29th Congress of the International Council
of the Aeronautical Sciences
St. Petersburg, Russia; September 7-12, 2014

MULTI-TERRAIN IMPACT SIMULATIONS OF A CRASHWORTHY COMPOSITE HELICOPTER SUBFLOOR

Thomas BILLAC*, Matthew DAVID, Mark BATTLEY***,**
Rodney THOMSON**, Christof KINDERVATER**, Raj DAS*,**

***The University of Auckland, Department of Mechanical Engineering,**
****German Aerospace Center, Institute of Structures and Design,**
*****Centre for Advanced Composite Materials, The University of Auckland,**
******Advanced Composite Structures Australia, CRC-ACS**

Keywords: *Crashworthiness, Composites, Fluid-Structure Interaction, SPH, Helicopter*

Abstract

Helicopters typically operate over a large variety of terrains, which justifies the development of crashworthy structures that can perform efficiently in most impact environments. Numerical simulation tools offer significant potential for reduction in development costs and time; however it is necessary to validate modelling approaches, particularly for complex loading scenarios such as multi-terrain impact.

The present work firstly investigated the suitability of the most commonly used equations of state to numerically model water with explicit Finite Element (FE) and Smoothed Particle Hydrodynamics (SPH) methods. From a simple benchmark case, numerical results indicated that the Smoothed Particle Hydrodynamics method together with the Murnaghan equation of state provide the best compromise between accuracy and efficiency in predicting the dynamics of a structure impacting onto water. The coupled FE/SPH modelling approach also showed superior accuracy to the more common Finite Element method in representing a soft ground like soil but appeared to be more sensitive to frictional effects.

Finally, the design of a crashworthy composite subfloor using trapezoidal energy absorbing elements is presented. The previously validated modelling approach was applied and demonstrated the good crashworthy potential of the structure in impact situations over different surfaces.

1 Introduction

Locations over which helicopters operate are not only limited to cleared hard grounds. One of rotorcrafts great advantages over other transportation vehicles lies in their ability to reach locations that present difficult land access and/or challenging terrains, such as rocky ground, soil or water. Hard landings or crashes can be caused by unfavourable flight conditions or mechanical failures. According to accident statistics, up to 80% of civil and military aircraft crashes happened on soft soil and water [1], highlighting the importance of designing multi-terrain crashworthy structures [2]. However, crashworthy helicopter subfloors are traditionally designed to be effective in hard ground impact scenarios and may not offer equivalent crashworthy performance on soft surfaces [3].

Through the use of reliable numerical tools with specific modelling guidelines, the behaviour of aircraft structures in different crash scenarios can be predicted and optimized. Nevertheless, modelling liquids or soft surfaces, such as water and soil, demands methods with the capability to capture the complex physical phenomenon involved [4]. Mesh based and meshless numerical methods provide the ability to handle complex Fluid-Structure Interaction (FSI) problems during impact [5-7]. Although more computationally expensive, SPH is very suitable for solving free-surface fluids interacting with deformable structures [8] and has been used on helicopter subfloors [9, 10].

Modelling water or soft surfaces such as soil requires a good understanding of the material constitutive laws that can best replicate the actual mechanical properties. To date, the most commonly used equations of state (EOS) for water in structural analysis commercial packages are the Gruneisen EOS [11, 12], the isotropic linear elastic hydrodynamic law, as described in [13], and the Murnaghan EOS [14].

In the case of soil modelling, NASA demonstrated that it can be represented using a material model that simulates the crushing through the volumetric deformations [15] and material constants which were obtained experimentally.

The present work firstly reviews the suitability of these EOS to model fluids such as water in the range of impact velocities specified by the aircraft design requirements [16]. Three numerical methods are assessed to model water. The FE method, using 8-node Lagrangian solids is first evaluated as it showed good efficiency and accuracy during the first instants of impact of a metallic helicopter subfloor onto water [17]. The second mesh based approach tested to model the fluid is the multi-material Arbitrary Lagrangian-Eulerian method (ALE). The last approach considered to model the fluid is the SPH method, which is a meshless Lagrangian approach. Lagrangian methods can be coupled together [18], reducing computational costs induced by the meshless one. The numerical analysis of a rigid sphere impacting onto water is carried out to compare the different numerical approaches and EOS, focusing on the accuracy of the results and the efficiency of the solutions.

A similar test case is then considered to investigate the potential of the combined FE/SPH approach to treat impacts on soil, extending the work conducted by NASA on soil impact of the ORION space capsule [19, 20].

Following validation of the modelling approach, it was then used as a predictive tool to understand the mechanical response of a crashworthy composite subfloor in impacts onto varied surfaces. The energy absorbing strategy is based on a previous design [21] developed for hard ground impacts. The structure is designed to achieve good energy absorbing potential and controlled crushing in scenarios involving different types of impact surfaces. The paper describes the subfloor design and the predicted energy absorbing performances using the previously validated modelling strategies.

2 Modelling water and soil for impact simulations

2.1 Water modelling

In numerical analysis, the modelling of fluids such as water is made through the use of an EOS that relates any change in volume or density to a certain change in pressure. FEA commercial packages offer a limited choice of models to represent fluid behaviour, and these were often initially developed to treat high energy impact or ballistic problems in solids. The most commonly used equations of state to model water are the Gruneisen EOS, the Isotropic Elastic Plastic Hydrodynamic law, also called linear polynomial EOS, and the Murnaghan EOS. The latter one was initially developed to treat shocks in fluids and appear to be the most suitable to ditching problems. The equation uses an adjustable bulk coefficient that makes the EOS more versatile and capable to cover a wider range of applications. From previous work [22], the authors observed that the two other EOS analytically overestimate the true bulk properties of the fluid.

The simple benchmark case of a rigid sphere vertically impacting onto the water surface [13] was considered to assess the accuracy of these EOS. Various numerical methods were also considered in order to evaluate their efficiency in solving the first 15 ms of the event. Three different approaches were considered to represent the water domain. First it was modelled with Lagrangian solid elements (FE). The SPH method was then employed in a second model, whereas the third one used the ALE method.

The sphere had a diameter of 218 mm, weighed 3.76 kg and was given an initial velocity of 11.8 m/s. Numerical results were compared to experimental data given in [23]. Accelerations were recorded at the centre of gravity of the sphere and a CFC 600 filter was applied. The sphere velocity during impact could then be derived (Fig. 1).

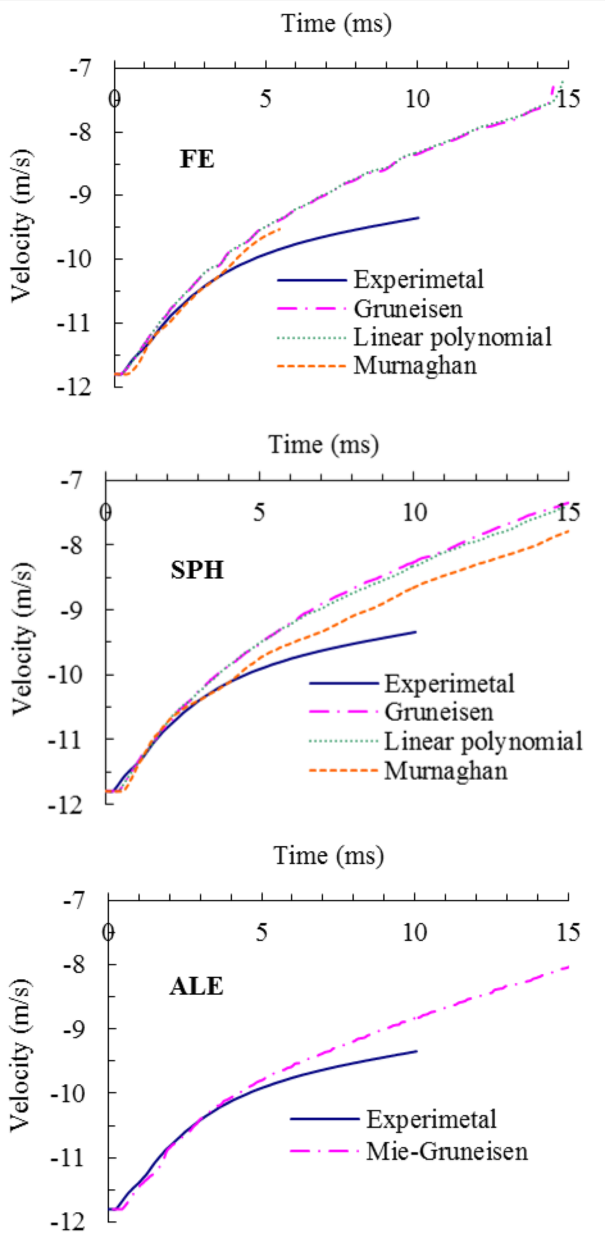

Fig. 1. Velocities of the sphere during water entry for various EOS and numerical methods

From the simulation results, the Gruneisen and Linear Polynomial EOS provide close responses to each other regardless of the numerical method employed. The Murnaghan EOS gives the most accurate response with both FE and SPH methods. Only the Gruneisen EOS was tested with ALE and resulted in an equivalent level of accuracy to the SPH method with the Murnaghan EOS. Due to large mesh distortions, the simulations with the FE method led to early terminations with the latter EOS. In terms of computational efficiency, the SPH method together with the Murnaghan EOS provides the best results. More details on this investigation of the different EOS and numerical methods for water modelling can be found in [22].

2.2 Soil modelling

Soil is a very complex material to model, especially because of its high sensitivity to environmental conditions. Therefore, for each application, the type of soil considered needs to be precisely characterized. NASA carried out an investigation on the type of soil found in the area around the Kennedy Space Centre in Florida and the material constants for MAT5 in LS-DYNA were derived [15]. Penetrometer tests were performed to validate the numerical modelling of the soft surface by comparing predictions of the accelerations of the rigid body (penetrometer) during impact and comparing them with experimental results [19]. Some variations could be observed in the experimental results, highlighting the inhomogeneity of the material. From the numerical simulation, using Lagrangian solids to represent the soil domain, the penetrometer acceleration was higher than the experimental data. The aim of this section is to assess whether the Lagrangian meshless method SPH could provide significant improvements to the predictions. The sensitivity of the penetrometer deceleration to the friction coefficient is also briefly investigated.

The test case presented in [19] is reproduced in LS-DYNA (version: ls971s R6.0.0) using the FE/SPH coupled approach to model the soil. Particles are used in the impact area whereas the domain is extended using Lagrangian solids. Convergence studies were carried out on the particle spacing and size of the SPH domain [22]. A friction coefficient μ was introduced in the contact between the penetrometer and the soil with a value set to 0.45, as experimentally measured in [19].

A comparison of the calculated penetrometer accelerations with either the FE or FE/SPH approaches and the effect of implementing friction in the model is presented on Figure. 2.

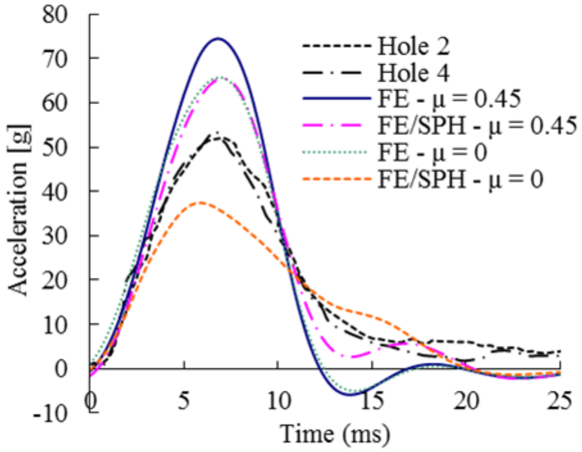

Fig. 2. Accelerations of the penetrometer during soft soil impact (Exp. vs. FE vs. SPH). Influence of the friction coefficient. Hole 2 and Hole 4 are experimental results.

When friction is activated, the prediction from FE model is consistent with the results presented in [19] and overestimates by 41% the maximum acceleration measured experimentally. The coupled FE/SPH approach provides a better correlation with a peak acceleration estimated at 65 g, which is only 24% greater than the experimental data.

Using the SPH method in the calculation has some consequences in terms of computational costs. The calculation of the first 40 ms of impact with the coupled approach was completed in 824 s using a single 3.33 GHz CPU, whereas it took 808 s with the FE model. The 2% increase in computational time is then insignificant considering the gain in accuracy brought by the use of the SPH method. Since the soil does not show extreme deformation and projection during impact in this test case, the impact area represented with particles could be reduced significantly without affecting the results accuracy as opposed to the modelling of a fluid such as water that requires a larger SPH domain to be able to reproduce the “splash” during impact.

A second series of simulations was carried out in which friction was not considered in the models. The maximum acceleration during impact is predicted to be 66 g, which corresponds to a reduction of 12% from the calculation with friction. The difference is much more significant when the SPH method is used as the drop in predicted maximum acceleration is of 43%. The meshless method is significantly more sensitive to the friction coefficient than the FE method. Accurate determination of the friction coefficient is therefore necessary to ensure the most accurate results possible if this modelling technique is employed.

3 Multi-terrain impact simulations of a crashworthy composite helicopter subfloor

3.1 Subfloor design

From a previous joint project between the German Aerospace Center (DLR) and the Australian Cooperative Research Centre for Advanced Composite Structures (CRC-ACS) a crashworthy composite frame for helicopters was developed [21]. The frame structure consisted of an upper non-crushing portion, a lower sacrificial energy absorbing portion, and a skin. Trapezoidal energy absorbing elements were utilized in the energy absorbing portion of the structure. The concept was tested both quasi-statically and dynamically using the DLR facilities and demonstrated good energy absorption capability in hard ground impact.

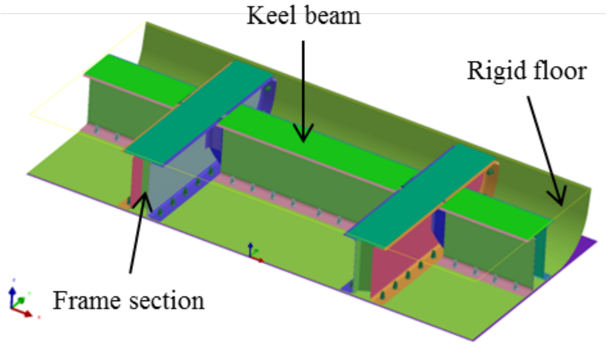

Fig. 3. Crashworthy helicopter composite subfloor concept

Based on this concept and using the same material system (woven carbon-fibre epoxy pre-preg fabric), a helicopter subfloor was designed consisting of two frame sections and one keel beam section (Fig. 3).

Figure 4 shows the energy absorbing elements contained between the frames. The dimensions of the specimens were chosen to fit into the test facilities presented at the end of the paper.

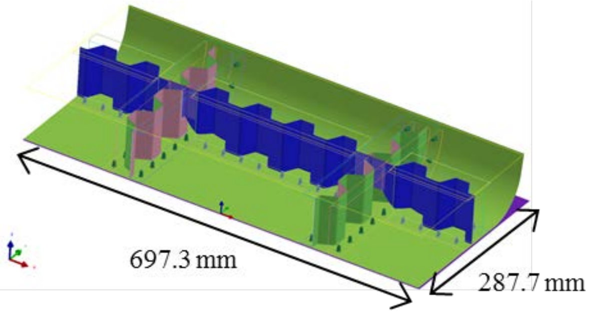

Fig. 4. Crashworthy helicopter composite subfloor concept (frames hidden)

Two types of intersection between the trapezoidal elements constituting the frames and the keel beam were considered (Fig. 5) as it is a key point in the structure in terms of failure mechanism and energy absorption. The first solution considered consisted in having a slot cut in the frames into which the keel beam slides down into. Reinforcement of the intersection was made by bonding additional brackets in each corner. Crushing of the energy absorbing elements is initiated from the bottom using a rounded corner at the intersection with the frame and keel beam. The alternative solution was to split the different beams and frames into several sections and join them together using bonded brackets. The first concept was adopted since it presented the advantage to be much simpler in terms of manufacturing and assembly operations.

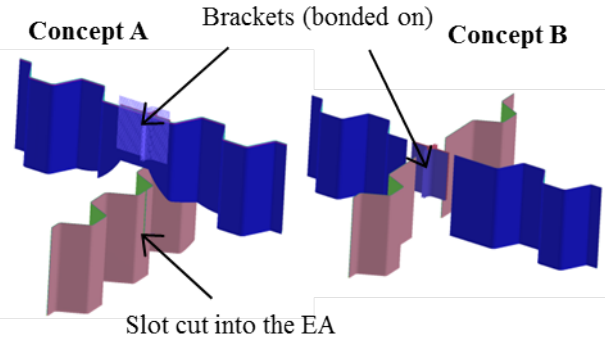

Fig. 5. Frame intersections concepts

Preliminary impact simulations on hard ground also showed better crushing performance from the first option (Fig. 6). The intersection of type A lead to a peak force of 91.17 kN, whereas type B resulted in a undesirable 15% increase in the peak force. Both intersection types considered could absorb the same amount of total impact energy of approximately 1.5 kJ.

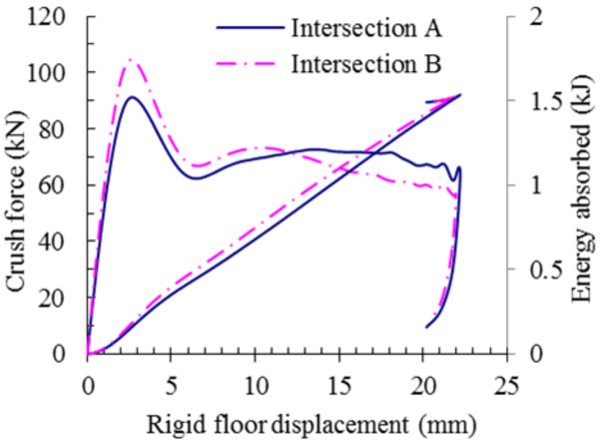

Fig. 6. Crush performance of the composite subfloor on hard ground for two types of intersections

3.2 Modelling Approach

The procedure undertaken consisted of firstly, the numerical modelling of damage development in the composite laminate. From the experimental crush tests of EA elements [24], the critical influence of both ply damage and delamination in controlling failure mode and energy absorption was identified and hence subsequently included in the numerical models. As an efficient way of modelling delamination failure in a composite laminate, the meso-scale composite damage model [25] was extended to stacked shells to allow interface delamination failures. In this stacked shell approach, the composite laminate is represented by multi-layered shell elements connected by cohesive interfaces [25], which are damaged and fail when the prescribed interface fracture energy is reached.

Numerical simulations were carried out with PAM-CRASH (v2009.0) to assess the impact performance of the composite subfloor in impact situations on hard ground, soil and water (Fig. 7). In all cases, an initial vertical velocity of 8 m/s was applied to the composite subfloor that impacts the ground or fluid in a perfectly flat fashion.

A rigid floor (displayed on figures as wireframe) entirely covered the subfloor and a mass of 120 kg was applied through this interface. The added mass was representative of the seat and occupant weight located above the subfloor section in an actual operating configuration. The half-subfloor itself weighs about 1.45 kg.

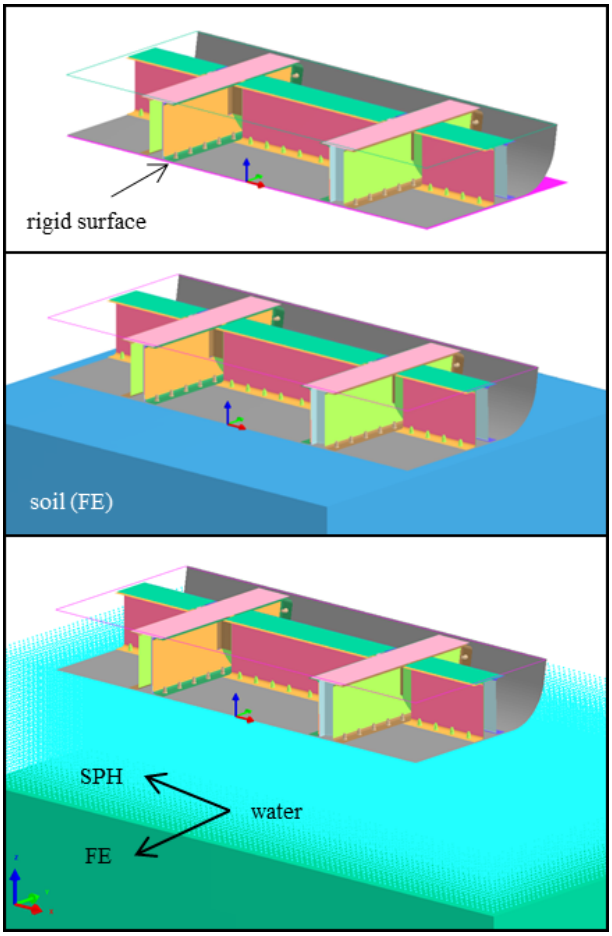

Fig. 7. Numerical models for impact simulations of a helicopter composite surfloor on varied surfaces

Modelling the impact surface for the hard ground impact case was carried out by representing a rigid plate onto which the subfloor is dropped.

The soil was modelled using the Lagrangian FE method as the SPH solver in PAM-CRASH (v2012.0) combined with MAT 2 did not provide satisfactory capability to represent the soil behavior. The soil domain constituted 11760 solid elements with a regular mesh size of 25 mm.

The FE/SPH coupled approach [18] was employed to represent the water domain, applying the Murnaghan EOS to replicate the fluid behaviour. The meshless subdomain was 200 mm deep, containing 104000 particles with a 10 mm spacing between them. The fluid domain was extended by 1300 mm using solid elements. The two sub-domains were connected using a tied interface.

3.3 Results from predictive impact simulations on varied terrains

The first 15 ms of the impact were simulated using 6 x 2.53 GHz CPUs. It took about 18.9 hours to complete the hard ground impact simulation whereas the computation time for the water impact calculation was 58.5 hours. The soil impact simulation took 19.1 hours using similar resources.

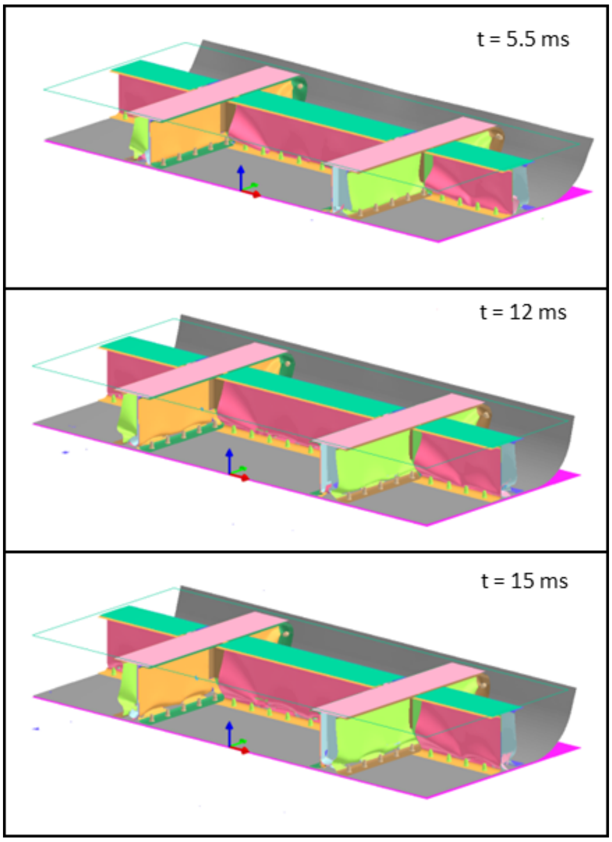

Fig. 8. Impact simulation of a helicopter composite subfloor on hard ground

As expected, a uniform crushing of the energy absorbing elements is achieved on hard ground (Fig. 8).

The impact simulation on soil (Fig. 9) shows significant deformations of the belly skin panel but a stable crushing behavior is obtained with progressive failure of the trapezoidal EA elements. Buckling of the beams faces is also reduced due to the lower crushing force during impact.

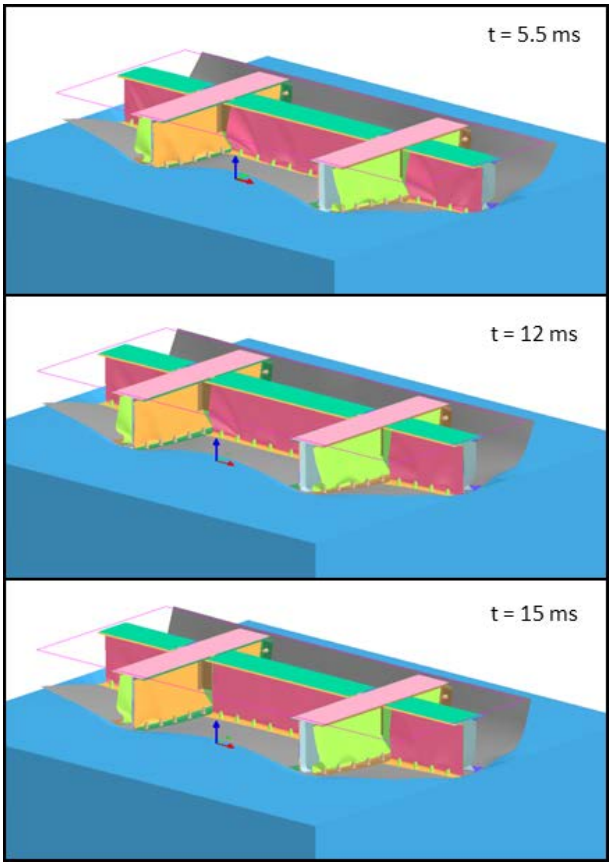

Fig. 9. Impact simulation of a helicopter composite subfloor on soil

Finally, from the water impact simulation of the subfloor, much larger deformation of the skin panel is observed, initiating crushing of the EA elements in the lower corners located on the subfloor centreline (Fig. 10). Despite the large deformation, no fracture of the belly skin is observed, which prevents water inrush through the structure.

Overall, impact simulations of the composite subfloor developed with DLR predicted a well-controlled impact behavior on all surfaces.

Vertical accelerations were recorded at a mass point located above the rigid floor. A CFC600 filtered was applied to the calculated accelerations presented on Figure 11.

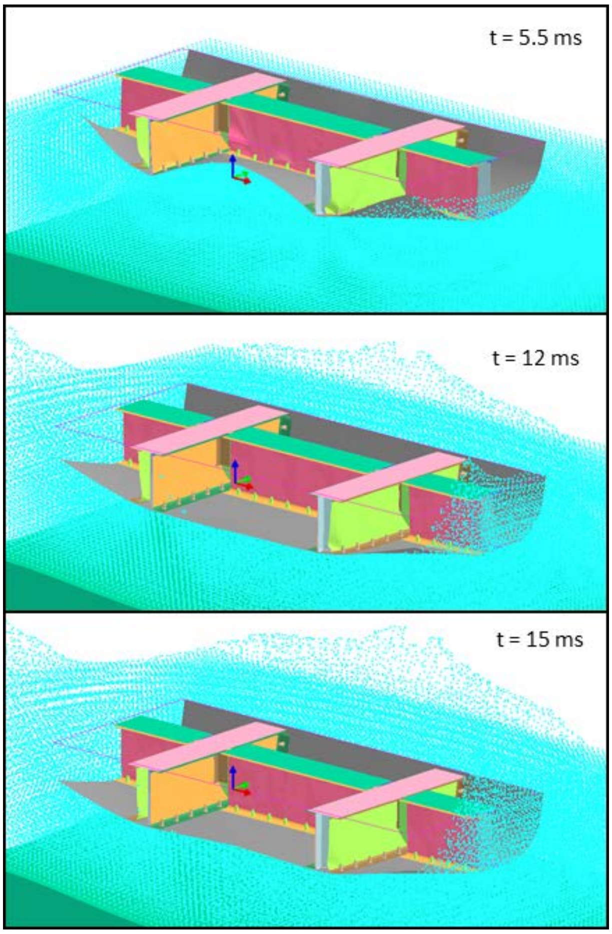

Fig. 10. Impact simulation of a helicopter composite subfloor on water using the coupled FE/SPH modelling technique

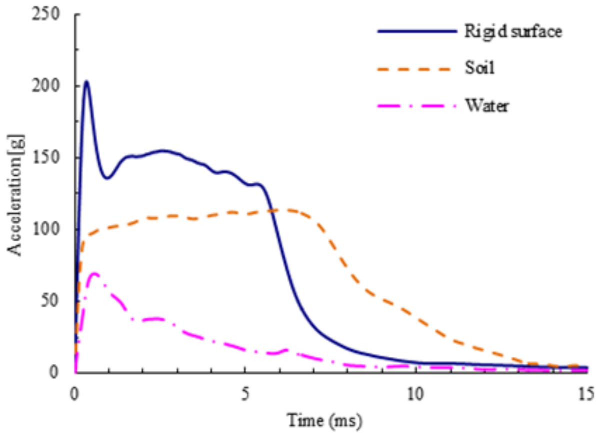

Fig. 11. Predictions of the subfloor accelerations during impact on different surfaces

The hard ground impact simulation predicted a maximum peak acceleration of 203 g. After the peak, a plateau is observed with an acceleration comprised between 125 and 150 g during 5 ms. In soil impact, no peak deceleration is observed. Instead, the calculation predicts a 7 ms constant deceleration of about 110 g before the structure finishes crushing. Finally, the calculated acceleration from the water impact simulation shows a peak of 69.4 g before progressively dropping towards zero. In impact on the soft surfaces, a significant amount of impact energy is absorbed by deformation of the fluid/soft material itself.

Experimental tests should confirm the crashworthiness capability of the design and support the predictions obtained through numerical simulations. Even though testing is still to be conducted with the composite subfloor, the predicted reduction of the average accelerations, moving from hard ground to water, agrees with the results presented in [2].

3.4 Test facilities for impact tests on varied surfaces

The subfloor is to be manufactured and tested on the different impact surfaces using the facilities at DLR BT (Stuttgart, Germany) and The University of Auckland (New Zealand).

Tests on both hard ground and soil will be carried out using the drop tower at the German Aerospace Centre as for the previous CRC-ACS project (Fig. 12).

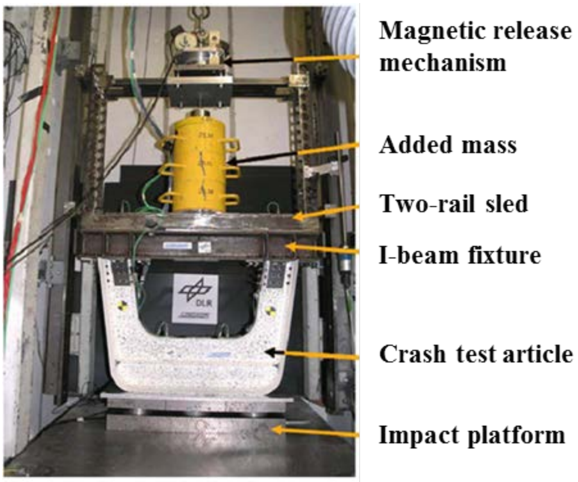

Fig. 12. Drop tower at DLR BT and testing setup on previous CRC-ACS project [21]

The water impact test is to be conducted using the Servo-Hydraulic Slam Testing System at The University of Auckland (Fig. 13).

Initially developed to study slamming loads on marine structures [26], the test rig can be used to conduct controlled water impact experiments for a wider range of test articles, including the scaled composite helicopter subfloor. A custom made specimen fixture is used to attach it to the moving part of the rig.

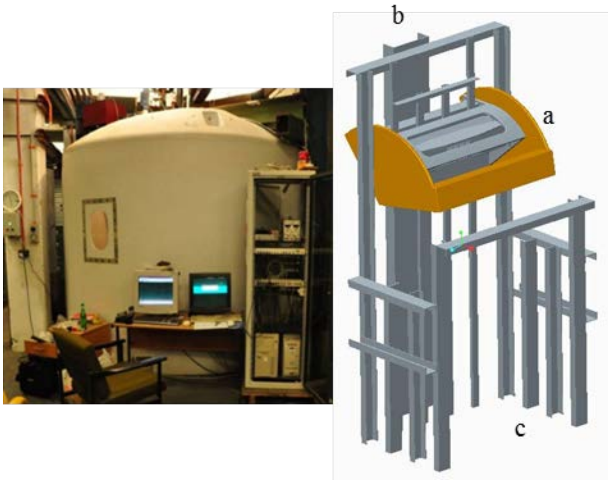

Fig. 13. Water tank (left) and schematic of the components inside the SSTS (right): a-Specimen fixture, b-Linear bearings and tracks, c-Aluminium support frame

The slamming facility can carry out impact tests up to 9 m/s, although it is typically used in the 1-7 m/s range. In its current configuration, deadrise angles from 0° to 40° are available. A maximum impact load of 80 kN needs to be respected during impact. In order to fit into the available space, articles should not be larger than 1000 x 600 mm. During the test, loads, strains, displacements and pressures can be recorded.

4 Conclusions

Because of the wide range of terrains over which helicopters operate, there is a need to develop designs with crashworthy capabilities not only in hard ground impact but also in soil and water impact situations.

Reliable predictive tools are important elements of the product development process. Advanced numerical methods have the capability to capture complex physical phenomena such as those involved in impact of a deformable structure onto soft ground or a fluid. Numerical methods including the Lagrangian mesh based method, the ALE method and a coupled Lagrangian FE/SPH approach were evaluated with a simple benchmark case of a rigid sphere before being applied to impact simulations of a crashworthy composite helicopter subfloor on varied terrains.

In the case of water modelling, the SPH method together with the Murnaghan EOS as the fluid's constitutive equation offers the best compromise between accuracy and efficiency to capture the dynamics of the rigid sphere during impact. The adjustable bulk coefficient in this EOS makes the model versatile, being able to cover a wide range of applications. The Gruneisen and Linear Polynomial EOS provide similar results to one another, regardless of the numerical method employed, overestimating the pressures inside the fluid elements and resulting in higher forces applied to the interacting object during impact.

Representing soil mechanical behaviour in numerical models is complex. Each application requires various characterization tests to be conducted to derive the material constants to input in the constitutive laws. Using the SPH method to represent the impact area of the soil domain demonstrated better accuracy over the Lagrangian FE method with only a slight increase in computational time.

A complete composite subfloor was developed from a previously validated concept for energy absorption in vertical crash. The modelling techniques investigated earlier on simpler test case were applied to predict the response of the subfloor in vertical impact on hard ground, soil and water. The subfloor showed different mechanical responses in each situation. The impact energy on hard ground could be efficiently absorbed by the energy absorbing elements in a very controlled way. Moving from hard ground to soil and water impact situations, the belly skin showed increasing deformations but no failure. As expected, only reduced and localized crushing was observed in the energy absorbing zone in those two cases. The different responses of the structure for each terrain highlight the necessity to take these effects into account in the design process to increase occupant's chances of survivability.

Upcoming experimental tests using the drop tower at DLR BT and the slam testing facility at The University of Auckland should enable the validation of the modelling approach adopted and provide guidance for the development of multi-terrain crashworthy helicopter structures.

Acknowledgements

This work was undertaken as part of a CRC-ACS research program, established and supported under the Australian Government's Cooperative Research Centers Program, in collaboration with the German Aerospace Center (DLR), Institute of Structures and Design. The authors wish to acknowledge the contribution of Pacific ESI colleagues, Mr D. McGuckin, Mr A. Chhor and Mr B. Cartwright. Gratefully acknowledged is the ongoing support of this work by ESI Group and in particular Dr A. Kamoulakos and Dr T. Kisielewicz.

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Contact Authors Email Addresses

Thomas BILLAC, The University of Auckland, Department of Mechanical Engineering, Auckland, New Zealand.
mailto: tbil708@aucklanduni.ac.nz

Matthew DAVID, German Aerospace Centre, Institute of Design and Structures, Stuttgart, Germany.
mailto: matthew.david@dlr.de

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