Summer Student Programme Report

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Abstract
SHiP Experiment aims at exploring the Hidden Particles sector. The decay vessel is a long structural steel hollow structure allowing the hidden particles to decay into Standard Model elementary particles to be detected. This very massive structure is expected to lay on the floor in a possible future underground facility at CERN, where the seismic activity is non-negligible. The dynamic analysis of the SHiP decay vessel is then an important step in the structural assessment of this part of the detector. As part of the SHiP collaboration activity, the seismic assessment of the SHiP decay vessel is conducted in order to give important recommendation for the geometrical and structural design of this structure. Thanks to Finite Elements and Response Spectrum analyses and through mechanical and programming software applications, an equivalent static analysis allowed to predict the seismic behaviour of such a vessel. The seismic assessment is mostly done by using probabilistic approach and plotting the structure fragility curves representing the probability of exceeding a certain limit state at a given earthquake intensity measure, in particular the Peak Ground Acceleration.

Keywords
SHiP, seismic fragility assessment, risk engineering, structural dynamics

1 Introduction

1.1 SHiP Experiment

A new fixed target experiment connected to the Super Proton Synchrotron (SPS) accelerator is proposed to search for "hidden" particles that have been predicted by various scientific models at CERN. These particles could help explaining mysteries such as dark matter, neutrino oscillations and the imbalance of matter in the Universe. The aim of the experiment is to find long-lived, weakly interacting particles. The SPS's high-intensity proton beam is used to search for these particles at different energy levels by using two different detection methods, either by observing their visible decays, or by detecting their scattering effects on electrons or nuclei.

Fig.1 shows SHiP detector. On the lower left side is the beam target surrounded by a hadron absorber. From this target, the collision at $\approx$ 400 GeV follows the white dashed line trajectory and goes through different systems before entering the decay volume. Somewhere in the latter, according to the theory, particles will decay (green and brown curves) before reaching the spectrometer and other detectors. All this phenomenon need to happen in complete vacuum to avoid hitting other non-desired particles that would distort the experiment. The entire system measures approximately 130 m in length, where the decay volume is 50 m long. It is this structure that I have been given to study.

Due to previous analyses conducted by members of SHiP collaborators, among which is the University of Naples Federico II, the first analyses ran on a so called "ring model" which represents only a 2.4 m long section of the downstream decay vessel shown in a red frame on Fig.1.

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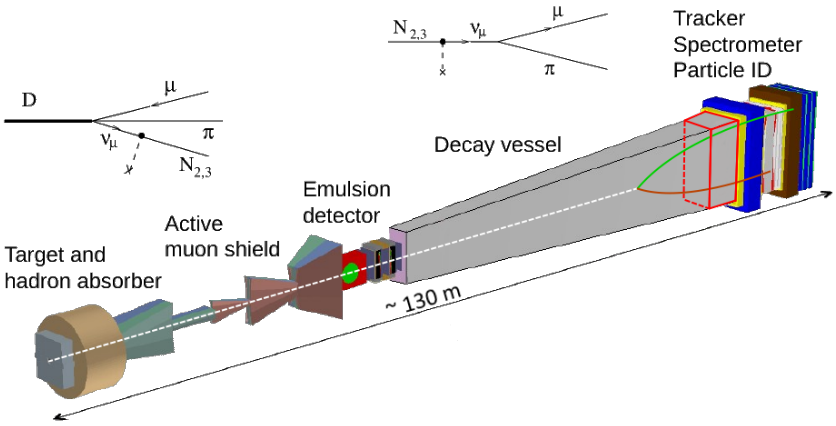

Figure 1: Sketch of the SHiP experiment facility

1.2 Decay vessel

The decay volume is a hollow squared base pyramid where the decays happen during the experiments. In order to capture a very accurate result in the detectors, the vessel is evacuated to eliminate the background from neutrinos interaction. As neutrinos and muons are very small elementary and interacting particles, they induce signal acquisition in the spectrometers. To prevent this interaction, the decay volume is surrounded by a thick 30 to 40 cm liquid scintillator producing light when interacting with unwanted particles. This system, explained in Appendix A, allows the physicists to know when a signal is created by a searched decay, or only by surrounding unwanted particles.

For the seismic fragility assessment study, two models have been studied independently: the "ring" model, and the "full" model. Both contains their own set of assumptions, but it is clear that the full model stays more reliable of the real behaviour of the decay vessel, which is why it was used for final assessment.

2 Decay Vessel Mechanical behaviour investigation

2.1 Finite Element model

Considering the 2023 version of the geometry, the finite element model has to take into account all the mechanical interactions to give adequate and representative results. This version, which was later improved, included 4 stiffening members at the top and bottom and 7 stiffening members on side walls. Theses numbers are some of the parameters to play within the geometry improvement analyses (2.4).

The ring and full decay vessel models were modelled using eight-point shell finite elements. The latter can model the 10 to 30 mm thick S355J0W steel sheets of the decay vessel, and are lighter in terms of computational time than solid elements. For physical experiment purposes, the inner vessel sheets (in red on Fig.2) are to be 30 mm thick, while the outer sheets and the stiffeners (in blue on Fig.2) are 10 mm thick.

The figure in Appendix B shows all the boundary conditions applied to the ring model in order to run the structural analyses. All the boundary conditions for the full model are shown in Appendix C. Another approach has also been studied of fixing all the grounded edges such as the supporting and the ones connected to the magnet and downstream spectrometer, while applying an horizontal acceleration in accordance to the earthquake record samples. As mentioned in Appendices B and C, the downstream decay volume is tightly contained inside a huge and heavy magnet and bolted to it. This led to the assumption of having a fully restrained back frame considering the magnet displaces the same exact way as the ground. In the full model, the upstream front end of the decay vessel holds a lid that cannot be represented on the ring model, whereas it is modelled by a constraint equation of the full decay vessel

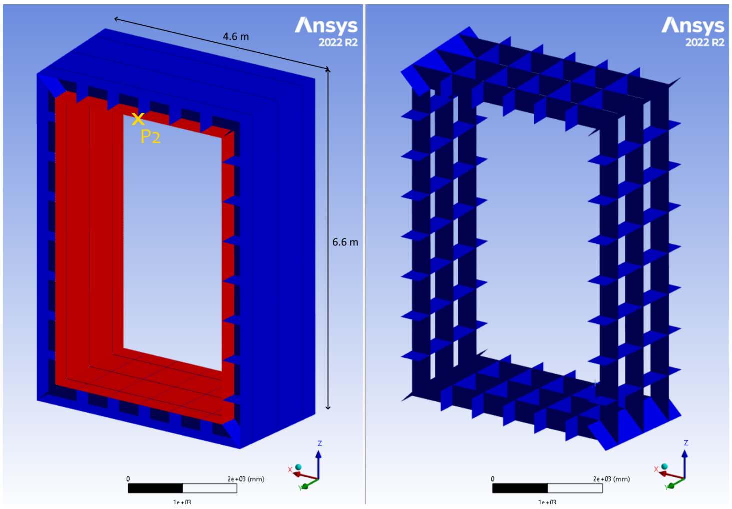

Figure 2: Ring model of 2.4 m meters long section

geometry to avoid having to mesh another complicated part. This is a fair assumption as the lid will be a plain structural steel massive front cap.

In order to conduct the structural assessment properly, I was provided with the EUROCODE 3: PRELIMINARY PART 1-14 and EUROCODE 3: PART 1-5 standards concerning the DESIGN OF STEEL STRUCTURES to give me a design methodology and to ensure that the structure qualification fully complies with this standard.

2.2 Modal analyses

To dynamically assess the decay vessel structure in seismic conditions, the first job was to analyse some typical earthquake records that the structure could be subject to. The raw seismic samples my supervisor provided me allowed to run Fast Fourier Transform in order to get typical frequency spectrum shown Fig. 3 of the earthquakes.

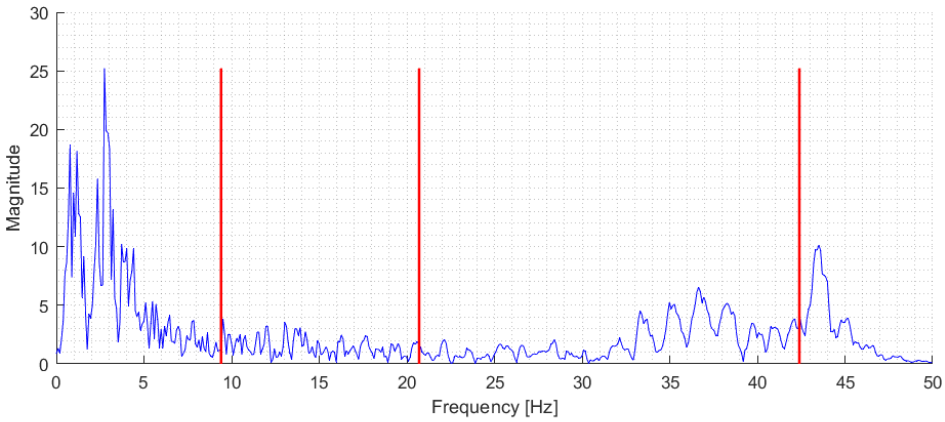

Figure 3: Frequency spectrum for typical earthquakes in Geneva region

Then I ran a modal analysis with ANSYS Mechanical software on the "ring" model to get the resonance modes. These are the frequencies at which the structure could be extremely sensitive if excited. A modal truncation allowed me to retrieve only the interesting natural frequencies regarding the seismic main excitation frequency range (from 0 to 5 Hz). The structure eigenfrequencies (resonance modes) are shown as red vertical lines in Fig.3.

The decay volume modal analysis is a useful tool to detect at a first glance whether an earthquake will or not have an impact on the structure behaviour. In future analyses, it was shown that certain earthquakes does not have any impact on the structure dynamic behaviour because the "ring" model could not be seen as representative of the overall dynamic behaviour of the vessel.

The red vertical lines characterize the natural frequencies of the "ring" model. The fundamental mode is the most critical one and the more exposed to earthquakes typical spectrum.

2.3 Time-history analyses

The objective of the time-history analysis is to assess the structural behaviour of the vessel, even during an active phase where the decay volume would be under vacuum and with walls filled of scintillating liquid. Mechanical time-history analyses are simulations where a structure is subjected to different accelerations that vary along time. It is here used to show that the dynamic behaviour of the structure can be investigated by equivalent non linear static ones, as resonance phenomena are not triggered.

The "ring" and the "full" decay vessel model were studied the one after the other. The dynamic analyses were initially done to represent the basic behaviour of the structure, so no geometrical non-linearities were taken into account, neither the structural and manufacturing defects, to avoid complicating the model. Later in the equivalent static analyses, a non-linear material model was applied to some relevant elements of the supporting structure to get more reliable results, even though the plasticity state was not reached. The analyses needed to be run on an High Throughput Computing (HTC) cluster because of the duration of the earthquakes time history records used as boundary conditions at the supports location, and the use of a fine mesh on a large structure.

In the late stage of the internship, the validation of the equivalent static analysis results allowed me to carry out the further analyses by constant values of the acceleration to the lumped masses implemented in the models. In other terms, this was simply done by applying a static force corresponding to:

$$F_{static} = m_{decay\ vessel} \cdot PGA \tag{1}$$

Where:

F_{static} is the force applied on the entire decay volume representing the dynamic behaviour
$m_{decay\ vessel}$ is the decay vessel mass, also taking into account the liquid scintillator
PGA is the peak ground acceleration of the considered earthquake

A set of benchmarking tests have been led in order to characterize this method, and the maximum error in the results stays below 3%. 125 analyses cases were run in order to get sufficient number of points for determining reliable indicators and criteria.

These analyses were accompanied by a set of experimental design values corresponding to most of the model parameters. This experimental design was done using the Latin Hypercube Sampling method and helped represent all the possible analyses cases considering manufacturing, geometrical and even input loads uncertainties.

2.4 Geometry improvements

The initial geometry to analyse at the very beginning had not been updated since 2018. By the time that separates this date from my first analyses, the decay vessel model and geometry did change though. Also, this 2018 geometry version was not at all optimized, so the first thing to do was to update to the new geometry.

Following meetings with Richard Jacobsson, Project Leader of SHiP, it has been clear that the lighter the structure would be the better. Then some optimization started, by reducing the stiffeners heights and optimizing all the sheets sizes. The number of stiffening members were also sets a variable parameter to change in order to get the optimal lighter geometry.

The tests ran during the optimization process take into account SHiP active phase loads such as the vacuum, the self-weight and the hydrostatic pressure but also the seismic loads that the decay vessel should handle.

3 Seismic fragility Assessment

To consider the assessment of the decay vessel regarding the seismic actions, it has been necessary to define the so called "limit states".

Three limit states were defined:

- $\rho \cdot \alpha_{ult,k}$: extracted from the Eurocode 3 Part: 1-5 [3] characterize the stress limit state by a minimum critical load multiplier to reach the buckling instability at the most critical point of the most concerned plate [3].
- $\sigma_{eq,VM}/f_y$: Von Mises strength criteria limit state taken relatively to the material yield stress.
- $\epsilon_{diag}/\epsilon_y$: ratio of the effective axial strain over the acceptable yield strain of the only diagonal support preventing the decay vessel to bend horizontally.
- $\epsilon_{diag}/\epsilon_u$: ratio of the effective axial strain over the acceptable ultimate strain of the only diagonal support preventing the decay vessel to bend horizontally.
- δ_{max} : limit state representing the serviceability of the decay vessel. In case the latter deflects too much from its original position, it would compromise the experiment capabilities and precision.

The dynamic analyses results allowed to retrieve the values of these limit state variables. The plots of the relevant limit states are shown in Appendix D.

The first limit state D.1 concerns the structural acceptance of the decay vessel wall plates. This is somehow the most safety related limit state as it gives a criterion of whether the decay volume will or not handle the seismic loads without presenting buckling phenomena in its outer structural elements. The natural logarithm of the real limit state value $\rho{\cdot}\alpha_{ult,\ k}$ sets *zero* as the threshold below which experimental design values must not fall, otherwise the structure would become unsuitable for use. This plots shows that the structure can handle at least a $1.5[g]$ PGA earthquake, which is well above the historical records for the Geneva region.

The diagonal brace support limit state D.3 shows up to which percentage of the material yield strain the effective diagonal strain goes. Reaching a value of $100\ \%$ would indicate that the diagonal brace supports has reached the plastic domain. This plastic domain is an irreversible deformation state which could necessitate immediate maintenance if reached.

The upstream decay vessel displacement limit state D.5 is important for the experimental physics section. In fact, it shows how much the decay vessel deflects at maximum in case of earthquake. This deflection, if too high, can cause experimental errors or damages on the upstream components of SHiP experiment. The threshold not to exceed is still not well defined as the upstream decay vessel mounting system is not yet well defined.

The fragility curve for the Von Mises criteria limit state is then plot Fig. 4 to show in one graph the result of the seismic decay vessel fragility assessment. This graph shows the probability of exceeding the limit state threshold versus the PGA. In Fig. 4 is plotted the probability curve of (to be completed).

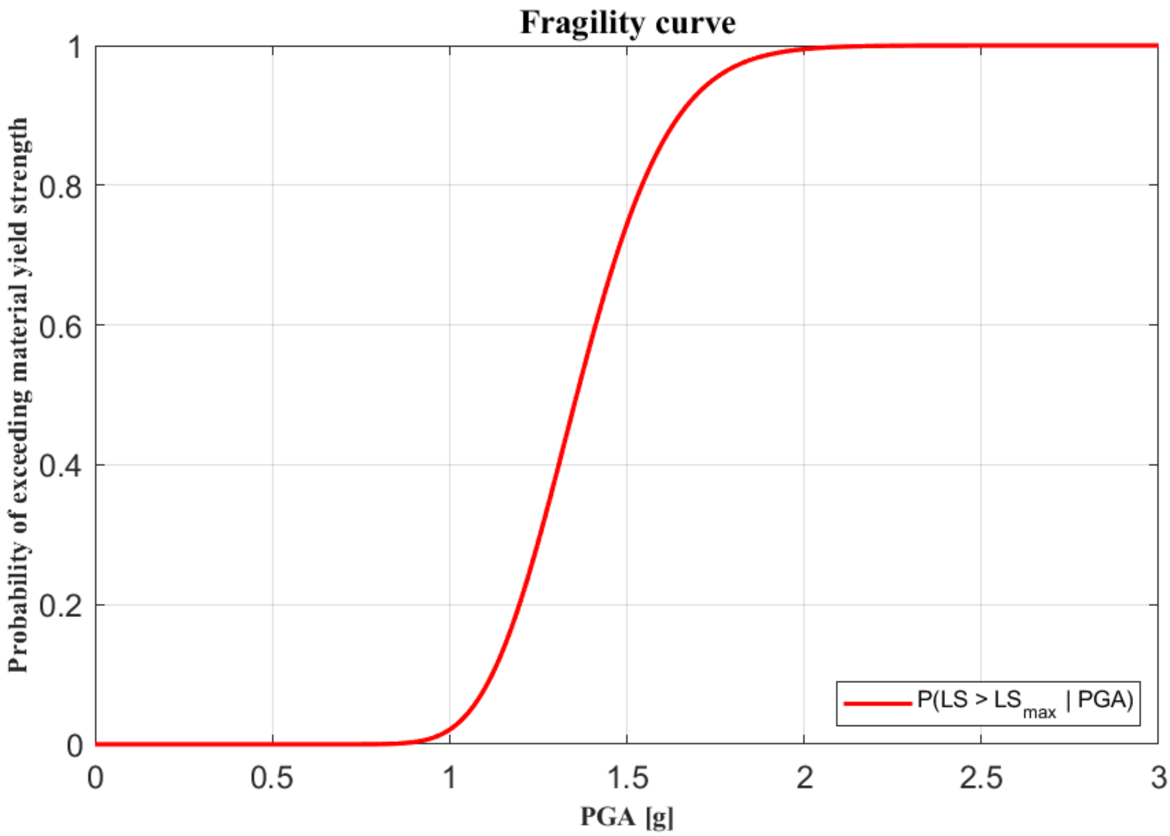

Figure 4: Final seismic fragility assessment using the fragility curves

Acknowledgements

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First and foremost, I would like to thank Marco Andreini, my internship supervisor in HSE Department, Deputy Leader of the Infrastructure and Building Safety Engineering and highly experimented in mechanical engineering and seismic risk assessment. His expertise and insights have been instrumental in shaping my professional growth. All the interesting chats we had helped me to develop tremendously and have definitely shaped my knowledge.

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In conclusion, I am grateful to everyone who played a part in making my internship experience rewarding and memorable. The knowledge and experiences gained during this internship will undoubtedly shape my future endeavors. Thank you all for your unwavering support and guidance.

Sincerely, Felix Bonnes

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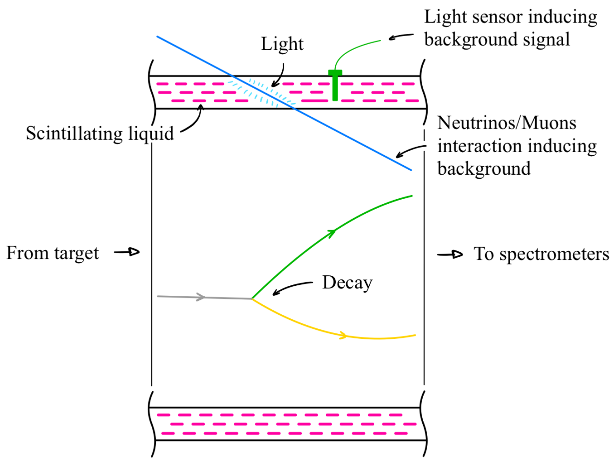
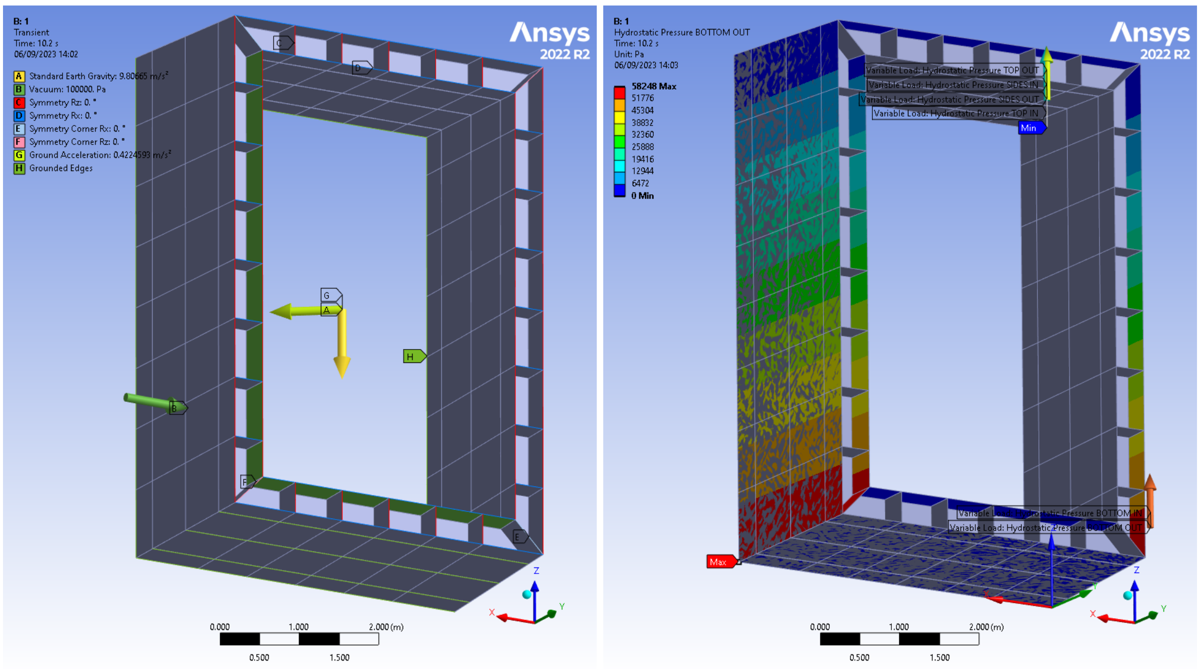
[3] The European Union Per Regulation 305/2011, Directive 98/34/EC, Directive 2004/18/EC, EN 1993-1-5: Eurocode 3: Design of steel structures - Part 1-5: General rules - Plated structural elements (2007)

Appendix

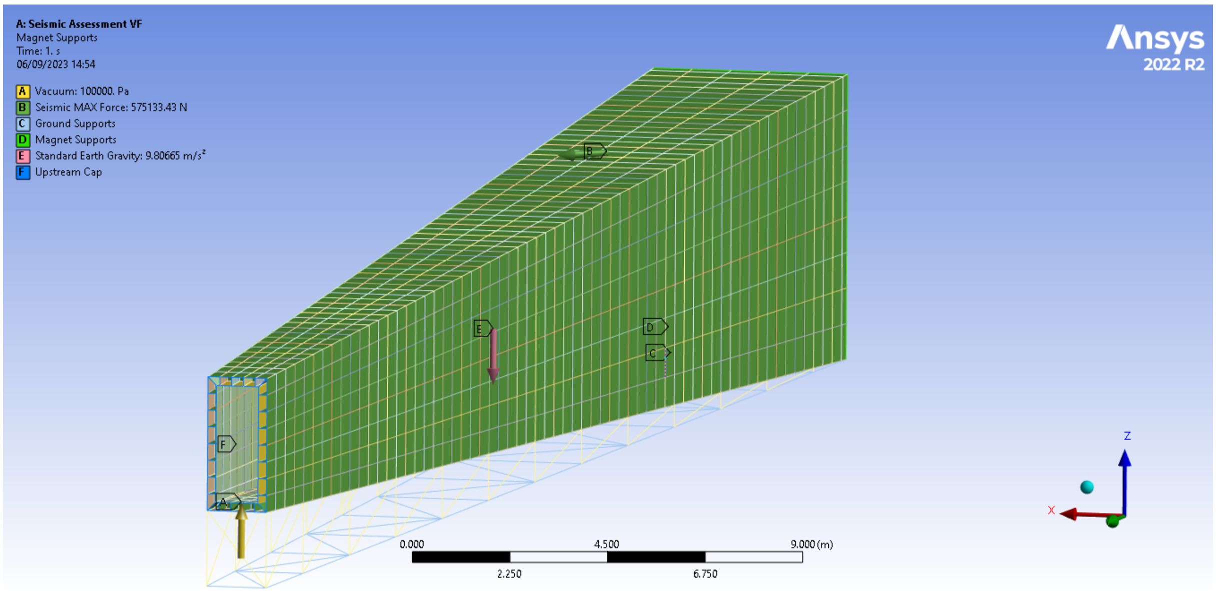
A Azimutal section of the decay vessel showing the usefulness of the scintillating liquid

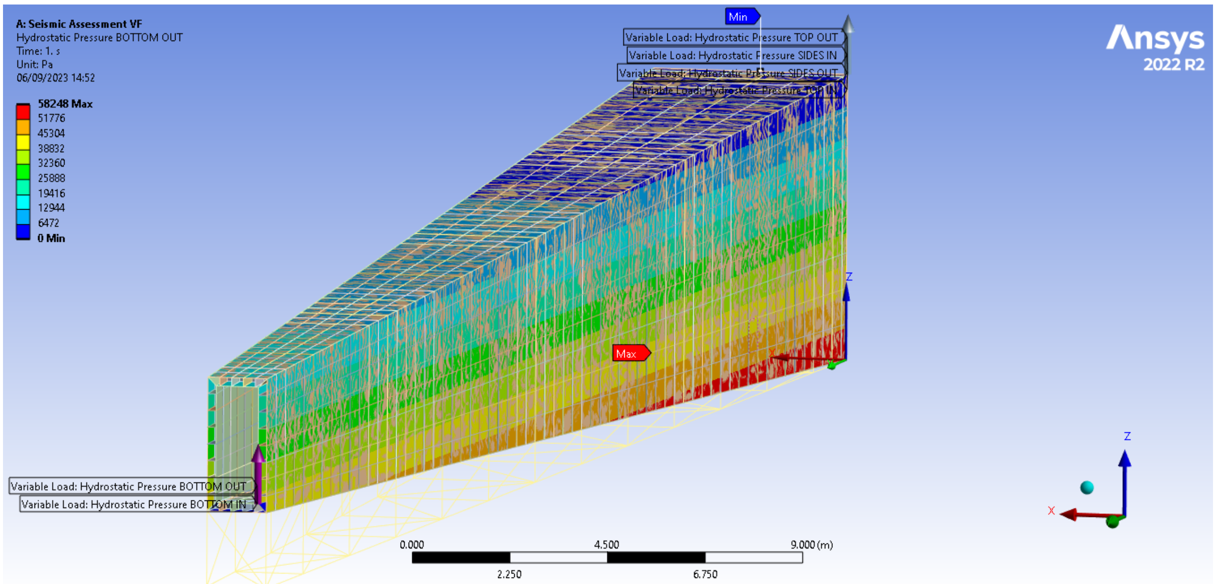


B Loads and boundary conditions applied to the ring model



C Loads and boundary conditions applied to the full model





D Fragility assessment limit states

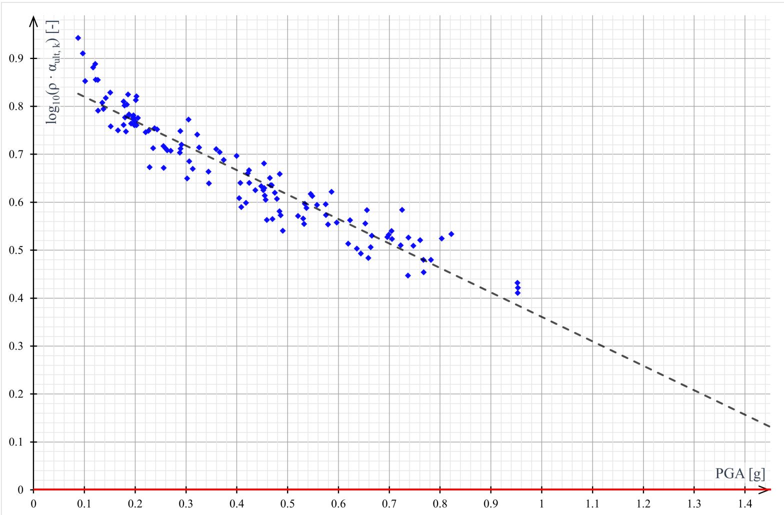


Figure D.1: Mechanical acceptance in regards to buckling limit state according to Eurocode 3 [3]

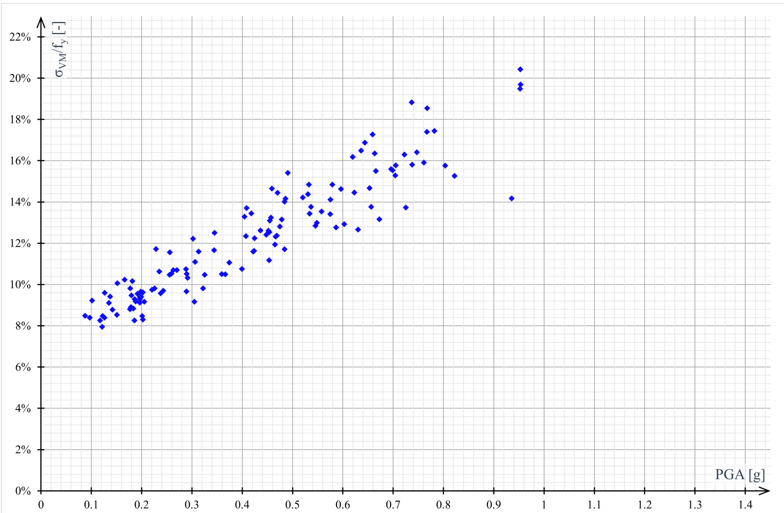


Figure D.2: Von Mises crtieria limit state relative to the material yield stress

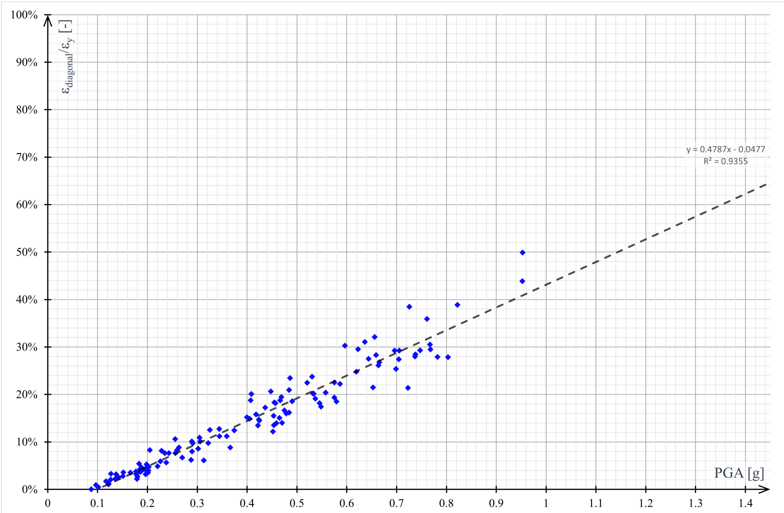


Figure D.3: Diagonal brace support strain limit state relative to the material yield strain

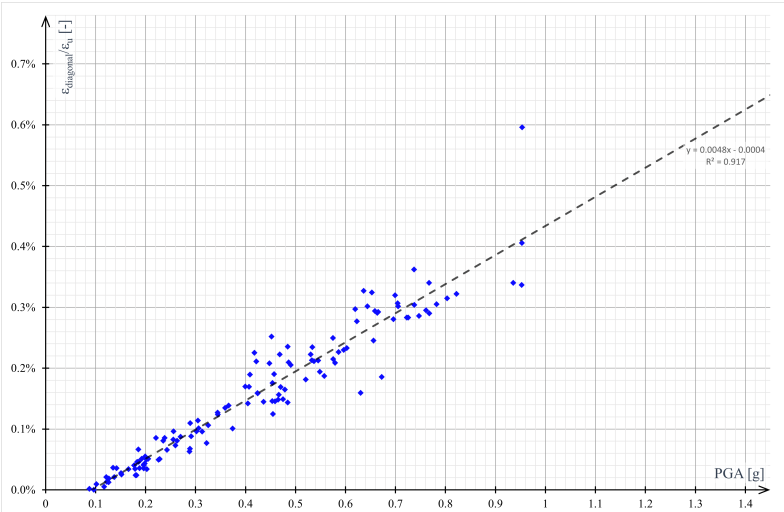


Figure D.4: Diagonal brace support strain limit state relative to the material ultimate strain

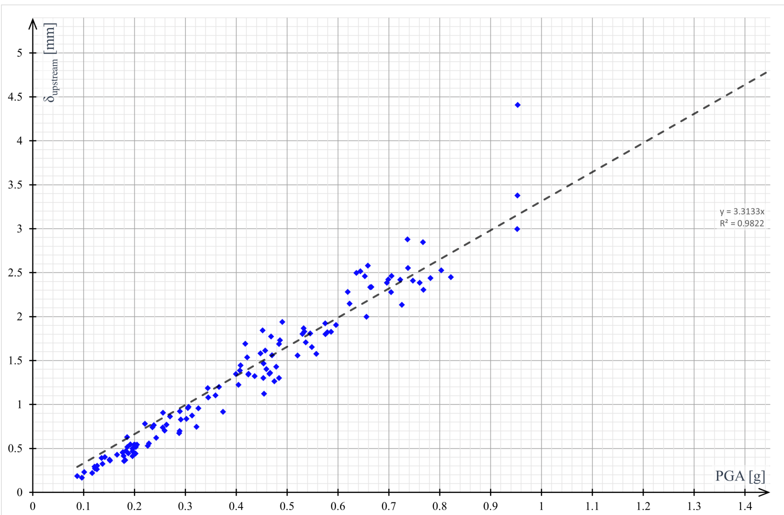


Figure D.5: Upstream decay vessel maximum displacement limit state