LANDING IMPACT SIMULATION AND TESTING APPROACHES-ALCATEL ALENIA SPACE EXPERIENCE

Topic area: SHOCK (*)

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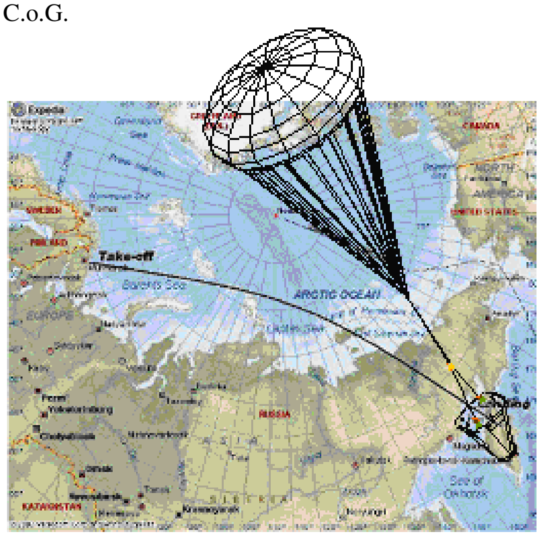
1. ABSTRACT

At early 2006, AAS-I starts the study on Landing impact due to the perspective on the Design of future entry vehicle.
As for every Discipline the study starts by simulating the event with the classical Crash formula based on impact velocity, no crash absorption by the vehicle structure and considering the ground as infinitely rigid.
Furthermore dedicated methodology activities are in progress to build-up the needed skill for the simulation and the testing of the landing impact. Trade-off on available commercial S/W's was carried out and two S/W candidates were selected and benchmarked as first industrial study case on a typical re-entry capsule (i.e. ESA- EXPERT).
The objective was the development of a correct methodology for modelling and simulating re-entry capsule impact using explicit non-linear dynamic finite element codes. Upgrading was done on the material modelling in order to include also yield stress, strain hardening and the maximum strain to failure. Due to the lack of the measured stress vs. the strain curves of the material involved ,the bilinear elastic-plastic material model was selected. The material is assumed to be elastic until stress is reached; after yield the material is assumed perfectly plastic. Various failure criteria of the elastic-plastic material was investigated vs. the EXPERT foreseen materials. Time histories of the various forms of energy as kinetic, internal, hourglass, interface and as well as the total ones was computed and critically examined to see the goodness of the modelling and the simulation approaches.
Another interesting industrial study case application is related to the ESA external Payload Coarse Pointing Device (CPD) landing simulation by Shuttle.
In this application an innovative test approach was proposed and applied for the generation of the expected landing impact acceleration level at the CPD –to-vehicle mechanical interface.
The landing impact simulated is related to a contingency landing generating a transitory event of 6.7g for 40 msec.
The test method proposed was based on the drop one instead of the classical half sine one on shaker.
In order to tune correctly the landing environment and also to avoid over stressing for the CPD shock sensitive units as the motors a testing approach was specifically defined.
This test approach foresees a calibration campaign with a dummy payload representative of the Payload mass properties.
The scope of the calibration test was the definition of the drop height and the needed mechanical interfaces between the Lab ground and the CPD mechanical interfaces.
Moreover , low ,intermediate and qualification drop heights were also defined as safety practice to be applied during the qualification test on the payload STM.
Acceleration and stress levels were measured during the drop impacts and they are part of AAS_I database that are used for the improving of the AAS-I landing impact skill by the correlation activity.
The purpose of the paper is to show this methodological evolution done on both aspects the simulated and the tested ones.

These industrial experiences are considered a milestone for the further improvement on the landing impact simulation and lab. reproduction.

2. INTRODUCTION

In the frame of ESA project it's foreseen to design ESA spacecraft. In the mission profile of this entry vehicle, it's foreseen a landing impact on soil in Kamchatka peninsula.
Being AAS-I the prime of this project it's requested to derive the acceleration induced by the landing impact at spacecraft C.o.G. and at equipment C.o.G.



(b) Barents Sea: $V_e = 6.862$ km/s

Figure 2-1: landing shock impact in Kamchatka peninsula

The objective of this work has been the development of a correct methodology for modeling re-entry capsule impact using explicit nonlinear dynamic finite element codes.
Space structures are typically manufactured from many thin shell parts and subsequently assembled by various fastening techniques. The structure of a re-entry capsule like in this case may contain aluminum of various strength grades, steel and composite materials. During a crash event, the structure experiences high impact loads which produce localized plastic hinges and buckling. This can ultimately lead to large deformations and rotations with contact and stacking among the various components.
Of particular interest here is the structural integrity and associated kinematics and stacking of components, forces transmitted through the various members, stresses, strains, and energy absorption.
In addition the crash event may be considered as a low to medium dynamic event, in comparison with ballistic impact, persisting for duration of 100-200 [ms].

The considered problem is too complicated to be solved in a closed form (analytically) therefore numerical techniques, at this time, appear to be the practical option. Mathematical modeling is commonly done by using differential equations. The numerical method, which is used, for solving these, is the Finite Element Method (FEM). It is well suited to digital computers and many software based on this method, have been developed.
The next subsections introduce a short description of the finite Element Method applied on crash simulations. The FE software, used in the work, is presented as well.

3. SIMULATION APPROACH

The discretised equation of motion for explicit FE formulation can be written as:

$$[M]\{\ddot{d}\}=\{F_{ext}\}-\{F_{\text{int}}\}$$

where $[M]$ is the mass matrix of the structure, $\{\ddot{d}\}$ is the nodal acceleration vector, $\{F_{ext}\}$ is the external force vector and $\{F_{\text{int}}\}$ is the internal force vector.
Time integration of the above ordinary differential equations resulting from the spatial discretization of the continuum is obtained by a central difference technique (one of the explicit time integration methods) as follows.
The solution is advanced from time t^n to time t^{n+1} by a time step Δt^n. The equilibrium equation is established at a known state n at time t^n and the unknown state $n+1$ at time t^{n+1} is to be solved.

$$[M]\{\ddot{d}^n\}=\{F_{ext}{}^n\}-\{F_{\text{int}}{}^n\}$$

The acceleration vector is found from the above equation:

$$\{\ddot{d}^n\}=[M]^{-1}\left(\{F_{ext}{}^n\}-\{F_{\text{int}}{}^n\}\right)$$

the velocity is updated:

$$\dot{d}^{n+\frac{1}{2}}=\dot{d}^{n-\frac{1}{2}}+\ddot{d}\Delta t^n$$

the displacement at the unknown state, time t^{n+1} are defined as:

$$d^{n+1}=d^n+\dot{d}^{n+\frac{1}{2}}\Delta t^{n+\frac{1}{2}}$$

Where :

$$\Delta t^{n+\frac{1}{2}}=\frac{\Delta t^n+\Delta t^{n+1}}{2}$$

Where n is the integration step, Δt is the time step, $\dot{d}$ and d are nodal velocity and displacement vectors respectively.

Using the initial conditions the nodal kinematics can be computed.
"Explicit" refers to a specific technique whereby the equilibrium is expressed at a moment in time where the displacements of all spatial points are already known. Accelerations are determined from the equilibrium, and a central different technique allows determining the displacements at the next time-step and repeating the process. The technique's attractiveness is that, since the displacements are known at the time for which is solved the dynamic equilibrium of the system this process requires the only inversion of the mass matrix, $[M]$.
Clearly, if a lumped-mass approach is used, the mass matrix is diagonal and no mass inversion is necessary. This results in a very fast algorithm, since a system of uncoupled equations is all that needs to be treated.
This method has been developed for solving transient dynamic problems, like crash process, but it can also be used for quasi-static analysis, like the forming process. It does not demand assembling and inverting of the stiffness matrix which then lead to less memory requirement.
The only drawbacks of the explicit algorithm are the conditional stability and the clear inability of the methodology to treat static problems. The conditional stability of the explicit integration algorithm means that the integration time-step must be smaller than or equal to an upper limit value given as the Courant condition:

$$\Delta t \leq \frac{l_c}{c}$$

where l_c is the characteristic length of the smallest element and c the speed of sound in the current material, which can be defined as:

$$c = \sqrt{\frac{E}{\rho}}$$

where E is the Young's modulus, ρ is the mass density.
Therefore the Courant condition is equal to saying that the analysis time-step should not exceed the smallest of all element time-steps determined by dividing the element characteristic length through the acoustic wave speed through the material of which the element is made. The requirement is equivalent to saying that the numerical time-step of the analysis must be smaller than, or equal to, the time needed for the physical stress wave to cross the element. It is the smallest element that determines the time-step. This can cause long calculation time. For typical automotive applications the time-step is of the order of 1 microsecond.
Due to this restriction, it is clear that explicit methods are best suited to treat problems of short duration and thus, high loading velocity and problems of highly nonlinear nature that require small time-steps for accuracy reasons.

3.1 Landing Impact Simulation

The objective of this work has been the development of a correct methodology for modeling and simulating re-entry capsule impact using explicit nonlinear dynamic finite element codes /RD2/.

The assumptions and approximations made in development of the model are listed, as follows:

- The impact condition is assumed to be 6 m/s vertical velocity, with no lateral, longitudinal, or rotational velocity components.
- A second impact velocity of 70 m/s has been investigated in order to take into account the eventuality of a parachute device failure.
- The impact surface is assumed to behave as a rigid surface.
- The material properties assigned to the elements representing the honeycomb core are estimated. No experimental data were available on components to determine the actual material properties. Thus, the values used in the model are based on engineering judgment.
- The equipment on the floor cross panels are assumed to behave as concentrated masses attached to nodes at their approximate location in the model. However, this non-geometric, non-physical representation cannot accurately simulate the behavior of the equipment during an eventual test.
- Where possible, the components are modeled using shell elements. However, beam elements were used to represent the reinforcing structures.

The model was executed for 0.03 seconds of simulation time on a UNIX based workstation computer. Requested output included the deformed geometry and acceleration time histories for several nodes whose positions correspond to the locations of the equipment.

Accurate material representations must be used in order to be successful in modelling impacts. These data often must be determined experimentally. As far as the crash simulation of the EXPERT capsule is concerned, the absence of an experimental database of material responses is the main obstacle to overcome in order to be more confident on the reliability of the results.

Because the input of this work has been the Expert's model originally used for modal analysis, extensive modifications were required to convert it for a crash simulation. These modifications regarded both the mesh and the materials representation (to include yield stress, strain hardening and maximum strain to failure as appropriate). In fact, due to the large deformations involved in a crash event, the nonlinear behavior of the material must be included in the material model, which should account also for the strain-rate effects.

By the time being, due to the absence of the experimental engineering stress vs. strain curves of the materials involved in the model, the linear elastic constitutive model (card *MAT_ELASTIC) has been adopted for the material, except for the ceramic nose component and for the aluminum honeycomb core panels.

A more detailed material representation has been implemented in RADIOSS EXPERT FE model .

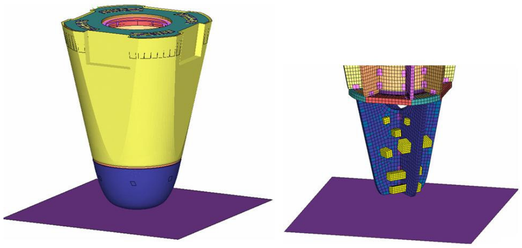


Figure 3.1-1: explicit FE Model for the landing impact simulation

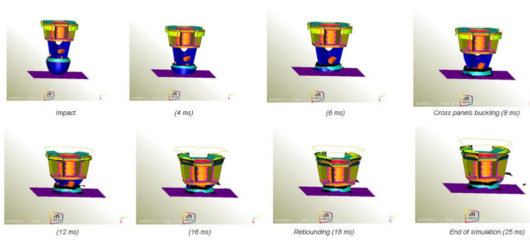


Figure 3.1-2: Landing impact dynamics

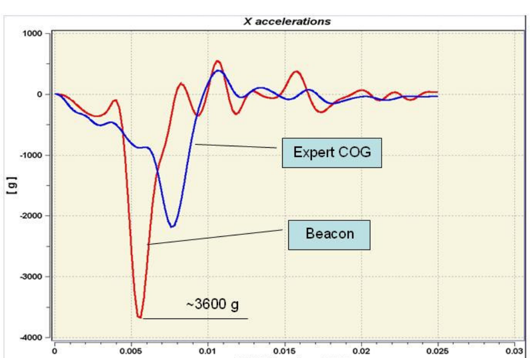


Figure 3.1-3: Simulation results

3.2 Water Landing Simulation

The estimation of the acceleration loads generated during the water splashdown event is an important task versus the definition of the design load factors requirement for the whole space vehicle and for its mounted equipments and payloads /RD1/.
In the frame of the FLPP/IXV program a water landing simulation activity was started in order to find the maximum expected acceleration levels examining several combinations of different landing scenarios from the nominal to its speed tolerance landing conditions.
These landing conditions are depending on various parameters and initial conditions as, for example: the IXV velocities, IXV re-entry orientation (i.e. pitch and roll) angles, wind speed and its angle of contact with the water wave.
The Intermediate Experimental Vehicle (IXV) is studied as a part of the FLPP project and its overall configuration is provided in figure 3.2-1 and the overall IXV aero-shape main dimensions are provided in figure 3.2-2.

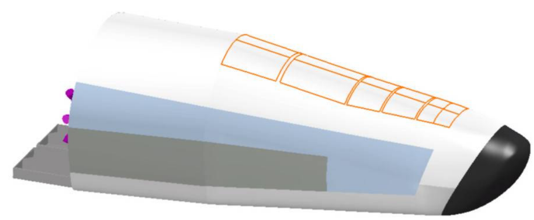


Figure 3.2-1 - IXV Configuration.

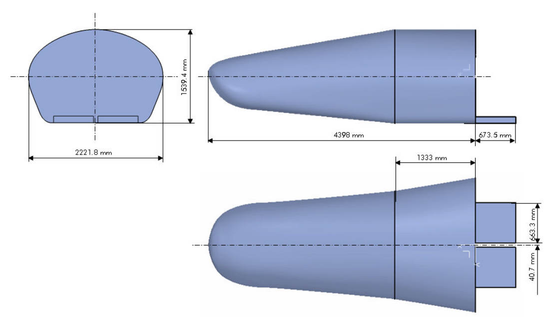


Figure 3.2-2 - IXV Aero-shape Main Dimensions.

A simplified finite element model of the IXV demonstrator vehicle was build up modelling only the external TPS and the aero-shell structure by 3D elastic elements. The general view of this model is shown in figure 3.2-3.
The reason of this approach is justified mainly by these two aspects: firstly because the layout of the internal primary and secondary structures is not completely established and secondly because in this manner it was possible to minimize the computational efforts maintaining in the same time the capability to capture the impact behaviour.

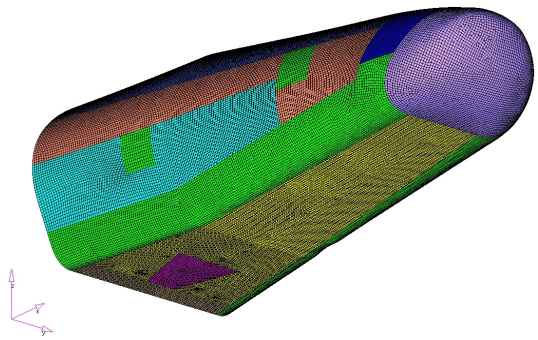
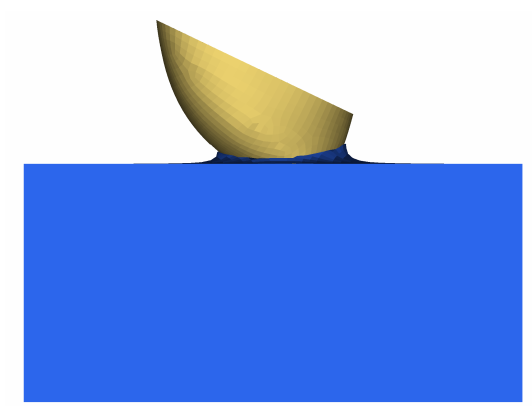
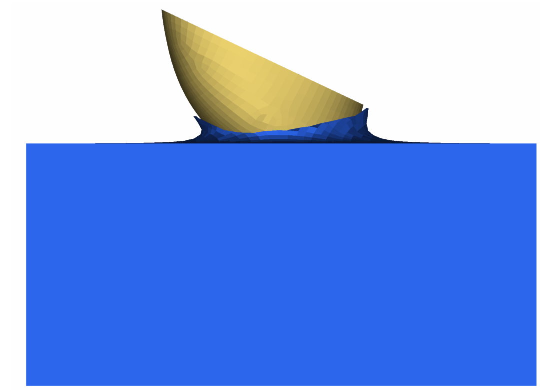


Figure 3.2-3 - IXV FEM model.

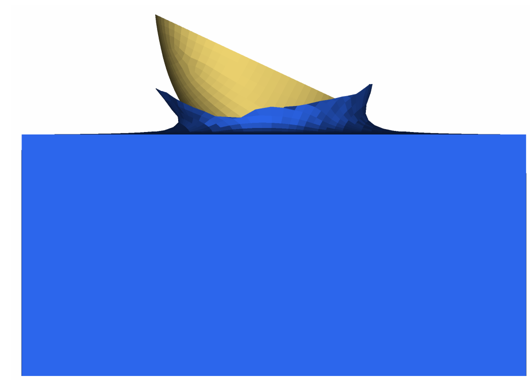
Then in order to get the correct inertia properties (i.e. Centre of Gravity and moments of inertia) an appropriate mass element was placed by an additional rigid body part.
The transient dynamic simulations were performed using the RADIOSS/Altair software, which is a commercial explicit finite element analysis code.
For all the studied landing condition cases the resulting acceleration profile at the centre of gravity and on other relevant locations were computed, and, in addition, it was estimated the contact force variation over time on the water-spacecraft contact surface.
Actually all the simulations are preformed using a Lagrangian mesh for the water model but it is planned to analysis the water splashdown also by an Arbitrary-Lagrangian-Eulerian (ALE) approach. In fact this ALE approach permits to model the IXV spacecraft by a Lagrangian mesh and the water and air parts by an Eulerian mesh.
The evolution of the motion of the IXV under the following landing simulation (vertical speed=5.0 m/s, pitch angle=90°, wave angle=0°) is shown in figure 3.2-4.



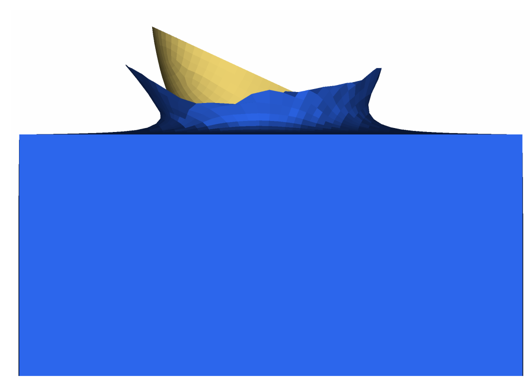
Time = 20 msec



Time = 30 msec



Time = 40 msec



Time = 50 msec

Figure 3.2-4 - IXV Landing simulation.

4. TESTING APPROACH

In the frame of the SOLAR mechanical qualification, the stress at the end-stops and the acceleration of moving parts have been measured by simulating its landing impact.
The testing activity has foreseen:

- *Calibration Test Campaign* by a calibration item for the characterisation of the selected AVM's and for the definition of the drop height

➢ *Landing Impact Test* for the SOLAR qualification vs. the Shuttle landing.

The test configuration has foreseen the CMA EQM integrating the three dummies payloads.

The Engineering Evaluation of the Landing Impact test data has been focused on derivation of:

- Stress at end-stop_to_CPD frame
- Acceleration (g) on the moving parts (Main Frame and Pointing Platform)
- Acceleration (g) on the upper part of the support

By this activity, the qualification of the SOLAR vs. the landing impact will be assessed.

5. TEST DESCRIPTION

The aim of the test is to reproduce the input of the Landing impact as defined by ESA (*i.e. impulse of 6.7g with a frequency content between (25 – 35 Hz*) The AAS-I proposed approach was based on an integrated ***Test-Analysis approach*** shown by figure 5-1.

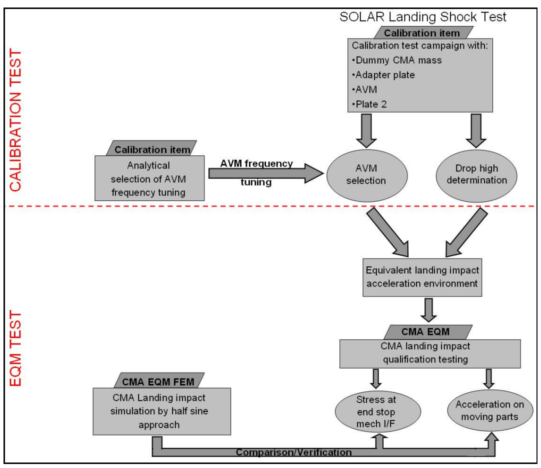


Figure 5-1 : Landing impact test integrated test-Analysis approach.

The proposed test campaign is based on following activities:
1) Calibration test
2) Qualification test
3) CMA EQM FEM Comparison/Verification

5.1 Calibration Test

A dedicated calibration test campaign has been done in order to define :

- *The needed AVM* to reproduce the input of the Landing impact as defined by ESA (i.e. impulse of 6.7g with a frequency content between (25 – 35 Hz)
- The requested drop height (h) to reach the specified impulse level (i.e. 6.7g in time domain)

This activity has been done by a dedicated calibration item as shown by figure 5.1-1 and figure 5.1-2
This item was compounded by :
- a dummy mass representing the CMA (CPD + 3 P/L's) (220 Kg)
- an equivalent CEPA simulator plate
- 8 AVM's
- a dedicated plate

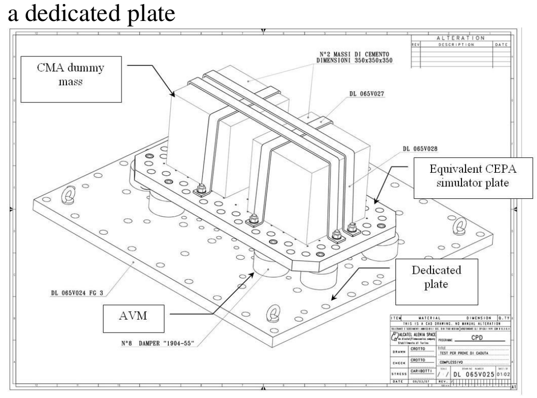


Fig. 5.1-1: calibration item drawings for the landing impact test approach tuning.

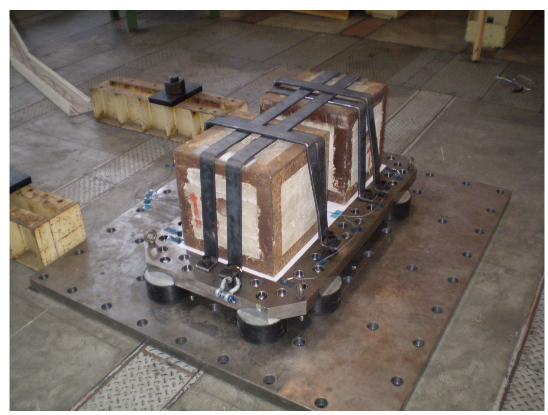


Fig. 5.1-2: calibration item drawings for the landing impact test approach tuning.

In this calibration test the acceleration (g) has been measured at equivalent CEPA simulator plate_to_dummy mass mechanical interfaces.

The drop method on how to perform the calibration test and the landing impact qualification testing is shown in figure 5.1-3

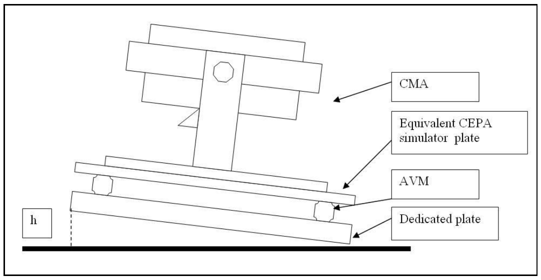


Figure 5.1-3: CMA EQM Landing impact calibration/ qualification testing method.

5.2 Qualification Test

After the definition of an equivalent Landing impact acceleration Environment, the Calibration item has been substituted by the SOLAR EQM model, as shown by figure 5.2-1 and figure 5.2-2

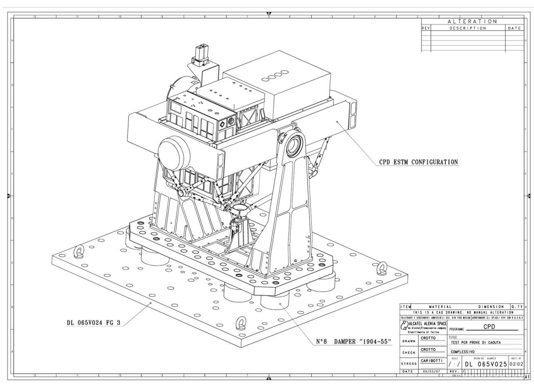


Figure 5.2-1: CMA EQM configuration for the landing impact qualification testing.

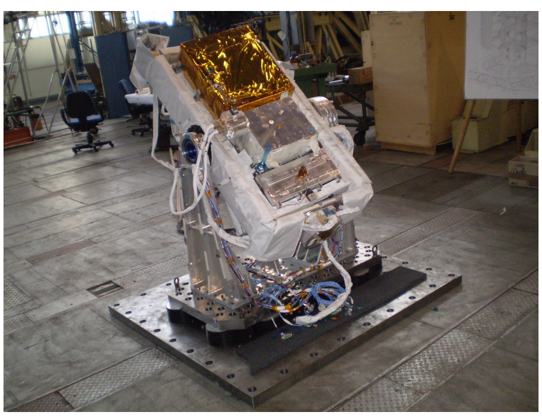


Figure 5.2-2: CMA EQM configuration for the landing impact qualification testing.

Due to the fact that the Balancing Masses System has been removed from the test article, the moving parts were set at the mechanical end-stops as shown by figure 5.2-2

The following test data have been measured:

- Stress at end-stop-CPD frame
- Acceleration (g) on the moving parts (Main Frame and Pointing Platform)
- Acceleration (g) on the upper part of the support

6. INSTRUMENTATION PLAN

The instrumentation plan shown by figure 6-1 and figure 6-2 considers the following sensors:

- To measure the landing impact input environment → <u>*4 mono-axial accelerometers (A1-A2-A3-A4)*</u>
- To measure the landing impact environment close to C.o.G → <u>*1 mono-axial accelerometer (A5) on a unit close to C.o.G*</u>
- To measure the moving parts acceleration (Main Frame and Pointing Platform) → <u>*2 mono-axial accelerometers (A6-A7)*</u>
- To measure the landing impact acceleration at upper part of the support → <u>*2 mono-axial accelerometers (A8-A9)*</u>
- To measure the stress at the stop ends → 4 <u>*strain-gauges (two mono-axial and two bi-axial)*</u>

Due to the fact that the Balancing Masses System has been removed from the test article, the moving parts were set at the mechanical end-stops as shown by figure 5.2-2

The accelerometers A1, A2, A3, A4, A8, A9 have been placed in Z direction (OOP of base plate).
The accelerometers A5 and A6 were rotated of 45° w.r.t the base plate (Derotation Angle-Main frame figure 6-1).
The accelerometer A7 was rotated of 25° w.r.t. the base plate (Indexation Angle-Pointing platform figure 6-1).

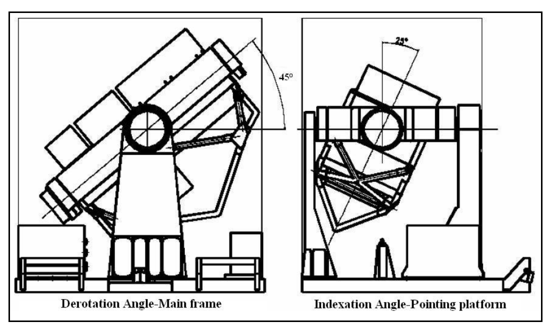


Figure 6-1: Derotation Angle and Indexation Angle of moving parts.

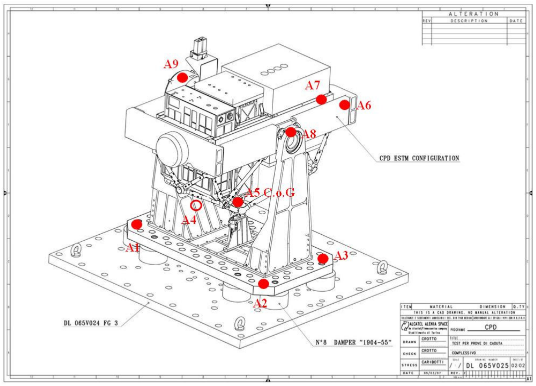


Figure 6-2: mono-axial accelerometers location to measure the landing impact environment.

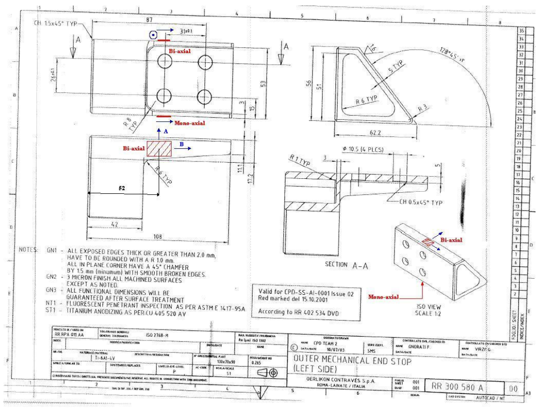


Figure 6-3: strain-gouges location to measure the stress.

7. TEST RESULTS

Both the calibration and the qualification tests had been successful, since all the success criteria have been satisfied.

7.1 Calibration test

The calibration test has been performed with 3 different drop heights:

- <u>*H1 = 2mm*</u> → the measured average value on accelerometers A1, A2, A3 and A4 (i.e. on the base plate) is 2.1g
- <u>*H2 = 7.5mm*</u> → the measured average value on accelerometers A1, A2, A3 and A4 (i.e. on the base plate) is 4.46g
- <u>*H3 = 23mm*</u> → the landing impact test from drop height H3 has been performed 3 times in order to check its repeatability.
  The measured average value on accelerometers A1, A2, A3 and A4 (i.e. on the base plate) is 7.01g, 6.71g and 7.11g.

For each drop height the followings are reported:

- Accelerometers A1, A2, A3 and A4 time histories
- Accelerometers A1, A2, A3 and A4 PSD

The calibration test with the drop height H3 = 23mm <u>*reached the requirements in term of acceleration, frequency tuning and repeatability.*</u>
→Predicted resonance frequency of the 8 AVM's=28Hz → measured 28.8Hz
By this tuning activity the adequacy of the selected AVM's is confirmed and the ATP for the qualification test was agreed AAS-I and ESA.

The calibration test with drop height H3=23mm has been repeated 3 times in order to check its repeatability.

7.2 Qualification test

The qualification test has been performed with 3 different drop heights:

- <u>*H1 = 2mm*</u> → the measured average value on accelerometers A1, A2, A3 and A4 (i.e. on the base plate) is 2.2g
- <u>*H2 = 8mm*</u> → the measured average value on accelerometers A1, A2, A3 and A4 (i.e. on the base plate) is 3.66g
- <u>*H3 = 28mm*</u> → the measured average value on accelerometers A1, A2, A3 and A4 (i.e. on the base plate) is 7.89g vs. 6.7g at around 28Hz vs. 25Hz to 35Hz. It was decided to exceed the average value of 6.7g in order to get for each mechanical interface of CMA at least the qualification level i.e. 6.7g

For each drop height the followings are reported:

- Accelerometers A1, A2, A3, A4, A5, A6, A7, A8 and A9 time histories
- Accelerometers A1, A2, A3 and A4 PSD
- Strain-gauges B1A, B1B, S1, B2A, B2B and S2 time histories
- Transmissibility A9/A1, A9/A4, A8/A2 and A8/A3

At the end of the test HW inspection has been performed (with the witness of PA) and no damages have been found.

7.2.1 <u>Qualification test H3=28mm</u>

It was decided to exceed the average value of 6.7g in order to get for each mechanical interface of CMA at least the qualification level i.e. 6.7g.
The qualification test with the drop height H3 = 28mm <u>*reached the requirements of acceleration and frequency tuning*</u>.
In fact the maximum acceleration measured by accelerometers A1, A2, A3 and A4 positioned on the base plate was at least 6.7g (see figures figure 7.2.1-1, figure 7.2.1-2, figure 7.2.1-3 and figure 7.2.1-4) and the measured Eigen-frequency of the suspended plate (on the accelerometers A1, A2, A3 and A4) was around 28Hz (see figure 7.2.1-12).

The micro-strain measured on the main support M.E.S end stop during the landing impact (full level) is 650mstrain as reported on figure 7.2.1-11, corresponding to 71MPa (650mstrain*110000MPa *10^-6)

Due to the fact that the other stress component are negligible, the Von Mises can be considered as equal to 71MPa, to be compared with 335MPa as induced by 7000N as reported on the design and the analysis report.

Furthermore the ultimate allowable stress of the titanium (Ti6AI-4V) is equal to 896MPa.

By those consideration the end stops can be considered qualified vs. the landing impact event.

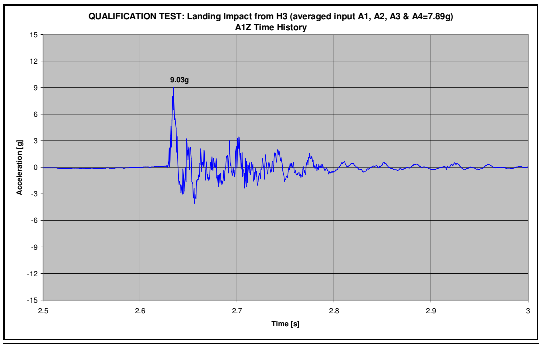


Figure 7.2.1-1: accelerometer A1Z time history from H3=28mm drop height.

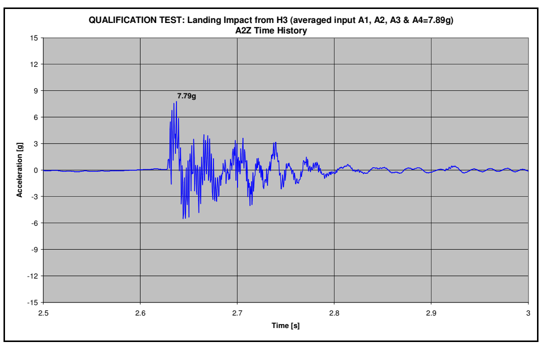


Figure 7.2.1-2: accelerometer A2Z time history from H3=28mm drop height.

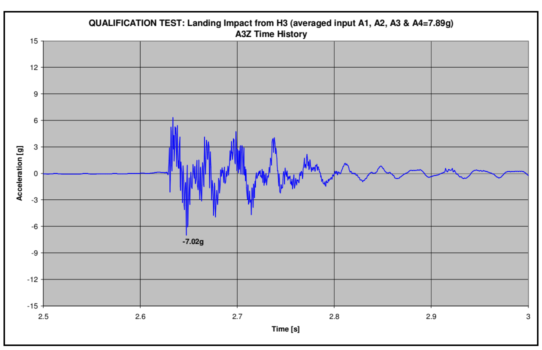


Figure 7.2.1-3: accelerometer A3Z time history from H3=28mm drop height.

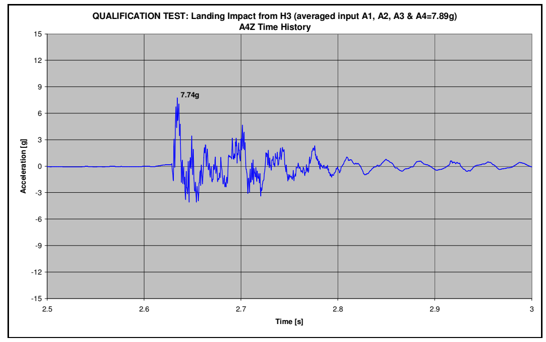


Figure 7.2.1-4: accelerometer A4Z time history from H3=28mm drop height.

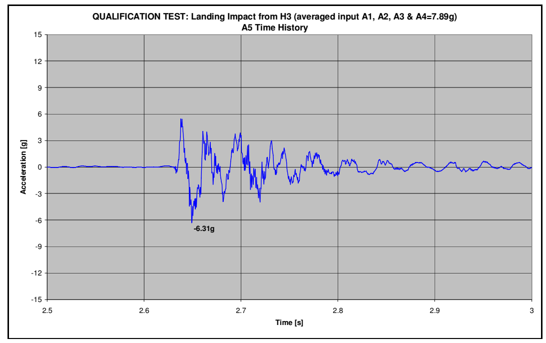


Figure 7.2.1-5: accelerometer A5 time history from H3=28mm drop height.

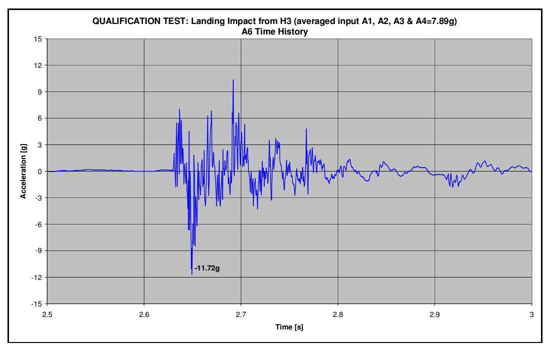


Figure 7.2.1-6: accelerometer A6 time history from H3=28mm drop height.

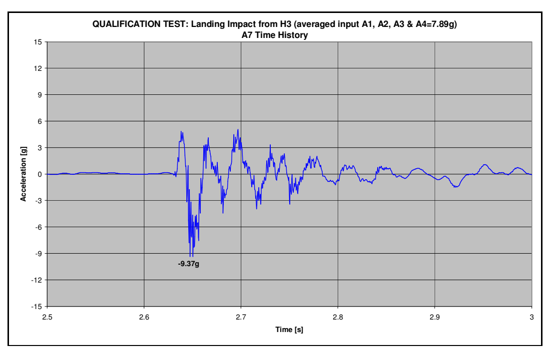


Figure 7.2.1-7: accelerometer A7 time history from H3=28mm drop height.

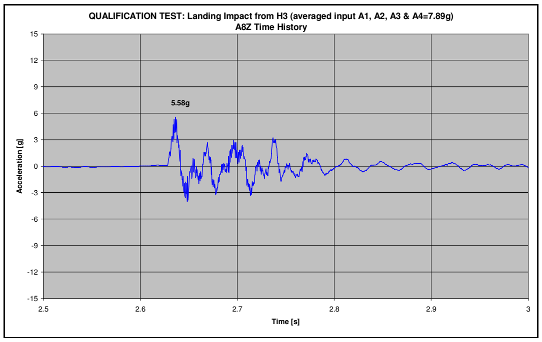


Figure 7.2.1-8: accelerometer A8Z time history from H3=28mm drop height.

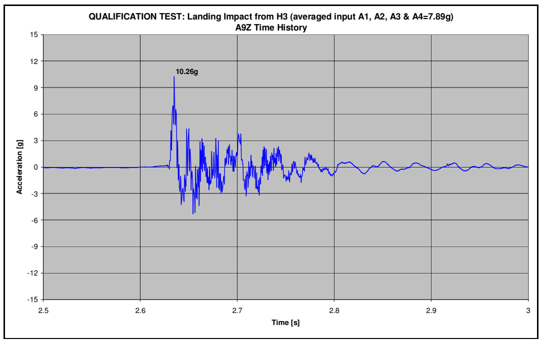


Figure 7.2.1-9: accelerometer A9Z time history from H3=28mm drop height.

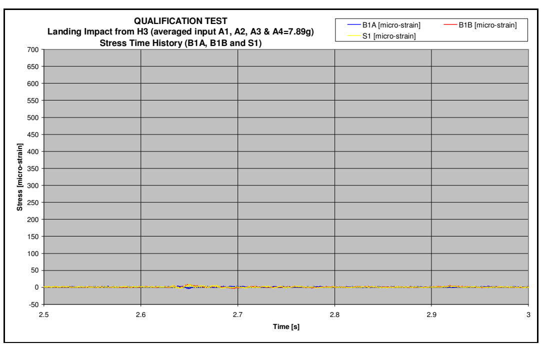


Figure 7.2.1-10: B1A, B1B and S1 stress time history from H3=28mm drop height.

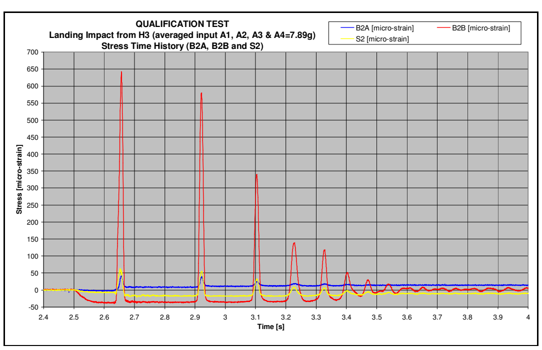


Figure 7.2.1-11: B2A, B2B and S2 stress time history from H3=28mm drop height.

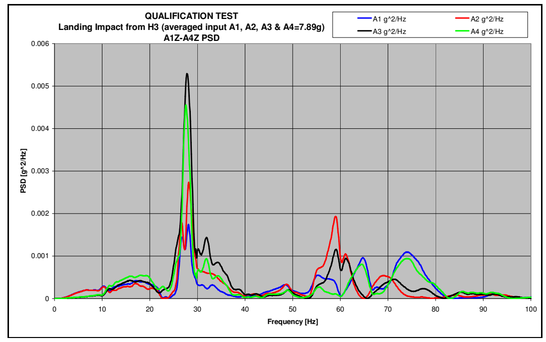


Figure 7.2.1-12: A1Z-A4Z PSD from H3=28mm drop height.

8. FURTHER INVESTIGATION

The following investigations are on going at AAS-I for a better spacecraft design vs. landing/water impact event:

- **Simulation aspect:** to set-up analytical and numerical methods/procedure for both the first cut (preliminary Design) and the accurate prediction (mature Design) derivation of the acceleration, deformation and stress induced landing impact event
- **Test data aspect:** to built-up a dedicated database of material as input for the landing impact simulation and the crushable structure design and analysis. The material types to be characterized by lab activities should include at least honeycomb, CFRP, CMC ones. The characterization shall include the compressive Stress vs. Volumetric strain for the honeycomb panel: plastic strain rate for the CFRP, CMC ones.

9. ACRONYMS

FEM	Finite Element Method
I/F	Interface

10. REFERENCES

/RD1/ G. Bartoletta, P. Alessi, G. Donadio: “Expert module: landing impact simulation” 26 April 2006

/RD2/ Justin D. Littell, Charles Lawrence, Kelly S. Carney: “Crew Exploration Vehicle (CEV) Water Landing Simulation” NASA, May 2007