HELICOPTER SUBFLOOR-INTEGRATED FUEL-TANK CRASHWORTHINESS

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ABSTRACT

Water impact of a helicopter in emergency is likely to have tragic consequences. In view of that, numerical models to predict helicopter crash performance during a water impact are of paramount importance.

In this paper, the crash behaviour of a (half filled) helicopter subfloor-integrated fuel-tank has been numerically investigated.

The finite elements model of a fuel-tank simulacrum was developed and validated referring to the data collected during ground impact drop-tests and hence used to investigate the crash performances of a fuel-tank with regard to the impact with a rigid and a fluid surface. The difficulties in modelling a fluid when using explicit codes based on finite element method suggested adopting two different approaches to model the fluid regions: Lagrangian and Arbitrary Lagrangian Eulerian. Advantages and disadvantages of these approaches have been highlighted.

Referring to the numerical results obtained, the differences between ground and water impact have been eventually discussed.

INTRODUCTION

Statistics show [1] that a significant number of helicopter accidents occur on water and that a water crash landing of a helicopter in emergency is likely to have tragic consequences for the occupants. The losses, *economical* and in *human lives*, justify the interest in the development of design methodologies to improve helicopter crashworthiness during a water impact.

Investigations made in last years concerning helicopter crashworthiness have brought to the publication of crash survival design guides and to the development of crashworthiness requirements. Nevertheless, the most of improvements have been done considering ground impact, even if water impact has been shown to be relevant for both civil and military operations.

The dynamics of a water impact causes more severe crash conditions than the ones of a ground impact at equivalent velocity. When impacting *solid* surfaces, loads distribute through subfloor high stiffness structural elements, designed to absorb impact energy. These elements crush progressively and lower skin is not involved. When impacting *water* surfaces, loads distribute differently and lower skin panels are loaded. Their failure prevents stiff elements from crushing and absorbing energy. In this scenario, the internal components are often exposed to water inrush that is likely to cause malfunctioning or collapse.

Subfloor-integrated tank crashworthiness is fundamental for accident survivability: the collapse of the fuel-system, as a consequence of an impact, is one of the main causes of death among the cabin crew. During a water impact, because of mutual influence between hydrodynamic loads and response of the structure, forces acting on the structures are difficult to reproduce.

Up to few years ago, due to the lack of relevant knowledge necessary to develop adequate simulation tools, the approach to the problem was mainly based on experimental full-scale tests. These tests are expensive, time-consuming and difficult to perform.

Several efforts have been provided to develop reliable numerical tools feasible to support the design of safer structures. In particular, nowadays, explicit codes based on *Finite Element Method* (FEM) are successfully used to analyse water impact [2]-[4]. The use of these codes have made possible to drastically reduce the number of tests to be performed. Nevertheless, the experimental tests remain *essential* to understand the complicate dynamics of a water impact and to validate the numerical models, as well.

Here, ground and water impact of a (half filled) helicopter subfloor-integrated fuel-tank has been numerically investigated. The FE numerical model of the tank was developed and validated referring to the experimental data collected during drop tests [6]-[8]. The attention, in particular, is focused on the differences between the ground and the water impact. The same topic, previously analysed [6], is here further investigated referring to different impact scenarios and, in particular, reproducing the influence on impact dynamics of the structure above the subfloor by means of ballast – the weight of which was meant to be representative of the weight of an actual helicopter structure. Fig. 1 shows the typical subfloor and cabin structure of a helicopter.

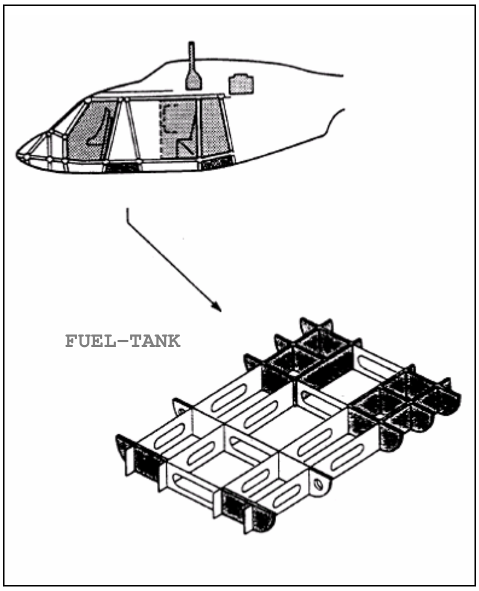


Fig. 1. Typical helicopter subfloor structure and housing for integrated fuel-tank.

Two different approaches were used to model the fuel inside the tank and the impacted water surface: the *Lagrangian* and the *Arbitrary Lagrangian Eulerian* (ALE) approaches. Advantages and disadvantages of these approaches have been highlighted and, referring to the numerical results obtained, the differences between ground and water impact have been discussed emphasizing the behaviour of the structure in the two different cases. Furthermore, the results obtained were compared with the ones collected in the previous analyses when the actual weight of the structure above the fuel-tank was not considered.

1 NUMERICAL MODEL OF THE TANK

The FE numerical model of the tank was developed and validated [7] referring to specific tests with a drop height of 7.5 m and a resulting impact velocity of about 12 m/s.

1.1 Fuel-tank structure model

1.1.1 Actual tank structure

The fuel-tank used in the test (Fig. 2) was a metallic box (670 mm width, 638 mm length, 300 mm height) apt to contain up to 80 KG of fuel.

The structure is an assembly of Aluminium alloy 2024-T42 panels jointed together by means of rivets and blind rivets.

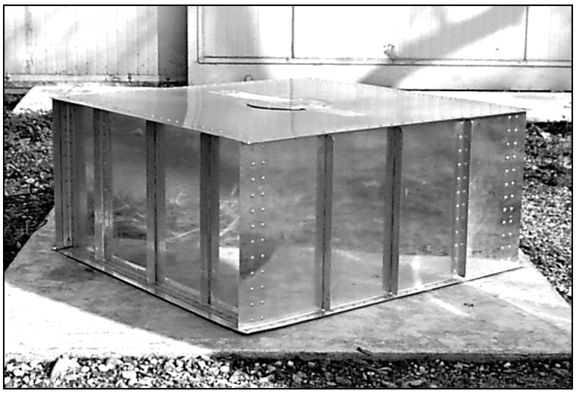


Fig. 2. One of the fuel-tank simulacra used in the drop-tests.

The panels have different thickness depending on their position in the structure of the helicopter subfloor (Table 1). On the sides of the tank, are riveted three vertical L-stiffeners.

	Length	Width	Thickness
Upper panel	670	638	0.51
Lower panel	638	670	1.02
Front/rear panels	336	595	1.02
Lateral panels	336	670	0.81
Front/rear panels	291	38	1.60
Lateral panels	193	40	0.80

Table 1. Nominal dimensions and thickness of the panels used in tank simulacra manufacture [mm].

1.1.2 FE model

The geometry of the tank is rather simple: nevertheless it was further simplified in order to build a quite regular FE mesh and hence focus on the interaction between the structure and the fluid. The characteristic length of the elements was the necessary compromise between the need to properly reproduce the buckling of the lateral panels of the tank and the need to have a regular but relative coarse mesh to reduce the required CPU-time. Eventually, the fuel-tank model consisted of 13464 four-node shell elements, having a reference length of 10 mm.

The elastic piecewise linear plasticity material model (*MAT_24 in [9]) was used to reproduce the mechanical behaviour of the Aluminium alloy. The influence of the strain rate was also considered by means of Cowper-Symond coefficients.

The riveted junctions were ignored: the benefits of modelling in details the fittings were considered not sufficient to justify the increase in model complexity and in required CPU-time. Furthermore, as observed in the tests, the number of collapsed rivets after the impact was negligible. On the contrary, the lifting system (a square frame built with steel C-beams welded together) had a relevant influence on the impact dynamics of the tank because of its stiffness and weight and, therefore, it was modelled in detailed as shown in Fig. 3.

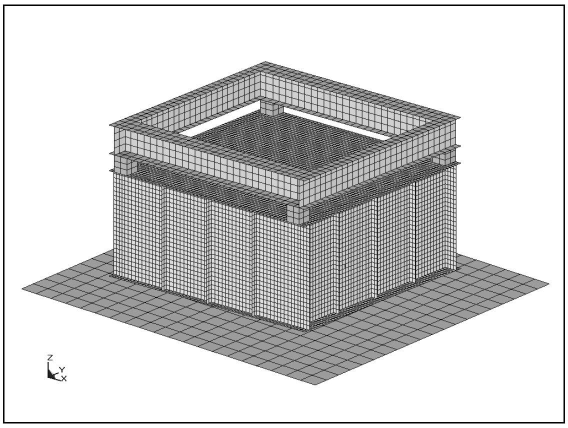


Fig. 3. FE model of the fuel-tank plus the lifting system and the ground.

1.2 The fluid inside the tank

Two different approaches were considered for the fluid inside the tank: the Lagrangian FE and the Eulerian/ALE approach.

In the drop-tests, the fuel-tanks were filled up to a half with water – which it is not the fluid usually put inside a fuel-tank but it is much safer for tests purposes.

1.2.1 Lagrangian FE model

The FE model of the fluid inside the tank consisted of 6300 eight-node solid elements with a characteristic length of 20 mm.

The material model was carefully chosen. In effort to accurately reproduce the features of the fluid inside the tank, several simulations were performed considering different constitutive laws. For each one of these models, different values of the characteristic parameters were tried and the results compared with experimental data. Eventually, it was concluded that the *null* material [9] associated with the polynomial equation of state was the most reliable compromise between the total CPU-time required for the simulation and the stability/accuracy of the solution.

The interaction between fluid and structure was reproduced via contact algorithm [9]: in particular, it was defined a bidirectional contact based on *penalty method* – recommended when the parts in contact have different mechanical properties.

1.2.2 ALE model

The ALE approach is originally meant to combine the advantages of Eulerian and Lagrangian approaches [6]. With regard to the considered problem, the fluid region at the initial instant plus a void surrounding region were modelled. The Eulerian mesh of fluid region consisted of 12716 eight-node elements. The ALE mesh was imposed to move following the mass weighted average velocity [9].

The same material model and equation of state adopted for the Lagrangian FE model were used.

The interaction between fluid and structure was reproduced via *coupling algorithm* [9]. In particular, the nodes of the fuel-tank Lagrangian mesh were imposed to have the velocity and acceleration equal to those of the points of the water surface with which are in contact, only in direction normal to the surface itself.

2 GROUND IMPACT

Using the numerical model described, a ground impact was considered. Initially, the actual test conditions were reproduced in order to validate the overall numerical model [7]. Subsequently, the impact scenario was modified: in particular, the lifting system was replaced with ballast in order to represent the part of helicopter structure over the fuel-tank. In that, the purpose was to obtain results closer to real cases than in previous similar analyses [7].

2.1 Numerical model

The numerical model previously described was completed with the FE model of the ground, consisting of 841 four-node shell elements.

In the experimental tests the ground was little deformable and, therefore, in the simulations it was defined as rigid [9].

The actual incidence of the fuel-tank was evaluated referring to the photographic documentation of the tests and reproduced rotating the fuel-tank FE model [8].

The interaction between the fuel-tank and the ground was defined by means the distributed parameter contact algorithm.

2.2 Numerical-experimental correlation

The results obtained after the simulations with the two different approaches to the fluid modelling were compared with the data collected during the experimental tests referring to the description of the event dynamics, the post-impact deformations of the structure and the impact deceleration [7], [8].

2.2.1 Description of the event dynamics

Considering the event dynamics, both the Lagrangian and the Eulerian approaches provided a reliable description of the sloshing of the fluid inside the tank – though rather different.

2.2.2 Deformations after the impact

The deformations after the tests (Fig. 4) were used as a reference to evaluate the accuracy of the simulation carried out with the two different approaches to the fluid modelling. The longitudinal and lateral displacements and the vertical shortening of the fuel-tank were considered. Eventually, a good agreement with the experimental data was obtained for both the approaches adopted.

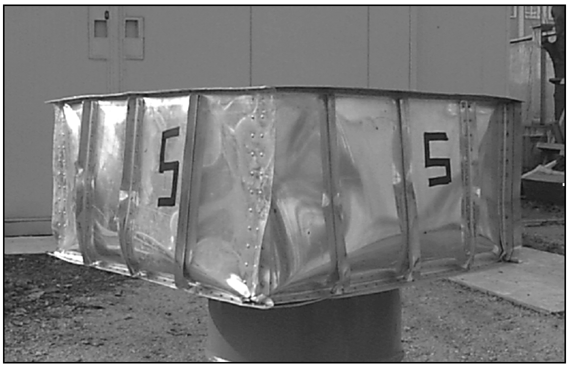


Fig. 4. Deformations of one of the fuel-tank simulacra in a photo taken after the drop-test.

2.2.3 Impact deceleration

As a further validation of the model, the impact deceleration was considered.

Independently from the adopted approach, the maximum and the mean values of the deceleration were close to the experimental ones, though the acceleration versus time profile was slightly different.

In view of the results obtained and referring to the experimental data, both the model was judged reliable and feasible for the analysis of the event considered – with the exception of the case [7], [8].

2.3 Ballasted fuel-tank

After validating the numerical model, the lifting system was replaced with ballast (Fig. 5) – the weight of which was representative of the weight of the actual helicopter structure over the portion of subfloor considered. The ballast was fixed to the tank along the longitudinal opposite side. Indicatively, the weight was fixed in 100 KG.

The results obtained after the simulations were evaluated referring to the description of the event dynamics, the post-impact deformations of the structure and the impact deceleration. A good agreement was obtained and the results were deemed reasonable.

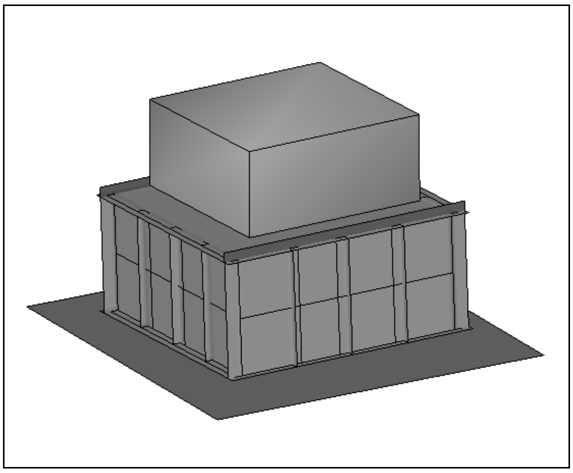


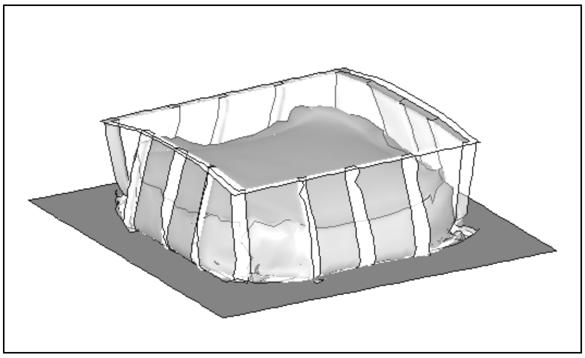
Fig. 5. The finite element model of the fuel-tank and the added ballast.

2.3.1 Description of the event dynamics

In Fig. 6, a direct comparison to evidence the differences between Lagrangian and ALE approaches in the description of the event dynamics is provided.

In particular, noticing that the Lagrangian FE model of the water inside the tank shows spikes due to the mesh distortion which are not present when adopting the ALE approach.

On the other hand, the behaviour of the ALE model of the water inside the tank (also due to the coarseness of the mesh) is closer to the one of a jelly material than to the one of a fluid.



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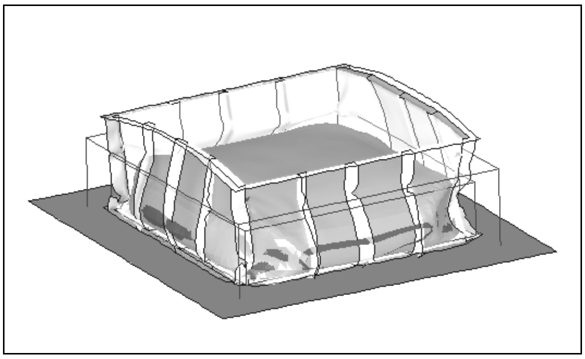

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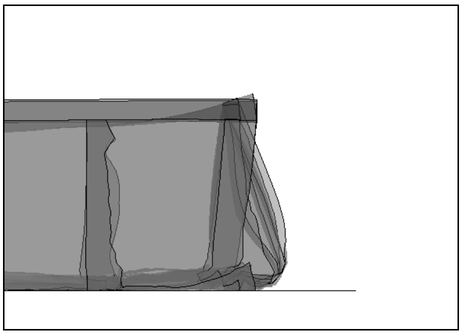
Fig. 6. Ground impact ballasted fuel-tank using (A) Lagrangian and (B) Eulerian approach for the fluid inside the fuel-tank.

2.3.2 Deformations after the impact

The deformations after the tests were used as a reference to evaluate the accuracy of the simulation carried out with the two different approaches to the fluid modelling. The longitudinal and lateral displacements and the vertical shortening of the fuel-tank were considered.

In Fig. 7 the deformations of the tank when adopting, in turn, the Lagrangian and the ALE approaches for the fluid inside the tank are shown. When adopting the Lagrangian approach, the vertical crushing of the corner that first impacts the ground is larger than the one obtained when adopting the ALE approach. The deformations of the tank are similar in the lower part but not in the upper part.

The differences in the tank deformation are a direct consequence of the interface forces modelling and basically depend on the forces that the fluid exerts on the tank walls. Adopting the ALE approach, the interaction forces are underestimated. On the other hand, adopting the Lagrangian approach, the interaction forces are overestimated – though this effect is known to be less significant than the dual one that affects the ALE approach. Experimental data show that the Lagrangian approach is in general more accurate.



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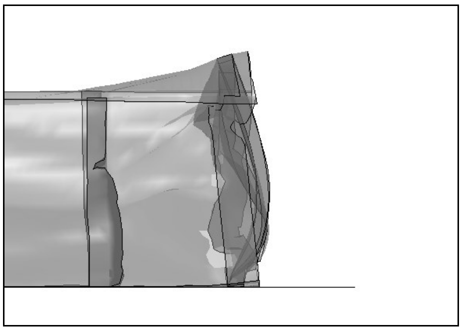

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Fig. 7. Fuel-tank deformations after a ground impact when adopting (A) Lagrangian or (B) ALE approach for the fluid inside the fuel-tank.

2.3.3 Impact deceleration

As a further comparison between the two different approaches, Lagrangian and ALE, the impact decelerations were considered.

In Fig. 12, the vertical deceleration versus time when adopting the Lagrangian and the ALE approach are shown. In particular, it is possible to notice that the accelerations in ALE model is rather higher than in Lagrangian one.

3 WATER IMPACT

A remarkable number of helicopter accidents occur on water. In view of that, designing water impact-proof helicopter is mandatory.

Using the ballasted fuel-tank models, the consequences of a water impact were investigated. The impact scenario is the same described in the previous analysis unless the ground was substituted by a water surface. The difference between ground and water impact and the dissimilar impact behaviour of the subfloor-integrated fuel-tank were highlighted.

3.1 The fluid surface

The dimension of the fluid region was fixed so that the mass of the fluid was such to avoid reflected waves and rigid motion of the mesh and hence unrealistic energy transfers.

The characteristic length of the elements, in turn, was fixed as to fill the fluid region with a reasonable number of elements and, at the same time, guarantee the accuracy of the solution and an appropriate representation of the dynamics of the event. Eventually, the fluid region was a square-base box: 1914 mm edge and 600 mm depth. Two different approaches were used for the water surface: Lagrangian FE and ALE approaches.

3.1.1 Lagrangian FE model

The Lagrangian FE model consisted of over 20000 eight-node solid elements. The mesh was finer in the impact region to conciliate accuracy and required CPU-time.

The constitutive law used for the fluid inside the fuel-tank was used also for the water region.

The interaction between the fuel-tank structure and the water surface was defined by means of an automatic bidirectional contact algorithm based on penalty method.

3.1.2 ALE model

The ALE model of the water region consisted over of 20000 eight-node solid elements. The mesh, the same of the Lagrangian FE model, was finer in the impact region to conciliate accuracy and required CPU-time.

In addition, an *initial void* [9] surrounding region was built above the free surface of the fluid to avoid fluid outflow.

The same constitutive law was used both for the fluid inside the tank and the fluid surface – i.e. water region.

The interaction between the fuel-tank structure and the water surface was defined by means of coupling algorithm and using the same parameters of the coupling between the structure and the fluid inside the fuel-tank.

3.2 Results obtained

The results of the water impact simulations obtained using the two different approaches were eventually compared.

Lacking experimental references, the comparison was necessarily based only on the advantages and disadvantages of the two different approaches. In particular, once again, description of the event dynamics, deformations of the fuel-tank structure and impact deceleration were considered. Furthermore, here, also the overall required CPU-time was keep in count.

3.2.1 Description of the event dynamics

With regard to the event dynamics, the Lagrangian (Fig. 8-A) and the Eulerian (Fig. 8-B) approaches provided reasonable descriptions of the sloshing of the fluid inside the tank – though slightly different.

Once again the Lagrangian model showed the typical spikes due to the FE mesh distortion whilst the behaviour of the ALE model is close to the one of a jelly material. This observation is applicable both to the fluid inside the tank and the fluid surface.

The different attitude of the two approaches is not only qualitative, but also quantitative – as shown by the different deformation of the tank after the impact.

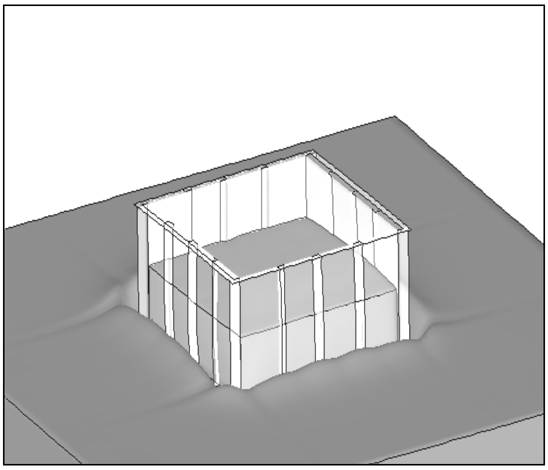
3.2.2 Deformations after the impact

The values of the post-impact longitudinal and lateral deformations and vertical shortening obtained with the two different approaches to the fluid modelling are rather different.

In Fig. 9, the deformation of the fuel-tank after the impact with the water is shown when adopting the Lagrangian and the ALE approach for the fluid inside the tank and for the fluid surface. The differences are evident.

With regard to the lower part of the tank, the deformations, when adopting the Lagrangian approach, are smaller than the ones obtained when adopting the ALE approach. At the same time, the penetration of the tank in the fluid region when adopting the Lagrangian approach is smaller than the one obtained when adopting ALE approach.

Once again, the differences observed are due to interface forces modelling – which, in particular, are responsible of different influence of the fluid inside the tank.



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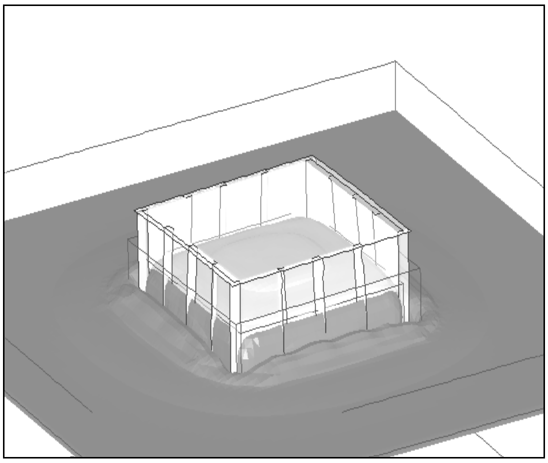

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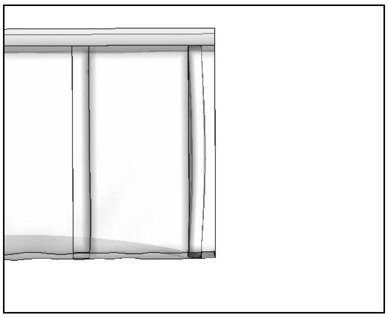
Fig. 8. Water impact of the ballasted fuel-tank adopting (A) the Lagrangian and (B) the ALE approaches to model the fluid regions.



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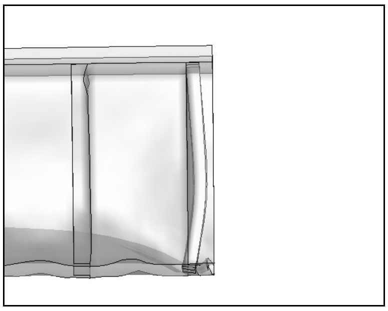

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Fig. 9. The fuel-tank deformations after the water impact when adopting (A) the Lagrangian and (B) the ALE approaches to model the fluid regions.

When adopting the Lagrangian approach the fuel-tank tends to rebound on the surface – as shown from the deceleration history (Fig. 13). The mesh distortion is critical, though the results are commonsense.

When adopting the ALE approach, the interaction forces are underestimated and hence the influence of the fluid inside the tank on the response of the lower panel is lessened. As a consequence the deformation of the lower panel is remarkable. For the same reason, when adopting the ALE approach, the penetration of the tank inside the fluid surface is deeper than the one obtained when adopting the Lagrangian approach.

The deformation of the tank walls (i.e. the lateral panels) is rather negligible independently from the approach adopted. This is a further proof that when impacting with a fluid surface the impact loads are such to nullify the impact energy absorption function of the subfloor.

3.3.3 Impact deceleration

The deceleration obtained when adopting the two different approaches under investigation, Lagrangian and ALE, are rather similar in the time profile, though the maximum values are different because of the difference in evaluating the interface forces.

In Fig. 13, the (vertical) decelerations versus time are shown: the differences between Lagrangian and ALE approaches are evident. Noticing in particular that, when adopting the Lagrangian approach, the deceleration is rather bigger than the one obtained when adopting ALE approach.

With regard to the water impact, the forces arising at the interface between the fuel-tank structure and the water surface had an influence on the deceleration. In that, the difficulties in defining the Lagrangian/ALE interface were the main responsible of the difference in the deceleration peaks.

3.3.4 Required CPU-time

When considering a water impact, it is necessary to discretise a large fluid region: as a consequence, the required CPU-time increases considerably (Fig. 10).

The CPU-time required for the ALE fluid model simulation was over four times larger than the one required for the Lagrangian FE fluid model simulation. In particular, using a plain PC (i.e. a Pentium 4 1700 MHz CPU – 256MB RAM PC), simulating 9 ms of the event adopting ALE approach to model the fluid inside the tank and the fluid surface approximately required sixteen hours CPU-time.

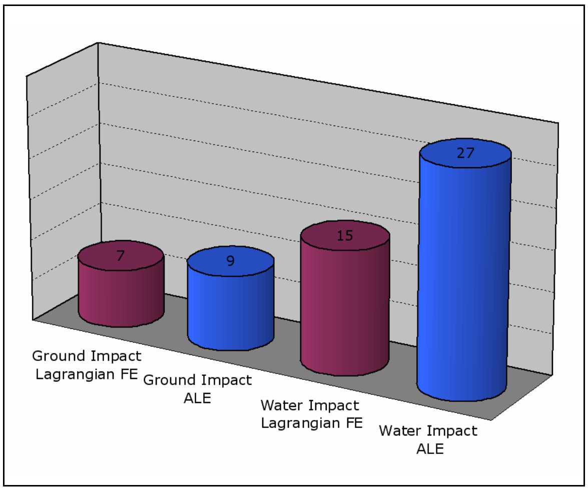


Fig. 10. Comparison between the two different approaches to fluid modelling with regard to the required CPU-time.

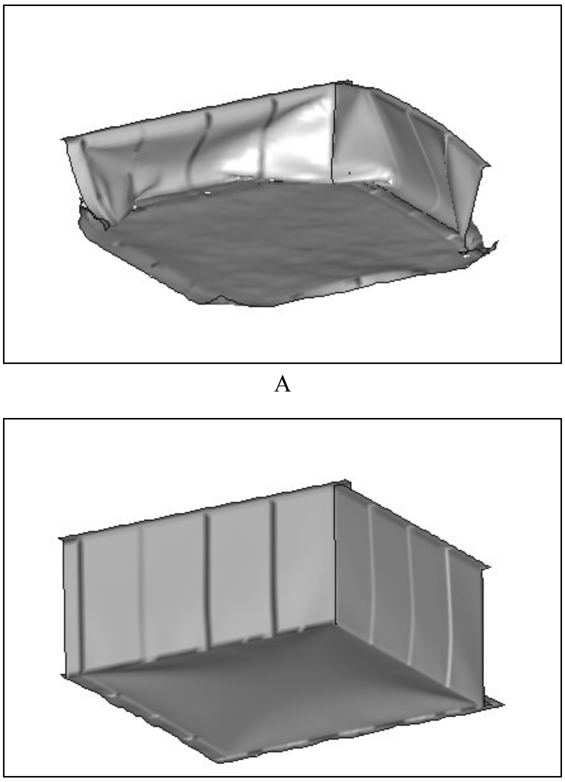
The much greater CPU-time required when adopting the ALE approach is basically due to the high time-per-cycle and to the memory allocation.

4. DISCUSSION

In view of the numerical results obtained after *ground* and *water* impact simulations, some considerations have been drawn.

4.1 Dynamics of the event

The dynamics of the event concerning the two different impact scenarios is rather different as also shown by the post impact-deformation in Fig. 11.



A

B

Fig. 11. The deformations of the fuel-tank lateral panels when considering (A) ground and (B) water impacts.

When impacting a *solid surfaces*, the impact loads distribute through the subfloor high-stiffness elements (Fig. 11-A) which crush progressively and absorb impact energy. The lower skin panel is not involved.

When impacting a *water surface*, the hydrodynamic loads distribute on the lower skin panel and that prevents the stiff elements from crushing and absorbing energy (Fig. 11-B).

Furthermore, since water is modelled as an incompressible fluid, the impact involves momentum transfer from the tank to the water: as a consequence, the total loads on the structure are smaller, but they distribute so that only lower panels are severely loaded. In that respect, the dynamics of a water impact causes more severe crash conditions than the one of a ground impact at equivalent velocity.

4.2 Deformations after the impact

The deformations of the fuel-tank after the impact (Fig. 11) substantially confirm what already observed when considering the dynamics of the event.

4.3 Impact decelerations

The impact deceleration profiles in time obtained with the different approaches and in the different impact scenarios embody the features both of the event considered and the approach adopted (Fig. 12 and Fig. 13).

With regard to the approach, Lagrangian FE and ALE provide similar deceleration time profiles. The differences in values and timings are mostly due to the different loads on the lateral panels.

With regard to the impact scenario, the differences are rather evident: high deceleration peak and short duration for the ground impact, lower acceleration peak and longer duration for a water impact.

The results obtained after the simulations further demonstrated that, when impacting the ground, the decelerations are higher. Indeed, the water has a relevant role in absorbing impact energy. In fact, in the first instants of the impact the energy transferred to the water is of the same order as the energy absorbed by the structure. Differently from a rigid impact surface, which does not absorb any of the kinetic energy, the water absorbed the larger part of the kinetic energy.

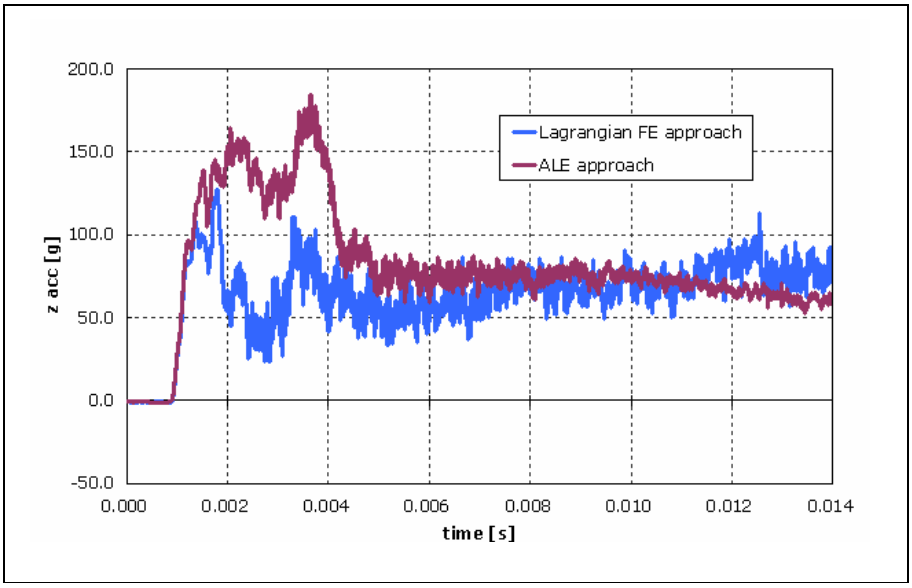


Fig. 12. Deceleration of the fuel-tank during a ground impact when adopting Lagrangian and ALE approaches.

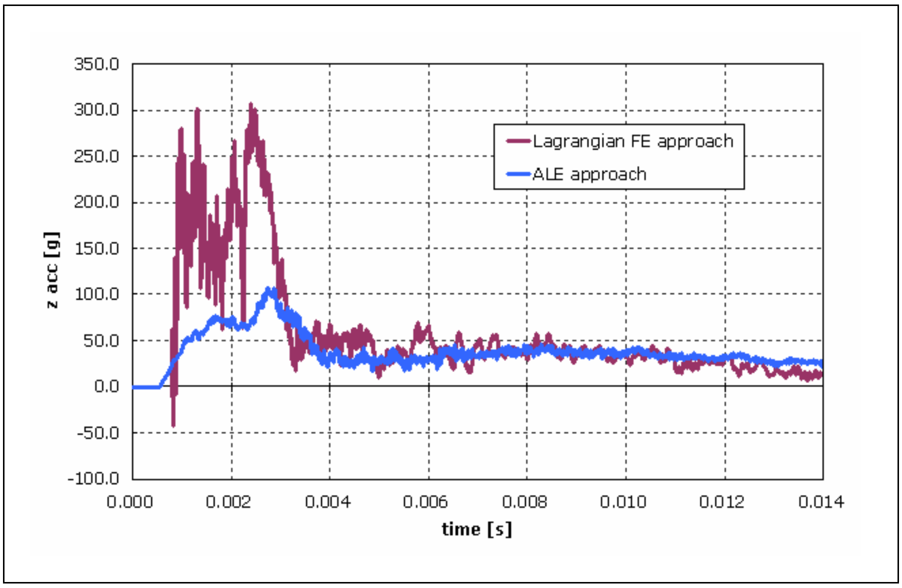


Fig. 13. Deceleration of the fuel-tank during a water impact when adopting Lagrangian and ALE approaches.

CONCLUSIONS

Water landing of a helicopter in emergency is rather likely to become a tragic event and, therefore, it is essential to develop numerical tool to increase helicopter crashworthiness with regard to this event.

Ground and water impact of a half filled subfloor-integrated fuel-tank have been investigated by means of an explicit nonlinear FE code. Two different approaches were adopted to model the fluid inside the fuel-tank and then the fluid surface: Lagrangian and ALE.

As a result, advantages and disadvantages of the two approaches and the differences between the two impact scenarios (concerning: dynamics of the event, impact deformations, impact loads and impact deceleration) have been highlighted.

Eventually, the explicit FE simulations proved to be a valid tool to investigate the event. In particular, it has been recognised that the Lagrangian approach is to be preferred when the early instants of the event are under investigation and fast simulation are required, whilst the ALE approach is mandatory when considering the overall dynamics of the event.

The differences in impact loads and structure response when considering ground and water impact and the importance to develop structure effective in both the impact scenarios have been drawn. Further analyses are necessary to investigate events such water inrush and to improve the design of the fuel-tank structure.

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