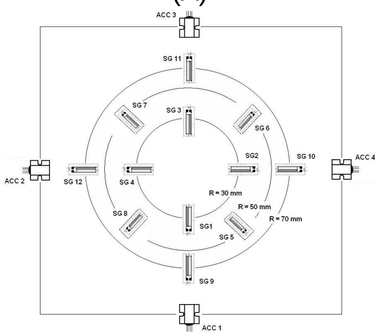
Strain gages
Twelve OMEGA KFG-5-120 strain gauges were installed on the skin panels to measure impact deformations. The strain gauges were placed on three circumferences of radius respectively of 30 mm, 50 mm and 70 mm – as shown in Figure 5-B.
The number and the placement of the strain gauges allowed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

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

Figure 4: The test facility



(A)



(B)

Figure 5: The transducers configurations (A) and the test article (B)

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 reasonable number of *sample points* during the initial phase of the impact when accelerations and deformations had a sudden growth. The value of the sampling rate was also decided in view to evaluate the delay between the accelerometers pulses.

1.5. Carried out tests

The water impact tests were carried out releasing the test article from prescribed heights. The facility used in the tests allows a maximum drop-height of 3.0 m. Nevertheless, to avoid local plasticity or cracks of the skin panels under investigation, the maximum drop-height was limited to 1.90 m and 1.50 m respectively for the Aluminium and the CFRP panels. Actual impact velocities and analytical predictions based on weights drop showed that the influence of the friction of the guides was negligible (the difference was within the 3%).

Carried out tests and measured impact velocities are listed in Table 1 and in Table 2. 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 tests. The impact incidence of the test article was evaluated on the basis of both high speed movies (Figure 6) and differences in acquired decelerations (pulse values and time delays). Only the tests with an impact incidence within 3 deg were considered acceptable. As a consequence, the number of tests carried out was larger than the one suggested from Table 1 and in Table 2.

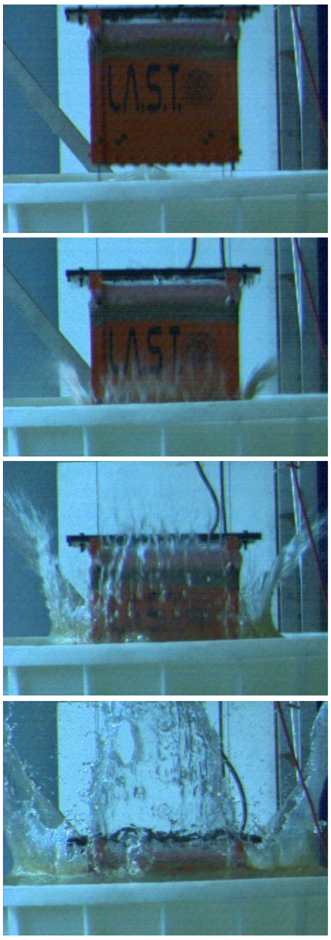


Figure 6: Frames from a high-speed test movie

Test #	Drop Height [m]	Impact velocity [m/s]
1	0.15	1.59
2	0.30	2.27
3	0.50	3.10
4	1.00	4.33
5	1.30	4.92
6	1.50	5.34
7	1.90	6.01

Table 1: Tests carried out with the Aluminium alloy skin panel

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

Table 2: Tests carried out with the CFRP skin panel

1.6. Data collected

Impact decelerations and deformations were acquired during the tests. A high-speed camera was used to film the dynamics of the event.

Impact decelerations
The impact deceleration time history of the Aluminium alloy and of the CFRP skin panel for three reference drop-heights are plotted in Figure 7 and Figure 8 respectively. Inspecting Figure 7 and Figure 8, it is possible to infer the general trend of the decelerations: a first peak and the following oscillations due to the test article response.

Impact deformations
The deformation time history of the Aluminium alloy and of the CFRP skin panel for three reference drop-heights are plotted in Figure 9 and Figure 10 respectively. Inspecting Figure 9 and Figure 10, it is possible to infer the general trend of the deformations: a first peak and the following oscillations due to the base panel vibrations.

1.7. Discussion

The repeatability of the tests in terms of collected data (impact decelerations and deformations) and the linear dependency on impact velocity 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 Figure 7-10: 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.
Considering *separately* the Aluminium alloy and the CFRP panel and comparing impact decelerations and deformations time histories, it is possible to notice that the response frequency is different for the two signals and, in particular, the deformations are less damped and less *sensitive* to the impact conditions (i.e. impact velocity and incidence) than the decelerations.
From the comparison between the data of Aluminium alloy and CFRP skin panel clearly appears that the impact decelerations of the Aluminium alloy panel are higher than the ones of the CFRP panel. On the other hand, due to the smaller thickness, the deformations of the CFRP panel are higher, and the frequency of the oscillation and the damping are smaller.
The difference between the two panels behaviour in terms of frequency and damping are due both to the different thickness of the panels and to the different mechanical properties of the materials.

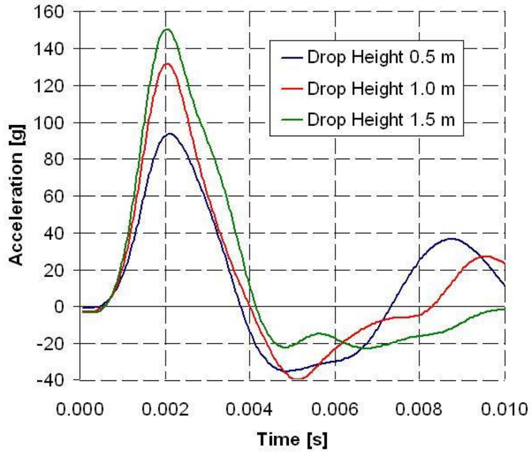


Figure 7: Impact decelerations for the Aluminium alloy skin panel

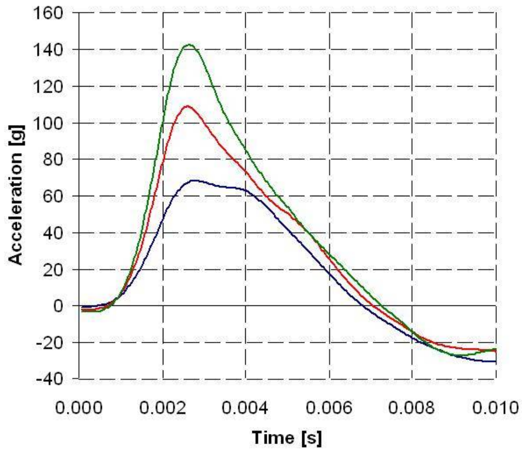


Figure 8: Impact decelerations for the CFRP skin panel

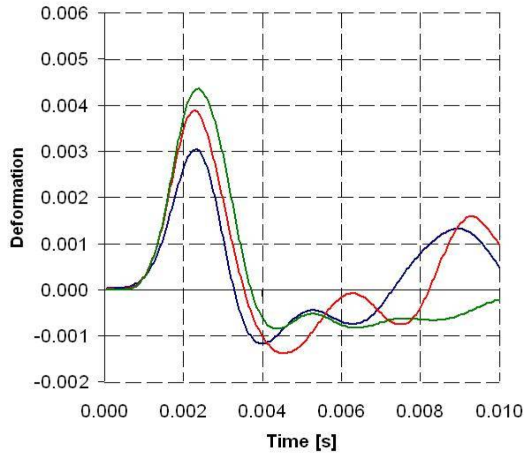


Figure 9: Deformations for the Aluminium alloy skin panel

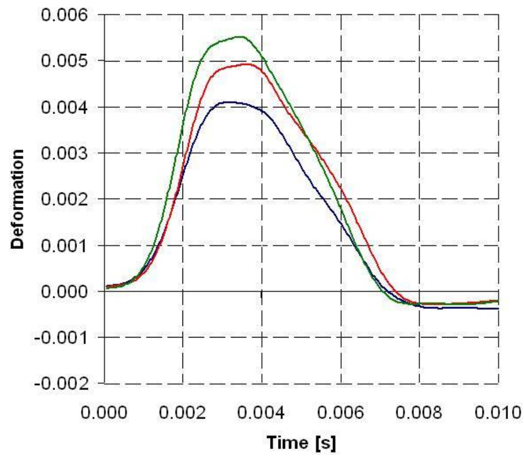


Figure 10: Deformations for the CFRP skin panel

2. NUMERICAL SIMULATIONS

The second phase of the research was devoted to develop and validate a reliable numerical model of the tests carried out. The Lagrangian Finite Element (FE) approach was adopted to model the test article. The Arbitrary Lagrangian Eulerian (ALE) approach was adopted to model the water region. Despite its known drawbacks, the Eulerian approach is usually preferred in fluid modelling to the Lagrangian FE one because it allows handling severe deformations without significant accuracy reduction.
The double symmetry of the problem was exploited and only a quarter of both the test article and the fluid region were modelled. Proper symmetry constraints were applied to both the Lagrangian model and Eulerian region.

2.1. FE model of the specimens

The skin panel was a square flat panel and, hence, it was possible to build a regular and uniform mesh on it consisting of 400 four-node shell elements. The chosen reference length (10 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.

Aluminium panel

The Belytschko-Tsay formulation with three integration points in the thickness was chosen for the shell elements. The elastic piecewise linear plasticity material model was adopted. The strain rate influence was considered introducing the Cowper-Symonds' coefficients. The failure of the panel was considered (however not necessary) defining a criterion based on the maximum effective strain.

CFRP panel

The CFRP panel was modelled accordingly with the *Lamination Theory* which allows modelling the stacking sequence and the fibre orientations of each lamina. One integration point for each lamina was defined. The composite material was modelled 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 almost uncoupled failure. The material parameters were chosen from a previous research aimed at developing numerical model able to capture the complex failure mechanism of composite structures [8].

2.2. FE model of the test article

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

The riveted joints and bolts were not modelled – neither the ones which fasten the skin panel to the test article. Indeed, it was observed that the benefits of modelling in details the fittings 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 modelled using specific *accelerometer* elements which allow to measure with accuracy the accelerations in local axis. Overall, 3371 elements were used to model the test article: 816 eight-node solid elements for the base frame, 2514 four-node shell elements for the lateral panels and the stiffeners, 37 point masses and 4 dedicated discrete elements type *accelerometer* [7]. The same material used for the Aluminium alloy skin panel was adopted for the test article, except for the stiffeners which were made with a different Aluminium alloy. The test article and the skin panel were placed over the fluid surface (Figure 11) and the initial velocity equals to the one measured during the tests was imposed to them.

2.3. ALE model of the fluid region

The water basin in the tests was a 1.5-m diameter *pool*. In effort to limit required CPU-time and 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 600 mm-side cubic box. The fluid region at the initial instant and a surrounding region were modelled. Overall, the ALE mesh consisted of about 140,000 eight-node solid elements. The mesh was refined below the test article, where the elements belonging to the fluid region have the same reference length of the elements of the skin panel. Moving along depth towards the bottom the mesh of the water region becomes progressively coarser. The *surrounding* region was modelled as initially void [7]. An automatic motion following mass weighted average velocity in ALE mesh was imposed to the ALE mesh. Reflected waves were avoided imposing *non-reflecting* silent boundary conditions.

A material which allows equations of state to be considered without computing deviatoric stress was used with a linear polynomial equation of state to model the fluid behaviour. The parameters for the materials are the known values for water. A pressure cut-off was defined to roughly model the effect cavitation in the water region. The interaction between fluid and structure was reproduced via *coupling algorithm*. In effort to keep the coupling definition simple, the standard parameters were used. In particular, 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 penalty 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.

2.4. 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.

Impact dynamics
The behaviour of both test article and the fluid region are alike the ones captured in the high-speed movie (Figure 12).
The ALE model provided a commonsense splash description: the behaviour of the fluid in terms of water mass motion is well reproduced but not the spray. When the amount of fluid in an element drops under a prescribed threshold, the solver used in the analysis [7] considers the element empty in order to reduce the required computational efforts without relevantly affecting the accuracy of the solution. On the other hand, if the mesh is not particularly fine, it also impedes from visualising the water sprays. A finer mesh was an option not considered because it would have meant larger computational resource and the numerical-experimental correlation in terms of impact deceleration and deformation was already satisfactory.

Impact decelerations
The numerical-experimental correlation in terms of impact deceleration is rather close for both the Aluminium alloy and the CFRP skin panel as shown in Figure 13 and Figure 14 respectively. The numerical peak is slightly smaller than the measured one but there is a over 90% correlation. The slope of the curve is well reproduced in particular in the raising part, whilst in the descendant phase it is slightly different. The duration of the numerical peak is smaller than the experimental one. The oscillations following the first peak are not captured by the numerical model.

Impact deformations
The numerical-experimental correlation in terms of impact deformation is rather close for both the Aluminium alloy and the CFRP skin panel as shown Figure 15 and in Figure 16 respectively. The correlation between the experimentally measured and the numerically computed deformation is in general rather close – when considering the mean elastic strains of the strain gauges on the first ring (i.e. internal circumference). The maximum value of deformation is well captured by the numerical model for both of the skin panels whilst the duration is overestimated or underestimated for the Aluminium alloy and for the CFRP panel respectively. Furthermore, the oscillations following the first peak diverge.

Required CPU-time
CPU-time is central for any *design-by-analysis* procedures and therefore it was here considered. The first 50 ms of the event were simulated using an Intel Core Duo 2, 2.66 GHz CPU – 4 GB RAM PC. The same simulation was run ten times and the average required CPU-time for both the specimens models was about 2 hours – which is about 1.5 greater than the average CPU-time required by simulations carried out using a FE model of the water region. Nevertheless, the accuracy of the ALE approach was higher than the Lagrangian FE one both in terms of description of the event and numerical-experimental correlation.

2.5. Water inrush

In effort to evaluate the behaviour of the composite panel after a structural failure, a water impact at 15 m/s was simulated. In Figure 17 the results of the simulation are shown. As predictable, the failure was localised in the centre part of the panel, where the deformations were larger. The water rushed into the structure at very beginning of the impact and went on flowing also when the vertical velocity of the test article dropped to zero. No failures were observed where the skin panel is bolted to the base frame.

2.6. Discussion

The ALE approach provided a common-sense description of the impact of the test article. With regard to the impact dynamics, the behaviour both of the test article and the fluid are rather similar to the ones appearing in the high-speed movies of the tests. Furthermore, numerical results are close to experimental data in terms of impact decelerations and deformations. In view of these results, the ALE method proved to be a convenient approach to analyse the water impact phenomenon and the fluid-structure interaction. Future developments will include investigations on the effect of air presence and cavitation in the fluid – which are at reach. Furthermore, water impact of structures characterised by more complex geometries and mechanical behaviour will be considered. A comparison with water region models based on meshless methods (SPH and EFG above all) seems also recommendable to further highlight *pros* and *cons* of the ALE approach.

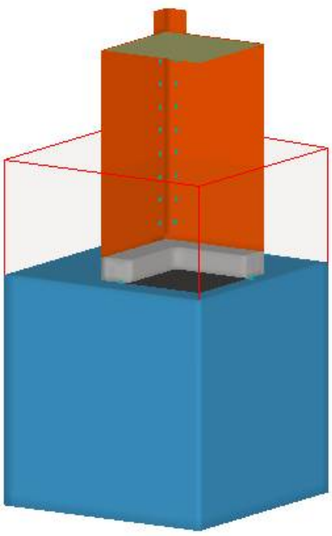


Figure 11: Numerical model

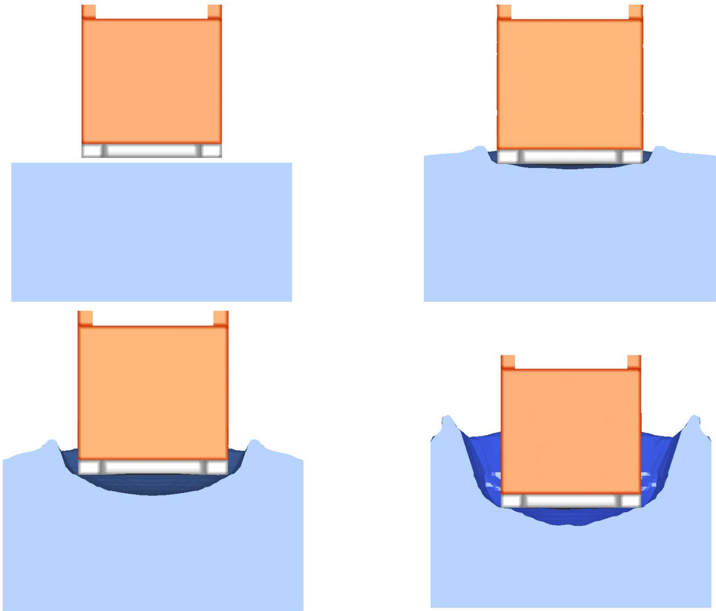


Figure 12: Numerical simulation of a water impact drop-test

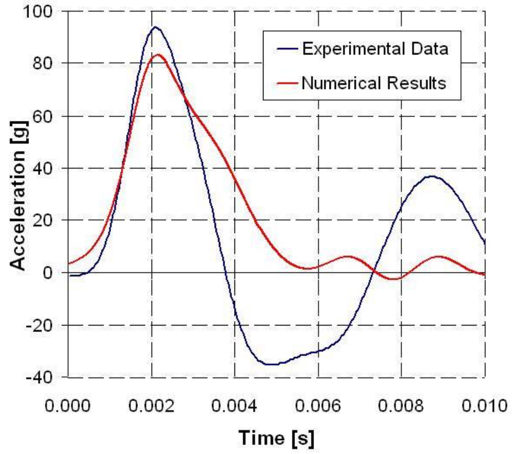


Figure 13: Impact deceleration for the Aluminium skin panel

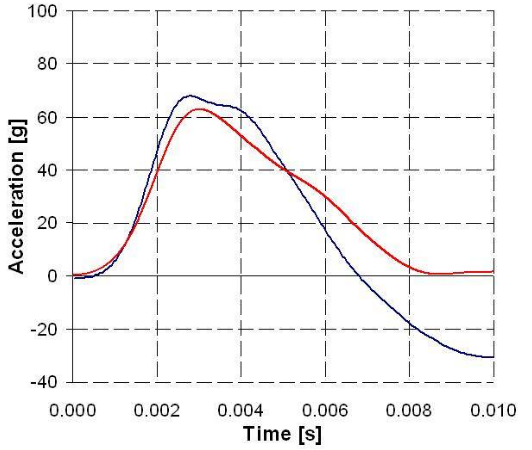


Figure 14: Impact deceleration for the CFRP skin panel

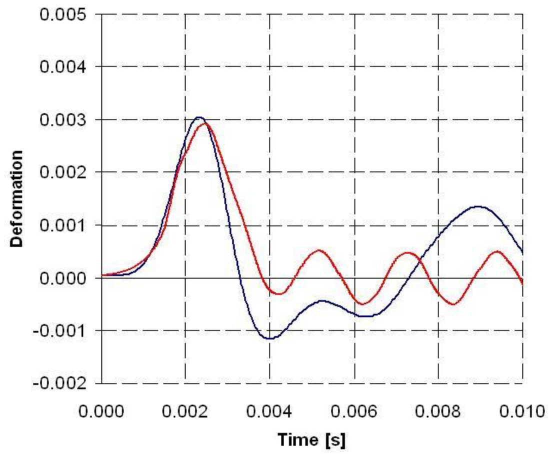


Figure 15: Impact deformation for the Aluminium skin panel

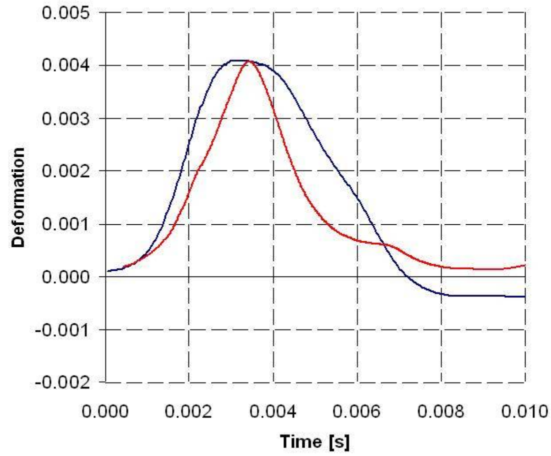


Figure 16: Impact deformation for the CFRP skin panel

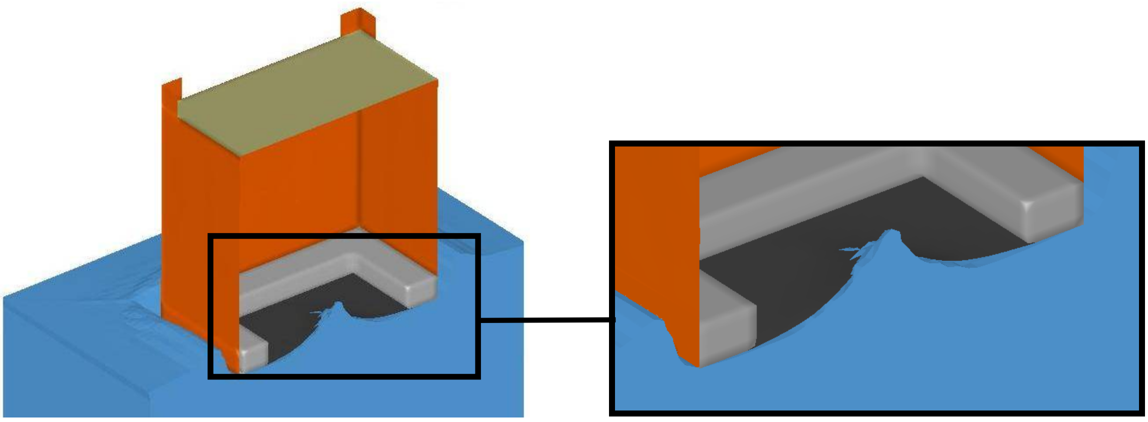


Figure 17: Failure of the CFRP panel and water inrush

CONCLUSIONS

Water impact of helicopters is 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 focused on fluid-structure interaction and on the difference between metallic and composite skin panels have been 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 an Aluminium alloy and 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 numerically reproduced adopting the ALE approach to model the fluid region. The feasibility of a model including the attitude of the ALE approach to reproduce water inrush after skin panel collapse was investigated. For both the Aluminium alloy and the CFRP skin panel a satisfactory numerical-experimental correlation was eventually obtained in terms of impact dynamics, impact decelerations and deformations.
The ALE approach was also feasible to investigate water inrush and was able to capture the water flowing inside the test article although, in order to have a better representation of the event, a finer mesh is mandatory. Eventually, despite the known drawbacks, the ALE approach proved to be a feasible analysis tool.

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