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Master Thesis

Optimization of Carbon Fiber Support Structures for the Upgrade of the Vertex Detector of the Belle II Experiment

Supervisors:

Prof. Mario Rosario Chiarelli

Prof. Stefano Bettarini

Ing. Andrea Moggi

Ing. Maurizio Massa

Candidate:

Margherita Rovini

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Abstract

The Belle II experiment, currently operating at the SuperKEKB collider in Tsukuba, Japan, is designed to explore physics beyond the Standard Model, with a particular emphasis on the study of CP violation in B-meson decays. Achieving the high luminosity required for such precision studies demands a vertex detector capable of combining excellent spatial resolution, mechanical stability, and a minimized material budget. Within this framework, the development of the new Vertex Detector (VTX), based on monolithic CMOS OBELIX sensors, has been proposed to replace the current PXD and SVD systems. This thesis focuses specifically on the mechanical design of the outer VTX (oVTX) support structures, which constitute the outermost layers of the detector, in particular on the optimization of the layer six ($L6$) ladder which is the most mechanical challenging layer .

The work begins with an overview of the experimental requirements and environmental constraints, including alignment tolerances, thermal management, radiation hardness, and robustness against mechanical stresses and seismic events. It then addresses the selection of structural materials, the design of ladder prototype, and its assembly processes, with particular attention to minimizing the material budget while ensuring long-term stability.

Then a dedicated chapter presents the experimental tests carried out on the prototype ladder to evaluate their mechanical response under controlled loading conditions. These measurements are complemented by finite element simulations performed with ANSYS, which allow validation of the design assumptions and guide possible optimizations.

The thesis concludes with a discussion of the trade-off to choose the optimized design. The trade-off has been conducted between the material budget evaluation and the minimum ladder deflection, highlighting the balance between mechanical performance and detector transparency requirements.

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List of Acronyms

ACP	Ansys Composite PrepPost
AIREX	Lightweight structural foam used as core
ALICE	A Large Ion Collider Experiment
ANSYS	Analysis System for Finite Element Analysis
CF	Carbon Fiber
CFRP	Carbon Fiber Reinforced Polymer
CMM	Coordinate Measuring Machine
CMOS	Complementary Metal-Oxide-Semiconductor
CTE	Coefficient of Thermal Expansion
DSSD	Double-Sided Silicon Strip Detector
FEA	Finite Element Analysis
GG52	Type of high-modulus carbon fiber
HM	High Modulus
IR	Interaction Region
iVTX	Inner Vertex Detector

M46J	High-modulus Toray carbon fiber
OBELIX	Outer Belle II monolithic CMOS sensor
oVTX	Outer Vertex Detector
PXD	Pixel Detector
RDL	Redistribution Layer
RSA	Rib Sub-Assembly
SM	Standard Model
SuperKEKB	Acceleratore di particelle del KEK, Giappone
SVD	Silicon Vertex Detector
VTX	Vertex Detector
VXD	Vertex Detector (PXD+SVD)

List of Symbols

A	Atomic number or Avogadro constant
E	Young's modulus [GPa]
K	Thermal conductivity [$W/(m^\circ C)$]
L	Ladder length [mm]
T	Temperature [$^\circ C$]
V	Volume [mm^3]
X	Equivalent thickness [mm]
X/X_0	Material budget (fraction of the radiation length) [%]
X_0	Radiation length [cm]
Z	Atomic number
Θ_0	RMS multiple scattering angle [rad]
α	Coefficient of thermal expansion (CTE) [ppm/K]
ϕ	Azimuthal angle [$^\circ$]
ρ	Density [kg/m^3]
θ	Polar angle (acceptance) [$^\circ$]
f	Natural frequency [Hz]
g	Gravitational acceleration [m/s^2]
t	Layer or ply thickness [μm]

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Chapter 1

The Belle II experiment

1.1 The physics of Belle II

High-energy physics investigates the fundamental particles and interactions that constitute matter and radiation. The primary tools of this field are particle accelerators, which generate new particles by colliding high-energy beams, and the complex detector systems built around them to identify and analyze the resulting collision products.

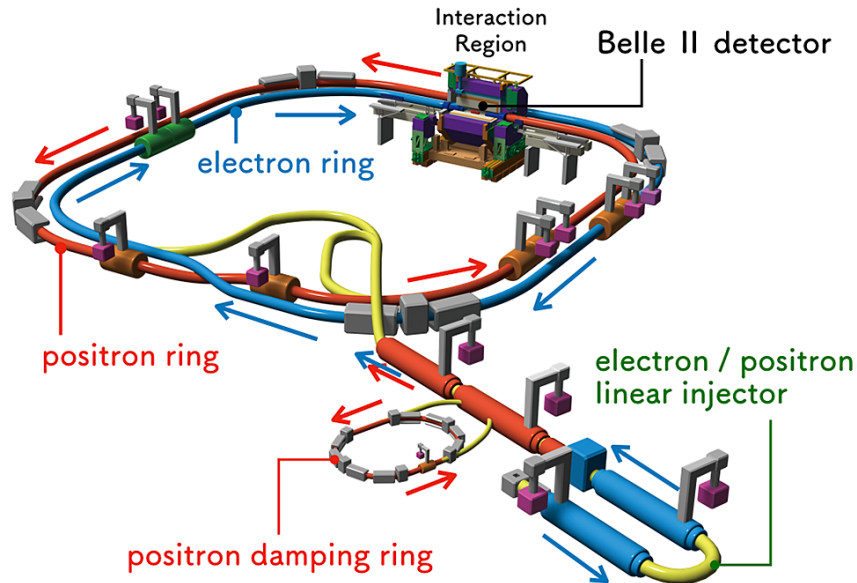


Figure 1.1: Schematic view of SuperKEKB Main Ring. The electron and positron rings have four straight sections named Tsukuba, Oho, Fuji, and Nikko. The electron and positron beams collide at the interaction point in the Tsukuba straight section.

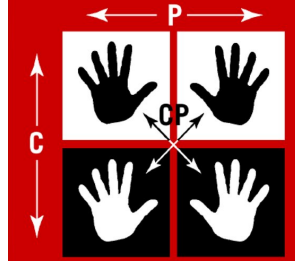


Figure 1.2: CP symmetry, a combination of the C transformations (charge conjugation of the particles) and P transformations (mirror reflection of the coordinates).

Belle II is a general-purpose particle detector operating at the SuperKEKB collider located at the KEK research center in Tsukuba, Japan. SuperKEKB is a next-generation B-factory, building upon the technological and scientific advances of its predecessors, PEP-II and KEKB. The principal aim of Belle II is to search for evidence of New Physics (NP). Although the Standard Model is one of the most experimentally validated frameworks in physics, it fails to account for several fundamental phenomena, most notably, the matter-antimatter asymmetry observed in the universe. CP violation is thought to play a role in this imbalance.

The CP symmetry is the combination of the charge conjugation $\mathbf{C}$, which converts a particle into its corresponding anti-particle by inverting the charge, with the mirror reflection $\mathbf{P}$, that is an inversion of the spatial coordinates (figure 1.2). Thus a violation of the CP symmetry introduces a difference between matter and anti-matter and it has been allocated inside the current theory of the fundamental interactions in particle physics, the so-called "Standard Model" (SM). Experimentally the CP violation has been discovered by the physicists Cronin and Fitch in the neutral K meson system in 1964 [1] and by the experiments BaBar [2] e Belle in the neutral B mesons in 2001. Quantitatively, the amount of CP asymmetry inside the SM has been proven (Sakharov, in 1967 [3]) not to be enough to explain the observed abundance of the matter in the universe, leaving unsolved the problem of the source of the matter/anti-matter asymmetry, a field where theories beyond SM (New Physics) might hopefully provide a solution. Therefore, SuperKEKB/Belle II aim to search for New Physics effects linked to CP violation.

High-energy accelerator such as SuperKEKB, called B-factory, are specifically de-

signed to study CP violation in B meson decays, a hypothesis originally proposed by Bigi, Sanda, and Carter in the 1980s [4]. B-factories facilitate electron-positron collisions at 7 GeV and 4 GeV . Beams of electrons and positrons are circulated in opposite directions in a circular accelerator and collide at a center-of-mass energy corresponding to the mass of the Upsilon meson (10.58 GeV). Due to the asymmetric beam energies, the decay products are boosted, increasing the spatial separation between the decay vertices of the two B mesons to measurable distances (order of $250\text{ }\mu\text{m}$ on average).

Another key feature of B-factories is the high instantaneous luminosity. Since the branching ratio for CP-violating decays of B mesons is on the order of 10^{-4} , an extremely large number of B mesons must be produced, necessitating high luminosity. Using the nanobeam collision scheme, SuperKEKB achieved an instantaneous luminosity of $5.1 \times 10^{34}\text{ cm}^{-2}\text{s}^{-1}$ as of December 27, 2024 (World record)[5], with a long-term goal of reaching $6 \times 10^{35}\text{ cm}^{-2}\text{s}^{-1}$, corresponding to an integrated luminosity of 50 ab^{-1} in the ten years of lifespan of the experiment [6].

Detectors like Belle II must handle extremely high data throughput within very short time intervals. Furthermore, due to the intense radiation environment, the detectors must maintain structural and electronic stability over extended operational periods without compromising data acquisition performance. Meeting these requirements demands extensive technological development, making the engineering effort equally important as the physics's theoretical studies and data analysis of the high-energy experiments. Finally, detectors at B-factories must accurately identify the particles produced in the collisions and precisely reconstruct the production vertices. These capabilities are essential for resolving the extremely short-lived and complex decay chains characteristic of B meson events.

1.2 The key parameters for a particle detector

To have a clear overview of Belle II detector and its functioning, it is important to understand the key parameters driving the design of an experiment in high-energy

physics. Below the main factor are listed:

- **Luminosity (L):** it is a key parameter of the performance of a collider in terms of its ability to produce particle interactions. It represents the number of particles passing through a unit area per unit time and is directly related to the rate ($\mathcal{R} = L \cdot \sigma$) of events occurring with a probability described by the cross-section σ . The instantaneous luminosity, expressed in $cm^{-2}s^{-1}$, determines how many events can be observed per second, and is given by the formula:

$$L = \frac{N_1 \cdot N_2 \cdot f}{A} \quad (1.1)$$

where:

- N_1 and N_2 are the number of colliding particles in each bunch,
- f is the collision frequency,
- A is the effective cross-sectional area of the beams at the interaction point.

The amount of recorded data is proportional to the integrated luminosity ($\mathcal{L}_{\text{int}}$), measured in inverse attobarns (ab^{-1}), reflects the total number of interactions accumulated over time and it is essential for estimating the expected number of events through the relation:

$$N = \mathcal{L}_{\text{int}} \cdot \sigma \quad (1.2)$$

where $\mathcal{L}_{\text{int}} = \int L dt$ is the time-integrated luminosity and σ is the cross-section of the process under study. At the Belle II experiment, high-luminosity electron-positron collisions are essential for exploring rare processes and testing the limits of the Standard Model.

- **Radiation lenght:** in tracking systems, minimizing the material of the detector is essential to reduce multiple scattering, which affects track resolution. The amount of material around the interaction point is quantified in terms of X/X_0 ,

equivalent thickness expressed in radiation length. The radiation length X_0 is a material's characteristic, which depends on the atomic number. Materials with lower Z are more transparent to radiation. Multiple scattering effect, related to the radiation length, causes particle angular deflections and becomes especially critical near the interaction point. Therefore, minimizing the material budget, especially near the interaction point, is critical to maintain accurate track measurements and ensuring the quality of the physics analysis. This parameter is going to be further discussed in section 2.2.1.

- **Hit rate:** it is the number of particle hits detected per unit area and time in a given part of the detector. It is typically expressed in MHz/cm^2 and reflects the sum of signal and background levels the detector must handle.
- **Integrated dose:** is the total amount of ionizing radiation absorbed by a detector component during its operation, usually expressed in megarad (in S.I. $1\text{ Gy} = 100\text{ rad}$). It is a key parameter for evaluating the radiation damage and designing radiation-tolerant systems.

1.3 The Belle II detector

Compared to its predecessor, Belle II detector is located at the interaction point of the SuperKEKB accelerator with instantaneous luminosity forty times greater than that of KEKB. Therefore, its design has been conceived to allow similar or better performance than Belle in a harsher environment characterized by a higher beam background and the necessity to collect a higher volume of data.

The main project requirements for Belle II are:

- High resolution on each decaying vertex (about $100\text{ }\mu\text{m}$) needed for all time-dependent measures;
- High impulse and energy resolution, necessary to distinguish particles of interest from background;

- Effective detection particle system, along all the experiment spectral momenta;
- Acceptance enough to cover the maximum solid angle, taking into account the asymmetry of the accelerator, to maximize statistics;
- Fast and efficient trigger system, which quickly selects interesting collision events filtering out background events;
- As low as possible material budget to have minimum uncertainty on tracking due to multiple scattering;

All these requests have led to the current structure of Belle II, composed of subdetectors eachone built to accomplish specific and different requirements. These various detectors are arranged in cylindrical layers around the beam pipe, optimized to detect any of the decay products in the reaction, figure 1.3. The whole Belle II detector is 8 meters wide, 8 meters high and weighs 1,400 tons altogether. Below, the subdetectors are presented in brief, starting from the interaction point (IP) until the outside,[7],:

- **VXD**, the vertex detector, the closest to the interaction point which is divided into two further subsystems. In December 2023, the first planned long shutdown was completed with the installation of two-layer Pixel Vertex Detector (PXD), which is VXD's innermost part. As the innermost sub-detector, multiple scattering effects need to be as minimum as possible. PXD utilizes active pixel sensors, for a material budget of 0.21% per layer. PXD consists of 51 sensors of two layers (numbered 1-2) and its main goal is the precise determination of the decay vertices. Outside PXD is the silicon-strip vertex detector (SVD) with four layers (numbered 3-6) that mostly extrapolates the measured tracks to PXD, defining the so-called region of interest (ROI), which significantly reduces the amount of data recorded by PXD. The SVD also performs standalone tracking for low-momentum charged particles and contributes to their identification by providing energy loss information. The six-layer VXD allows to determine the position of the vertices with a precision better than 100 μm . As its upgrade is the core of this thesis, it will be discussed in more depth in the next paragraph.

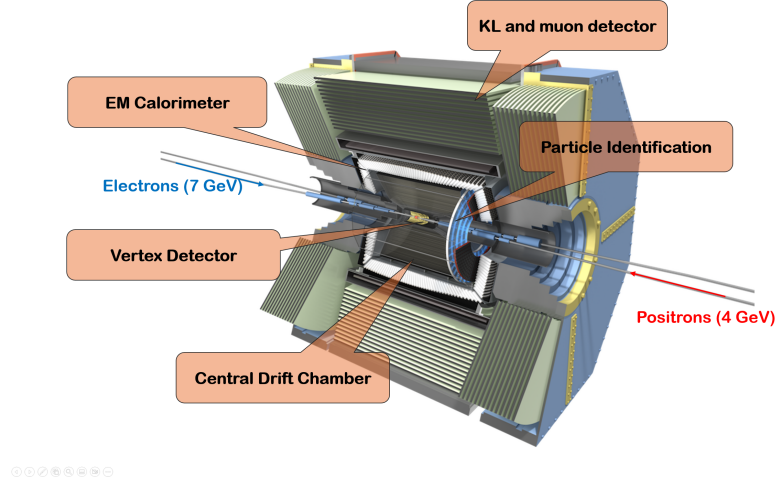


Figure 1.3: Belle II detector with all its components.

- **CDC**, Central Drift Chamber, detects charged particles and measures their momentum under magnetic field. It also provides pulse height information of the charged particle to identify particle species. The signal pulse height is proportional to the energy loss of the charged particle. Also, the time between particle passing in the cell and the signal creation is measured, which is called “drift time”.
- **TOP and ARICH**, the two Cherenkov detectors, their objective is to identify particles through their different Cherenkov light cones, emitted throughout their path.
- **ECL**, the electromagnetic calorimeter, measures the angle and energy of photons.
- After ECL, there is the **superconductive solenoid** which creates a magnetic field of about 1.5 T , allowing bending of charged particles to measure transverse momentum.
- **KLM**, KL–Muon detector, it is used to detect particles with long time of life like KL mesons and muons (approximately one per event). KLM consists of the barrel part with 15 layers and two end caps, forward and backward, with 14 and 12 layers, respectively. Two inner barrel layers and entire end caps are instrumented with scintillator strips; 13 outer barrel layers are instrumented with Resistive Plate Counters (RPC).

1.4 The current Belle II Vertex Detector VXD

In order to provide context for the planned upgrade of the Vertex Detector (VTX), this section presents a brief overview of the current Belle II Vertex Detector (VXD). Understanding its design and performance is essential, as the goal of this thesis is to contribute to the optimization of its successor. The VXD was specifically developed to offer enhanced spatial resolution compared to its predecessor in the Belle experiment, compensating for the lower Lorentz boost at SuperKEKB. This improvement is achieved with more precise point resolution, a reduced inner radius and a low material budget. Moreover, it must operate in a high background environment with a hit rate of $20(3) \text{ MHz/cm}^2$ and an integrated yearly dose of $2(0.2) \text{ Mrad}$ at a radius of $14(40) \text{ mm}$. Figure 1.4 shows the cross-section view of the Belle II vertex detector. It is composed of two layers of DEPFET pixel sensors (PXD), with the innermost layer at 14 mm from the interaction point, and four layers of double-sided silicon strip sensors (SVD).

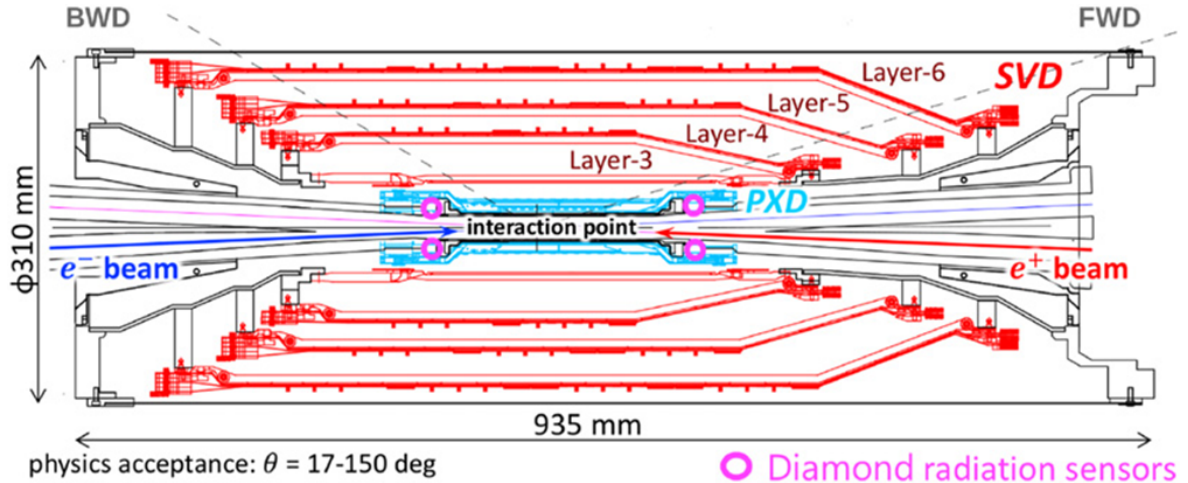


Figure 1.4: The cross-section view of the Belle II vertex detector: SVD and PXD are represented with red and light blue colour, respectively. The pink circles indicate the positions of the diamond sensors installed on the beam pipe.

1.4.1 Pixel Detector PXD

The two layers of PXD are mounted on the 20 mm diameter beam pipe at a radius of 14 mm and 22 mm from the interaction point (IP), counting 8 and 12 ladders re-

spectively according to design. A ladder is formed by two PXD modules coupled symmetrically together with an edge-to-edge glue joint. As depicted in Figure ??, PXD module, with dimensions $1.5 \times 8.5 \text{ cm}^2$, is made up of three main regions:

- The active area, which hosts 250×768 pixels with a varying pixel size of $50 \times 55 - 85 \mu\text{m}^2$. This design allows for both signal detection and first-stage amplification within each pixel, leading to low noise performance and enabling the creation of a thin, radiation-hard detector.
- The balcony alongside the sensitive area,
- the End-Of-Stave (EOS) region of the module,

The readout electronics at EOS are the components with the highest power consumption and heat dissipation, which require active cooling. Thus, the EOS of the modules is mounted on the Cooling Block (CB), which is cooled by a two-phase CO_2 cooling system. Active cooling is also used for the pixel matrix and the balcony area by utilizing carbon tubes around the detector with N_2 flow. The module powering, the control signals and the data transmission are transferred via the Kapton cables at the outer side of the modules. Each ladder has an overlap of 1 mm with the near ladder: this helps symmetrically cover all the area along the beam-pipe with an acceptance angle between 15° and 150° . Furthermore, the overlapping of the sensitive area permits to evaluate the alignment of the ladder and to improve the reconstruction of the particle path increasing the vertex resolution. The material budget of each sensor is around $0.2\% X_0$.

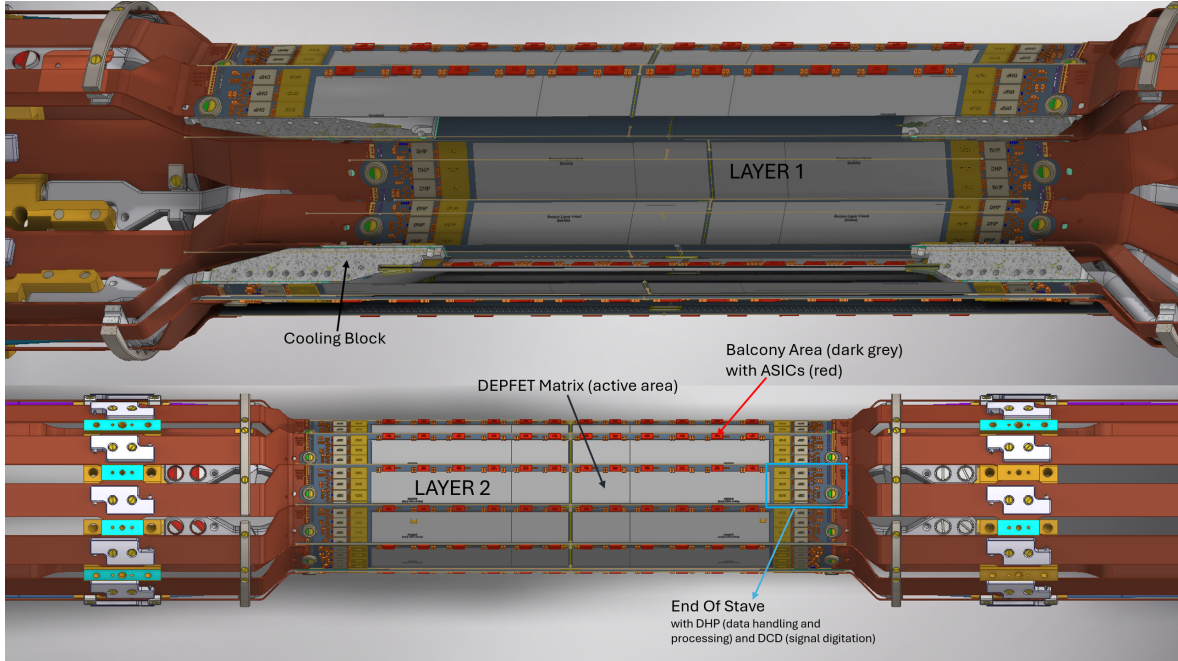


Figure 1.5: Complete CAD design of the PXD from Belle II collaboration.

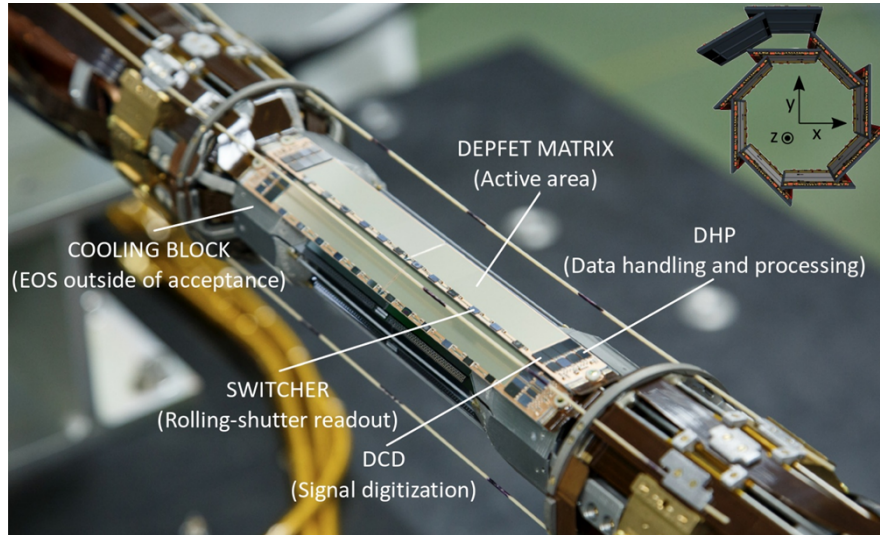


Figure 1.6: The PXD mounted around the interaction point.

1.4.2 SVD: the Silicon-Strip Vertex Detector

The SVD detector [8] consists of four layers with cylindrical symmetry numbered 3, 4, 5 and 6 with a radius distance from IP of 39 mm , 80 mm , 104 mm and 135 mm , which are composed of seven, ten, twelve and sixteen ladders with two, three, four and five sensors, respectively. As for PXD it covers an acceptance angle from 17° to 150° . Its material budget is 0.7% of the radiation length X_0 per layer on average.

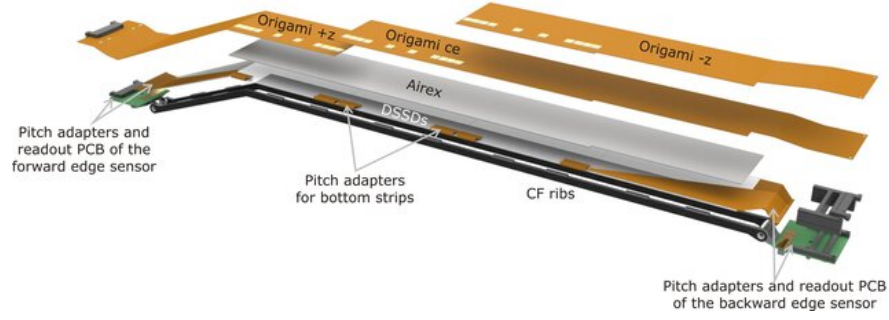


Figure 1.7: Exploded view of a layer 6 SVD ladder from Belle II collaboration. From bottom to top: rib sub-assembly, four rectangular and one trapezoidal DSSDs, pitch adapters, hybrid boards at both ends of the ladder, AIREX foam, three versions of origami flexes.

The underlying sensor technology is based on the well-established Double-sided Silicon Strip Detector (DSSD) design. The SVD employs a total of 172 DSSDs, covering an active area of approximately 1.2 m^2 and comprising around 224,000 individual readout strips. In Layer 3, each module contains two smaller-pitch, rectangular DSSDs. Layers 4 through 6 use larger rectangular sensors in the central region, and trapezoidal sensors in the forward and backward regions, giving the ladder modules a lamp-like shape.

The mechanical integration of each individual detector and their thermal control are also challenging. Each layer is organized in mechanically and electrically independent subsystem called ladders (Figure 1.9). Two carbon fiber (CF) reinforced ribs, with a 3mm light core, were chosen as the mechanical support structure, onto which the sensors are glued with epoxy. For thermal control an active cooling based on dual-phase CO_2 is needed to remove heat produced by the electronic part of the sensors. On the origami board, all chips are aligned, such that they can be cooled using a single tube flowing dual-phase CO_2 . At their ends the ribs are glued into aluminium blocks called end-mounts, creating the Rib Sub-Assembly (RSA). In L4, L5 and L6 precisely milled pins are inserted into holes located underneath the hybrid boards in the center of the end-mounts. With these pins, named “kokeshi-pin”, the ladders are plugged into the precision holes of the end-rings and finally fixed with set screws. On the forward side there is a sliding mechanism to compensate for the thermal expansion of the ladder.

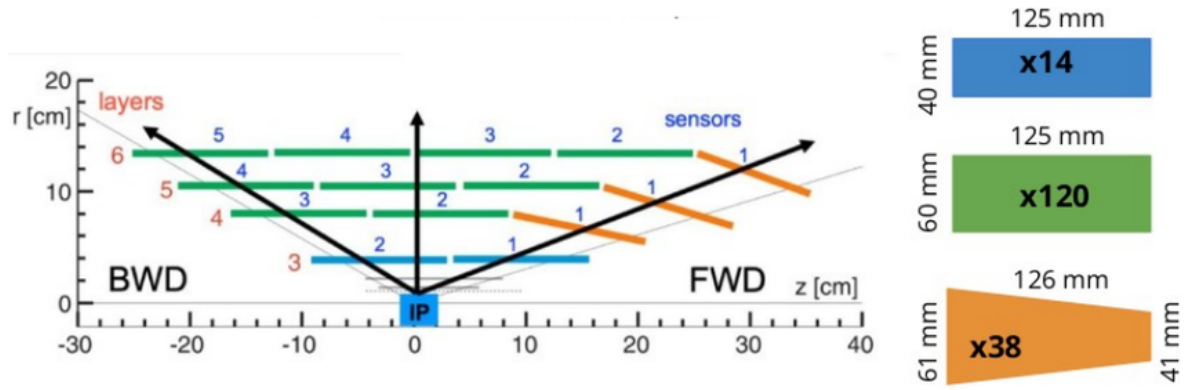


Figure 1.8: Schematic picture of SVD sensors forming the different layers.

Type	Number of readout strips		Readout pitch (μm)		Thickness (μm)
	P side	N side	P side	N side	
Small	768	768	50	160	320
Large	768	512	75	240	320
Trapezoidal	768	512	50 - 75	240	300

Figure 1.9: SVD table summarizing the parameters for each type of sensor.

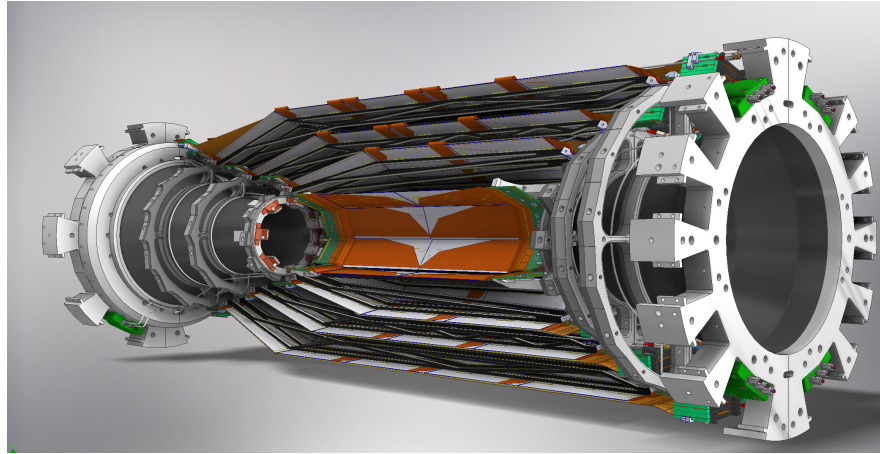


Figure 1.10: SVD CAD design of one halves from Belle II collaboration.. The end-rings are designed in total but it is possible to see the dividing line of the two halves in the end-ring itself

The entire SVD is longitudinally divided into two azimuthal halves, which are separately assembled before being mounted on the beam pipe and the PXD layers. The ladders of each half are supported and held in position at their two ends by joining the ladder aluminum end-mounts to stainless-steel (half) end-rings precisely glued on forward and backward carbon-fiber (half) end-cones. Lastly, as for PXD, ladders have an overlapping zone of about 1 mm to avoid blind zone and to help with the alignment.

1.5 The Upgrade of the Inner Detector

Since 2019, VXD has been operating providing high quality data with an efficiency greater than 90%. Although PXD and SVD have been built to cope with high background radiation, the operating peak luminosity is $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ is largely below the goal luminosity of $6 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$. Reaching new levels of luminosity is going to increase also the backgrounds, therefore PXD and SVD performances could be negatively affected. In addition, the background occupancy in SVD is below 0.4% in Layer 3 so there was no need for a background rejection strategy in data reconstruction. Increasing the luminosity, the background occupancy could become 3% in Layer 3, and while it is still below SVD operational limits, margins against adverse effects are limited. The upgrade program is therefore motivated by several considerations [9]:

- Improve detector robustness against backgrounds.
- Provide larger safety factors for running at higher luminosity.
- Increase longer term subdetector radiation resistance.
- Develop the technology to cope with different future paths, for instance if a major interaction region (IR) redesign is required to reach the target luminosity.
- Improve overall physics performance.

The innovation effort for Belle II is going towards the realization of a CMOS-based successor to PXD and SVD detectors at a lower overall cost. The monolithic CMOS option is presented as the baseline of the VXD upgrade and is implemented through the development of the OBELIX sensor discussed below. For the upgrade project it is assumed that the new vertex detector would occupy the same volume as the current VXD (between 14 mm and 135 mm radius). A good particle hit spatial resolution below $15 \text{ }\mu\text{m}$ is required, along with a low material budget around $0.2\% X_0$ per layer for the inner radii and $0.3 - 0.8\% X_0$ per layer for the outer radii.

1.5.1 The VTX layout

Among the various possibilities considered for the Belle II upgrade, the development of CMOS-based successor to the PXD and SVD has emerged as the most promising solution [9]. The monolithic active pixel sensor in CMOS technology has the potential to provide higher granularity, thinner sensors equipped with the amplifying electronics at a lower overall cost. The upgrade is therefore based on this technology with the installation of a sensor called OBELIX. This detector concept would improve the tracking robustness against backgrounds and would also improve the track reconstruction for low momentum particles and vertex position resolution. With this VTX design concept the expectations are:

- Improvement in the robustness against backgrounds, thanks to a minor occupancy given by greater segmentation and readout speed.
- Higher efficiency in tracking particles, in particular for low-cross-impulse particles and therefore higher resolution at vertex. In terms of numbers it is needed a spatial resolution less than $15\mu m$, a temporal resolution less than $100ns$ and a maximum hit rate of $120MHz/cm^2$
- $10\mu s$ latency at $30kHz$ for more complex Belle II trigger
- Lower integration time than PXD.
- Lower bandwidth thanks to a first reading system directly integrated in CMOS sensors.
- Power series supply system for the internal layer to reduce the amount of supply cables and with that the material budget,
- Better integration with the detector to leave more space for shielding and collimators in the interaction region.

To have a better understanding of the VTX's objectives, table 1.1 summarizes the requirements obtained by the simulations:

Table 1.1: Key performance parameters of the Belle II VTX from simulations [9]

Parameter	Value
Spatial resolution	$< 10\text{--}15\ \mu\text{m}$
Material budget (Inner–Outer layers)	$0.1\text{--}0.8\% X_0$
Max hit rate	$120\ \text{MHz}/\text{cm}^2$
Time precision	$< 100\ \text{ns}$
Trigger frequency	$30\ \text{kHz}$
Trigger delay (latency)	$5\text{--}10\ \mu\text{s}$
Radiation hardness (TID)	$< 1\ \text{MGy}$
Radiation hardness (fluence)	$< 5 \times 10^{14}\ n_{\text{eq}}/\text{cm}^2$
Power consumption	$< 300\ \text{mW}/\text{cm}^2$

The current VTX baseline design consists of six detection layers: the ones with radius below 30mm are grouped in the iVTX design, while layers at outer radii are grouped in the oVTX configuration. The VTX proposal consists of six barrel-shaped staggered layers, all equipped with the same sensor. In the azimuthal direction, each layer is segmented in elements called stave, table 1.2 presents the layers with their geometric requirements such as distance from the IP, number of sensors for each stave and gap between staves. It is important to note that layer from 3 to 6 are divided in A and B fig. 1.11, this represents the staggered configuration of each layer in which staves are overlapped in the angle direction. The radial configuration and the number of stave per layer was obtained with an iterative process, based on computer simulation, between the engineering design possibilities and the physics needs. The stave, which extends over the whole length of the respective layer, is the basic building block of the detector. The stave contains all structural and functional components, thus making it the smallest operable part of the detector. The design of the stave differs due to their active length, varying from 120 to 730 mm to cover the required acceptance

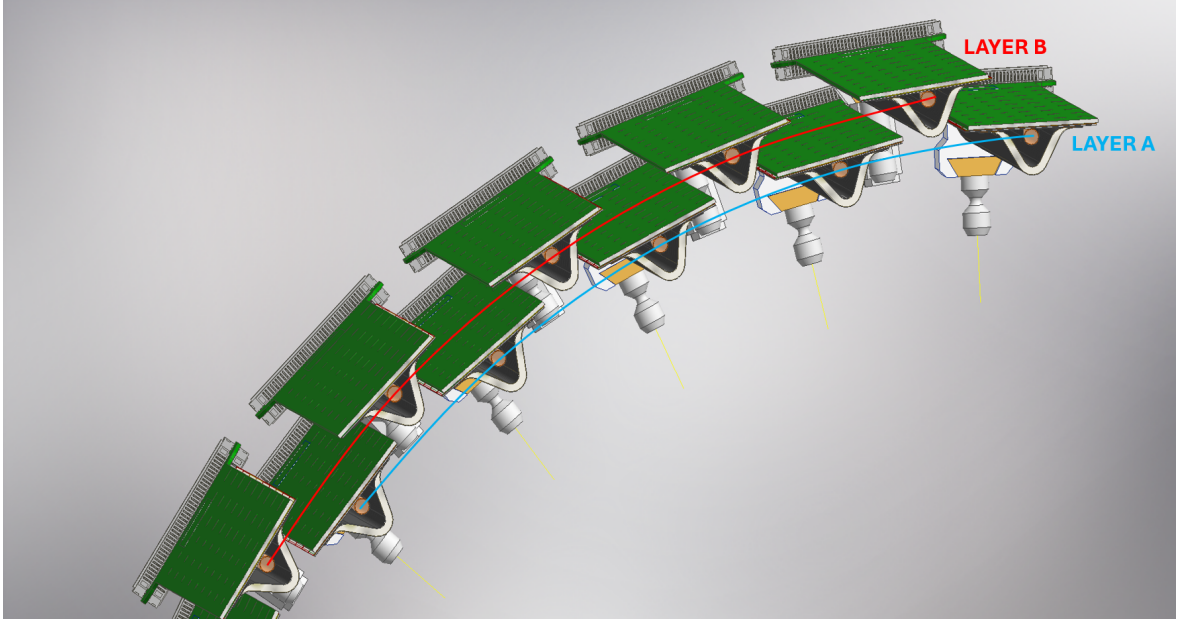


Figure 1.11: L6 staggered assembly with focus on layer A (blue) and layer B (red).

($17^\circ < \theta < 150^\circ$). The two innermost layers (iVTX) follow an all-silicon stave concept, the outermost (oVTX) layers require carbon fiber support structures, called ladder, and flex print cables.

Table 1.2: Geometric specifics of each VTX layer

Layer	Radius [mm]	Lenght [mm]	# Ladders	# Sensors	Shift [mm]	Gap [mm]	φ [°]
1	14.1	120	6	4	0.0	0.1	–
2	22.1	–	10	4	0.0	0.1	–
3A	62.5	365	15	12	0.0	0.1	73
3B	69.0	365	15	12	0.0	0.1	85
4A	82.5	485	18	16	0.0	0.1	85
4B	89.0	485	18	16	0.0	0.1	75
5A	108.0	606	24	20	0.0	0.1	86.25
5B	114.5	606	24	20	0.0	0.1	78.75
6A	133.5	730	30	24	0.0	0.1	87
6B	140.0	730	30	24	0.0	0.1	81

The two innermost layer of iVTX are placed at radii 14 and 22 respectively, the material budget target for each layer is of about $0.2\% X_0$. Such light layer is possible due to moderate overall surface of these two layers, below 400 cm^2 , the low power

dissipation and the few connections needed for sensor operations. Four contiguous OBELIX sensors block diced out of the production wafer and thinned $50\ \mu\text{m}$ are the essential part of the monolithic structure. The sensors are subsequently interconnected along the stave via a Redistribution Layer (RDL), which routes the signals to a single connector located at the back end of the ladder, where a flex cable is connected.

A more traditional approach drives the oVTX stave concept for the outer layers, strongly inspired by the design successfully developed for the ALICE ITS2 [10]. Each stave (1.12) is made of the ladder, composed of a light carbon fiber support structure and a cold plate including tubes for liquid coolant circulation by negative pressure, a row of sensors glued on top of the cold plate and finally two flex print cables connecting each half stave to a connector. A sliding mechanism is foreseen to compensate for thermal load-induced deformations, expected to be a few tenths of a millimeter according to similar studies.

For Layer 3 a single flex exiting on the backward side of the detector can be foreseen to allow more room for machine components on the forward. An important update for the oVTX design is the use of the same ladder design for all layers. The cross section is going to have an omega shaped carbon fiber structure which is expected to minimize the material budget of the ladder at $0.5\% X_0$.

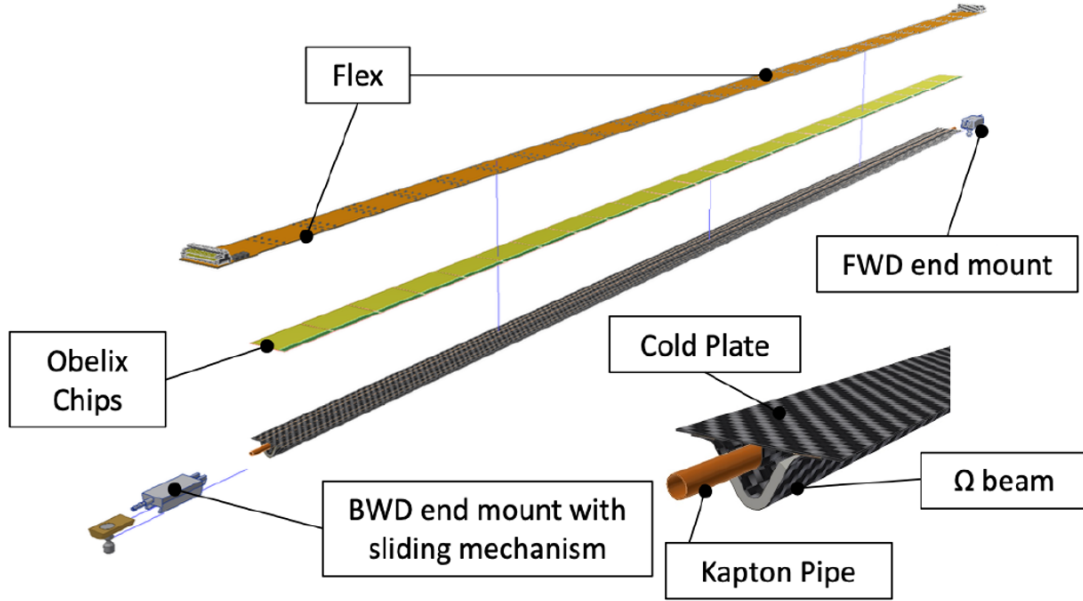


Figure 1.12: The design of oVTX stave.

The VTX proposed detector is expected to work at room temperature. The sensor temperature will be monitored both internally and with additional thermal sensor on the stave support structure. The usage of the sensor all over the detector allows a unique control and power system. A significant reduction of services is expected compared to the current VXD, due to the smaller cross section of data cables as there is extensive use of optical fiber and a less complex cooling system. For the oVTX thermal studies have been conducted: it has been experimentally demonstrated with kapton heaters mimicking uniform dissipation that demineralized water flowing at 15°C with a speed of 10 m/s is effective in cooling a single ladder. Thermal simulations with not uniform heating have been performed assessing small temperature gradients on the stave.

1.5.2 Silicon sensors

The sensor converts the energy deposited by a charged particle (or photon) into an electrical signal. In the case of silicon sensors, the energy is absorbed by the silicon semiconductor material, generating mobile charge carriers in the form of electron-hole pairs. An electric field applied across the sensor causes these carriers to drift toward the

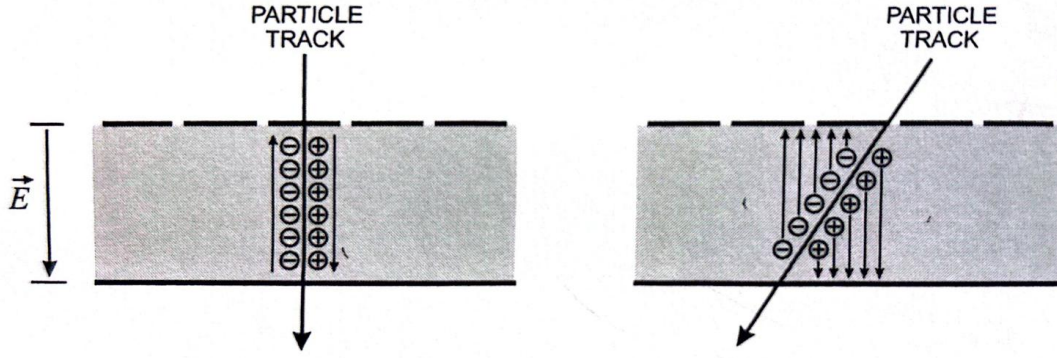


Figure 1.13: Segmenting the sensor electrode provides position information. Angled tracks deposit charge on two or more electrodes.

electrodes, inducing an electrical current. The number of electron-hole pairs produced is proportional to the absorbed energy; therefore, by integrating the signal current, one obtains the total signal charge, which is directly proportional to the deposited energy.

The electrodes of the sensor can be segmented to provide spatial information. The magnitude of the signal detected by a given electrode depends on its position relative to the charge generation site, as illustrated in Figure 1.13.

Segmenting one electrode into strips allows the extraction of position information in one dimension. When a particle crosses the sensor at an angle, it typically deposits charge across multiple strips. By evaluating the relative charge collected by each strip, interpolation techniques can be applied to achieve a position resolution better than what would be expected from the strip pitch alone.

In a colliding-beam experiment, typical strip pitch (center-to-center spacing) ranges from 25 to 100 μm . The strip lengths vary from a few centimeters to several tens of centimeters and are usually aligned parallel to the beam axis to measure the azimuthal coordinate ($r\phi$). The maximum strip length per sensor is constrained by the silicon wafer size (typically 10 to 15 cm for detector-grade silicon). Therefore, multiple sensors are often connected ("ganged") together to form longer electrodes

1.5.3 The OBELIX Chips

OBELIX, figure 1.14, is a new-generation silicon pixel sensor developed for the upgrade of the Belle II Vertex Detector. It is a fully monolithic CMOS sensor, meaning that both the sensitive silicon area and the readout electronics are integrated on a single chip. Designed using a 180 nm CMOS technology, OBELIX offers high granularity with small pixel sizes ($33 \times 33 \mu\text{m}^2$), allowing for precise tracking of charged particles [11].

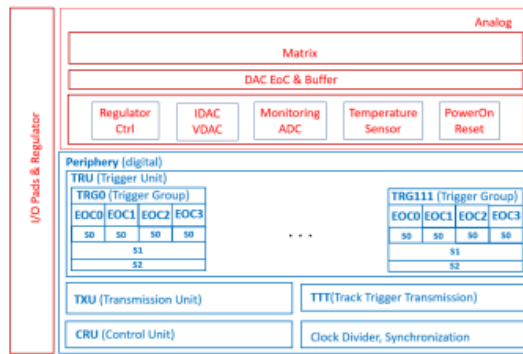


Figure 1.14: Functional description of OBELIX

The sensor is optimized for high-rate environments, capable of handling up to 120 MHz/cm² of particle hits, with excellent spatial resolution ($< 15 \mu\text{m}$) and time precision ($< 100 \text{ ns}$). Its low material budget and power consumption make it well-suited for applications in particle physics where minimizing detector mass and heat is critical.

Chapter 2

Engineering Design of Tracking System

This chapter presents the design requirements for the construction of the outer vertex detector (oVTX), outlining the rationale behind these necessities. The oVTX structures have been meticulously designed to meet stringent mechanical criteria such as structural integrity and geometric stability as well as nuclear requirements, including radiation hardness and minimal material budget to ensure transparency to ionizing radiation. Below, the key parameters guiding the design and the material selection are detailed, including mechanical strength, radiation length and radiation tolerance.

2.1 Mechanical structure requirements

The mechanical design of tracking detectors plays a critical role in ensuring precise and stable particle track reconstruction. This section discusses the structural and material requirements needed to support high-performance silicon detectors in the context of the Belle II experiment.

Silicon detectors are typically segmented into modules, from a few tens to several thousands, the size of which is defined by wafer and chip sizes. Large coverage will usually require the spreading of these modules over a large volume. Tracking will usually

require linking measured positions from several modules. The position and dimensional stability of the tracking modules over time are precisely determined by the supporting structures, which should not degrade the module-internal measurement accuracy (at level of microns) with minimal material. These structures must also integrate the cooling system to ensure that the maximum operating temperature of critical system components, such as the readout electronics and silicon detectors, is not exceeded.

Minimizing the material budget is crucial for optimizing detector performance, as it enhances both the detection efficiency (the ratio of detected tracks to the tracks produced by an event) and the detector's effectiveness (the precision of track reconstruction). While active silicon sensors are the core of particle tracking, a substantial portion of the material budget originates from non-sensitive components including mechanical supports, cables, electronics, and cooling systems. This additional material impacts detector performance by:

- increasing the probability of multiple scattering, bremsstrahlung, and photon conversions (2.2.1),
- degrading the momentum resolution and track reconstruction accuracy,
- complicating vertex reconstruction and pattern recognition.

Therefore, minimizing the material contribution from support structures is a key design consideration in modern tracking detectors, particularly in high-luminosity environments like Belle II.

Design decisions related to geometry, manufacturing tolerances, and structural stability are dictated by the stringent requirements for precise track reconstruction. Therefore, the final design is the result of an iterative process that integrates engineering input with the needs of the physics analysis. Furthermore, the interfaces between the mechanical structures of the stave and the components they house, such as the cooling system, optical fibers, electrical wiring, and electronic devices, must be carefully defined and maintained. The interfaces with other sub-detectors within the Belle II

experiment must also be precisely specified and respected to ensure seamless integration.

It is also essential to minimize the deflection of the supporting structure, as any deformation could alter the spatial positioning of the detector modules, leading to inaccuracies in track reconstruction. The stresses developed in the materials, even if modest, must be carefully evaluated to prevent long-term phenomena such as micro-creep.

2.1.1 Geometric and dimensional requirements

The geometry of the tracking system is a highly complex subject, primarily due to the large number of tracking modules and their strict spatial constraints and alignment requirements. Below, the different geometric constraints for oVTX are presented.

The first geometric requirement, arising from the physics of collision events, is the acceptance cone defined by $17^\circ < \theta < 150^\circ$. As discussed in the first chapter, the aim of Belle II is to detect the decays of B mesons produced in electron-positron collisions at 7 GeV and 4 GeV respectively. The difference in beam energies defines the collision as asymmetric. Due to this energy imbalance, the center-of-mass (CM) frame is not at rest in the detector frame but rather boosted along the direction of the more energetic electron beam.

This boost originates from the conservation of momentum in the asymmetric collision. In the detector frame, the two incoming beams, electrons at 7 GeV and positrons at 4 GeV, do not carry equal and opposite momenta. As a result, the total longitudinal momentum of the system before the collision is non-zero and directed along the axis of the higher-energy beam. After the collision, this net momentum is conserved, causing the decay products to be preferentially emitted in the forward direction in the detector

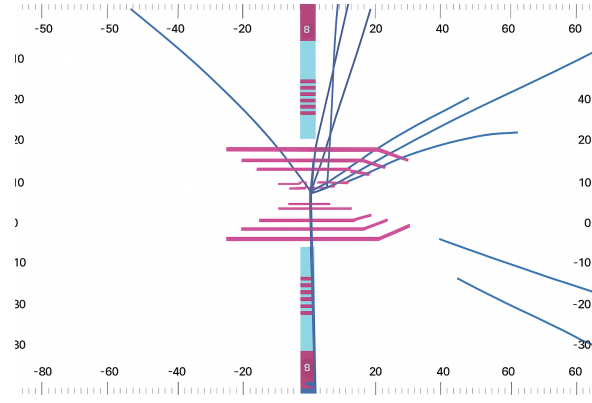


Figure 2.1: One of the first collisions of Run2 observed in the Belle II detector, it can be seen that the decay products are shifted toward the forward side

frame.

Consequently, as a direct consequence of the boost, the decay products tend to move forward along the CM boost direction, instead of being emitted isotropically. In particular, the forward motion of the B mesons allows for spatial separation of their decay vertices along the beam axis. This spatial displacement is essential for reconstructing the decay time difference (Δt) between the two B mesons, a key observable to measure CP violation in the B-meson system. Without the boost (i.e., in a symmetric collision configuration), the B mesons would decay nearly at the same point in space, rendering time-dependent CP studies practically impossible.

From an engineering standpoint, this directional asymmetry defines an interaction cone in the polar (θ) direction, with decay products preferentially emitted following the electron beam direction. As a result, the acceptance angle is smaller on the forward side of the detector (FWD, 17) and larger on the backward side (BWD, 30), which has direct consequences for the mechanical layout and the service infrastructure.

Specifically, less space is available for service modules on the forward end, since a larger detector volume is required to accommodate ladders and sensors that cover the full range of particle trajectories in that direction. Conversely, the backward end benefits from a wider acceptance angle, allowing for more generous space allocation for services and reducing mechanical constraints during their integration. Figure 2.2 rep-

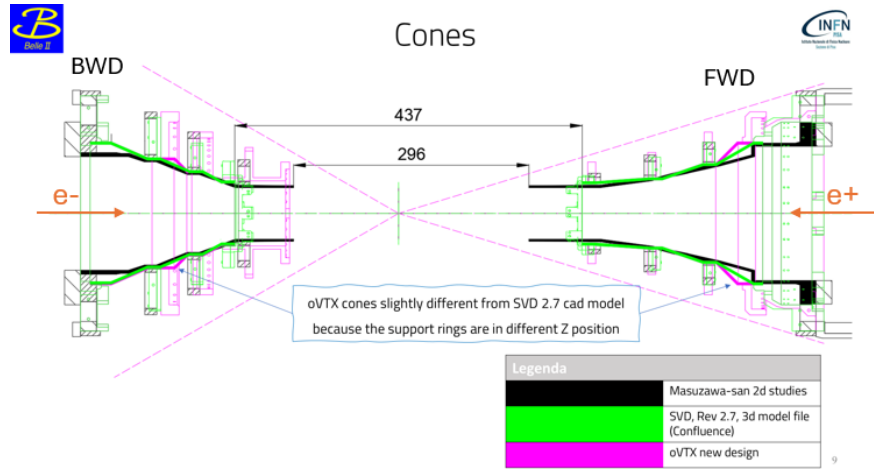


Figure 2.2: Interactions cone for the oVTX upgrade, presented in purple, slightly differs from the previous cone of SVD, green.

resents the new cones of the oVTX design (purple) compared to the previous SVD design (green). The new cones conservatively respect the current inner volume.

Another fundamental set of geometric requirements concerns the hermeticity and mechanical tolerances of the vertex detector. To guarantee hermetic coverage, the spatial distribution of the chips must allow only minimal gaps, with tolerances mainly defined in the longitudinal direction. Figure 2.3 illustrates the structure of a chip, highlighting three distinct regions: the guard ring (red), the periphery (green), and the matrix (yellow), which is the active area. Within a High-Density Interconnect (HIC), the maximum allowed longitudinal gap between adjacent chips is $100\mu m$, fig. 2.4 .

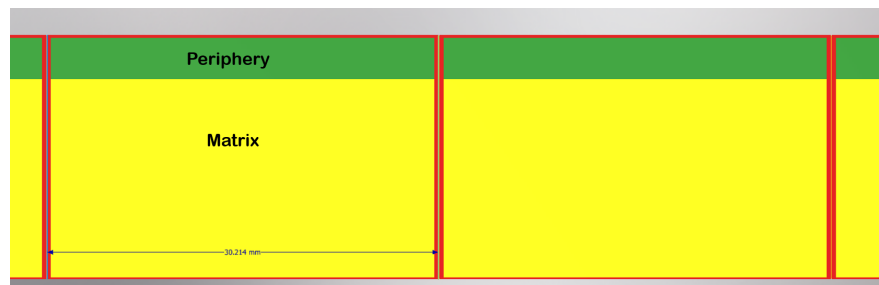


Figure 2.3: Schematic representation of the sensors over the oVTX ladder. 30.214 mm is the longitudinal dimension of the chip.

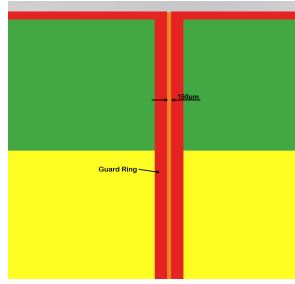


Figure 2.4: Longitudinal gap between adjacent chip.

In the azimuthal direction, no gaps are allowed; on the contrary, the chips must overlap to ensure a minimum active area overlap of $200\ \mu\text{m}$. To achieve this overlap and guarantee full azimuthal coverage, the layers are designed in a staggered configuration. Each layer is divided into two sublayers, A and B, which are placed at slightly different radii, with a minimal radial offset between them, as illustrated in Figure 2.5. The minimum required $200\ \mu\text{m}$ overlap between the matrices of chips from sublayers A and B is indicated by the distance between the two blue lines.

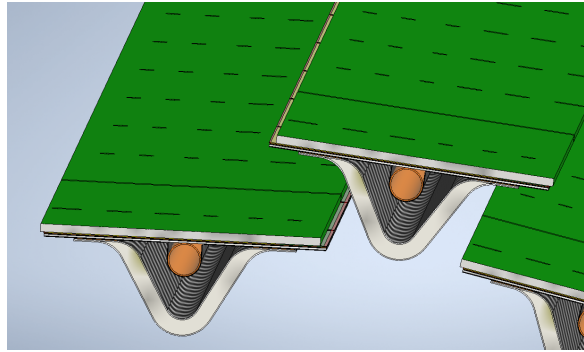


Figure 2.5: Staggered design of two adjacent stave from layer A and B

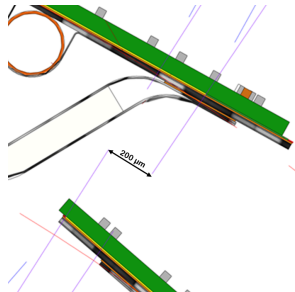


Figure 2.6: Overlap between adjacent ladder from layers A and B.

To achieve the geometric radial overlap minimum requirement between ladders A and B, the in-plane positioning tolerances are presented in figures 2.7 for each oVTX

layer. Starting from the layout configurations, the overlap between two adjacent ladders is calculated considering two lines from the interaction point to the vertices of the active areas of two adjacent ladders, belonging to the same layer, one internal (A) and one external (B).

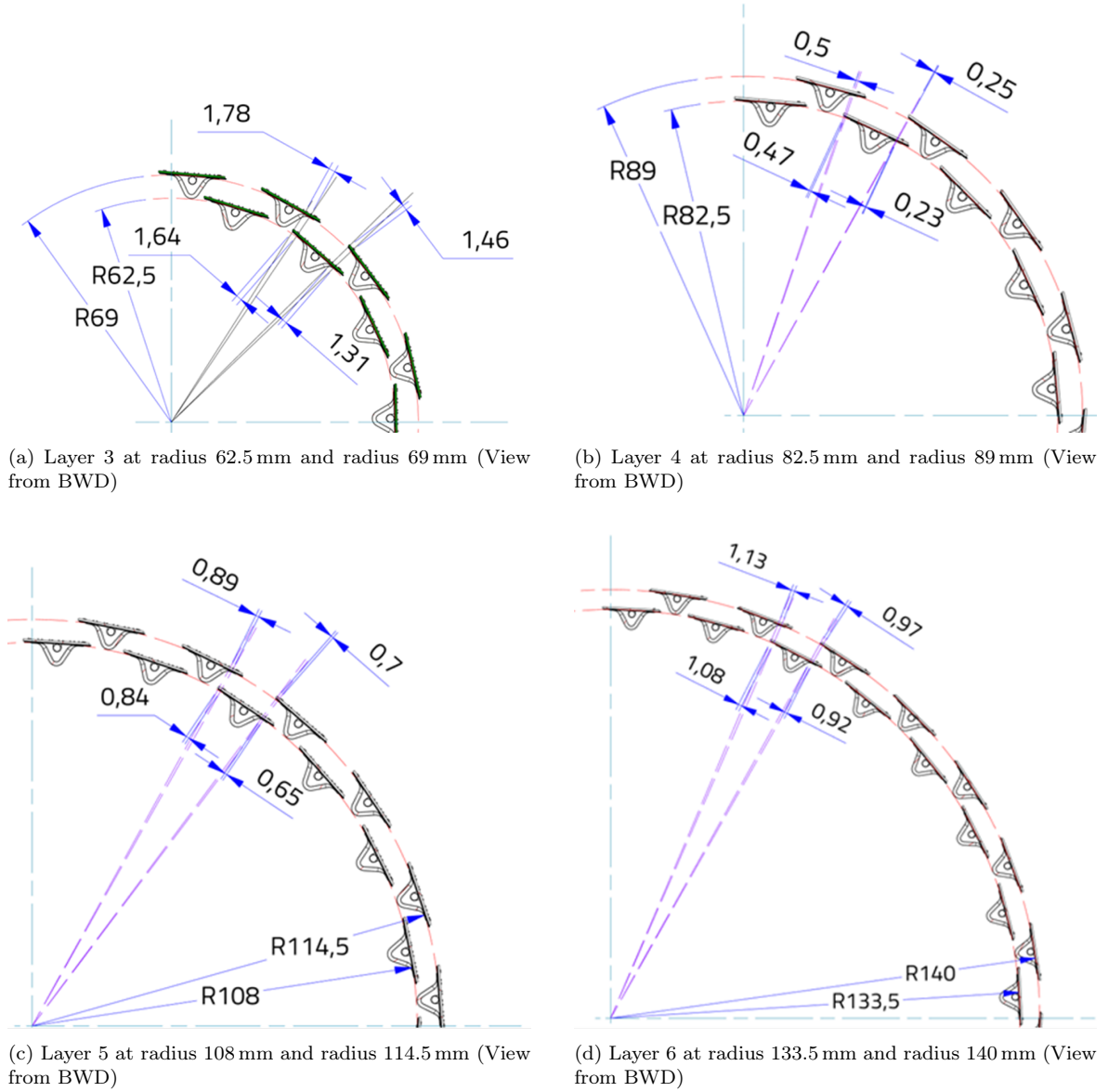


Figure 2.7: Geometrical layout of layers 3 to 6 at increasing radii (View from BWD).

Additional mechanical constraints arise from the need to avoid physical contact between the staves. For the oVTX, the minimum nominal stave-to-stave gap in the $r\phi$ plane is 1.53 mm and the maximum is 3.1 mm.

Other important geometric requirements are alignment and positioning tolerances:

the maximum allowable spatial displacement is $10\ \mu m$ from the nominal position. This value comes from the pixel resolution ($\pm 10\ \mu m$) which is linked to the pixel pitch ($30\ \mu m$). The tolerance is obtainable by existing technology which has already been used in similar active projects. However, since the mistakes made by Computer Numerical Control (CNC) machine tools are around $30\ \mu m$, it is possible to understand the difficulties to maintain our margin below $10\ \mu m$ for a carbon fiber structure built gluing dozens of pieces together with precision jigs.

It can therefore be concluded that it is necessary to build a mechanical structure which can place silicon detectors in the required position to fully exploit their high spatial resolution. To compensate for manufacturing tolerances, adjustable assembly fixtures are employed, allowing precise alignment under a Coordinate Measuring Machine (CMM). Then it is necessary to perform a procedure called "software alignment", which is the measurement of the actual position of all detectors after their installation on the structure. It is based on results from cosmic ray runs and large-scale computing simulation of physics samples mimicking the accelerator operation during real data taking and it is repeated periodically during the shut-down of the accelerators. The procedure is based on several iterations: it starts with the detectors positioned in space with the uncertainty of the mechanical support structure, i.e. the clearance of the ladders. The data, acquired by the detectors as charged particles pass through them, are analyzed and the spatial position of each individual detector is "virtually adjusted" iteratively, until the χ^2 of the track fits is minimized. The tracks themselves have a precisely known shape (straight lines for cosmic rays in the absence of a magnetic field).

During the experiment, the data acquisition system reconstructs the tracks by considering the detectors in their correct positions, as determined during the alignment procedure. Therefore, the support structure must ensure mechanical stability below $10\ \mu m$ during the operating period under stable conditions (6 to 12 months) between successive alignments, in order to consistently maintain reliable track reconstruction.

It has been demonstrated that, after a few iterations and with a few thousand tracks, the software alignment procedure can achieve a spatial positioning accuracy better than 4 to 5 μm for each individual detector module.

2.1.2 Operating environmental conditions

The environmental conditions throughout the system's operational lifetime represent key constraints that must be taken into account during the entire design phase and inevitably influence the selection of suitable materials.

Temperature During operation time, the heat produced by the readout electronics and the detectors themselves would, in a short time, raise the tracker's temperature to unacceptable levels, ultimately compromising its proper functioning and damaging the sensors. The maximum acceptable temperature is determined from the chosen electronic component characteristics and from the radiation dose impacting the detectors: as the irradiation increases, the operating temperature of the silicon detectors should be progressively lowered (down to 30°C) to ensure their proper functioning with a maximum temperature non-uniformity less than 5°C.

For the thermal design of the system, it is required that during operation the temperature of all components always remains below the maximum allowable temperature for end-of-life operation (10 years of irradiation). It has been demonstrated that the maximum temperature allowable for Belle II VTX sensors is 30 °C. To this end, a flow of demineralized water underpressure at 15°C is maintained inside the tracker volume to remove any heat transferred to the environment through natural convection. Therefore, the detector cooling system is still sized so that all the generated heat is removed by the coolant, in compliance with the maximum allowable temperatures.

Humidity The environment inside the trackers must be kept as dry as possible during operation (relative humidity < 5%). This is a very important condition, because the

presence of condensed vapor or ice on the silicon modules or on the micro-solder joints would inevitably lead to short circuits that would compromise the functioning of the modules themselves.

As mentioned above, the desired relative humidity value will be achieved through the flushing of dry air. However, it cannot be ruled out that during shutdown periods of the experiment the structure may be temporarily placed in relatively humid environments for maintenance operations.

Earthquake Given that the Belle II experiment is located in Japan, a region with a high seismic activity, environmental conditions must also take into account earthquakes, as designed system should be resilient against them. Seismic events typically involve vibrational frequencies in the range from $2Hz$ to $40Hz$. To avoid resonant amplification of mechanical vibrations, which could lead to structural failure, it is crucial to design support structures with natural frequencies well outside of this seismic band. To this end the VTX will be mounted with specific locations identified for fixing the VTX structure that will help isolate the system from vibrations. Here is just a brief summary of the frequency range of earthquakes, to refer to when performing simulation of structural elements.

There are different seismic waves related to earthquakes that break down into compression (P), shear (S), and surface (Rayleigh and Love) waves [12]. P waves travel through the Earth at a speed of about 1500 miles per hour and start initial vibrations of buildings. These are followed by S waves that provide side-to-side vibration. Buildings use rubber bearings that help isolate these vibrational modes and reduce the potential damaging effects arising from the complex impact of P and S waves. Lastly, the Rayleigh and Love waves cause low-frequency vibrations.

This seismic frequencies translates into vibrational spectra that are observed on Belle II detector as discussed in [12]. To calculate the relative displacement of the Belle II detector and the QCS, certain seismic analyses were done with data gathered from the measurements of the earthquake waves. The earthquake data were obtained from the National Research Institute for Earth Science and Disaster Resilience (NIED), which is

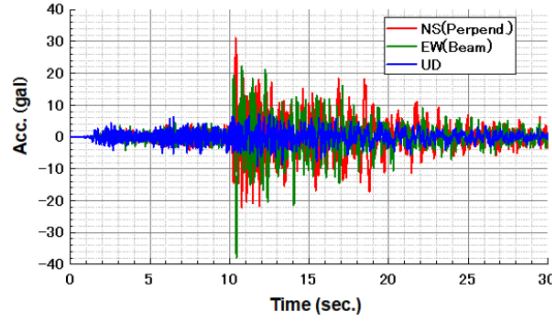


Figure 2.8: Accelerator response spectrum in three directions for the earthquake, November 1st, 2021, datas were obtained from the National Research Institute for Earth Science and Disaster Resilience (NIED), which is located 3 km from KEK in the same neighbourhood ($1gal = 0.01m/s^2$).

also researching earthquakes and is located 3 km from KEK in the same neighbourhood. An earthquake with 3.5 intensity occurred on November 1st, 2021, with its epicentre 300 km away from KEK at a depth of 50 km. The time history of the earthquake in three directions is shown in fig. . Figures 2.9 show the vibrational spectra from an earthquake in 2021. The amplitude of vibrations falls off quickly on a logarithmic scale and is compatible with the expectation that the high-amplitude vibrations are below 40 Hz. The duration of vibrations for this earthquake is $O(30)$ seconds. The three lines in each of the figures correspond to three directions that are being measured.

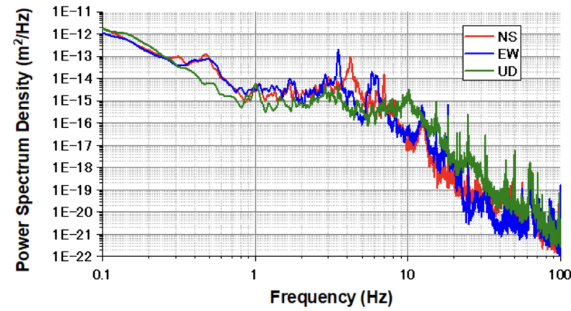


Figure 2.9: From [12], examples of the frequency spectra in logarithmic scale measured with microtremors were measured on the Belle II detector with the solenoid turned off.

Table 2.1 shows the displacements calculated for Belle 2 and the QCS magnets. The QCS displacements are up to $65\mu m$. It is thought the reason why this is so small is that the QCS resonant frequency is mis-matched to that of the earthquake, and so that the magnet moves with the floor. The all Belle II detector exhibits displacements up to 3.4mm.

Table 2.1: Measured Intensities at QCS and Belle II

Date	Intensity	QCS	Belle II
Apr. 12 th , 2020	3.5	0.065 mm	2.1 mm
Mar. 20 th , 2021	3.5	0.017 mm	0.7 mm
Nov. 1 st , 2021	3.5	0.014 mm	0.8 mm
Mar. 16 th , 2022	4.3	0.023 mm	3.4 mm

iVTX will be mounted on the beampipe that is coupled via bellows to the QCS magnets, and displacements of up to $O(60\mu m)$ are expected for the detector based on the study presented in 2022 [12]. For oVTX the order of magnitude of possible displacements is yet to be studied, but is necessary to consider frequency ranges of earthquake to design the oVTX ladder in order that its natural frequencies are out of this range, to avoid structural resonance condition. In addition, some consideration should be given to the spacing between the iVTX and oVTX to ensure no contact between the inner and outer VTX.

Enviromental condition summary Here are summarized the environmental conditions presented early in this subsection. The data are taken from [9], [12].

Operating and safety condition	
Maximum allowable temperature for sensors	30°C
Relative humidity	< 5 %
Earthquake safety	Natural frequency > 40 Hz

2.2 General requirements for materials

The requirements that the materials used in the Belle II tracker must meet are very similar, on one hand, to those of aerospace structures, in terms of lightness and mechanical strength, and on the other hand, to those of particle detectors used in nuclear power reactors, namely stability under radiation and transparency to ionizing particles.

The choice of material for VTX is therefore a compromise among many factors:

- transparency to radiation, i.e., high radiation length (X_0);
- stiffness (high Young's modulus);
- radiation resistance
- low sensitivity to temperature variations (low CTE - coefficient of thermal expansion);
- low sensitivity to humidity (low hygroscopicity);
- stability over time;
- low rate of gas and solvent release;
- high thermal conductivity.

Furthermore, the choice of material must also take into account several additional factors, including safety concerns, the commercial availability of the material in the small quantities required for the intended application, the ability of the industry to manufacture it in the necessary shapes and sizes, as well as the overall cost of both the raw material and its production.

2.2.1 Radiation Length: Multiple Scattering

The primary purpose of detection systems such as the one under consideration is, as already mentioned, the reconstruction of the trajectories of charged particles produced in the collision of positron and electron beams at very high energies. For this reason, it is necessary to minimize the material budget inside sensible region to avoid introducing excessive disturbance into the measurement. In fact, a charged particle traversing a material medium is deflected by multiple scattering, which constitutes a principal source of track reconstruction uncertainty. One must therefore use materials that are as transparent to radiation as possible. This can be achieved by considering the density and atomic structure of the substance; in the field of high-energy physics

it is convenient to measure material's thickness in units of radiation length (X_0).

Formally, the radiation length X_0 is defined as the mean distance over which a high-energy electron loses $1/e$ of its energy by bremsstrahlung emission, i.e. by the production of a continuous photon spectrum through Coulomb interactions.

The dependence formula for X_0 is shown:

$$X_0 [\text{cm}] \simeq \frac{716.4 A}{Z (Z + 1) \ln\left(\frac{287}{\sqrt{Z}}\right) \rho} \quad (2.1)$$

Here, A is the Avogadro number, Z is the atomic number of the traversed material and ρ is the material density. Consequently, the radiation length X_0 depends inversely on Z : materials with a lower atomic number exhibit longer radiation lengths and, therefore, greater transparency to high-energy particles. It is also important to note that the radiation length is typically expressed in centimeters. This choice of unit facilitates the analysis of multilayer structures composed of different materials, as the total radiation length of the entire lay-up can be obtained by the linear sum of the individual material contributions, each expressed in terms of their respective X_0 values.

The significance of this parameter in the design of high-energy particle detectors is further underscored by multiple scattering. As a relativistic particle traverses a medium, it not only loses energy, but it is also deflected by an angle Θ_0 (the RMS scattering angle) due to successive electromagnetic interactions with the nuclei of the material. Although the fractional energy loss per traversal is small, large angular deviations can compromise the precision of track reconstruction.

A simplified model of the phenomenon can be described by the expression :

$$\Theta_0 = \frac{13.6 \text{ MeV}}{\beta c p} z \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \ln\left(\frac{x}{X_0}\right) \right] \quad (2.2)$$

Where:

Θ_0 Root-mean-square scattering angle (radians)

$\beta = v/c$ Particle velocity relative to the speed of light

c Speed of light in vacuum

p Momentum of the incident particle (MeV/ c)

z Charge number of the incident particle (in units of e)

x Thickness of the material traversed (cm)

X_0 Radiation length of the material (cm)

At this point, it becomes clear how crucial the choice of materials and their spatial distribution within the tracker is. The closer a material is placed to the interaction region, within the sensitive region, the more critical its impact becomes. Conversely, outside the detector's acceptance cone, minimizing the material budget isn't relevant, as it does not affect the precision of the measurements.

2.2.2 Specific Stiffness and Young's Modulus

The mechanical design of structures such as those under consideration is essentially based on limiting displacements rather than stress values. In particular, to avoid micro plasticity phenomena, it is important to operate well below the elastic limit of the material. The reference value for each material can be the micro yield point, i.e. the stress level at which residual strains on the order of 10^{-6} occur. Sometimes, the stresses induced by mechanical and thermal loads during the operation of the apparatus may be well below the internal residual stresses of the material, resulting from manufacturing processes that have not been thoroughly analyzed.

In addition to static mechanical and thermal loads, dynamic loads must also be taken into account, such as the stresses produced during handling of the equipment and the vibrations generated in the experimental cavity by various auxiliary devices, such as pumps, motors, fans, etc. It is therefore necessary that the structural materials used

are as stiff as possible in order to avoid low-frequency resonance phenomena, as well as intolerable displacements caused by static and thermal loads.

In such a context, the classification of materials based solely on the Young's modulus is not sufficient. Whereas in the aerospace field the key parameter is the specific stiffness E/ρ , in the design of support structures for particle trackers in high-energy physics it is more appropriate to classify materials according to the product of Young's modulus and the material's radiation length, that is EX_0 .

Table 2.2 reports the most common structural materials and their properties:

Material	ρ (kg/m ³)	X_0 (cm)	E (GPa)	K (W/m ² C)	CTE (ppm/K)	Resistivity (10 ⁻⁸ Ω·m)	EX_0 (GPa·cm)	KX_0 (W/cm ² C)
Austenitic stainless steel	8027–7640	1.76	200–193	16.3–14.2	18.7–14.9	78–69	352	29
Titanium and alloys	5065–4373	3.56	127–76	20–7	10.8–8.1	199–48	452	71
Beryllium and alloys	2076–1855	35.3	289–186	213–151	16.2–11.5	4.3–3.4	10200	7518
Nickel and alloys	9245–7806	1.4	234–131	86–10	17.2–11.2	135–748	327	120
Copper	8941–8885	1.43	124	391–194	17.6–16.7	3.82–2.8	177	559
Cobalt and alloys	9134–8055	1.5	231–207	29–9	17.8–12.2	99.5–6.24	346	43
Tungsten and alloys	19653–13369	0.35	406	167	4.5	5.48	142	58
Gold	19320	0.33	82	298	14.2	2.19	27	98
Silicon	2333	9.36	107	83.7	4.67	1.5e7	1000	783
Magnesium alloys	1827–1342	13.6	45–41	137–50	39.2–25.2	15.25	612	1863
Aluminum alloys	2700	8.9	80–70	234–117	24.7–22.3	4.9–3	712	2082
Carbon-carbon composites	1900	20	152	246	0.10	n.d.	3040	4920
Carbon-epoxy composites	1460	20	150	15	0.10	n.d.	3000	300
Graphite-epoxy composites	1577	20	276–134	52	0.10	n.d.	5520	1040
Beryllia	1989–1685	31	399–269	164	8	n.d.	12369	5084
Alumina ceramic	2730	10	345–207	34.6	7.74	n.d.	345	346
Polyamides	1439	28.7	4.8–3.1	0.99–0.36	50–45	n.d.	n.d.	n.d.
Aluminum nitride	326	25	276	140–220	n.d.	n.d.	6900	5500

Table 2.2: Mechanical, thermal and electrical properties of various materials. [13] [14] [15]

The materials offering the best performance (i.e. a high EX_0) are beryllium-based composites, both metallic and sintered (beryllia). Unfortunately, these materials are

difficult to machine by conventional chip-removal techniques due to the extreme toxicity of beryllium dust. Consequently, their use has been discouraged in favor of other compounds, such as ceramics (alumina and aluminum nitride) for precision structures and carbon fiber–epoxy composites for structural components.

2.2.3 Radiation Hardness

When a charged particle passes through a silicon detector module, it undergoes both ionising and non-ionising energy losses. These two mechanisms are quantified respectively by the Total Ionising Dose (TID) and the Non-Ionising Energy Loss (NIEL). The ionising component leads to the generation of electron-hole pairs within the semiconductor material. If an external bias voltage greater than the full depletion voltage is applied, the generated charge carriers can be fully collected and processed, resulting in a measurable signal that is relevant to the experiment's physics goals.

Due to the reverse-bias operation of these detectors, a small but persistent leakage current is always present during operation. Typically, the detector breakdown voltage exceeds the full depletion voltage, which prevents immediate failure under standard operating conditions.

On the other hand, NIEL accounts for the energy loss due to interactions between incoming particles and the detector material, resulting in radiation-induced damage. While charged particles primarily affect the bulk silicon, neutral particles tend to damage the detector's surface layers. The current flowing through the silicon, denoted as I , can be expressed as:

$$I = I_0 + I_d \cdot \Phi \quad (2.3)$$

Here, I_0 represents the ionisation-induced current, I_d is the leakage current coefficient, and Φ is the accumulated radiation dose.

A direct consequence of radiation damage is a rapid increase in leakage current, even at relatively low doses. This rise in current negatively affects the signal-to-noise ratio,

leading to reduced measurement precision and detector resolution. Additionally, the voltage required for full charge collection (depletion voltage) increases over time and may eventually approach the breakdown voltage, posing a risk of thermal runaway. This phenomenon can cause the detector to operate unstably or even lead to the irreversible failure of its sensitive components.

Once damaged by radiation, a silicon detector cannot be repaired. Therefore, during the design phase, an estimate is made of the total radiation dose the detector can tolerate over its operational lifetime. It is important to note that fully radiation-hardened silicon detectors do not exist. However, cooling is a critical mitigation strategy, as it significantly reduces the leakage current. For instance, lowering the detector temperature by 7 K can decrease the radiation-induced leakage current by approximately a factor of two. For this reason, an efficient cooling system is essential to maintain detector performance, ensure accurate measurements, and dissipate heat generated by the associated electronics and readout systems.

Radiation not only affects the detector itself but can also interact with the surrounding components involved in its construction and operation, such as mechanical supports and cooling systems. These materials must withstand the expected radiation environment throughout the detector's lifetime without undergoing chemical, physical, or structural degradation. Therefore, radiation-hardened materials, those capable of resisting high radiation doses without significant deterioration, are preferred.

Common radiation-induced effects on materials include:

- **Changes in physical properties:** Radiation can alter mechanical and electrical characteristics. For example, certain polymers exhibit increased thermal conductivity after irradiation. Some materials may also undergo accelerated ageing, as seen in specific carbon fibre-reinforced plastics (CFRPs), where resins degrade faster under radiation as a consequence of the changes induced of the molecular structure.
- **Surface and structural modifications:** Radiation may impact material morphology

and crystallinity, affecting properties such as tensile strength, abrasion resistance, hardness, and porosity. Adhesives used in precision assemblies can lose bonding effectiveness under prolonged exposure.

- Radiolysis: Nuclear radiation can break molecular bonds (similarly to photolysis), producing highly reactive and potentially hazardous byproducts. For example, coolants might decompose into substances that react with or damage the piping system, leading to blockages or leaks. CERN has conducted dedicated studies to assess the suitability of coolants and associated materials for radiation environments.
- Deposition effects: Material degradation under radiation may result in residues accumulating on surfaces, reducing thermal conductivity, clogging cooling lines, or altering the material's surface characteristics.

The problem of radiation-induced degradation of these structural materials has not been extensively studied so far because the radiation levels, to which the previously considered structures have been exposed during their operational lifetime, have never been as high as in the current case. Indeed, for the high-energy physics experiments that will be carried out with SuperKEK, also due to its high luminosity, the situation will be much more severe than it has ever been in the past. However radiation hardness is a great concern, but let's take into account that SuperKEK is not an hadron machine so the total level of radiation is still lower than other collider as LHC at CERN. So being a subject of great interest in a large range of scientific fields, there are a great number of technical reports from institutions around the world regarding radiation damage and radiation compatibility of numerous engineering materials and fluids. For instance, CERN [16] has collected information from extensive radiation damage testing of most engineering materials and fluids. So also if there are not specific study on Belle II, CERN yellow books are a great baseline for oVTX design.

During the PXD conception phase, extensive studies [17] have been carried out to estimate the radiation dose to which the two PXD layers will be exposed to during their lifetime in Belle II. These simulations showed that the inner layer will receive a dose between $10 - 20 \text{ kG}_y$ per year. Assuming an expected lifetime for Belle II of 10 years, this gives a total dose of approximately 200 kG_y , table (2.3) shows the expected radiation dose for each PXD layer dividing the radiation in their main background sources..

Table 2.3: Individual components of the expected radiation dose per Snowmass year (smy, 10^7 s) based on simulations . The numbers represent the average dose over the entire ladder for both PXD layers.

Layer	Synchrotron	Beamgas	Touschek	Bhabha	Two-photon	Total
1	0.14	0.17	0.21	0.94	18.41	19.9
2	0.01	0.05	0.20	0.24	4.44	4.9

For the PXD sensor [17], the measurements presented show that after a photon irradiation of the sensor matrix of up to a total dose of 266 kG_y , the system performance is stable if the sensor voltages are adjusted accordingly. The Signal to Noise Ratio (SNR) showed no degradation in performance during radioactive source measurements, with SNR of over 30 at the end of the irradiation. Therefore, it is important to study and consider the effects of radiation on the stave structure and on its stability.

The primary factor responsible for changes in the macroscopic mechanical properties of polymers is the breaking of polymer chains combined with the formation of cross-links between adjacent chains. Another major source of degradation is the loss of adhesion between the matrix and the fibers, which can lead to local separation of the fiber layers (micro-delamination). This degradation can be further accelerated by the presence of oxygen and reactive gases such as O_3 and NO_x . Although, no operational data are yet available for carbon fiber structures exposed to long-term radiation in service conditions, laboratory tests have identified classes of materials that retain good structural integrity even after absorbing radiation doses exceeding those expected for Belle II.

2.2.4 Moisture Absorption in Composite Materials

When a composite material is exposed to moisture for long periods of time, its mechanical properties can be affected. In particular, moisture absorption has been found to cause delamination between the composite layers and decohesion at the fiber–matrix interface. Therefore, it leads to matrix plasticization, interface debonding, delamination, and loss of mechanical performance. Controlling the moisture content in a composite material is one of the key challenges in ensuring structural stability. Two main strategies are typically employed to address this:

- the use of surface coatings that provide complete isolation from the external environment;
- the use of advanced materials specifically designed for space applications, which minimize moisture absorption.

As in other cases, material selection is not straightforward and must balance conflicting requirements.

2.2.5 Outgassing

Volatile substances present in the materials used, such as solvents and moisture, can be released over time into the surrounding environment. The main issues associated with these releases are outlined below:

- The released substances can contaminate the silicon wafers to the point of impairing their operation. Such contaminants, including amines, are often found in many of the epoxy resins used to pre-preg carbon fiber. It is therefore essential to obtain compliance certificates to ensure the suitability of the materials for use.
- Structural stability is also affected by moisture released as vapor from the materials, as this can lead to changes in the geometry of the structure.

Chapter 3

oVTX structure design

3.1 Overview

A comprehensive structural analysis has been conducted for the stave assembly of the oVTX Upgrade to evaluate its performance under loading conditions, as well as to assess stress distribution, deformation, and frequency response once installed in the Belle II experiment. Finite Element Analysis (FEA), validated through experimental testing, has been employed to predict structural behavior and optimize the mechanical design.

To meet the stringent requirements for the detector support structures, namely high stiffness combined with minimal mass, the design has relied extensively on the use of Carbon Fiber Reinforced Polymer (CFRP). On one hand, the ability to tailor the mechanical properties of CFRP to match the specific design needs makes it an ideal material choice. On the other hand, the significant anisotropy inherent in CFRP materials necessitated continuous refinement of both the finite element model and the input material parameters. This chapter presents a detailed overview of the test analyses I performed.

In parallel with the Ansys FEA simulations at INFN Pisa, I developed a ladder prototype starting from its three key components: the "so called" omega beam, the cold plate including the integrated cooling tube, and a 3D-printed end piece. After fabricating the mold and assembling the components using adhesive bonding, the prototype

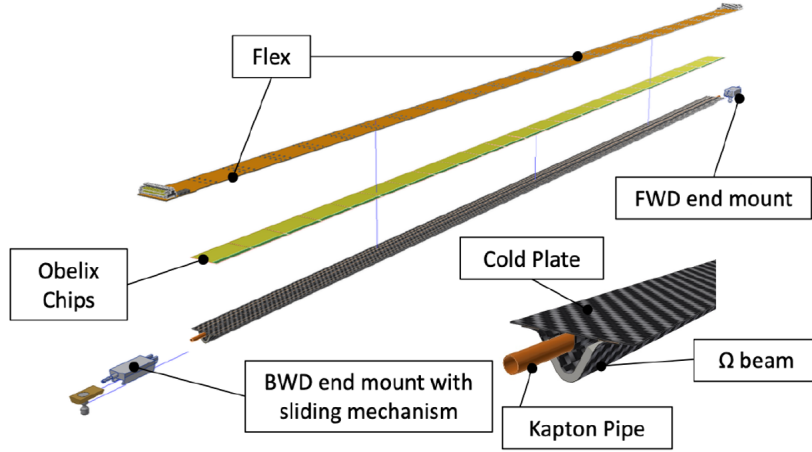


Figure 3.1: The design of oVTX stave.

was tested under loading conditions. These tests allowed for the experimental assessment of the ladder's maximum deflection and the validation of material properties, which were then accurately implemented in the FEA simulations. The resulting data were used to predict the flexural and torsional stiffness of the structure, as well as its natural vibration modes, through an optimization process.

As a reminder, the primary objective of this thesis is the mechanical optimization of the Layer 6 (L6) ladder 3.1, which represents the most challenging component of the oVTX detector in structural terms. This is the reason why simulations and experimental tests presented in this work are specifically focused on the L6 ladder.

Section 3.2 provides a detailed overview of the L6 ladder design, explaining the main motivation on material selection.

3.2 Material Selection for the Ladder Construction

Two key structural parameters drive the achievable accuracy and stability of the chip positioning: the ladder's sag under its own weight and its first natural frequency. The sag quantifies the displacement of the chips from their nominal positions due to gravitational effects, directly impacting the precision of the detector. Meanwhile, the first natural frequency defines the susceptibility of the structure to resonance phenomena,

where external excitations may induce vibrations, causing dynamic displacements of the chip positions. Both parameters, for a given mass, are dependent on the overall stiffness of the ladder structure, which is primarily provided by the omega beam bonded to the cold plate.

The stiffness of the omega beam is governed by three main factors: the elastic modulus of the composite material, the geometric rigidity, defined by the moment of inertia of its cross-section, and the boundary conditions, namely the stiffness of the connections between the ladder extremities and the end-rings through a special pin called *kokeshi*[18]. While similar considerations apply to the cold plate, its geometric configuration is largely constrained, and therefore only the material choice can be adjusted for optimization.

Due to the ultralight design, complex geometry, and the pronounced anisotropy of the composite materials, the finite element model required continuous refinement. This included updating both the mesh and the input material properties to improve its validation with experimental data. An extensive test campaign, aimed at the experimental characterization of flexural and torsional stiffness as well as the natural vibration modes, was conducted to calibrate the model. The finalized and validated model has then been used to reliably predict the structural behavior of the oVTX layers.

This section describes the materials selected for the construction of the oVTX stave. Among structural materials, carbon fiber reinforced plastics (CFRPs) represent the most efficient choice due to their excellent mechanical and thermal properties. CFRPs are composed of carbon fibers embedded in a polymer matrix, typically epoxy or cyanate ester. Cyanate esters are generally preferred in high-radiation environments, as they offer superior radiation hardness and a low coefficient of moisture expansion (CME), ensuring dimensional stability under varying humidity conditions.

In the context of silicon detector applications [19], only high-performance carbon fibers are relevant. These fibers are typically classified based on tensile modulus (see

figure 3.2). High modulus (HM) fibers range between 400 and 700 GPa, while ultra-high modulus (UHM) fibers extend from 700 to 1000 GPa. UHM fibers are particularly suitable for applications requiring high stiffness, although their brittleness and lack of flexibility make them unsuitable for scenarios where high strength is needed. Consequently, they are usually limited to unidirectional configurations.

In particle physics, carbon fibers such as K13C2U and K13D2U are widely adopted for

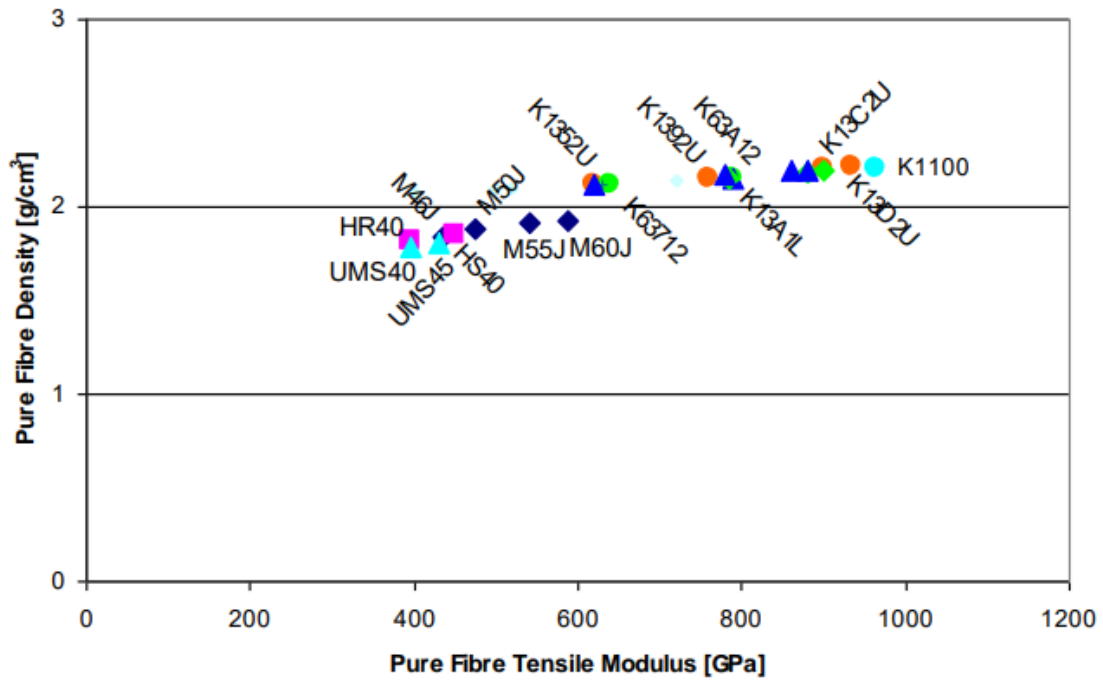


Figure 3.2: List of carbon fibres represented based on tensile modulus on the x-axis and fibre density on the y-axis [19].

their ultra-high modulus, around 900–935 GPa, as well as their high thermal conductivity (figure 3.3). When strength is a priority and a very high thermal conductivity is not essential, woven HM fibers like M55J can be a suitable alternative. M55J or M46J fibers are not only more cost-effective but also significantly easier to source on the market.

One of the main advantages of carbon fibers lies in their highly anisotropic thermal conductivity. Heat conduction along the fiber axis is high and correlated with the modulus, while transverse conductivity is significantly lower, by as much as three orders of magnitude. The coefficient of thermal expansion (CTE) of a unidirectional CFRP layer is typically slightly positive in the transverse direction, but negative along the

fiber axis (around $-10^{-6} \text{ m}/(\text{m} \cdot ^\circ\text{C})$). By carefully choosing the orientation of individual plies, it is possible to design laminates with quasi-zero CTE in selected directions. Notably, these configurations do not always coincide with the highest-stiffness layups.

The components of the L6 ladder prototype are manufactured from materials selected to meet demanding requirements in terms of stiffness, thermal performance, and radiation hardness, as described in sections 3.2.1 3.2.2.

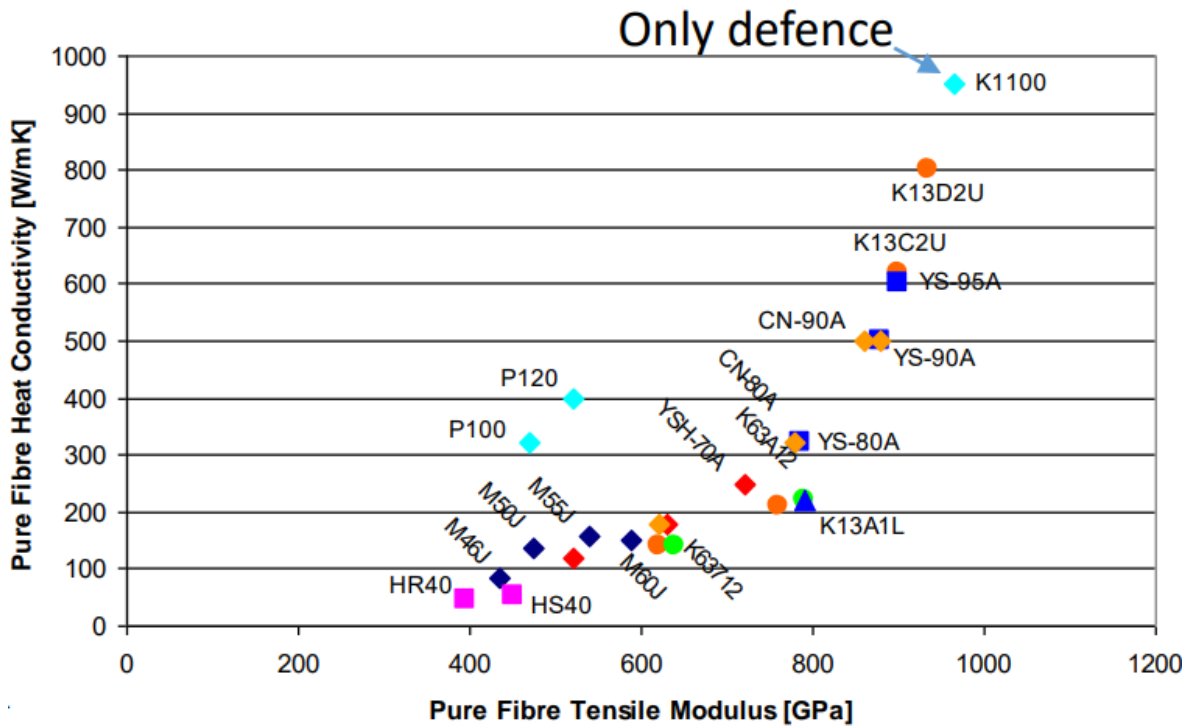


Figure 3.3: List of carbon fibres represented based on tensile modulus on the x-axis and fibre thermal conductivity on the y-axis. K13D2U is a high heat conductivity fibre [19].

3.2.1 The Cold Plate

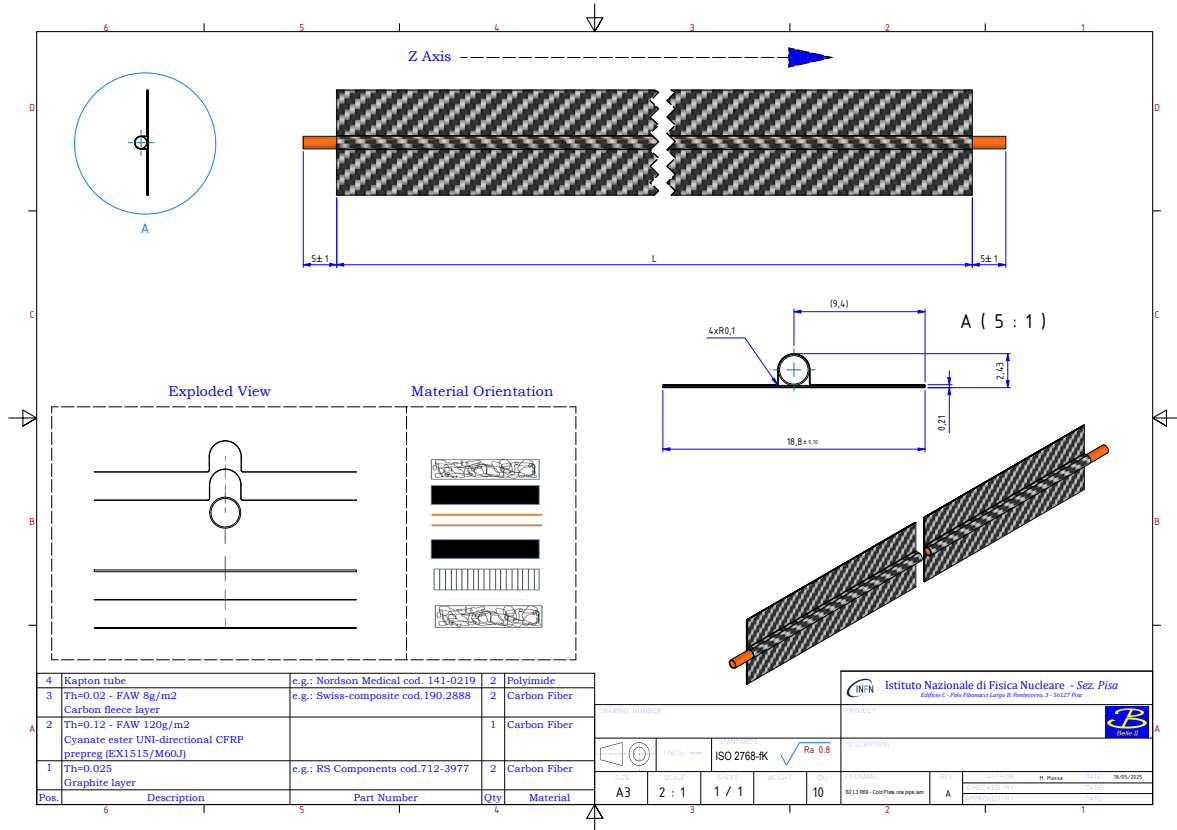


Figure 3.4: Mechanical drawing of L6 cold plate prototype

The cold plate 3.4 serves as the structural and thermal interface for all mounted electronic components. It is a thin plate lay up 730 mm long and 18.2 mm wide. Its multilayer architecture, arranged from top to bottom, is composed of the following materials:

- Carbon Fleece:** A 20 μm non-woven fabric composed of short carbon fibers randomly oriented and loosely bonded into a flexible mat. Unlike traditional woven carbon fabrics, its isotropic in-plane properties offer enhanced versatility. A ply of carbon fleece can be introduced as a protective layer for the graphite. Thanks to its soft and conformable structure, the fleece distributes local stresses, reduces the risk of scratches or graphite dust dispersion.
- Graphite Layer:** Comprised of 30 μm compressed graphite sheets, this layer acts as an efficient thermal spreader. With an in-plane thermal conductivity rang-

ing between of $1500\text{W}/(\text{m} \cdot \text{K})$, it effectively redistributes localized heat loads, particularly in proximity to embedded cooling pipes. In addition to thermal management, the graphite layer offers moderate mechanical stiffness, with an elastic modulus in the range of 10 to 20 GPa and a density of approximately 1.5 to $2.0\text{ g}/\text{cm}^3$.

- **Unidirectional K13D2U Carbon Fiber Reinforced with**

EX-1515 Cyanate-Ester resin: The structural core of the sandwich is formed by a $150\text{ }\mu\text{m}$ thick unidirectional composite layer. It consists of high-modulus, pitch-based K13D2U carbon fibers embedded in an EX-1515 resin matrix. These fibers exhibit exceptional stiffness (approximately 935 GPa) and high thermal conductivity along the fiber axis, reaching up to $800\text{ W}/(\text{m K})$. In its unidirectional composite form, this material provides optimal performance for both mechanical reinforcement and in-plane thermal conduction (see Table 3.1). K13D2U has been adopted in the cold plate structure as a superior alternative to the GG 52 P WS 100 composite, as further discussed in 3.5 section. The resin system for the CFRP is a cyanate ester resin, which is preferable to epoxy resin for its low humidity absorption and better dimensional stability over time (Table 3.2). It provides optimal mechanical properties, high radiation resistance, low moisture absorption, and low outgassing while retaining excellent toughness, a low $118\text{ }^\circ\text{C}$ stress-free temperature, and long out time. The resin system excels in its ability to resist microcracking, even when subjected to thermal cycling and high levels of radiation exposure. EX-1515 can be post-cured, freestanding, to increase thermal performance for temperature-critical structures. Furthermore, its CTE of $61 \times 10^{-6}\text{ m}/(\text{m} \cdot ^\circ\text{C})$ partially compensates for the negative CTE values of carbon fibers. For the test and simulation, 934 Epoxy Resin was selected, as it was easier to find and to handle, plus cheaper on the market than the cyanate ester resin.

- **Kapton Pipe:** Below K13D2U UD in strict contact with it, there is the kapton pipe with 2mm internal diameter and with an approximate thickness of $20\text{ }\mu\text{m}$

necessary for the cooling system. It will host the $10m/s$ water flow to cool the OBELIX chips and their readout.

- **Graphite Layer:** A second graphite layer is included to mirror the top thermal spreading function and to ensure symmetric thermal behavior and mechanical balance across the cold plate.
- **Carbon Fleece:** The bottom-most layer replicates the top fleece configuration, enhancing overall EMI shielding and ensuring structural symmetry.

Table 3.1: Mechanical and thermal properties of the K13D2U/934 epoxy composite.

Property	Direction	Value
Tensile Modulus (E)	Longitudinal	560 GPa
	Transverse	3 GPa
Tensile Strength	Longitudinal	1800 MPa
Thermal Conductivity (k)	Longitudinal	$800 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$
	Transverse	$6 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$
Coefficient of Thermal Expansion (CTE)	Longitudinal	$-0.5 \times 10^{-6} \text{ K}^{-1}$
	Transverse	$30 \times 10^{-6} \text{ K}^{-1}$

Table 3.2: Typical properties of CYCOM 934 epoxy resin

Category	Property	Value
Thermal	Glass Transition Temperature (T _g)	121–127 °C
	Continuous Use Temperature	~ 100 °C
	Thermal Decomposition Onset	> 300 °C
Mechanical	Tensile Strength (RT)	75–85 MPa
	Tensile Modulus	3.1–3.5 GPa
	Compressive Strength	240–260 MPa
	Flexural Strength	120–130 MPa
	Interlaminar Shear Strength (ILSS)	70–75 MPa
Physical	Density	~ 1.25 g/cm ³
	Resin Content in Prepreg	35–40 % (wt)

3.2.2 The Omega Beam

The omega beam structure forms the lower part of the oVTX ladder. It is a composite sandwich structure consisting of two plain woven pre-preg carbon fiber skin layers (GG 52 P 100 WS) and a 1 mm thick Rohacell foam core. Figure 3.5 presents the Inventor AutoCAD drawing with the specifications which were used to build the prototype and to insert inside the Ansys simulation.

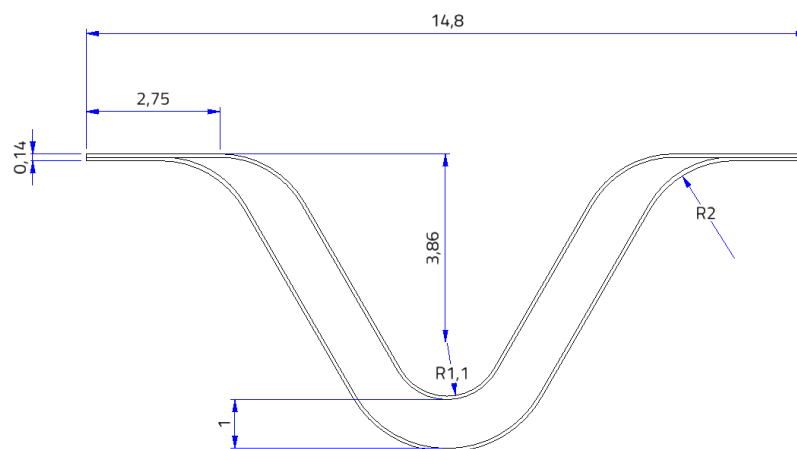


Figure 3.5: Omega Beam drawing on Invetor software

The omega shape was chosen to meet design requirements such as optimization of torsional stiffness, material budget minimization and manufacturing feasibility for composites. Although in principle only the cold plate is functionally required to support the sensors and the corresponding flex circuits, relying solely on the cold plate would be insufficient from a mechanical standpoint.

Indeed, the cold plate alone behaves like a thin flat plate whose torsional constant can be approximated as:

$$J_{\text{open}} \approx \frac{1}{3} b t^3 \quad (3.1)$$

where $b = 18.2 \text{ mm}$ is the width and t is the thickness. This configuration results in a low torsional stiffness as a result of the open-section geometry.

In contrast, the addition of the Omega Beam transforms the assembly into a closed-section profile, significantly enhancing the torsional rigidity. The polar moment of inertia for a closed section is given by:

$$J = \frac{4A_m^2}{\int \frac{1}{t(s)} ds} \quad (3.2)$$

where:

- A_m : represents the area enclosed by the midline of the thin-walled section;
- s : curvilinear coordinate;
- t : represents the variable thickness of the closed thin-walled section as a function of the curvilinear coordinate s .

Similarly, the bending stiffness of the cold plate alone is drastically lower compared to that of the full omega beam structure. In fact, the estimated second moment of area increases from 0.005 mm^4 (cold plate only) to 209.131 mm^4 in the omega + cold plate configuration (in the direction 1 shown in Figure 3.6).

The omega profile was also preferred over a classic C-shaped profile for ease of manufacturing: the omega geometry avoids sharp corners, employing rounded transitions

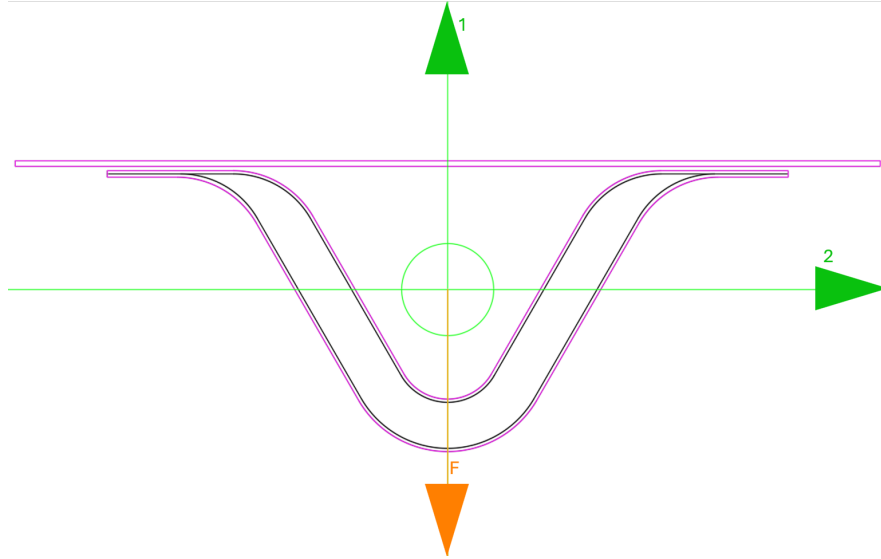


Figure 3.6: Frame from the calculus of the moment of inertia on AutoCAD software

instead. This greatly facilitates the layup of pre-impregnated fibers, improves fiber continuity and reduces stress concentrations, thereby minimizing the risk of delaminations or micro cracks in the composite. As previously mentioned, the omega beam consists of:

- One lower layer of GG 52 P 100 WS, a lightweight (0.07 mm) carbon fiber prepreg laminate using plain-woven fabric. The fibers are of type 12K HS 40 12P, featuring excellent epoxy compatibility and impregnation. The key mechanical properties are:
 - Tensile modulus: 425 GPa
 - Tensile strength: 4.61 GPa
 - Density: 1.85 g/cm³
- The Millifoam RHC51HF is a rigid polyurethane foam used as the core material in the sandwich. Thanks to its high mechanical stability and low density, it is ideal for applications in vertex detectors, presenting a negligible material to traversing particles, a 1 mm thick layer of foam can be used without compromising performance. A summary of the composite properties is provided in Table 3.3. The Millifoam RHC51HF stands out for its excellent strength-to-weight ratio,

Property	Unit	Typical value	Notes
Density	kg/m ³	≈ 51	Rigid polyurethane foam
Compressive strength	MPa	1.0 – 1.5	Direction- and condition-dependent
Elastic modulus (compression)	MPa	15 – 30	Indicative value
Maximum service temperature	$^{\circ}C$	80 – 100	Short-term, non-structural
Water absorption	%	Low	High closed-cell content
Dimensional stability	–	Excellent	Over a wide temperature range
Workability	–	Easy	Cuttable, machinable
Compatibility	–	Epoxy, vinyl ester	Excellent surface adhesion

Table 3.3: Technical characteristics of Millifoam RHC51HF foam.

thermal stability, and ease of machining. It is therefore an ideal choice for the core of lightweight, mechanically robust sandwich structures already used in support structures of high-energy physics detectors.

3.2.3 Structural Adhesive

The various parts of the tracker structure and the components of the detection module are joined together by means of adhesive bonding. For structural bonding, two types of adhesives are used:

- ARALDITE AW106/HV953U by CIBA–GEIGY to bond coldplate and omega beam
- ECCOBOND 45/Catalyst 15 by Henkel for the cold plate and silicon gluing

AW106/HV953U is a structural epoxy adhesive that cures at room temperature within 24 hours and has been thoroughly tested under ionizing radiation, demonstrating good resistance to radiation doses up to $4 MG_y$.

AW106 is the epoxy resin, while HV953U is the hardener. The data provided by CIBA–GEIGY for this adhesive are shown in Table 3.4

Adhesives used to bond the silicon detectors to the frame must primarily satisfy two requirements:

- facilitate heat transfer,
- minimize deformation caused by thermal stresses.

Technical Datasheet: Epoxy System AW106 / HV953U	
Properties Before Curing	
Physical st. (AW106/HV953U)	Viscous liquid / Syrupy, slightly alkaline
Color	Cream / Yellow – brown
Viscosity at 25 °C	30 – 50000 cPs / 25 – 40000 cPs
Specific gravity at 25 °C	1.15 – 1.25 g/cm ³ / 0.9 – 1.0 g/cm ³
Flash point	210 °C / 50 – 55 °C
Mixing Ratio	
By weight	AW106: 100 / HV 953 U: 80
By volume	AW106: 100 / HV 953 U: 100
Pot Life (100 g mixture)	
At 20 °C	135 minutes
At 30 °C	85 minutes
Curing Conditions	
At 20 °C	15 hours
At 25 °C	12 hours
At 40 °C	3 hours
At 70 °C	50 minutes
Technical Characteristics (After Curing)	
Temperature resistance	-60 °C to +60 °C
Shear strength (tensile test)	14 – 17 N/mm ²
Test conditions	Anticorodal 100B samples, 5 days at 20 °C

Table 3.4: Technical properties of adhesive AW106/HV953U.

The reduction in chip size and the trend toward highly integrated components lead to heat generation over small surface areas: one Obelix chip power densities is up to 0.2 W/cm^2 . To dissipate such power densities, it is necessary to use adhesives with good thermal conductivity. Thermal stresses arise from the different coefficients of thermal expansion (CTE) of the materials used. These stresses must be carefully considered during the design of the module, as they can lead to excessive deformation, potentially causing damage to the interconnections between the electronic components mounted on it. Such damage could definitely compromise the functionality of the detection module. Table 3.5 reports thermal expansion coefficients of materials commonly used in electronics.

Material	Thermal Expansion Coefficient ($10^{-6}/\text{K}$)
Silicon	3
Alumina (Al_2O_3)	7
Aluminium Nitride (AlN)	4
Copper	17
Aluminium	27
FR-4 (XY-plane)	16
Epoxy	45
Silver-Glass	17
Silver-Epoxy	45
Alumina-Epoxy	33
Millifoam	38

Table 3.5: Thermal expansion coefficients of materials commonly used in electronic components.

One way to reduce the deformations caused by thermal stresses is to use materials with closely matched CTE values. An alternative approach is to use adhesives with a low elastic modulus, which allow differential expansion between materials while generating only low internal stresses. Table 3.6 lists the mechanical properties of commonly used adhesives and soft solders. It is evident that the most suitable adhesives for our

purposes are silicone-based or "stress-free" types.

Adhesive Type	Elastic Modulus (GPa)	Poisson's Ratio
Tin Lead Solder	68.94	0.35
Indium Solder	34.97	0.35
Silver-Glass	68.94	0.35
Standard Epoxy	2.06	0.35
Silver-Epoxy	6.89	0.35
Alumina-Epoxy	13.78	0.35
Silicone	0.10	0.45
Polyurethane	0.14	0.45
Stress-Free Epoxy	0.12	0.45

Table 3.6: Mechanical properties of commonly used adhesives and soft solders.

To bond the silicon detector chip to the composite cold plate, the adhesive epoxy system ECCOBOND 45 with Catalyst 15 is going to be employed. This is a two-component epoxy resin with tunable mechanical properties, depending on the resin-to-hardener weight ratio. Two formulations can be used for the bonding process: a rigid mix (100:50) and a flexible mix (100:150). The rigid formulation exhibits a relatively high elastic modulus (2 GPa) and provides strong structural adhesion but may introduce significant thermal stress due to the mismatch in coefficients of thermal expansion (CTE) between silicon and the composite substrate. Conversely, the flexible formulation greatly reduces stiffness (estimated elastic modulus 0.1–0.2 GPa), offering better balance between thermal cycling stresses and mechanical strength. The adhesive is also electrically insulating, thermally stable up to 90 °C, and well-suited for bonding dissimilar materials such as semiconductors and composite structures. Table 3.7 presents the physical properties for the rigid formulation.

Property	Value
Coefficient of Thermal Expansion (below T_g), ASTM D3386	$58 \times 10^{-6} \text{ m}/(\text{m} \cdot ^\circ\text{C})$
Coefficient of Thermal Expansion (above T_g), ASTM D3386	$158 \times 10^{-6} \text{ m}/(\text{m} \cdot ^\circ\text{C})$
Glass Transition Temperature (T_g), ISO 11357-2	48 $^\circ\text{C}$
Thermal Conductivity	0.35 W/m·K
Shore Hardness, ISO 868 (Durometer D)	80
Water Absorption (24 hours), ASTM D570	0.2%

Table 3.7: Physical properties of ECCOBOND 45 with Catalyst 15 (100:50 mix ratio).

3.3 Assembly of the Ladder Prototype

3.3.1 Bonding of Ladder Prototype Components

As the first experimental step in this thesis work, a prototype incorporating a K13D2U-based cold plate was developed to study the deflection due to sagging when replacing GG52 woven carbon fiber with unidirectional fiber. The starting configuration featured the omega beam separated from the cold plate with the Kapton pipe integrated. The first objective was to permanently bond the two parts.

To carry out this operation, I designed and helped fabricating custom bonding tools for both the omega beam and the cold plate, in order to ensure proper alignment and control during the gluing process. Since only one K13D2U cold plate was available, extreme care was taken to avoid any errors.

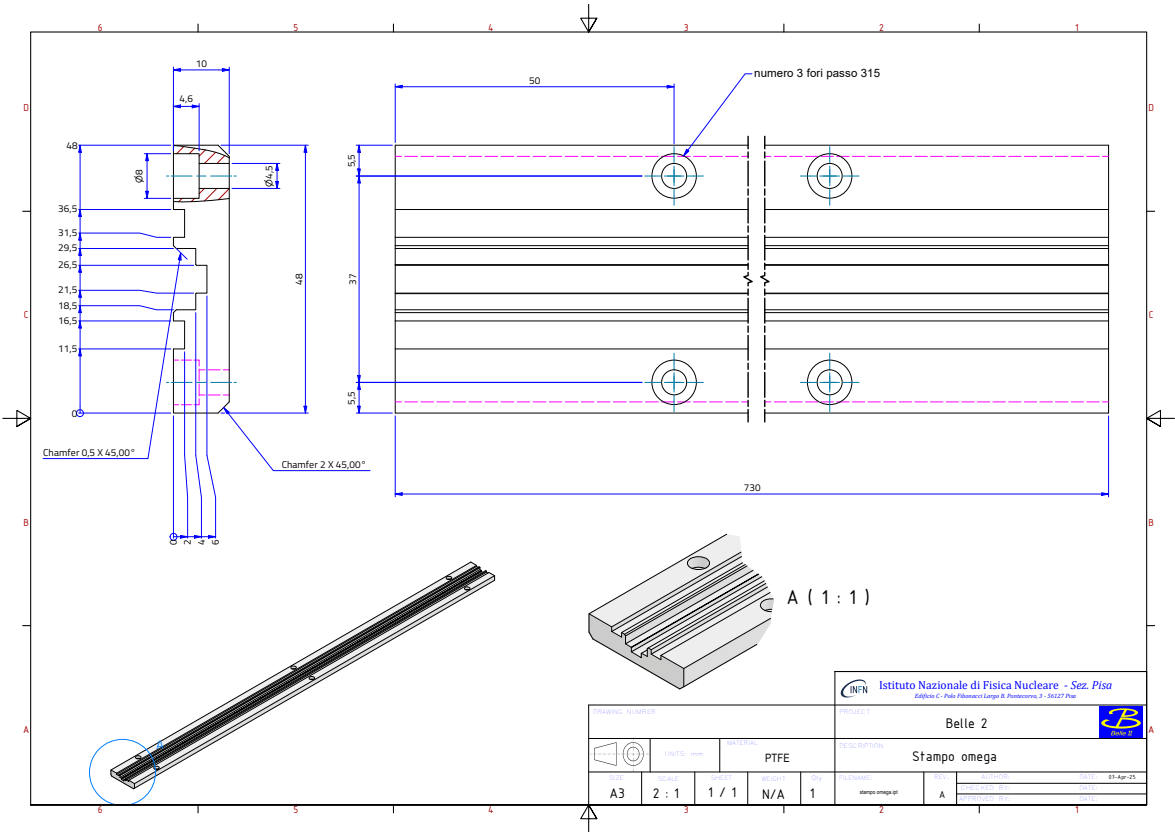


Figure 3.7: Mechanical drawing of the PTFE stamp for the omega beam

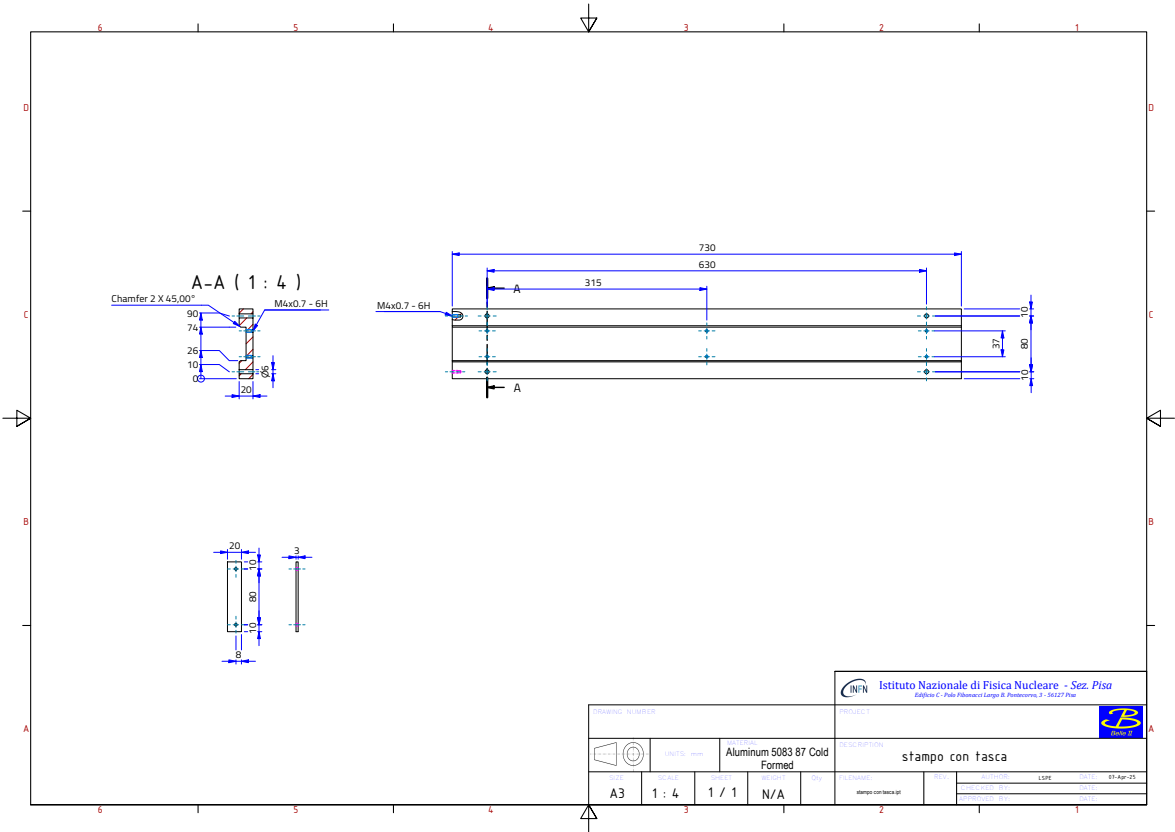


Figure 3.8: Mechanical drawing of the support stamp in aluminum for the omega beam. On the bottom left side is possible to see the drawing of the aluminum block.

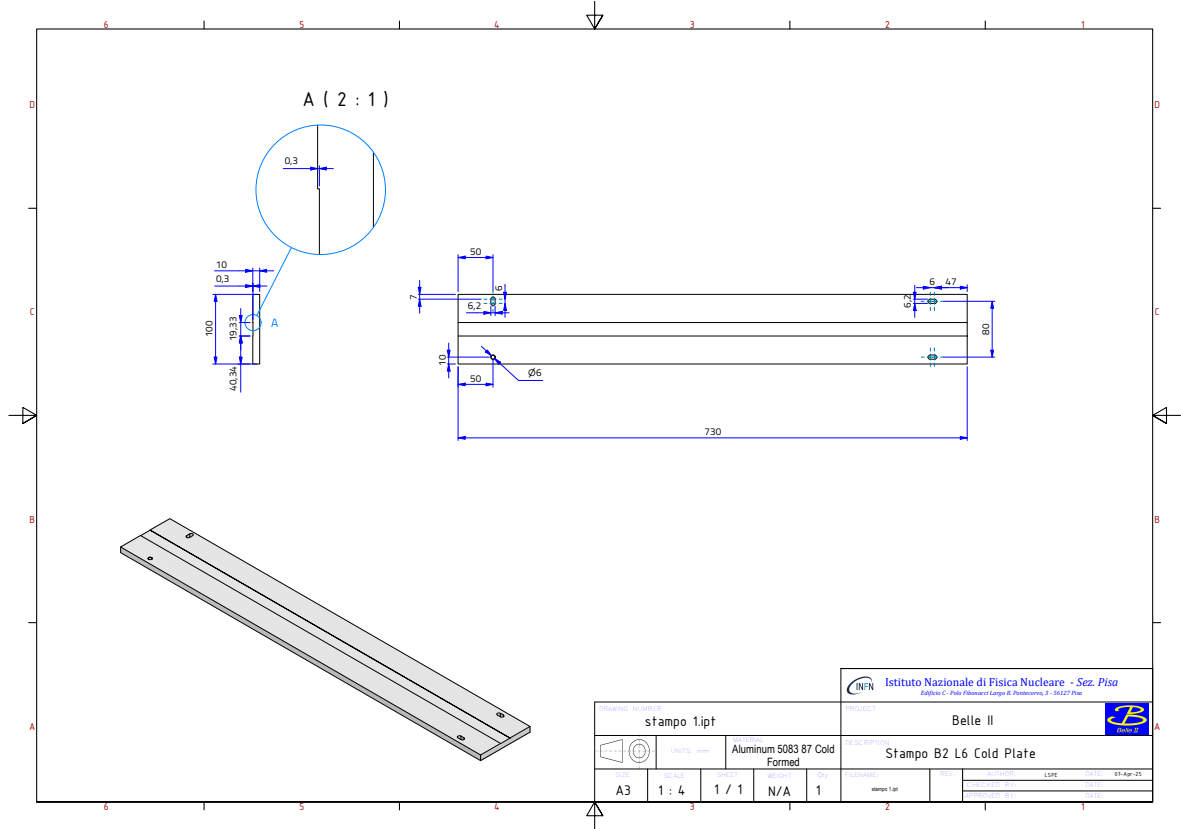


Figure 3.9: Mechanical drawing of the stamp for the Cold Plate

A PTFE mold was prepared for the omega beam (Fig. 3.7), which was subsequently inserted into a secondary aluminum fixture made of 5083 alloy (Fig. 3.8), and the assembly was secured using M6 flat-head screws. The use of PTFE was intended to prevent adhesion between the jig and the bonded components in case of glue overflow and in addition it is easier to shape.

As it can be seen in Figure 3.7, two grooves were machined on either side of the omega beam housing to accommodate potential excess adhesive and prevent unwanted spreading. Figure 3.10 illustrates the finished piece after the milling process. The aluminum mold, Fig. 3.8, provided additional mechanical support to the PTFE insert, ensuring dimensional stability during machining and the bonding phase. In the drawing shown in Fig. 3.8, a small aluminum block is visible at the bottom, designed to ensure the correct positioning of the ladder within the assembly. To prevent any risk of unintended bonding in case of adhesive overflow in that direction, I later inserted a PTFE strip between this aluminum block and the glued assembly.



Figure 3.10: Omega beam mold after the milling process

For the mold of the cold plate, the cap of the entire mold, I used 5083 alloy since glue overflow was not a concern in this case. This is due to the fact that the cold plate is wider than the omega beam (Fig. 3.9), allowing any excess adhesive to flow outside the bonding region without affecting the structural integrity.

In this mold, the critical dimensions with the tightest tolerances are the depth and width of the cold plate seating area. These must be precisely machined to ensure that the cold plate is correctly positioned on top of the omega beam. A clearance along the width direction could lead to misalignment or lay-up failure, while excessive depth would prevent proper contact between the cold plate and the omega beam, compromising the bonding process. At the end, the two parts of the mold were aligned and locked in place using fastener pins to prevent relative movement. However, after the assembly, I observed a slight clearance between the two halves. To eliminate this and ensure proper contact, six M6 screws were added, allowing the two components to be securely clamped together with precise alignment.

After completing the milling process, the components were bonded together using Araldite 2011. The adhesive was applied to the contact surface of the omega beam, where it interfaces with the cold plate. The cold plate was held in position using standard adhesive tape, which was chosen for its ease of removal after curing. The assembly was left undisturbed for over 24 hours to ensure proper curing of the glue. Figure 3.11 shows the assembly during the gluing process.

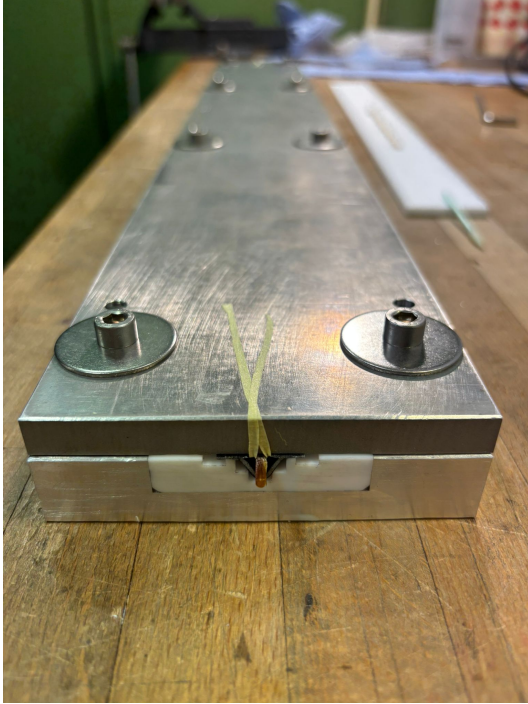


Figure 3.11: Curing process with Araldite 2011

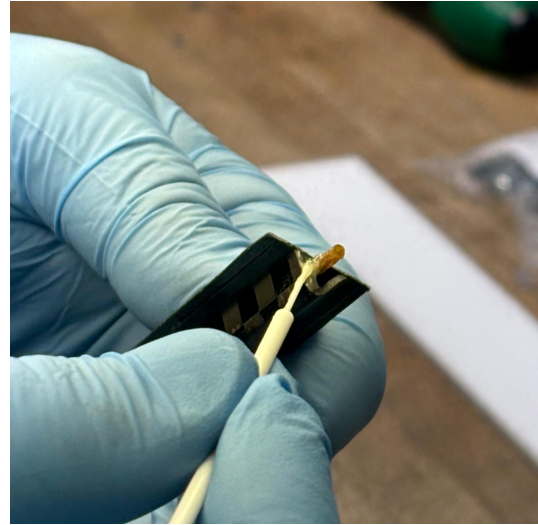
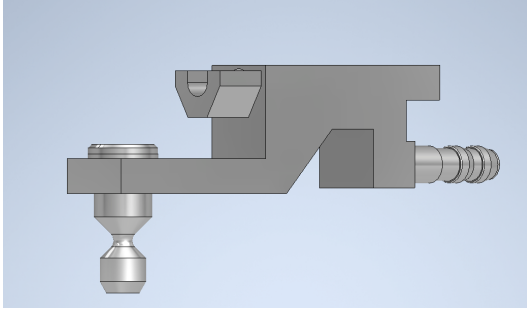


Figure 3.12: The glue has been put in the space between the omega and the cold plate, following the omega borders and the kapton pipe outline

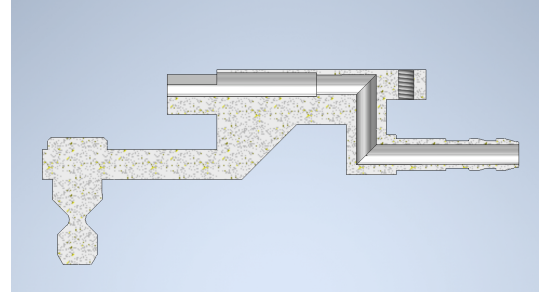
3.3.2 Design and Installation of Ladder End Pieces

To make the test of the ladder's mechanical deflection as realistic as possible, I decided to install at its extremity a simplified replica of the end pieces. The replica was fabricated in resin using a 3D printer. The key difference between the actual component and the replica, aside from the material choice, was the decision to manufacture it as a single integrated piece, incorporating the kokeshi-pin directly into the end piece structure. As shown in Fig. 3.13b, the end piece includes a through-hole, designed as a simplified reproduction of the actual channel through which water will flow. After the manufacturing process, the resin end pieces were bonded to the ladder prototype using Araldite 2011 (Fig. 3.12).

A Bosch profile with an housing plate was employed to ensure the correct positioning during assembly, Fig. 3.14. This auxiliary support was necessary because, in the real configuration, the kokeshi pin is designed to be inserted into the end ring and therefore, without a proper housing, it interferes with the stability of the ladder and the gluing



(a) The Kokeshi pin, the cylindrical part in the front, is completely integrated in the end piece



(b) Half section of the end piece

Figure 3.13: Sketch of the 3d replica of the end piece

process. The housing plate fixed to the Bosh profile effectively replicated the housing of the end ring, allowing the end pieces to be aligned and secured without interfere with the ladder free-standing.



Figure 3.14: Bonding process with the kokeshi pin inserted in the housing plate fixed in the Bosh profile

After this final procedure the L6 ladder was ready to be tested, fig. shows the final prototype.

3.4 Experimental set up

The aim of the test is to study the deflection of the ladder under loading conditions. A similar test was previously conducted on an earlier prototype equipped with a woven cold plate instead of a unidirectional one. The objective of the present analysis is therefore to determine whether the change in fiber type, from a “dummy” cold plate

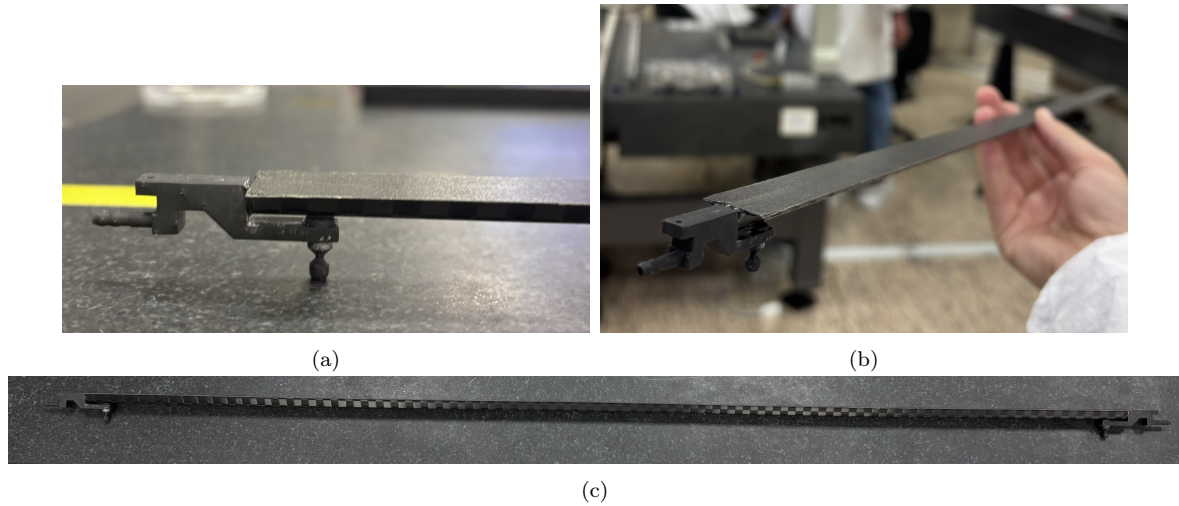


Figure 3.15: L6 ladder ultimate prototype.

made of 70- μm GG52 plain-woven fibers to the actual cold plate manufactured with 120- μm unidirectional K13D2U fibers, affects the maximum deflection, and to quantify the magnitude of this effect.

The measurements were carried out using a DEA Hexagon Optical CMM, with the ladder prototype mounted on a Bosch profile, the same employed during the bonding process. The ladder was fixed to the measurement bench by clamping the end pieces, fig. 3.16, thereby replicating the double-clamped boundary conditions at both extremities.



Figure 3.16: Clamped ladder on workbench

I performed two measurements: the first in the unloaded condition, and the sec-

ond with a concentrated load of 20 g applied at mid-span. This concentrated load is intended to reproduce the overall load that the structure will experience once the additional components of the stave (e.g. Obelix chips and flex circuits) are integrated, the total amount is precisely 15,2 g which gives a safety factor of 31 % with the 20 g mass employed 5.12. In this 31 % factor, it can be included the water flow mass. However, in the actual configuration, the load will not be concentrated in the center, but rather distributed along the entire length of the ladder.

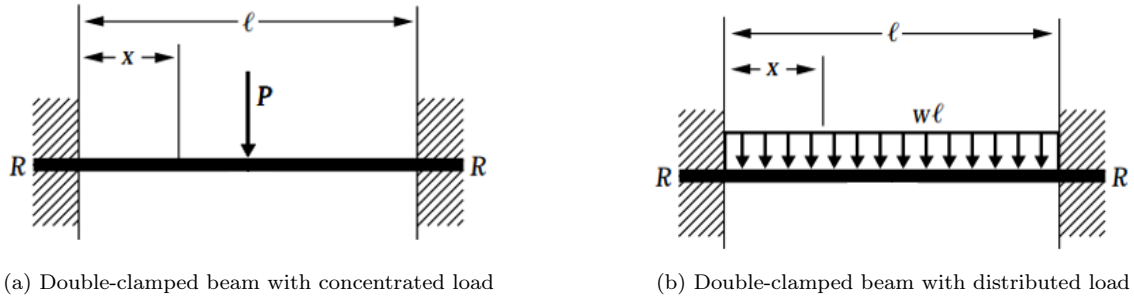


Figure 3.17: Beam theory for Double-clamped beam

A relationship can nevertheless be established between the beam behavior under a concentrated load and that under a distributed load. According to beam theory, the mid-span deflection of a double-clamped beam subjected to a uniformly distributed load, figure 3.17b, is equal to half of the deflection produced by an equivalent concentrated load with the same boundary conditions, beam geometry and properties; figure 3.17a. The formulas for deflection in both cases are reported below:

$$\delta_{\max} = \frac{P l^3}{192 E I} \quad (\text{concentrated load at mid-span}) \quad (3.3)$$

$$\delta_{\max} = \frac{w l^4}{384 E I} \quad (\text{uniformly distributed load}) \quad (3.4)$$

where:

$\delta_{\max}$: maximum deflection [m]

P : concentrated load applied at mid-span [N]

w : uniformly distributed load per unit length [N/m]

l : beam length [m]

E : Young's modulus of the material [Pa]

I : second moment of area [m⁴]

In order to carry out the measurements, a reference system was first established. The procedure started from one corner of the unloaded ladder. A series of points was acquired with the optical measurement head along the edge on one side and subsequently along the opposite side. From these point sets, two lines were reconstructed, which defined the axes of the reference system; their intersection was taken as the origin.

After setting the coordinate system, measurements were performed on the ladder in both the unloaded and loaded conditions. The optical microscope followed the same route in both cases, measuring the x and y coordinate of the point as distance from the origin and z coordinate, as the depth respect to the origin. The depth measurements were taken manually trying to measure the depth at which the ladder point was on focus. The acquisition was carried out along the mid-span axis, enabling a direct evaluation of the deflection at the most critical location.

3.5 Test results

The objective of the test was to assess the extent to which the introduction of a unidirectional fiber Cold Plate reduces the deflection of the ladder. To illustrate this effect, graph 3.18 reports the results obtained with the woven-fiber cold plate, while

graph 3.19 corresponds to the test performed with the unidirectional-fiber cold plate. A comparison between the two datasets clearly shows that the use of unidirectional carbon fiber significantly decreases the maximum deflection under loading condition, it was valued considering the maximum delta value which indeed decreased from $749\ \mu m$ to $359\ \mu m$. This result highlights the effectiveness of the unidirectional cold plate, despite its higher cost and the greater complexity associated with its fabrication.

Nevertheless, both graphs reveal an initial warping of the ladder in unloaded condition not only connected to the ladder's weight itself but also to the manufacturing process. In the second test, this initial deflection reached a maximum of $1.62\ mm$, which is considered unacceptable. It must be noted that each ladder prototype was produced using a single mold. Given the large aspect ratio of the ladder and its reduced thickness, this manufacturing approach increases the likelihood of imperfections, which may in turn contribute to the warping observed in the unloaded configuration. Such warping must therefore be carefully considered in future fabrication processes and in the design of subsequent models, and will be addressed in consultation with the manufacturing company.

So, after conducting the test, I was able to prove that the replacement of the woven carbon fiber with the unidirectional carbon fiber in the cold plate was worth the effort and the cost. Additionally, I obtained experimental results that I can now use to calibrate the computer simulations. My next objective is therefore to make the Ansys simulations converge with the experimental data, in order to ensure that the numerical model is sufficiently accurate to validate future design choices.

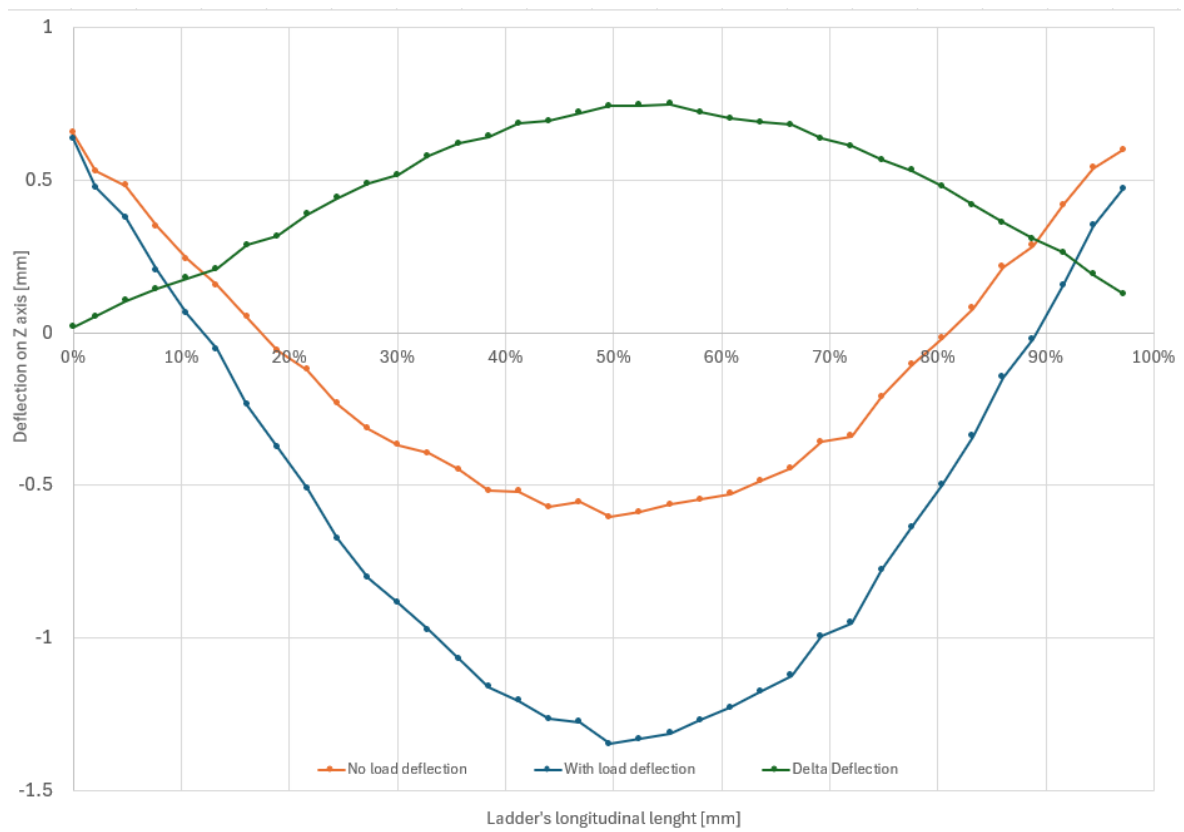


Figure 3.18: Deflection test for L6 Ladder with Woven Cold Plate. Experimental measurements: **orange** corresponds to the values without load, **blue** those with an applied load of 20 g, and **green** represents the delta between the two conditions.

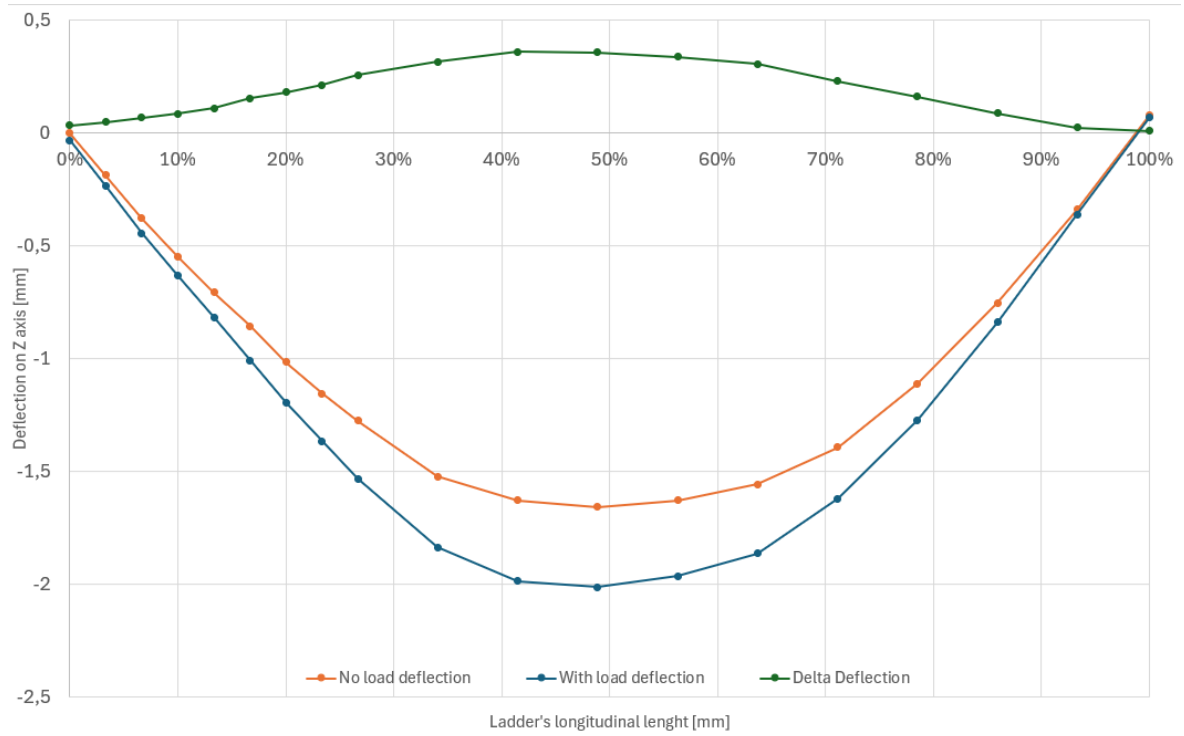


Figure 3.19: Deflection test for L6 Ladder with UD Cold Plate. Experimental measurements: **blue** corresponds to the values without load, **orange** those with an applied load of 20 g, and **green** represents the delta between the two conditions.

Chapter 4

Ansys FEA Simulation

This chapter discusses the finite element analyses conducted during the study. The initial simulations were carried out to align the prototype's experimental tests with the corresponding Ansys simulations, ensuring that the virtual model faithfully represented the physical system. After validating the numerical model, different strategies were investigated in the Ansys's environment to optimize the design. The finite element methodology adopted for the simulations is outlined below. The ANSYS analysis process was divided into several steps:

1. **3D CAD Model:** INVENTOR AUTOCAD, a 3D CAD modelling tool, has been used for the creation of the 3D geometry of the part/assembly.
2. **Clean Up and import the 3D CAD Model:** Some features of the 3D CAD geometry were not relevant for the finite element analysis (FEA), yet they significantly increased the complexity of the meshing process. Such non-essential details were therefore removed from the CAD model using ANSYS SpaceClaim, the 3D CAD modelling tool integrated in the ANSYS suite. Further simplifications of the solid model were also introduced for components whose geometry and function allowed them to be more appropriately represented as shell elements.
3. **Defining Material Properties:** For each parts material properties have been chosen. Materials used are isotropic and orthotropic. For the orthotropic material

the definition of the element orientation is fundamental for the correct attribution of the material properties. Shell elements require respectively the definition of cross section properties and the lay-up and thickness.

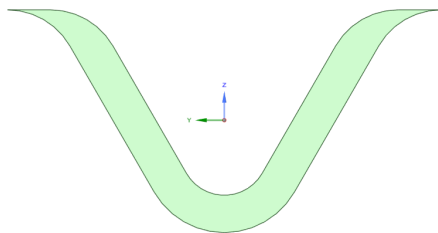
4. **Modeling of composite laminates with ANSYS Composite PrepPost (ACP):** ANSYS Composite PrepPost (ACP - Pre) is a dedicated pre-processing environment within ANSYS designed for the modelling, analysis, and design of laminated composite materials. In ACP Pre, users define the material properties, layup sequences, ply orientations, and their placement on the geometry. The software allows the creation of orthotropic material models and the specification of individual ply characteristics, such as thickness and fiber orientation. The graphical interface ensures a clear visualization of the laminate definition, supporting accurate and efficient model setup. ACP Pre integrates seamlessly with the ANSYS structural solver, enabling detailed simulation of the mechanical behavior of composite materials under various load conditions.
5. **Meshing:** It is performed to discretize the geometry into small pieces called elements or cells. The analysis accuracy and duration depends on the mesh size and orientations. The mesh size must be optimized balancing the finite element analysis speed versus the accuracy of the results. The domain has to be meshed properly into elements of specific shapes such as triangles and quadrilaterals. Triangulation is the most flexible and well-established way in which to create meshes with triangular elements. The additional advantage of using triangles is the flexibility of modelling complex geometry and its boundaries. The disadvantage is that the accuracy of the simulation results based on triangular elements is often lower than that obtained using quadrilateral elements. Quadrilateral element meshes, however, are more difficult to generate in an automated manner and it has been performed by using local mesh tools to force algorithms to create a quadrilateral and well defined mesh. Different types of elements or different parts of assembly have been connected using linear contacts to limit the computational time.

6. **Defining Boundary and Loading Condition:** Boundary and loading condition have been defined according to the tests performed. These conditions have been applied either to geometrical identities (points, lines or curves, surfaces, and solids) or to elements or grids.
7. **Solve:** ANSYS Solvers solves problem for the defined material properties, boundary conditions and mesh size. Direct Sparse Solver, based on a direct elimination of equations, has been used for a static structural analysis, while for modal analysis Block Lanczos Solver based on Lanczos method has been used (**Appendice**).
8. **Post Processing:** The result can be viewed in various formats: graph, value, animation etc. Results studied in analysis are displacement for static structural analysis and firsts modal frequencies for modal analysis.

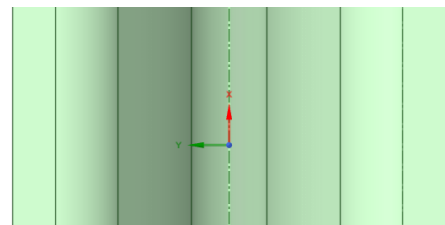
4.1 Simulation Setup and Validation

4.1.1 The SpaceClaim model

The ladder was initially modeled in different environments. Starting from the Inventor AutoCAD model, the core of the omega beam was first separated from the skin layers and the cold plate in order to simplify the simulation. The cold plate and the carbon fiber skin layers were modeled using thin shell elements (figures 4.2 and 4.3), following the slenderness criterion ($D/L < 10$), whereas the core was represented with 3D solid elements (figure 4.1).



(a) Core – front view



(b) Core – upper view, the reference system is place in the middle.

Figure 4.1: SpaceClaim Core model of L6 Ladder. It presents the chosen reference system: the x-axis lies along the midline of the ladder and is aligned with the fiber direction, the y-axis corresponds to the transverse direction of the fibers, and the z-axis completes the system.

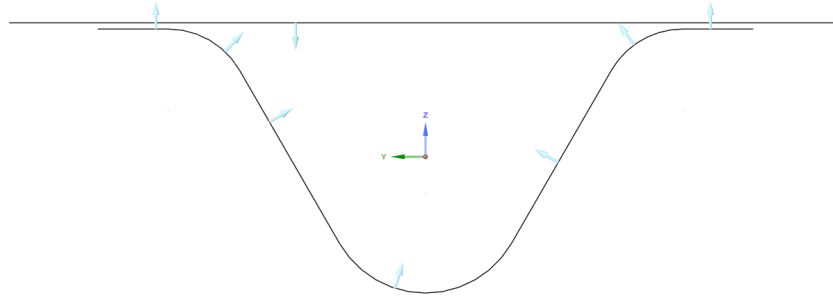


Figure 4.2: SpaceClaim representation of the middle surface of the lower skin layer and the cold plate. The arrow indicates the normal axis, which defines the orientation along which the thin shell elements will be generated.

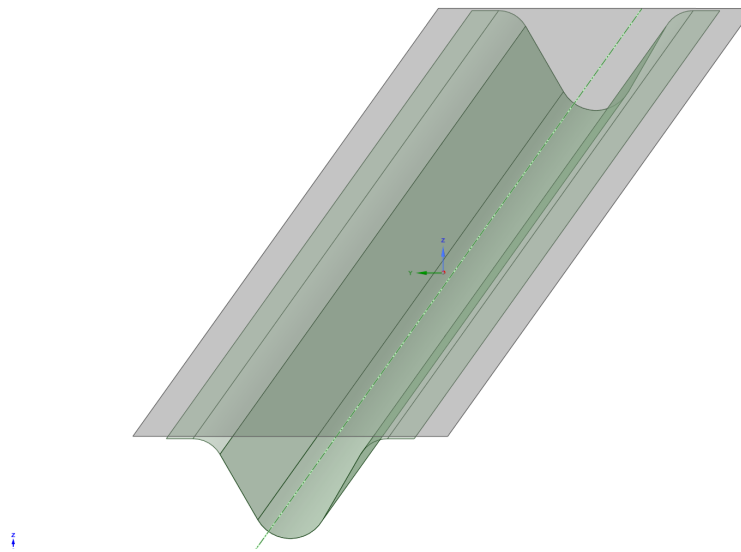


Figure 4.3: Cold plate and skin layer

4.1.2 Material properties

Following the standard Ansys workflow, the next step involves defining the material properties. Although this may appear straightforward, it resulted to be a critical aspect for the accuracy of the simulation and it was the main reason why tuning with experimental tests was required. The challenge arose from the use of composite materials: since they are made of both fiber and matrix, the datasheets for the individual constituents are available, but the effective properties of the composite are far more difficult to determine. In my case, this issue specifically concerned the skin layers of the omega beam. The prepreg employed for these layers was GG 52 PWS 100 X1 120HM 48%, where X1 120 denotes the type of epoxy resin used. The company responsible for

fabricating the ladder did not possess the datasheet for the final composite; however, after several iterations, it was determined that the material exhibited properties comparable to those of the composite summarized in the table 4.1:

Property	Value	Unit
Tensile Strength (0° Warp)	930 - 1149	MPa
Tensile Strength (90° Weft)	847 - 1036	MPa
Tensile Modulus	54 - 67	GPa
Compression Strength (0°)	670	MPa
Compression Strength (90°)	592	MPa
Compression Strength ($\pm 45^\circ$)	819	MPa
ILSS (Interlaminar Shear)	88	MPa
In-Plane Shear Strength	714	MPa

Table 4.1: Mechanical properties similar to GG 52 PWS 100 X1 120HM 48%

Due to the existing uncertainties in defining composite properties, the manufacturer recommended reducing the tensile modulus by 20% for the FEA simulations. The material properties implemented in the Engineering Data module are therefore presented in table 4.2 .

Property	Value	Unit
Young's Modulus X direction	55	GPa
Young's Modulus Y direction	55	GPa
Young's Modulus Z direction	3	GPa
Poisson's Ratio XY	0.05	—
Poisson's Ratio YZ	0.3	—
Poisson's Ratio XZ	0.3	—
Shear Modulus XY	3.6	GPa
Shear Modulus YZ	3	GPa
Shear Modulus XZ	3	GPa

Table 4.2: Orthotropic elastic properties inserted in Ansys FEA for the GG 52 PWS 100 X1 120HM 48%

For other materials the data inserted followed the tables 3.1 and 3.3 of the previous chapter.

4.1.3 ANSYS Composite PrepPost (ACP) setup

ANSYS Composite PrepPost (ACP-Pre) provides a dedicated environment for the modelling and analysis of laminated composite materials. Within the scope of this study, a key advantage is the possibility of representing the omega beam as a single, continuous composite structure, rather than as three separate entities (core and two skin). This approach allows for a more realistic structural analysis. Furthermore, both for the omega beam and the cold plate, ACP enables an advanced optimization process by allowing modifications to the stacking sequence, specifically in terms of ply orientation and the number of plies. Such flexibility is fundamental in exploring different laminate configurations and improving the overall mechanical performance of the structures under investigation. ACP-Pre is subdivided in workflow stages, here are presented the modules that I utilizes for the ladder's simulation:

- **Geometry Import:** The starting point of any ACP project is the geometry. In this case, the two separate parts of the ladder model, previously cleaned in SpaceClaim, are imported together into ACP. This combined geometry then serves as the basis on which composite layups and definitions are applied.
- **Rosettes:** Local coordinate systems used to define the fiber orientation. Rosettes ensure that the fiber direction is consistently interpreted across different regions of the model. For the ladder model I needed two rosettes: one for the omega beam and one for the Cold plate. For both cases the rosetta was put with the x-axis direction along the fiber direction and the z-axis along the stack-up sequence.
- **Materials:** Definition of the composite constituents, such as fiber, matrix, and core materials. These material systems form the database from which plies are built. Each material has its own mechanical properties (elasticity, strength, density) and are directly taken from the engineering data system that I tailored before.
- **Plies (Fabrics):** The plies are the fundamental building blocks of the laminate.

Each ply represents a single layer of material, defined by its thickness, fiber orientation angle, and material system. By stacking multiple plies, complex laminates with tailored stiffness and strength properties can be achieved. In this project, the core plies consist of Milifoam with a thickness of 1 mm; the skin layers are made of GG 52 composite with a thickness of $70\text{ }\mu\text{m}$ for each ply. Ultimately, the cold plate is conservatively assumed to be composed of unidirectional K13D2U with a thickness of $120\text{ }\mu\text{m}$, since the other substrate layers have negligible thickness and mechanical properties.

- **Stackups (Layups):** The stackup defines the ordered sequence in which plies are arranged to form the laminate. This stacking sequence is a critical aspect, as it determines the overall anisotropic behavior of the structure. ACP facilitates the definition and modification of stackups, allowing for performance optimization through variation of ply orientation and sequence. For the test prototype simulation, the creation of the stackup was straightforward, as each layer of the ladder structure is composed of a single ply. To fully define the stackup, it is necessary to specify both the ply angle and whether each ply is woven or unidirectional. In this project, the ply angle was set to 0° for both the cold plate and the skin layers. For the core, no explicit stackup configuration was required, since it was directly imported as virtual geometry.
- **Oriented Selection Sets:** After defining the stackups, oriented selection sets are created. They link the stacking sequences to the geometry regions by using the previously defined rosettes. This guarantees that fiber orientations and stacking directions are correctly applied to the selected surfaces of the ladder model.
- **Modeling Groups:** Modeling groups serve as the link between the composite definitions and the finite element mesh, consolidating one or more oriented selection sets and assigning them to the solver as element sets. In this project, two separate modeling groups were created: one for the omega beam and one for the cold plate. Each modeling group is further subdivided into modeling plies. For

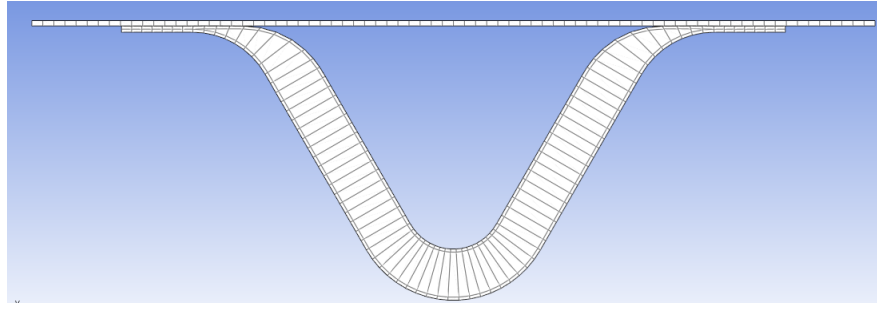


Figure 4.4: Set up geometry in Ansys ACP

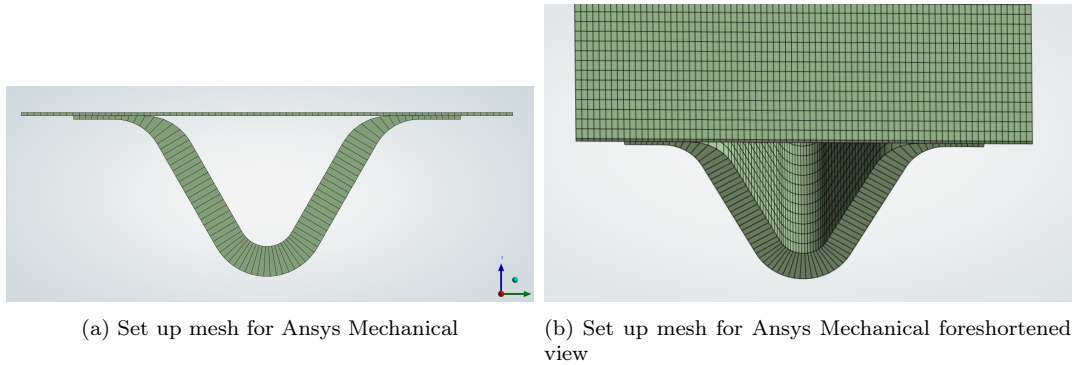


Figure 4.5: Ansys Mechanical mesh representation

the omega beam, three modeling plies were defined: the upper skin layer, the core, and the lower skin layer. In contrast, the cold plate required only a single modeling ply. A key aspect that enabled the creation of an optimal simulation model was the incorporation of the core as virtual geometry. Consequently, the thickness of the core's modeling ply was automatically derived from the virtual geometry, ensuring consistency and reducing manual specification errors. Figure 4.4 illustrates the appearance of the geometry within ACP, while figure 4.5a presents the ladder mesh as imported into ANSYS Mechanical, demonstrating that the omega beam is treated as a single continuous component rather than as three separate layers.

4.2 Ansys Mechanical

4.2.1 Set-up

After completing the configuration in Ansys ACP, the analysis was extended to Ansys Mechanical. The first step consisted in verifying the quality of the mesh (Figure 4.5), followed by the definition of the boundary conditions and loading scenarios.

The contact definitions were imported directly from ACP: the cold plate and the lower skin, which is modeled as a single shell element together with the upper skin, were bonded in order to reproduce the glued interfaces present in the prototype.

To reproduce the experimental setup, the ladder was constrained at both ends with fixed supports, simulating the rigid end pieces of the physical prototype.

Regarding loads, the structure was subjected to standard gravitational acceleration. Two specific load cases were then considered:

- **Distributed load:** a total mass of 20 g was uniformly applied to the cold plate, corresponding to a force of 0.2 N in the negative z-direction.
- **Concentrated load:** the same 0.2 N force was applied at the mid-span of the cold plate, distributed over a narrow strip of elements.

See Appendix B for Ansys ACP setup, mesh quality analysis and mechanical simulation constraints.

4.2.2 Results

Static analysis

The main objective of the static analysis was to determine the maximum deflection of the ladder under the weight of the other stave components (i.e. chips and aluminum flex). The numerical predictions were compared with the experimental measurements, and the finite element model was calibrated to achieve agreement with the experimental data.

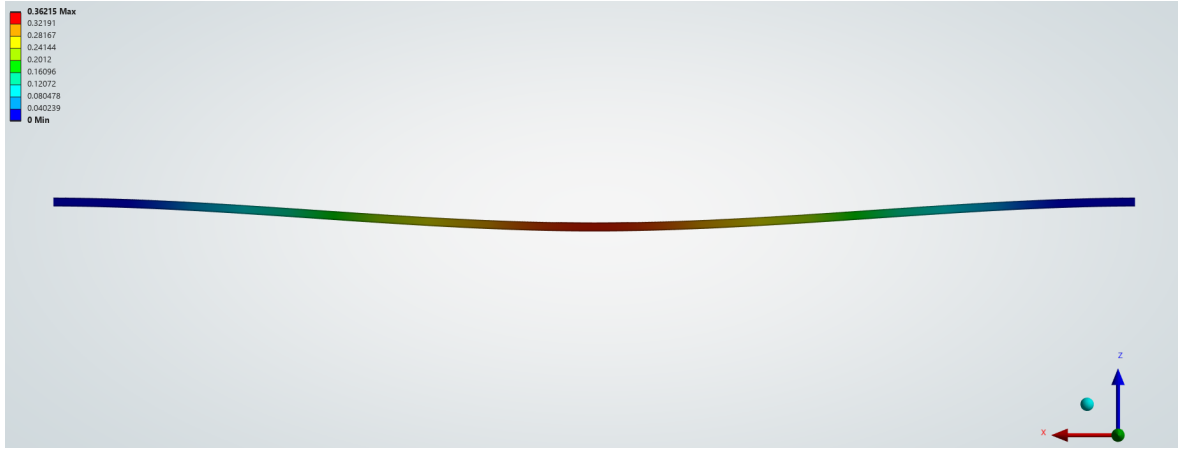


Figure 4.6: Deflection in z-axis direction under concentrated load [mm].

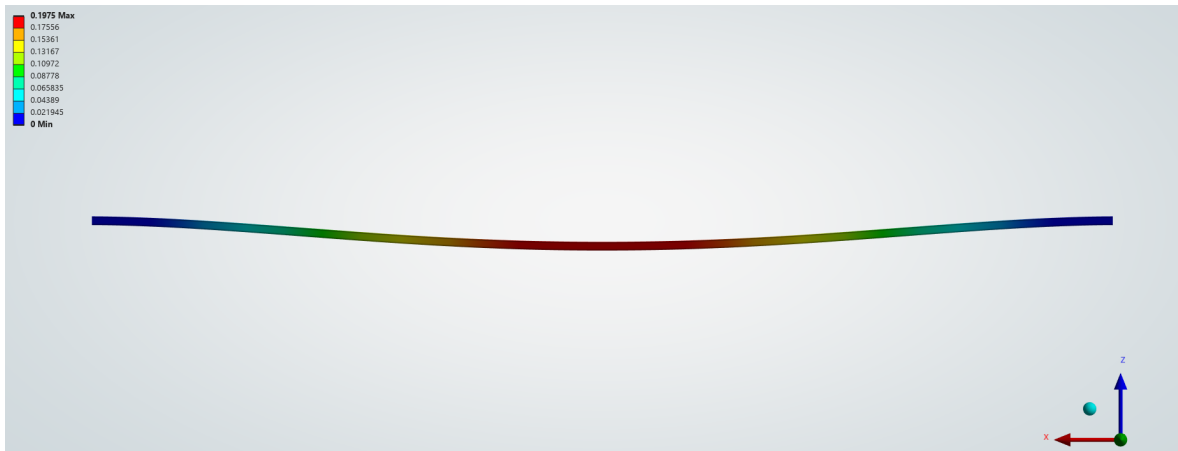


Figure 4.7: Deflection in z-axis direction under distributed load [mm].

The tuned model was then used to support the optimization of both the cold plate and the omega beam lay-ups.

For the concentrated load case (20 g applied on the center of the ladder), the maximum displacement predicted by the model was $362\ \mu m$ (fig. 4.6), which is in excellent agreement with the experimentally measured deflection of $359\ \mu m$ (fig.3.19). For the distributed load case, the maximum deflection occurred at mid-span and reached a value of $197.5\ \mu m$, in close accordance with theoretical expectations based on beam theory (Figure 4.7). These results confirm the successful calibration of the finite element model, providing a reliable basis for the subsequent optimization of the ladder structure.

Modal analysis

The modal analysis was performed both to further validate the static deflection study and to investigate the dynamic behavior of the ladder. The ladder behavior was analyzed under a double fixed support configuration. The ladder mass was calibrated such that the cold plate effectively included the contribution of the kapton tube. The first natural frequency of the system was found to be 74.5 Hz , which exceeds the minimum requirement of 40 Hz set for seismic safety. Table 4.3 shows the first five vibration mode with their respective frequency. Nonetheless, further optimization aimed at increasing this frequency would provide further robustness and improved resistance of the structure under dynamic and seismic stress.

Table 4.3: First five vibration mode with their respective frequency.

Mode	Frequency [Hz]
1	74.5
2	197.1
3	317.5
4	367.6
5	373.8

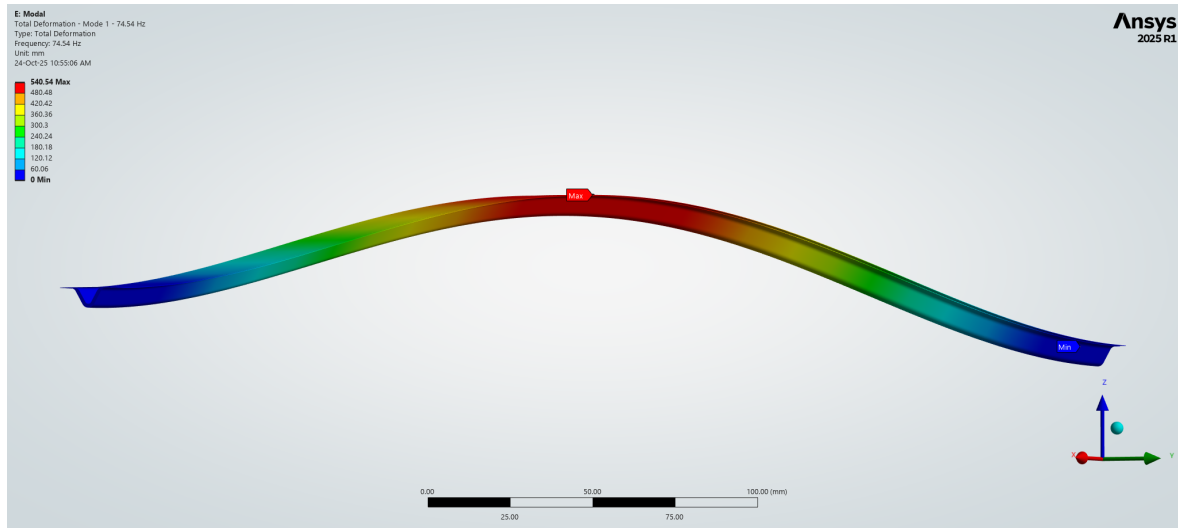


Figure 4.8: Ladder first modal frequency at 74.5 Hz

4.3 The Ansys-Based Mechanical Optimization

After validating the virtual ladder model, I was finally able to begin the mechanical optimization phase. The main aspects identified for improvement were:

- reduction of ladder warping in the unloaded condition;
- reduction of ladder sag under a 0.2 N load;
- increase of the first natural frequency above 40 Hz , in order to comply with earthquake safety requirements.

It should be noted that all possible optimization strategies will ultimately be compared in terms of material budget. While reducing deflection is an important goal, any additional material must be carefully evaluated with respect to its impact on particle deviation, as already discussed in Chapter 2, section 2.2.1.

4.3.1 Addition of T300 reinforcement

In close collaboration with the manufacturer, the first solution proposed was to apply a $150\text{ }\mu\text{m}$ thick layer of T300 unidirectional prepreg on the lower side of the beam (Figure 4.9). Torayca T300 is a standard-modulus carbon fiber, less expensive than high-modulus alternatives such as M46J or K13D2U, and much easier to source on the market, even in small quantities or as sample material. The mechanical properties of the T300 unidirectional carbon fiber prepreg with epoxy resin are summarized in Table 4.4. This solution was considered promising, as it would increase the stiffness of the omega profile and, at the same time, reduce overall deflection.

Nevertheless, a complete replacement of the current woven skins with a single layer of unidirectional (UD) fibers was not deemed feasible, since this configuration could lead to delamination problems. For laminates with UD fibers, multiple layers with different orientations are usually required, or alternatively a hybrid solution combining one UD layer with woven fabric, as in presented in this subsection.

Property	Value	Unit
Density	1490	kg/m ³
Young's Modulus X direction	121	GPa
Young's Modulus Y direction	8.6	GPa
Young's Modulus Z direction	8.6	GPa
Poisson's Ratio XY	0.27	–
Poisson's Ratio YZ	0.40	–
Poisson's Ratio XZ	0.27	–
Shear Modulus XY	4.7	GPa
Shear Modulus YZ	3.1	GPa
Shear Modulus XZ	4.7	GPa

Table 4.4: Mechanical properties of T300 UD Prepreg (dataset values).

Table 4.5: First five vibration mode with their respective frequency.

Mode	Frequency [Hz]
1	119.2
2	308.2
3	322.3
4	448.5
5	562.1

This was the first optimization performed in Ansys. The set-up was identical to the ladder prototype simulation, with the only modification being the addition of a $150\ \mu\text{m}$ T300 UD layer modeled as a midsurface.

The mechanical simulations showed clear improvements. Under a concentrated load, ladder deflection decreased from $362\ \mu\text{m}$ (prototype) to $146\ \mu\text{m}$ (Fig.4.10), while under a distributed load it was reduced from $197.5\ \mu\text{m}$ to $72.3\ \mu\text{m}$ (Fig.4.11). The simulation seems promising as the deflection under distributed load dropped below the $100\ \mu\text{m}$ target value.

The modal analysis also confirmed the effectiveness of the modification: the first eigenfrequency increased from $74.5\ \text{Hz}$ to $119\ \text{Hz}$, well above the $40\ \text{Hz}$ safety threshold (Fig.4.12). Table 4.5 shows the first five vibration mode with their respective frequency.

Given its performance and cost efficiency, this solution was identified as the most suitable option for the new ladder prototype. However, other solutions were also investigated to verify that the ladder with the T300 reinforcement represented the optimal feasible design.

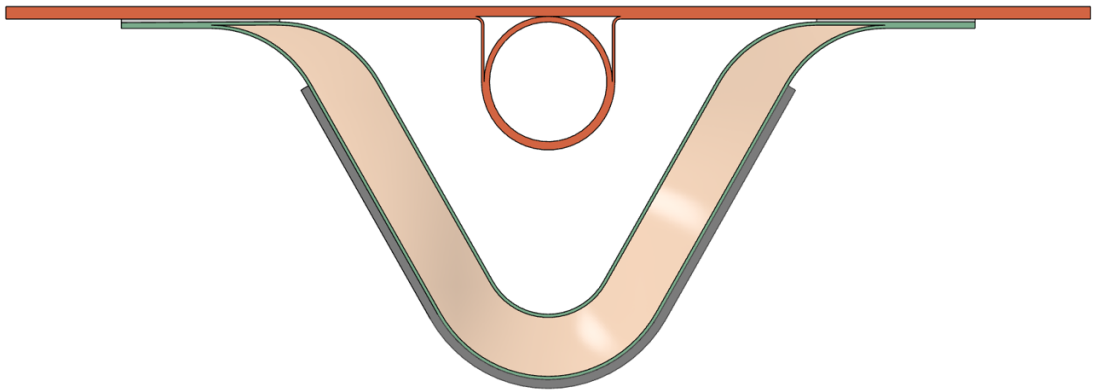


Figure 4.9: Ladder design with T300 reinforcement (grey) under the lower GG52 skin.

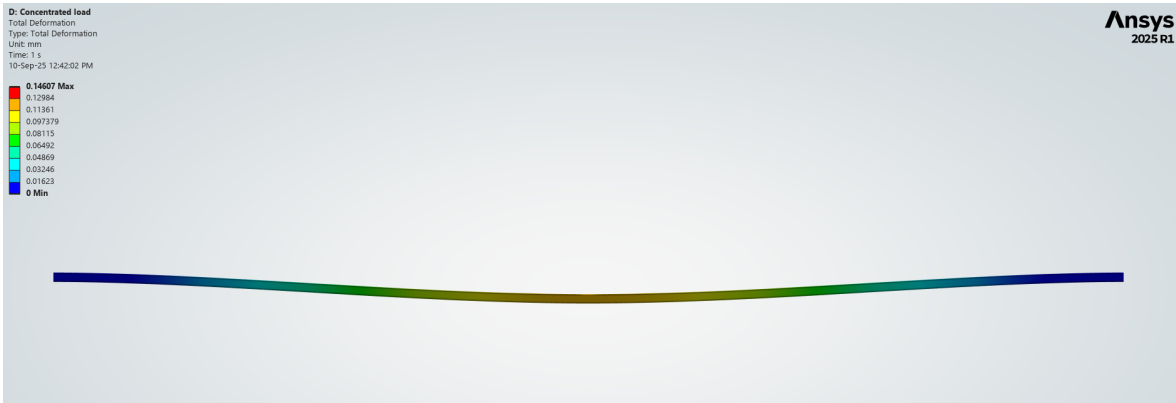


Figure 4.10: Mechanical Ansys Static Simulation with concentrated load for the ladder with T300 UD reinforcement [mm].

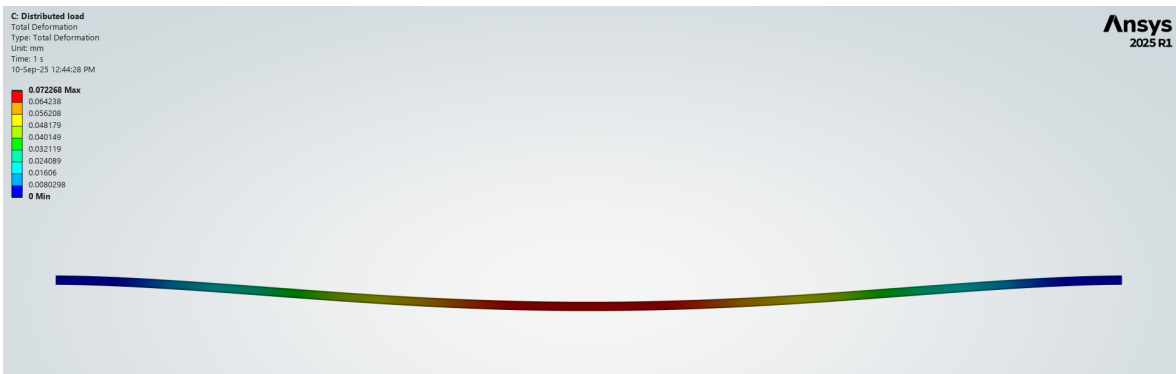


Figure 4.11: Mechanical Ansys Static Simulation with distributed load for the ladder with T300 UD reinforcement [mm].

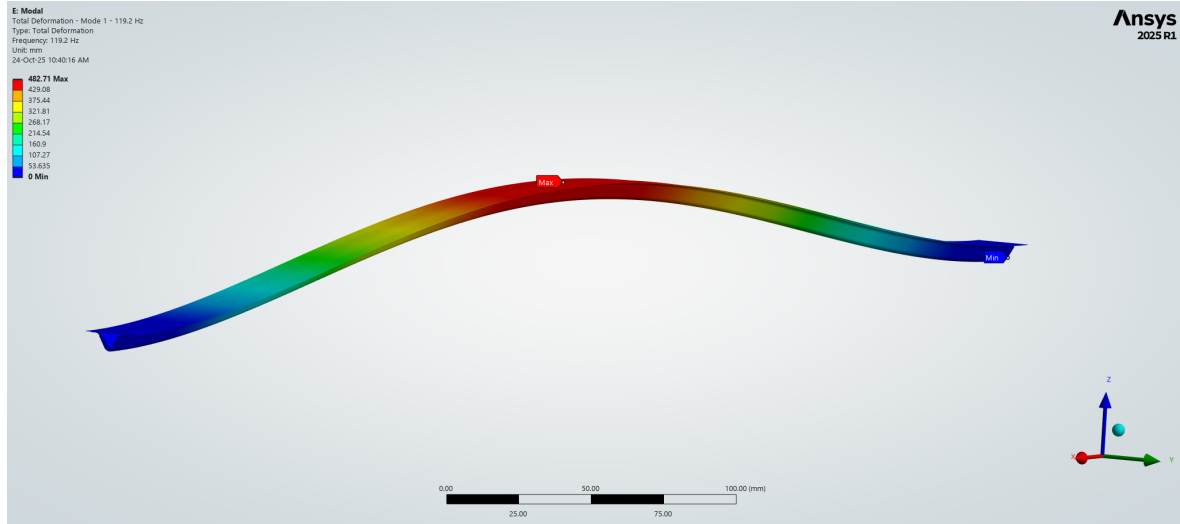


Figure 4.12: Mechanical Ansys Modal simulation with double fixed support for the ladder with T300 UD reinforcement. Mode 1, $f = 119 \text{ Hz}$

4.3.2 Skin Layer with carbon fiber M46J

The second solution considered in this study involved replacing the $70 \mu\text{m}$ GG52 woven carbon fiber skin layer with two unidirectional M46J carbon fiber plies per skin layers, combined with an epoxy resin matrix, each with a thickness of $150 \mu\text{m}$. The increased thickness is expected to mitigate warping of the ladder in its unloaded state and to reduce deflection under applied loading. Table 4.6 provides a comparison of the different two types of high-modulus fibers evaluated in this work for the skin layer of the omega beam. Although M46J fiber exhibits a higher elastic modulus compared to GG52 fiber, as it falls into the ultra high-modulus category, and it also offers an upgrade in tensile modulus when it comes to composite properties (Fig. 4.7), in particular M46J is unidirectional compared to GG52 which is implemented as woven and with a significant reduction in cost. The objective of this simulation is therefore to assess the variation in deflection resulting from the use of a higher-modulus, higher-cost fiber, while simultaneously increasing structural stiffness, and ultimately to determine whether this trade-off justifies the associated increase in material budget.

Each stackup in ANSYS ACP consists of two $150 \mu\text{m}$ M46J UD layers, with fiber orientations of 0° and 90° , resulting in a total thickness of $300 \mu\text{m}$ for both the upper and lower skins of the omega beam. Figures 4.13 and 4.14 present the results for the

Fiber	Tensile Modulus (GPa)	Tensile Strength (GPa)	Density (g/cm ³)
M46J	434	4.2	1.84
GG52	425	4.6	1.90

Table 4.6: Comparison between M46J and GG52 carbon fibers

Composite	Tensile Modulus in fiber's direction (GPa)
M46J	121
GG52	55

Table 4.7: Comparison between composite properties of M46J UD and GG52 woven

deflection under a concentrated load and for the free-free modal analysis, respectively. The results indicate that the maximum deflection under concentrated load is $107\text{ }\mu\text{m}$, which is significantly lower than the $146\text{ }\mu\text{m}$ observed for the ladder reinforced with T300. In terms of modal behavior, the first eigen frequency of the M46J model is 115 Hz, which is comparable to the value obtained for the T300 reinforced configuration. Table 4.8 shows the first five vibration mode with their respective frequency.

Table 4.8: First five vibration mode with their respective frequency.

Mode	Frequency [Hz]
1	114.9
2	277.3
3	302.1
4	492.1
5	560.9

4.3.3 Additional skin layers of GG52

As the last configuration considered in the optimization process, the option of adding additional GG52 woven plies to the stackup of each skin layer was evaluated. In the ladder prototype, each skin layer consisted of a single ply with a thickness of $70\text{ }\mu\text{m}$. For this new simulation, three additional plies were introduced, with fiber orientations as reported in Table 4.9, leading to a total stackup thickness of $280\text{ }\mu\text{m}$ for each skin.

For this configuration, the results are reported in Figure 4.15 and Figure 4.16. The maximum deflection under a concentrated load is $170\text{ }\mu\text{m}$, while under a distributed load it is $102\text{ }\mu\text{m}$. Both values are higher than those obtained with the T300 reinforcement, indicating a reduction in structural performance. Similarly, in terms of modal

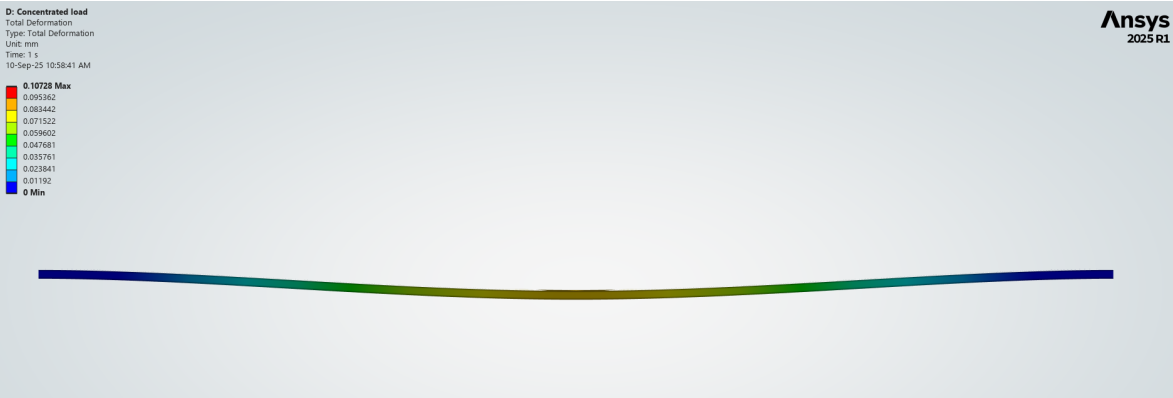


Figure 4.13: Mechanical Ansys Static Simulation with concentrated load for the ladder with two layers of M46J UD [mm].

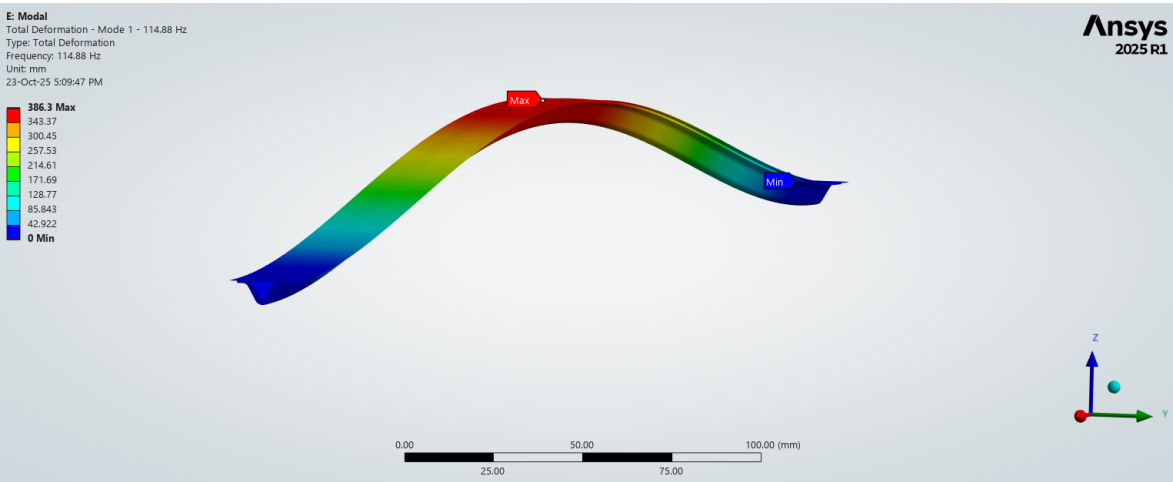


Figure 4.14: Mechanical Ansys Modal simulation with double fixed support for the ladder with two layers of M46J UD. Mode 1, $f = 115\text{ Hz}$

	Fabric	Angle
1	70 um fabric	0.0
2	70 um fabric	45.0
3	70 um fabric	-45.0
4	70 um fabric	0.0

Table 4.9: Stackup for lower and upper skin layer for the optimization of the omega beam

behavior, the first resonance frequency is 76.6 Hz, which does not represent an improvement over the value achieved in the prototype simulation. Table 4.10 shows the first five vibration mode with their respective frequency.

Table 4.10: First five vibration mode with their respective frequency.

Mode	Frequency [Hz]
1	76.6
2	206.8
3	225.5
4	395.5
5	515.9



Figure 4.15: Mechanical Ansys Static Simulation with concentrated load for the ladder with $280\ \mu m$ of GG52 skin layer [mm].

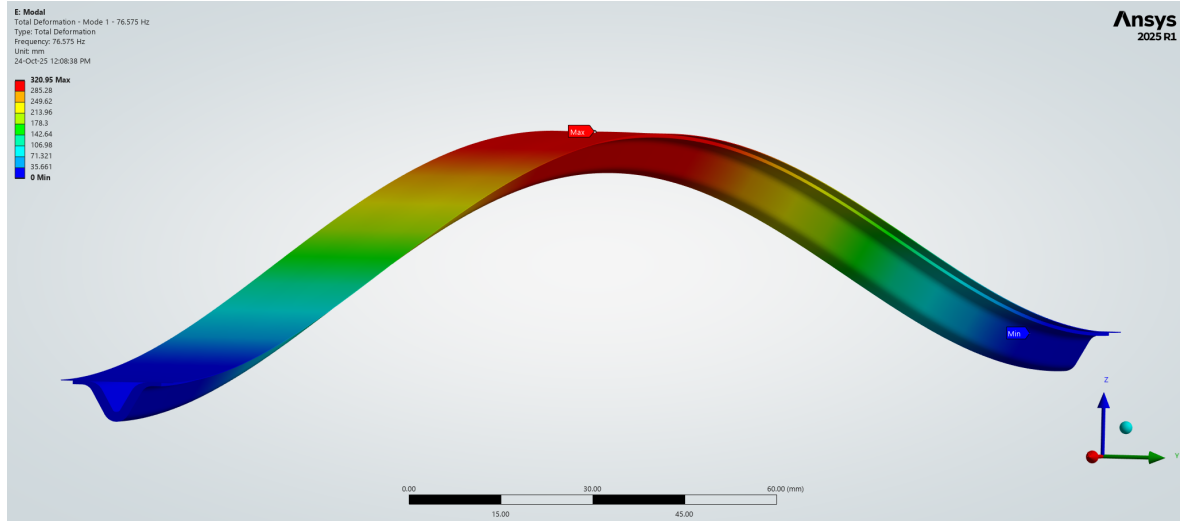


Figure 4.16: Mechanical Ansys Modal simulation with double fixed support for the ladder with $280\ \mu m$ of GG52 skin layer. Mode 1, $f = 76.6\ Hz$

Another simulation was performed with an additional GG52 layer. In this configuration, the four layers, corresponding to a total thickness of $280\ \mu m$, were applied only to the lower side of the omega beam, while the upper skin was left with a single $70\ \mu m$ layer. This design was introduced following the concept of the T300 reinforcement, which, as suggested by the manufacturer, was placed only on the lower side of the omega beam.

For this design, the maximum deflection under a concentrated load is $187\ \mu m$, while the first resonance frequency is $79.2\ Hz$. Table 4.11 shows the first five vibration mode and their respective frequency.

Mode	frequency [Hz]
1	79.2
2	215.4
3	267.6
4	414.8
5	546.6

Table 4.11: First five vibration mode with their respective frequency

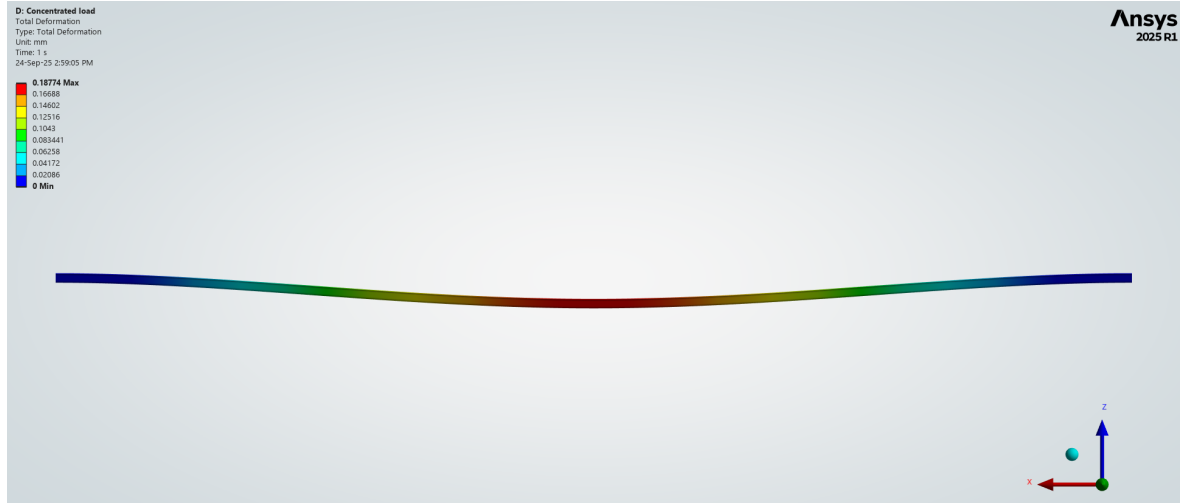


Figure 4.17: ANSYS static simulation with concentrated load for the ladder with a $280\ \mu\text{m}$ GG52 lower skin layer and a $70\ \mu\text{m}$ GG52 upper skin layer [mm].

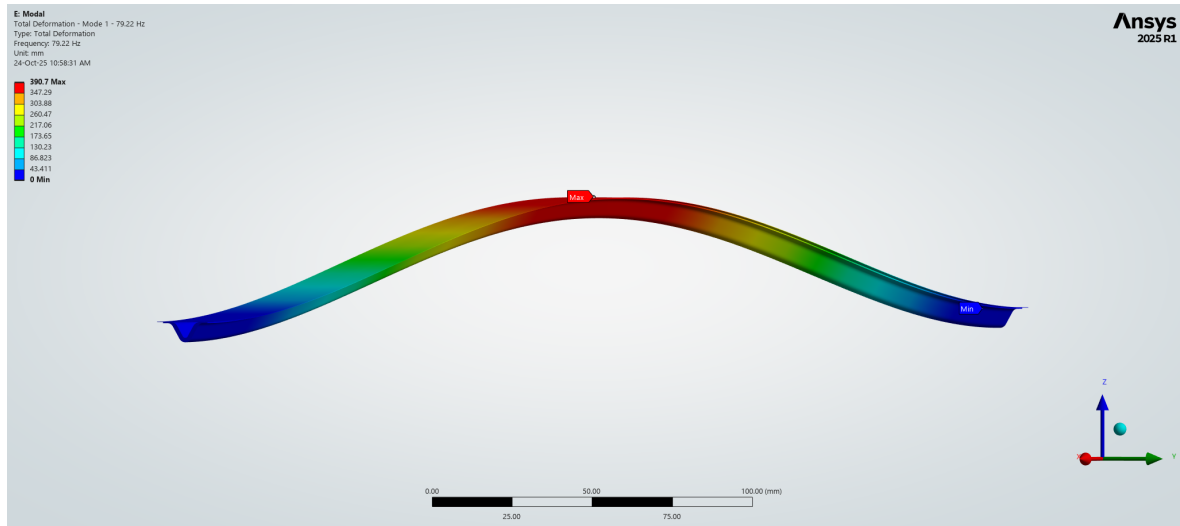


Figure 4.18: ANSYS modal with double fixed support simulation for the ladder with a $280\ \mu\text{m}$ GG52 lower skin layer and a $70\ \mu\text{m}$ GG52 upper skin layer. Mode 1, $f = 79.2\ \text{Hz}$

4.3.4 Optimized design comparison

To provide a clearer overview, Table 4.12 summarizes the performance of the optimized designs presented in this thesis. From a purely mechanical perspective, the best-performing design is the one employing two $150\ \mu\text{m}$ M46J layers, followed by the configuration with the T300 reinforcement. In the next chapter, these results will be further evaluated with respect to the material budget, in order to achieve a suitable trade-off that satisfies both mechanical and material requirements.

Design	Max deflection (0.2 N load)	First modal frequency with double fixed support
Prototype	362 μm	74.5 Hz
T300 reinforcement	146 μm	119 Hz
150 μm M46J (x2)	107 μm	115 Hz
280 μm GG52	170 μm	76.6 Hz
280 μm + 70 μm GG52	187 μm	79.2 Hz

Table 4.12: Summary of the performances of the optimized designs.

4.4 Additional ANSYS Mechanical simulation

From a mechanical perspective, the most promising reinforcement configurations are the T300 and M46J. Following discussions with the manufacturing company, which recommended adopting the T300 reinforcement, additional ANSYS mechanical simulations were performed to better understand the ladder's behavior under realistic conditions.

As a first step, the applied loads on the ladder were refined as follows:

- the gravitational acceleration was left unchanged;
- the load generated by the other components of the stave was adjusted to 0, 15 N , removing the previously applied safety factor;
- the weight of the cooling water was added at the center of the cold plate. Assuming a stationary water flow inside the kapton pipe, the corresponding load was estimated to be 0.089, N .

Furthermore, it was necessary to account for the fact that the stave will be mounted on a cylindrical cone, meaning that it will not remain in the previously analyzed orientation but will rotate according to the cone's geometry. Therefore, additional simulations were conducted to evaluate the deflection under loading conditions at different orientations.

Assuming the standard position corresponds to 0° , two additional configurations were studied at 90° and 180° changing the directions of the three loads. This extended analysis aimed to assess potential torsional effects, determining whether they can be considered negligible or if they may represent a critical limitation for the system. Fig.

4.19 shows the deflection in 0° configuration under the new loading conditions, the maximum deflection is currently $85\mu m$ compared to the $72.3\mu m$ with the distributed load of 0.2 N . For the ladder rotated of 90° the total maximum deflection is $11.9\mu m$, but fig. 4.20 shows a torsional deflection of the ladder, its value is $3.43\mu m$ in the z direction and $0.362\mu m$ which can be both considered negligible. For the 180° layout the maximum deflection is $85\mu m$, the same as the 0° layout. Table 4.13 summarizes the deformations for all the three configurations.

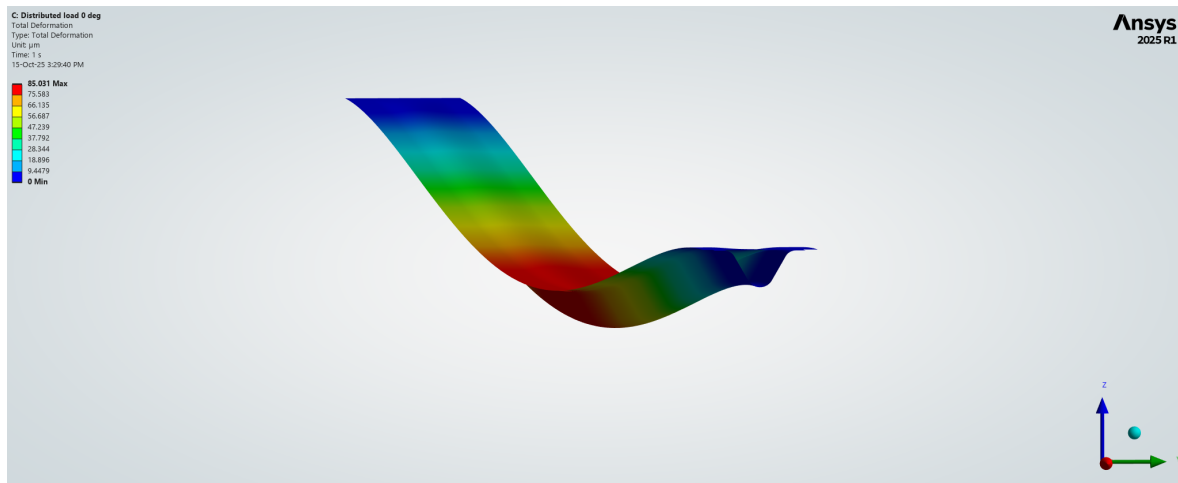


Figure 4.19: Ladder's total deflection in 0° layout [μm].

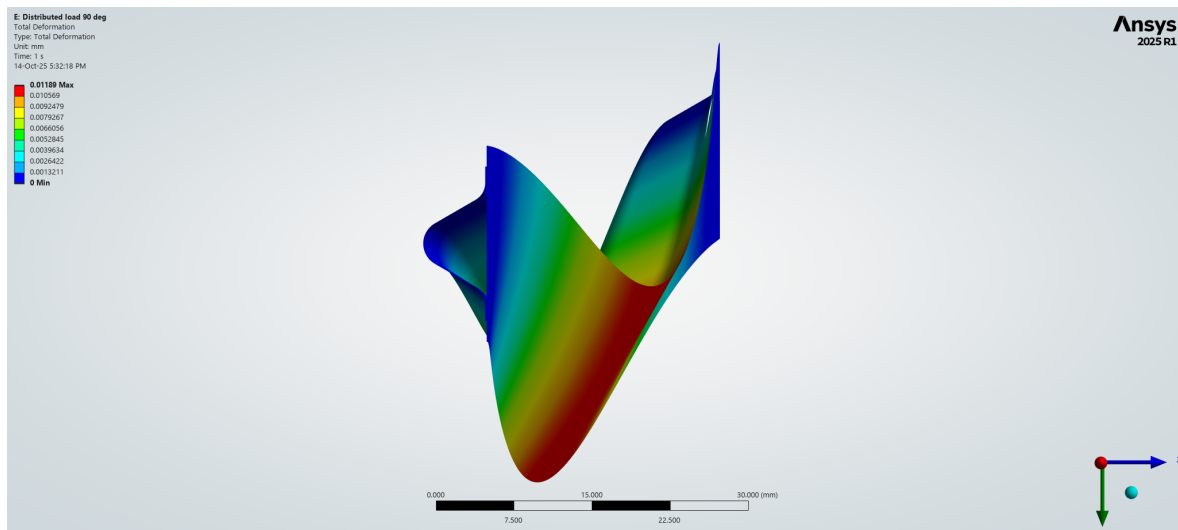


Figure 4.20: Ladder's total deflection in 90° layout [μm].

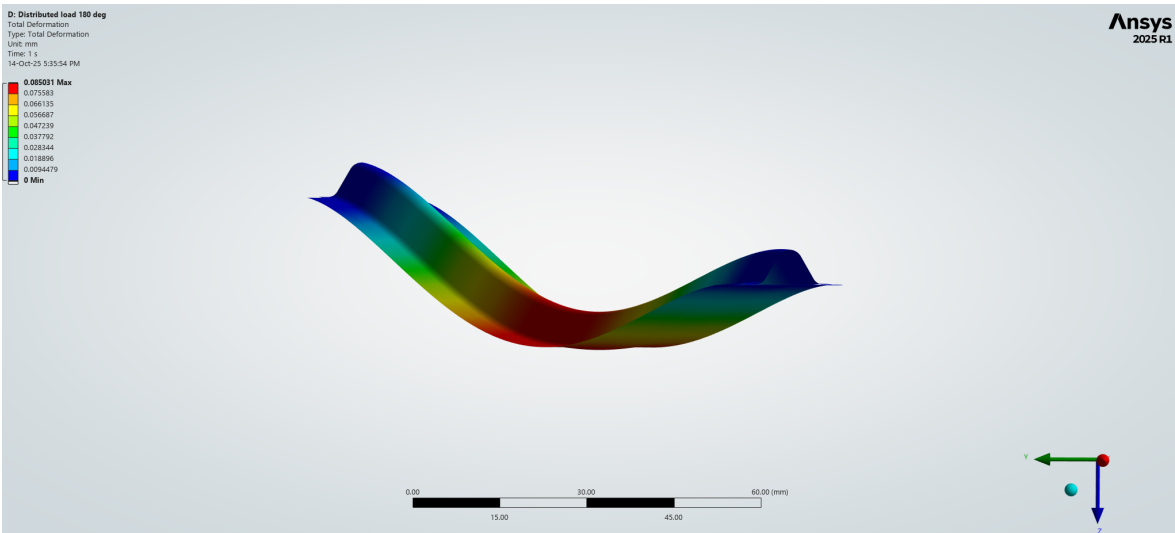


Figure 4.21: Ladder’s total deflection in 180° layout [μm].

Layout	Total Deformation (μm)	X direction (μm)	Y direction (μm)	Z direction (μm)
0°	85	1.64	0.037	85
90°	11.9	0.36	11.38	3.43
180°	85	1.64	0.037	85

Table 4.13: Ladder’s deformation on key configurations

Chapter 5

Material budget evaluation

As the final step of the optimization process, it was necessary to evaluate and compare the material budget associated with each optimized design. The material budget, as previously discussed, is defined as X/X_0 . To calculate this quantity for the ladder design, both X and X_0 must be determined. The value of the radiation length X_0 is reported in the material properties table [20]. Conversely, X represents the equivalent thickness of the design under evaluation, and therefore varies across the different optimization configurations.

In general, the calculation of X must take into account that particles do not always impinge perpendicularly on the material surface; in most cases, they interact at a finite incident angle. As a first-order approximation, however, all particles are assumed to be incident perpendicularly. Non-perpendicular incidence can be easily accounted for by scaling the result with the cosine of the inverse of the polar angle of the tracks.

The equivalent thickness can be expressed as:

$$X = \frac{V}{\text{equivalent width} \cdot \text{length}} \quad (5.1)$$

where V is the total volume traversed by the particle, while the denominator corresponds to the equivalent projected area of the ladder (equivalent width $\times$ length). In other words, the equivalent thickness corresponds to the uniform thickness that a flat material would need to have, given the same volume and projected area, in order to

produce the same contribution to the material budget.

The data, for the volume of each component of the omega beam, have been taken directly from the iProperties of Inventor AutoCAD design. The ladder's length and equivalent width were taken from the design of the ladder itself. Tables 5.1, 5.2, 5.3 and 5.4 show the value for each design.

Component	Volume (mm ³)	Eq. Width (mm)	Length (mm)	Eq. Thickness (mm)	X_0 (cm)	X/X_0 (%)
Upper skin 70 μ m GG52 Woven	1015	18.812	730.00	0.074	26.08	0.028
Millicell Foam 1 mm	10354	18.812	730.00	0.754	544	0.014
Lower skin 70 μ m GG52 Woven	1105	18.812	730.00	0.080	26.08	0.031

Table 5.1: Equivalent radiation length for perpendicular track for the test prototype ladder.

Component	Volume (mm ³)	Eq. Width (mm)	Length (mm)	Eq. thickness (mm)	X_0 (cm)	X/X_0 (%)
Upper skin 70 μ m GG52 Woven	1015	18.812	730.00	0.074	26.08	0.028
Millicell Foam 1 mm	10354	18.812	730.00	0.754	544	0.014
Lower Skin 70 μ m GG52 Woven	1105	18.812	730.00	0.080	26.08	0.031
Reinforcement 150 μ m T300 UD	2276	18.812	730.00	0.166	26.08	0.064

Table 5.2: Equivalent radiation length for perpendicular track for the ladder with T300 reinforcement layer.

Component	Volume (mm ³)	Eq. Width (mm)	Length (mm)	Eq. Thickness (mm)	X_0 (cm)	X/X_0 (%)
Upper skin 300 μ m M46J UD	4350	18.812	730.00	0.317	26.08	0.121
Millicell Foam 1 mm	10354	18.812	730.00	0.754	544	0.014
Lower skin 300 μ m M46J UD	4650	18.812	730.00	0.339	26.08	0.130

Table 5.3: Equivalent radiation length for perpendicular track for the ladder with 300 μ m M46J UD layers.

Component	Volume (mm ³)	Eq. Width (mm)	Length (mm)	Eq. Thickness (mm)	X_0 (cm)	X/X_0 (%)
Upper skin 280 μ m GG52 woven	4060	18.812	730.00	0.296	26.08	0.113
Millicell Foam 1 mm	10354	18.812	730.00	0.754	544	0.014
Lower skin 280 μ m GG52 woven	4343	18.812	730.00	0.316	26.08	0.121

Table 5.4: Equivalent radiation length for perpendicular track for the ladder with 280 μ m GG52 layers.

Component	Volume (mm ³)	Eq. Width (mm)	Length (mm)	Eq. Thickness (mm)	X_0 (cm)	X/X_0 (%)
Upper skin 70 μ m GG52 woven	1015	18.812	730.00	0.074	26.08	0.028
Millicell Foam 1 mm	10354	18.812	730.00	0.754	544	0.014
Lower skin 280 μ m GG52 woven	4343	18.812	730.00	0.316	26.08	0.121

Table 5.5: Equivalent radiation length for perpendicular track for the ladder with 280 μ m GG52 lower skin layer and 70 μ m GG52 upper skin layer .

After evaluating the contribution of each layer of the omega beam, the results were summed to obtain the total material budget of the beam, this part of the work is

shown in the next section 5.1. The same procedure was applied to all other parts of the ladder: first, the individual materials were separated to quantify their specific contribution to the material budget, and then were aggregated to determine the total for each macro-component (i.e., cold plate, flex, and chips). The remaining components remain unchanged across different design optimizations, as the scope of this work is exclusively focused on the optimization of the ladder support structure. Tables 5.6, 5.7, 5.8, 5.9, and 5.10 provide a detailed breakdown of the other stave's components, including their geometrical properties, radiation length, and material budget.

The combined contribution of all these components yields a total material budget of 0.458 %, as summarized in Table 5.12. It is evident that the flex dominates the overall budget; its contribution is already minimized using custom flex circuits in aluminum instead of copper, however it is essential for data acquisition.

Component	Qty	Volume (mm ³)	Nominal thickness (mm)	Width (mm)	Length (mm)	Eq. thickness (mm)	$X_0(\text{cm})$	X/X_0 (%)
Carbon fleece (upper)	1	274.480	0.020	18.812	730.00	0.020	106.8	0.002%
Graphite paper (upper)	1	343.100	0.025	18.812	730.00	0.025	26.56	0.009%
K13D2U – 120 mm	1	1646.880	0.120	18.812	730.00	0.120	26.08	0.046%
Graphite paper (lower)	1	404.541	0.025	18.812	730.00	0.029	26.56	0.011%
Carbon fleece (lower)	1	323.633	0.020	18.812	730.00	0.024	106.8	0.002%

Table 5.6: Cold plate material budget summary with negligible glue

Component	Qty	Inner dia. (mm)	Outer dia. (mm)	Cross section (mm ²)	Length (mm)	Total vol. (mm ³)	Width (mm)	Eq. thk. (mm)	$X_0(\text{cm})$	X/X_0 (%)
Polyimide pipes (141-0083)	1	2.032	2.223	0.638	700.41	446.843	18.812	0.034	28.41	0.012%
Demineralized water	1	–	2.032	3.241	730.00	2366.137	18.812	0.172	35.76	0.048%

Table 5.7: Material budget summary for polyimide pipes and demineralized water.

Position	Qty	Width (mm)	Length (mm)	Thickness (mm)	$X_0(\text{cm})$	X/X_0 (%)
Araldite 2011 between cold plate and chips	1	18.812	730.00	0.050	33.5	0.015 %
Araldite 2011 between chips and flex	1	18.812	730.00	0.050	33.5	0.015 %

Table 5.8: Araldite 2011 material budget for layers between cold plate, chips and flex.

Component	Material	Volume (mm ³)	Qty	Total vol. (mm ³)	Width (mm)	Length (mm)	Eq. thk. (mm)	$X_0(\text{cm})$	X/X_0 (%)
Flexible Printed Circuit (FPC)	Polyimide	3542.543	2	7085.09	18.812	730.00	0.516	28.57	0.181%
Ground	Aluminum	156.688	2	313.38	18.812	730.00	0.023	8.897	0.026%
Tracks Pads and Vias	Aluminum	52.767	2	105.53	18.812	730.00	0.008	8.897	0.009%
Power	Aluminum	161.315	2	322.63	18.812	730.00	0.023	8.897	0.026%

Table 5.9: Material budget for Flex on backward and forward side.

Component	Material	Volume (mm ³) from CAD	Qty	Total vol. (mm ³)	Width (mm)	Total Length (mm)	Eq. thk. (mm)	X_0 (cm)	X/X_0 (%)
Chips	Silicon	28.489	24	683.736	18.812	725.14	0.050	9.369	0.053%

Table 5.10: Material budget summary of silicon chips.

Component	Material	Width (mm)	Length (mm)	Thickness (mm)	X/X_0 (%)
Coating for electrical insulation	Parylene	18.812	730.000	0.010	0.003 %

Table 5.11: Material budget summary of Parylene coating for electrical insulation.

Component	X/X_0 (%)
Cold Plate	0.071%
Pipes & Coolant	0.060%
Glue	0.030%
Flex FW + BW	0.241%
Chips	0.053%
Parylene	0.003%
Total	0.458%

Table 5.12: Summary of Layer 6 R140 Radiation length except the omega beam.

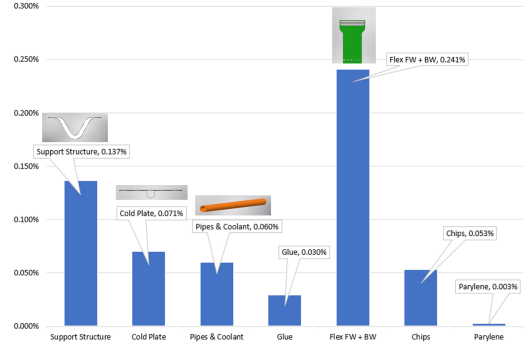


Figure 5.1: Material budget graph for ladder with T300, comparison between all stave's components.

5.1 Trade off between the sag and the material budget results

As the final part of this work, a trade-off analysis was performed between the results obtained from the study of the maximum sag and those derived from the total material budget. Table 5.13 summarizes the comparison across all optimization designs. It can be immediately observed that two configurations, the first employing M46J and the second using $300\ \mu\text{m}$ GG52, exhibit excessively high total material budgets, rendering them unsuitable for the ladder requirements, particularly since the associated reduction in maximum deflection is not so significant.

From this analysis, it can be concluded that the most effective optimization design is the $70\ \mu\text{m}$ GG52 woven with $150\ \mu\text{m}$ T300 reinforcement. This configuration achieves a substantial reduction in deflection, reaching $72.3\ \mu\text{m}$ under a distributed load of $20\ g$, while the material budget increases by only $0.06\ \%$. In contrast, the alternative designs

Omega beam design	Total eq. thickness (mm)	Max sag under concentrated load (μm)	Total X/X_0 for Omega Beam (%)	Total X/X_0 (%)
Test prototype	0.908	362	0.073	0.531
T300 reinforcement	1.074	146	0.137	0.595
Two plies of 150 μm M46J UD	1.410	107	0.265	0.723
280 μm GG52 woven	1.366	102	0.248	0.707
280 μm + 70 μm GG52	1.144	187	0.163	0.622

Table 5.13: Comparison between eq. thickness, maximum sag and material budget for optimization design

show an increase of approximately 0.2 % in the material budget with no corresponding mechanical benefit.

It is important to highlight the critical design value of the material budget. For every new design iteration, the complete geometric configuration and its associated material composition must be delivered to the physics simulation team. These elements serve as inputs for detailed Monte Carlo simulations, which evaluate how each structural modification affects key performance aspects such as tracking accuracy, multiple scattering, and vertex resolution. Consequently, the material budget is not just a mechanical or engineering parameter, it is an integral part of the physics validation workflow. Providing a transparent and quantitative breakdown of the material contributions ensures that any design proposal can be rigorously assessed in terms of its impact on the detector's physics capabilities. This requirement underscores why even minor increases in material budget, if not justified by significant mechanical improvements, can lead to a design being considered unsuitable.

Conclusion

This thesis has presented the design, optimization, and validation of the mechanical structure of the Layer 6 (L6) ladder for the Belle II outer Vertex detector upgrade. Starting from the definition of the stringent experimental requirements, the work has progressively addressed the engineering challenges associated with minimizing the material budget while ensuring high stiffness, dimensional stability, and robustness under operational conditions.

The original contribution of this study lies in the last two chapters, where both experimental and numerical approaches were combined to achieve a reliable design methodology. First, a prototype of the ladder was developed and tested to evaluate deflection and stiffness. These measurements were then used to calibrate and validate the finite element models, ensuring accurate representation of the anisotropic behavior of composite materials. The integration of experimental data with Ansys Composite PrepPost (ACP) allowed the construction of a robust digital twin, capable of predicting structural performance under different loading and boundary conditions.

The final optimization phase highlighted the trade-off between maximum sag reduction and material budget increase. Among the explored configurations, the solution combining a $70\text{ }\mu\text{m}$ GG52 woven laminate with a $150\text{ }\mu\text{m}$ T300 unidirectional reinforcement emerged as the most effective. This configuration provided a significant improvement in mechanical stability, reducing deflection by more than 70 %, while increasing the material budget only marginally (+0.064 %). Alternative optimization strategies, although effective in reducing sag, resulted unsuitable due to their excessive radiation length contribution.

Finally, the geometric configuration and the detailed material budget derived from this work will be provided to the physics simulation team as input for the Monte Carlo studies. These simulations will assess the impact of the proposed design on the overall detector performance, completing the physics validation phase.

Overall, this work demonstrates that an integrated experimental and numerical workflow is essential for the successful design of ultralight, high-precision detector support structures. The validated methodology not only ensures compliance with the current Belle II requirements but also provides a solid foundation for future developments in high energy physics experiments, where increasingly demanding luminosity conditions will further challenge the balance between mechanical robustness and transparency to radiation.

5.2 Further studies and activities

The next steps of this research will focus on the collaborative construction of a new prototype in partnership with industry. A series production of ten ladders will be carried out using a single integral mold, with the objective of further reducing the deflection under no-load conditions. Subsequently, the ladders will undergo the same experimental validation procedure, including the standard deflection test under a 20 *g* load. In parallel, the first thermal simulations will be performed using kapton heaters to emulate the heat dissipation of the sensors. Should these tests yield promising results, the work will advance towards a practical assembly simulation of the full stave structure. This iterative approach will allow progressive refinement of both the structural and thermal behavior of the detector support system, paving the way for its integration into the Belle II upgrade.

As the design of Belle II detector advances it will be necessary to evaluate precisely

the vibrational response of the ladder. A possible future development of this work could involve performing a non-deterministic dynamic analysis of the oVTX structure under seismic excitation. Specifically, it would be appropriate to analyze the system's response as a function of the Power Spectral Density (PSD) of ground acceleration taking into account the transmission of vibrations through the intermediate structural elements up to the oVTX assembly. The goal would be to estimate the Root Mean Square (RMS) amplitude of the dynamic response and then evaluate peak values, for instance by considering 2σ or 3σ levels, to obtain a more realistic assessment of the possible maximum displacements or deformations. Furthermore the upcoming ladder prototype will be tested under scanning laser doppler vibrometer, which allows non-contact vibration measurements on any surface, to further analyze its vibrational mode. Such an analysis would provide a deeper understanding of potential structural resonance conditions and allow verification of the adequacy of the structural design with respect to the actual earthquake frequency range. This approach would go beyond the simple assumption that ensuring a fundamental frequency above 40 Hz is sufficient, providing instead a more complete and reliable evaluation of the dynamic behavior.

Appendix A

Flex Weight Estimation

Volumes for one flex:

$$V_{Chips} = 28.376 \text{ mm}^3 + 12 \cdot 340.512 \text{ mm}^3$$

$$V_{PCB} = 3542.5 \text{ mm}^3$$

$$V_{Glue} = 2 \cdot 365 \text{ mm} \cdot 18.8 \text{ mm} \cdot 50 \mu\text{m} = 686.2 \text{ mm}^3$$

$$V_{Power_plane} = 161.3 \text{ mm}^3$$

$$V_{Tracks_pads_vias} = 53 \text{ mm}^3$$

$$V_{Ground_plane} = 156.7 \text{ mm}^3$$

$$V_{ParyleneN} = 365 \text{ mm} \cdot 18.8 \text{ mm} \cdot 10 \mu\text{m} = 68.62 \text{ mm}^3$$

Densities:

$$\delta_{Si} = 2.42 \text{ g/cm}^3$$

$$\delta_{Kapton} = 1.37 \text{ g/cm}^3$$

$$\delta_{ParyleneN} = 1.11 \text{ g/cm}^3$$

$$\delta_{Al} = 2.7 \text{ g/cm}^3$$

$$\delta_{Glue} = 1.05 \text{ g/cm}^3$$

Weights (pressing between the two end pieces):

$$W_{Chips} = \delta_{Si} \cdot V_{Chips} = 0.824 \text{ g}$$

$$W_{Power_plane} = \delta_{Al} \cdot V_{Power_plane} = 0.436 \text{ g}$$

$$W_{Ground_plane} = \delta_{Al} \cdot V_{Ground_plane} = 0.423 \text{ g}$$

$$W_{PCB} = \delta_{Kapton} \cdot V_{PCB} = 4.853 \text{ g}$$

$$W_{Tracks_pads_vias} = \delta_{Al} \cdot V_{Tracks_pads_vias} = 0.143 \text{ g}$$

$$W_{Capacitors} = 500 \cdot 0.330 \text{ mg} = 0.165 \text{ g}$$

$$W_{Glue} = V_{Glue} \cdot \delta_{Glue} = 0.721 \text{ g}$$

$$W_{ParyleneN} = V_{ParyleneN} \cdot \delta_{ParyleneN} = 0.076 \text{ g}$$

Total Weight:

$$W_{Tot} = W_{Chips} + W_{Power_plane} + W_{Ground_plane} + W_{PCB} + W_{Tracks_pads_vias} + \\ W_{Capacitors} + W_{Glue} + W_{ParyleneN} = 7.641 \text{ g}$$

For each L6 ladder we have 2 flex and the total weight is:

$$W_{flex_L6} = 2 \cdot W_{Tot} = 15.281 \text{ g}$$

For the test the nominal weight has been increased of around 31%.

Weight Percentage increase:

$$W_{Test_and_Simu} = 20 \text{ g}$$

$$W_{increase} = \frac{W_{Test_and_Simu} - W_{flex_L6}}{W_{flex_L6}} \cdot 100 \approx 30.9\%$$

Appendix B

Data sheet of composite similar to
GG 63 PWS 100 X1 120HM 48%



Microtex Composites SRL,
Via Toscana, 59
59100 Prato (PO)

Roll Number / Article	23246 / GG0063-PWS100---000000999E3150HM48
-----------------------	--

Resin System	E3-150HM
Stacking Sequence	24 plies of GG63-PWS for All Properties
Specimens Resin Content	45,0%

Cure Cycle	90 minutes at 135°C, 6.0 bar, Heating Ramp Rate = 2°C/min, Cooling Ramp Rate = 3°C/min.
Post Cure Cycle	-

Property	Orientation	Specimen Vf (%)	Actual Vf Value	Normalized Value*	Test Standard
Tensile Strength (MPa)	0° Warp	44,5%	930	1149	ASTM D3039
Tensile Modulus (GPa)			54	67	
Tensile Strength (MPa)	90° Weft	45,0%	847	1036	ASTM D3039
Compression Strength (MPa)	0° Warp	45,0%	670	819	ASTM D6641
Compression Strength (MPa)	90° Weft	45,6%	592	714	ASTM D6641
In-Plane Shear Strength (MPa)	± 45°	44,6%	88		ASTM D3518
ILSS (MPa)	0° Warp	50,1%	56		ASTM D2344

Figure B.1: Carbon Structure similar to GG 52 PWS 100 X1 120HM 48%

Appendix C

ANSYS input

C.1 ANSYS Workbench

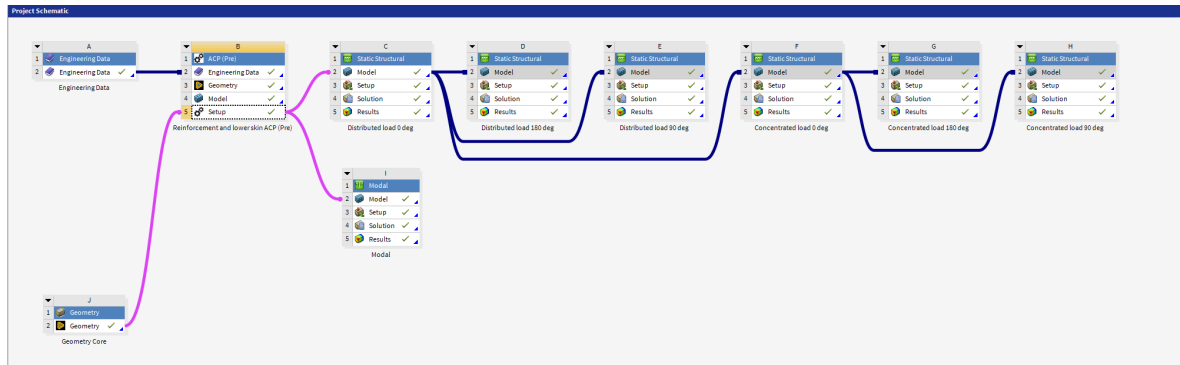


Figure C.1: Ansys Workbench.

C.2 ACP Pre configuration

C.2.1 Material properties

Definition of the orthotropic material properties (fiber–matrix combination), including elastic constants, Poisson ratios, and density. In a unidirectional composite lamina, the material is orthotropic, meaning that its mechanical properties differ along three mutually perpendicular directions. Among these, the two main in-plane directions are:

- E_1 (**Longitudinal modulus**): This is the Young's modulus along the fiber direction (the 0° axis). Since the fibers are much stiffer than the matrix, E is dominated by the fiber properties and is therefore relatively high.

- E_2 (**Transverse modulus**): This is the Young's modulus perpendicular to the fiber direction, within the plane of the lamina. It mainly depends on the matrix properties and the fiber–matrix interaction.

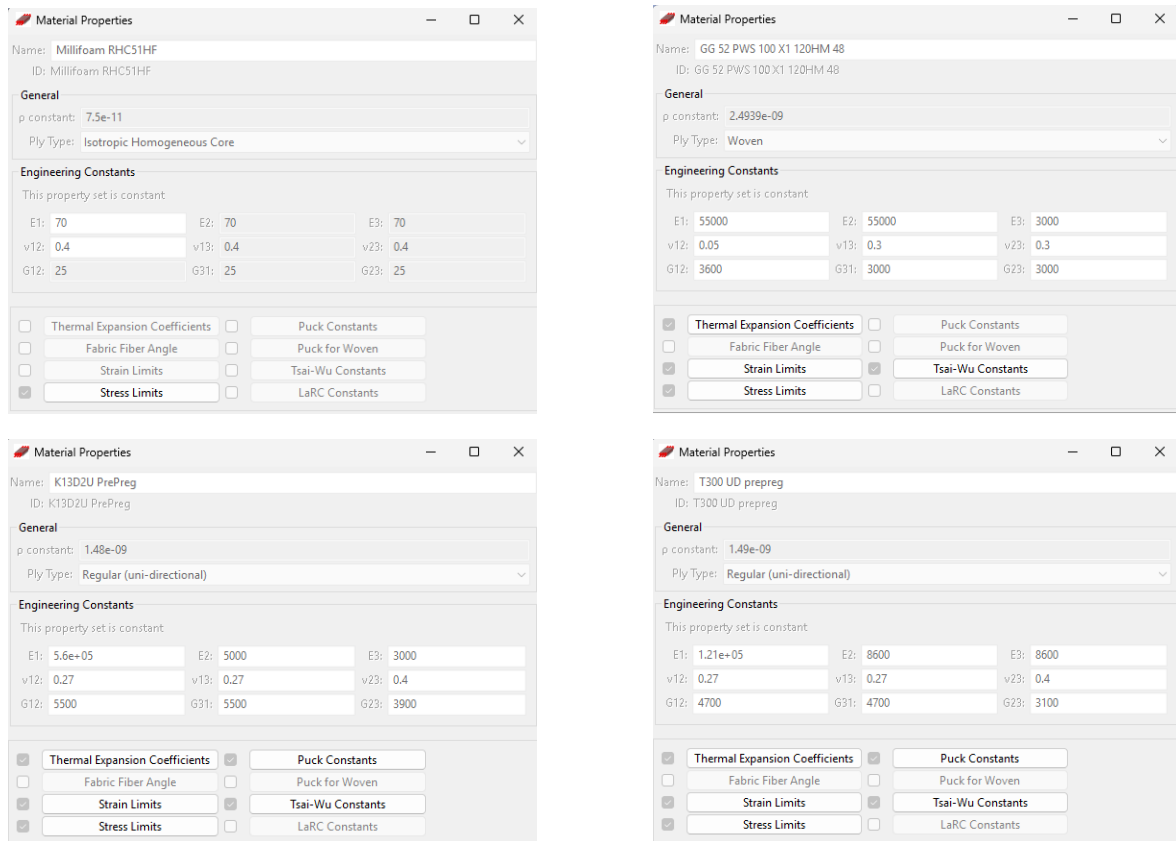


Figure C.2: ANSYS ACP Material properties from Data Engineering.

C.2.2 Fabrics

The fabric stage defines the actual plies that will be used in the laminate. Each fabric is linked to a material and includes information such as ply thickness, type (unidirectional or woven), and reference orientation. Fabrics act as building blocks for the subsequent layup. In ANSYS ACP, the polar plot displayed in the fabric section provides a graphical representation of the in-plane stiffness variation of a composite ply as a function of the fiber orientation.

It visually illustrates the anisotropic nature of the material that is, how the elastic response changes depending on the loading direction relative to the fibers.

- The radial distance from the center of the plot represents the stiffness (E) in that

direction. A longer radius means the material is stiffer in that direction.

- The angle on the plot corresponds to the loading direction relative to the fiber orientation (0° is along the fibers, 90° is transverse to them).

Then in the case of composite with plies in different direction, as the configuration with additional layers of GG52 (see 4.9), the stackup step is needed. In this step, the sequence of plies is created by arranging multiple fabrics with specific orientations and thicknesses. This forms the laminate layup that represents the structural composition of the composite component. Fig. C.7 shows the stackup set needed for the simulation with the additional plies of GG52 (4.3.3)

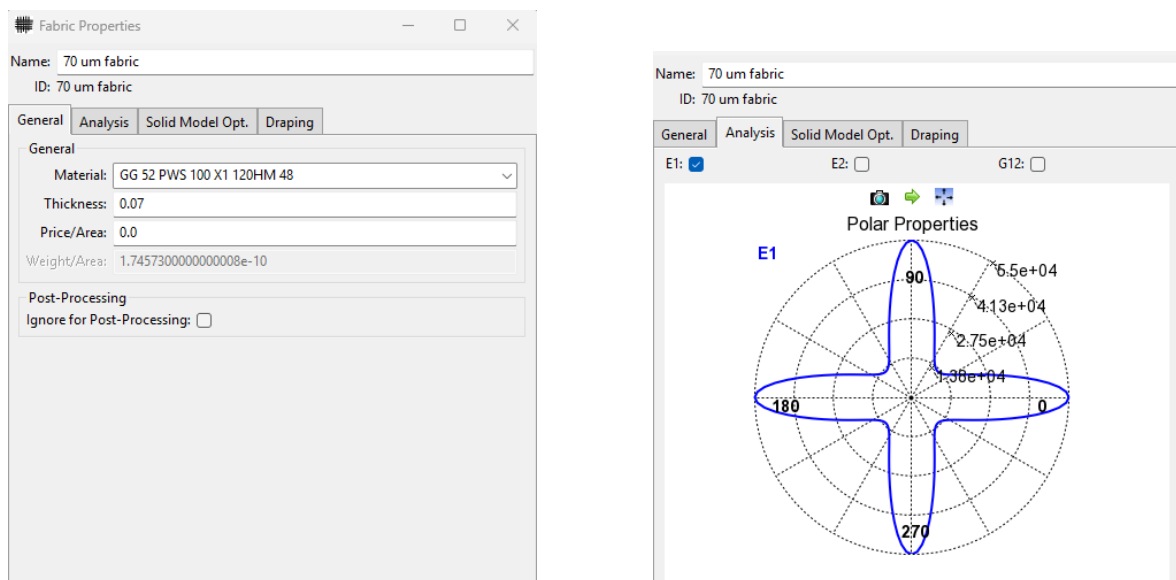


Figure C.3: GG 52 PWS 100 X1 120HM 48 ACP Fabric.

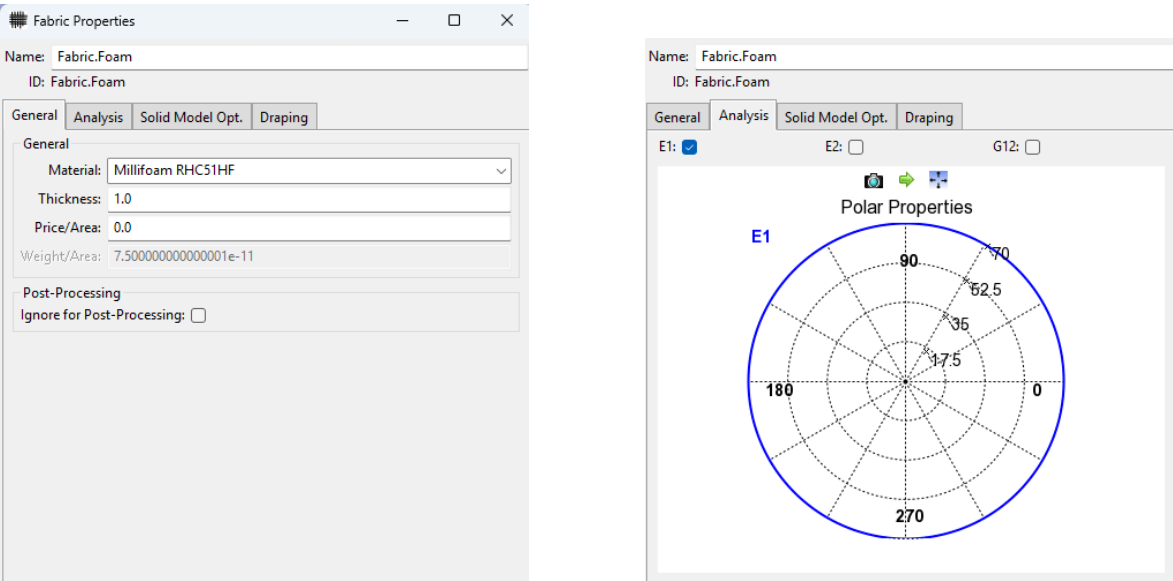


Figure C.4: Milifoam ACP fabric.

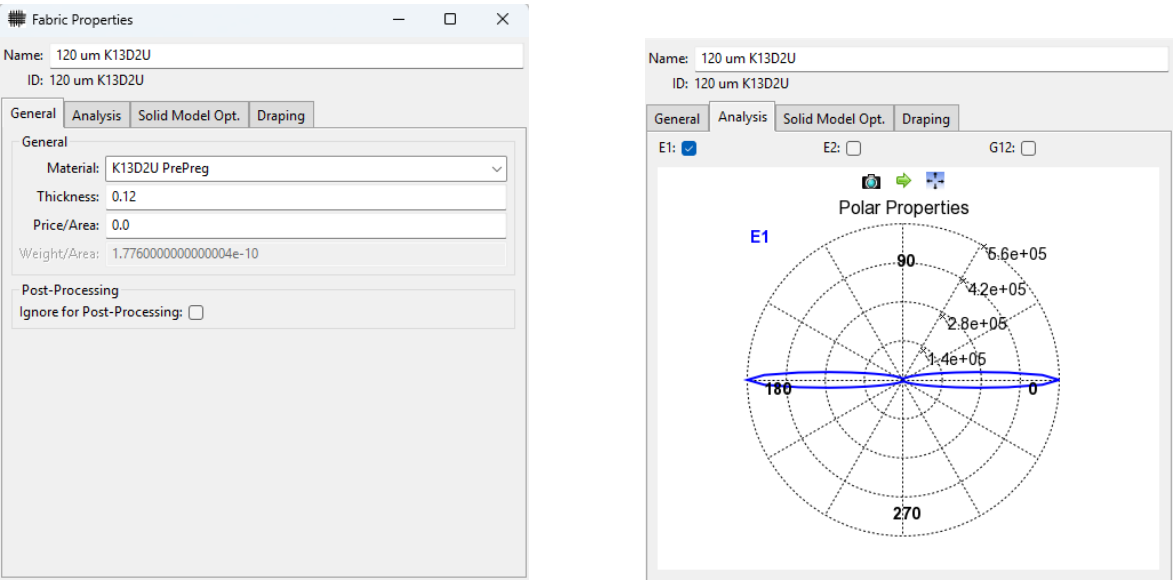


Figure C.5: K13D2U ACP fabric.

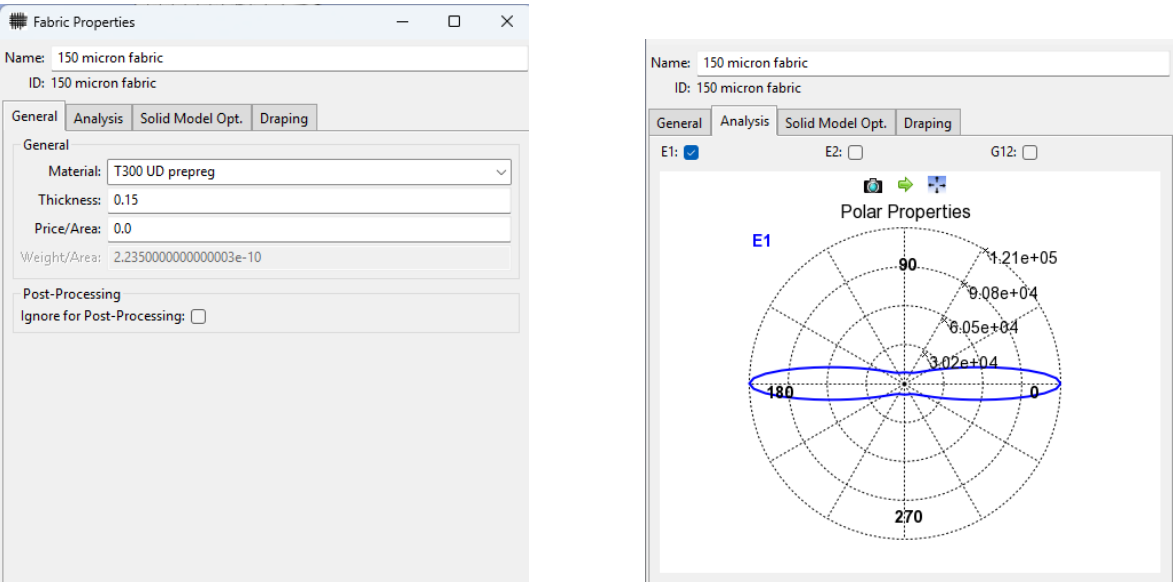


Figure C.6: T300 ACP fabric.

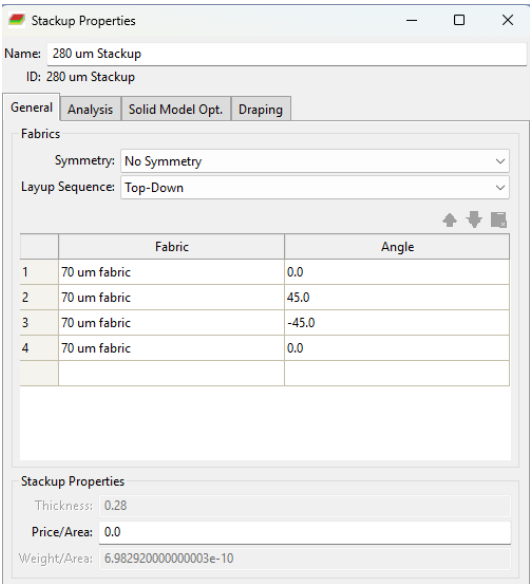
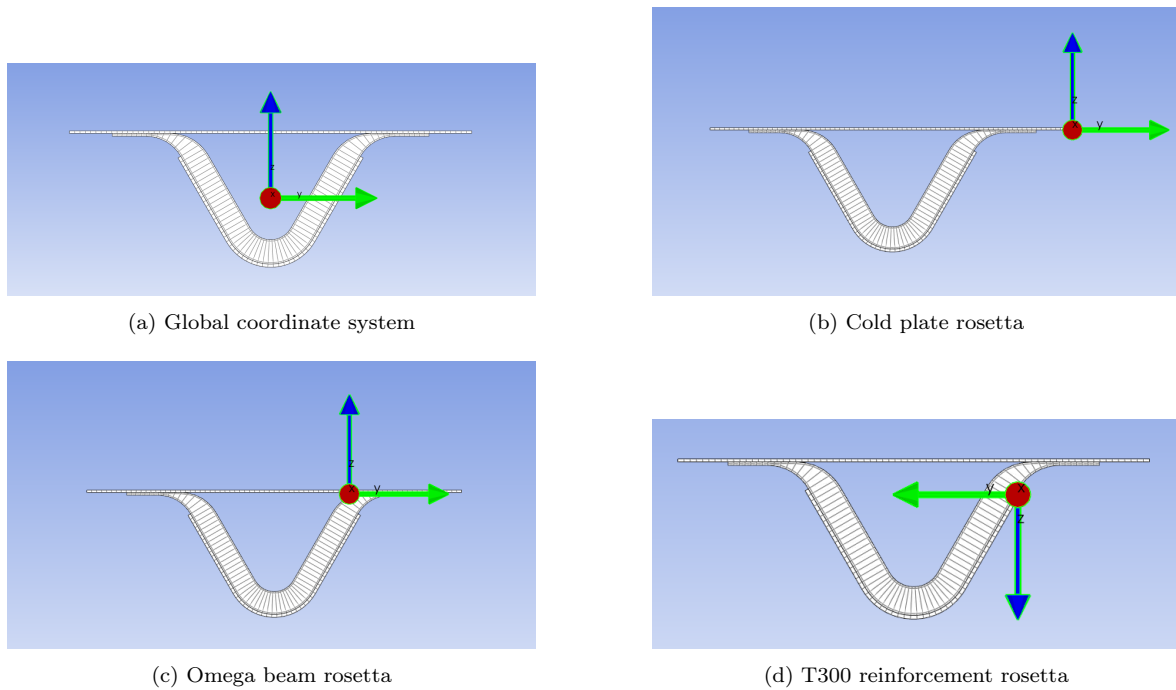


Figure C.7: GG52 stack up sequence in ACP set up

C.2.3 Rosette

The rosette defines the local coordinate system that determines the reference fiber direction (0° on the surface of the model). This step is essential for ensuring that the fiber orientations are consistent with the geometry, especially for curved or complex surfaces. After defining the rosette, the next step is the element orientation definition, where the local directions of the finite elements are aligned with the rosette, ensuring that the material axes in the analysis correspond to the intended fiber directions within

the mesh.



C.2.4 Modeling groups

Finally, the modeling group links the defined stackups, rosettes, and element orientations to the corresponding regions of the finite element model. This association allows different parts of the geometry to have distinct laminate definitions. In ANSYS ACP, the Virtual Geometry option within a Modeling Group allows the user to create simplified geometric representations that serve as reference surfaces for the definition of the composite layup. This feature is particularly useful when the imported finite element mesh does not have an ideal topology for applying fiber orientations or ply definitions directly. By using virtual geometries, ACP internally generates surfaces or volumes that represent the shape of the composite component in a simplified manner. The layup definition (stackup, rosette, element orientation) is then applied to these virtual entities instead of the original mesh. During export, ACP automatically maps the composite information back to the actual finite elements.

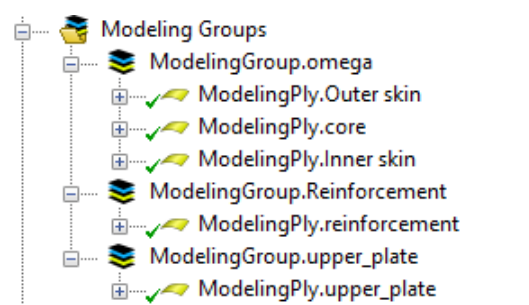


Figure C.9: ACP Modeling groups outline.

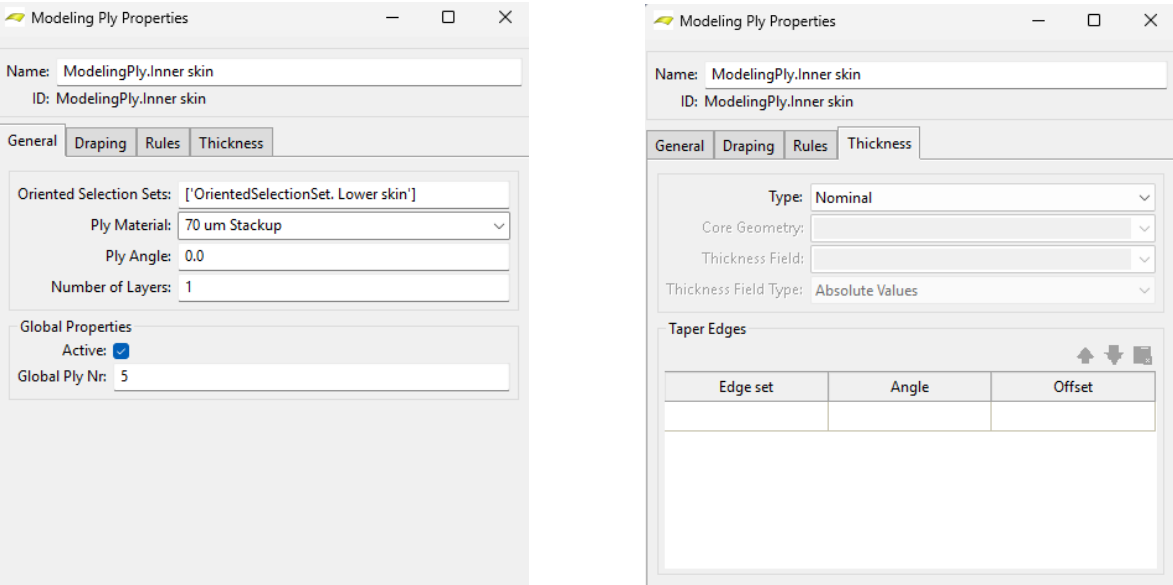


Figure C.10: Modeling ply of the inner layer of the omega beam. The same has been done for the outer layer.

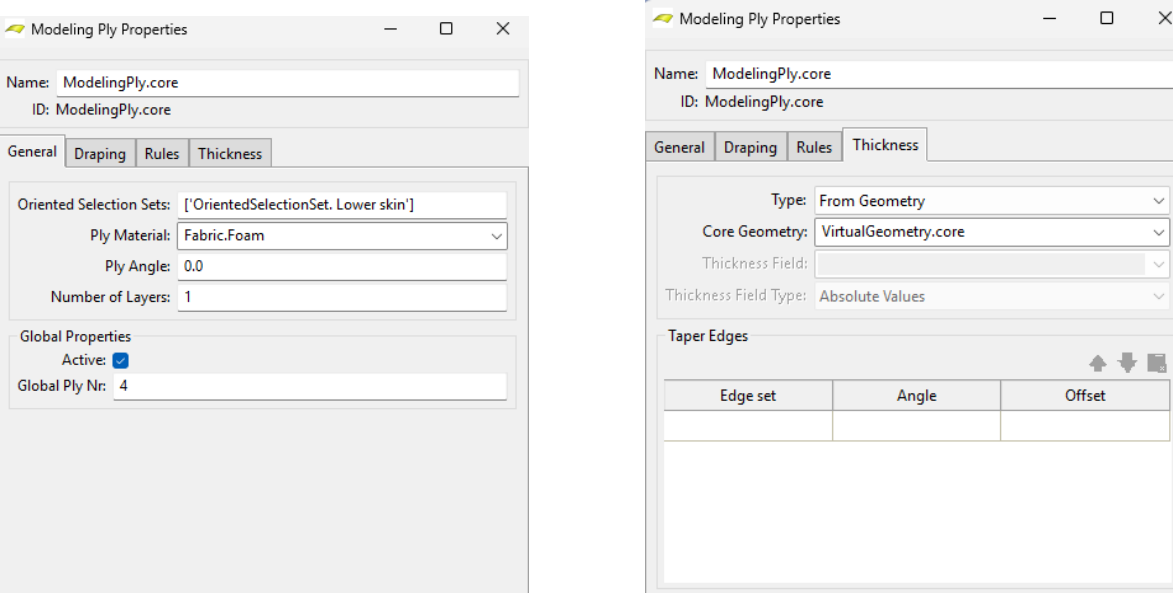


Figure C.11: Milifoam core modeling ply. It can be seen that the thickness of this ply is not nominal but is taken from the Virtual Geometry, therefore from the Space Claim core model.

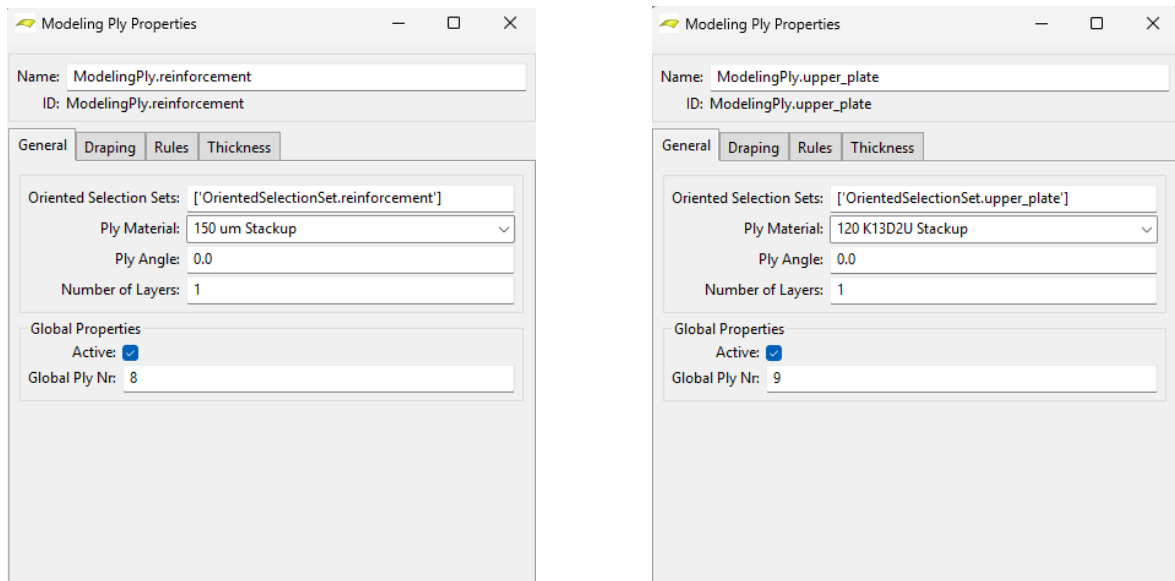


Figure C.12: T300 and K13D2U modeling ply, their thickness has been taken from the stackup nominal value.

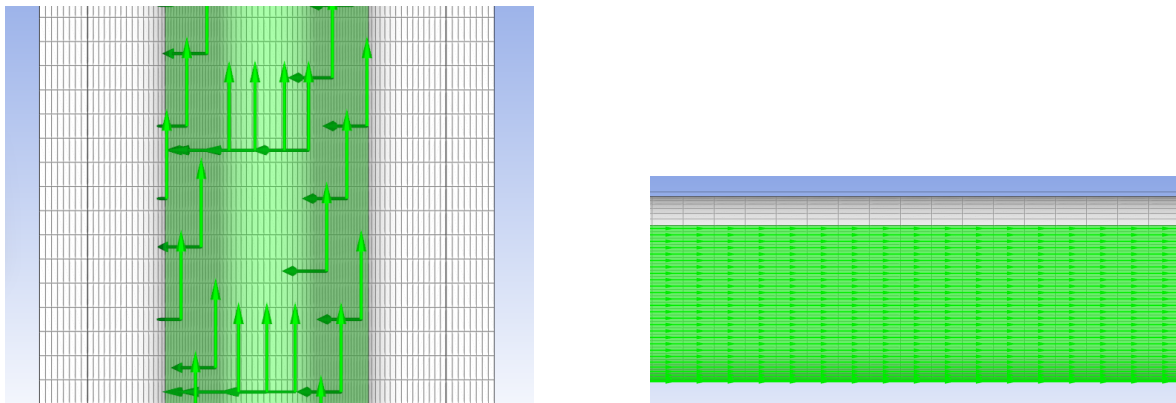


Figure C.13: Omega beam skin layer fiber orientations: light green is the longitudinal direction of the fibers, dark green the transverse direction.

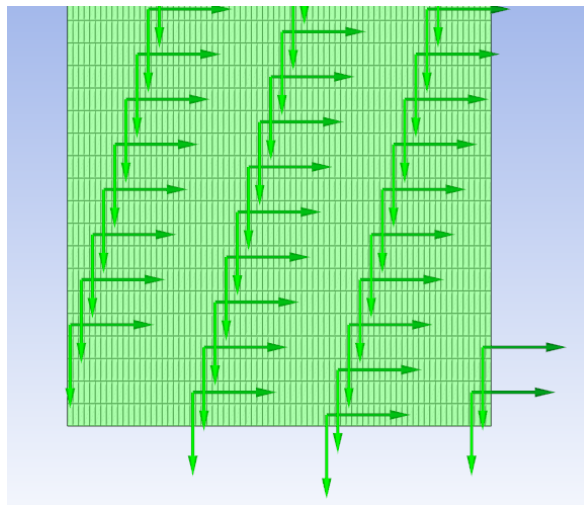


Figure C.14: K13D2U fiber orientations: light green is the longitudinal direction of the fibers, dark green the transverse direction.

C.3 ANSYS Mechanical

C.3.1 Mesh quality evaluation

Before running any finite element simulation, it is essential to evaluate the quality of the generated mesh, as it directly influences the accuracy, stability, and reliability of the numerical results. In ANSYS, mesh quality assessment is performed using a set of standard indicators that quantify how close each element is to its ideal geometric shape and how well the mesh is distributed over the entire model. Among the most commonly used metrics are skewness and orthogonal quality C.15.

- Skewness indicates how much an element deviates from its ideal geometry. Highly skewed elements can introduce numerical errors and reduce the accuracy of the solution, especially in areas of high stress gradients, fig. C.16.
- Orthogonal quality measures how well the element faces and edges align with each other. A well-orthogonal mesh contributes to stable and accurate results, while low orthogonality can lead to poor convergence or unrealistic stress distributions, fig. C.17.

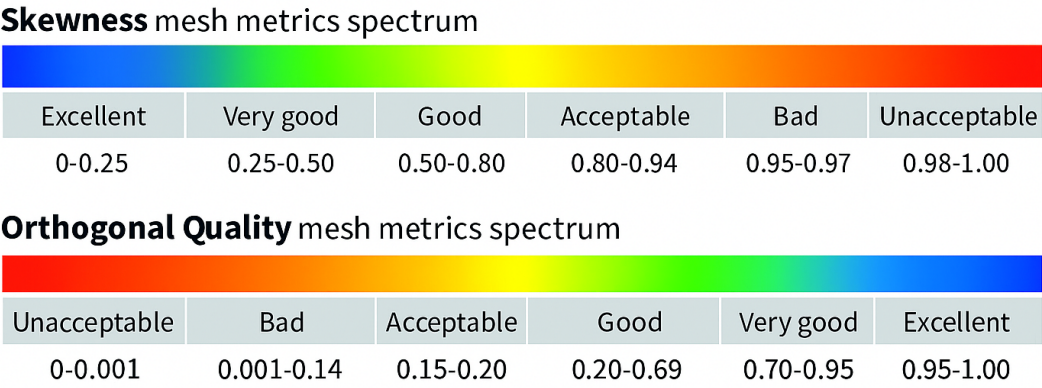


Figure C.15: Skewness and orthogonal quality mesh metrics spectrums.

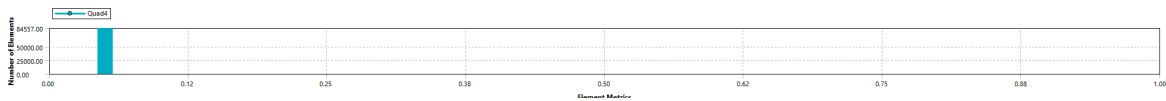


Figure C.16: Mesh average skewness quality.

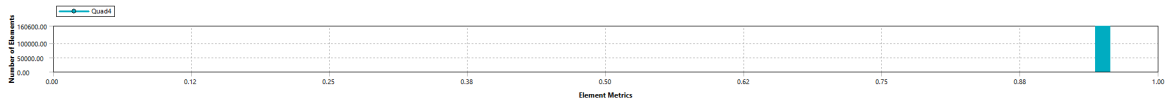


Figure C.17: Mesh average orthogonal quality.

C.3.2 ANSYS Mechanical input

Here the following figure shows the input put inside the solver to correctly simulate the ladder configuration. Fig. C.18 shows the fixed support put on the ladder’s front and back face, the constraint has been put only on the edges. Fig. C.19, C.20, C.21 and C.22 shows the four different loads applied on the ladder 0° layouts.

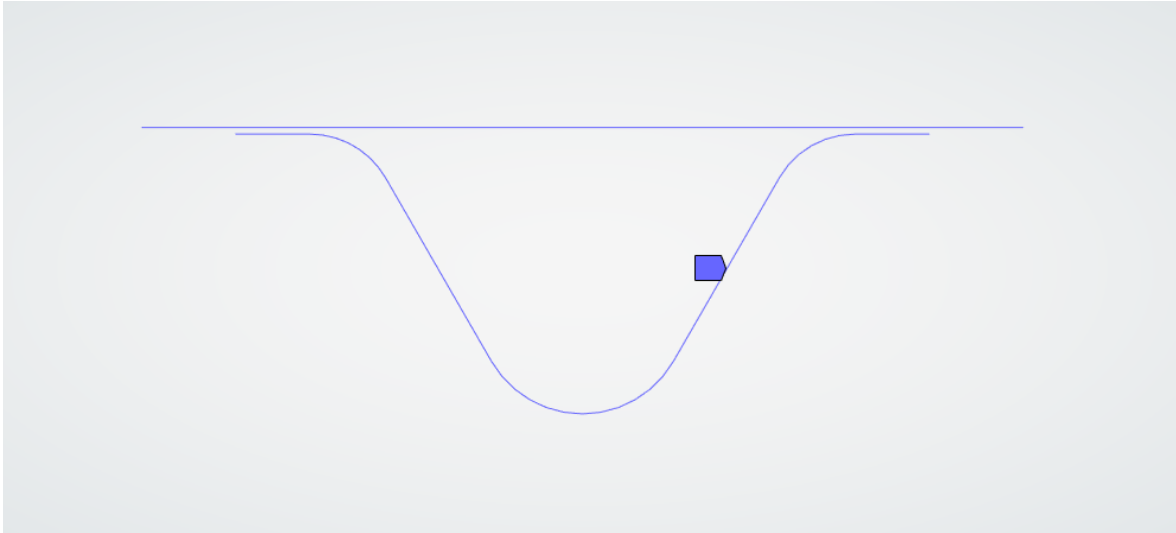


Figure C.18: Fixed support on ANSYS Mechanical.

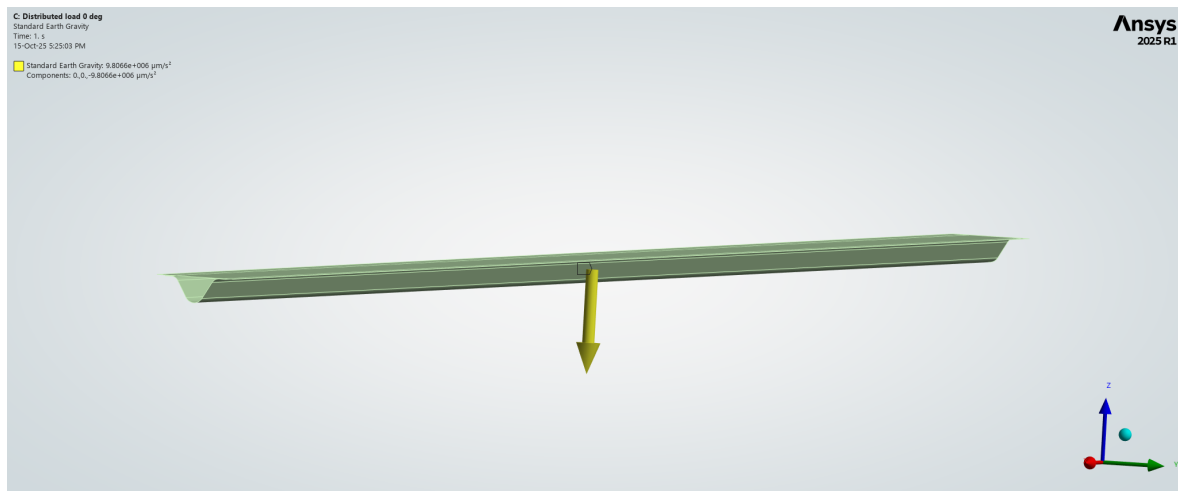


Figure C.19: Standard earth gravity on -Z direction.

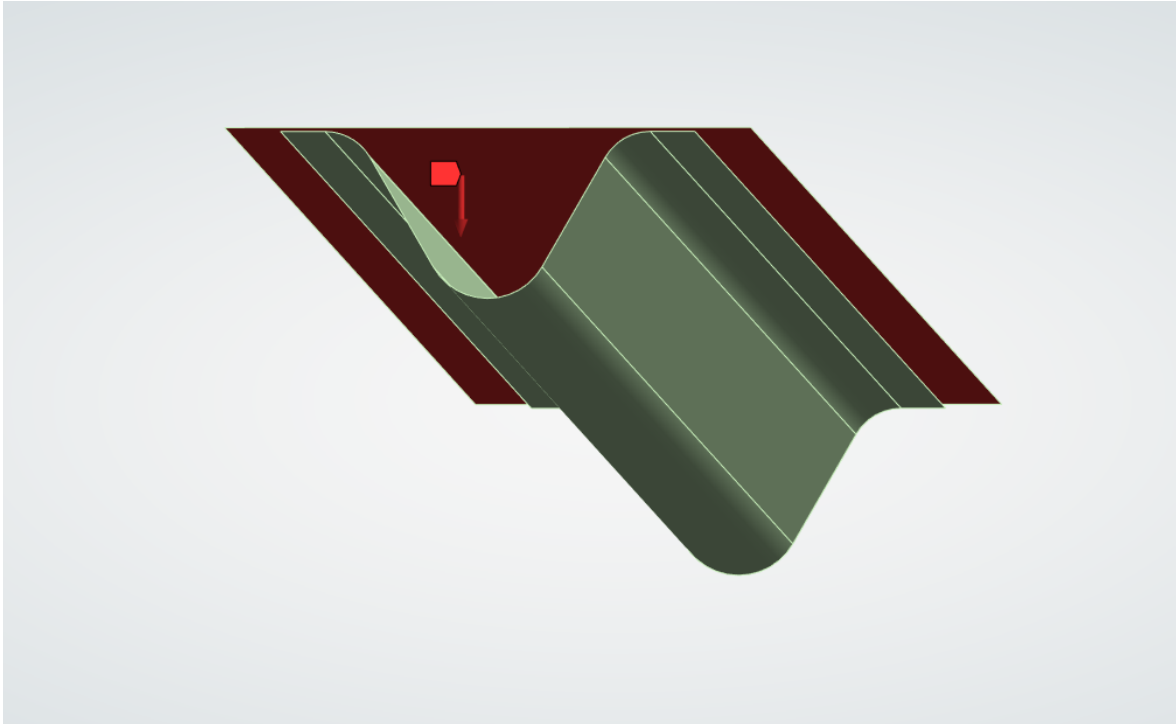


Figure C.20: Distributed load applied on the cold plate.

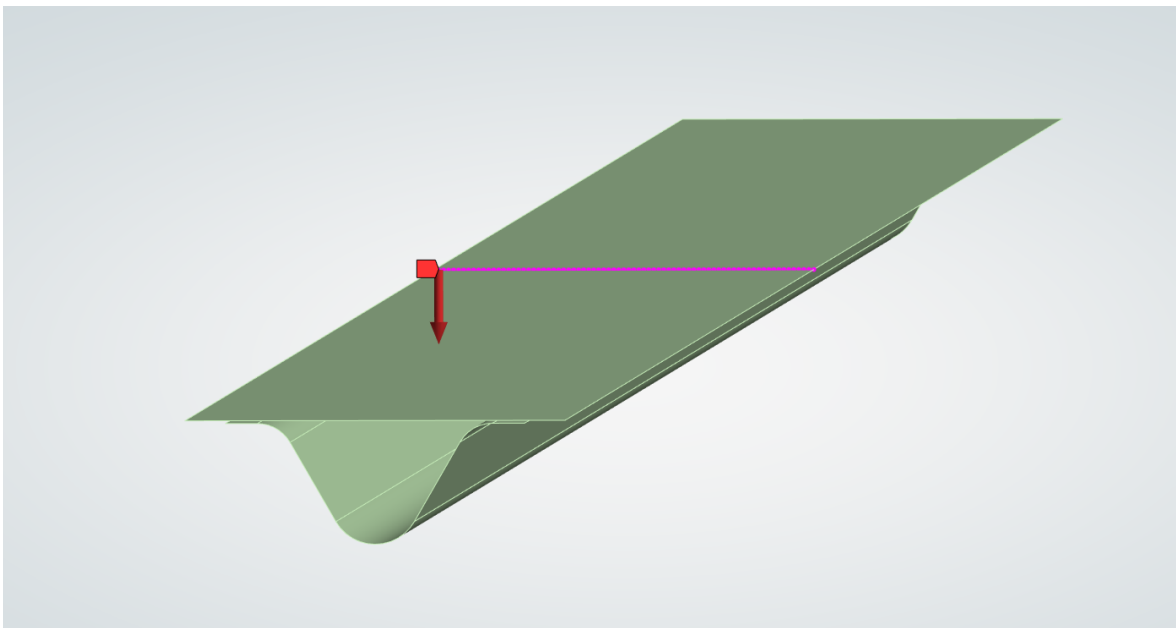


Figure C.21: Concentrated load applied on nodes strip in the middle of the ladder.

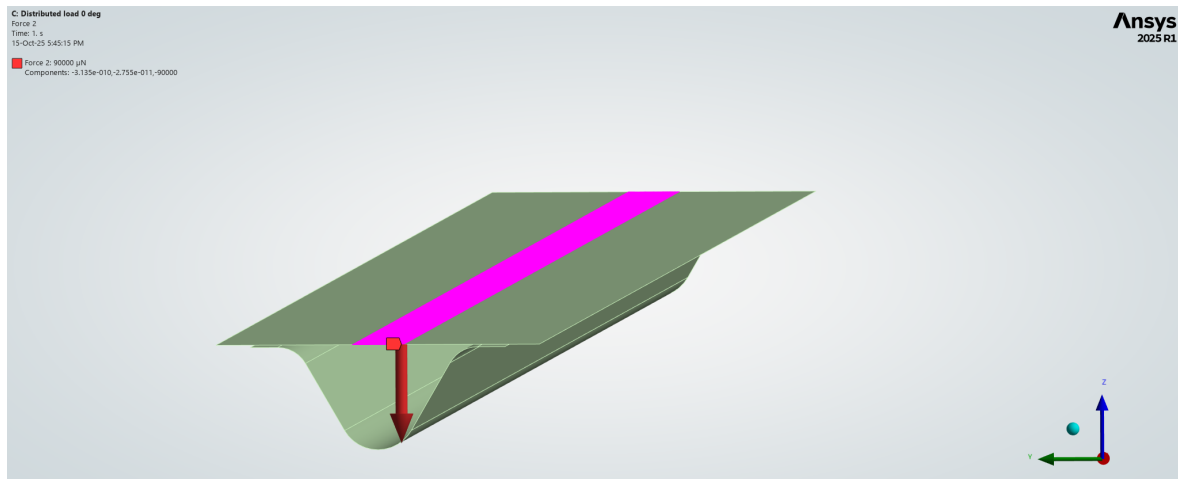


Figure C.22: Distributed water load applied on element strip in the middle of the ladder.

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