Numerical Analysis on Water Impact

Jyrki Majamäki
Eurocopter Germany
Ottobrunn, D-81663
Germany
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OVERVIEW

The helicopter impact on rigid ground has been on focus for several years and principals from Aircraft Crash Survival Design Guide, or FAR as minimum, are integrated more and more into late design concepts. No doubt, the rotorcraft survivability has been positively influenced by the measures. Introduction of the crashworthy seats or crashworthy fuel system are factors of primary significance improving the survivability of a modern helicopter. While the requirements or the guidelines derive from ground impact, water impact of a helicopter has started to receive more attention. It has been acknowledged that impact on water has significant differences in the physics. The different physics (fluid-structure interaction) and longer duration of impact sequence place new requirements for analytical means.

Reliable in-depth analyses of a water impact are extremely resource hungry and difficult to execute, not to mention that a validation with a test is equally complex – particularly in a case of simplification to a component level. The purpose of a study made in Eurocopter was initially to define typical impact scenario including speeds and attitudes for a typical helicopter water impact scenario. At the same time, analytical methods for the simulation of a water impact were compared. Results from drop tests of generic shapes on water were obtained in correspondence with AG15 Garteur study group. These tests were performed by LaST crash lab of Politecnico di Milano. With these results it was possible to validate the analysis, compare available methods and define pros and contras. The primary difficulty was the balance between complexity and computing performance.

Whereas the structural model can be produced from old experience/knowledge, necessary verification of the water model needs to be performed. It was necessary, for example to assess following primary questions:

- Necessary size of the water "pool", effect of wave reflections
- Necessary discretion level of the water mesh (element size)
- Usable material laws
- Analysis method: Lagrangian impact on Lagrangian Water, SPH water model, Lagrange Structure impact on Eulerian Water model

From Eurocopter Germany side the study has now mostly concentrated on applying Eulerian method, whereas Eurocopter France works more with SPH approach. Since the Euler-Lagrange calculation method is rather new in the used analysis code and still developed, part of the problem is defining different parameters for fluid-structure interaction and intensive verification work required. For both approach inside Eurocopter the explicit simulation code Radioss was used.

In the end, after establishing the modelling guidelines for the water impact simulations and verifying the water model the knowledge was applied to a practical problem. A verified simulation model, from a real-life drop-test of a composite transport helicopter cabin on rigid ground, was taken as basis and completed with a verified water model. The analyses were performed and a comparison was made between structural impact on rigid ground (as in drop test) and on water considering rigid structure and deformable structure.

1. SIMULATION METHOD

For the analysis work Eurocopter Germany has been concentrating in Euler-Lagrange approach for modelling the fluid-structure interaction problem. The partial reason is the history with MSC.Dytran that has been used in the company for previous studies, for example CAST-Project. The analysis code that is currently used is Radioss, which is nowadays commonly used both in Eurocopter Germany and France. Simultaneously Eurocopter France has been doing similar study using the SPH-approach for solving the fluid-structure interaction. At the moment there is no clear advantage from using one method or another, both have their strengths and deficits.

The fluid-structure interaction in Radioss using combined Euler and Lagrange modelling is realized using a special contact interface (TYPE 18), which form a flow boundary for Eulerian material, based on surface definition from Lagrangian elements.

Shortly, the Lagrangian mesh means a mesh based on classical structure elements, where the mesh deforms with the loads. Eulerian mesh on the other hand remains undeformed and the material flows through the mesh.

The advantage of TYPE 18 interface is that the interface allows deformable or even failing structural surfaces. Surfaces are also not required to form a closed volume.

The disadvantage of the method is that definition of the required parameters for the interface, for example stiffness scale factor and gap has to be done on case by case basis and may influence the accuracy of the analysis. It is also difficult to decide the necessary size of the fluid elements and the required size of "the pool", in order to avoid wave reflections. Since the recommendation is to enclose the complete structure inside the Eulerian mesh in the beginning of the analysis it is also required to model large volume of air, which in case of a water impact itself is rather uninteresting element. Initial trials showed that having a structure outside the Eulerian mesh will replace a volume inside the mesh and cause a general raise in pressure. However, this problem can be countered by setting the ambient air pressure to zero (in fluid and air mesh) and limiting the size of the contact interface only to the surfaces that come into contact with water. The necessary air space is an area where a further reduction in element number can be achieved, but a further studies and comparisons are still to be made.

Starting with unnecessary fine mesh rapidly increases the amount of elements required for the whole Eulerian volume.

Additionally, the Eulerian Mesh can feature so called "silent boundaries" which provide a form of damping and thus a continuum constrain for the boundaries of the mesh, roughly equalling to an unlimited volume where waves are not reflected back.

2. VERIFICATION OF THE ANALYSIS

2.1. Drop-Test Specimen

In the frame of the AG15 Garteur group Politecnico di Milano performed series of drop-test with two different shaped specimens. One of the specimens was in a shape of a wedge and the second one was a semi-circular form.

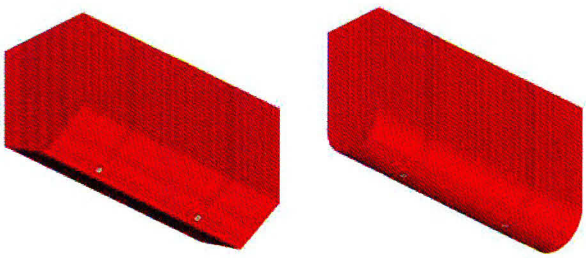

Figure 1 Wedge and Semi-Circular Specimen used by Politecnico di Milano[1]

Two drop heights were used, one from 1 m height and one from 3 m height. Specimens were equipped with one accelerometer and 6 to 8 pressure sensors.

2.2. Model Description

A series of simulations were carried out in order to define the necessary dimensions of the Euler mesh block, so that the results are not influenced by the wave reflections anymore. Trials were made with different element size in the impact zone. Additionally testing was made in order to see, how "aggressively" the mesh can be stretched outside the impact zone in order to minimize the total number of elements.

The specimens themselves were modelled as rigid bodies.

As mentioned, the fluid-structure interaction was modelled with TYPE 18 contact interface of Radioss. Mostly bi-phasic material law LAW37 was used for water and air model. Additionally, for the modelling of silent boundaries LAW6 and LAW11 materials were used. Trials were made using LAW51 as well, but it was found out that the modelling was very prone to errors.

The accelerations at c.g of the rigid body were recorded for comparison. The comparison with pressure sensors was obtained by defining separate TYPE 18 interfaces at the location of the sensors and recording the contact forces. The forces were then divided by the area of elements in order to obtain pressure.

2.3. Comparison of Results

A good correlation was obtained between the simulations and the drop test results. Particularly, the impacts with the higher velocity correlated well. Figure 2 show a comparison of acceleration during the impact between the simulation and the test for the wedge specimen. Figure 3 shows another comparison between pressure sensors from the drop test with the semi-circular specimen.

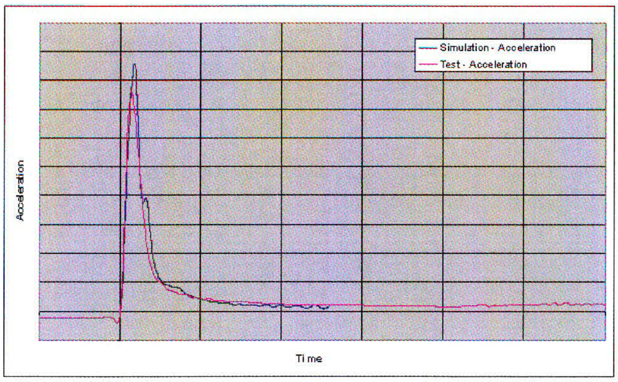

Figure 2 Comparison Test vs. Simulation, Acceleration of the Specimen after Impact

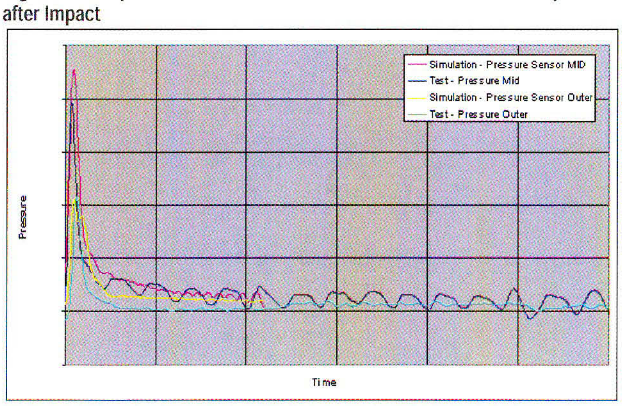

Figure 3 Comparison Test vs. Simulation, Pressure on Pressure Sensors of the Specimen after Impact

2.4. Modelling Guidelines

It was established that the most important parameters that influence the results are:

1) Element size in the water mesh
2) Water mesh size (overall dimensions)
3) Interface definition (stiffness factor and gap)

2.4.1. Element Size

It was noted that the element size always influenced the results, however it was established that there is a practicable lower limit which provides a balance between model size and accuracy. In this case the Euler element size was 15 mm, approximately 3% of the specimen width. Additionally it was noted that the small element size caused a notable reduction in time-step. This was not necessarily visible in initial time-step, but few milliseconds after the impact the drop in the time-step was more pronounced for small elements and at times analysis were making hardly any progress at all.

Additionally, it was later established that it is sufficient to use regular, good quality elements in the Euler mesh in the impact area (below the specimen), but outside this area the mesh can be stretched. It was noted that 10% increase from one element to another in lateral direction and 5% increase in vertical direction does not influence the results significantly.

2.4.2. Water Mesh Size

A somewhat unexpected result was obtained when the necessary size of the Euler mesh block was studied. It was found out that the deviations in vertical impact were gradually present when the Euler mesh was less than twice the size of the specimen, even the depth of the water was not as significant parameter as the width. Air part height was initially slightly higher than the specimen so that the specimen was fully inside the Eulerian mesh. The comparisons were mainly performed with a simplified 2D-model (Figure 4) using the wedge shaped specimen and larger impact velocity.

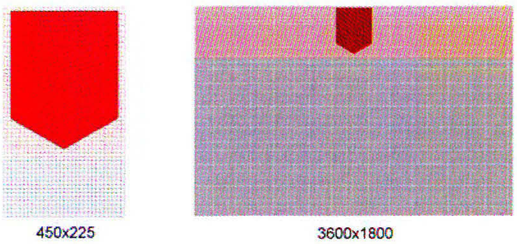

Figure 4 Smallest and Largest Mesh Size Comparison Models

The results from several size comparison analysis are shown in Figure 5.

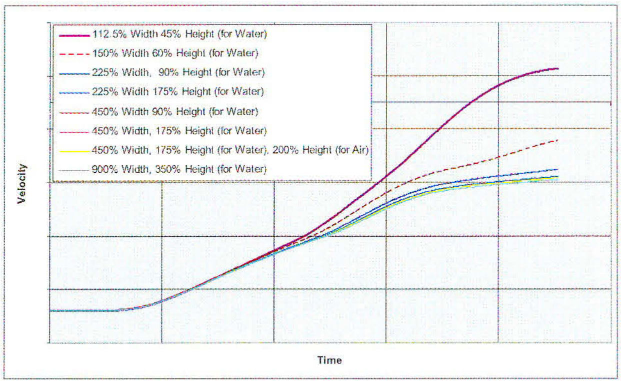

Figure 5 Comparison of Mesh Block Size Influence on Results

Here it was noted that mesh size has hardly any effect above 450% width and 90% height (in respect to specimen dimensions). Perhaps a more appropriate measure for the water height is the depth of the water. It was found out that the specimen sunk some 25-30% of water depth during the simulated impact. This relatively shallow water had no such an impact as the lateral width of the water. In all trials the air volume corresponded to the size of the specimen, thus enclosing the specimen completely into the Eulerian mesh at the beginning of the analysis. Only exception was the second last analysis where twice the size of air volume was used. This had no effect on results.

2.4.3. Interface Definition

It was established that the TYPE 18 interface has two significant parameters, the interface gap and the stiffness scale factor. It was found out that a good initial practise to use approximately factor 1.5 times the typical element edge length on impact area (either Euler or Lagrange element).

It is notable here that due to this fact the element size mentioned in chapter 2.4.1 has an influence on the gap definition and this way directly relates to the geometric accuracy of the model. Saying that the typical element size is 10% of the specimen width means that contact gap would influence material 15% on both sides of the specimen.

The second parameter stiffness scale factor of the interface is simply defined by equation:

$$STFAC = \frac{\rho \cdot v^2 \cdot A_{el}}{gap}$$

Here A_{el} is an area of a typical element in the impact zone, gap is the interface gap, v impact velocity and ρ is density of the fluid.

3. WATER IMPACT ANALYSIS WITH REAL STRUCTURE

After establishing modelling guidelines the next step was to apply analysis on a real structure. ECD performed NH90 centre fuselage drop-test on rigid ground 2002. As the model was available and verified structural model it was possible to exchange the impact surface from a rigid plate to an Eulerian water. The open question in this kind of impact is the energy absorbing effect provided by the water and the differences in structural behaviour during the impact. As the design is mainly dedicated to ground impact it was interesting to see how well it is able to cope with the different element – water.

The analyses were performed in three steps.

1) Actualized simulation of the real drop-test on rigid ground
2) Simulation of the rigid centre specimen
3) Simulation of the deformable centre fuselage on water

3.1. Centre Fuselage Impact on Rigid Ground

The model was derived from the old centre fuselage drop-test article (CTA) model. The impact conditions were taken from the real drop-test, level attitude and app. 3 m drop height.

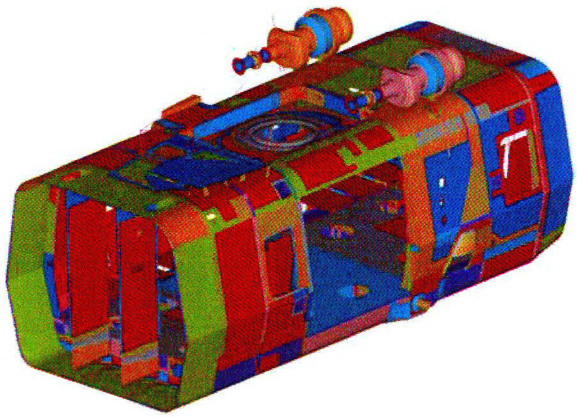

Figure 6 Centre Fuselage Model

The internal fuel was modelled with mass elements on the bottom-shell as it was considered too complex to later have internal fluid model, and perform a simulation with impact on water. Comparison of Main Gearbox (MGB) accelerations between the simulation and test is shown in Figure 7. The correlation between the test and the analysis in compared primary parameters is very good.

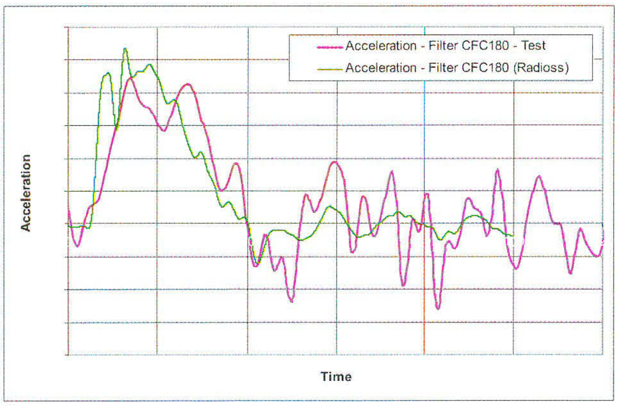

Figure 7 Comparison of MGB Accelerations, Radioss Simulation vs. Test

3.2. Verification of the Water Model with Rigid Fuselage Model

It was necessary to perform analyses verifying the modelling of the Eulerian water block once more. This was done using a rigid body model of the centre fuselage. The real challenge was to find a balance between model size and accuracy.

Initially, a model was already made before fully establishing general guidelines as mentioned in chapters 2.4.1, 2.4.2 and 2.4.3. This model (Figure 8) had a water app. 1.6 times the width of the centre fuselage and extended the same amount of distance to the front and rear of the fuselage. The depth of the water was only 20% of the whole fuselage, but on the other hand the similar to chapter 2.4.2 it was found out that the fuselage sunk 50% of the water depth in the simulation interval. Additionally, the air volume did not enclose the fuselage – on the other hand the surface used for interface definition did not form a closed volume and was only limited to the parts of the model that were actually inside the air volume. Additionally, the element size was 20 mm in impact zone, which is somewhat larger than used previously for the Garteur-simulations, however, here 20 mm is only app. 1% of the specimen width. Therefore, the model is not considered the best possible, but a relatively good compromise between size and accuracy. For the full 3D water model app. 2.1 million nodes were needed. The model did not feature silent boundaries with LAW11.

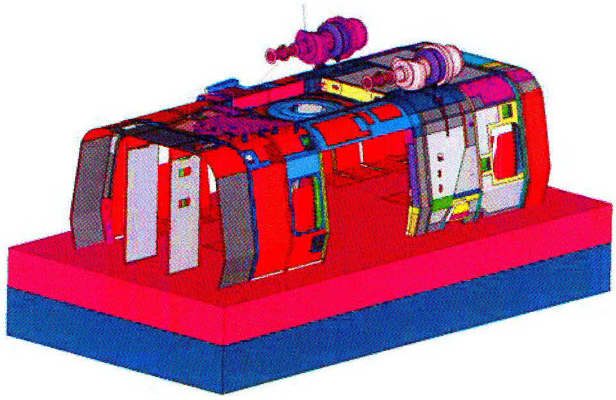

Figure 8 Initial Rigid Body Model for Water Impact Simulation (Model 1)

Second run was made with model that was app. 0.8 m larger than the bottom-shell in lateral directions and some 1.25 m deep using 15 mm element size in impact zone.

It was considered sufficient to treat the model as symmetrical around the XZ-plane and still use half the water model (See Figure 9). The element size used for the impact zone was 15 mm edge length and as a result the model had already 3.8 million nodes for the water alone. As the complete model is necessary to analyse with full 3D model without symmetrical boundary conditions it turned out that the resulting 7.6 million nodes for water does not provide a suitable balance between performance and accuracy. As a matter of fact with the available hardware it was not possible to execute the full 3D-model.

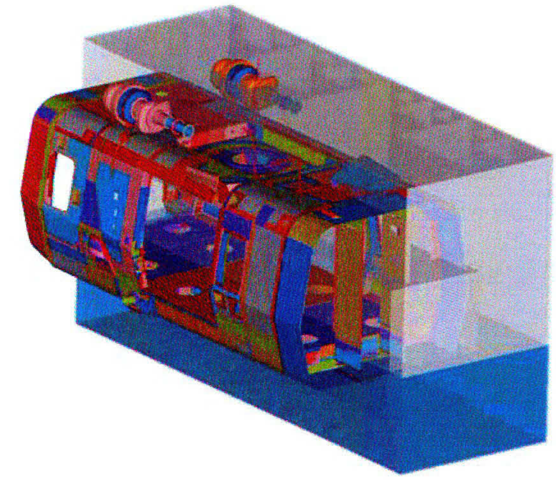

Figure 9 Rigid Centre Fuselage Model with Eulerian Water and Air (Model 2)

Third model was generated trying to reach a smaller number of nodes for following simulation with elastic model. For the initial size of elements on impact zone 20 mm was chosen, stretching and the size of the model size were similar to the finer model. A total number of 2.3 million nodes were needed for half model.

The used model dimensions are given in Table 1. Dimensions are given for width as if the model was reflected full 3D model for comparison.

Model	Length (mm)	Width (mm)	Depth (mm)	Number of Nodes
1	6835	3635	1108	2.1 M (full model)
2	6708	4520	1270	3.8 M (half model)
3	7073	4912	1413	2.3 M (half model)

Table 1 Dimensions of the Used Water Models

After the analysis was performed it was noticed that the simulation with Model 1 was performed with wrong RBODY c.g option and the outcome was a weight of 7.8t instead of the intended 6.4t. A trial was made to scale the accelerations with the mass difference in Figure 10. Generally the accelerations show a good correlation, confirming the feasibility of the coarser mesh. It is noteworthy that Model 1 (scaled) and Model 3 have a very close match, which can be directly due to same element size in the immediate impact zone or a result from same gap and STFAC in interface definition. Model 2 show marginally lower acceleration.

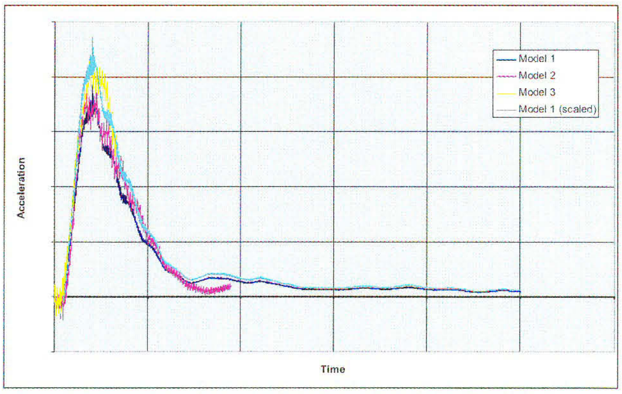

Figure 10 Comparison of Acceleration from Rigid Body Simulations

3.3. Water Impact with Elastic Model

As a final step the fully elastic structure model used in the simulation of the ground impact was taken and brought to impact with the verified water model. It was noted that the Model 2 could not be made to run due to the model size of 7.4 million nodes. The comparative run with Model 1 with elastic fuselage model was executed and currently the Model 3 is running.

Based on simulations with rigid fuselage with model 1, it can be expected that the results from model 3 do not significantly differ.

First comparisons have been made between the ground impact model and the water impact model. The comparison, particularly between the rigid body models and the elastic models is difficult due to the fact that elastic models provide information, such as mass point accelerations for each heavy mass, whereas in a rigid model this information is given only for c.g.

A trial was made to take a mass biased average of heavy mass items' velocity and acceleration and compare this with the rigid body accelerations. Another possibility is the momentum information from the analysis, but unfortunately the momentum of the water seems to be included in the output as well and the result the comparison is not accurate after some time after the impact.

Heavy mass items could be compared directly between the elastic model simulations, both on water and on rigid ground. Figure 11 show a comparison between Main Gearbox (MGB) and right side engine velocity over time for ground and water impact with elastic models. It can be seen that the ground impact velocity drop is initially much faster than in a water impact, indicating a harder impact and higher deceleration

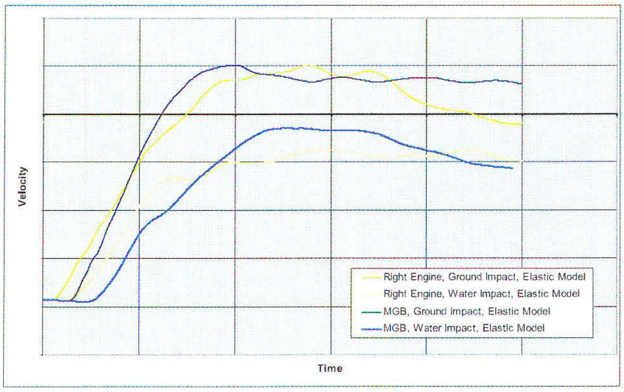

Figure 11 Comparison of Heavy Mass Item Velocity, Water Impact vs. Ground Impact

The accelerations are shown Figure 12 confirming the velocity plot, the accelerations are from peak value indeed almost 40% higher for the ground impact than the accelerations obtained for the water impact. The duration of the water impact is also significantly longer as it can be seen in the Figure 11, here the velocity has not reached zero (black line) for water impact for the duration of the simulation.

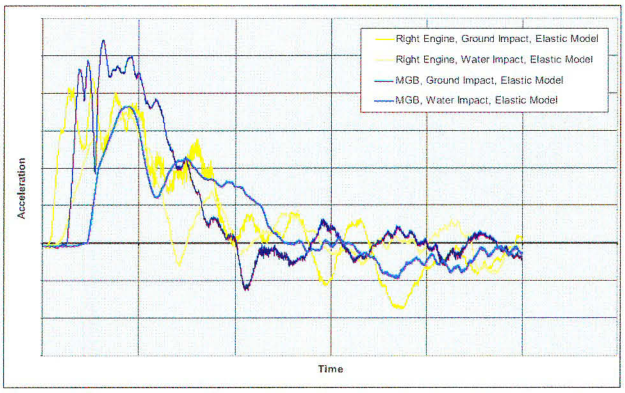

Figure 12 Comparison of Heavy Mass Item Acceleration, Water Impact vs. Ground Impact

Finally Figure 13 show a trial to compare a general c.g velocity for ground and water impact. Unfortunately the curves are not particularly accurate basis for comparison. As already mentioned the rigid model (Model 1, dotted curve) had wrong mass and therefore not fully comparable with the others. The calculation of the averaged velocity from the mass items for elastic model is also severely influenced by different local load limiters attached to the masses. For example, the passenger masses are located on a crashworthy seat model which deflects during the impact. This is largely the cause for the difference shown in the curve. The elastic model on water impact initially slows down less and later comes closer to the rigid model result again. The averaged velocities show similar tendency as Figure 11, the ground impact appears to be harder.

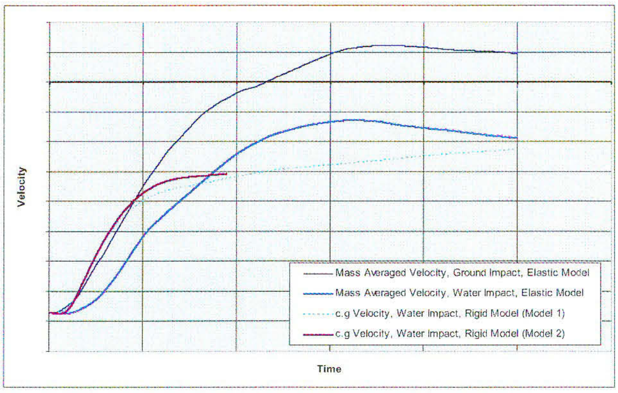

Figure 13 Comparison of Velocities for Ground and Water Impact

The structural reaction is also different between water and ground impact. First obvious difference is the strain on the fuselage bottom-shell caused by the pressure loads. Analysis indicate damaged layers (Figure 14), but rupturing is not detected. Partially, this could be an actual benefit of having the fuel weight resting on the bottom-shell directly, countering the bulging caused by the water pressure. This is also confirmed by more damage indications in the fuselage rear part (to the right on the picture), here the last tank compartment is empty. A second positive factor is the bending stiffness of a honeycomb sandwich skin in comparison to conventional sheet metal skin.

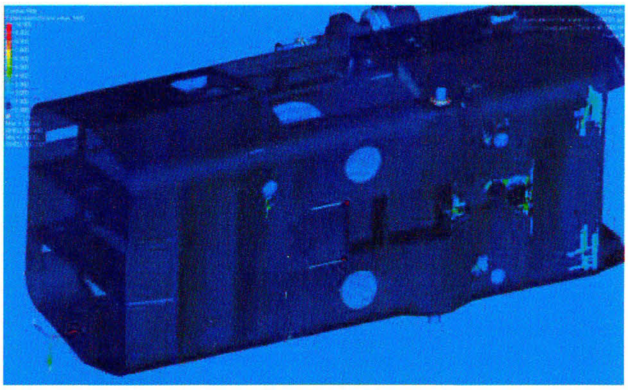

Figure 14 Damaged Composite Layers on Centre Fuselage Bottom-Shell, Water Impact Simulation

Another difference is the loading of the primary structure and cabin integrity. Whereas, the ground impact causes significant strains on fuselage sections, the strains are only moderate during the water impact. This is shown in comparison in Figure 15, the chosen fuselage section (Section #8) is one supporting the MGB and engine weight. The pictures are generated at different moments of time featuring the peak loading. It can be seen that during the water impact the sides of the frames hardly show green yellow colour, which indicate more than 3 ‰ difference. The energy absorbing subfloor area is not crushed in water impact, whereas the middle of the frame is damaged due to bending from water pressure. Generally, the damage above the helicopter floor level is not taking place during the water impact.

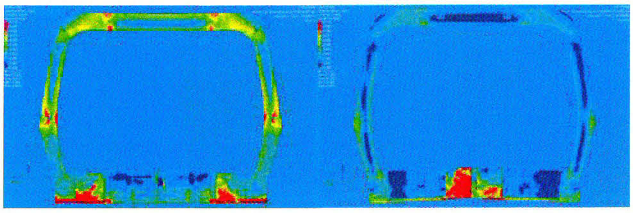

Figure 15 Strains on Fuselage Section #8 during Impact, Ground Impact Left, Water Impact Right

4. CONCLUSIONS

A study was made verifying analytical means of simulating a water impact with explicit simulation code Radioss. The chosen method applied Eulerian elements for modelling the water and conventional Lagrangian elements for structure. The fluid-structure interaction was accomplished with TYPE 18 contact interface.

It was found out that modelling the water is significantly influenced by the element size in the impact zone and the definition of the TYPE 18 interface. The elements can be stretched outside the immediate impact zone without influencing the results too much. An overly large water "pool" is not necessary, which is a unexpected result, as well as the fact that lateral size has more influence than the actual depth of the water. It is necessary to include sufficient air volume above the water, but it was already noted that the used analysis models can be still reduced in this regard. The analyses are a compromise between computing performance and accuracy, limitation being in computing performance at the moment. At the moment the analysis could be performed in 2xDual Core Opteron CPUs, with better hardware the parallelisation capability and good scalability of Radioss better results can be obtained.

As first result after simulating real helicopter structure it was found out that the impact on rigid ground seems to be more demanding for structural integrity and heavy mass retention as the impact on water. This is also supported by helicopter accident statistics. Even the rigid NH90 centre fuselage, featuring a large flat surface, produced an intermediate acceleration peak of around 40 g as maximum. This is largely covered by static load factors used in the dimensioning of the primary structure. It is also an indicator that more could be achieved in terms of crashworthiness by studying a more optimized shape that produces even smaller acceleration peaks rather than concentrating in structural solutions to provide energy absorption in sub-floor impact zone during the water crash. Existing measures such as crashworthy seats already provide significant improvement in terms of passenger safety in acceleration environment.

5. ACKNOWLEDGEMENTS

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