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A multi physical digital representation of the space capsule splashdown event in the Simcenter environment to accelerate analysis of impact condition, structural design and human body loading

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Abstract

The landing of a re-entering space craft into the water, the capsule splashdown, is a key critical physical loading condition for the astronauts during a space mission. A multi physical digital representation of the load case within the Simcenter environment is presented that allowed a fast evaluations of impact parameters like speed, impact angle, sea state and their effects on the loadings of the astronaut's body and the capsule structure.

The methodology combined cutting edge simulation technologies of three different engineering streams: CFD, structural and occupant simulations. Previous publications [1,2] on free fall lifeboats had shown the value of the simulation methods in a similar kind of loading case that now had been enhanced and used to assess safety in the capsule splashdown.

1. Introduction

The landing of a re-entering space craft into the water, the capsule splashdown, is a key critical physical loading condition for the astronauts in a space mission. A consideration is that these loads will hit astronauts whose bodies are weakened due to the long stay in space. Furthermore, the splash causes high pressures and acceleration loads on the structure. As capsules are developed to be reused multiple times, this splash loads should not cause permanent deformations. Other important structural aspects are the integrity of the outer shell, avoid water entering the cabin and secure the opening of the exit door for a quick evacuation. Now that private companies are pushing to bring the space travel hurdle down for the space tourism exploitation, the safety of the re-entering capsules deserves some more attention and can benefit from technology advances made in other industries.

The space capsule splash is still a special case. Never, the less the more common case of the free-fall lifeboats is similar and previous research on this case resulted in methods that should be also applicable to Space capsule splash. Within the Norwegian standard for free-fall lifeboats the DNV-ST-E406 [3] criteria are defined for the occupants.

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Body part	*Human load measure*	*Requirement for characteristic value of human load measure*	*Explanation*
Abdomen, thorax and thoracic spine	T12_3ms (acceleration resultant)	60*g*	
	T12_x (x acceleration)	60*g*	x acceleration of lowest vertebra in thoracic spine
	T12_y (y acceleration)	20*g*	y acceleration of lowest vertebra in thoracic spine
	T12 Fz_c	6700 N	Compression force in lowest vertebrae thoracic spine
	Lap belt force	4000 N	Per belt, assuming two belts and equal forces in left belt and right belt. Requirement is only applicable in case of bad pelvis engagement, where lap belt penetrates abdomen.
Head	HIC_{36}	650	
	Rotational accelerations a_x, a_y, a_z	2500 rad/s^2 1800 rad/s^2	if $\Delta\omega < 30$ rad/s if $\Delta\omega > 30$ rad/s
Neck	NFx_a	788 N	Neck shear force, anterior
	NFx_p	733 N	Neck shear force, posterior
	NFy	900 N	Upper neck lateral shear force
	NFz_c	−1500 N	Upper neck axial compressive force
	NFz_t	1500 N	Upper neck axial tensile force
	NMx	62 Nm	Lateral bending moment
	NMy_e	−73 Nm	Upper neck extension moment
	NMy_f	190 Nm	Upper neck flexion moment
	Nkm	1.1	Rear impact, whiplash motion
Femur	Femur compressive force	3800 N	
Chest	Frontal viscous criterion	0.25 m/s	
	Frontal compression	22 mm	

Table 1: Injury criteria as defined in the DNV-ST-E406 **[3]**

Most space systems are very complex and expensive by nature. They include advanced materials and combine a multitude of physics. Consider highly controlled propulsion systems, for example, or robotic systems with built-in artificial intelligence. There are so many parameters involved in the development of those that engineers need a digital twin to even come close to success. At the heart of this digital twin are realistic, prediction-capable simulation models to optimize all system aspects simultaneously, from the beginning of the design cycle. A digital representation of the load case is necessary to assess development variants and maximize the safety with respect to the other design criteria like weight and size. A complete representation requires multi-physical approach to model the fluid dynamics of the splash, structural stresses and human body dynamics.

The Xcelerator™ portfolio from Siemens Digital Industries Software is an orchestrator for any space program. Xcelerator is a comprehensive and integrated portfolio of software, services and an application development platform that speeds digital transformation.

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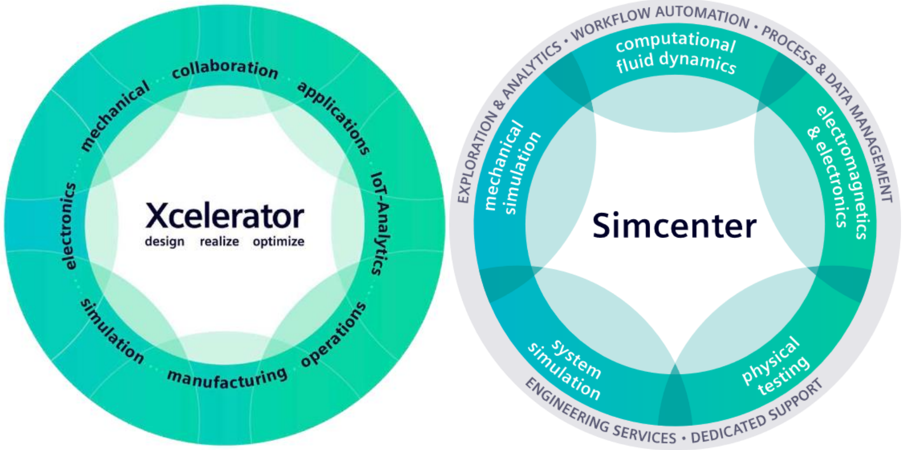

Figure 8: Siemens' Xcelerator portfolio and Simcenter performance engineering solutions

The Simcenter solutions portfolio within Xcelerator, the Simcenter™ solutions portfolio for the digital twin focuses on all the engineering aspects required during space system design and development. Simcenter uniquely integrates multiphysics system simulation, 3D CAE (structures, thermal, fluid dynamics, electromagnetics) and physical testing, and combines this with design exploration and data analytics, all in one environment. It is an open, scalable and flexible engineering platform that helps space agencies and businesses accurately predict all product performance aspects, optimize designs and deliver innovations faster and with greater confidence. All the technology that is needed for simulating the splash load case are integrated in Simcenter portfolio.

A crash or sled test is a common approach to measure occupant loadings or injury in high acceleration loading conditions. These tests use normally Anthropomorphic Test Devices (ATDs), also called crash test dummies. The ATDs will measure physical loadings like neck forces, femur forces, head accelerations or chest compression. From this data various injury values can be calculated. Most crash safety protocols assess injury risk by defining injury value limits that represents an acceptable injury risk for a certain injury severity. Physical testing is expensive and time-consuming and cannot possibly cover the design space needed for the assessment and development of the space capsule safety splash condition where similar as life boats the safety assessments needs to consider the various sea states and impact condition variations. On top of that, the space capsule motion in a splash shows quite some rotational motion and translational acceleration levels which are difficult or impossible to transfer to a testing device as used for e.g. automotive safety.

A key innovation in the Norwegian standard is that human models are allowed for injury risk assessment. Modern virtual human models allow a better biofidelity as the ATDs, because they not limited due to hardware constraints. In addition, these ATDs were developed to mimic human response to loading in specific impact directions. The use of an omnidirectional Human Body Models (HBM) in virtual testing requires fewer compromises and allow wider range of load cases to evaluate more realistic the human responses to the loads. Virtual testing is the only practical solution to cover the range of landing conditions as occur with the space capsule splash.

This paper presents a virtual multi-physical methodology of the space capsule splash and the results of a study on some key design and loading condition parameters that affect the safety performance.

2. Methodology

2 Methodology

The space capsule design of this work was based on NASA's Orion capsule. The overall specifications of the capsule are listed in the table below.

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Capsule Specifications	
Diameter	5 m
Height	3.3 m
Landing weight	9300 kg
Occupants	2-6
Material	Aluminium-lIthium Alloy

Table 2: Capsule specifications

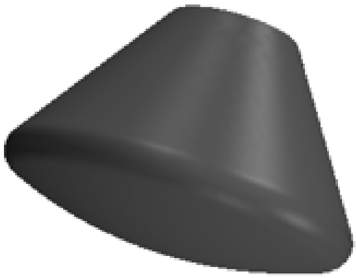

Figure 2: CAD Design

The simulation methodology was basically split in three types of simulations technologies for each engineering stream.

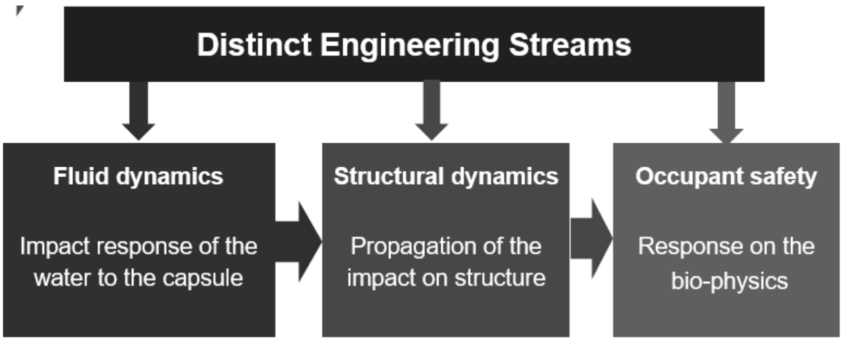

Figure 3: The three engineering streams

Then the simulation methodology was applied in an integrated way to investigate the influence of various load case parameters and analyse the splash impact dynamics up to the injury values with respect to the Free-Fall lifeboat standard.

Computational Fluid Dynamics (CFD) was used to simulate the effect of space capsule’s interaction with water surfaces. A Volume of Fluid (VOF) Multiphase model was used to model the immiscibility between water and air on numerical grids capable of resolving the interface between the 2 phases. Simcenter STAR-CCM+’s inbuilt wave model is paired with the VOF model to impose sea wave conditions within the domain. The Dynamic Fluid Body Interaction (DFBI) was also added to this simulation which allows to simulate the motion of the capsule as a 6-DOF (Degrees of Freedom) body with the displacement and rotation resulting from the defined mechanical and Multiphysics interaction. Within each time step, Simcenter STAR-CCM+ applies the resultant force and moment on the grid body and solves the governing equations of motion to find the new position and orientation of the capsule. Overlapping grid technique called “Overset Mesh” is used to capture the motion of the capsule body. In total the

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model exists of 3 million cells, 2.2 million for the environment and 0.8 million for the overset mesh of the capsule, see picture below.

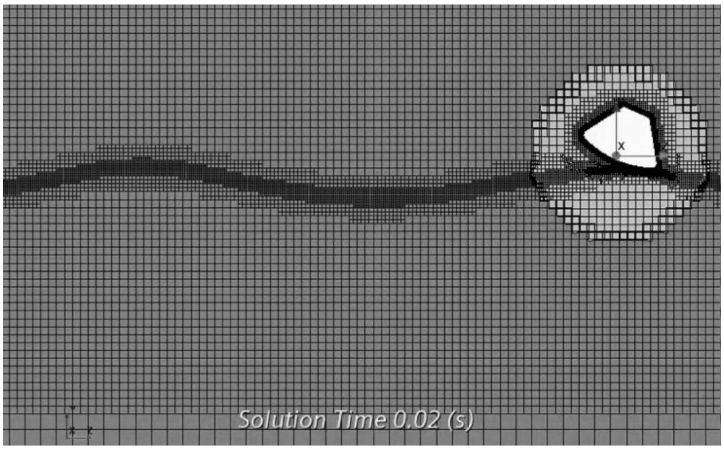

Figure 4: The CFD representation with the off-set mesh of a splash load case

The adaptive mesh refinement (AMR) is applied to the water and air interfaces and is a dynamic method that refines or coarsens cells based on adaptive mesh criteria as the flow solution progresses. Solution quantities are automatically interpolated to the adapted mesh.

The structural model was defined by the mesh generated automatically from the CAD data and the material properties of aluminium-lithium alloy. The mesh is also an input for the CFD solver, such that pressure data can be generated for each of the elements of the structural mesh. With the NASTRAN solver and pressure data the FEA is solved to calculate the stresses in the structure.

Occupant simulation

The occupant safety model was built as a hybrid multi-body and FE model in Simcenter Madymo. In principle the occupant safety model comprises of four systems: capsule environment, seat, seat belt and occupant. The environment contains all possible contact surfaces like floor and foot support, that could be assumed to be rigid with respect to human body. This environment model is also the system that will get a prescribed motion based on the information derived in the CFD and FEA analysis. The other systems were positioned and attached w.r.t to this environment. The solving takes place by the Simcenter Madymo solver which has an explicit multibody and explicit FE solver.

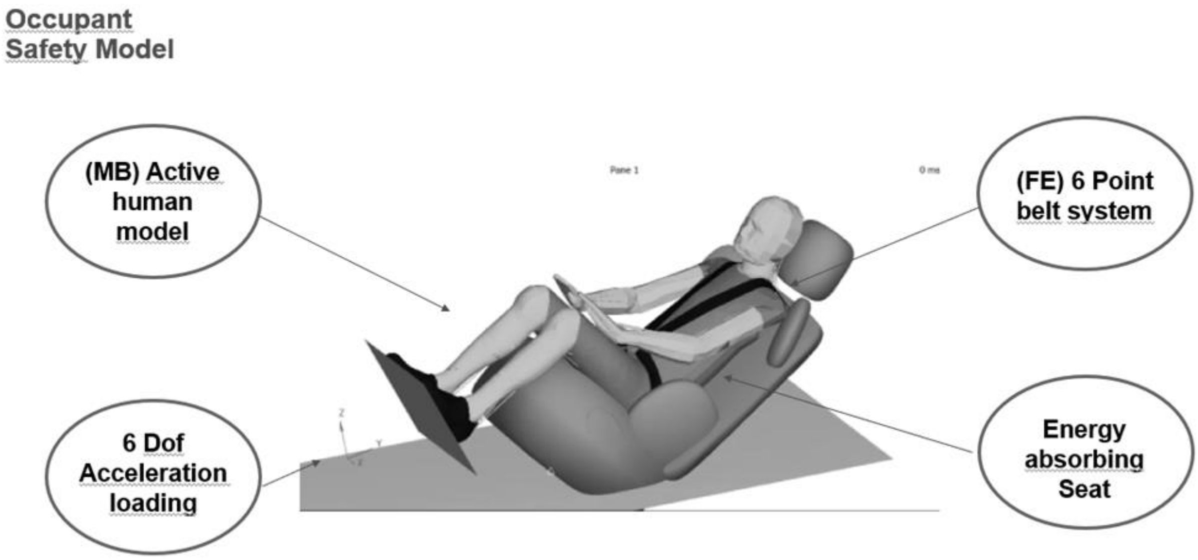

Figure 5: The occupant safety model in Simcenter Madymo.

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The seat was attached to the floor and modelled with a force-deflection characteristic representing the foam stiffness in a contact interaction with the occupant, see figure below. The curve was scaled to the specific properties of the different seat cushion parts.

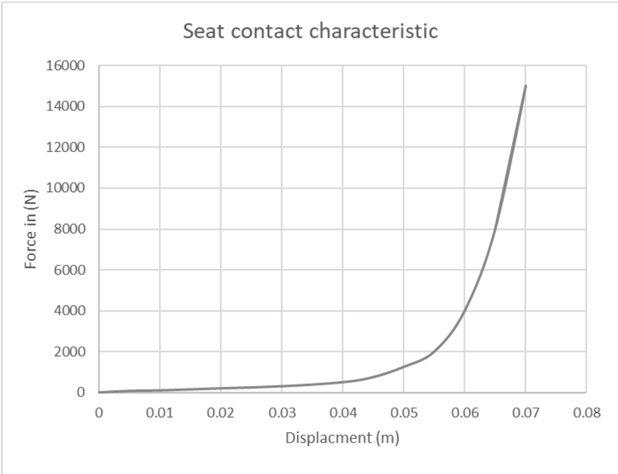

Figure 5: Seat contact characteristic used for the seat back.

The safety belt was a classical 6-point belt system with all the mounting points attached to the seat. The webbing was modelled with FE membrane elements for the webbing that interacts with the occupant and Multi-Body restraints for the connections between the FE parts and structure.

The occupant model [4] was the active human model that is available in the Simcenter Madymo database. The model is a full multi-body model with a faceted surface to have an accurate representation of the human body. It had been validated in multiple load cases under high g loading and low g loading conditions [5,6,7]. A key feature of the model is that it has muscle restraints and activators that allow together with the build in controller to simulate typical human stabilization behaviour. The figure below explains the construction of the human model.

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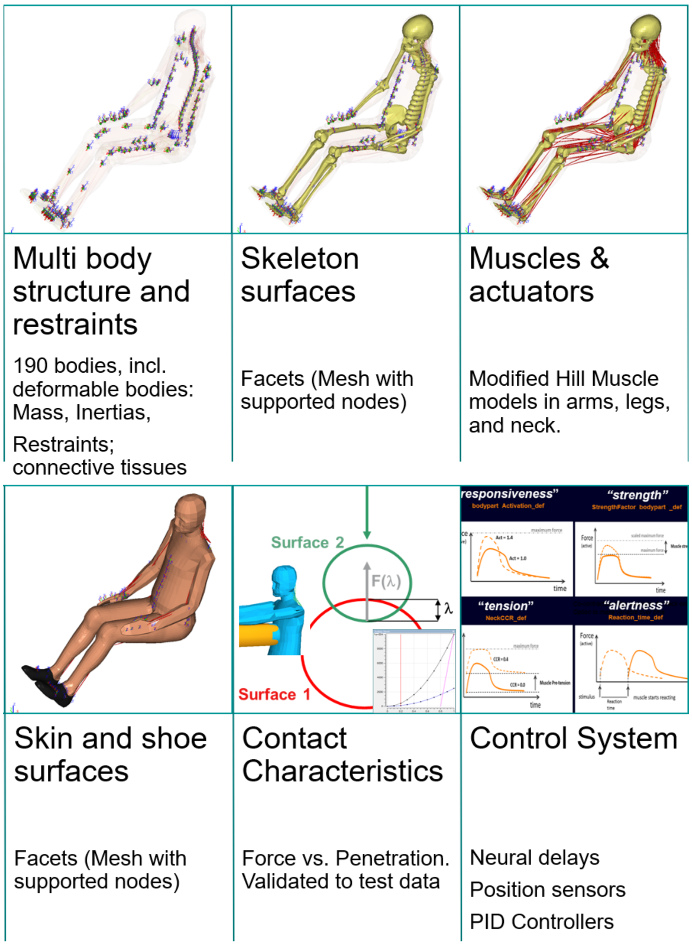

Figure 6: The active human model structure in Simcenter Madymo [4].

After positioning the active human model into the seat, a settling run was needed to set the initial status of the controllers to obtain a model in equilibrium. Once the settling was done, the initial joint positions and control initiation parameters were imported in the model.

A process automation of the simulation chain was set up in the HEEDS environment. First the different processes and data flows were coupled. See figure below with the scheme of the process automation.

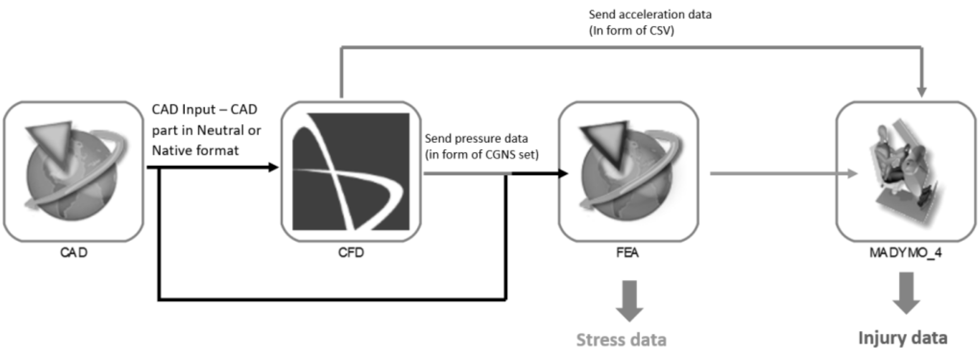

Figure 7: Process flow for the automation.

Secondly, the design space exploration has been set by defining load case parameters for the landing condition, sea state, human state, seat position and seat foams, see table 2 below. The exploration took place by using full factorial and Taguchi exploration schemes for developing response surface models for the design exploration.

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Parameter	System	Min.	Max.
Wave height	Sea	0 m/s	2 m
Wavelength	Sea	20 m	50 m
Drop speed	Capsule	10 m/s	15 m/s
Drop angle	Capsule	0 degree	45 degree
Horizontal speed	Capsule	0 m/s	2 m/s
Seat Angle w.r.t capsule floor	Capsule interior	0 degree	40 degree
Seat Rotation w.r.t capsule vertical axis	Capsule	0 degree (facing forward)	180 degree
Seat back foam stiffness	Seat	100%	200%
Seat head foam stiffness	Seat	100%	200%
Seat back foam thickness	Seat	50%	150%

Table 2: Parameter settings of the design exploration space.

The objective of the analysis is to understand the mechanics to develop some guidelines on the best landing condition and identify potential safety issues within the design space. First the affects of the landing condition on the capsule kinematics and acceleration has been explored. Secondly, the on most representative landing condition the seat position and characteristics have been varied to identify the safety risks.

3. Results

The results analysis took place on different levels. First, the effects of the landing condition on the capsule kinematics and acceleration had been explored. Secondly, for the most representative landing condition the seat position and characteristics were analysed to identify a best range for the safety system assessment.

The peak acceleration of the space capsule was mainly affected by Angle, followed by the drop speed, see figure 8 below. An acceleration level of 9g is about the maximum of g Force encountered in e.g. jet fighters [8]. On the other side an acceleration level of 30g or higher were at a level like the occupants in a car crash [9].

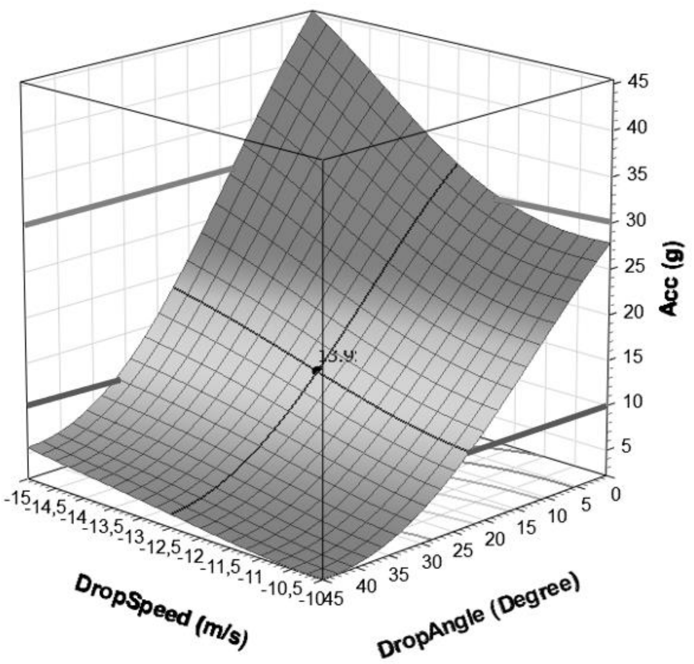

Figure 8: Response surface plot of the max. acceleration of the lifeboat c.o.g. as a function of the drop speed and drop angle.

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Assuming a fixed landing angle (25 degrees) and drop speed (10 m/s) the results showed that with only changing wavelength the max. acceleration increased with 50% from the lowest results to the highest, see figure 9.

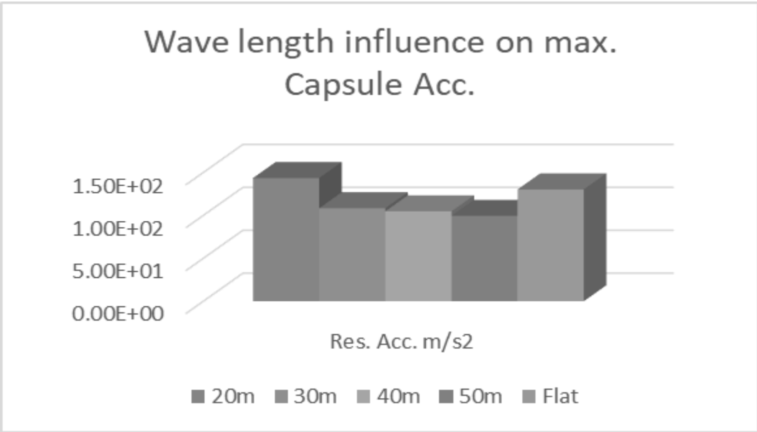

Figure 9: Response surface plot of the max. acceleration of the lifeboat c.o.g. as a function of the drop speed and drop angle.

Simulation with high angles of 45 degrees showed a risk of a flip over motion which was considered not very comfortable for the occupants, see figure below.

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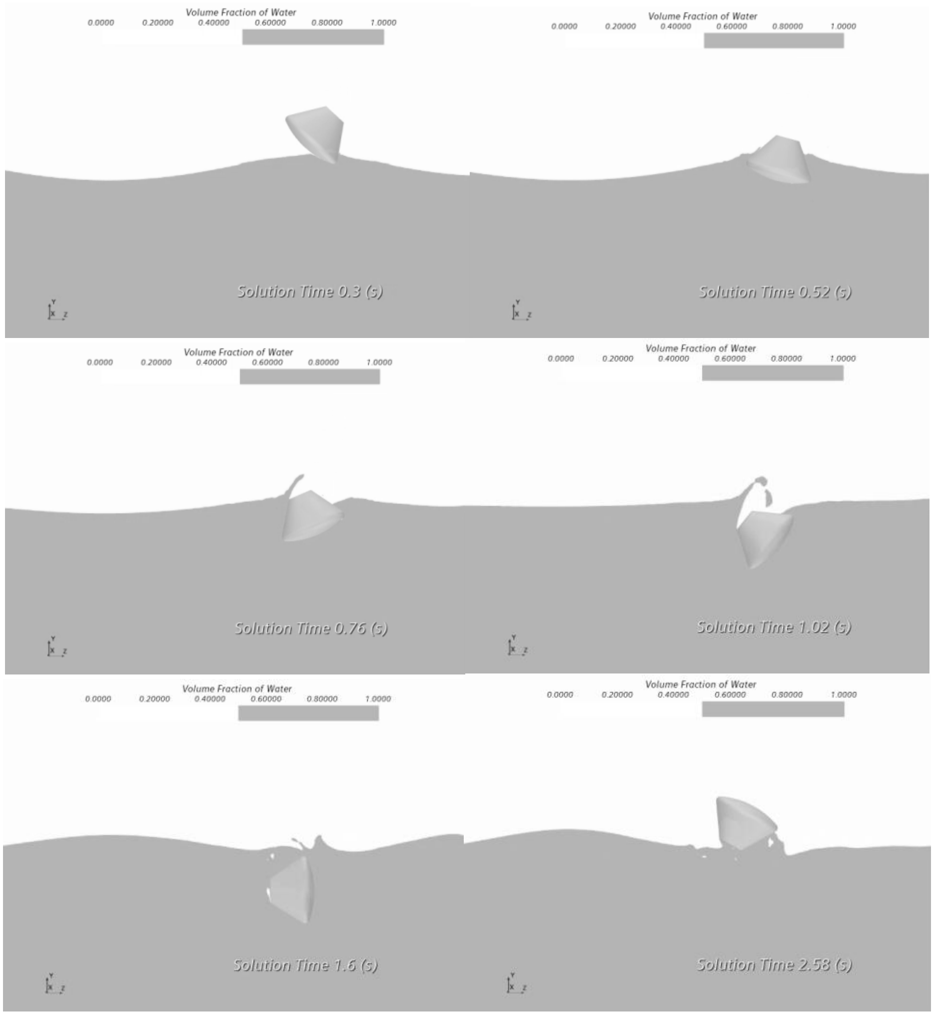

Figure 10: Animation of the flip over motion at 45 degrees impact in.

The maximum value of all the occupant injury criteria for all the load cases with 25 degrees impact angle and 10 m/s drop speed, values were normalized to the limits of the DVN standard, see figure 11 below.

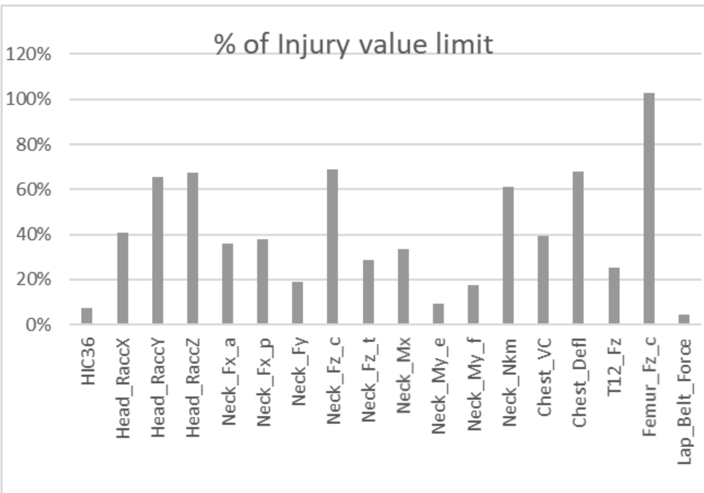

Figure 11: The injury values relative to the DVN limits.

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Remarkably, the femur loads appeared to be the most critical injury value. Further analysis of the results showed that for certain cases the seat back cushions bottomed out, see figure 12 below. When the high acceleration loading occurred at the moment that the seat back cushion is fully compressed, the inertia force of the legs is enough to generate forces just above the DVN limit.

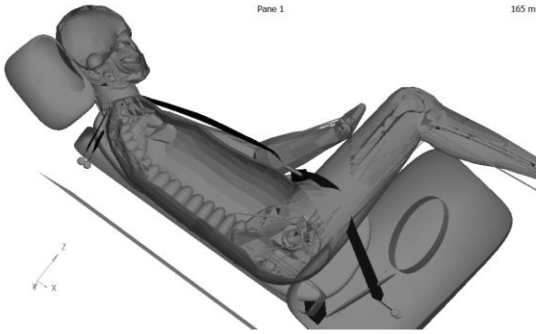

Figure 12: At 165ms after the start of the splash the seat back cushion is already fully compressed.

The effect plot of the femur compression force, see figure 13 below, indicated that an increased seat back foam thickness and higher seat angle had the most potential to reduce the femur loads.

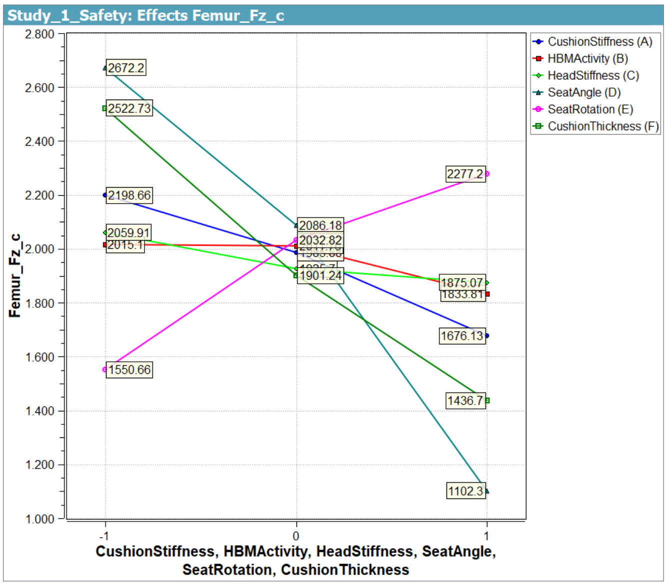

Figure 13: The main effects plot for the Femur compression load.

Another important injury value was the head Y-rotational acceleration. This value was above 60% of the injury limit and the effect plot, see figure 14 below, showed that human activity played an important role in this response. This activity parameter affected the head rotational acceleration more than the seat angle or head rest stiffness.

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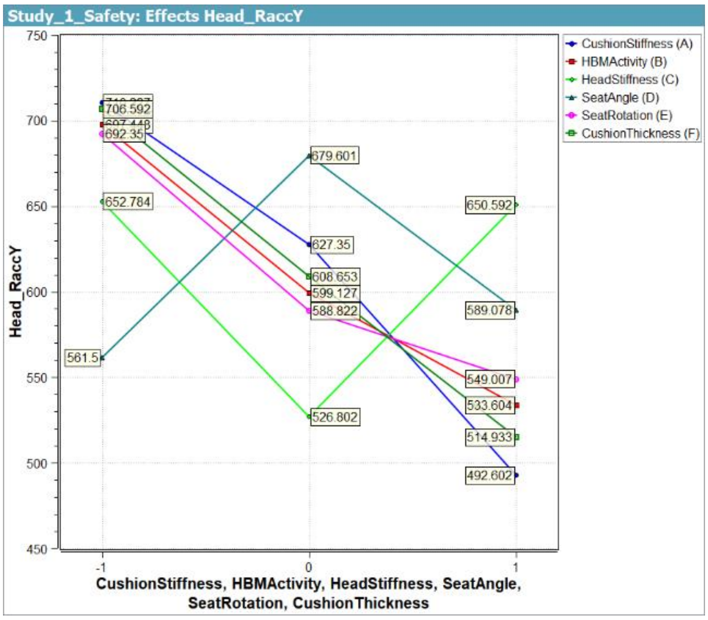

Figure 14: The main effects plot for the Head Y-Rotational acceleration.

4. Discussion

Within the space capsule development, a test plan needs to be developed and executed to validate the integrated model for the various model levels from components to full system. The methodology as used for the free-fall lifeboat projects contained tests that were used for the validation of the simulation models, but some more investigation would be needed to understand which tests and conditions would be the most adequate for the space capsules.

Although simulations have been performed with an AHM model it would be recommended to include in the analysis also simulations with an ATD as a validation option for the full system. Although testing with humans is possible in low-g scenarios, the difficulty lays in the large variation of human that complicates the validation analysis. Furthermore, a test plan would be scheduled typically for the worst-case scenarios which might results in injury risks that are no longer acceptable for volunteer testing.

While a simulated human will respond differently to an ATD, the fact that they are both validated on biofidelity against experimental data gives some confidence that the risk levels are comparable. The active human model which was chosen for simulation of the occupants in this study has been validated to multiple PHMS and volunteer tests [5, 6, 7].

There are of course other factors, not investigated in this work, that will play a role in the load case; e.g variation in sea current, sea wave phase and rotational motion of the capsule at the moment of impact. The occupant is also a considerable source of variation that must be taken into account for a robust safety design – in the real world the initial position will of course vary, as will size, sex, age and weight. Currently such variability is largely lumped together in the definitions of injury risk limits. Even so, adding such factors is feasible due to the efficient simulation method that would allow creation of a surrogate models to investigate safety risks in a broader analysis.

5. Conclusions

Despite emerging priorities, including time and cost, the overall quality perception of space products will to a large extent depend on safety and reliability (technical risk). With those priorities weighted against each other, it becomes increasingly important that space organizations follow a rigorous approach to risk assessment during design to analyse and understand the potential impact of decisions on safety, reliability and operational availability.

In the splash event the drop angle of the capsule played a main role to keep the capsule acceleration in a range where the injury values could be kept below the safety limits. The basic safety restraint concept with 6-point seat belt and

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energy absorbing seat foam did perform well. The challenge will be to design the space craft that also in the harsh conditions at the ocean is capable to maintain the main load case parameters between certain limits.

The validity of the injury value assessment methodology is heavily dependent on the validity of the occupant safety model used to generate the injury values. Virtual human modelling allowed a more biofidelic representation of the occupant, especially in cases where the reactivity of the human occupants during a motion of the vehicle will affect the dynamics of those inside, and in load cases that deviate from the typical unidirectional loading of current occupant safety regulations. By adjusting the activity parameters of the human model, it can be altered to represent for example a decrease in the astronaut's muscle activity due to a long stay in space.

The work showed that Simcenter provides an integrated digital twin approach that allows engineers to evaluate the safety of spacecraft designs against cost and operational efficiency, from the very early stages of the design process. This digital risk twin combines modelling with analysis to identify the expected behaviour and the impact of potential failures and risks associated with a design configuration in an objective, repeatable and traceable process.

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