

POLITECNICO DI TORINO

Dipartimento di Ingegneria Energetica

I Facoltà di Ingegneria

Corso di Laurea Magistrale in Ingegneria Energetica e Nucleare

Tesi di Laurea Magistrale

Studio della meccanica di supporto e del posizionamento dei sensori per il nuovo tracciatore nell'esperimento ALICE al CERN.



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Ottobre 2016



Acknowledgments

First I would like to thank my supervisors Eng. Silvia Coli and Eng. Corrado Gargiulo for his great support during this work. They always had time to answer any questions, give support and helpful hints.

I want to thank my academic tutors Prof. Sandra Dulla, Prof. Daniela Grasso and Prof. Fabio Subba for giving me the possibility to carry out my Master's thesis at the CERN Detector Technologies Department (EP-DT) and at the Laboratory of Istituto Nazionale di Fisica Nucleare (INFN) of Turin. This allowed me to improve my knowledge in the area of detector construction, Finite Element Analysis and grow in the stimulating environment of CERN.

Special thanks go to Prof. Stefania Beole' and Eng. Elisa Laudi who always had time to answer questions and provide great help.

Abstract

(Italian)

Nel 2020 il tracciatore interno dell'esperimento ALICE dei laboratori del CERN sarà sostituito con uno nuovo interamente basato sui sensori pixel chip. Gli aspetti più critici nella costruzione di questo tracciatore sono il preciso posizionamento e la stabilità dei sensori nel tempo.

La prima parte di questa tesi riguarda lo sviluppo di una procedura per il posizionamento dei sensori che è stata sviluppata ai laboratori dell'Istituto Nazionale di Fisica Nucleare di Torino. La procedura è divisa in diversi step, che utilizzano programmi semi-automatici per gestire la macchina a controllo numerico utilizzata per posizionare i sensori. Alla fine della procedura di assemblaggio la posizione dei sensori è controllata e salvata allo scopo di mantenere una precisa descrizione dei componenti.

Questa procedura verrà utilizzata in cinque diversi laboratori, quattro in Europa e uno negli Stati Uniti, nei quali sarà assemblato parte del tracciatore.

La seconda parte del lavoro si focalizza invece sul disegno e sull'analisi delle strutture di supporto del tracciatore. Il lavoro è stato fatto al CERN con il gruppo di ALICE responsabile della meccanica e del raffreddamento.

I componenti meccanici devono garantire il corretto posizionamento e la stabilità dei sensori rispetto al fascio di particelle. Le strette tolleranze, la minimizzazione del materiale in prossimità del punto di interazione del fascio e la stabilità nel tempo guidano il disegno delle strutture di supporto. Il disegno delle strutture e la laminazione dei materiali compositi utilizzati sono stati ottimizzati attraverso l'utilizzo di codici agli elementi finiti. Lo scopo di queste analisi è stata la determinazione delle massime deformazioni di questi componenti sotto l'azione del proprio peso e la valutazione delle risposte dinamiche indotte da sorgenti esterne di vibrazione.

La realizzazione e la caratterizzazione dei prototipi, realizzati sulla base dei risultati delle analisi, hanno permesso di validare il disegno finale delle strutture.

Abstract

(English)

The Inner Tracking System Detector of the ALICE Experiment at CERN laboratory will be replaced in 2020 with a new detector entirely based on pixel sensor chips.

The most critical aspects in the construction of this detector are the precise positioning and the stability of the sensors over time.

The work of this thesis starts with the development of a procedure for the positioning of the sensors and has been performed at INFN of Turin. The procedure is split in several steps each of them based on semi-automatic programme to control a Coordinate-Measuring Machine that position the sensors. At the end of the assembly procedure the position of the sensors is verified and recorded such to provide a detailed map.

This procedure will be used in five laboratories, four in Europe and one in the United States, where the detector will be assembled.

The second part of the work is focused on the mechanical design and analysis of the global support structure of the Inner Tracking System, and has been performed at CERN in close contact with the ALICE group responsible for the Mechanics and Cooling of the detector.

The mechanics has to guarantee the correct position and stability of the sensors respect to the Experiment beam line. The design of these structural components is driven by tight tolerances, material minimization in the detection area and stability in time. The structure geometries and composite material layout has been optimised by using Finite Element Code. The aim of the Finite Element Analysis performed is the determination of the structures maximum deflection, due to the detector own weight, and the evaluation of the dynamic response to external vibration sources.

The production and the characterisation of the prototypes, based on the results of the analysis, has permitted the final validation of the structures design.

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List of Acronyms

ALICE	A Large Ion Collider Experiment	LHC	Large Hadron Collider
ATLAS	A Toroidal LHC AparatuS	LHCb	Large Hadron Collider beauty experiment
CERN	Conseil européen pour la recherche nucléaire	LS2	Long Shutdown 2
CFRP	Carbon Fibre Reinforced Plastic	MAPS	Monolithic Active Pixel Sensor
CMM	Control Measuring Machine	MFT	Muon Forward Tracker detector
CMS	Compact Muon Solenoid	MPC	Multi Point Constraint
COSS	Conical Structural Shell	MRS	Machine Reference System
CP	Cold Plate	NIEL	Non ionizing energy loss radiation
CYSS	Cylindrical Structural Shell	OB	Outer Barrel
DB	Detector Barrel	PB	Power Bus
DCaL	Dijet Calorimeter detector	PHOS	Photon Spectrometer detector
DoF	Degree of Freedom	PID	particle identification
EMCaL	Electro Magnetic Calorimeters	PP	Patch Panel
EW	End-wheel	PW	prepreg woven
FEA	Finite Element Analysis	QGP	Quark-Gluon Plasma
FIT	Fast interaction Trigger system	RS	Reference System
FPC	Flexible Printed Circuit	SB	Service Barrel
GEM	Gas Electron Multiplier detector	SDD	Silicon Drift Detector
HIC	Hybrid Integrated Circuit	SF	Space Frame
HMPID	High-Momentum Particle Identification Detector	SPD	Silicon Pixel Detector
HS	Half-Stave	SSD	Silicon Strip Detector
IB	Inner Barrel	TID	Total ionizing dose radiation
IP	interaction point	TOF	Time-of-Flight detector
ITS	Inner Tracking System	TPC	Time Projection Chamber detector
L0, 1, 2	Inner Layer 0, 1, 2	TRD	Transition Radiation Detector
L3, 4	Middle Layer 3, 4	UD	unidirectional prepreg
L5, 6	Outer Layer 5, 6	YETS	Year End Technical Stop

Introduction

ALICE (A Large Ion Collider Experiment) at the Large Hadron Collider (CERN) is addressing the study and the characterisation of the Quark Gluon Plasma (QGP). This is the state of the matter in the early moment of the Universe and in ALICE it is investigated by means of the collisions between ultra-relativistic heavy ions particles. Indeed, the extreme conditions of temperatures with the Pb-Pb collisions allow to study the QGP signatures revealing the QGP formation.

Chapter1

Until now, the ALICE apparatus has two crucial limitations concerning the overall material budget and the read-out rate capabilities. Actually, the first degrades the impact parameter resolution whilst the latter restricts the detector to use only a small fraction of the Pb-Pb collisions. For this reason, an upgrade of the innermost detector, e.g. the Inner Tracking System (ITS), will fully enhance the features of current system even if it will miss the particle identification functionality, energy loss information.

The ITS of ALICE experiment will be substitute in 2020, during the Long Shutdown 2 (LS2). The new ITS is designed to have a low material budget and high spatial resolution, thus ensuring to efficiently reconstruct the particles tracks together with a faster event read-out. In addition to this the new ITS has to provide a fast insertion and removal for yearly maintenance of its main components.

With these purposes, the upgraded system will be equipped with 7 layers of pixel chips developed by using the Monolithic Active Pixel Sensors (MAPS). The seven ITS layers are divided in two groups. The Inner Barrel (IB), grouping the innermost three layers, and the Outer Barrel (OB), consisting of the outermost four layers. Both IB and OB will be inserted in a structure called Cage that will permit the insertion and extraction of the barrels and will provide their support and the final alignment with the beamline.

Each Layer is segmented in elements called Staves. 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 main challenge in the construction of the ALICE Tracker Detector is in the precise positioning of the chip sensors in space and in maintaining their position stable over time by using the lightest possible mechanical structure. The mechanical structure should also provide the cooling necessary to remove the heat dissipated by the chip.

Chapter2

The position and stability concepts are applied from the smaller component, the chip, to the bigger one, the Barrel.

This chapter describes the assembly process that has been developed for the construction of 144 Outer stave 1,5m long, based on the precise positioning of 98 chips. The procedure is split in several steps each of them based on the use of a Coordinate-Measuring Machine to guarantee the precise chips alignment. The work of this thesis focuses on the development of semi-automatic programmes for the control of the coordinate measuring machine during the entire stave construction process, starting from the metrological qualification of the tools, through the chips alignment, and ending with the final assembly verification. The programs has to guide the users during the assembly steps in order to guarantee the quality and uniformity of the large number of staves that will be produce in different assembly centres.

Chapter 3

Once the Stave is completely assembled, it is integrated in a structural support called End-wheel that provides the stave spatial cylindrical distribution for each layer. The assembly of the layers to form the Inner Barrel Detector and the Outer Barrel Detector is stiffened by an external structural shell called Cylindrical Support Structure. The Detector Barrels have an extension, called Service Barrel that permits the routing of the services towards the outside of the Experiment and guides the installation. The assembly of the Detector and Service Barrel is supported and aligned inside the Cage that also provides the mechanical supports of the Beam pipe.

The design of all these mechanical components, is driven by tight tolerances, material minimization in the detection area and stability.

The structural analysis and experimental characterisation, performed for the definition of the design of the components describe above, is presented in this chapter.

The analysis, based on Finite Element simulation, has the aim to determine the structures maximum deviation from the nominal configuration, due to the detector own weight, and to evaluate the structures stability respect to external vibration sources.

In order to fulfil the challenging requirements for the support structures, defined in term of high stiffness and minimum mass, the design of the Detector components has been based on the use of composite materials that allows to achieve high structural and thermal performances in the desired directions while minimizing the weight.

Experimental test at different levels have been performed to validate the predicted behaviour and to optimize the structure geometries and composite material lay-up.

The structural final design shall be a compromise between the results coming from analysis and the limit in the manufacturing of the composite material.

Chapter 1

The Inner Tracking System Upgrade

1.1 The present Inner Tracking System

1.1.1 About CERN, LHC

At CERN, the European Organization for Nuclear Research, physicists and engineers are probing the fundamental structure of the universe. They use the world's largest and most complex scientific instruments to study the basic constituents of matter, the fundamental particles. The particles are made to collide together at close to the speed of light. The process gives the physicists clues about how the particles interact, and provides insights into the fundamental laws of nature.

The CERN has been founded in 1954, it was one of Europe's first joint ventures and now has 22 member states. Its laboratories are located along the Franco-Swiss border near the city of Geneva. Since then, CERN's facility has been growing with the addition of many new elements. [1]

The last one is the Large Hadron Collider (LHC): the largest and most powerful particle accelerator in the world. [2]

There are four main experiments presently held at the LHC:

- ALICE: designed specifically to study heavy-ion collisions. It investigates the properties of the quark-gluon plasma, thus going back to the first instants after the Big-Bang.
- ATLAS: Higgs and supersymmetry (SUSY) research.
- CMS: same purpose as ATLAS but different technical design.
- LHCb: study of beauty production and asymmetries between matter and antimatter.

1.1.2 The ALICE experiment

As anticipated before, the ALICE (A Large Ion Collider Experiment) is a dedicated heavy-ion detector at CERN-LHC which has the aim to study the physics of the strongly interacting matter. In particular, this experiment exploits the extreme temperature and energy densities which are created from the Pb-Pb collisions in order to investigate the formation and the characteristics of a new state of matter which is called the Quark-Gluon Plasma (QGP). [3]

This is the state of the matter in the early moment of the Universe and in ALICE it is investigated by means of the collisions between ultra-relativistic heavy ions particles. Indeed, the extreme conditions of temperatures obtained in Pb-Pb collisions allow researchers to study the QGP signatures revealing the QGP formation.

A direct observation of the phenomenon is impossible since the QGP lifetime is about 10^{-23} s and it does not exist any hardware trigger able to reveal it. The ALICE expectations in the first run were to observe a QGP at extreme conditions of temperature ($T > 170$ MeV) as a weak-interacting gas of quarks and gluons. In contrast, ALICE recognized that the QGP is a strong coupled plasma similar to an inviscid liquid, confirming the results provided by previous CERN experiments.

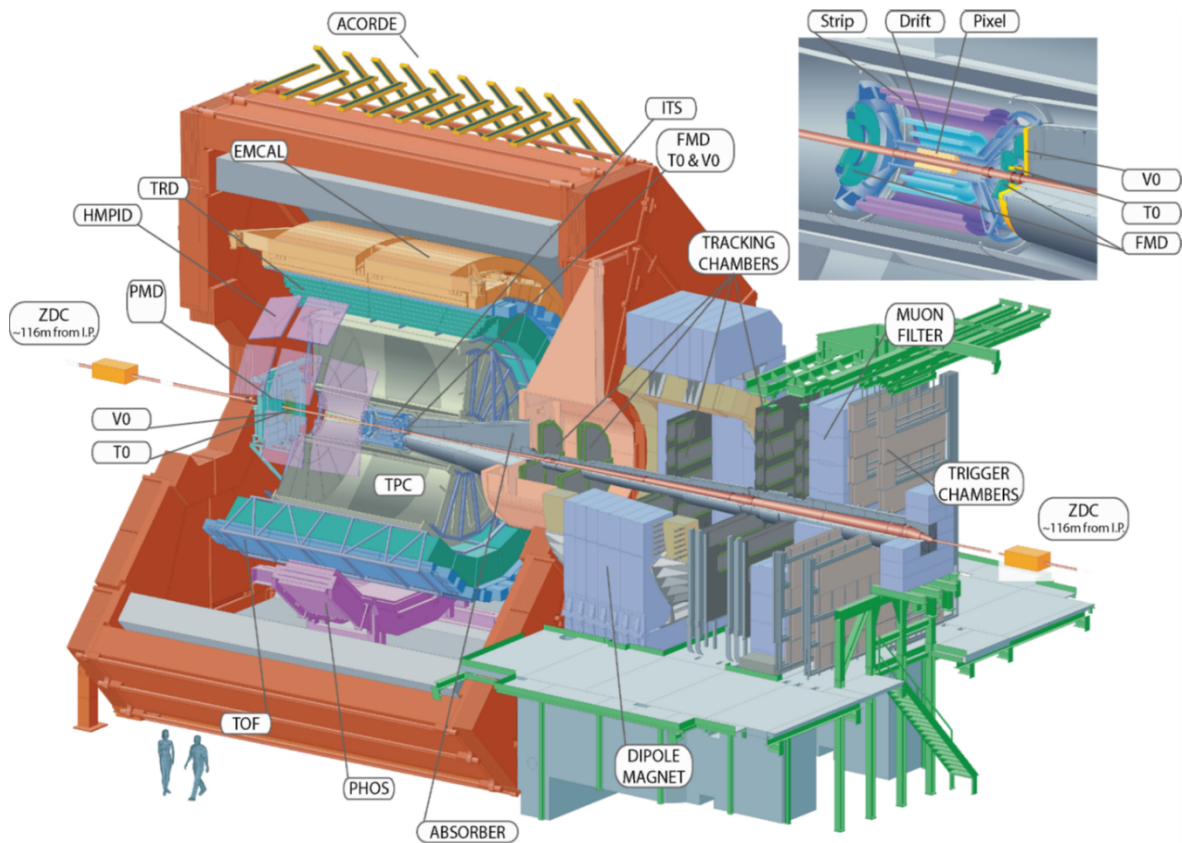


Figure 1.1: ALICE, schematic layout. [3]

1.1.3 ALICE Detector

The reconstruction of events with the extremely high number of charged tracks produced in heavy-ion collision constitutes the main experimental challenge. The ALICE detector has been specifically designed to detect up to 8000 charged particles per rapidity unit per event. This corresponds to the expectation values available at the time of the experiment design. The acceptance of the detector has to be wide enough to provide significant coverage in order to study the signatures of the QGP phase.

The detector apparatus, depicted in Figure 1.1, is divided in three main parts, covering different pseudorapidity¹ intervals and serving complementary purposes:

- Central barrel, covering the pseudorapidity region $|\eta| < 0.9$.
- Muon arm, covering range $-4 < \eta < -2.5$.
- Forward detectors.

This thesis is mainly focused on the detectors present in the central barrel, so I will not describe in detail the muon arm and the other forward detectors.

1.1.4 Central barrel

The experimental apparatus has cylindrical symmetry around the beam axis, covering the total azimuthal angle. All the central detectors are embedded in a 0.5 T magnetic field provided by a room temperature solenoid magnet.

The ALICE detectors in the central barrel allow the particle identification (PID) in the mid-rapidity interval ($|\eta| < 0.9$), over a wide range of transverse momentum.

The central barrel detectors perform PID using the specific energy loss of a charged particle traversing a medium, the transition radiation emitted by charged particles when crossing the boundary between two materials, and the time of flight that it takes to a charged particle to reach a detector's sensitive volume from the interaction point.

The central barrel includes the Inner Tracking System (ITS) which consists of six layers of silicon detectors, the Time Projection Chamber (TPC) which is the main tracking detector, the Transition Radiation Detector (TRD) for electron identification and the Time-of-Flight (TOF) for charged particle identification.

In addition, other three detectors with smaller acceptances are located at mid rapidity: the High-Momentum Particle Identification Detector (HMPID), which consists of an array of Cherenkov detectors designed to identify high-momentum particles and two electromagnetic calorimeters, the Photon Spectrometer (PHOS) and the Electromagnetic Calorimeters (EMCaL and DCal).

¹ Pseudorapidity (η) = $-\ln \tan \frac{\theta}{2}$, where θ is the angle made by the particle trajectory with the beam pipe. Pseudorapidity is useful in LHC, where the composite nature of the colliding protons means that interactions rarely have their centre of mass frame coincident with the detector rest frame, and where the complexity of the physics means that η is far quicker and easier to estimate than rapidity (y). Furthermore, the high energy nature of the collisions mean that the two quantities may in fact be almost identical.

1.1.5 The present ITS detector

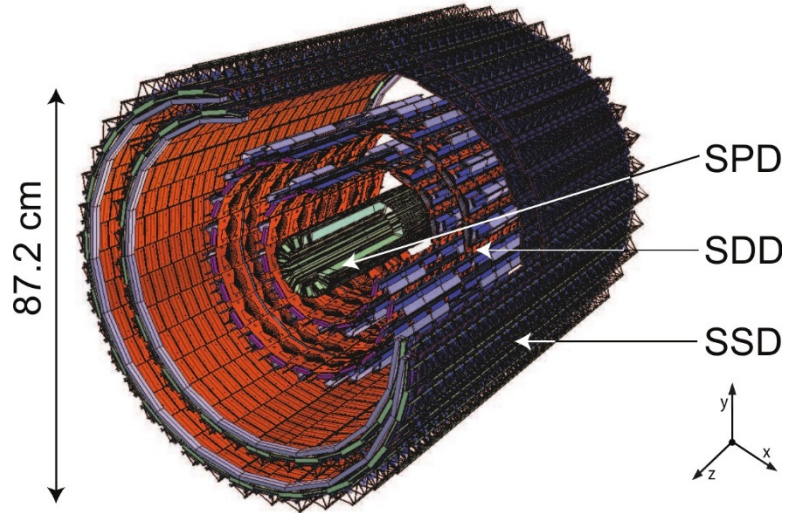


Figure 1.2: The present ITS, layout [3]

The ITS is the innermost detector of the central barrel, It is composed of six cylindrical layers of silicon detectors coaxial with the beam pipe to which it is anchored, so that no relative movements can occur. The two innermost layers are equipped with pixel detectors (SPD). They are followed by two layers of drift detectors (SDD) and lastly by two layers of double-sided strip detectors (SSD). The layout of the ITS is reported in Figure 1.2.

The SPD plays a fundamental role in the determination of the coordinate of the collision point (primary vertex) and in the measurement of the track impact parameter, which is crucial to separate secondary tracks originating from weak decays from prompt particles produced at the primary vertex.

Energy loss (dE/dx) measurements are provided by the last four layers of the ITS detector (SDD and SSD) thanks to their analog readout. PID feature will be miss in the ITS Upgrade as described in section 1.2.2

The ALICE TPC detector adds PID information using specific energy loss measurements as well.

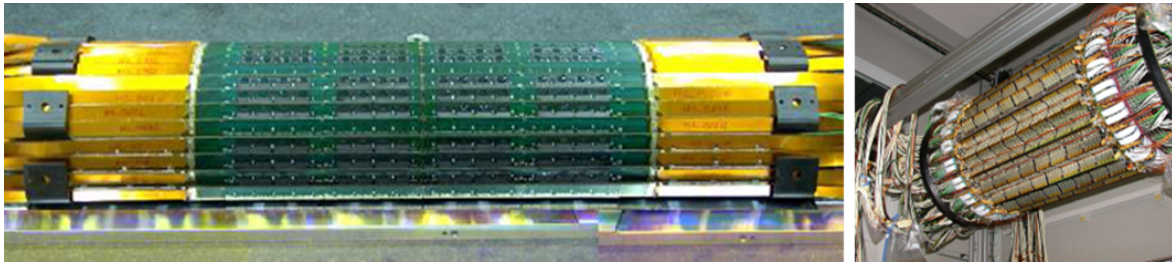


Figure 1.3: The ITS detectors. [3]
(Left)The half SPD detector layers assembled; (Right) the SDD detector completely assembled.

1.2 The new Inner Tracking System

1.2.1 ALICE Upgrade plans

The ITS of ALICE experiment will be substitute in 2020, during the Long Shutdown 2 (LS2), with a new one, whole based on Pixels Chips. The upgrades include:

- A new beam pipe², with smaller diameter;
- A new, high-resolution, low-material Inner Tracking System;
- Upgrade of the Time Projection Chamber, consisting of the replacement of the wire chambers with Gas Electron Multiplier detectors and new pipelined read-out electronics;
- Upgrade of the read-out electronics of Transition Radiation Detector, Time Of Flight detector, and Muon Spectrometer for high rate operation;
- Upgrade of the forward trigger detectors;
- Upgrade on the online systems and offline reconstruction and analysis framework.

These plans are presented in the ALICE Upgrade Letter of Intent. [4]

1.2.2 ITS Upgrade design objectives

Despite of the success of the current ITS in the first characterisation of the QGP, an upgrade strategy have been studied for this system in order to enable it to carry out the physics program of ALICE. The two starting points that justify such an upgrade are the increase in the integrated luminosity³ up to 10 Nb^{-1} , which calls for high statistics, and the precision measurements at low transverse momentum. So the new ITS has to be able to read-out and record all the Pb-Pb interactions at 50 kHz and to have an enhanced vertexing and tracking capabilities at low p_t .

The design objectives of the ITS upgrade are grouped below: [5]

- **Improve impact parameter resolution by a factor 3 respect the current value.** This goal will be achieved by:

- **Getting closer to the interaction point (IP).** Thanks to the reduction of the beam pipe diameter at a value of 19 mm, even the first ITS layer radius will be reduced from 39 mm to 22 mm.

The detection layers are located at radii between 22 mm and 400 mm and cover the pseudo-rapidity range $|\eta| < 0.9$ for vertices located within 60 mm with respect to the nominal interaction point (i.e. $\pm 1 \sigma$ of the luminous region). The outer radius is determined by the available volume inside the TPC bone and necessity to match tracks with those from the TPC.

² Tube, kept at ultrahigh vacuum, in wich the beams travel.

³ Luminosity (L) is the ratio of the number of events detected (N) in a certain time (t) to the interaction cross section (σ): $L = \frac{1}{\sigma} \frac{dN}{dt} [Nb^{-1}]$.

- **Reducing the entire material budget.** Reducing the material budget of the first detection layer is important in order to diminish the effect of the multiple scattering which modifies the particles trajectories so deteriorating the detector tracking efficiency. For this reason the new ITS will be equipped with Monolithic Active Pixel Sensors (MAPSs) which can be thinned down to 50 μm . This thickness represents a gain factor of seven respect to the 350 μm of the present detector. With the MAPS technology the pixel chip can be optimized in order to minimize the power consumption so lighting the mechanical, cooling and the other ancillary detector structures. In this way the ratio x/X_0^4 will be lower than 0.3% for the Inner Layers and 1% for the Outer Layers.
- **Increasing the detector position resolution.** The overall detector technology is based on the pixel sensors which allow for a precise position resolution thanks to the reduction of the pixel size down to $\sim 30 \times 30 \mu\text{m}^2$; currently is $50 \mu\text{m} \times 425 \mu\text{m}$.
- **Enhance tracking efficiency and pT resolution at low pT.** In order to increase the detector granularity, the upgraded ITS will have seven layers instead of six. But the major improvements is the granularity of the outermost layers with the replacement of the SDDs and the SSDs with pixel detectors.
- **Fast read-out.** The new detector will miss the particle identification feature. Actually, it was demonstrated that the benefits which come from the measure of the ionisation in the silicon layers, mainly in the low momentum region, will be marginal. For this reason a binary read-out was chosen as the most suitable for the upgrade. Furthermore, the new detector will guarantee an improvement factor of 100 for the read-out rate capabilities since it has to be able to read event by event the Pb-Pb interactions at a rate greater than 100 kHz.
- **Fast insertion/removal for yearly maintenance.** A careful design of the entire apparatus has been planned in order to have a layout which allow the fast substitution of the damaged detector modules during YETS (Year End Technical stop), around ~ 3 months.

⁴ The radiation length (X_0) of a material is the mean length (in cm) to reduce the energy of relativistic charged particles by factor $1/e$ by bremsstrahlung effect.

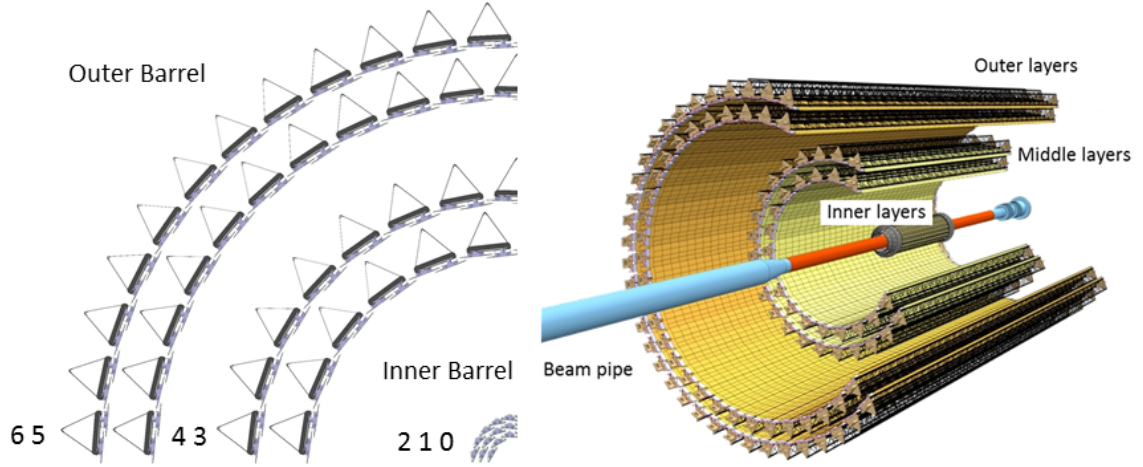


Figure 1.4: ITS Upgrade layout. [5]

1.2.3 ITS upgrade layout

The design of the new ITS is conceived as a two-barrel structure: the Inner Barrel (IB), formed by Layers 0 to 2, and the Outer Barrel (OB), formed by Layers 3 to 6.

The three Layers of the IB are also referred to as the Inner Layers, with Layers 3 and 4 as Middle Layers and Layers 5 and 6 as Outer Layers.

In the azimuthal direction, each Layer is segmented in elements called Staves. 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 three Inner Layers are built with identical Staves, while the Staves of the OB Layers have a different layout due to their longer length. The Staves of the Middle and Outer Layers have the same layout although those of the latter are almost twice the length of the Middle Layers ones.

The total number of Staves is 144, 48 staves for Inner Layer, 54 for Middle Layer and 90 for Outer Layer; details drawings of Layers Layout and their coverage are shown in Appendix A.

Table 1.1: ITS Upgrade Layout

Parameter	Inner Barrel			Outer Barrel			
	Inner Layers			Middle Layers	Outer Layers		
Layer	0	1	2	3	4	5	6
Min. Radius [mm]	22.4	30.1	37.8	194.4	243.9	342.3	391.8
Max. Radius [mm]	26.7	34.6	42.1	197.7	247.0	345.4	394.9
Length [mm]		271		843		1475	
Pseudo-rapidity coverage	± 2.5	± 2.2	± 2.0	± 1.5	± 1.4	± 1.4	± 1.3
Active area [cm ²]	421	562	702	10483	13104	32105	36691
Number of Pixel Chip	108	144	180	2688	3360	8232	9408
Number of Staves	12	16	20	24	30	42	48
Staves overlap in $r\phi$ [mm]	2.23	2.22	2.30				
Pixel Chip Spacing				150 μm			

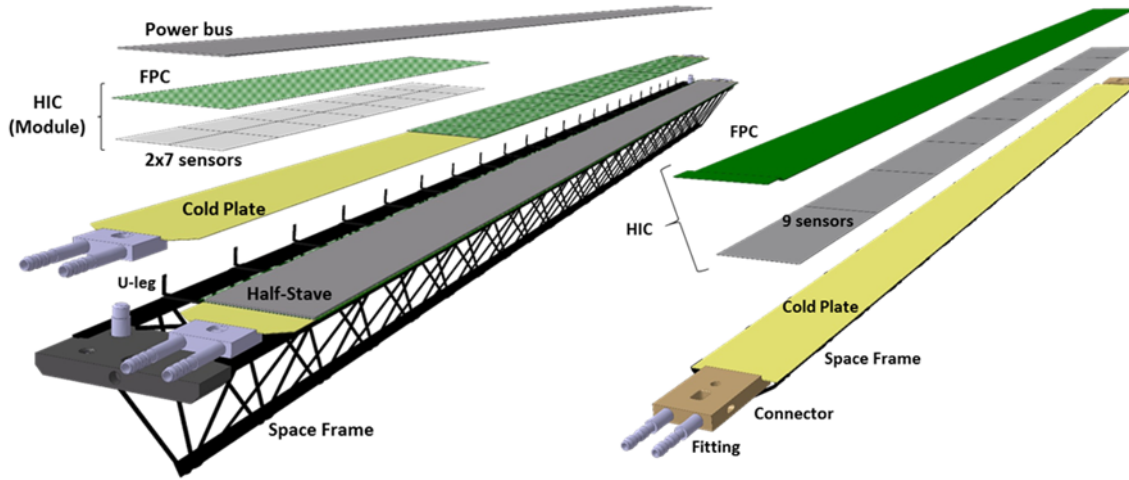


Figure 1.5: Inner and Outer Barrel Stave design.

1.2.4 Detector Stave design

The conceptual design of both IB and OB Staves is based on the following elements:

- **Space Frame (SF)**: a carbon fibre support structure providing the mechanical support and the necessary stiffness;
- **Cold Plate (CP)**: a sheet of high-thermal conductivity carbon fibre with embedded polyimide cooling pipes, which is either integrated within the Space Frame (for the IB Staves) or attached to the Space Frame (for the OB Staves). The Cold Plate is in thermal contact with the Pixel Chips to remove the generated heat.
- **Hybrid Integrated Circuit (HIC)**: an assembly of a polyimide Flexible Printed Circuit (FPC) on which a number of Pixel Chips, namely 9 and 14 for the IB and OB Staves respectively, and some passive components, are bonded, this assembly is also called **Module** for the OB Stave;
- **Half-Stave (HS)**: the OB Staves are further segmented in azimuth in two halves, called Half- Staves. Each Half-Stave, extending over the full length of the Stave, consists of a Cold Plate on which a number of Modules are glued, namely four and seven for Middle Layers and Outer Layers, respectively.

Space Frame and Cold Plate

The layout of the ITS Stave mechanics and cooling consists of a Space Frame and one or two Cold Plates. The Cold Plate is made of a high thermal conductivity carbon fibre laminate embedding polyimide cooling pipes. The chips are glued directly on the Cold Plate.

The heat is conducted into the cooling pipes by the carbon fibre structure and is removed by the coolant flowing in the pipes.

For mechanical stability the Cold Plate is stiffened by the Space Frame, a light filament wound carbon structure with a triangular cross section. The concept of a Cold Plate and a Space Frame applies to both the IB and OB Staves but the specific implementation of each Layer is tailored according to the different geometrical and thermal constraints.

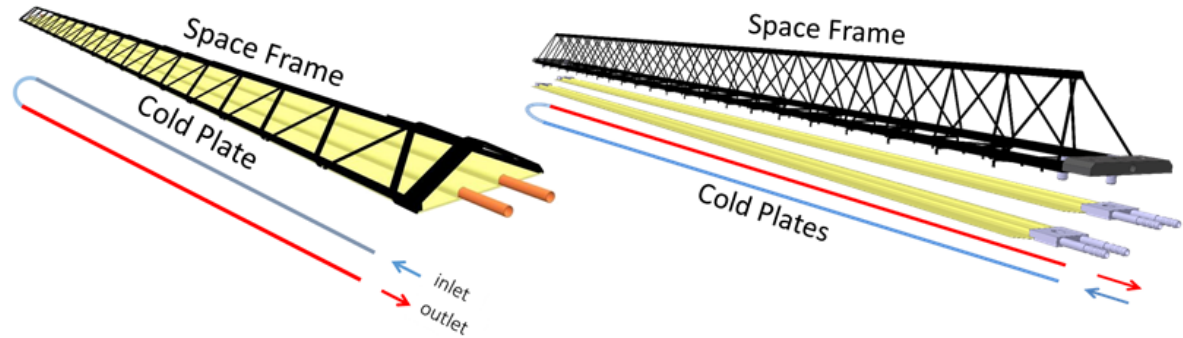


Figure 1.6: Space Frame and Cold Plate cooling scheme.
(Left) Inner Barrel; (Right) Outer Barrel.

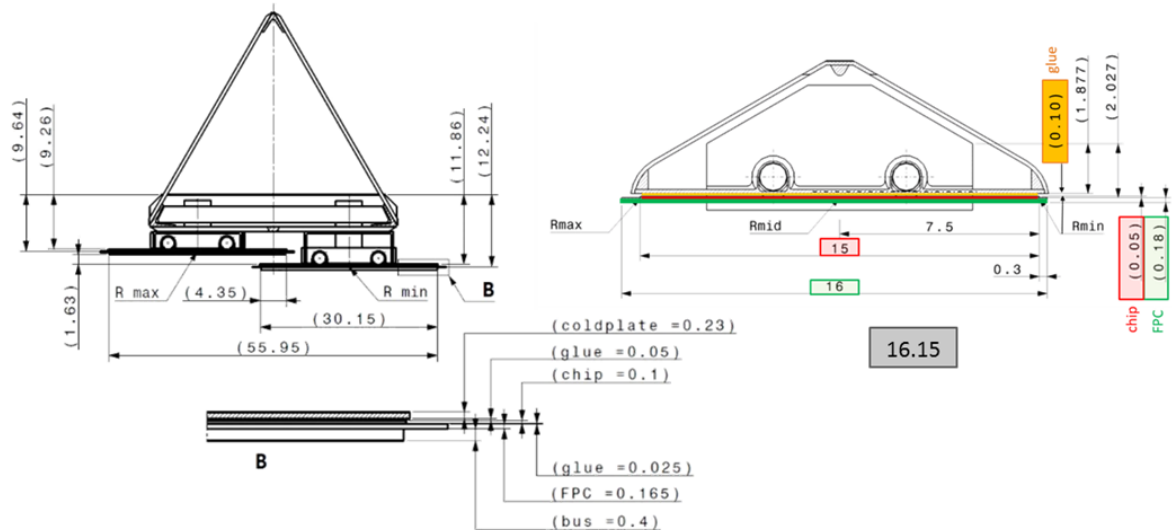


Figure 1.7: Front view of Staves assembled.
(Left) OB Stave; (Right) IB Stave [mm].

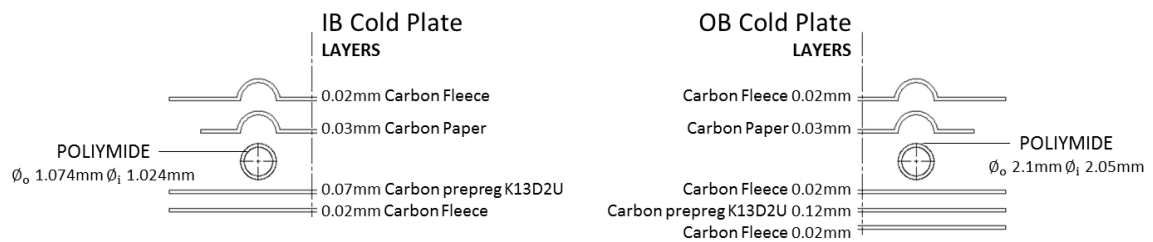


Figure 1.8: Cold Plates lay-ups
(Left) IB Stave; (Right) OB Stave.

MAPS chip

Monolithic Active Pixels Sensor is the technology chosen for the ITS upgrade since it allows to build a Pixel Chip which integrates the sensor matrix and the read-out electronics in one silicon wafer and the hybridization process will not be necessary anymore. Indeed, MAPS thickness can be thinned down to 50 μm and there is the possibility to achieve very small pixels sizes 10 μm x10 μm or less.

This characteristic turns out in benefits in terms of overall detector material budget and production cost reduction. It has to be pointed out that until now the ALICE experiment is the first one at CERN using this monolithic approach against the hybrid one to solve the two major issues in the accomplishment of its physics goals.

Flex Printed Circuit

As describe before the FPC distributes the clock and configuration signals, as well as the data read-out and power connections (only for IB stave) to all Pixel Chip in a HIC.

In order to minimise the mechanical stress on the 50 μm -thin chips, polyimide PI2611 having a Coefficient of Thermal Expansion (CTE) of 5 ppm/K [6] has been adopted in alternative to standard material (having CTE of 21 ppm/K). For comparison the CTEs of Si and C are 3 ppm/K and 1.18 ppm/K, respectively.

Power bus

For the Outer Barrel Stave a dedicated Power Bus (PB), extends over all FPCs of the Half-Stave, providing analogue and digital power as well as ground connections. The baseline powering scheme is based on a conservative parallel connection: all chips in a HIC (Module) are directly connected to the analogue and digital power planes of the FPC, which are in turn fed by the PB serving the Half-Stave.

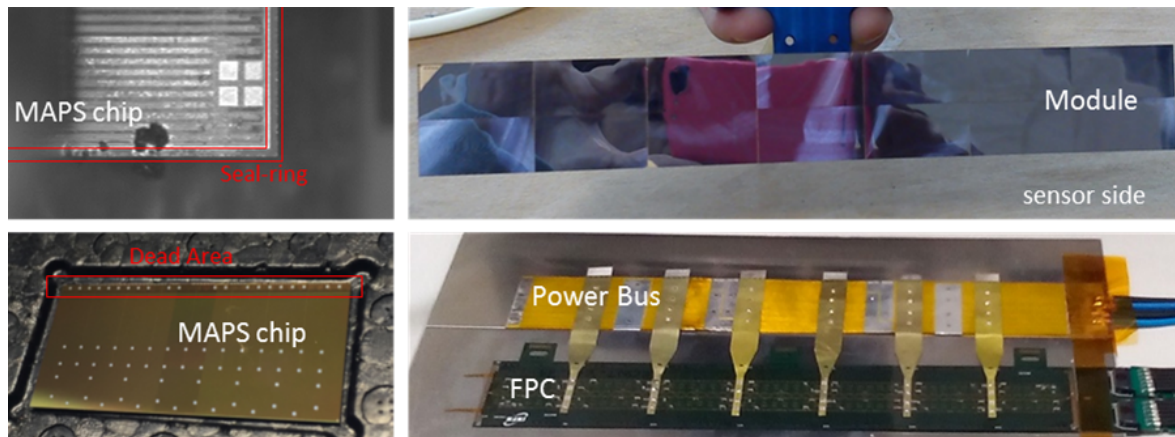


Figure 1.9: MAPS chip, FPC and PB.

In the figures the MAPS chips, a Module with 14 Pixel Chips and a FPC connected to a piece of PB are shown.

The Dead Area of MAPS chip, where no pixel are present, is on one of the long side and it is 1.2 mm wide.

The ring surrounding the chip, and then the pixels, is called seal-ring.

On the left pictures details of Dead Area and seal-ring of a chips are highlighted.

Inner Barrel Stave

Each IB Stave will be instrumented with one HIC, which consists of nine Pixel Chips in a row connected to the FPC, hence covering a total active area of 15mm x 271.2mm, including a 150 μ m gap between adjacent chips along z. The HIC is glued to the Cold Plate with the Pixel Chips facing it in order to maximize the cooling efficiency. Figure 1.5 shows a schematic layout of the IB Stave.

An extension of the FPC at one side connects the Stave to a patch panel that is served by the electrical and signal cables. A mechanical connector at each end of the Stave allows the fixation and alignment of the Stave itself on the end-wheels, describe in section 1.2.6.

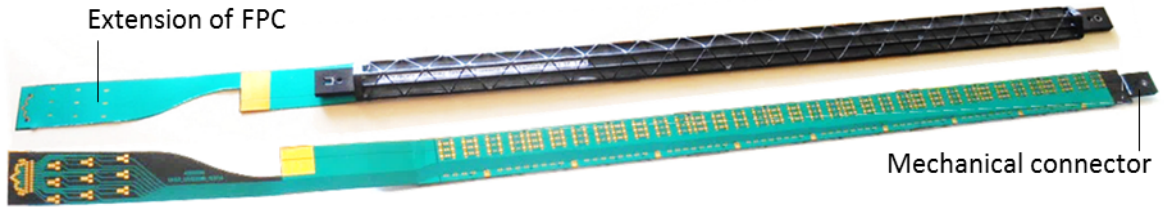


Figure 1.10: IB Stave assembled.

Outer Barrel Stave

The Staves of the Middle and Outer Layers are identical, except that the Outer Layer Stave is nearly twice as long. The basic concept of the OB Staves is very similar to the IB ones. However, the Staves of the OB are split azimuthally in two Half-Staves, each longitudinally further segmented in four or seven HIC for the Middle and Outer Layers, respectively. The design of the Space Frame of the OB Staves is derived from the ladder frame of the outer layers of the current ITS. It supports two Cold Plates, with the respective integrated cooling pipes, each carrying four or seven HIC. From here forward, all references will be made to the Stave layout of the Outer Layout. The layout and components of the OB Stave are highlighted in Figure 1.5. The Cold Plates are connected to the Space Frame by U-shaped connectors. In order to achieve a nearly full coverage, the two Cold Plates of a Stave overlap in the r- direction, as shown by the Stave cross section in Figure 1.7. The HIC of the OB Staves consists of an array of two rows of seven chips each, connected to a common FPC that is approximately 3 cm wide and 21 cm long.

1.2.5 Stave requirements

The Stave design is driven by the general upgrade objectives, i.e. get closer to the IP, reduce material budget, fast insertion/removal and by the following requirements:

- **Hermeticity.**

The chip spatial distribution has to fulfil the hermeticity requirement i.e. a minimum gap among chips is accepted in the longitudinal direction only.

The longitudinal gap between adjacent chips within HIC has to be less than $150\ \mu\text{m}$, while the longitudinal gap between active area of adjacent HIC has to be less than $200\ \text{mm}$.

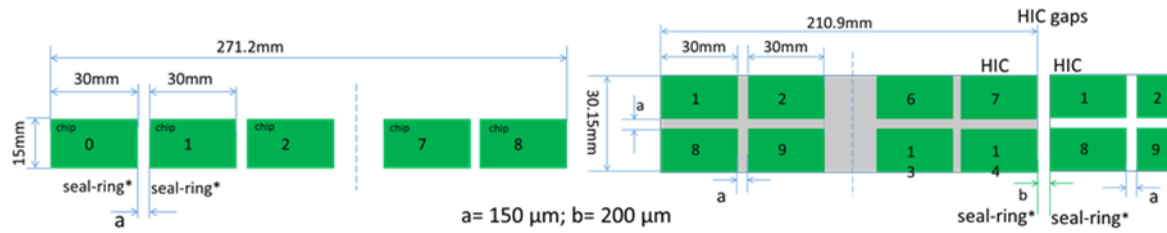


Figure 1.11: Gap chips design for hermeticity.

(Left) IB Stave (Right) OB Stave

*the chip edge extend out of the seal-ring by a minimum of $+10\ \mu\text{m}$, and a maximum of $+25\ \mu\text{m}$.

In the azimuthal direction no gap between chips is admitted, on the contrary the chips overlaps such to ensure a minimum active area overlap of $200\ \mu\text{m}$.

In order to guarantee such overlap the in-plane position tolerance is $\pm 400\ \mu\text{m}$ for the Inner Staves and $\pm 875\ \mu\text{m}$ for Outer Staves.

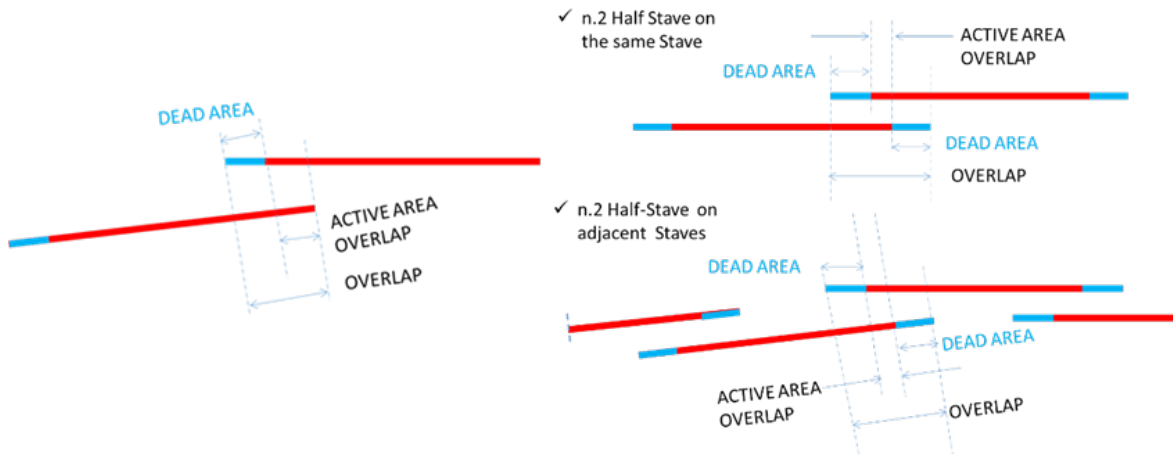


Figure 1.12: Overlap and in-plane-position tolerance of Staves.

(Left) IB Stave; (Right) OB Stave.

Chip overlap of Inner Stave and Outer Stave are $2200\ \mu\text{m}$ and $4350\ \mu\text{m}$ respectively. Dead area is $1200\ \mu\text{m}$.

- **Mechanical gap.**

The stave position tolerance has another constraint coming from the necessity to avoid contact between stave.

In the IB Stave the minimum nominal gap (o) is in the Layer 2 and it is $0.981\mu\text{m}$, therefore the Stave out of plane tolerance is around $\pm 490\mu\text{m}$.

In the OB Stave it has to be taken into account two different possible contacts, Stave to Stave and Half-Stave to Half-Stave. For the Stave to Stave gap the minimum nominal gaps are in-plane (i) $1941\mu\text{m}$ and out of plane (o) $2022\mu\text{m}$, the tolerances are in-plane position around $\pm 970\mu\text{m}$ and out of plane position around $\pm 1011\mu\text{m}$. For the Half-Stave to Half-Stave gap the minimum nominal gaps are in-plane (i) $1687\mu\text{m}$ and out of plane (o) $1595\mu\text{m}$, the tolerances are in-plane position around $\pm 843.5\mu\text{m}$ and out of plane position around $\pm 797.5\mu\text{m}$.

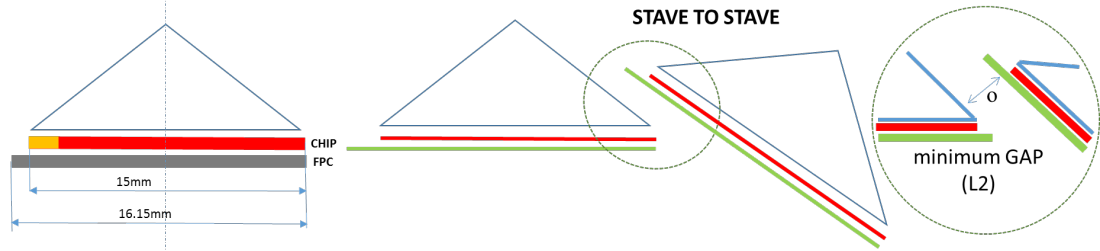


Figure 1.13: Mechanical gap of Inner Stave, schematic view.

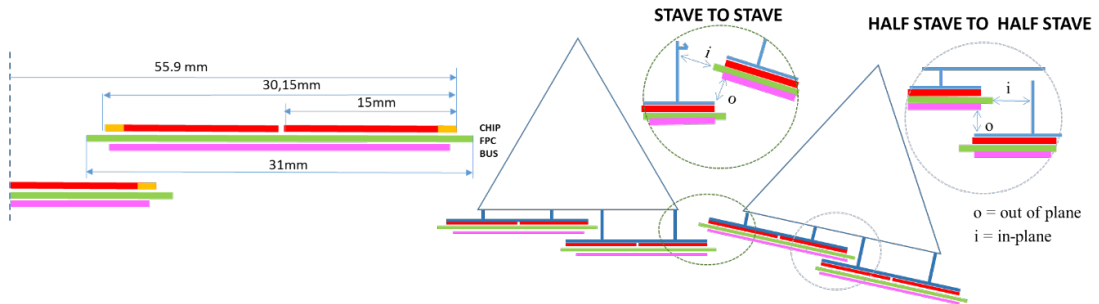


Figure 1.14: Mechanical gap of Outer Stave, schematic view.

- **Alignment Tolerance** The detector alignment is based on particles tracks; the whole tolerance on the position of sensors in space have to be less than $500\mu\text{m}$
- **Stability.** In the short-term, the detector cannot be calibrated, therefore the chip position has to be kept stable within $5\mu\text{m}$ range.
- **Cooling.** For a correct MAPS chip operation, the temperature of chip has to be less than 30°C with a maximum temperature non-uniformity less than 5°C .

- **Radiation**

The detector has to survive to the radiation dose for the whole operative period without degradation in the performances and in the structural stability. The radiation level are:

- Total ionizing dose (TID) radiation hardness 2700 krad for the IB, 100 krad for the OB.
- Non ionizing energy loss (NIEL) radiation hardness $1.7 \times 10^{13}\text{ MeV neq/cm}^2$ for IB and $1.0 \times 10^{12}\text{ MeV neq/cm}^2$ for the OB.

These values consider a safety factor of 10, i.e. 10 times the radiation load integrated over approved programme, taking into account 6 years of operation.

- **Flammability.** It has to comply with LHC Fire Safety Instruction (IS-41) [7].

Material budget

The design of the Inner Stave accounts for the tight requirement on the material budget, which is limited to 0.3 % X_0 ⁵. Table 1.2 reports the estimated contributions of the IB Stave to the material budget.

A detailed study of the material distribution across the Stave has been performed, using ALIroot program, after the optimisation of each component. In Figure 1.15 the azimuthal distribution of the Layer 0 material traversed by the particles at $\eta = 0$ is shown. Neighbouring Staves are partially superimposed to ensure the detector hermeticity. The highest peaks correspond to the overlap of the reinforced structures along the edges of the Space Frame to guarantee the required stiffness and the narrow spikes to the reinforcement implemented in the upper vertex. The peaks around 0.5 % X_0 are due to the polyimide cooling pipes embedded in the Cold Plate, which have an inner diameter of 1.024 mm and a wall thickness of 25 μm , assuming they are fully filled with water. The average value of 0.282 % X_0 fulfils the specifications, which are of extreme importance for the achievable impact parameter resolution.

Table 1.2: Estimated contributions of the Inner Layer Stave to the material budget

Stave element	Name	Material	Thickness [μm]	X_0 [cm]	X_0 %
HIC	Chip	Silicon	50	9.34977	0.0530
	Glue	Glue	100	44.3693	0.0230
	Aluminium	Aluminium	50	8.87938	0.0563
Cold Plate	Kapton	(PolyCH2)	136.1	28.4101	0.0479
	Water	Water	109	35.7585	0.0306
	Carbon Plate	K13d2u2k	70	25.8653	0.0270
	Carbon Fleece	Carbon Fleece	42.7	106.242	0.0040
	Carbon Paper	FGS003	34.3	26.5604	0.0129
Space Frame	Top Vertex	M55J6k	9.57		0.0037
	Side Vertex (2)	M55J6k	38		0.0146
	Top Filaments (all)	M60J3k	9.8		0.0049
Total					0.278

The detailed description of contributions in azimuthal direction of the OB Stave to the material budget is shown in Figure 1.16. The estimated overall material budget is within reach of the required ~ 1 % X_0 . Similarly to the IB, neighbouring Half-Staves are partially per imposed to ensure the detector hermeticity, thus giving rise to the peaks around 2 % X_0 . The highest peak is due to whole layer overall, others peaks are due to the polyimide cooling pipes embedded in the Cold Plate, assuming they are fully filled with water.

⁵ The radiation length (X_0) of a material is the mean length (in cm) to reduce the energy of relativistic charged particles by factor $1/e$ by bremsstrahlung effect.

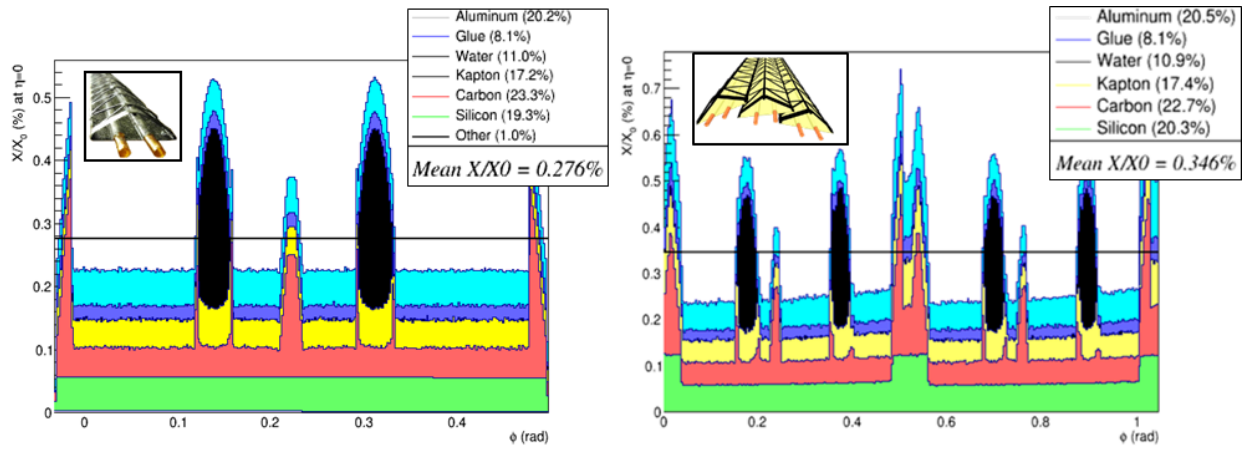


Figure 1.15: IB material budget.

(Left) Single Stave, for perpendicular tracks; (Right) tilted Stave with overlap, inclined tracks.

(Left) The peaks around 0.5% X_0 are due to the polyimide cooling pipes fully filled of water.

(Right) The highest peaks correspond to the overlap of the reinforced structures at the edges of the Space Frame, while the narrow spikes to the reinforcement at the upper vertex.

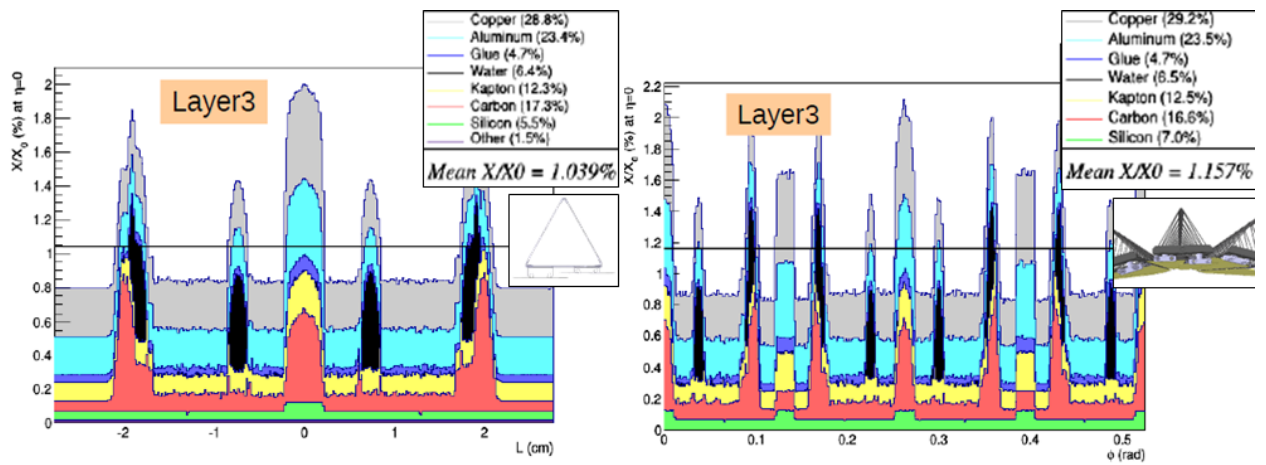


Figure 1.16: OB material budget.

(Left) Single Stave, for perpendicular tracks; (Right) tilted Stave with overlap, inclined tracks.

1.2.6 Global support structure

The main mechanical support structures of the ITS have the shape of barrels supported inside an integration structure named Cage that extend over the whole length of the TPC bore. Two barrels, the Inner Barrel (IB) and the Outer Barrel (OB), hold in position, respectively, the three Inner Layers and the four Outer Layers of the ITS. Furthermore, each barrel is divided into two halves, top and bottom, which are mounted separately around the beam pipe.

Each barrel is composed of a Detector Barrel (DB) section and a Service Barrel (SB) section (Figure 1.18). The Staves are housed in the Detector Barrel and are connected via electrical signal connections (e-links) and power cables to external patch panels. The external patch panels are located immediately outside of the TPC, and are accessible from the ALICE mainframe. The Service Barrel integrates the cable trays that support the e-links and power cables through their routes from the detector Staves to the patch panels. Pipes that connect the ITS on-detector cooling system to the cooling plant in the cavern are also routed through the Service

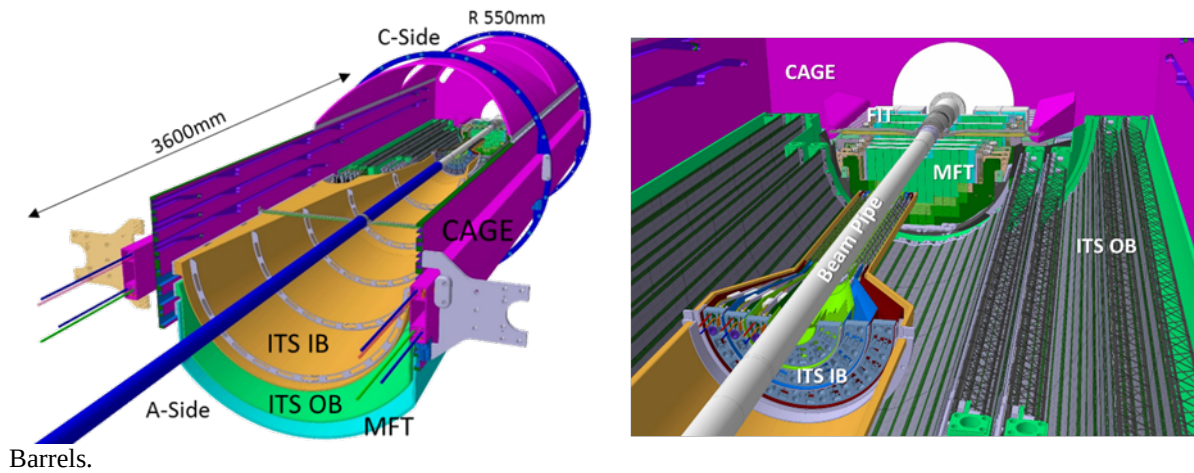


Figure 1.17: Global support structure design.
(Left) Outside view; (Right) Inside view.

Global support structure requirements

The layout of the new ITS mechanical structure (Figure 1.17) has been developed to fulfil the following design criteria:

- minimize material in the sensitive region;
- ensure high accuracy in the relative position of the detector sensors;
- provide an accurate position of the detector with respect to the TPC and the beam line;
- locate the first detector layer at a minimum distance to the beam pipe wall;
- ensure structure thermo-mechanical stability in time;
- facilitate accessibility for maintenance and inspection;
- facilitate assembly and disassembly of the detector layers and Staves.

In addition, the new ITS has to fulfil the requirements set by the integration of the new Muon Forward Tracker (MFT) and a new set of detectors that will be part of the Fast Interaction Trigger system (FIT).

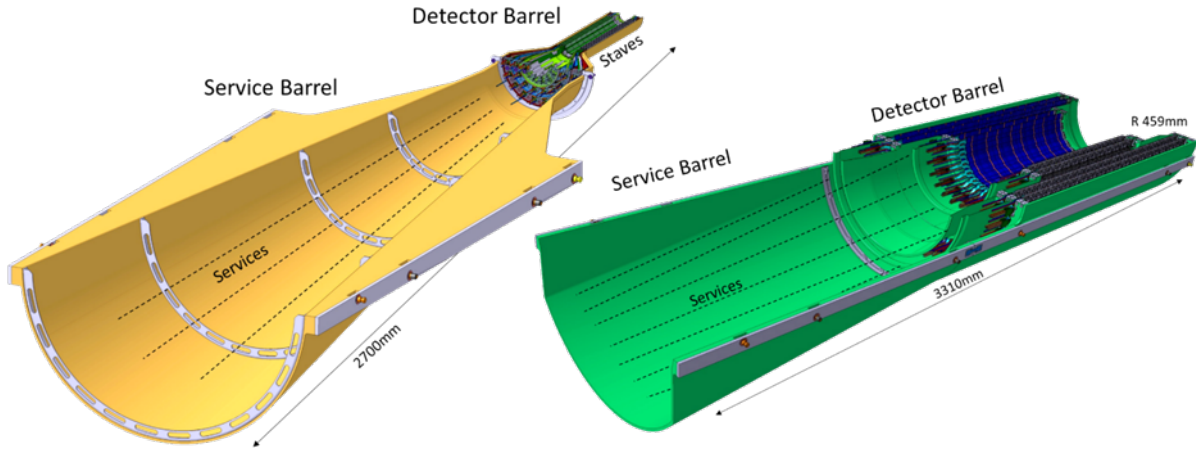


Figure 1.18: Half-barrels.
(Left) Inner Detector and Service Barrel; (Right) Outer Detector and Service Barrel.

Detector Barrel structure

The main structural components of the Detector Barrels are the End-wheels (EW) and the Cylindrical and Conical Structural Shells (CYSS and COSS). In Figure 1.21 and Figure 1.22 are shown respectively the Inner Barrel Detector and Outer Barrel Detector. The End-wheels, which are light composite end-rings, ensure the precise positioning of the Staves in a layer. They provide the reference plane for the fixation of the two extremities of each Stave.

In the IB and OB, the position of the Staves in the reference plane is given by a ruby sphere and ruby pads, screwed in the reference plane and matching a precise reference hole in the mechanical connectors at both extremities (Figure 1.19 and Figure 1.20).

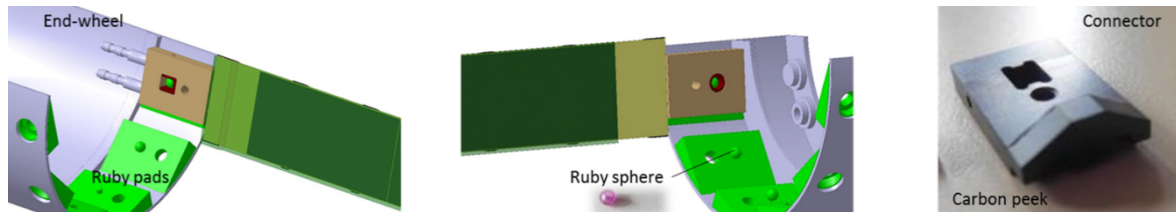


Figure 1.19: IB End-wheel and Stave connection.
(a) A-Side connection; (b) C-Side connection; (c) Inner Stave Connector prototype.

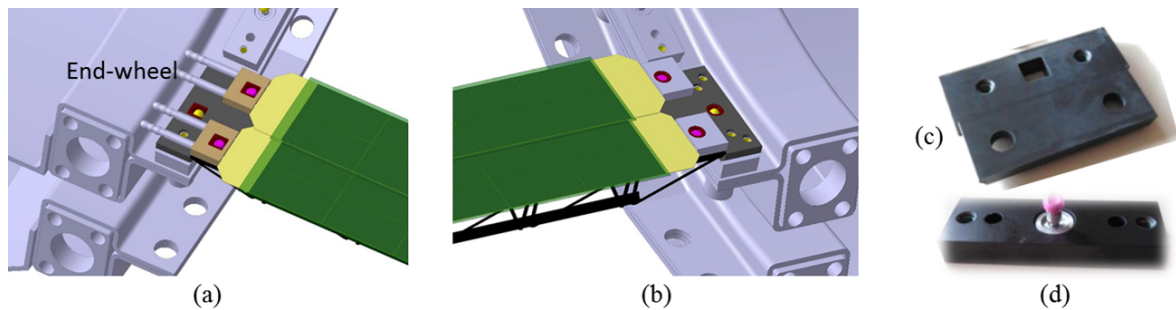


Figure 1.20: OB End-wheel and Stave connection.
(a) A-Side connection; (b) C-Side connection; (c) Outer Stave Connector prototype; (d) Ruby sphere, 2 μm accuracy.
The accuracy coupling is around 5 μm

The different layers are connected together to form the barrel; an outer Cylindrical Structural Shell connects the opposite End-wheels of the barrel and avoids that external loads are transferred directly to the Staves.

In order to minimise the material budget in the detection area, the following design choices have been adopted:

- The IB is conceived as a cantilever structure supported at one end outside the OB acceptance;
- The OB has no intermediate mechanical structures amongst the four detection layers.

The OB is designed to allow each half to be opened in two concentric parts, constituted by the sub-assembly of Layers 3–4 and Layers 5–6. This modularity permits the independent assembly of the Middle Layers (3–4) and Outer Layers (5–6) and their connection at the end of the integration phase. The connection of the two sets of layers is obtained by two Conical Structural Shells located at the extremities of the detection area.

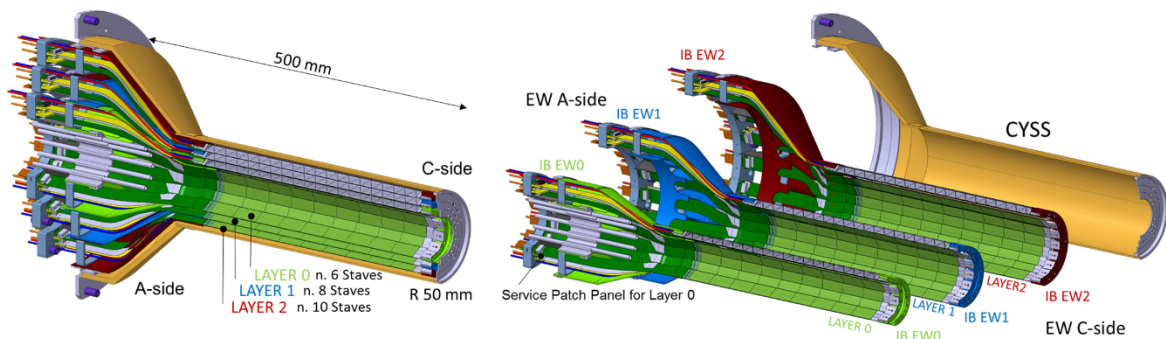


Figure 1.21: Inner Detector Barrel assembled and exploded view, half-barrel.

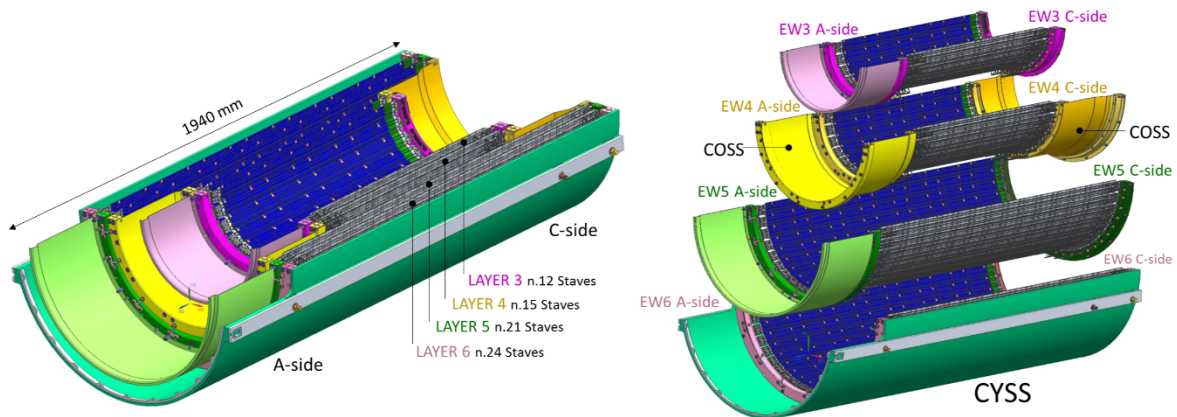


Figure 1.22: Outer Detector Barrel exploded and assembled view, half-barrel.

Service Barrel structures

The closest point of access to the TPC bore is at one side of the Experiment (A-side) at about $z = -3$ m (beam line direction from IP). Therefore, the services attached to the detector barrel and extending out to $z = -3$ m must be inserted or retracted together with the detectors.

All services, including cooling pipes, power, and signal cables, will be integrated into the Service Barrel that is an extension of the Detector Barrel. Power cables will be grouped with the cooling tubes in the Service Barrel in order to remove the heat they generate.

The SB copies the shape of the TPC cone in order to distribute the services outside the acceptance of the forward detectors.

The assembly composed of half-Detector Barrel and half-Service barrel is inserted or extracted from the TPC bore by means of two sets of lateral rollers fixed on the barrels and sliding on their corresponding rails provided by the Cage. Rollers, engaging Cage rails, are aligned respect to the detectors. For the Inner Service Barrel four primary rollers (two for each half-barrel) drive the detector final position. For the Outer Detector and Service Barrel, two additional rollers are used for a total of six rollers (three for each half-barrel). Each primary roller blocks a limited number of degrees of freedom such to realise a configuration as close as possible to isostatic, Figure 1.23. Few additional secondary rollers are used in the barrel to drive the insertion and realise a simple support against the gravity action.

The Service Barrel itself is a light composite structure that has to provide both structural stiffness and dimensional stability, to guarantee a precise installation of the ITS inside the TPC.

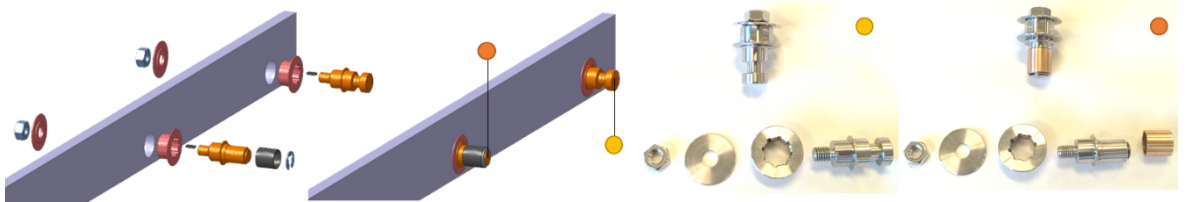


Figure 1.23: Rollers that engage the Cage rails.

Shown from left to right: exploded and assembled rollers fixed on the bar of Inner Service Barrel; with yellow mark the prototype of the primary roller; while with the orange mark the secondary roller.

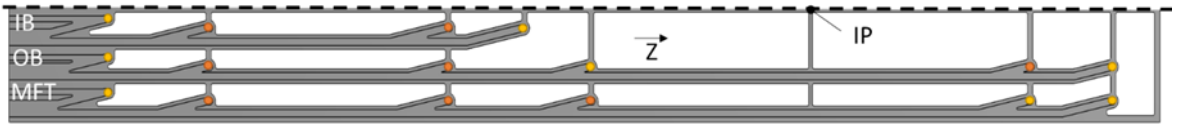


Figure 1.24: Rollers positions on the Cage rails.

Different colours identify the two different rollers as shown in the previous figure.

Also MFT Service Barrel is engaged with the same roller concept.

Details on the slot of the Cage rails where the two rollers are coupled are shown in the next figure.

Cage structure

The Cage is the mechanical structure which holds the detectors during its insertion and removal, and in the operational position. The detector cage is a stiff cylindrical shell based on a light composite sandwich, which is fixed inside the TPC bore and provides a common support for the ITS and MFT barrels and the beam pipe.

The Cage incorporates two of the three supports of the beam pipe central section, one at the C-side and one in the middle, while the third support (A-side) is outside of the TPC on a bracket directly fixed to it.

The Cage sits on brackets fixed at the two stiff rings of the TPC cylindrical bore, in the middle horizontal plane. An additional support point is provided on the external ring of the TPC conical bore on A-side. At the interface with the TPC, the Cage provides a levelling system that allows for a fine-tuning of its position with respect to the beam (Figure 1.27). The system, based on remotely controlled movable mechanical parts, can be used at the different stages of the beam pipe and detectors alignment.

At its interior, the Cage provides the precise guiding rails needed for the insertion of the detector-service half-barrels. One set of rails for each half-barrel is used at the vertical side wall of the cage. The rails are in Aluminium 5052, embedded in the composite sandwich structure that constitutes the Cage side wall. During insertion, the half-barrels move on wheels guided by the rails. The rail design is such to keep the barrel at a safe distance from the beam pipe and its support. The clearance reaches the design value only a few centimetres before the final position.

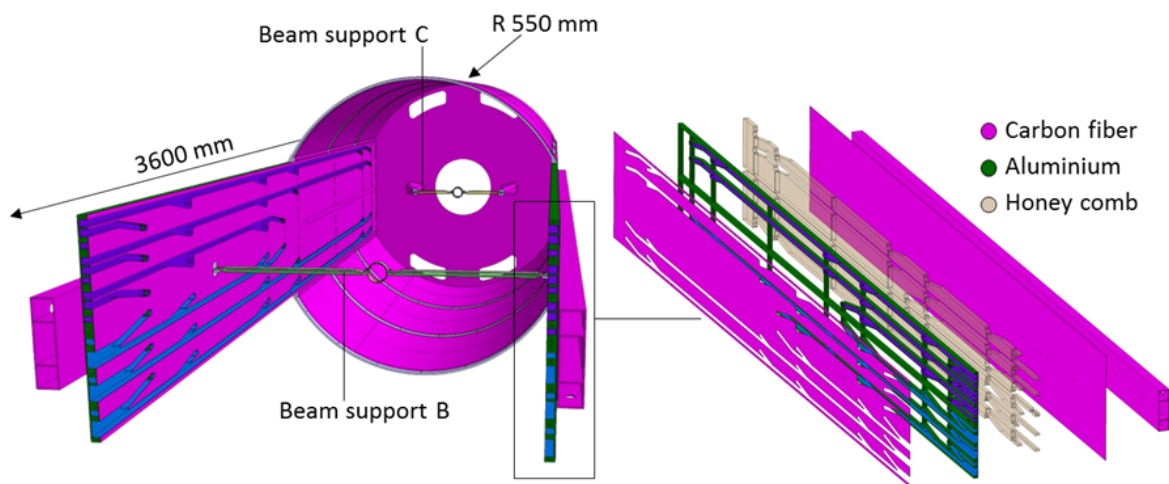


Figure 1.25: Cage structure assembled and guiding rails exploded view.

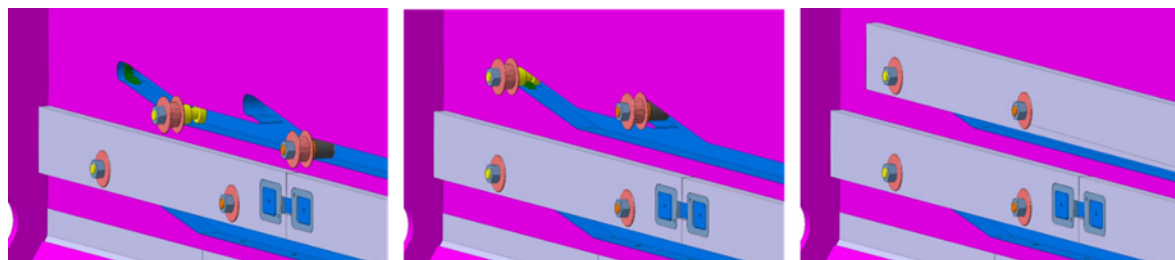


Figure 1.26: Rollers on the Cage rails, different views.

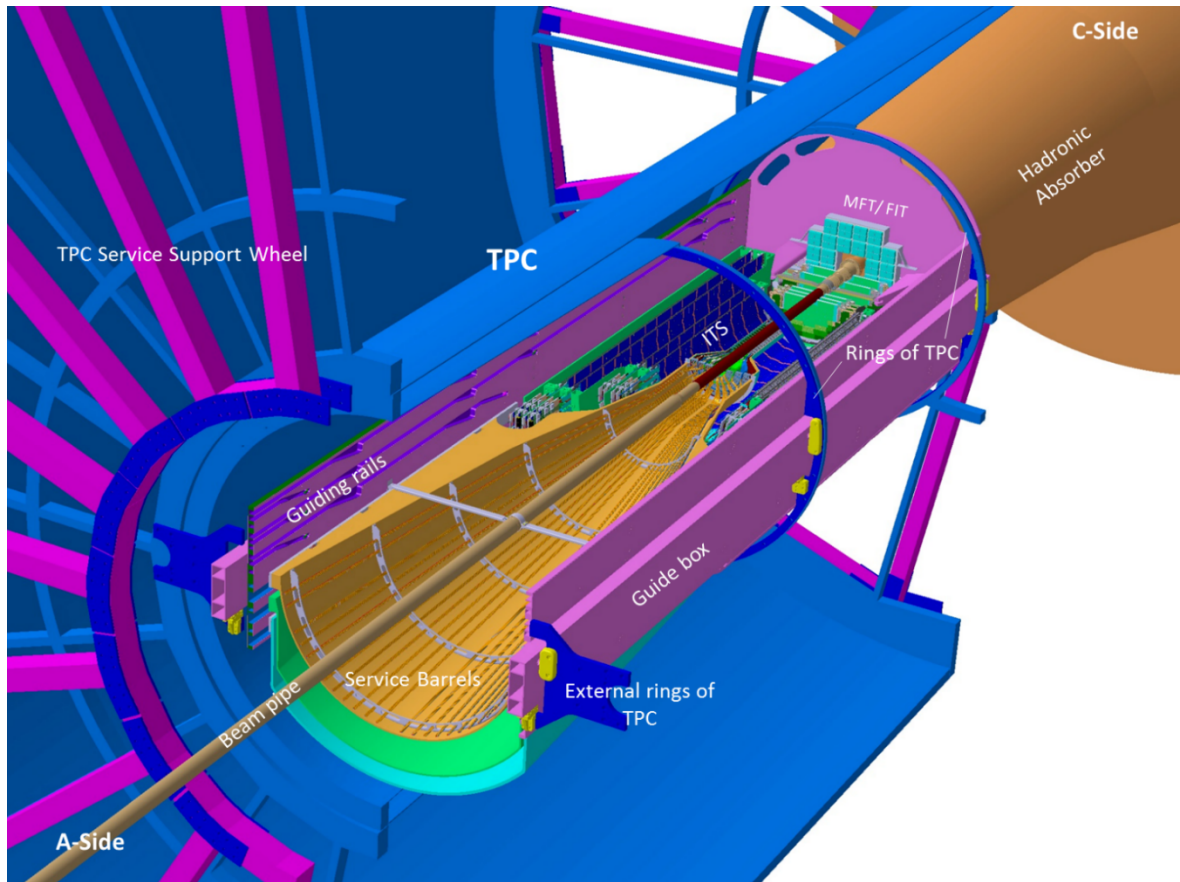


Figure 1.27: Interfaces of Cage with TPC and Hadronic Absorber.

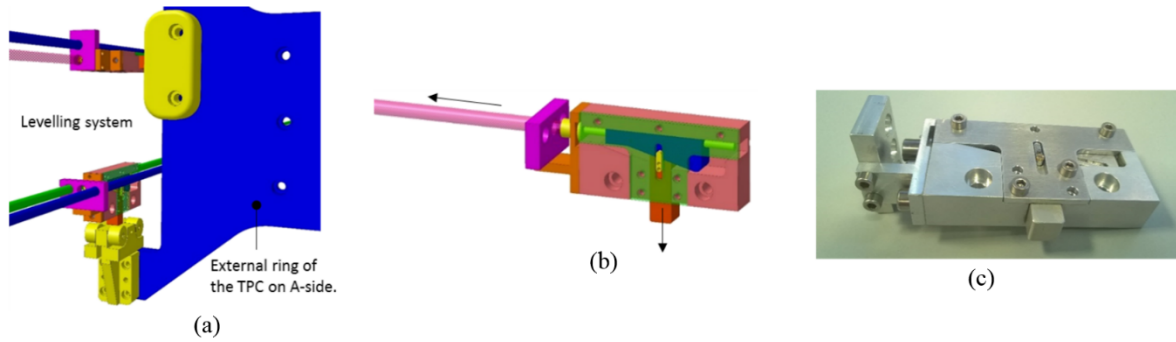


Figure 1.28: Levelling system of Cage.

- (a) The levelling system and its interface with the TPC external ring;
 - (b) The central figures shows the functioning principle of the levelling system; (c) photo of the mechanism.
- The adjusting range is $\pm 4\text{mm}$

1.2.7 Beam pipe

The beam vacuum pipe represents the main interface between the experiment and the LHC machine. It must therefore fulfil a dual set of requirements.

The ALICE experimental requirements include maximum transparency to particles, limited beam-gas background, and conformity with the environmental and installation constraints. The accelerator requirements include safe operation of the machine, adequate beam aperture, and severe vacuum conditions compatible with ultimate LHC performance. The ALICE beam pipes extend over 19m on either side of the interaction point and consist of three sections: RB24-section, central section, RB26-section. The present central section of the beam pipe is 4.8m long with about 4m in beryllium inside the TPC. One side is limited by the hadronic absorber, which penetrates inside the TPC, and on the opposite side by a large vacuum valve.

The connection to the contiguous beam pipe sections is made via bellows to avoid induced displacements.

With respect to the beam pipe currently installed in ALICE, the central section of the new beam pipe will have a total length of 5.5m (Figure 1.29). This implies relocating the vacuum valve 1.5m away from the TPC. This modification of the central section of the beam pipe is necessary to allow the positioning of the new ITS around the beam pipe before it is moved inside the TPC.

Material used for the central section are Beryllium near the interaction point and Aluminium for others parts. Beryllium part is 888 mm long and has a thickness of 0.8mm, while Aluminium parts near to Beryllium one has a thickness of 1 mm; these dimension are the result of a compromise between physic requirement and mechanical and manufacturing constraints.

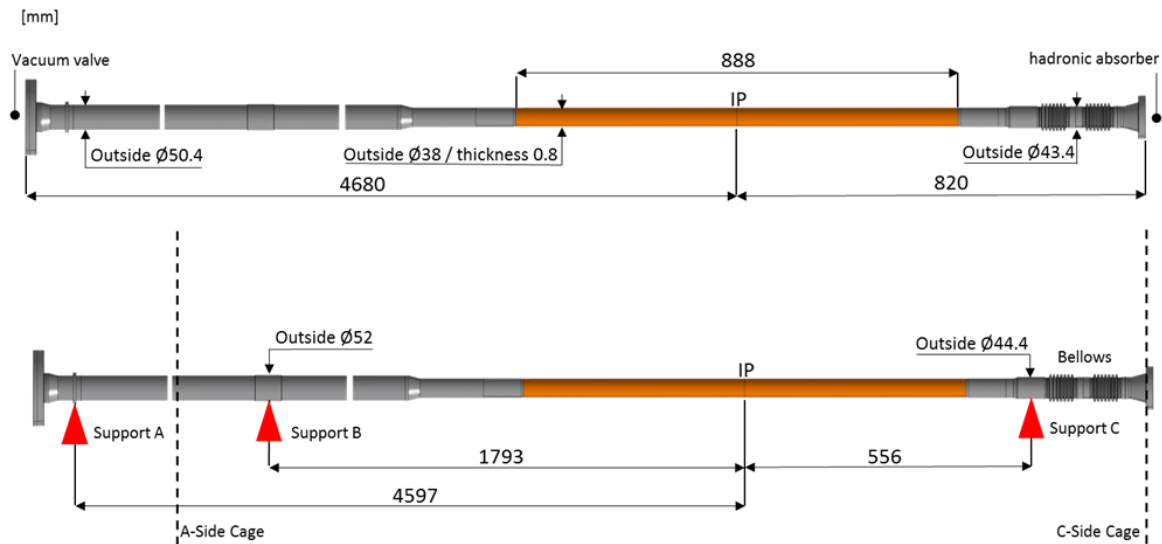


Figure 1.29: Central section of ALICE beam pipe views.

1.2.8 Survey and mechanical alignment

The survey and alignment requirements for the ITS detector elements can be separated into two different categories.

First, the different ITS elements must be placed at the nominal position within a specified tolerance (assembly and installation), typically of the order of few tenths of millimetres, to permit adequate positioning of sensors in terms of overlapping and to preserve proper clearance for smooth installation and maintenance.

Second, the position of the silicon sensors and their stability in time during operation have to be known with a tight accuracy, of the order of few microns for the IB and few tens of microns for the OB.

Although the mechanical structure of the ITS is designed to provide precision and stability with the required level of accuracy, several factors influence the uncertainty of the position of the detectors:

- the manufacturing accuracy of all components;
- the tolerance after assembly of the components in the barrel;
- the deformation of the components under load;
- the global positioning uncertainties related to the installation procedure;
- possible vibrations of the mechanical support structure;
- thermal expansion of the components;
- others long-term effects such as the settling of different parts of the ITS structure and surrounding ALICE interfaces.

The required precision of the final position of the ITS detectors can only be ensured if the position of the components relative to each other is measured during each step of the assembly process.

Assembly

The assembly can be divided in three main step:

- **Stave:** Each Pixel Chip in the Stave will have reference markers on the visible side of the sensor which are very accurately related to the pixel array. By using a 3-dimensional Control Measuring Machine (CMM), equipped with an optical probe, these marks will allow the determination of the relative positions of the Pixel Chips within a Stave. Their positions will be known with respect to external reference on the FPC and on the Stave.

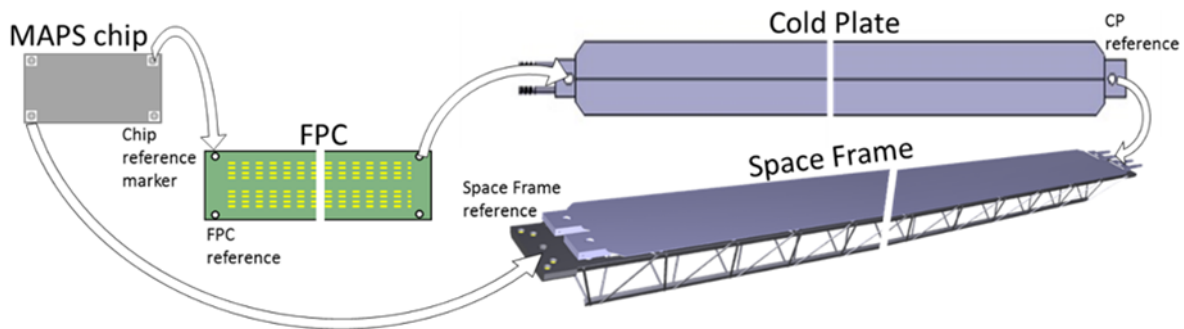


Figure 1.30: Stave reference, schematic view.

- **Half-layer:** The next step will be the precise measurement of the position of the Staves on the End-wheels to form a half-layer. The Stave's relative position will be measured and referred to reference points on the End-wheels.

At this level, non-contact optical measurement of the pixel sensor positions will be related to contact measurement of targets on the End-wheels. Targets for contact measurement will be housed in metrology holes provided in the End-wheel structures.

- **Half-layer to Detector Barrels:** After the layers are assembled in a half-barrel, they will be related to each other and to common reference targets on the Detector Barrels, which will be visible to an external survey system.

Following insertion of the half-barrels, their position will be surveyed by a tracking system, through line of sight along the beam pipe from the A-side. By using targets on the End-wheels and on the barrels, the ITS local coordinate system will be related to the ALICE global system, i.e. to the beam axis.

As the quite small angle of view of the inserted ITS from A-side degrades the quality of a photogrammetric measurement, a laser tracking system is preferred.

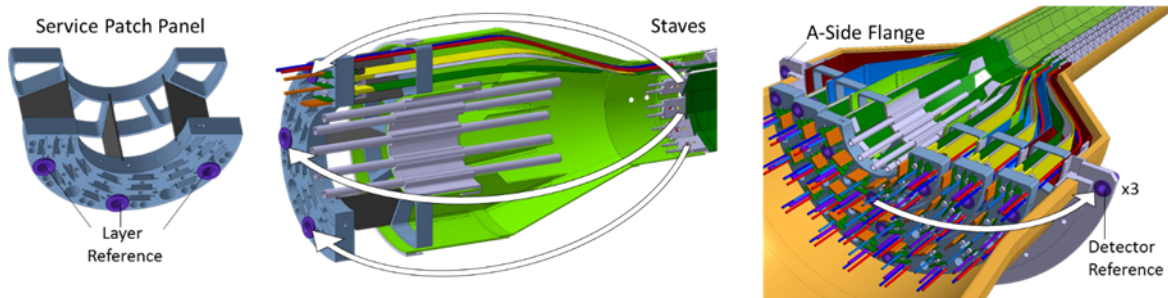


Figure 1.31: IB Detector reference; schematic view.

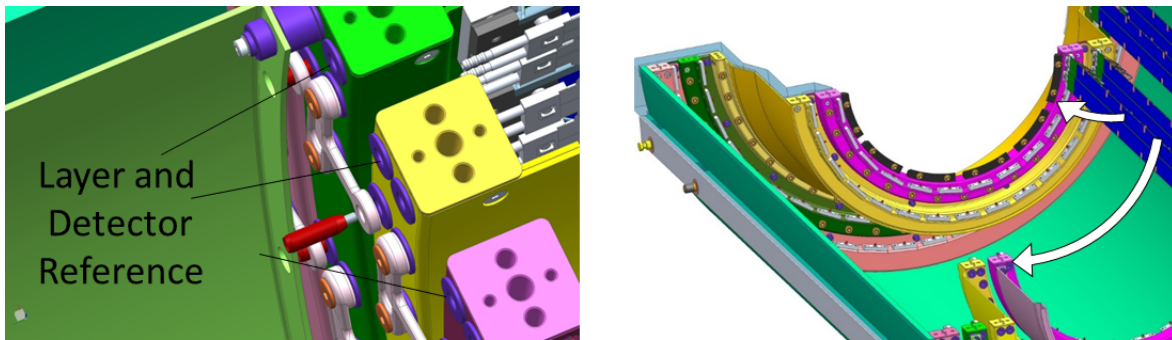


Figure 1.32: OB Detector reference; schematic view.

In the pictures a schematic views of the correlation among the different references are shown. The precision of the measured position of the detectors in the global ALICE coordinate system is determined by the accumulation of the measurement errors in each of the steps described above, for this reason the Pixel Chip position, (chip reference markers) when possible, will be direct related to the last reference elements.

Installation

The Cage, with the beam pipe already fixed and aligned inside, is installed in the TPC. Beam pipe is connected and baked prior to the detector installation. This operation only happen once, the Cage will remain permanently inside the TPC after its installation. While removal of the cage is in principle possible, it would imply the opening of the beam pipe vacuum (i.e. moving the TPC).

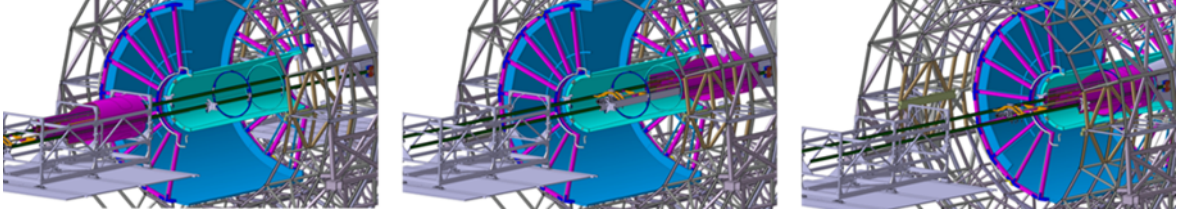


Figure 1.33: Cage installation
(Left) TPC extract; (Centre) Cage inserted; (Right) TPC re-inserted.

From the parking position, where it is mounted around the beam pipe, outside the TPC, the ITS will be translated over a distance of about 3m to reach its final position, with the innermost layers (L0) at 2.8mm radial distance from the outer wall of the beryllium beam pipe. During the translation, the detector progressively approaches the final radial distance, in order to account for the different diameters of the central section of the beam pipe, and to pass the beam pipe supports. The installation sequence foresees the insertion of the MFT barrel followed by the ITS Outer Barrel and the ITS Inner Barrel. The two half-barrels (up and down) slide separately on the rails, forming a hermetic structure when they reach the final position.

The rails are designed to keep the axis of the half-barrels parallel to the beam axis at all times.

This avoids interferences during the installation. In the last few centimetres of translation along the z-axis, the half-barrel approaches the beam pipe with a radial movement to reach the final position.

The accurate positioning of the half-barrels in z is provided by precise mechanical stops located at the end of the translation route and the possibility to adjust the rollers positions.

Stability

To ensure that the detector position does not change in time, active monitoring of some elements of the ITS will be required during its operation. The construction of the ITS and its location within ALICE limits the choice of the monitoring techniques that can be used. On the C-side, where access is prevented by the hadronic absorber, a fixed measuring device will provide the measurement of the position of the targets on the Detectors Barrels. The relative position of the ITS and the TPC will be monitored by an optical system.

These metrology and survey data serve as starting points for the final alignment, based on the reconstruction of tracks. The continuous tracking of the barrel position can be used to crosscheck the possible relative displacement of sensors made evident by the tracks reconstruction, caused by displacement or deformation due to external factors e.g. vibration, thermoplastic movement and settling of different parts. The alignment process must therefore be repeated periodically.

Chapter 2

Outer Layers Stave assembly

2.1 Overview

This chapter focus on the project developed for the assembly of the Outer Layers Stave at Istituto Nazionale di Fisica Nucleare (INFN) of Turin.

The Outer Layers Stave assembly is split in several steps, most of them carried out under a Coordinate-Measuring Machine (CMM) to reach the required precision for the chips positioning in the Stave and to provide their final metrological survey after the assembly.

The assembly steps are:

1. HS assembly
2. Stave assembly
3. Metrological survey
4. PB connection
5. Stave test
6. Stave validation

These steps are performed in a clean room with controlled temperature, $20\text{ }^{\circ}\text{C} \pm 1^{\circ}\text{C}$ and humidity at $50\% \pm 5\%$.

The first three steps are crucial to the precise positioning of the 196 chips that constitute a Stave.

The chips are aligned in two rows of 7 units and connected to the FPC to form a module (2x7 chips). This phase was not covered by this work as responsibilities of different groups, CERN and INFN Bari.

Seven modules are then aligned and glued to a Cold Plate to form a Half-Stave. Sequentially two Half-Staves are glued to the Space Frame to form a Stave. The Half-Stave and Stave precise construction are the object of the work presented in this section as well the final measurement of the 196 chips position for the full Stave characterisation.

In order to get the nominal position of a general components, reference elements have to be identified on each component (Module, HS and Stave) and defined in a Reference System,

The steps of the assembly procedure will be described in a dedicated section where the corresponding tools will be detailed, while the CMM and the main programs developed for the assembly will be described later in this section.

2.2 Outer layers Stave concepts

A brief description of the main characteristic for the Outer Layers Stave assembly procedure is shown in this section, while an extended description is detailed in section 1.2.4.

The Outer Layers consists of two cylindrical layers, Layer5 and Layer6, 42 and 48 staves respectively, coaxial with the beamline and symmetric respect to the interaction point (Drawing in Appendix A).

The OB Stave is composed by two Half-Staves glued by a large number of U-legs to the same Space Frame. Each Half-Stave consists of 7 modules aligned and positioned on a 1.5 m long carbon support, the Cold Plate. 14 (2x7) chips, connected to a common Flexible Printed Circuit by wire bonding, realise a Module. Modules are connect between them by a flexible bridge and are connected by cross cable to the Power Bus.

The two Half-Stave are called Upper and Lower HS based on their position on the Space Frame.

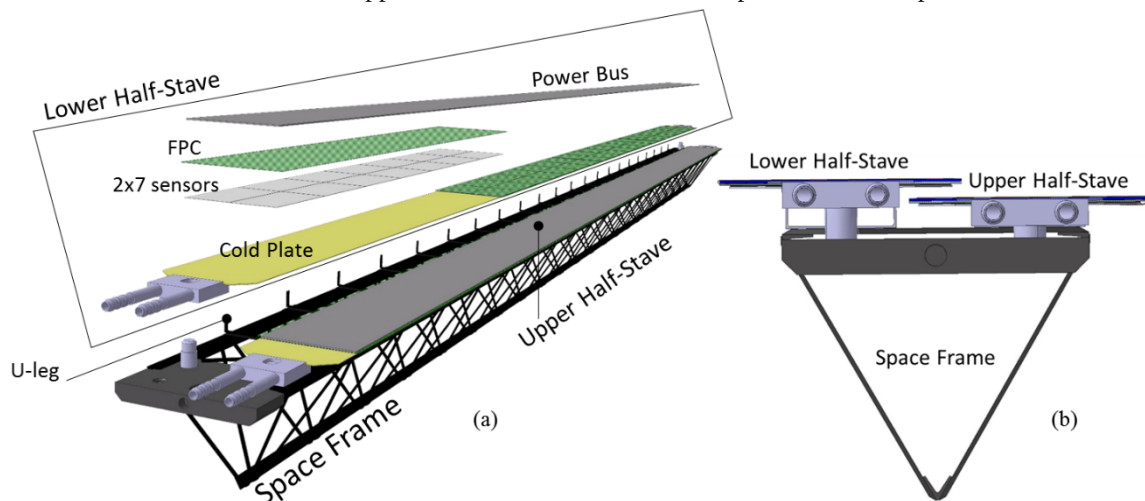


Figure 2.1: Outer Layers Stave, overview.
(a) Isometric view; (b) front view.

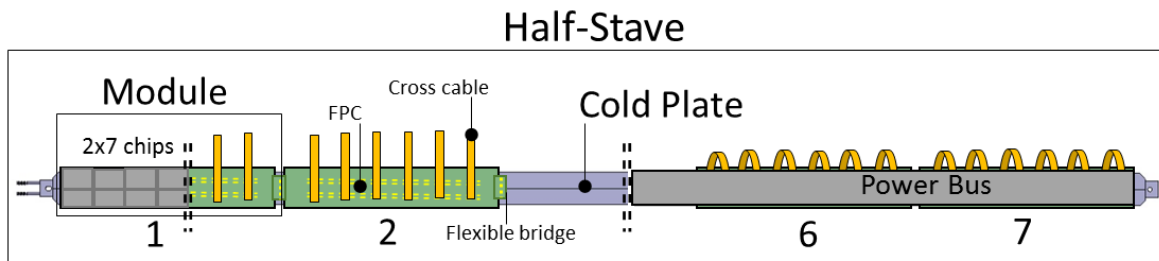


Figure 2.2: Half-Stave, overview.

2.3 Reference System definition

The starting point for the assembly procedure is the definition of a Reference System (RS). Three RS have to be defined: one for the Half-Stave assembly, one for Stave assembly and one for the Stave metrological survey. These are the RS used for the assembly of all the Staves.

2.3.1 Reference System for Half-Stave assembly

The Half-Stave is assembled on a tool base called HS Removable Base. The Reference System is on the base and it is independent from the Cold Plates, which, for their length and lack of rigidity, cannot be considered as a reference.

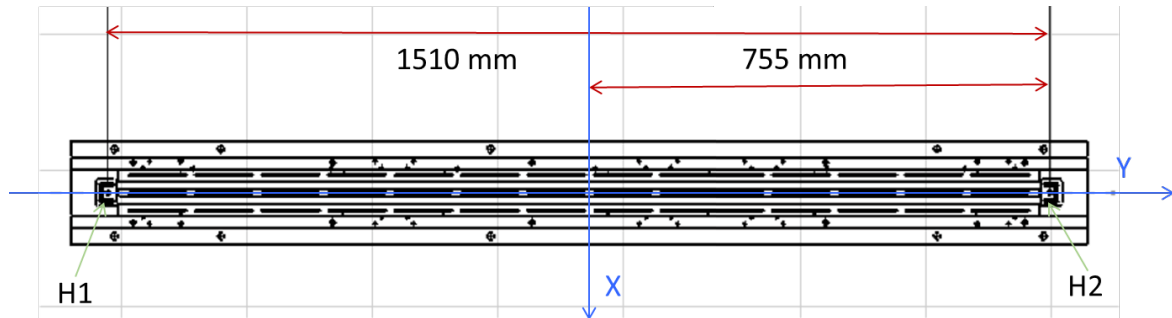


Figure 2.3: Reference System for Half-Stave assembly.

Y axis, aligned with longitudinal direction, corresponds to the line which connects the two pin holes H1 and H2, machined on the Base, X axis is theoretical defined by CMM as perpendicular to Y axis. The Z axis is perpendicular to XY plane (defined as top plane of the HS Removable Base, measured with touch trigger and optical probe and machined with a required planarity of less than 50 μm along full stave length). The system origin has been chosen as the point at 755 mm from H2 along Y.

HS Removable Base

The HS Removable Base is used as CP support and it is the reference for XY plane, materials used are stainless steel (AISI410) and Teflon⁶. [8] The main property, which drive the selection of stainless, has been the low CTE parameter (9.9 $\mu\text{m}/\text{m}/^\circ\text{K}$) while the Teflon has been chosen to avoid undesired adhesion of the parts to the base during the gluing processes.

The base is equipped with vacuum to hold the CP in plane and it is removable to allow the module to module connection step under a microscope positioned on a near worktable. Two bases are used to speed the assembly procedure, when a Half-Stave and its base is under module to module connection procedure, the other base is used to assembly another Half-Stave.

⁶ PTFE=Polytetrafluoroethylene, CERN provides plates composed by a layer of metal (bondable) and a layer of Teflon made through a particular chemical process.

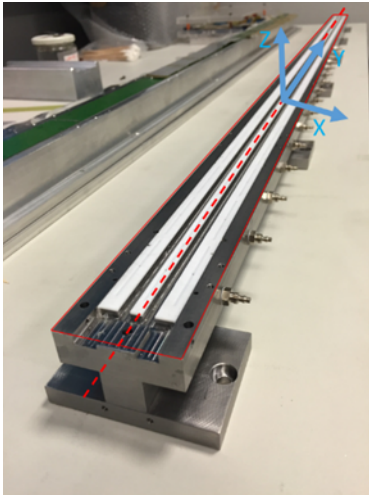


Figure 2.5: HS Removable base.
On the base a schematic view of the
Reference System is shown.

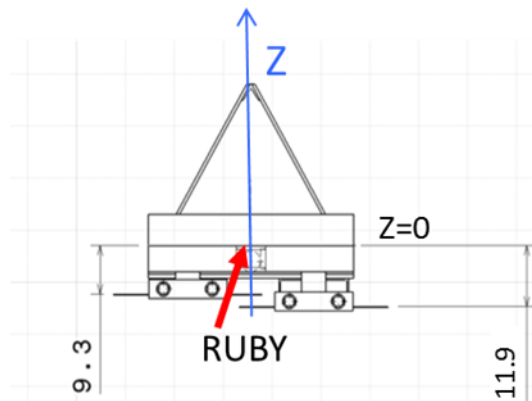


Figure 2.4: Reference System for Stave assembly; lateral view.

2.3.2 Reference System for Stave assembly

Ruby spheres and ruby pads mounted on Space Frame Support (Figure 2.7) maintain Space Frame in position and define an ideal Reference System. These ruby spheres are mounted on ruby pads, one on each side. The Y direction is the line which connects the rubies. The Z direction is defined by the two planes of the ruby pads and it has a positive upwards direction. The system origin is at 770mm from one ruby.

The two HS, once rotated, are glued to the Space Frame at two different offsets by U-legs. The CP plane of the Lower HS stays at -11.9 mm from the Z=0, while the CP plane of Upper HS stays at -9.3 mm (Figure 2.4). Both the HS central axis stays at 12,9mm from the Y axis of the RS.

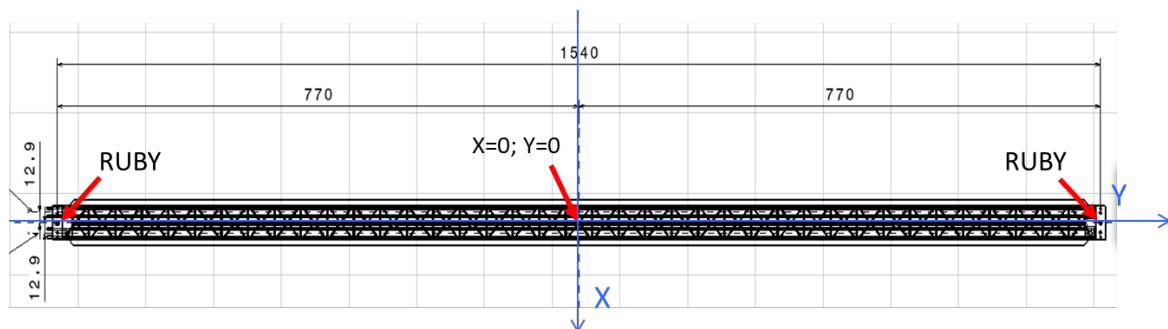


Figure 2.6: Reference System Stave assembly; top view.

Space Frame Supports

Space frame Supports are two columns used to hold the Space Frame during stave assembly, they are made of stainless steel and equipped with ruby pads; these ruby pads are placed in position with reference mask; same reference mask will be used in all assembly sites.

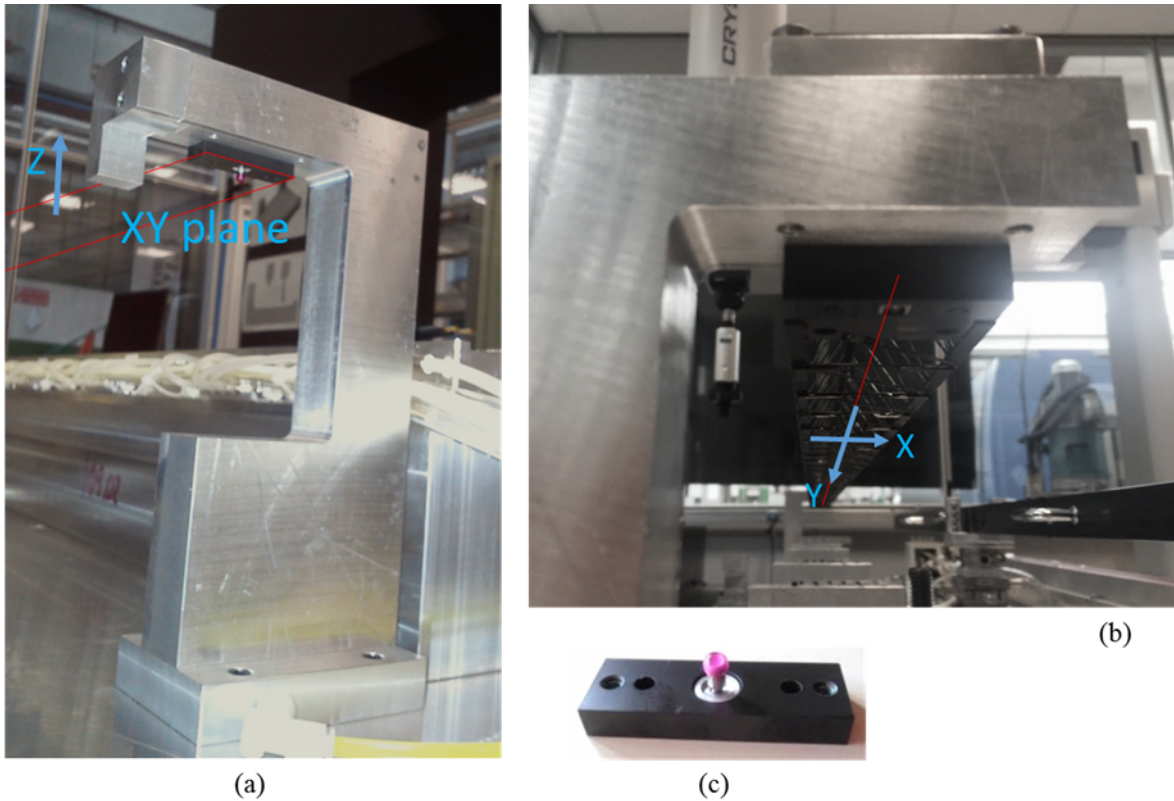


Figure 2.7: Details of Space Frame Support
(a) XY plane definition; (b) X and Y axis definition; (c) ruby sphere mounted on a ruby pad.

2.4 Half-Stave assembly

For the Half-Stave assembly the procedure is divided in the following steps:

1. Cold Plate positioning
2. Glue deposition
3. Module alignment(x7)
4. Metrological survey of reference markers
5. Module to Module connections

For each Module the glue deposition and Module alignment steps are done together due to glue curing time, then glue deposition and Module alignment steps are repeat seven times, one for each module, using a determinate module sequence, as described in the glue deposition section.

Following section will describe each of these steps and when necessary tools and jigs used in these step are described.



Figure 2.8: Half-Stave during assembly using dummies modules

2.4.1 Cold Plate positioning on the HS Base

The Cold Plate is a flexible carbon fibre structure, it cannot be used as alignment reference and it must be positioned in the area covered by the chips. The position is defined by mechanical stops. First the two dowel pins of H1 and H2 holes are inserted, then the other ones that correct the lateral positions of CP. Therefore the CP is fixed to the base by vacuum for the whole procedure, while lateral dowel pins are removed. The time needed to Cold Plate positioning is ~10 minutes.



Figure 2.9: Cold Plate in position; with vacuum and dowel pin of H1.

2.4.2 Glue deposition

The goal is to cover most of the chip surface for mechanical support purpose avoiding glue reflow between chips and out of the module. ECCOBOND 45W1 has been chosen based on the compatibility with CERN requirements due to long experiences in the use in the detectors at CERN. [9]

Main characteristic of the glue are:

- controlled flexibility epoxy adhesive
- semi rigid formulation: 50% ECCOBOND – 50% CATALYST
- can be cured at room temperature (8-24hrs)
- Reliability in an under radiation environment.

Procedure and tools

Seven glue sticker, one for each module, are positioned on the Cold Plate, its goal is to control glue deposition. These masks are inserted using a dedicated mask positioner (Figure 2.11.Left), vacuum and dowel pins are used to hold the mask on the positioner; when the positioner is on the HS Removable Base the vacuum and dowel pins are removed and the sticker side of the mask is glued on the HS Removable Base.

The procedure starts with the alignment of the module 4 in order to reduce alignment errors respect to the origin (in the middle of module 4).

The masks have a sort of tab in the smart side, used for the extra glue collection and it is also useful to pull the mask out from base after glue spread. The position sequence of masks on the HS Removable Base is shown in figure below.

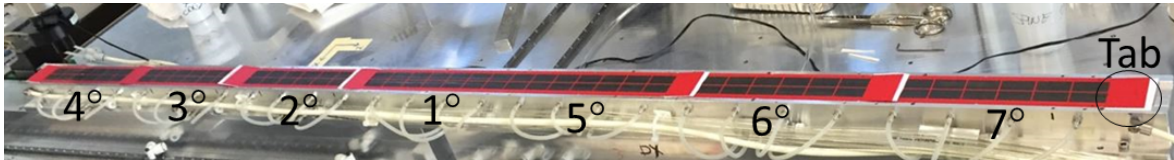


Figure 2.10: Glue deposition sequence and oriented of the masks

From now the attention is concentrate on a single module for its assembly. The glue is inserted on the mask windows thanks to a glue dispenser (Figure 2.11.Centre), composed by a syringe and a holder that are slide along the HS base. A glue-leveling spatula (Figure 2.11.Right) spread glue on the entire window areas and therefore the mask is removed from Cold Plate. At this point it is possible to proceed with to align and to glue the module alignment.

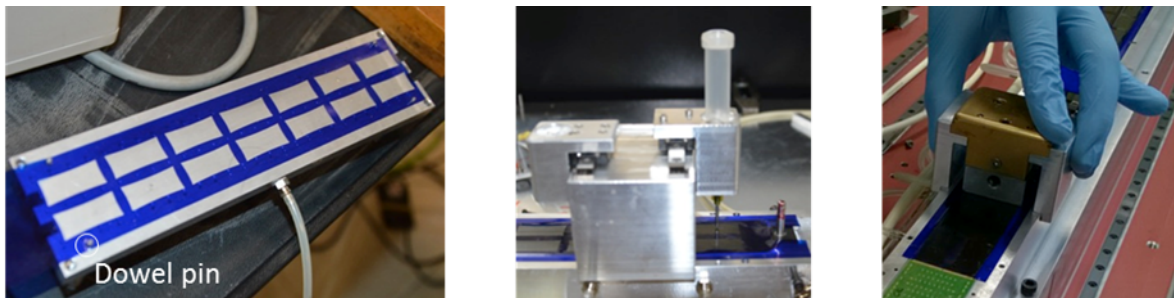


Figure 2.11: Tools for glue deposition procedure.

(Left) glue mask positioned on the mask positioner; (Centre) glue dispenser; (Right) glue levelling spatula.

In order to get efficient spread and covering of glue on the CP a test campaign has been done. During test campaign, Cold plates have been equipped with transparent dummies modules to allow the inspection of the glue deposition. Different mask thickness, different mask windows shapes and dimensions and different weights above the module during curing (useful to maintain module position fixed) have been analyzed.

The final choice of mask type is shown in Figure 2.12, the shape of window mask is rectangular, it allows glue area within 200-300 μm from chip edges; the material is polyvinyl adhesive with a thickness of 90 μm and the weight during curing is around 200g.

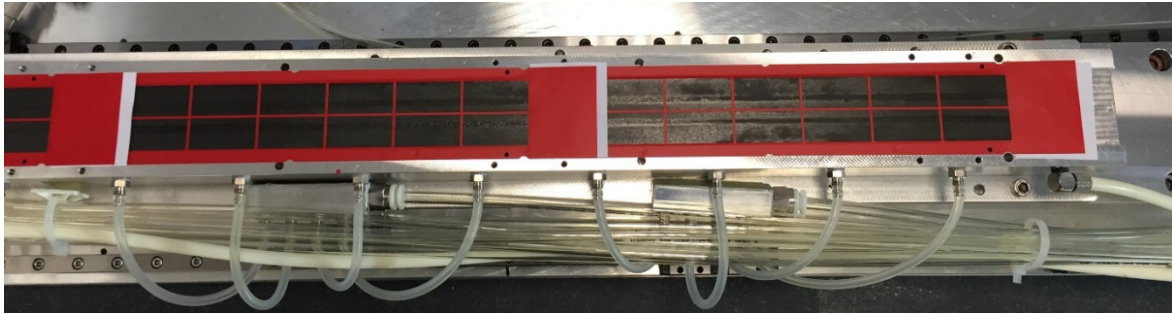


Figure 2.12: The selected mask. Among the several available, for the final gluing.

2.4.3 Module alignment

In each corner of a module a cross is used as reference marker; the nominal positions of these cross markers are used to align the module. Thanks to the optical probe marker of the CMM (green cross in Figure 2.13) the cross marker on the angle of the modules are placed in nominal position. Precise module movement on the corresponding position is done by a tools called Module Gripper and Module Alignment Station.

The module Alignment and positioning requires 5 steps:

- **Rotation of the module around Z:**
This is the first alignment operation and the other ones depend on it.
- **Shift along X:**
Due to first step is useful to align one corner only.
- **Shift along Y:**
It is aligned a corner near module already positioned to prevent modules overlaps.
- **Move down until Module touches the glue on the Cold Plate:**
This movements down is follow by video probe to control unwanted movements.
- **Final position refinement, if necessary:**
Due to glue presence the Module can shift during module bonding, if it happens a final position refinement within limits is done.

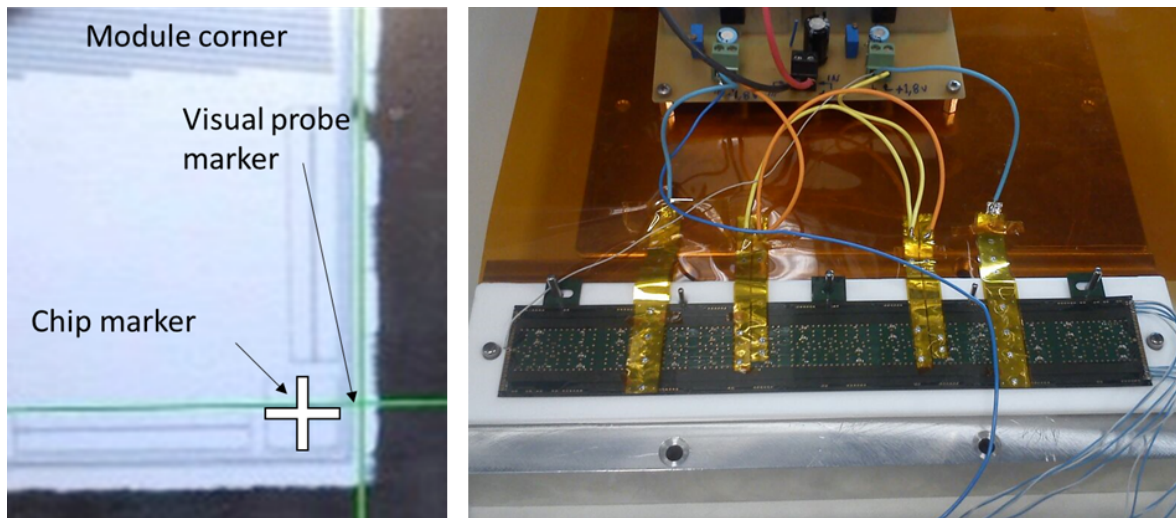


Figure 2.13: Module alignment.

(Left) Picture of optical probe that frames a reference marker of a Module corner; (Right) first real Module aligned

Module Gripper and Module Alignment Station

The Module Gripper is made in aluminum and it holds the module by vacuum. Vacuum holes (or vacuum suction cups) positions depend on the shape of the FPC module. Due to the fact that FPC is under development and the final shape is not yet available final vacuum holes positions is not yet fixed.

To allow a good alignment on Module Gripper, the module is put on a base called Module Box and aligns to Module gripper by two dowel pins; then vacuum system of gripper is on and the Module can be transferred on the HS Removable Base.

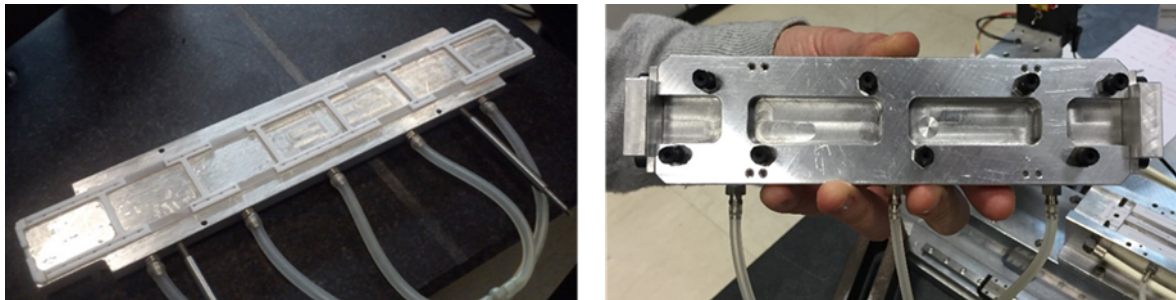


Figure 2.14: Examples of Module Gripper.

In the right picture the latest version with new vacuum holes.

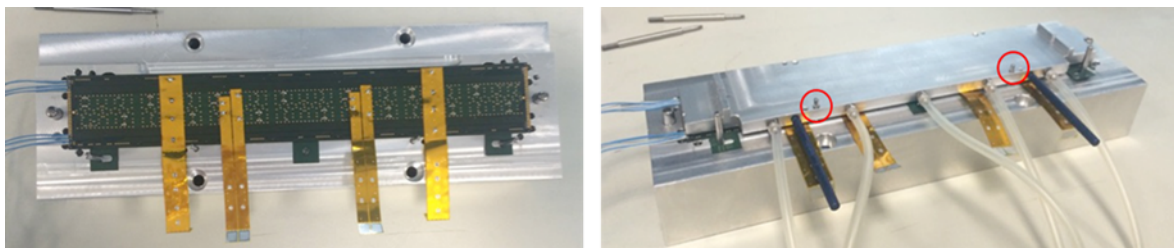


Figure 2.15: Module Gripper procedure.

(Left) Module positioned on the Module Box; (Right) Module Gripper on module, dowel pins shown in red circles.

To align the Module on the Cold Plate, the Module Gripper is fixed by vacuum to the Module Alignment Station support. This station can slides on rails along the HS Removable Base and has a blocks for an approximate positions near the corresponding modules. Once the station is on the position near the module, the module alignment starts.

Module Alignment Station has four motion micrometric stages, they permits a module alignment within 20 μm precision. On the top of Module Gripper there is a micrometric stages for rotation along Z, while on the base of station for translations along X, Y and Z ones.

An electronic safety device on the top of station is used to control the Module slope; four red lights, which correspond to 4 corners of module are on. Once one side of the module touch with a determined pressure the CP, its light is off; the module is considered in position when all four lights are off.

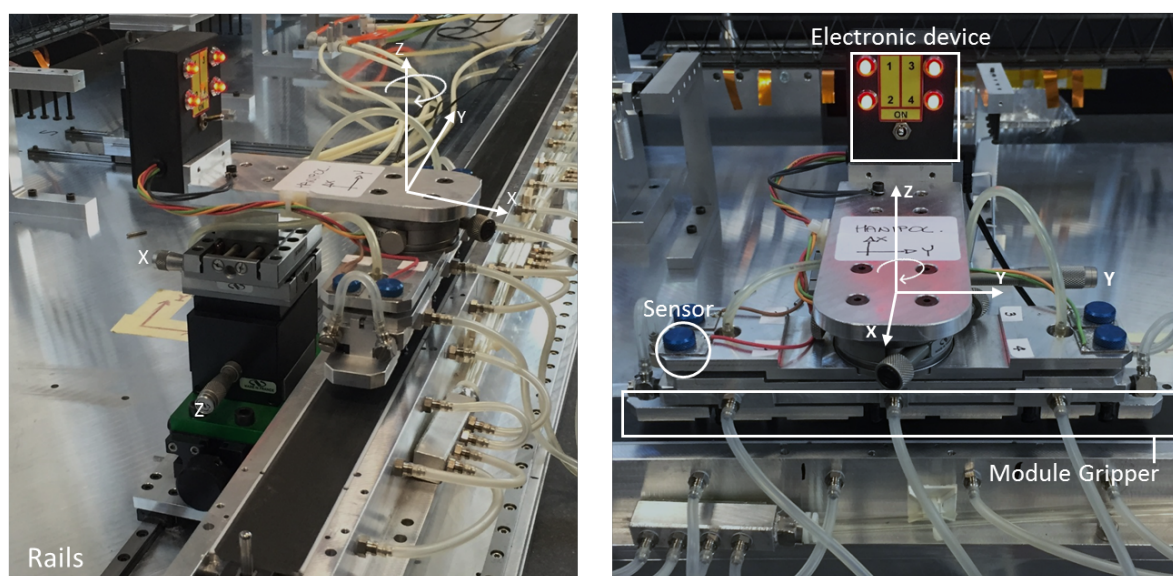


Figure 2.16: Module Alignment Station with Module Gripper.
(Left) Isometric view; (Right) front view.

2.4.4 Module to Module connection

Modules are interconnected by means of flex bridges soldered to pads present on each edge of an FPC. Each bridge is made of a single layer kapton flex circuit hosting a certain number of lines, aimed to connect differential pairs from adjacent modules. These bridges are double sided circuit. Lines run on top and bottom layers and are connected by through-vias.

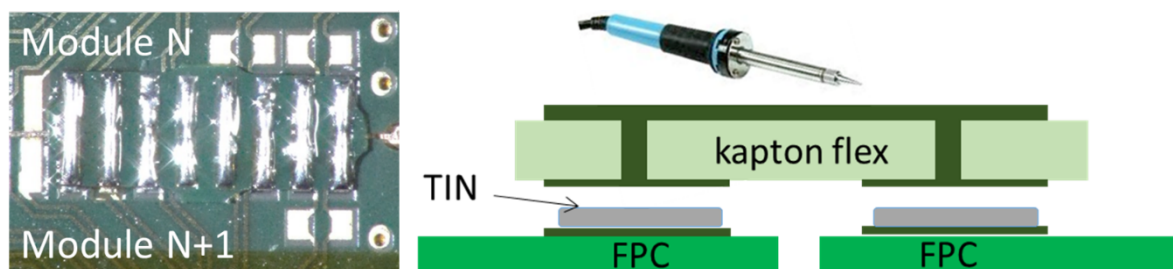


Figure 2.17: Module to module connection.

Bridges are placed on the adjacent FPCs and are aligned with respect to those. After accurate alignment the bridges are tin welded to the solder pads on the FPCs. Melted tin flows through vias and get the bridge soldered to the FPC. Tools to align the bridges and test the electrical continuity between modules are being developed.

2.5 Stave assembly

Each HS is picked up and rotated to be located under the space frame. The two Half-Stave are aligned in nominal position under Space Frame; first of all Upper HS is aligned.

Stave assembly can be divided in the following steps:

1. **HS rotated and placed under Space Frame:** the HS is picked up and rotated to be put under the space frame by means of the jig called Handling Bar.
2. **HS aligned in Stave Reference System:** thanks to CMM and using a reference markers for HS, Half-Stave is aligned by using the Handling Bar, details about this procedure is shown in section below.
3. **HS glued to Space Frame:** glue used is a 2-component epoxy with long work time (around 80 minutes) while the curing time is 7 hours.

Same steps are repeated for Lower HS; it has been estimated that the time to complete this assembly is around 2 working days, one for each Half Staves assembly.

2.5.1 The Handling Bar

The Handling Bar is used for Half-Stave manipulation, it has to keep the HS flat (which ideally corresponds to XY reference plane) and put Half-Staves in the nominal position under Space Frame. Therefore, this tool is used to transfer the HS from the first Reference System to the second one.

The bar is composed by carbon fibre material and it is equipped with suction elements, vacuum tubes and feet to fix it to the HS Removable Base (Figure 2.18).

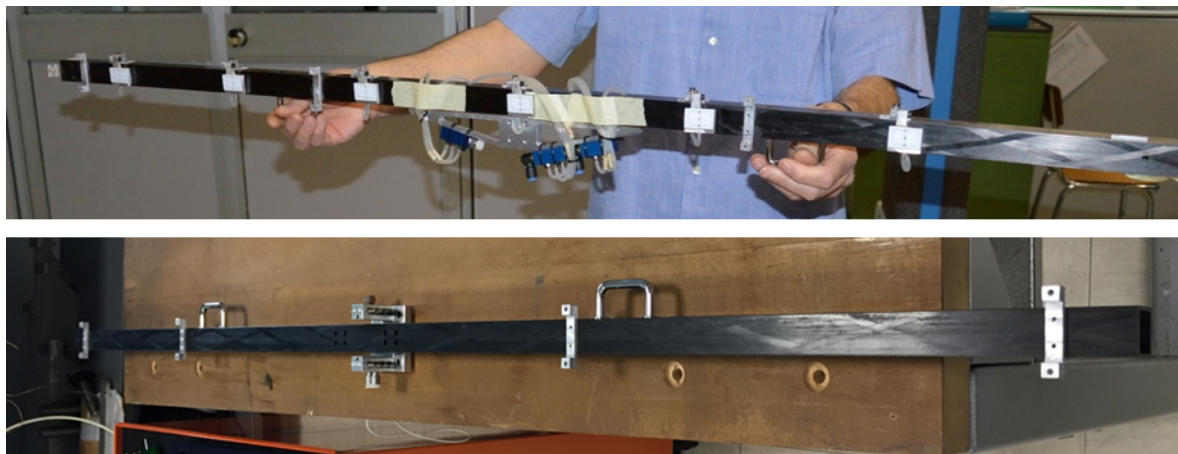


Figure 2.18: Handling bar.
(Top) The old prototype; (Bottom) the new prototype.
Prototype on whole bar are ready and final validation test is ongoing.

When Handling Bar is fix to the HS Removable Base, the suction elements are adjusted with screws to perfectly fit the Cold Plate plane and then the vacuum system of the bar is on. Several shape of suction elements

has been taken into account, the presents one that ensure the best grip is shown in Figure 2.19.b. Unfixing the feet of the bar and switching off the vacuum system of the HS Removable Base is then possible to move the HS without loose XY reference plane.

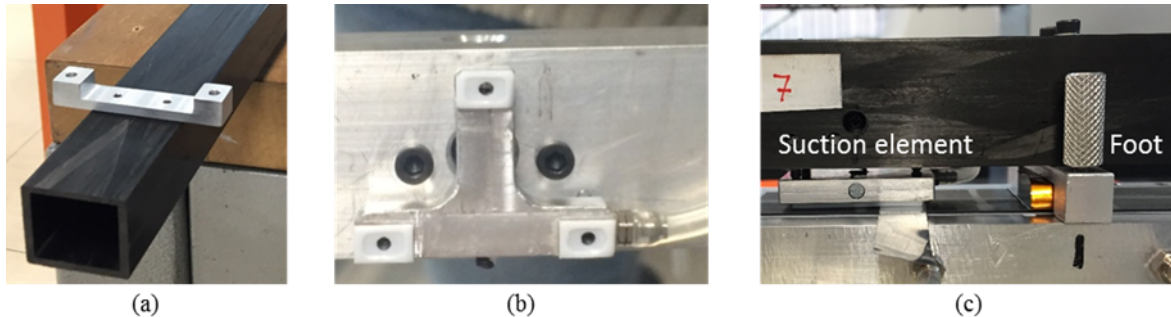


Figure 2.19 : Details of Handling Bar.

(a) One of the four feet bar; (b) last prototype of suction element; (c) the bar on the HS Removable Base.

2.5.2 Stave Alignment Station

The Handling Bar is held on the Stave Alignment Station, its XY plane orientation is pre-aligned with XY plane of RS of the Space Frame Support; however corrections are possible playing with suction elements. The station has four motion micrometric stages for HS alignment within 80-100 μm precision, for rotation around Z and for translation around X, Y and Z (Figure 2.20).

The Stave Alignment Station slides on rails to place HS under Space Frame and also it has a block to a first Half-Stave alignment before to place the HS under Space Frame.

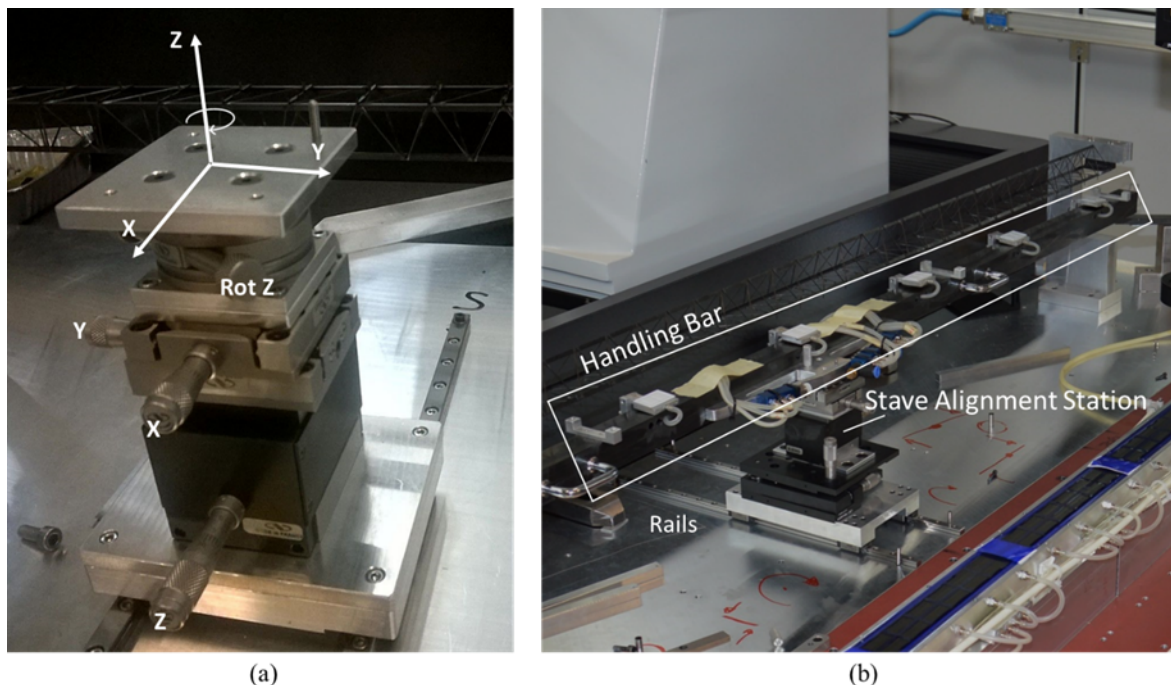


Figure 2.20: Stave Alignment Station and micrometric stages:

(a) Rotation around Z and translation along XYZ; (b) old station with Handling Bar inserted.

2.5.3 HS alignment and glued

As anticipate before, the Cold Plate plane should be pre-aligned with the XY reference plane, however in a middle position that has 20 cm offset in X from Stave RS, the CP plane planarity and alignment with reference plane is controlled and then insert under Space Frame to the final alignment (this step can be jump in the future if it will be considered not necessary).

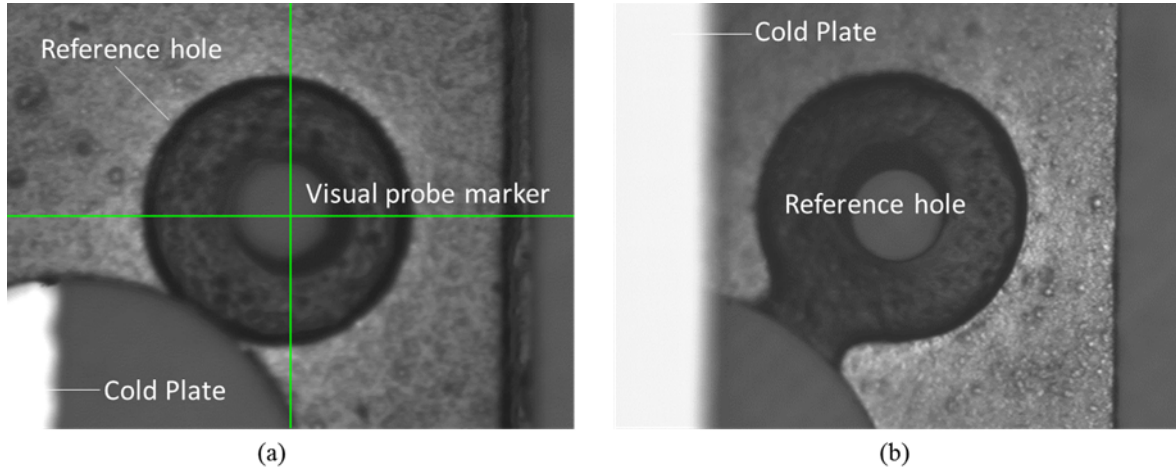


Figure 2.21: Reference hole on the FPC:
(a) FPC hole from top; (b) FPC hole from bottom

Being the reference markers on chips no more visible at this stage, a new reference visible at any assembly step has been chosen. These new references are holes on both sides of each FPC. The ideal positions of these reference holes in the Stave reference frame are calculated and HS is aligned to match this positions.

Once HS has been aligned, U-legs are glued to the Cold Plate by 2-component epoxy glue with working time around 80 minutes and a curing time of 7 hours.

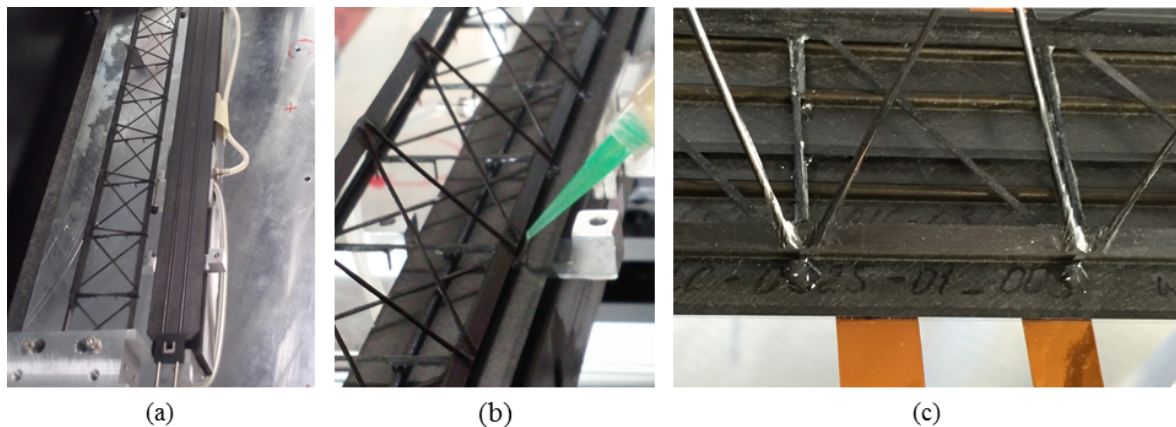


Figure 2.22: HS alignment and glued.
(a) HS alignment; (b) deposition of glue; (c) Half-Stave glued.

2.6 Metrological Survey

Metrological Survey have to be performed after HS assembly and after Stave assembly. This survey permits to have at for each assembly steps the real position of the chips, and perhaps to correct the error due to assembly.

After the Stave assembly, the Space Frame is rotated and almost all the chip markers are visible through the specific holes in the FPC (except the hidden holes due the HS overlap).

A final metrological survey will be saved in a database and used for the calibration of the detector.

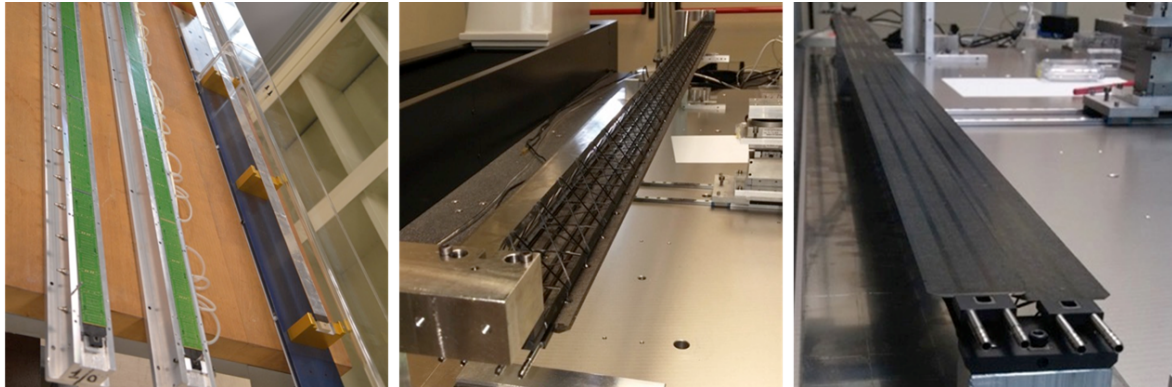


Figure 2.23: Metrological Survey.

(Left) On the HS Removable Bases; (Centre) on the Space Frame supports; (Right) on the last metrological survey station.

2.7 Power Bus soldering and folding

After the last assembly and measure, a dedicated jig is used in which Power Bus will be soldered.

Cross cables and Power Buss are soldered by tin soldering procedure, each cross cable has four point of soldering and the diameter of pads size on the Power Bus is 3 mm. Figure 2.24 shown a prototype of soldering station with a dummy Module and a piece of dummy Power Bus cable; dowel pins are used to align the PB.

Finally the two Power Bus are folded onto HS, this procedure is under development, a present option is to use jigs with a clips shape to maintain Power bus folded onto HS. From now the elements can be considered Stave.

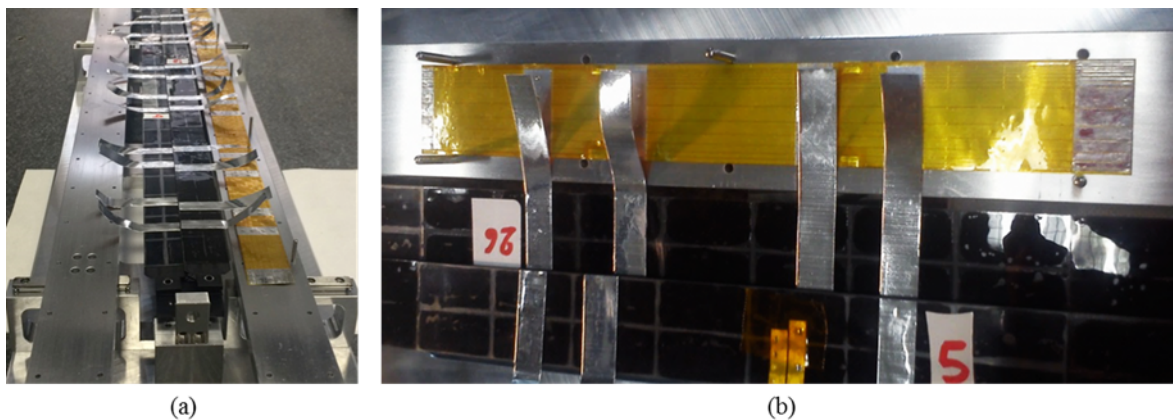


Figure 2.24: Prototype of soldering station.

2.8 CMM machine program

INFN of Turin has the responsibility of Outer Layers Stave assembly procedure and it coordinates the activities of the other assembly sites, which are:

- Laboratorio nazionale di Frascati (LNC) in Italy;
- Laboratory of Daresbury (United Kingdom);
- National Institute for Subatomic Physics (Nikhef) in Netherlands.

The Lawrence Berkeley National Laboratory (LBNL), in USA, perform the assembly of the two Middle Layers (with shorter Half-Staves, composed by 4 modules instead of 7), utilizing (and scaling) the same procedure used by INFN of Turin.

In order to guarantee the correct nominal positions and to reduce the risks of human errors during module alignment, a number of semi-automatic programmes for the CMM has been developed for this thesis work. The programmes allow to operate always in automatic mode, or, when needed, leave the possibility to continue in manual way. These programmes will be used in all the production sites, where compatible with the CMM, otherwise, they will be used as guidelines for not compatible CMM.

The Coordinate-Measuring Machine and tools chosen for the assembly is the Mitutoyo CRYSTA Apex S 9206, with a stroke of 2000mm x 900mm x 600mm, a touch trigger probe, an optical probe with objective 10X, and autofocus. [10] The contact-type probe (touch trigger probe) takes measurement touching the element to be measured while optical probe can detects edges, points and holes from images data of workpiece magnified by CCD⁷ Camera. This is extremely useful for measuring elements which cannot be measured using a contact-type probe and objects that cannot be subjected to any measurement force.



Figure 2.25: The Mitutoyo tools for assembly and metrological survey.

On the left picture is shown the Mitutoyo CRISTA Apex S9206 machine, while on the centre, the vision probe and on the right, the touch probe. The video probe used is Mitutoyo Quick Vision Probe (QVP), the touch trigger probe is Mitutoyo TP200; they are attached at a Motorized Probe Head (Mitutoyo PH10MQ) that control the position of the probes. [10]

⁷ Charge Coupled Device technology

2.8.1 Reference system programs concepts

A CMM has its reference system called Machine Reference System (MRS), while to create the RS of the Half-Stave, a detailed procedure has to be followed and will be hereafter described; the same applies for the definition of the Stave RS.

RS-200 is load by a semi-automatic program called Localisation_Base1 that put the video probe close to the elements that define the reference.

The automatic program Alignment_Base1, allows to define the RS-202 that has better accuracy, starting from RS-200. The RS-202 is the one used during HS assembly.

Every time that the machine is turned on, the program Alignment_Base1 must be reloaded to create the RS-202.

Indeed, in case of unexpected event (large temperature variation, accidental hit of the probe, or human errors, etc.) the program Localization_Base1 is reloaded to mount RS-200 based on the semi-automatic procedure; because the probe is not any more calibrated.

Usually the reference elements, H1 and H2, used to define the RS-200 and RS-202, are covered by the Cold Plate. It is necessary then to create a temporary Reference System (RS-200temp and RS-202temp), visible by the optical probe during each step of the assembly, which by translation and rotation offsets will lead to the final RS for each program.

The translation and rotation values between a temporary and a final RS are calculated by trigger probe, and each HS Removable base has its own proper values.

The XY plane (the base top surface) is the same for RS-200temp (or RS-202temp) and the final one RS-200 (or RS-202), while the origin and the Y axis direction are different. For the temporary one they are defined by dowel pin holes on the side of the HS Removable base.

Knowing the distances from the final one to the temporary one, it is easy to switch between them.

For what concern Stave assembly, the semi-automatic program is called Localisation_Ruby that mounts RS-210 and the automatic program is called Alignment_Ruby that mounts RS-212.

The XY plane of the temporary Reference Systems for the Stave assembly (RS-210temp or RS-212temp) is create by using the plans of the ruby pads fixed on top of columns tools. The origin and the Y axis direction are defined by holes on these ruby pads.

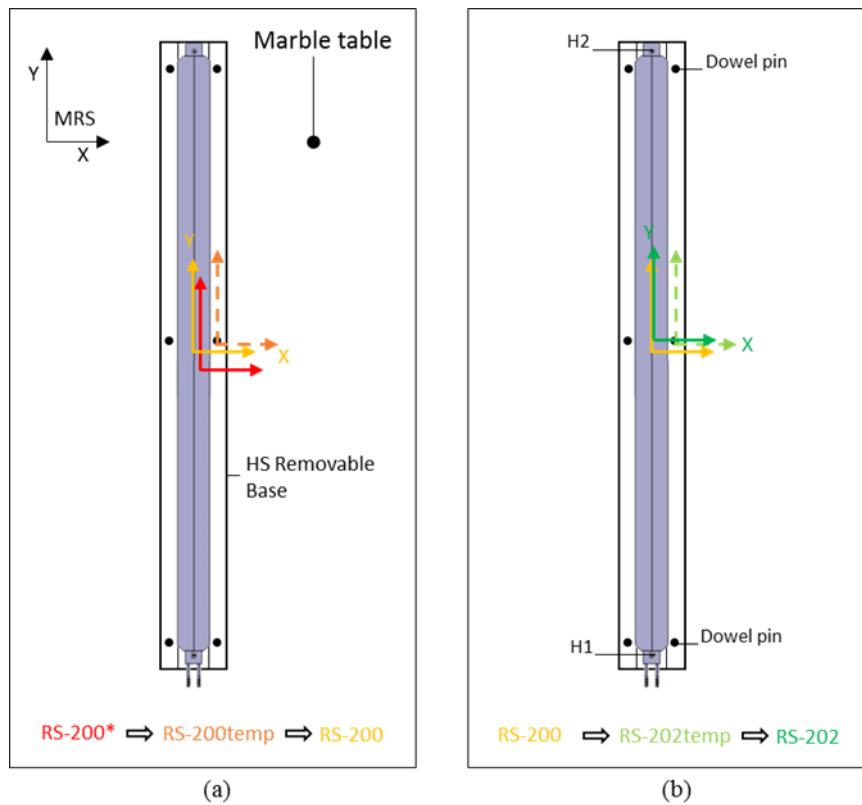


Figure 2.26: HS programs for the Reference Systems, overview:
 (a) Localisation_Base1, semi-automatic; (b) Alignment_Base1, automatic.
 RS-200* is the one that has lost the calibration.

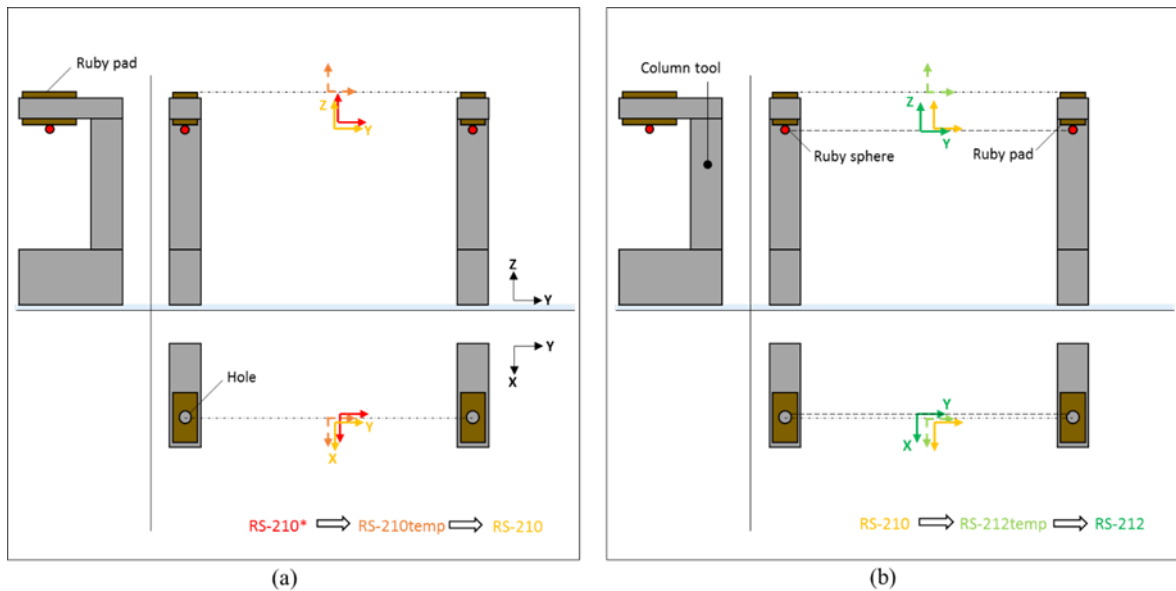


Figure 2.27: Stave programs for the Reference Systems, overview:
 (a) Localisation_Ruby, semi-automatic; (b) Alignment_Ruby, automatic.
 RS-210* is the one that has lost the calibration.

2.8.2 Module alignment program concept

The programme starts calling RS-202 as Reference System of overall alignment; the programme has a dialog design window in which user can choose the actions of optical probe in order to have a flexible programme. Dialog design window permits to move the probe in the desired position avoiding obstruction elements, minimizing human errors and accidental hits.

For example if we are aligning the module respect to the rotation in Z, the machine, by measuring point A and point B, calculates the error and moves to the correct position to permit the operator to rotate the module up to the point the target get visible and centred under the probe. After alignment and positioning of all modules on the CP it is possible to save marker positions in an Excel file.

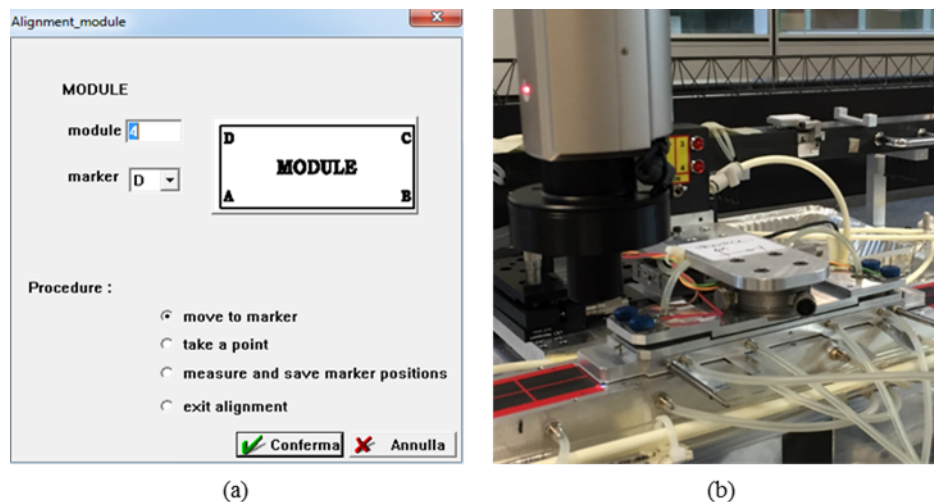
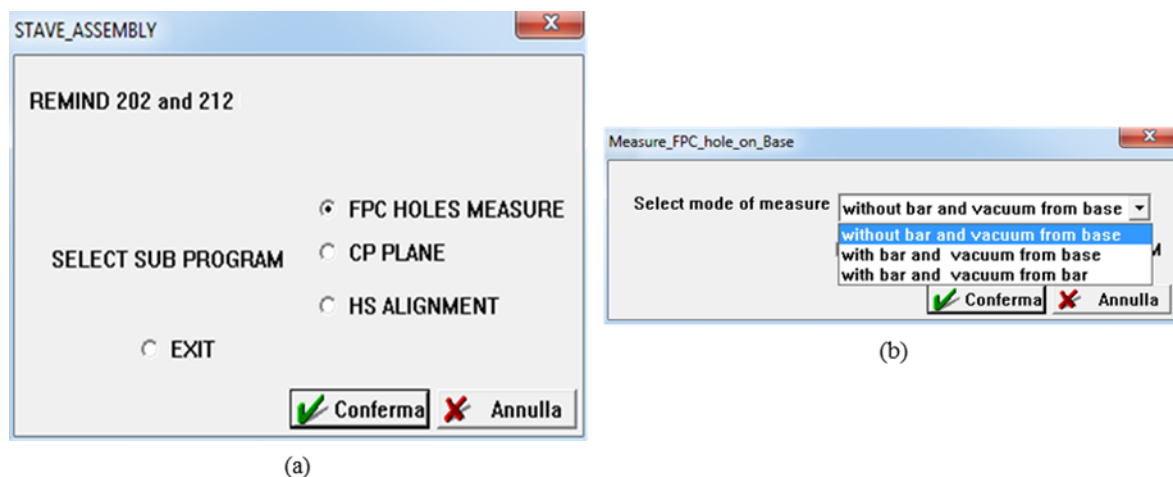


Figure 2.28: Module alignment program.

(a) Main dialog window of program; (b) optical probe and Module Alignment Station during alignment.



(a)

(b)

Figure 2.29: Dialog window of Half-Stave alignment program.

(a) Main dialog window; (b) Dialog window of FPC hole measure subprogram.

2.8.3 Half-Stave alignment program concept

This program is less flexible than the previous one due to the presence of several steps that must not be forgotten. Before starting, both alignment programs for RS-202 and RS-212 has to be run, then a main dialog window appears; this splits the main program in three sub programs that concentrate on three different steps; selecting one of them it is possible to proceed to:

FPC hole measure

Measure FPC holes (used as reference for entire alignment), from HS removable base using RS-202. It's possible to get the positions of the holes in three different stages (Figure 2.29): the first measurement is done with the HS taken by the vacuum on the base, the second is done when the Handling Bar is connected to the HS and the third one when the vacuum is switched from the base to the Handling Bar. The subprograms controls the variations of the position of the different configurations and verify that they are within the acceptable tolerance. All values are stored in an Excel file.

CP Plane

After that the Handling Bar is rotated and fixed to the Stave Alignment Station; that is positioned in the its nominal configuration defined by the blocking point. This program is used to control if the reference XY plane of CP is well oriented with respect to XY plane of RS-212, if not the CP reference plane is adjusted by acting on the Handling Bar suction elements and verify by this program.

HS alignment

The aim of this program is to position the CP reference holes in nominal position respect to the Stave. The positions of markers are already saved in the main program if the main program is not stopped, it's possible to insert values by using a manually insertion.

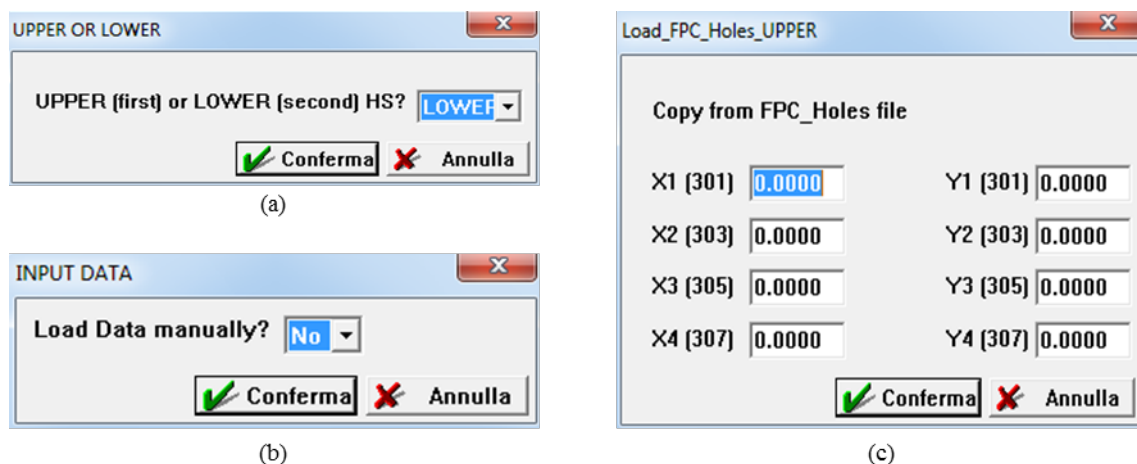


Figure 2.30: Initial dialog windows used in "HS_alignment".
Dialog windows "a" and "b" pop up first, window "c" appears only if data need to be reloaded manually, in that case the program will not allow to insert incorrect values.

The program distinguishes between Upper HS and Lower HS procedures alignment. Due to the Stave layout the access for the measurement is limited at the two external edges of the HSs. Each HS will be aligned by using the accessible reference holes.

The alignment in Y direction (Z rotation) is performed as first step, then the exact position in X and Y (X and Y translation) is achieved and finally the HS is translated in Z nominal position (Z translation). After this last step XY plane of HS is controlled again and it is possible to adjust by playing with suction elements again. Once an optimum condition has been reached it is possible to save the final reference holes positions and proceed to the gluing of the HS on the Space Frame.

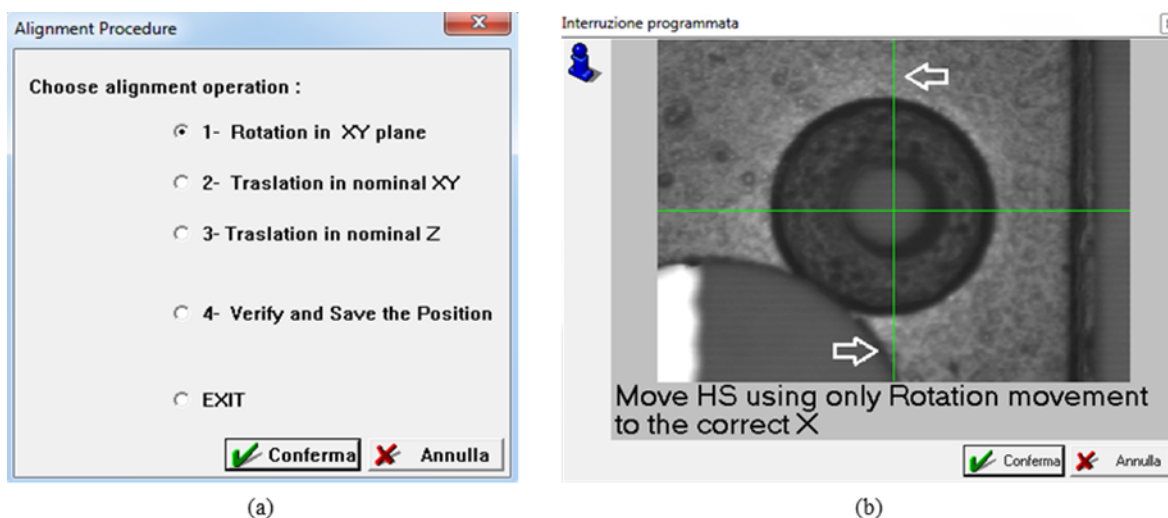


Figure 2.31: View of windows during HS process of alignment.
(a) Dialog window of alignment operation; (b) break window during Z rotation alignment.

2.8.4 Metrological program

Specific programs for the dimensional characterisation of all the jigs used and of all the components assembled have been developed. A full inspection has been performed by using these programs such to ensure that the final assembly is not affected by any out of tolerance in the parts. The measurements are associated to the different components, identified by a serial code, and are stored in a data base. The metrology already performed on several parts has been analysed to have a statistic characterisation of them.

Chapter 3

Detector structures design

3.1 Overview

Structural analysis has been performed for the major components of the ITS Upgrade to verify different loads conditions, stress, deformation, frequency response once installed in the ALICE experiment. Detailed Finite Element Analysis (FEA), validated by experimental test, has been used for the prediction of the behaviour and the optimization of the design of the Detector mechanics.

The component under investigation are:

- Inner Barrel Stave;
- Inner Detector and Service Barrel;
- Outer Detector Barrel;
- beam pipe support;
- Cage structure.

In order to fulfil the challenging requirements for the detector support structures, defined in term of high stiffness and minimum mass, the design of the detector components has been based on the use of Carbon Fibre Reinforced Plastic (CFRP), Appendix C.1..

If from one side the possibility of tailoring the material properties of the CFRP material, depending on the design needs, has made of these materials the ideal choice, on the other side the large materials anisotropy has requested a continuous tuning of the finite element model and of the different material properties used as input. A large test campaign has been used for the experimental determination of the material properties as well to predict then the flexural, torsional stiffness and natural mode of vibration.

The description and results of the analysis performed will be shown in this chapter; detailed results are shown in the Appendix D. The finite element approach followed in the analysis is illustrated here after. Analysis done can be divided in steps:

1. **3D CAD Model:** CATIA, a 3D CAD modelling tools, has been used for the creation of the 3D geometry of the part/assembly. For some analysis it resulted to be easier to redesign the part directly in ANSYS Design Modeler program (next step).
2. **Clean Up and import the 3D CAD Model:** Some features of the 3D CAD geometry may not be that important for the FEA but increase the complexity of meshing drastically. Irrelevant features have been removed from the CAD model, this it has been done either in ANSYS Design Modeler, a 3D CAD modelling tools of ANSYS, or in CATIA.

A further simplification of the solid model has been performed for those parts that, for their shape and function, have been simulated as shell or beam element.

3. **Defining Material Properties:** For each parts material properties have been chosen. Materials used are isotropic materials and orthotropic. For the orthotropic material the definition of the element orientation is fundamental for the correct attribution of the material properties. Beam and shell elements require respectively the definition of cross section properties and the lay-up and thickness.
4. **Meshing:** Meshing 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. With the increase in mesh size, the finite element analysis speed increase but the accuracy decrease. 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 difficulty to generate in an automated manner and it has been performed by using local mesh tools to force algorithm to create a quadrilateral and well defined mesh. Different type of elements or different parts of assembly have been connected using linear contacts to limit the computational time (Appendix B.4).

5. **Defining Boundary and Loading Condition:** Boundary and Loading condition have been defined according to the analysis performed. These conditions have been applied either to geometrical identities (points, lines or curves, surfaces, and solids) or to elements or grids.
6. **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 (Appendix B.5).
7. **Post Processing:** The result can be viewed in various formats: graph, value, animation etc. Results studied in analysis are displacement, stress (Von Mises) for static structural analysis and firsts modal frequencies for modal analysis.

3.2 Inner Barrel Stave analysis

3.2.1 Overview and aim

The stave design and carbon composite lay-up have been optimized based on a finite element analysis and experimental tests.

The two key structural parameters that define the achievable accuracy and stability in the position of the chips are the Stave sagging under its own weight and the first natural frequency of the Stave. The sag provides the information on the deviation of the chips final position respect to the nominal one while the first natural frequency indicates the frequency at which an external impulse can induce resonance phenomena in the structure resulting in oscillations of the chip positions. The sag and the natural frequency for a given mass depend on the Stave stiffness that is mainly provided by the Space Frame.

The Space Frame stiffness is the sum of three contributions: the elastic module of the material used, the shape rigidity defined by the inertia of the section of the Space Frame and finally the boundary conditions, i.e. the rigidity of the connection of the extremities of the Stave to the end-wheels.

The ultralight structure, the geometry relative complexity and the large materials anisotropy have requested a continuous tuning of the finite element model and of the different material properties used as input. The large test campaign and the experimental determination of flexural, torsional stiffness and natural mode of vibration have permitted to optimize the model that will be then used to predict the behaviour of the Inner Barrel Detector. The analysis has been presented in the ITS Upgrade- Stave Engineering Design Review on 3th May 2016 [11].

3.2.2 Model

Geometry and mesh

The cold plate and the embedded pipes are modelled with thin shell elements based on the ratio limit ($D/L < 10$) while the wound Space Frame is modelled using beam elements associated with proper filament section, the connectors at the two extremities are meshed with solid elements.

The ANSYS type elements used are SHELL281 for shell, BEAM189 for beam, SOLID186 for solid elements details about these elements are in Appendix B.3. Shell elements of the Cold Plate have been well orientated because orthotropic materials are present in the lay-up.

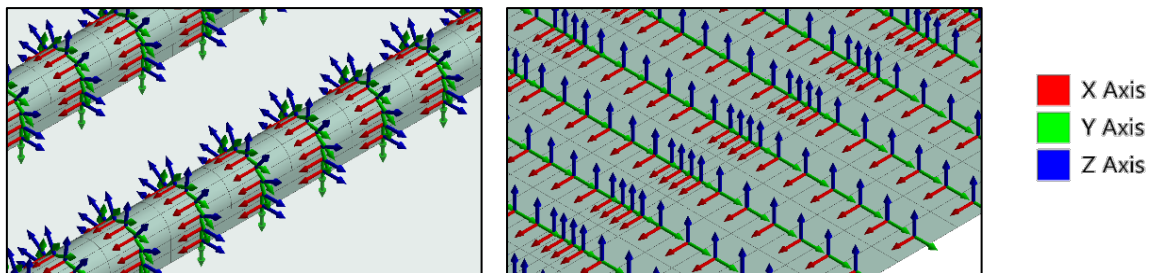


Figure 3.1: Orientation of Cold Plate shell elements.

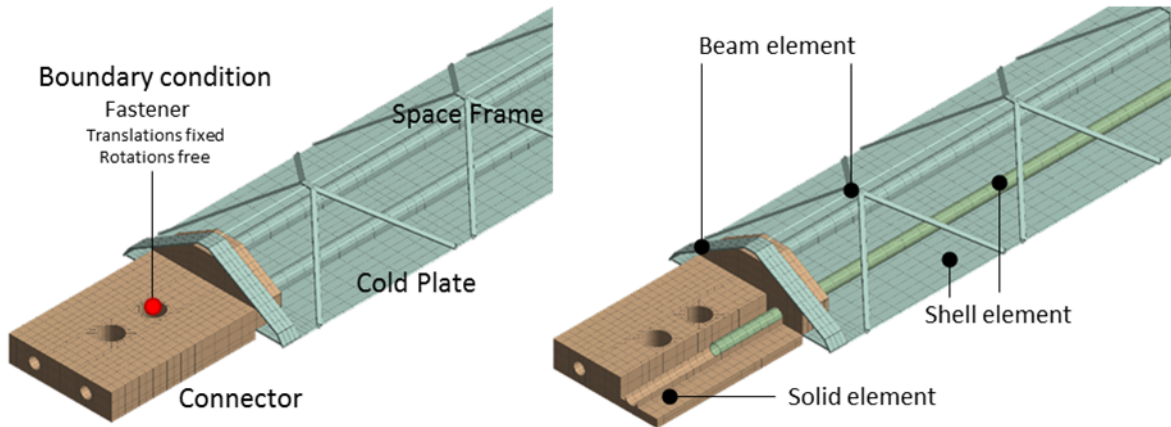


Figure 3.2: Geometry and mesh of Inner Barrel Stave.

Boundary condition and contacts

The two connectors at the extremities of the stave are fixed by bolts that are modelled constraining translations and rotations at corresponding nodes.

For a good correlation with the tests, different boundary conditions i.e. different degrees of freedom (DoF) have been blocked to verify the stiffness of the connection at the bolted interface.

The matching nodes of the beam and the shell have been merged to simulate the glued contacts, while between solid and shell/beam parts pure-penalty contacts has been adopted (Appendix B.4).

The load cases considered consist in the stave mass subjected to the acceleration gravity. For model tuning and direct comparison to test results, additional load cases were considered by assuming a lamped mass of 20g applied at the centre of the stave to simulate HIC. Acceleration gravity imposed is 9.8066 m s^{-2} .

Different load cases were considered by sweeping the direction of the acceleration gravity vector such to consider the stave spatial orientation in the barrel.

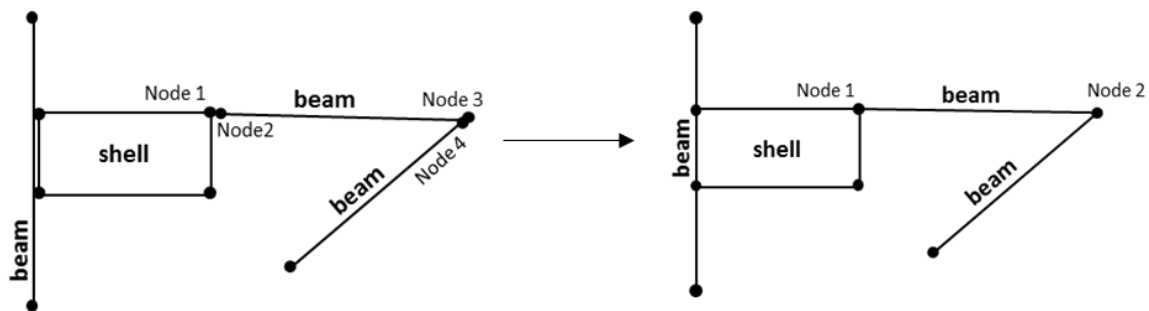


Figure 3.3: Schematic view of the connection between shell and beam elements.

3.2.3 Results

Static analysis

Static analysis had the objective to determine stave maximum sag under the HIC mass load for different stave orientations. The analysis was compared to the test results and the finite element model tuned to match the results. The tuned model was used to optimize the Cold Plate lay-up as well the Space Frame construction

Different boundary conditions at the stave extremities were considered to determine the impact of the fixation at the extremities and to compare this with the real behaviour.

The predicted maximum displacement is for a stave orientation of 0° (gravity normal to Cold Plate plane), under a lamped mass of 20g applied at the centre of the stave is $17\mu\text{m}$.

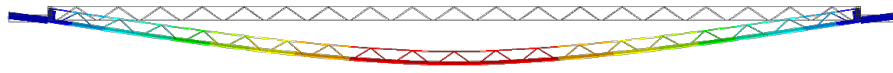


Figure 3.4: IB stave maximum displacement

Modal analysis

Different approaches have been followed to take into account the compliance of such a joint. Either the nodes have been merged and the material elastic properties of the filament reduced, or the nodes have been coupled with 3D spring elements and the K elastic constants tuned to match the experimental results. The modal analysis has been used as a mean to fine tune the finite element model based on test results. A sine sweep test for experimental evaluation of the real final system natural frequencies has been performed.

The sensitivity of the Space Frame behaviour for both IB and OB to the internal constraint (carbon threads connections) and the external boundary conditions (connection at the stave extremities), i.e. to the overall rigidity of the system is reflected in the difficulties to match the correct numerical values for the frequencies above the first natural one. A good correspondence of the modal shapes for the first three natural frequencies has been achieved. Modal shapes for the inner barrel Space Frame (no Hybrid Integrated circuit considered), are shown in Figure 15 with a first flexural mode predicted at the natural frequency of 180 Hz.

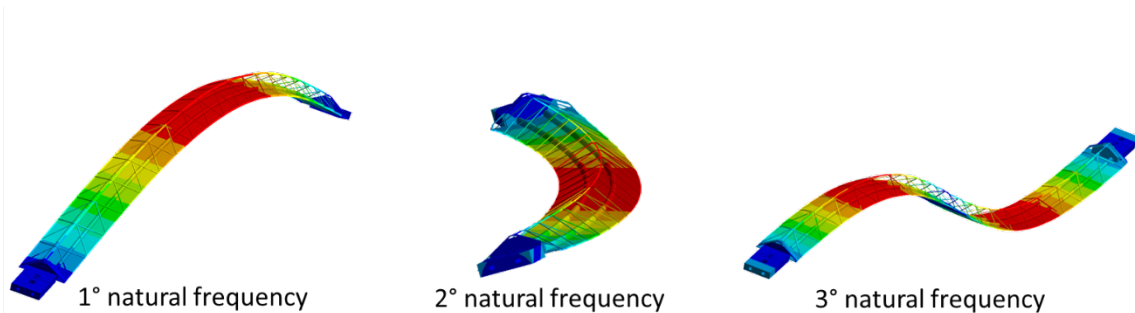


Figure 3.5: IB stave modal frequencies

3.2.4 Prototype

As anticipated in section 1.2.4, the layout of the ITS Stave consists of a Space Frame and a Cold Plates. The Cold Plate is made of a high thermal conductivity carbon fibre laminate embedding polyimide cooling pipes. The chips are glued directly on the Cold Plate by means of epoxy glue (Eccobond 45).

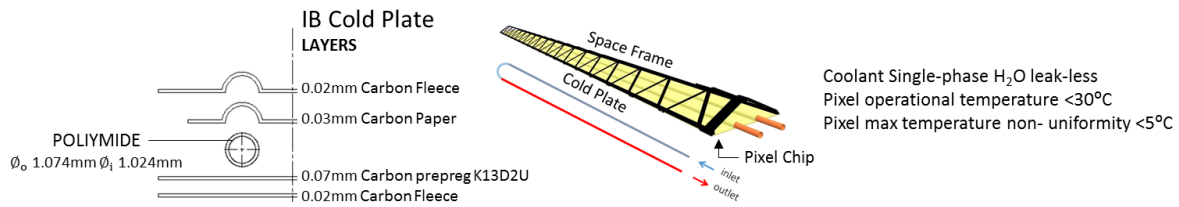


Figure 3.6: IB Stave, schematic view.
(Left) Cold Plate lay-up, (Right) cooling pipe.

The heat is conducted into the cooling pipes by the carbon fibre structure and is removed by the coolant flowing in the pipes. For mechanical stability the Cold Plate is stiffened by the Space Frame, a light filament wound carbon structure with a triangular cross section. For the Space Frame, the specific stiffness and the low Z are the parameters driving the design. Therefore, the choice is in the use of high modulus carbon fibre with a Young's modulus larger than 300GPa, M55J and M60J carbon fibres. [12] [13]

For the Cold Plate, the carbon fibre has to comply with the tight requirements in terms of heat removal capacity; this leads to the use of high thermal conductivity carbon fibres ($k > 600 \text{ W m}^{-1}\text{K}^{-1}$), such as carbon K13D2U unidirectional prepreg [14]. The resin system for the CFRP considered for the ITS is mainly cyanate ester resin, EX-1515. [15]

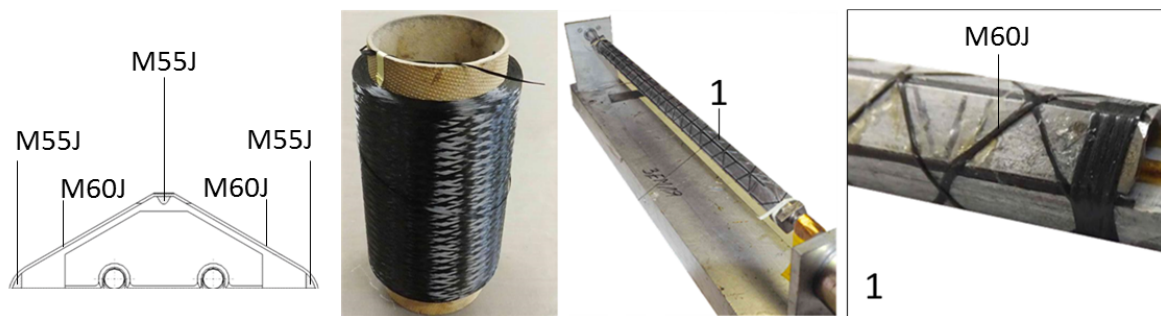


Figure 3.7: IB Space Frame materials and construction.

From the left to the right: frontal view of the IB Stave, Carbon fibre spool, Space Frame during construction and detail of the construction.

The choice of the material for the cooling pipes embedded in the structure is driven by the requirement of low material budget and high thermal conductivity. A suitable compromise among these requirements is the use of a plastic tube with a thin wall. Polyimide (X0 ~28 cm) small diameter pipes with 1.024mm inner diameter and 25 μm thin walls are considered for the IB Staves. The pipes are always embedded in the carbon structure and never directly exposed. In this way their intrinsic fragility and tendency to pinch and buckle under localised load does not affect their use. Polyimide shows high radiation hardness up to at least 107 Gy. [16]

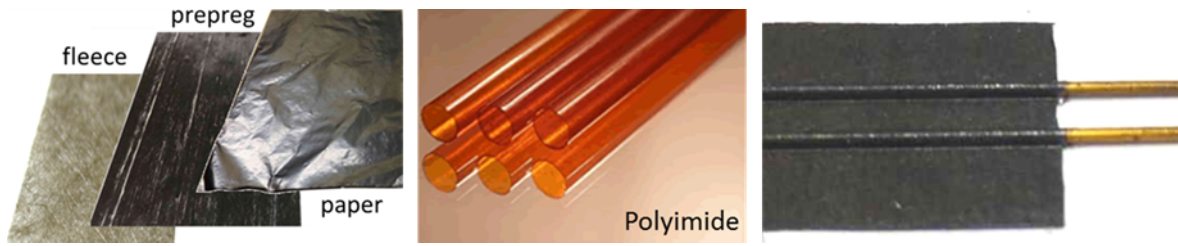


Figure 3.8: IB Cold Plate materials.

(Left) Carbon fleece, unidirectional prepreg and Carbon paper; (Centre) Polyimide pipe; (Right) Cold Plate assembled.

An extensive characterisation of the stave structural performance and extensive thermal tests have demonstrated the capability of the system to ensure proper operating conditions to the chips and related systems. The cooling system was tested in pressure and under vacuum and all the components have been qualified. The results of the stave structural design qualification campaign are presented in the following sections.



Figure 3.9: IB Stave prototype.

(Left) IB Stave without the connectors; (Centre) IB Stave top view; (Right) IB Stave bottom view.

3.2.5 Experimental characterisation

Bending test

The stave stiffness was determined by a three-point bending test. The test was carried out by applying a lumped mass to the centre of the Space Frame, simply supported (free rotations) at the two extremities or clamped (all translation and rotation blocked). Tests have been performed for 0° and 90° spatial orientations. From the test results, the Stave behaviour under working conditions, i.e. distributed mass and clamped extremities, has been extrapolated.

The recorded sag has been also used to have a first estimate of the first natural frequency of the structure that has been then validated by devoted vibration tests.

The displacement sensor used for the tests is the MT 1201 by Heidenhain with a grating period of 4 μm and an accuracy of $\pm 0.2 \mu\text{m}$. The force transducer used is the S2M-10 by HBM which is a S-type force transducer with accuracy of $\pm 0.02 \text{ N}$.

The results of the test are presented Figure 3.10 as displacement in μm versus the applied load in kg.

For the IB Space Frame, under the assumption of a distributed mass of 0.004 kg, corresponding to the HIC weight and of Stave with clamped extremities (all translations and rotations blocked), maximum sag between 4 μm and 9 μm and have been predicted for 0° orientation and 2 μm to 4 μm for 90° orientation. First natural frequency is estimated above 100 Hz.

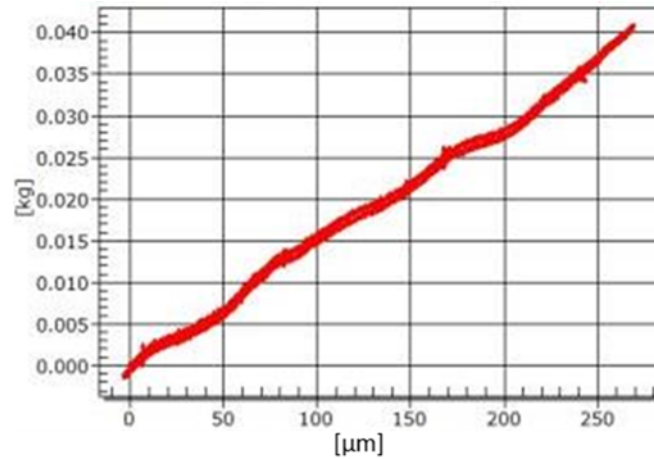


Figure 3.10: IB bending test, results.

Torsional test

The characterisation of the mechanical resistance to torsion is performed by applying a twisting moment to the specimen and measuring the torque.

$$GI\varphi = ML/\varphi; \quad (\text{Eq. 1})$$

where M is the applied momentum, L the length of the Space Frame and φ is the rotation angle measured. φ is obtained by recording the displacement of two pints A and B at the base of the Space Frame. The length measuring system used in this test is a Tesatronic TT20 unit with 0.2 μm accuracy.



Figure 3.11: IB torsional test; configuration.

Table 3.1: IB torsional test.

G	F	M	A-B	tg φ	φ	GI φ
[g]	[N]	[Nm]	[μm]	[rad]		[Nm ²]
5	0.05	0.005	180	0.004	0.004	0.38
10	0.09	0.009	470	0.010	0.010	0.29
15	0.14	0.014	572	0.012	0.012	0.36
20	0.19	0.019	758	0.016	0.016	0.36
25	0.24	0.024	1254	0.026	0.026	0.27

Stave dynamic characterisation

For the ultralight IB stave, since the mass of an accelerometer would affect the measure, given the low mass of the structure, the response was recorded by a 1-D optical scanning vibrometer, PSV-500 model from Polytec, that provides 70 points of measurements on the structure with a 0.5 kHz bandwidth. The test was performed first on the naked carbon structure. Natural frequencies and damping factor are listed in the following table.

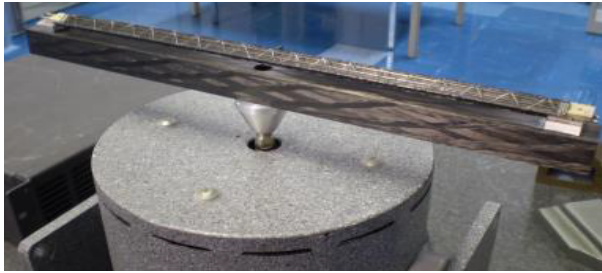


Figure 3.12: IB modal analysis test; configuration.

Table 3.2: IB modal analysis test; without HIC.

Label	Frequency [Hz]	Damping [%]
1st flexion mode	167	0.568
2nd flexion mode z	461	0.293
3rd flexion mode z	764	0.406

As it is possible to see, the first natural frequency is 167 Hz and the second natural frequency is 461 Hz. The measure has been repeated for the Space Frame with the glued HIC. The result shows a decrease of about 10 Hz for the first flexural mode.

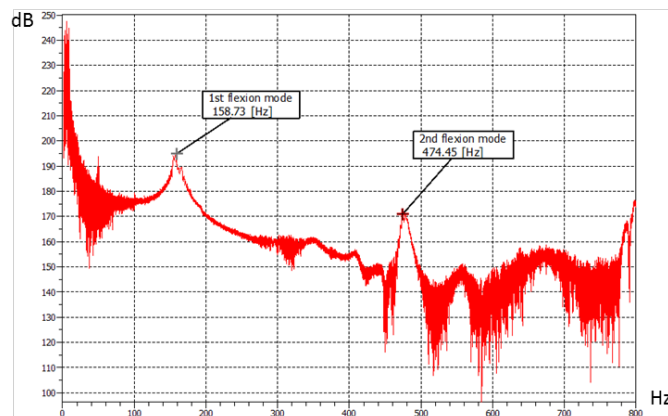


Figure 3.13: IB modal analysis; with HIC.

Air flow vibration test

An air circulation is foreseen inside the detector volume to uniformly the temperature.

A vibration test has been performed to determine if the air circulation affects the Space Frame stability.

The IB Stave has been inserted in a wind tunnel and it has been tested by using a conservative air speed of 3.2 m/s to be compared with a design value of 1m/s.

Thanks to a laser sensor, optoNCDT 2300 [17], the vibration of the Stave has been evaluated and the results are shown in the following graph. The two different wind directions, along and across the Stave axis have been controlled.

The maximum measured displacement with an air speed of 3.2 m/s is less than 4 μm for both configurations; this result provides confidence that an air speed of 1 m/s, doesn't influence the pixel stability and then its functionality.

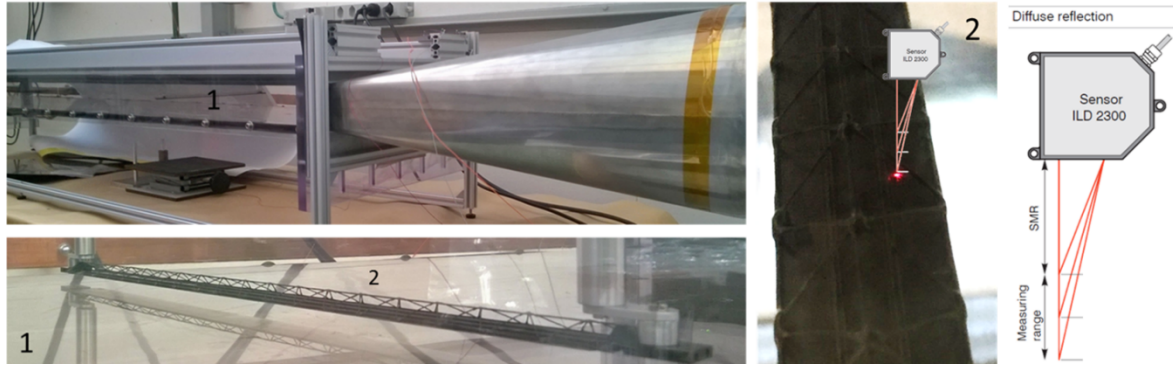


Figure 3.14: Air flow vibration test, set up.
The optoNCDT 2300 laser sensor has been used, with a resolution of 0.08 μm at 20Hz.
Start of measuring range (SMR) is 30 mm. [17]

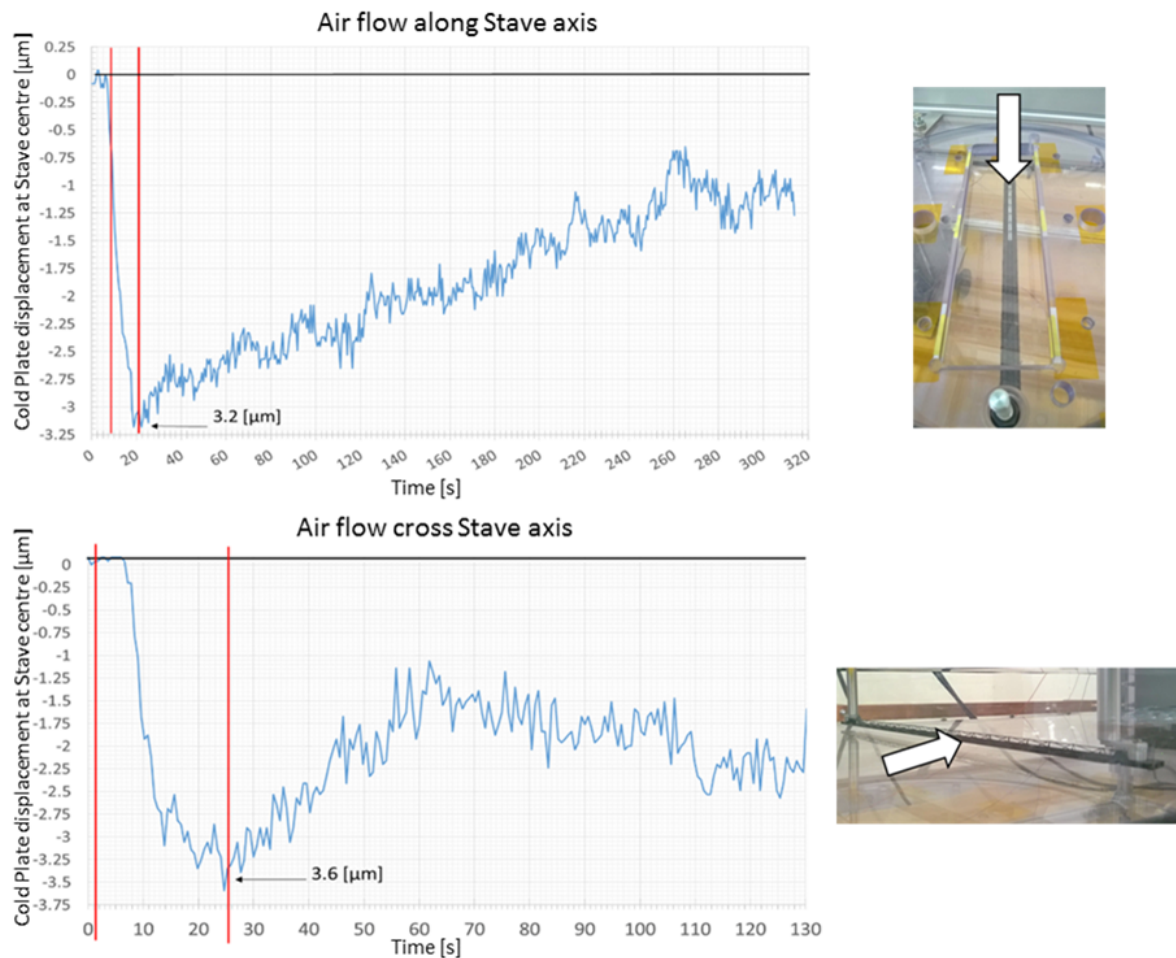


Figure 3.15: Air flow vibration test, results.
(Top) Air flow along stave axis and air speed 3.2m/s;
(Bottom) Air flow across Stave axis and air speed 3.6 m/s.

3.3 Inner Barrel Detector analysis

3.3.1 Overview and aim

The aim of this analysis is to improve the stiffness of the Inner Barrel Detector structure, such to minimize the detector sag and increase the first frequency of resonance.

Decreasing the maximum sag permits to achieve a better position of chips, that is one of the main requirements for the Detector design while the maximisation of the natural frequencies aims to increase the detector stability.

The detector half-barrels cantilevered inside the detection volume such to minimize the material in this area. It is fixed at the extremity of the IB Service Barrel that provides the mechanical support and the precise positioning.

As first step, the analysis has been focused on the optimisation of the IB Detector Barrel. In a second step the IB Service Barrel has been optimised in a joint analysis with the IB Detector Barrel.

A parametric analysis has been performed assuming the maximum sag as reference variable.

The analysis has been presented in the ITS Upgrade- Detector Barrel Mechanics Engineering Design Review on 20th July 2016. [18]

3.3.2 Model

Geometry

A simplified shell geometry has been developed from the 3D Cad model. 3D solid bodies have been replaced by shells based on the ratio limit ($D/L < 10$).

Connectors at the EW have been transformed in shell elements utilizing an average thickness (1.5mm). This is an approximation that has been considered not affective the aim of this analysis, due to the fact that we are not interested to a stress configuration and localized deformation in that areas.

The structure middle plane has been assumed as reference surface for the analysis. A customised, detailed choice for the surface has been developed in the overlapping area such to better approximate the section inertia.

Mesh

Eight nodes quadratic thin shell elements have been used for the discretisation of the surfaces: SHEEL281 ANSYS. BEAM 189 ANSYS is the other element type introduced for the representation of the staves (see section below). A correct orientation of elements is mandatory whenever orthotropic materials are used. A convergence mesh study has been performed to choose the lighter configuration of elements (less number of elements).

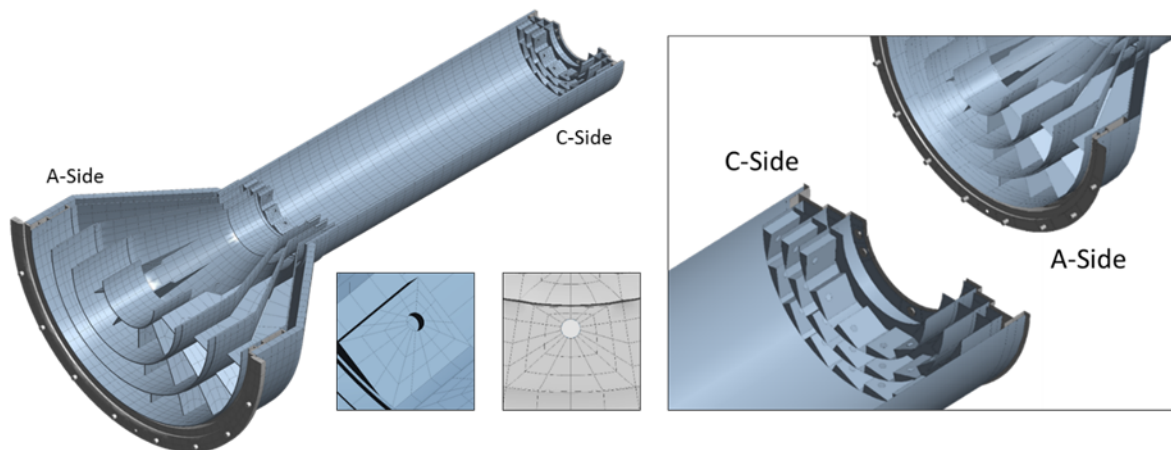


Figure 3.16: Geometry and mesh of Inner Detector Barrel.
(Left) Mesh and mapped mesh near the holes are shown in the detail boxes; (Right) Details of geometry.

Boundary conditions and contacts

The following boundary conditions have been considered in the model:

- Constraints:
 - Connection among layers;
 - fixation of flange that interfaces the Service Barrel.
- Loads:
 - Mass of Staves connectors ;
 - Electronic components loads.

The load condition consists in the mass of the structures and of the supported electronics and Patch Panel (PP) under the gravity acceleration (in static structural analysis). Loads have been simulated by applying a distributed mass on the relevant surfaces.

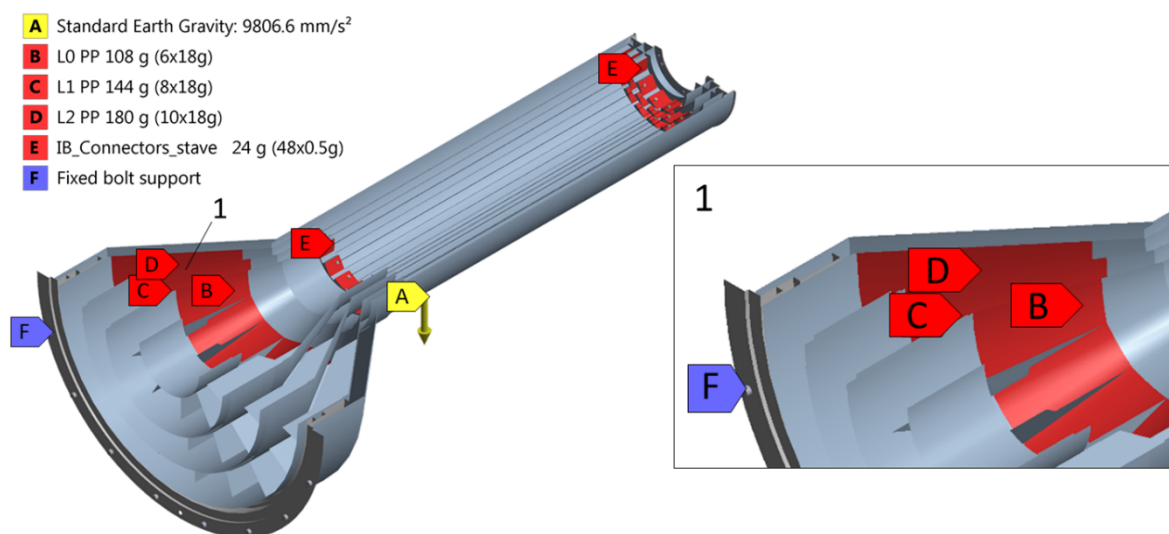


Figure 3.17: Inner Detector Barrel boundary conditions.

The Detector Barrel has been clamped at the interface flange with the Service Barrel. The DoF at the end of the bolts (beam elements) have been blocked and No contact constraint have been introduced at the flange that connect the Inner Detector Barrel to the Inner Service Barrel, this resulting in a more compliant overall constraint.

Glued interfaces have been simulated by coupling the Dof of the matching surfaces, ANSYS Multi Point Constraint (MPC) linear contact have been used (details in Appendix B.4).

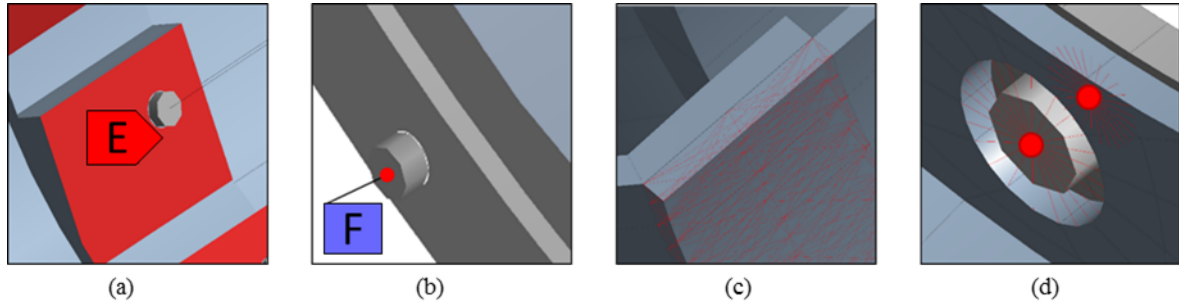


Figure 3.18: Details of boundary conditions.
(a) Distributed mass of the Stave connector applied; (b) bolt at the flange blocked;
(c) Glue interface; (d) bolted connection (beam element).

IB Stave simulation

In order to reduce the simulation time and the model complicity, it has been decided to simulate Stave with a beam elements that maintain the main characteristic of the part (flexural and torsional stiffness).

Beam elements properties like Area Moment of Inertia properties and Young and Shear Modulus have been tuned on the basis of experimental results (bending and torsional test) performed on the Stave. The results of the Test are listed below (details about Structural Stave Test are shown in section 3.2.5).

Flexural stiffness $EI_x \sim 0.3 \text{ Nm}^2$, $EI_y \sim 1.41 \text{ Nm}^2$;

Torsional stiffness $GI_p \sim 0.33 \text{ Nm}^2$.

A good approximation has been reached by using isotropic material properties for beam:

$E = 20 \text{ GPa}$, $G = 7.69 \text{ GPa}$, $\nu = 0.3$, $\rho = 1429 \text{ Kg/m}^3$.

The inertial properties choose are:

$I_{xx} = 15 \text{ mm}^4$, $I_{yy} = 70.5 \text{ mm}^4$, $I_{xy} = 0 \text{ mm}^4$, $J = 43.2 \text{ mm}^4$, $A = 3.96 \text{ mm}^2$, $L_{\text{beam}} = 300 \text{ mm}$.

Beams representing the Staves have been coupled to the End-wheels by bolted connection (Figure 3.19).

The mass associated to the beam element accounts for the carbon structure and the HIC, while the mass of the connectors at the extremities of the Stave has been considered as a distributed load directly applied on the EW surfaces.

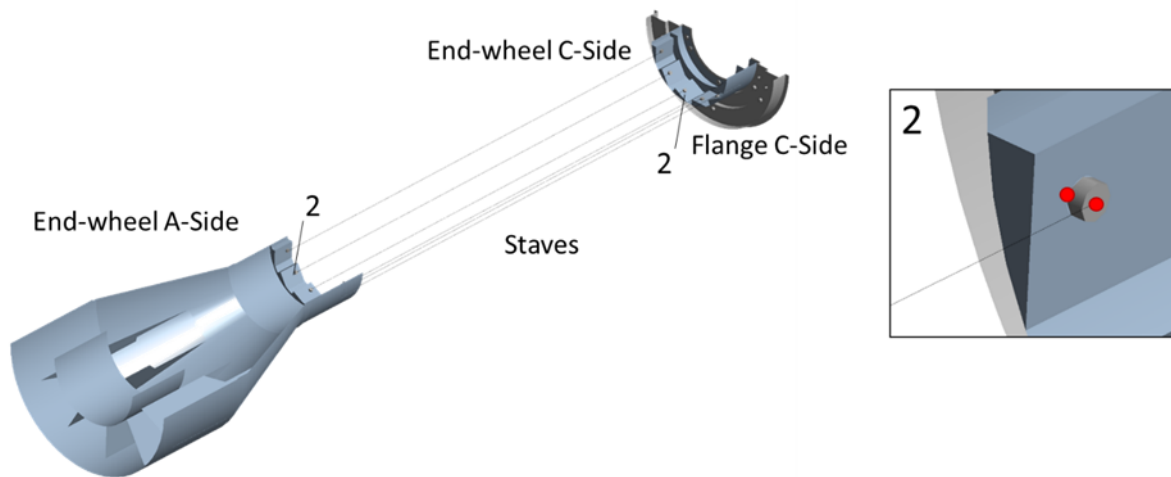


Figure 3.19: IB Stave beam simulation

Contact between different layers

The contacts between Layers L0-L1, L1-L2, CYSS-L2, are different from normal glued contact, they should block displacement in X, Y direction (Figure 3.20.a) while they should allow for displacement in Z directions. This contact design is under studies an example of how it can be done is shown in Figure 3.20.a.

The aim of such design is to permit thermoelastic deformations of the Stave to avoid to introduce stresses in the Stave. Thermoelastic test have demonstrated that the CTE of the Stave is $2 \mu\text{m/m/K}$ resulting in a maximum expected deformation of $1.2 \mu\text{m}$ for the Stave length of 300 mm and a maximum temperature range variation of 2°C .

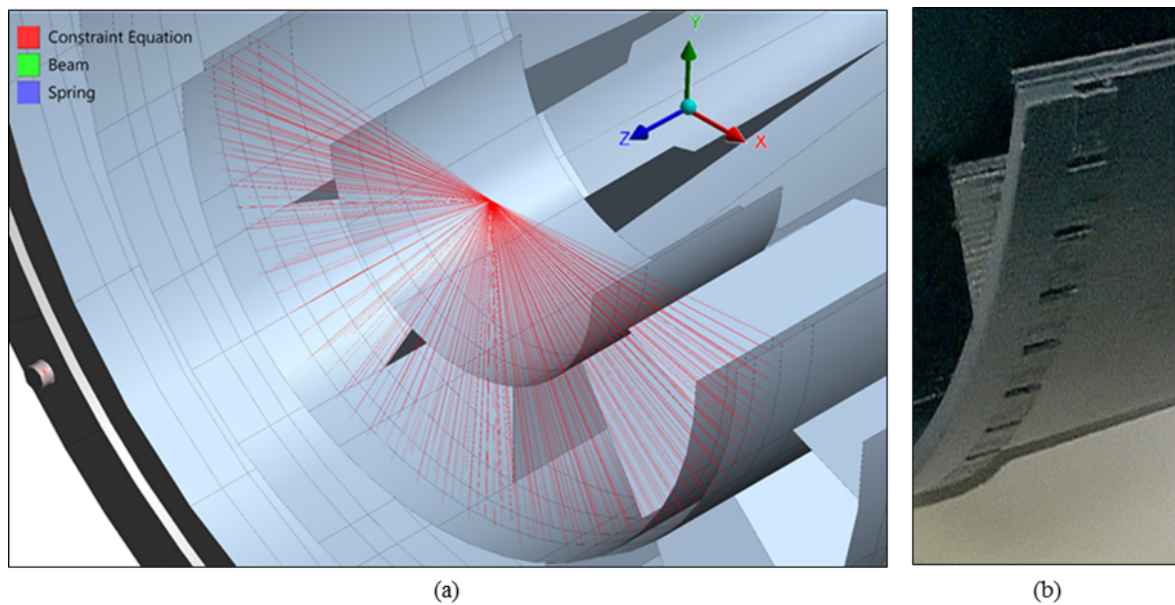


Figure 3.20: Contact between layers.
(a) Detail of Joint connection; (b) Detail of prototype part of this contact.

3.3.3 Baseline

A Baseline design, based on a starting CAD model and first prototypes produced, has been assumed for the study of the IB Detector Barrel. Lay-up and relative materials properties are shown in Appendix D.1

The FEA model has been built through sequential steps of complexity and verification of the model have been performed at each step.

In a first run only the structural shells have been considered without introducing the Staves in the simulation. In a second step all the Staves, approximated by beam elements with tuned properties such to match the test results have been introduced.

Maximum sag and first natural frequency have been computed for the fully assembled half-detector. A predicted value of 0.142mm for the sag and of 46 Hz a first flexural natural frequency have then been assumed as starting point for the structural optimization.

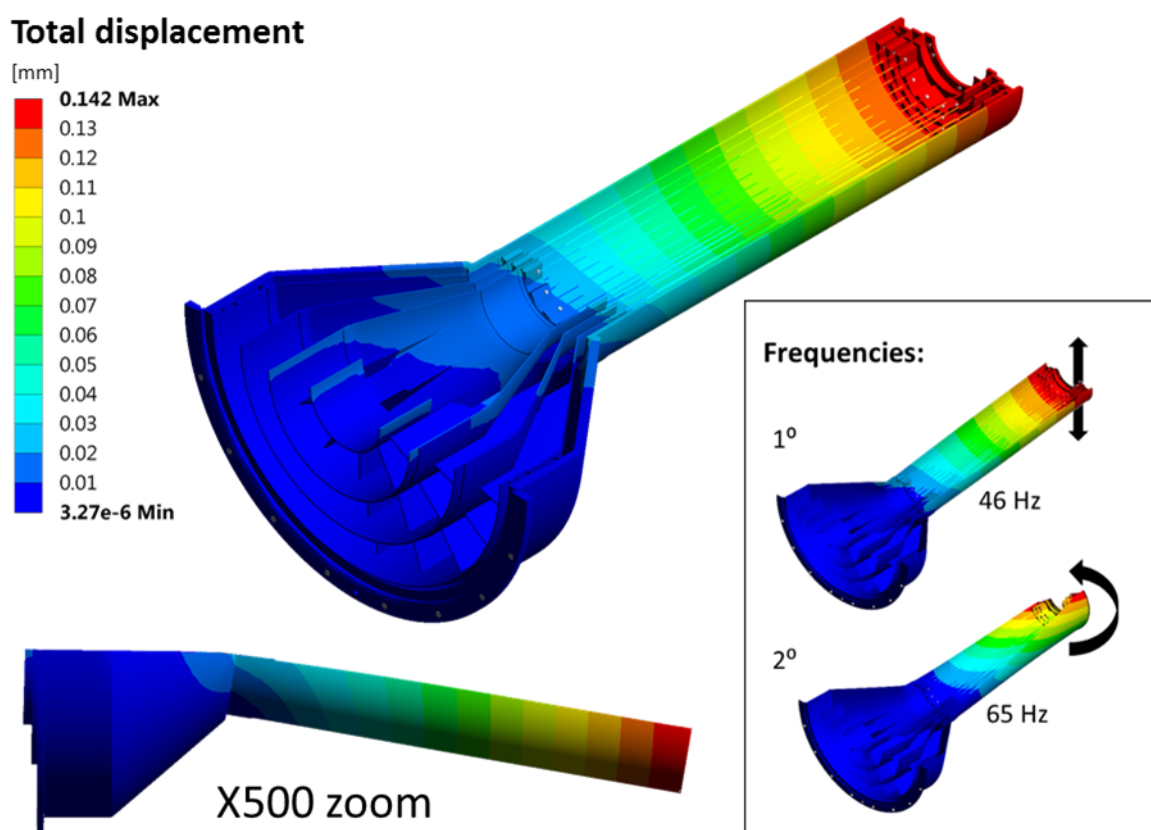


Figure 3.21: Inner Detector Barrel Baseline, results.

3.3.4 Optimisation

The goal of the structural analysis is to minimise the maximum sag of the IB Detector and to maximise the first natural frequency. In order to achieve that an optimisation of the lay-up of the different carbon structures has been carried out.

The stiffness of the IB Detector Barrel is mainly determined by the outer structural shell, the Cylindrical Structural Shell.

The structural optimisation has focused therefore on the CYSS. The CYSS is constituted by two sections, a cylindrical part and a conical part glued together.

The optimisation process based on thickness and materials lay-up tuning had to take into account the severe limit imposed by the material budget constraint coming from the Physics requirement.

The Optimisation procedure has been performed through the following steps:

- Case.1 Cylindrical part optimisation;
- Case.2 Conical part optimisation;
 - a. Optimize T1 thickness
 - b. Optimize T2 thickness
- Case.3 Change flange C-side part from Aluminium material to Carbon material.
- Case.4 Change foam material.

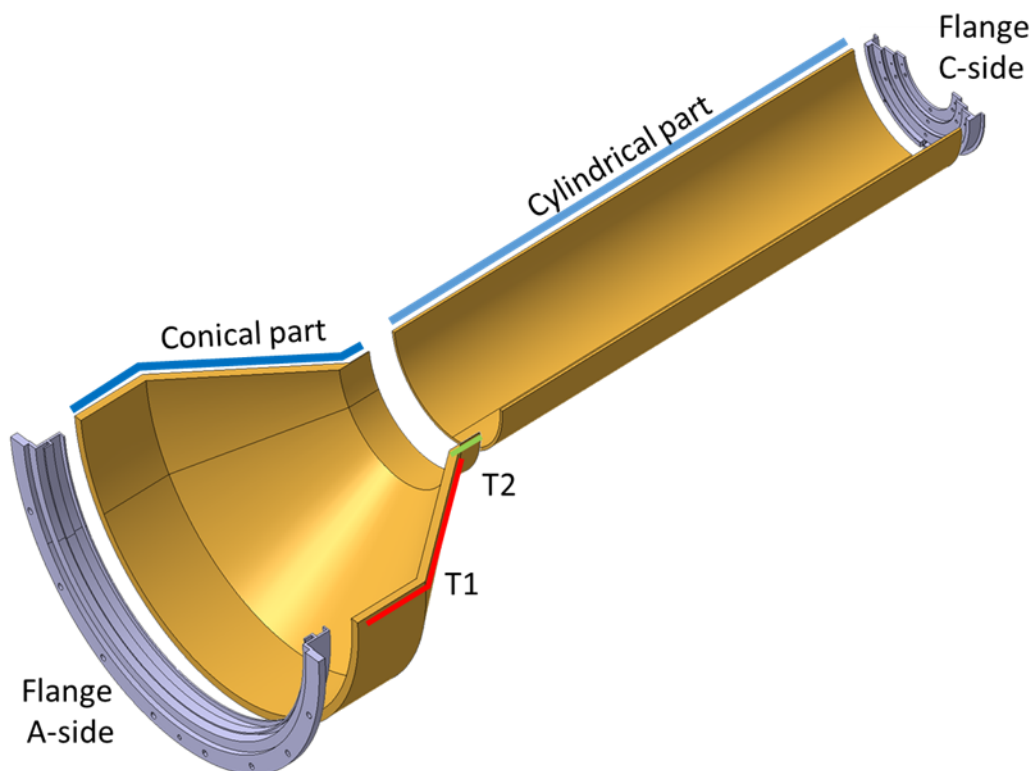


Figure 3.22: Nomenclature of IB CYSS.

Case.1 Cylindrical part optimisation

The cylindrical structure is a carbon sandwich made of a 1.6mm core of foam, Rohacell 51 IG [19], and two skins each of them made by 2 plies of 0.1 mm of carbon fibre prepreg ,T300 1K prepreg woven (PW) [20].

In the optimisation study the sandwich total thickness, the foam thickness, the skin thickness and their carbon lay-ups have been assumed as parameters. Different combinations of the parameters variation have been studied and reported in a summary plot shown in the picture, where the gain in sag reduction, respect to the Baseline design, is plotted versus the increase of thickness necessary to achieve such reduction.

The limit imposed by the minimum material budget requirement is traced in the plot as a dashed black line and set at 25% increase in the thickness respect to the Baseline design.

From the results analysis it can be concluded that the increase in the skin thickness not always results in a reduction of the sag, while the most effective parameters appears to be the core thickness, traced by the blue line in the plot. Nevertheless the gain in term of sag reduction at the limit imposed by the material budget is as low as 2% respect to the design Baseline. It has been decided therefore to keep the Baseline design as the final design for the cylindrical part.

Further consideration have been performed on the material of the core, and foam with higher mechanical properties (stiffness) have been considered in a second step of optimisation.

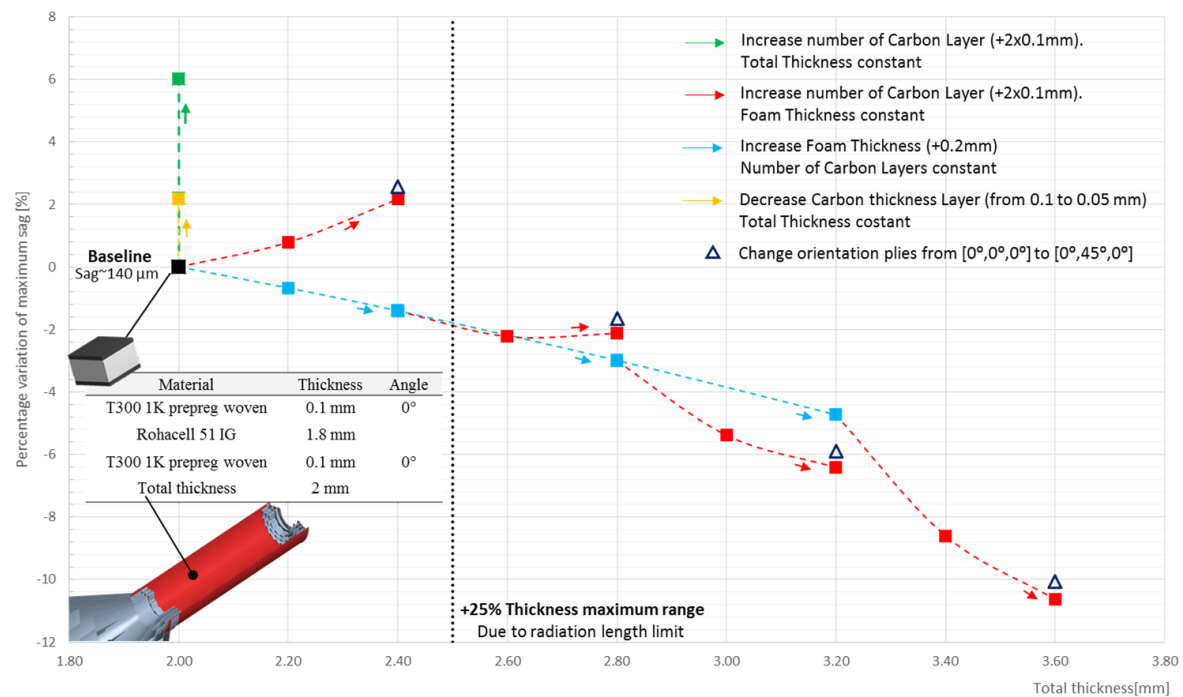


Figure 3.23: Optimization Case.1 Cylindrical part optimization, line chart.

Case.2 Conical part optimisation

The conical part is a carbon sandwich, and for the optimisation study has been divided in two sections as shown in Figure 3.22, section T1 and section T2.

The optimisation process has followed the same approach used for the cylindrical structure, meaning that the parameters used are the thickness of the core and skins as well as the overall sandwich thickness.

In addition the analysis has been performed in two steps. In the first step the T1 section has been optimised, keeping unchanged the T2 section. In a second step the T2 section has been optimised starting from a layout that takes into account the T1 optimised section and the derived changes on T2. This means that being T1 and T2 parts of the same structure the change of the numbers of layers in the carbon skin of T1 results in the same change in the skin of T2 for the material continuity.

T1 tuning

The results of the optimisation of the T1 section is described in the Figure 3.24.

The driving parameters of this analysis is the increase of the thickness of the sandwich skin (red line in the plot). Three lay-up with an increasing number of laminate in the sandwich skin have been considered and listed as Option 1, 2 and 3 (Figure 3.25). For each option the effect of an increase in the foam thickness has been also analysed (blue lines). A maximum sandwich thickness of 6.2mm has been assumed as upper limit for this analysis based on the construction process limits.

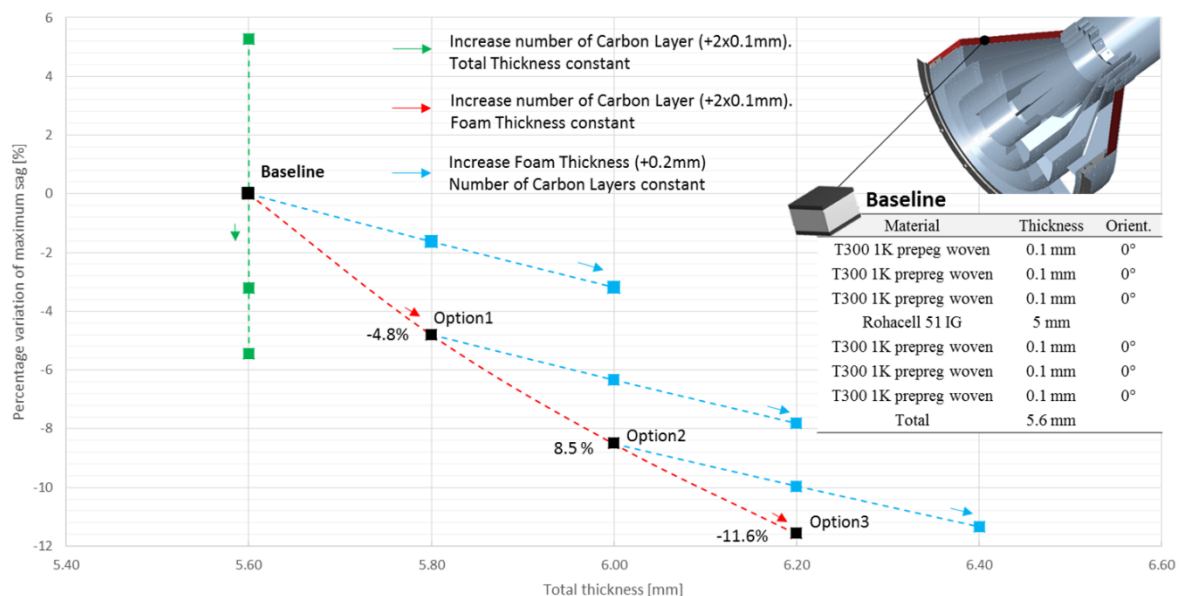


Figure 3.24: Case.2.a Conical part optimization line chart, T1 thickness.

T2 tuning

For the optimisation of the T2 surface the different laminate Options (1, 2, 3), coming from the optimisation of the T1 surface, have been considered as starting point. An initial target thickness for the T1 surface has been fixed at 1,2mm and the carbon ply lay-up modified accordingly as shown in Figure 3.25.

It has been noticed that the increase in thickness in the T2 area is more effective than in T1 area, therefore, in order to minimise the material budget, the Option 1 has been assumed for the T1 surface, while a laminate with a 1,4mm thickness has been considered for the T2 surface, see Figure 3.26.

The maximum sag for the chosen optimised configuration is presented in Figure 3.25 where a reduction of about 20% is predicted compared to the design Baseline.

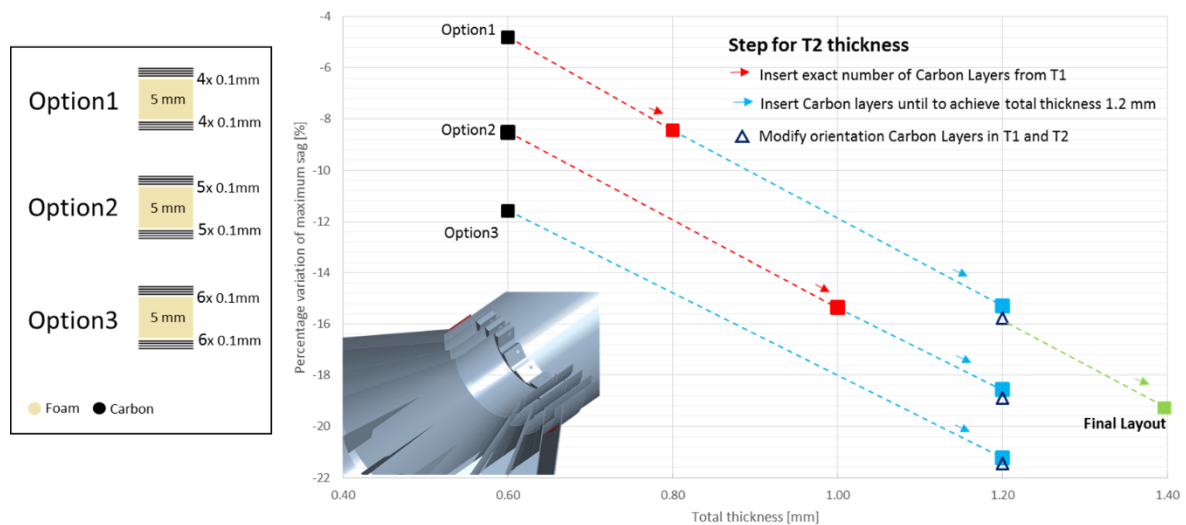


Figure 3.25: Case.2.b Conical part optimization line chart, T2 thickness.
On the left a schematic lay-ups of T1 options thickness are shown.

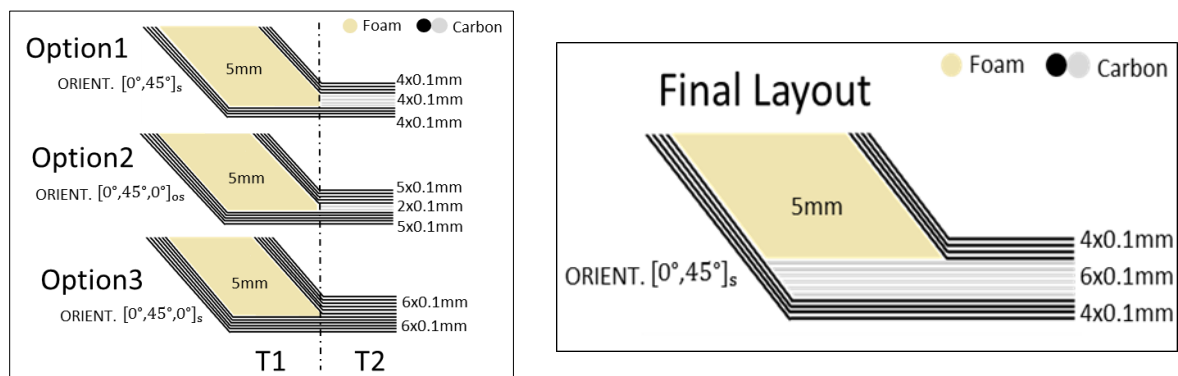


Figure 3.26: Schematic lay-ups of final options.
(Left) Final options 1, 2, 3; (Right) Final Layout chosen.

Case.3 Change C-side flange

A reduction of the mass/stiffness for the flange at the C-side has been considered.

A detailed analysis has been performed by replacing the aluminium material of the flange with a carbon composite material, and the sag reduction has been evaluated, resulting in a reduction of about 14% respect to the baseline design.

The reduction of the material density from aluminium to carbon results in a reduction of the flange mass that has an evident impact on the sag, being this mass at the extremities of the barrel. Further development of the Detector Barrel design have required the opening of a large number of holes on this flange for air cooling purposes. This has led to reconsider the aluminium for the flange material, due to the implicit reduction of the flange weight and the easy machining. Based on these recent design development the use of aluminium material for this flange is being reconsidered.

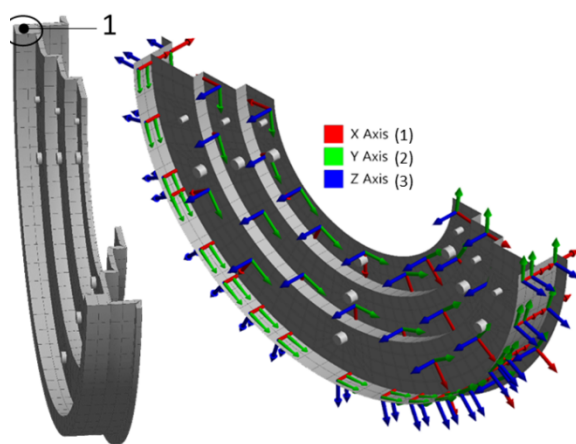


Figure 3.27: C-side flange characterisation.

*the lay-up $[0^\circ/45^\circ/0^\circ]_{os}$ means an odd symmetry lay-up $(0^\circ/45^\circ/0^\circ/45^\circ/0^\circ)$.

**the lay-up $[0^\circ/45^\circ/0^\circ/45^\circ/0^\circ]_s$ means a symmetry lay-up $(0^\circ/45^\circ/0^\circ/45^\circ/0^\circ/0^\circ/45^\circ/0^\circ/45^\circ/0^\circ)$.

Table 3.3: C-side flange lay-up.

#	Material	Thickness	Orientation
Surface I			
5	T300 1K PW	0.1 mm	* $[0^\circ/45^\circ/0^\circ]_{os}$
1	ROHACELL 51 IG/IG-F	2.5 mm	
5	T300 1K PW	0.1 mm	* $[0^\circ/45^\circ/0^\circ]_{os}$
Total		3.5 mm	
Others surfaces			
10	T300 1K PW	0.1 mm	** $[0^\circ/45^\circ/0^\circ/45^\circ/0^\circ]_s$
Total		1 mm	

Case.3 Change foam material

The foam material in the cylindrical part (Rohacell 51 IG) has been replaced by Rohacell 110 IG [19], with higher mechanical properties (stiffness) but also a higher density that slightly increases the material budget. However the gain of Rohacell 110 IG is around 20 % respect to the optimized configuration with Rohacell 51 IG. Mechanical properties are in Appendix C.3.

Optimisation results

The final optimised Inner Detector Barrel layout, sum of the different optimization steps described in the previous sections is shown here after. The maximum predicted sag is about 80 μm and the first resonance frequency is larger than 50 Hz. This represent a reduction of the maximum sag of 44 % respect to the design Baseline, while first and second resonance frequencies have been increased respectively by 18 and 12 Hz.

The third modal shape shows the Stave resonance that is compatible with test modal frequencies results for the IB Staves.

The analysis is based on conservative assumptions, namely all the connections at the interfaces have been considered simply bolted and the contribution of the surface contact has been neglected. The results cope with the stiffness requirement and will be assumed as starting point for a further analysis that will take into account the stiffness of the structural behaviour of the Service Barrel to which the IB Detector Barrel is fixed. A range of other possible optimisation found during analysis can be taken into account if necessary.

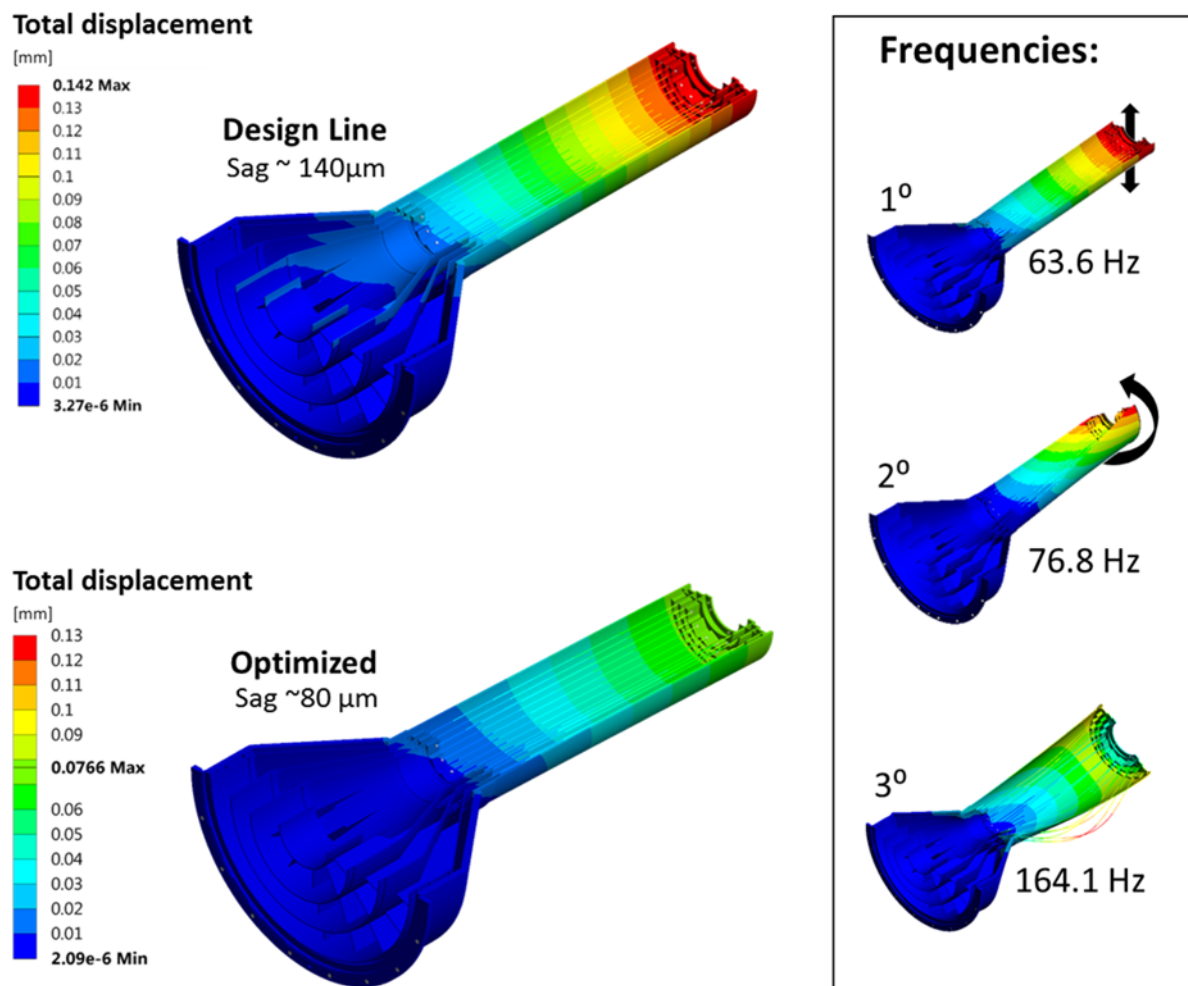


Figure 3.28: Inner Detector Barrel optimized results.

3.3.5 IB EW prototype and layer assembly process

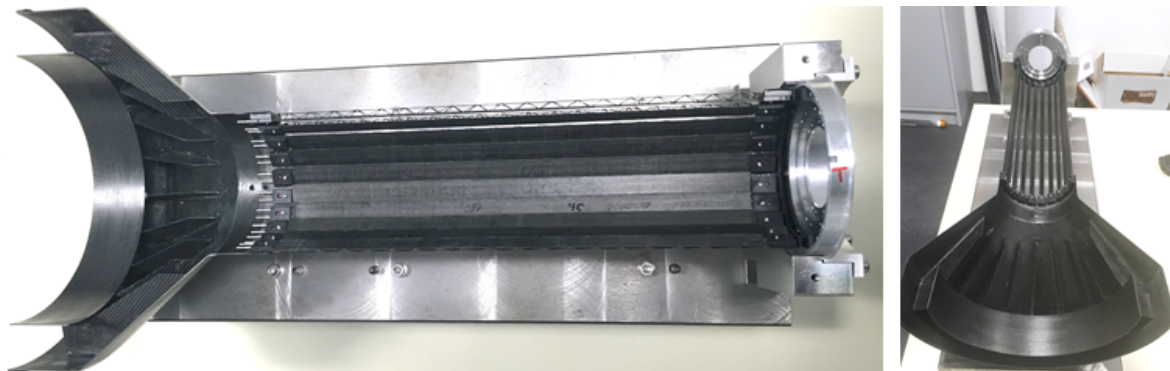


Figure 3.29: End-wheels Layer 2 prototype, assembled.

Based on the structural analysis a prototype of the Layer 2 has been produced. The production of the composite parts has required the development and machining of a series of very precise moulds, used for the stratification of the different plies of carbon preregs. After the manual lay-up is performed according to the sequence defined by the FE analysis, the parts go into a curing process that consists in the application of a pressure and temperature cycle. The pressure, needed to compact the material, is applied by pulling vacuum in the Vacuum Bag that is applied as last layer on the composite plies.

The part is then inserted in an oven where a temperature of 120°C is applied for 2 hours. At that point, once the part is completely polymerized it is removed from the mould. Different CFRP are needed for the realization of the End-wheels. The different parts are assembled and glued by using devoted jigs, which provide the required tight accuracy. Here below pictures show the different phases of the production and of the final layer assembly.

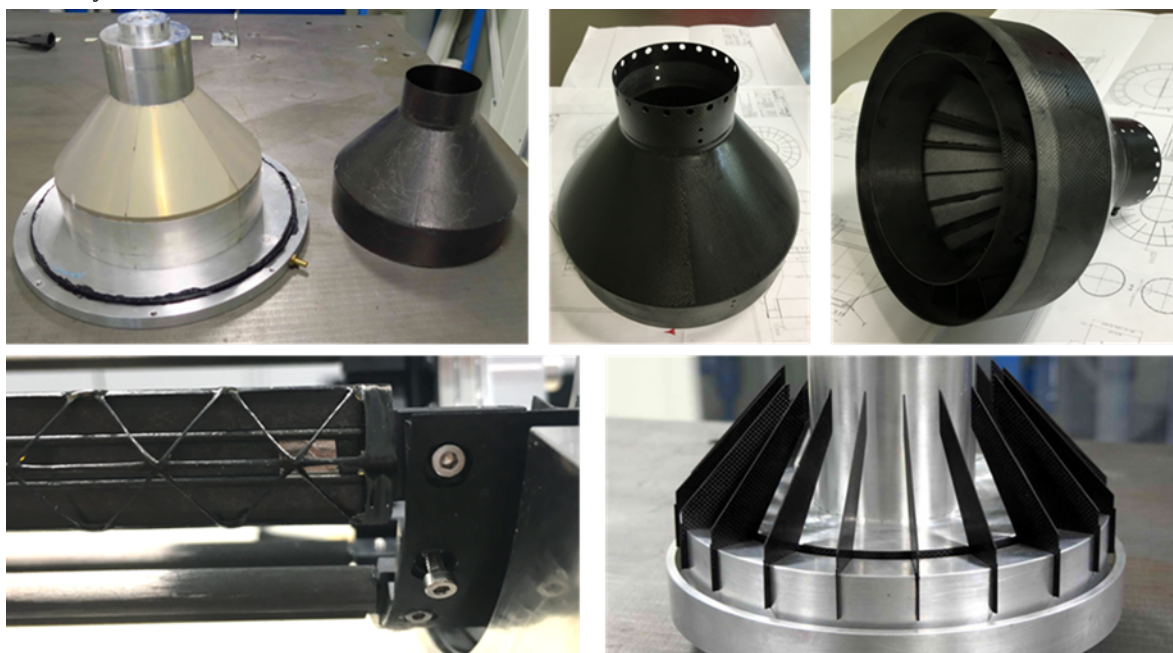


Figure 3.30: Moulds and details of End-wheels Layer 2 prototype.

3.4 Inner Service Barrel analysis

3.4.1 Overview and aim

As described before the Inner Detector Barrel is a cantilevered inside the detection area in order to minimise the material. The entire weight will be supported by the Service Barrel rollers that are inserted in the Cage rails

The objective of this analysis is to evaluate the maximum sag at the extremities of the Detector Barrel once coupled to the Service Barrel, as it will be in the operational configuration. A modal analysis will be performed to understand the effect of the Service Barrel stiffness and the connection to the Cage on the detector first natural frequency.

An optimization of this component has been performed to decrease the maximum sag.

3.4.2 Model

Geometry and mesh

As for the Inner Detector Barrel, a simplified shell geometry has been developed from the 3D Cad model of the IB Service Barrel (Figure 3.31), and has been used for the FEA. After the removal of irrelevant geometrical details, the shell geometry has been mapped meshed. The shafts and the flanges have been coupled to the composite shell of Service Barrel by using MPC, to simulate the glue, Figure 3.33.a. (Appendix B.4).

The ANSYS type elements used are SHELL281 (Appendix B.3).

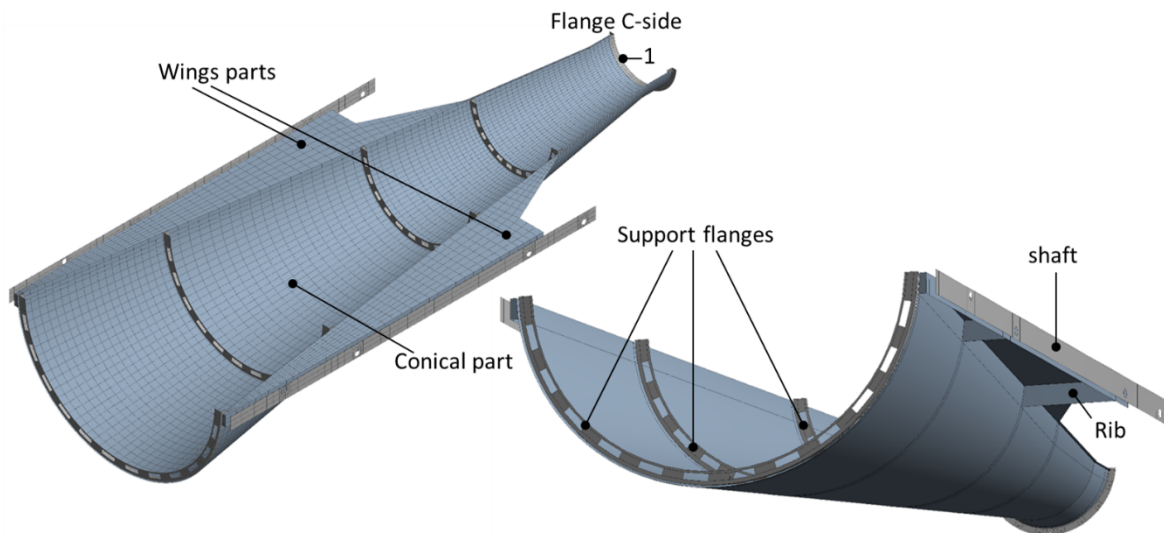


Figure 3.31: Geometry and mesh of Inner Service Barrel.
(Left) Mesh; (Right) Geometry.

Boundary conditions and contacts

The IB Service Barrel structure supports the detector services, i.e. power and data cables, cooling lines, ventilation ducts. Their weight has been proportionally distributed on the conical surfaces shown in red in Figure 3.32 (proportional to the length of the surfaces).

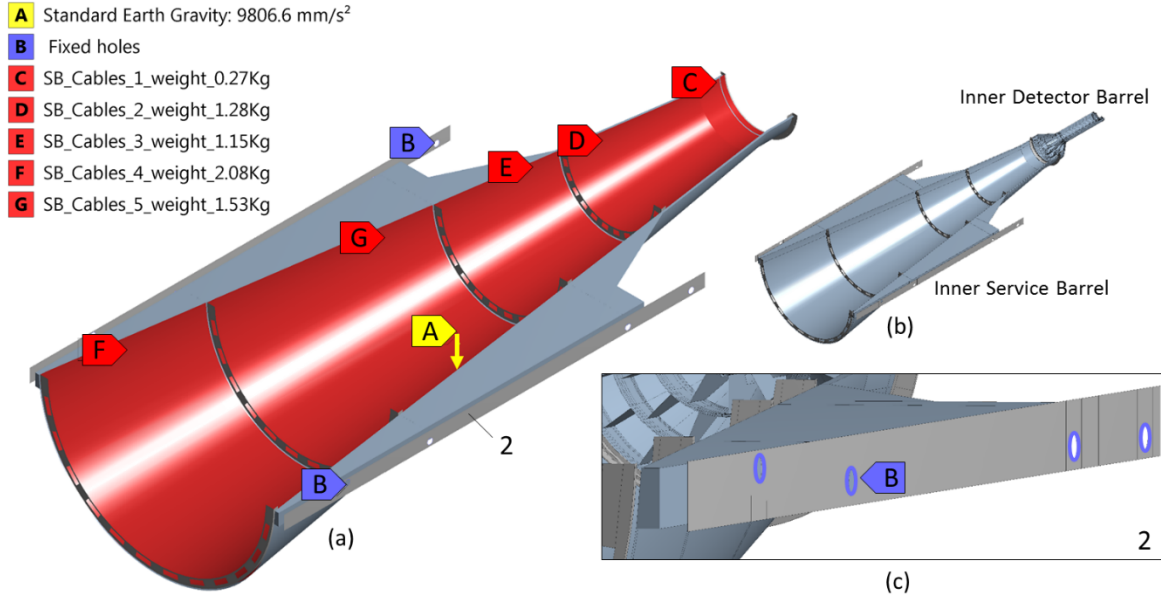


Figure 3.32: Inner Service Barrel, boundary conditions.
(a) Overview; (b) Detector and Service Barrel assembled; (c) detail of fixed supports.

The IB Service Barrel is connected to the Detector Barrel at the interface flange with bolts that have been simulated through beam elements, details highlights in Figure 3.33 with number 1. For the Inner Detector Barrel the same boundary condition have been used, expect for the fixation described before.

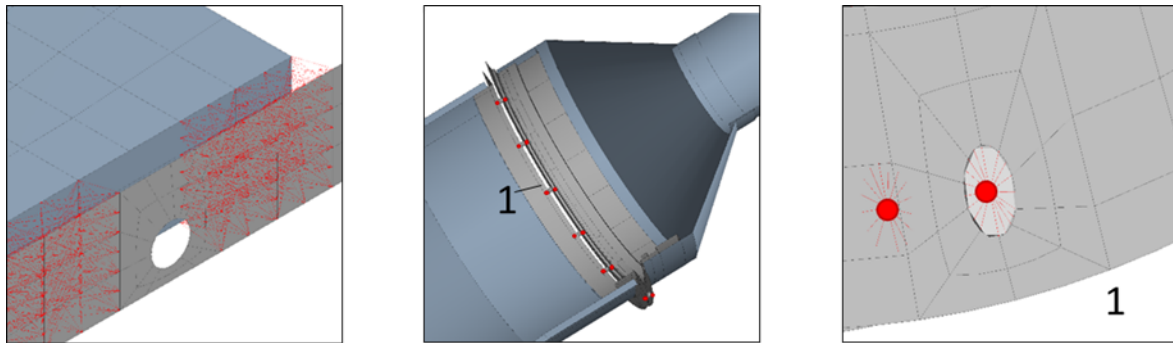


Figure 3.33: Boundary conditions, details.
(Left) MPC between right shaft and composite shell; (Centre) connection between Service and Detector flanges;
(Right) beam element connection between flanges.

3.4.3 Optimisation

In the following section the optimised layout will be presented, while several intermediate configuration has been studied and used to arrive to the final one, details can be found in Appendix D.3

An isotropic material, 4 mm thick, that approximates a carbon quasi-isotropic lay-up of the wings, ribs and conical parts has been considered as starting point to optimize the structure design. The Carbon isotropic (Appendix C.3) material has a density of 1450 Kg/m³ and isotropic properties, elastic modulus 50000 MPa and a Poisson ratio 0.3.

The results show an increase of the maximum sag respect to what reported in section 3.3.4. This reflects the compliance of the support provided to the Detector Barrel by the Service Barrel, respect to the ideal condition of a clamped Detector Barrel. The maximum sag is around 286 μm . The modal shape associated to the first natural frequency shows that the Inner Service Barrel with this type of lay-up is less stiff than the Detector Barrel.

In order to stiffen the Service Barrel, the use of the same material considered for the Detector Barrel would lead to an increase of the thickness that can create problems of interference with the other neighbour structures, as well an increase of the material budget.

For this reason, materials with higher elastic modulus, but more expensive and more difficult workability, have been considered such as carbon fabric prepreg with stiffer fibres (M46J [21]) and stiffer foam (Rohacell 300 WF [22]). Thanks to this, acceptable results have been found by reducing back the thickness to the nominal value. The same total thickness and lay-ups have been considered for the conical, ribs and wings parts; details of the lay-ups are in Appendix D.3.

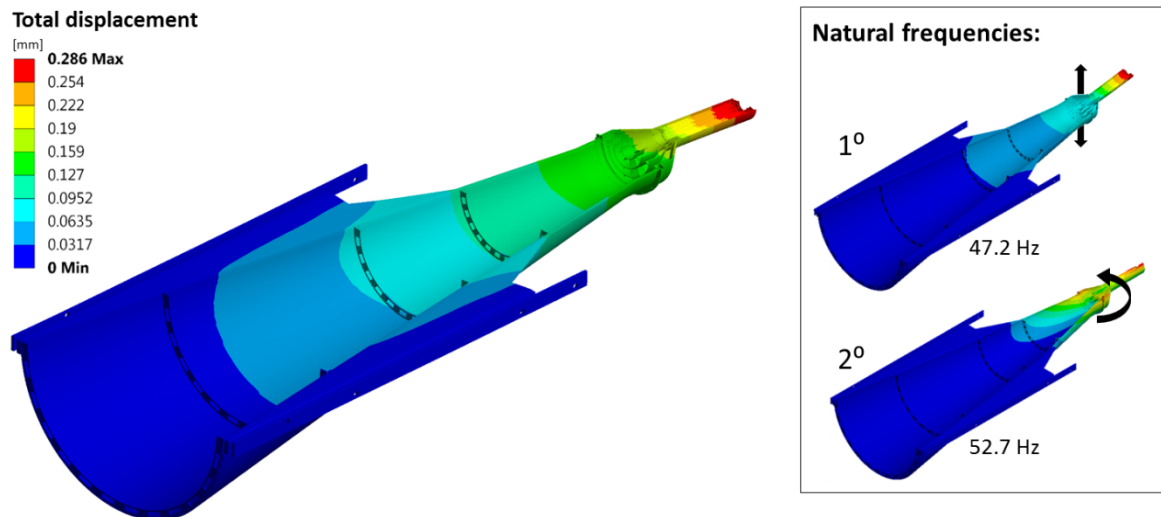


Figure 3.34: Inner Service Barrel, starting point results.
Carbon quasi-isotropic lay-up.

Results are shown in the figures below, the maximum sag is around 230 μm and the first frequency increases up to 54 Hz.

Further optimisation that can be considered are the addition of new flanges in the conical part, the change of the geometry of the wings surfaces (providing it is compatible with the detector services) and the change of the ribs lay-ups.

As described before the ribs lay-up is the same of the wings and conical part, but the wings and the conical parts can be made with a single mould and then the ribs parts can be glued. These last components could be done with different lay-up respect to the others; an idea is to insert a whole carbon lay-up thanks to its simple shape (rectangular).

Figure 3.35: Inner Service Barrel optimised lay-ups, total displacement.

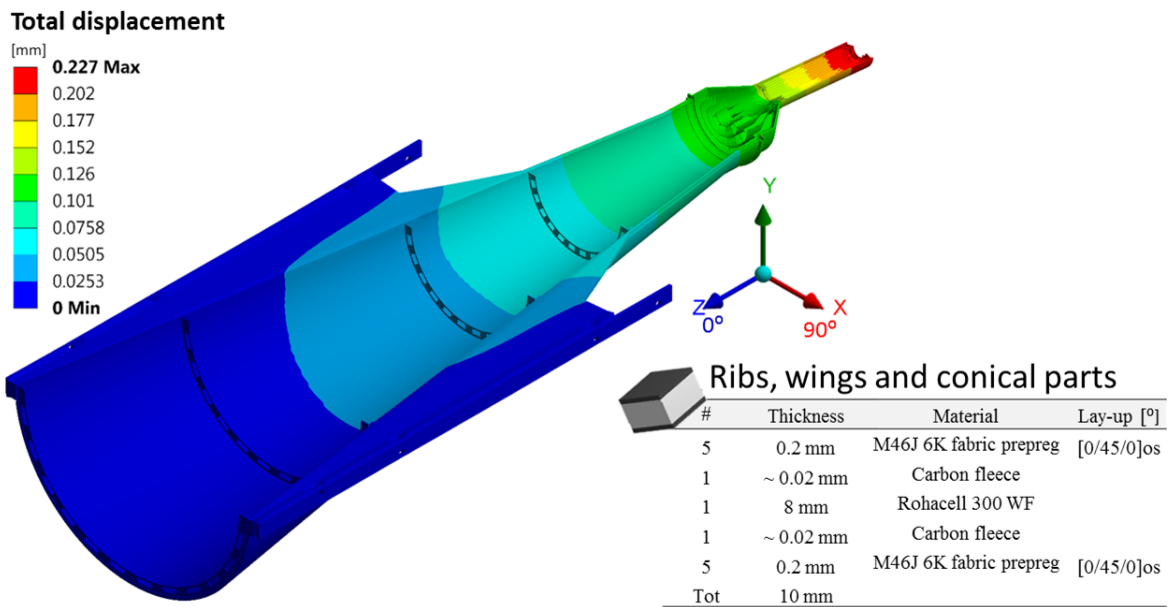


Table 3.4: Ribs, wings and conical parts lay-ups.

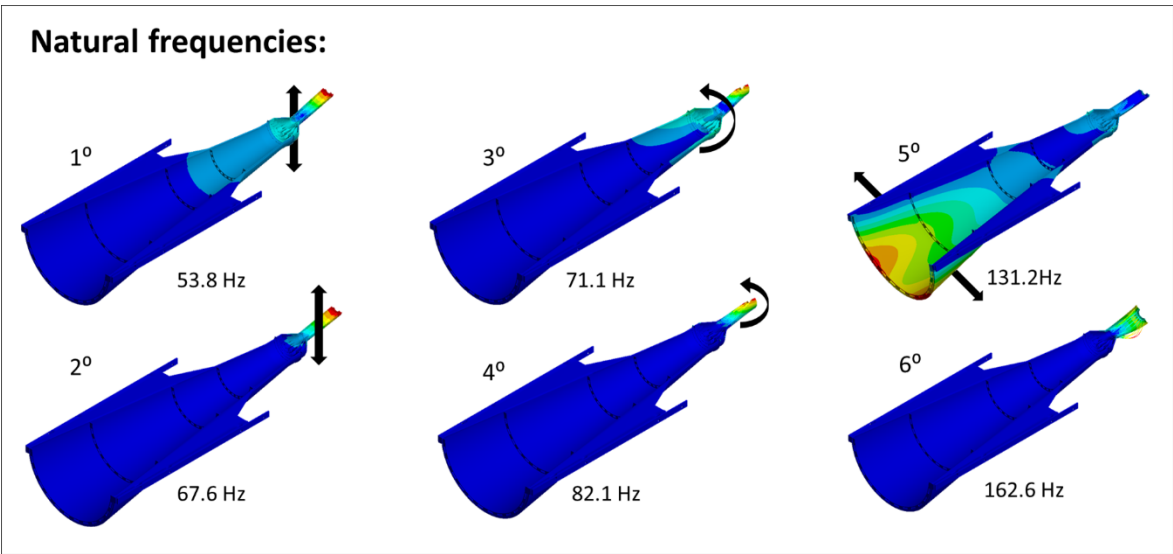


Figure 3.36: Inner Service Barrel optimised lay-ups, natural frequencies.

3.4.4 Production and mock-up

The production of the IB Service Barrel implies the development of a devoted mould and a detailed procedure. The dimensions of the parts requires the use of a large autoclave (2500mm in length, 1000 mm in diameter). This development has started and the design of the mould and of the jig is progressing. The material selected on the basis of the FEA is being procured.

For the verification of all the aspects related to the installation and final positioning a mock-up of the Inner Service Barrel has been realized and is being used.

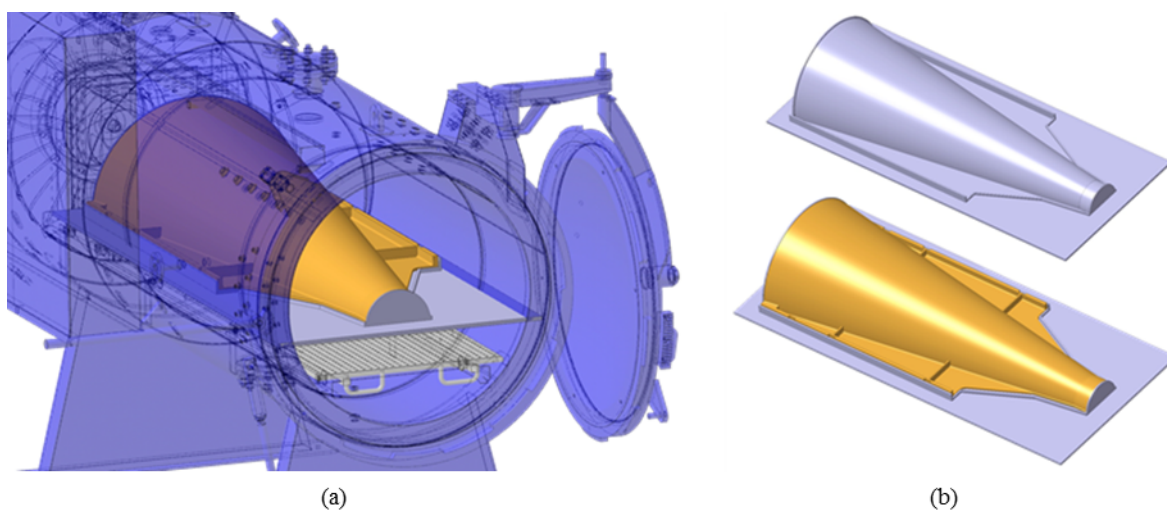


Figure 3.37: Inner Service Barrel production.

(a) CERN EP-DT department autoclave; (b) mould of Inner Service Barrel.

This mould, the High-Temperature Tooling Foam Board, can be used from ambient to high temperatures and under pressure conditions. Blocks can be bonded to make large, complex-shaped tooling. Material is machinable and offers fast surface preparation. It can be used several times with a controlled cool-down rate.

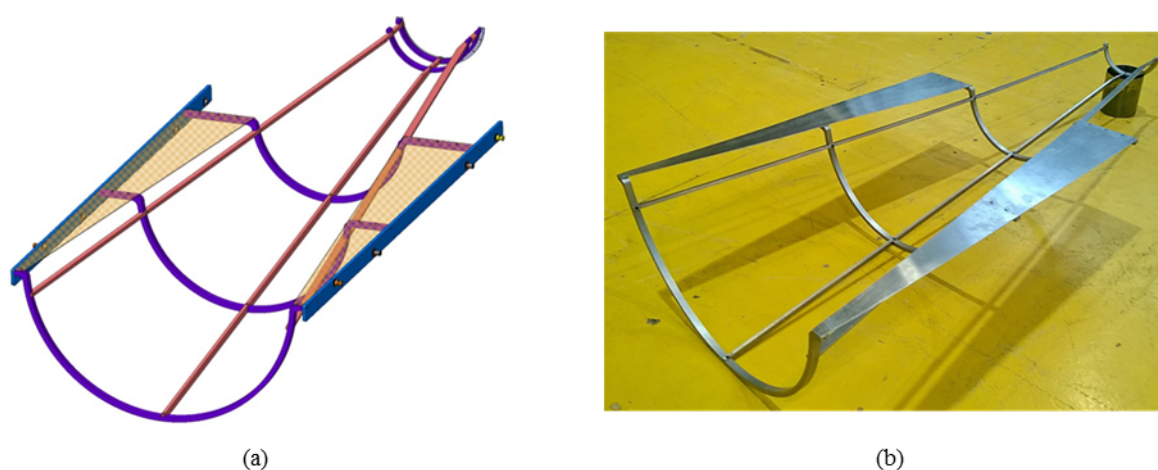


Figure 3.38: Inner Service Barrel mock-up.

(a) 3D CAD model; (b) mock-up done.

3.5 Outer Barrel CYSS analysis

3.5.1 Overview and aim

CYSS Analysis has been performed to ensure that CYSS not only protects the staves from direct contact or impact during assembly and commissioning but also avoids that external loads can be directly transferred to the stave.

The CYSS has to be stiffer than the Stave assembly; similar to two parallel springs, the “K” rigidity of CYSS has to be of a larger order of magnitude respect to the Stave “K” (Figure 3.39).

Three possible designs of CYSS with different lay-up have been compared to find the stiffer configuration, at the same time manufacturing constraints have been also taken into account.

It is then fundamental for this analysis a correct evaluation of the stave stiffness that has been performed through devoted bending and vibrational tests.

The analysis has been presented in the ITS Upgrade-Detector Barrel Mechanics Engineering Design Review on 20th July 2016. [23]

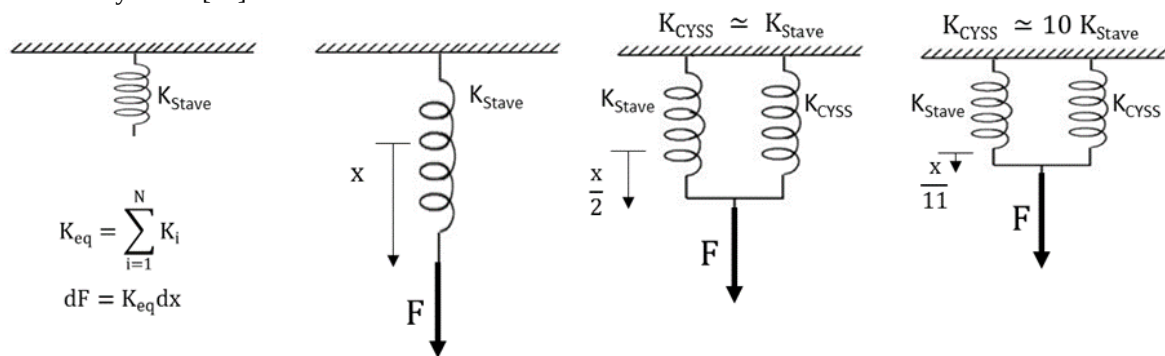


Figure 3.39: CYSS and Stave stiffness behaviour, schematic view.

OB Stave experimental characterisation



Figure 3.40: OB Stave prototype.

(Left) Space Frame and Cold Plate; (Centre) only Space Frame; (Right) only Cold Plate.

Bending test

For the OB Space Frame the mechanical properties of several prototypes were measured. First, the dimensions of a bare Stave and its stiffness were measured. Then, connectors were glued and the stave was mounted on a devoted jig.

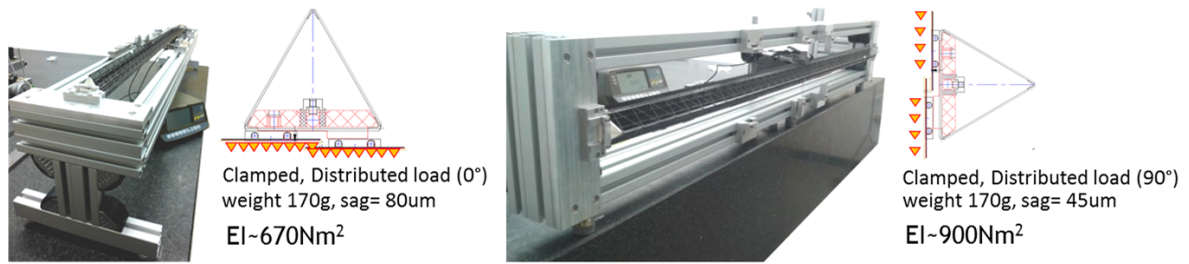


Figure 3.41: OB bending test, set up.

The following formula were used for the flexural stiffness determination:

$$EI = \frac{FL^3}{48f} \quad (\text{Eq. 2})$$

where F is the force, L the length between the supports, f the sag. For the measurement of the bending properties, the ladder was loaded in the middle, with both ends simply supported. The sag was measured for two perpendicular orientations of the ladder.

The sag f of a beam with stiffness factor EI resting on two points with distance L is given by:

$$f = \frac{1}{a} \frac{FL^3}{EI} \quad (\text{Eq. 3})$$

where a is dependent on the type of fixation. Theoretical values are:

- Both ends free, concentrated load at stave middle section $a=48$.
- Both ends fixed, concentrated load at stave middle section $a=192$.
- Both ends free, distributed load $a=384/5$ (with $F= qL$, q =distributed load).
- Both ends fixed, distributed load $a=384$.

The sags measured in the different test configurations, together with the appropriate values for the determined EI , are used to calculate a . It is clear from the values of a that the ideal condition of both-ends-fixed in the stave operational configuration is not obtained.

It is also observed that in the Outer Barrel Stave the Cold Plates glued to the Space Frame slightly increase the overall stiffness of the structure especially in the 90° direction; this is reflected in the increased a value recorded from the test on the fully assembled stave.

Table 3.5: OB Stave bending test; results.

Space Frame		sag[mm]	length[mm]	EI[Nm2]	a	
Free	0° , concentrated load	0.17	1490	676	48	
Free	90° , concentrated load	0.128	1490	901	48	
Expected clamped	0° , concentrated load	0.047	1540		192	expected
Clamped	0° , concentrated load	0.126	1540		72	measured
Expected clamped	90° , concentrated load	0.035	1540		192	expected
Clamped	90° , concentrated load	0.091	1540		74	measured
Stave Full scale 2015						
Expected clamped	0° , concentrated load	0.047	1540		192	expected
Clamped	0° , concentrated load	0.119	1540		76	measured
Expected clamped	90° , concentrated load	0.035	1540		192	expected
Clamped	90° , concentrated load	0.076	1540		89	measured
Expected clamped	0° , distributed load	0.012	1540		384	expected
Clamped	0° , distributed load	0.083	1540		109	measured
Expected clamped	90° , distributed load	0.009	1540		384	expected
Clamped	90° , distributed load	0.047	1540		145	measured

Torsional test

The characterisation of the mechanical resistance to torsion is performed by applying a twisting moment to the specimen and measuring the torsion.

The length measuring system used in this test is a Tesatronic TT20 unit with 0.2 μm accuracy.



Figure 3.42: OB torsional test, set up.

The Middle Layer Space Frame torsional stiffness results are reported in the following Table; the predicted torsional stiffness is $GI_p = 11.5 \text{ Nm}^2$.

Table 3.6: Predicted torsional stiffness for the Middle layer Space Frame.

G[g]	F[N]	M[Nm]	A-B[μm]	$\text{tg}\phi$ [rad]	ϕ	GI_p [Nm ²]
0	0	0	0	0.000	0.000	0.00
40	0.39	0.041	152	0.003	0.003	11.71
60	0.59	0.062	232	0.005	0.005	11.5
80	0.78	0.082	304	0.006	0.006	11.71
120	1.18	0.124	470	0.01	0.01	11.36
180	1.77	0.185	704	0.015	0.015	11.37

For the Outer Layer Space Frame the experimental torsional stiffness is reported in the following Table and it is $GI_p = 11 \text{ Nm}^2$.

Table 3.7: Predicted torsional stiffness for the Outer layer Space Frame.

G[g]	F[N]	M[Nm]	A-B[μm]	$\text{tg}\phi$ [rad]	ϕ	GI_p [Nm ²]
0	0	0	0	0.000	0.000	0.00
40	0.39	0.041	280	0.006	0.006	10.78
60	0.59	0.062	420	0.009	0.009	10.78
80	0.78	0.082	540	0.011	0.011	11.71
120	1.18	0.124	840	0.018	0.018	11.78
180	1.77	0.185	1240	0.026	0.026	10.95

The complete Outer layer stave composed by the Space Frame and two Cold Plates was also tested and the results are reported below. The experimental torsional stiffness for the fully Stave is $GI_p = 11.5 \text{ Nm}^2$.

Table 3.8: Experimental torsional stiffness for the fully Stave.

G[g]	F[N]	M[Nm]	A-B[μm]	$\text{tg}\phi$ [rad]	ϕ	GI_p [Nm ²]
0	0	0	0	0.000	0.000	0.00
40	0.39	0.041	230	0.005	0.005	13.12
60	0.59	0.062	370	0.008	0.008	12.23
80	0.78	0.082	490	0.010	0.010	12.31
120	1.18	0.124	780	0.016	0.016	11.61
180	1.77	0.185	1130	0.024	0.024	12.02

Stave dynamic characterisation

For the determination of the first natural frequency of the 1.5m stave a sine sweep was applied through an electromagnetic shaker and vibration recorded by accelerometers

Resonance Search was performed between 5 - 500 Hz. At 0,1g.

Two accelerometers on the test fixture were used as control, while a central low mass accelerometer placed on one of the Cold Plate was used to record the stave response.

Table 3.9: Shaker

N.	Equipment	Manufacturer	P/N	S/N
1	Ling Electronics - SHAKER: L.E 335; AMPL: DMAX; S/N:128	Ling Electronics	C335	2016
2	Controller SCADAS SCM05V	LMS		53121107



Figure 3.43: OB Stave vibration test, accelerometers set up.

Table 3.10: Accelerometers

CH	ModelAcc	Manufacturer	S/N	SENSE mV/g
1	KS 94-100	MMF	4032	102,51
2	KS 94-100	MMF	4035	101,24
10	352C23	PCB	LW173544	5,29

Frequency Response Function for the measurement point and respect to the control points are reported below. The analysis was performed first on the naked stave structure and was then repeated with a mass simulator of the HIC and Power Bus that will equip the stave.

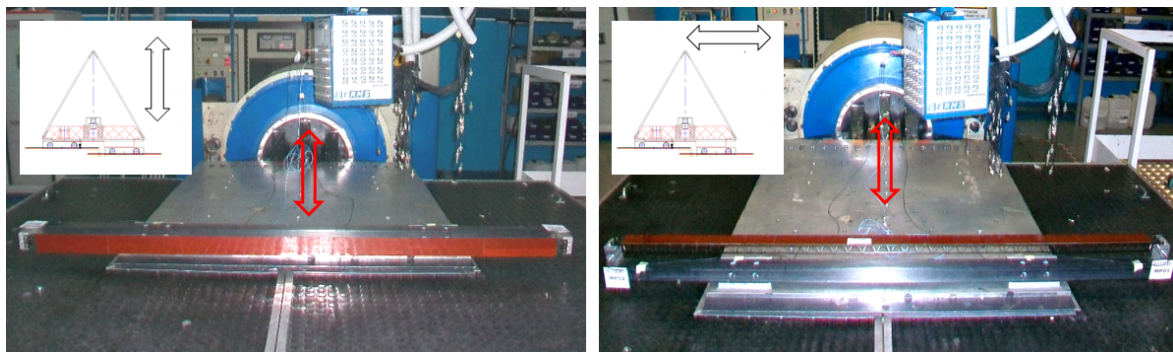


Figure 3.44: OB Stave vibration test, overall set up.

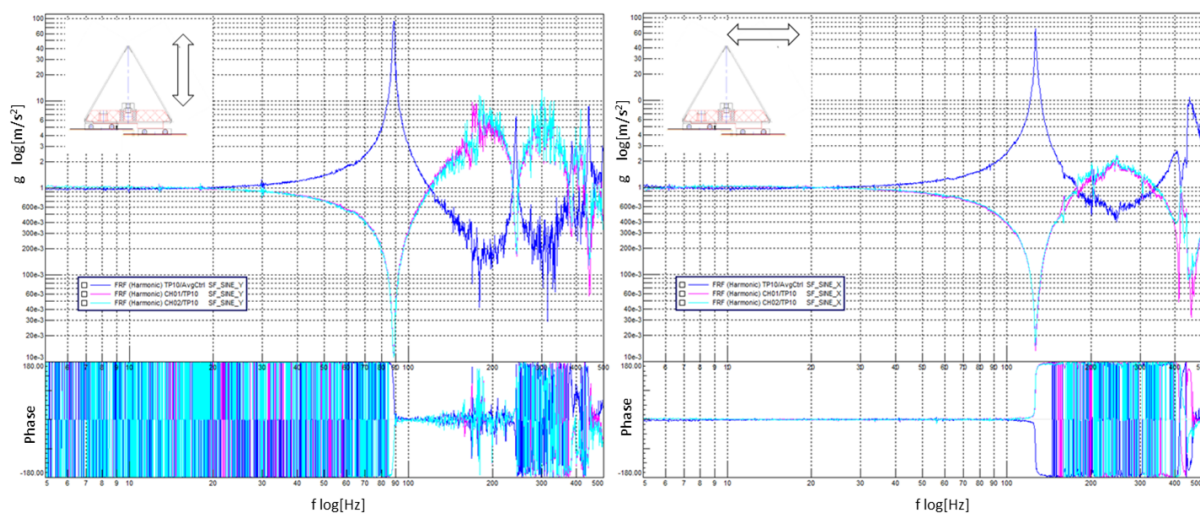


Figure 3.45: OB naked Stave vibration test, results.
(Left) 1^o natural frequency 88.6 Hz, out of plane; (Right) 1^o natural frequency 126.6 Hz, in plane.

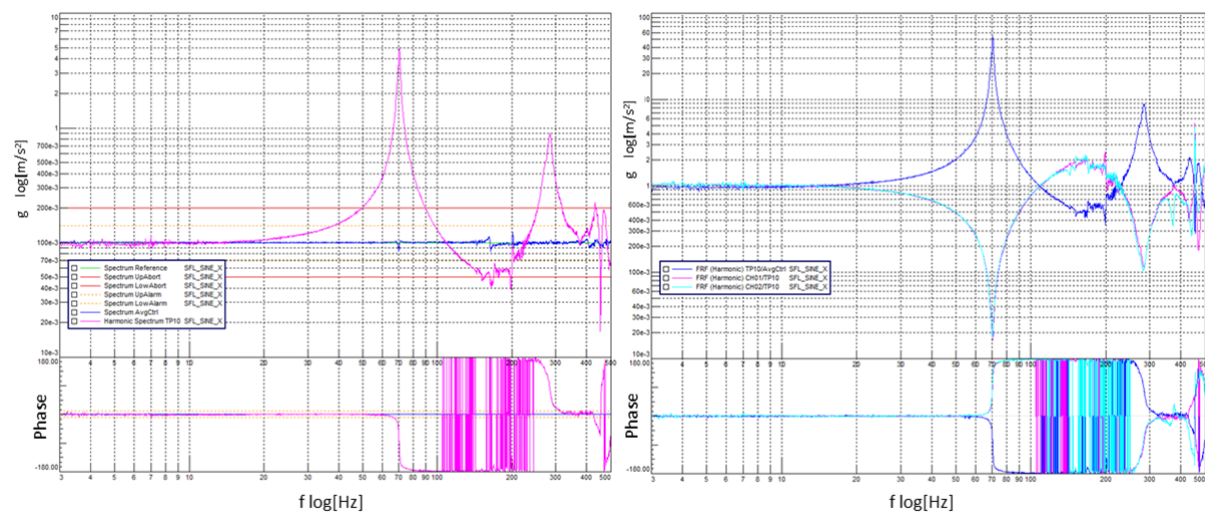


Figure 3.46: OB Stave vibration test with mass simulator, results.
(Left) 1^o natural frequency 88.6 Hz, out of plane; (Right) 1^o natural frequency 126.6 Hz, in plane.

3.5.2 Model

Geometry

Half of the Detector Barrel has been considered in the analysis such to simplify the FE model, based on the symmetric properties of the structure and of the applied loads. CYSS and End-wheels have been reduced to shell surfaces while for the Staves beams representation have been used, similar to what was presented for the IB Stave shown in section 3.3.2 . In first approximation connectors and other services of the Detector Barrel have not been take into account.

Mesh and contacts

Elements used are SHELL281 and BEAM188 (Appendix B.3). Most of the components are free meshed due to the presence of a lot of features and holes; a good mesh quality has been achieved by tuning the mesh parameters. Simple part like CYSS and COSS have been mapped meshed.

To have a light model, contact between EW6 and CYSS have been deleted merging the two structures in a single one, an accurate lay-up of surface has been done to do not loose stiffness properties of these part.

Different EW are connected by mechanical triangular connectors and bolts, these elements have been simulated using beams for bolts and shell for the triangular connectors. The EW and Triangular connectors matching holes are fixed by using joints connection (Appendix B.4), this type of connections is shown below.

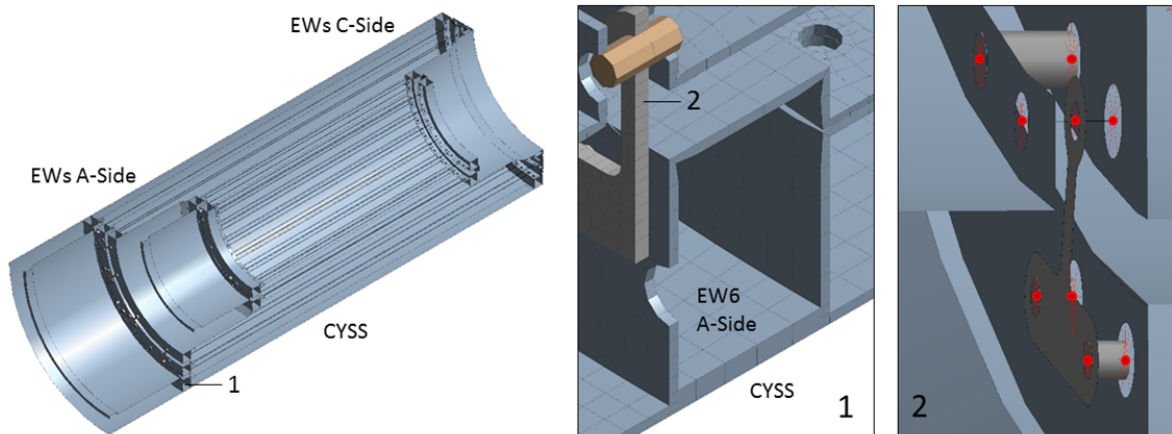


Figure 3.47: Outer Detector Barrel, geometry and mesh.
(Left) OB Detector overall model; (Centre) detail of the mesh and EW6 and CYSS merged; (Right) details of the triangular connectors and the beam connections between layers.

Boundary condition

The aim of the analysis is to perform a comparative analysis in term of torsional stiffness between the Stave assembly in the barrel configuration and the torsional stiffness of the CYSS itself. Goal is to achieve a torsional stiffness for the CYSS that exceed the Stave assembly stiffness.

Therefore regardless of the real load a torsional load has been applied at the A-side while keeping fixed the C-side. The evaluation of the rotation at the opposite side C-side provides the torsional stiffness in the different configurations.

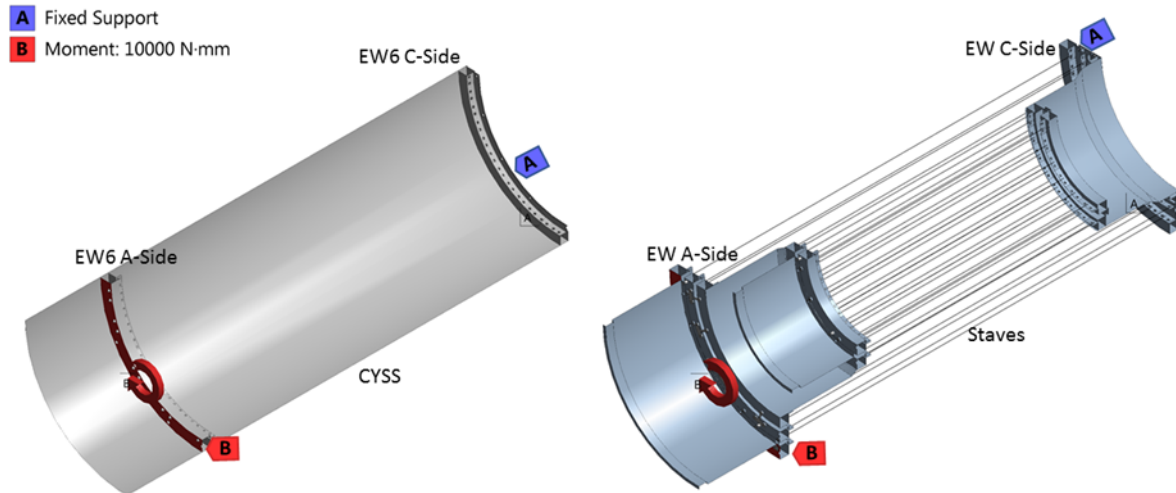


Figure 3.48: OB CYSS boundary conditions.
(Left) CYSS and EW6; (Right) EWs and Staves

OB Staves simulation

The OB OL staves have been simulated with beam elements (Figure 3.49). Beam elements properties (Areal inertial properties, Young and Shear Modulus) have been tuned on the basis of experimental results (bending and torsional test) performed on the stave.

A good approximation has been reached by using isotropic material properties for the beam:

- Material
 $E=32.5 \text{ GPa}$, $G=10.9 \text{ GPa}$, $\rho=1420 \text{ Kg/m}^3$.
- OL Geometry properties
 $A=105.2 \text{ mm}^2$, $I_{yy}=10380 \text{ mm}^4$, $I_{xx}=5878 \text{ mm}^4$, $I_{xy}=-527 \text{ mm}^4$, $J=1054.5 \text{ mm}^4$, $L=1540 \text{ mm}$.

For ML staves same material have been used, and same stiffness properties.

Beam elements representing the staves have been coupled to the End-wheels by coupling the DoF through Joint connections (Appendix B.4).

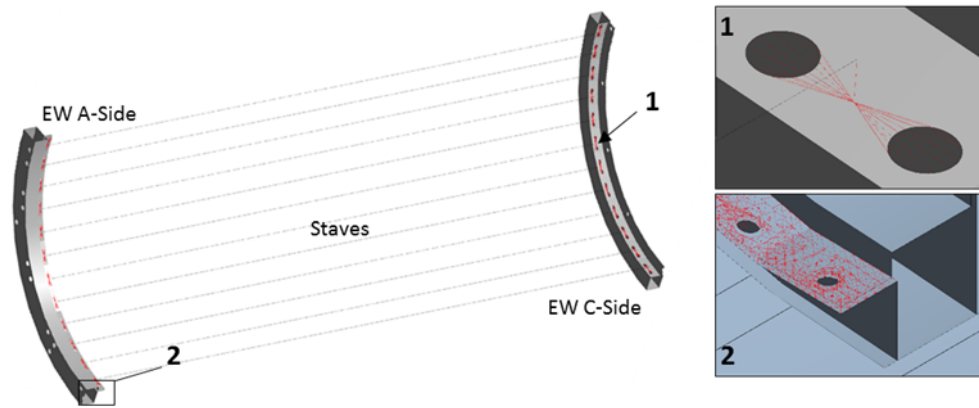


Figure 3.49: OB Stave simulation.

Joints connections are shown in the detail 1 while an example of bonded contact (MPC) between the two “lips” is shown in detail 2.

3.5.3 Analysis procedure

Based on test results, the material of the End-wheels can be compared to an isotropic material with:

$E=50 \text{ GPa}$; $\nu=0.3$, $\rho=1450 \text{ Kg/m}^3$.

This material has been used in all the simulations for the EWs, while for triangular connectors titanium has been used.

The boundary conditions for the fully assembled barrel with Staves and no CYSS, described in the previous paragraph, were applied to predict the maximum deformation that has been used for a comparison with the CYSS behaviour.

The CYSS has been studied with the whole Layer 6 keeping the same boundary condition.

Three possible designs of CYSS with different lay-up of this has been compared to find the best one taking into account construction procedure too. They have been so called: Cylindrical Laminate and Sandwich, Waved Laminate.

Cylindrical Laminate and Sandwich designs geometry have similar shape, the difference are in the thickness and in the lay-up. The Cylindrical Laminate one is a laminate made by a lay-up of several carbon plies, while the Sandwich has a sandwich layout made by two skins of different carbon plies and a core of different foam types.

The Waved laminate Design has a different geometry, in this case the CYSS is split in 2 different laminate glued together, one with a cylindrical shape and the other one with waved shape glued to cylindrical one.

Material used for lay-up of different design are: T300 6K prepreg woven (Carbon ply) [20] , Rohacell 51 and Rohacell 110 IG (Foam) [19]; see Appendix C.3.

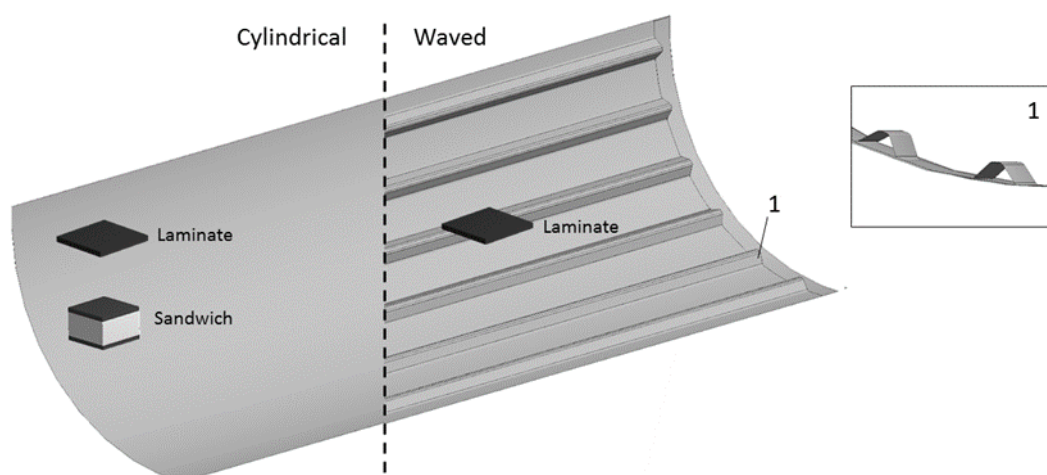


Figure 3.50: Designs of OB CYSS with different lay-up.

3.5.4 Results

The sandwich option results to be the best solution that provides a stiffness for the CYSS larger than the Detector Barrel Stave assembly, the results of the other options are shown in Appendix D.2.

Other options that could improve the torsional stiffness, have been considered, like the use of a sandwich design with waved shape for the skin and a filled gap between the two skins with foam. For construction complexity finally they have not been taken into account in the optimisation analysis.

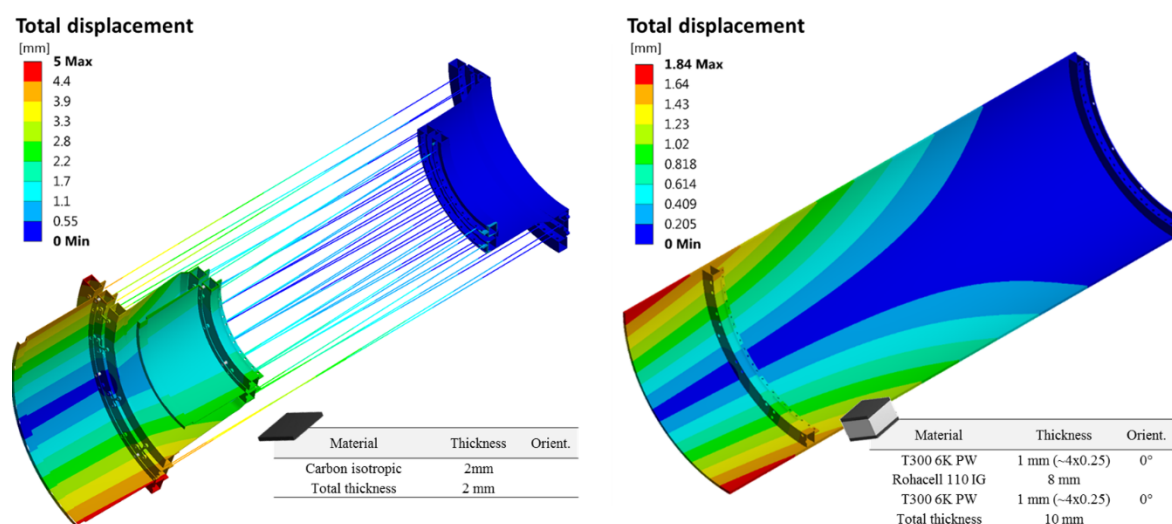


Figure 3.51: OB CYSS analysis, results.

3.6 Outer Barrel overall analysis

3.6.1 Overview and aim

The aim of this analysis is to predict the maximum sag; verify that is in an acceptable range, and find the first component that goes in resonance. A first analysis has been performed based on solid model and mesh. This new analysis has also the aim to compare new results with the old ones. The old results shows a maximum sag that is more than $400\mu\text{m}$ in the Stave Layer 5. If this is again confirmed, the new analysis should find the compliant parts that lead to this maximum sag.

The analysis has been presented in the ITS Upgrade-Detector Barrel Mechanics Engineering Design Review on 20th July 2016. [24]

3.6.2 Model

The model is the same used for the CYSS analysis; except the boundary conditions. To simulate the real block the model displacement has been blocked as shown in the figure below. The C-side End-Wheel has been blocked in Z Y direction while A-side ones only in the Y direction.

Symmetry condition has been adopted for the half structure. The load condition consists in the Barrel own mass under the acceleration gravity.

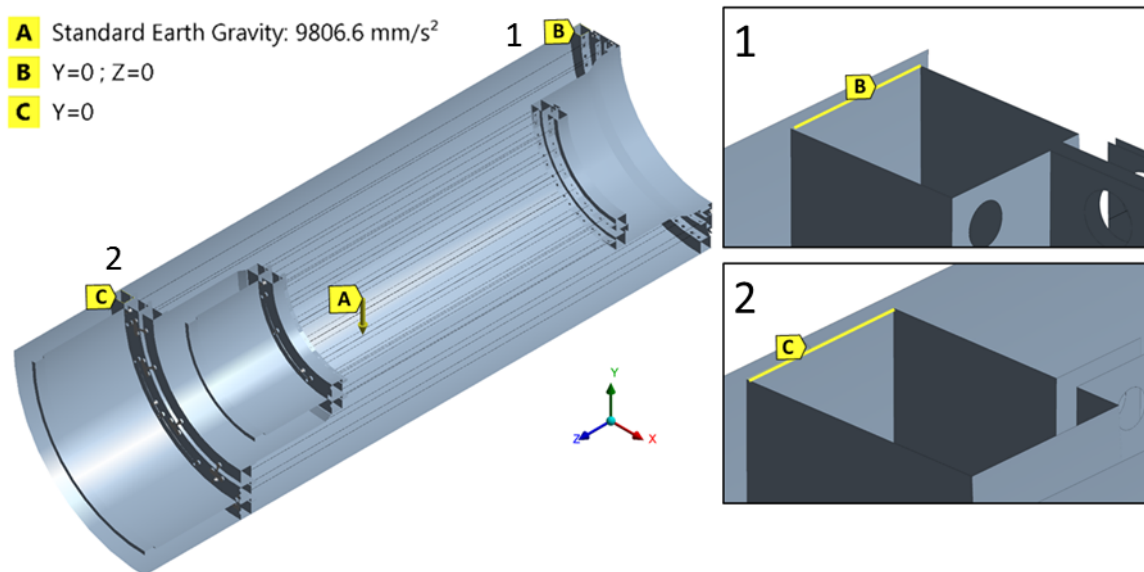


Figure 3.52: OB Detector overall, boundary conditions.

3.6.3 Results

The analysis was compared to the previous results; the new results confirm the same order of magnitude of the maximum displacement and the location of where it occurs (in the central Stave of Layer 5).

A detailed components analysis has find out that the problem is in the End-wheel geometry and stiffness.

The EW geometry has a “lips” shape that provides a compliant support to the fixation of the Stave ends.

This move the Stave far away from the ideal nominal configuration in which the Stave ends are rigidly blocked on the EWs. The results of that is an increase of the sag of the Stave whose maximum is reached in the middle.

Based on these results the geometry support has been changed to a similar shape of EW6 C-side to achieve a better rigidity, see Figure 3.54.

Modal analysis shows that the lowest resonance frequencies, the first at 34 Hz belongs to the staves while the CYSS first natural frequency is at 97 Hz.

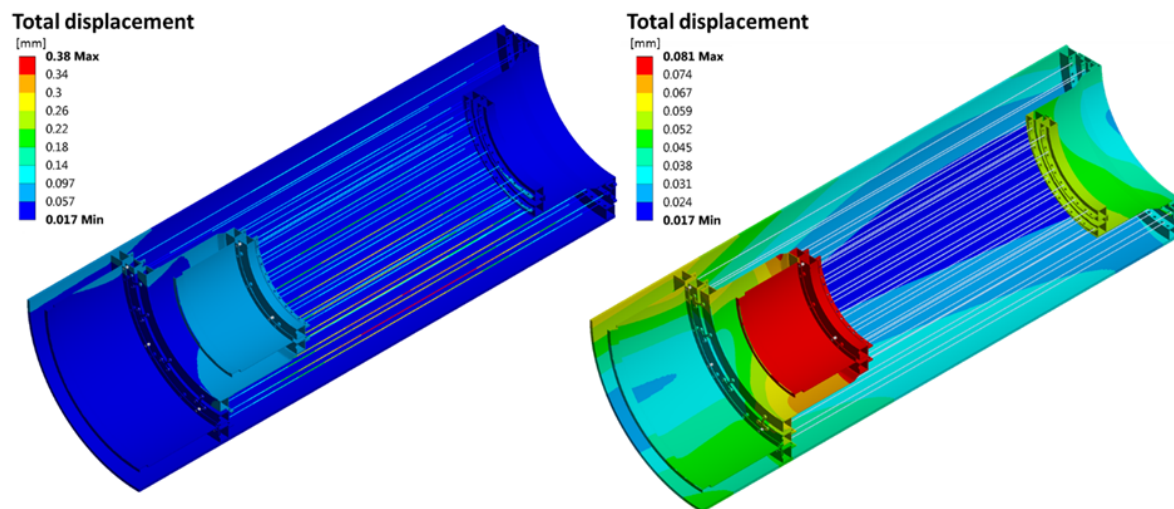


Figure 3.53: Outer Detector Barrel total displacement.
(Left) Overall; (Right) End-Wheel and CYSS only.

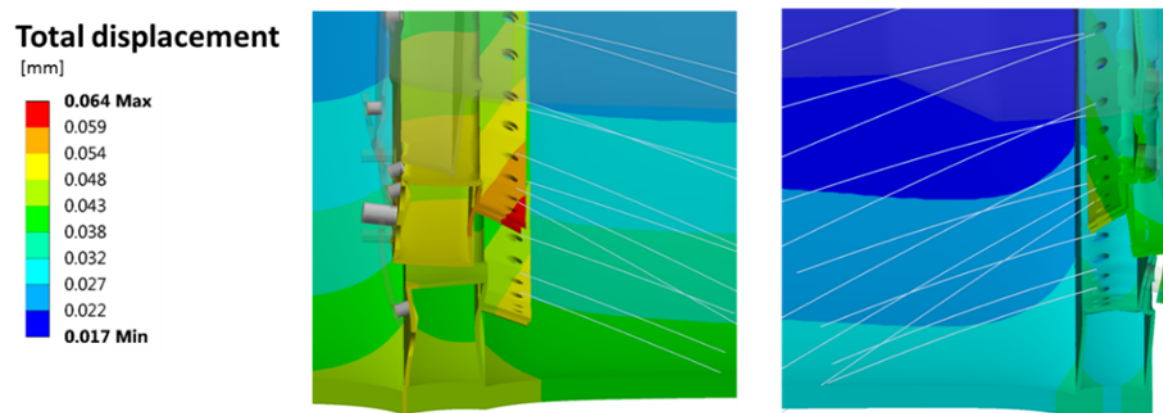


Figure 3.54: Outer Detector Barrel total displacement, End-Wheels 5 and 6 details.
(Left) A-Side; (Right) C-Side. (~x1000 zoom)

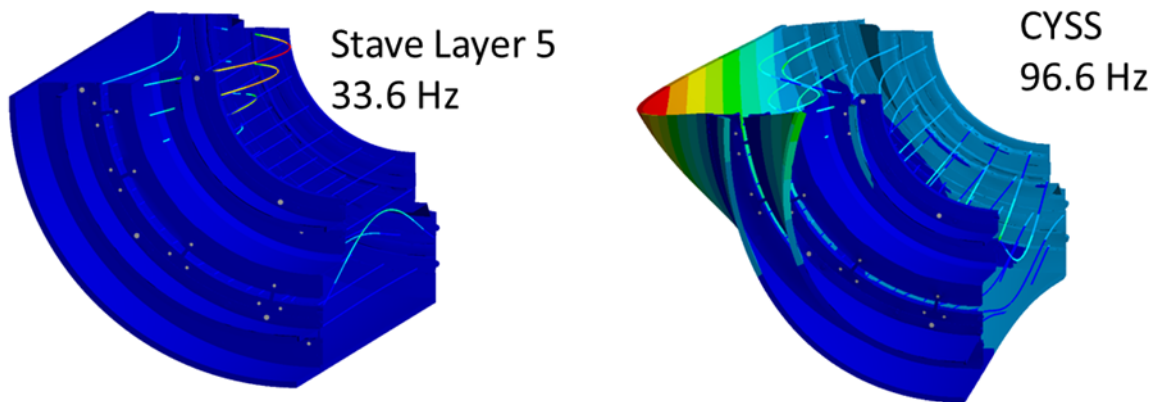


Figure 3.55: OB Detector modal analysis results.

In the Figure in the left the First resonance frequency is shown, and it occurs in the Staves of the Layer 5 that is less blocked. In the Figure on the right the First resonance frequency that occurs in the CYSS is shown.

3.6.4 OB EW prototype and mock-up

A Prototype of the EW for Layer 5 and 6 has been produced based on the FEA performed. Load test have been performed to verify the overall stiffness of the parts. The EW has been loaded with a force at one extremity, while the other has been blocked.

The recorded displacements have been used to calculate the EW stiffness. The test has been repeated but changing the load direction.

The prototype has been also used to validate the procedure used to install all the staves on the two opposite EW. A 3D printed mock-up have been also produced to be used in a further step of verification of the services routing at the end of the stave.

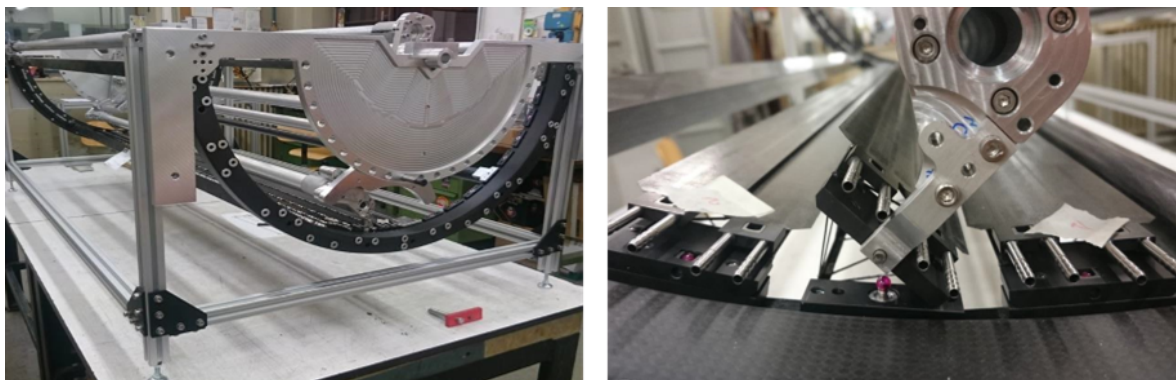


Figure 3.56: OB EW prototype and Stave assembly.
(Left) Jig for the assembly; (Right) Detail of Stave and EW assembly.

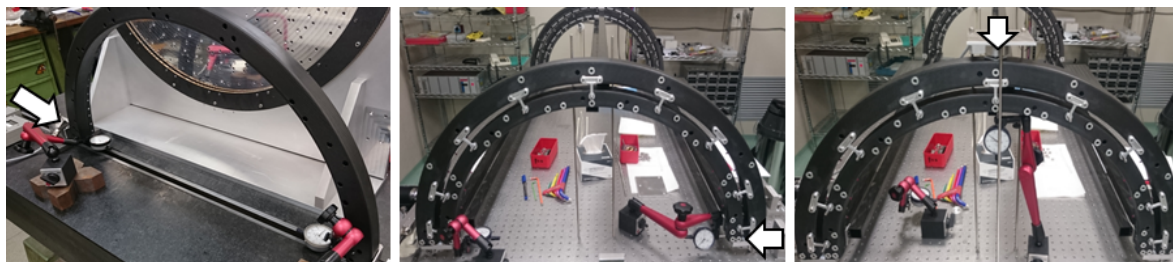


Figure 3.57: OB EW prototype, during measurement.
Measurement on a single wheel to tune simulations gives as isotropic elastic dummy material modulus $E \sim 50-55$ GPa.

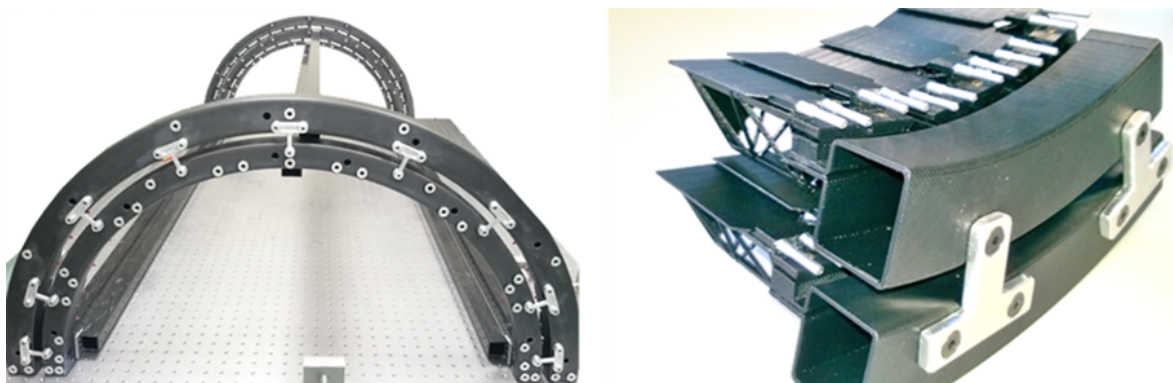


Figure 3.58: OB EWs assembly.
(Left) Carbon prototype; (Right) 3D printed mock-up.

For the verification of all the aspects related to the installation and final positioning a mock-up of the Outer Barrel has been realized and is being used.

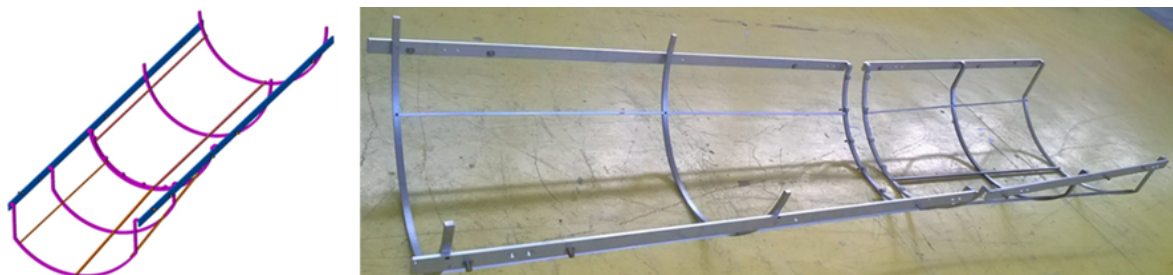


Figure 3.59: Outer Barrel mock-up.
(Left) 3D CAD model; (Right) mock-up done.

3.7 Beam pipe support analysis

3.7.1 Overview and aim

The aim of this analysis is to improve the stiffness of the beam pipe support structure, such to minimize the detector sag; the supports under investigation are support B and support C, the two supports that are directly connected with the Cage structure.

In a first step the beam pipe has been blocked with ideal support in order to have a starting reference point.

Then a model based on solid elements and averaged isotropic material has been developed for the beam pipe supports (Baseline). After that a shell model has been used in order to take into account the lay-up of composite materials. The results of the shell model and solid model are consistent.

The composite lay-up for the beam pipe supports has been optimized to minimize the beam pipe sag and to get closer to the ideal supports case.

3.7.2 Ideal supports

Model

A simplified shell geometry has been used for beam pipe, the whole surfaces have been mapped using quadratic and quadrilateral mesh elements, SHEEL281 (Appendix B.3). Thanks to the symmetry in the YZ plane the model has been cut and the corresponding symmetry boundary conditions have been inserted.

The constraints are applied in B and C, that simulate the ideal two supports on the Cage, they block X and Y displacement and left free the Z one.

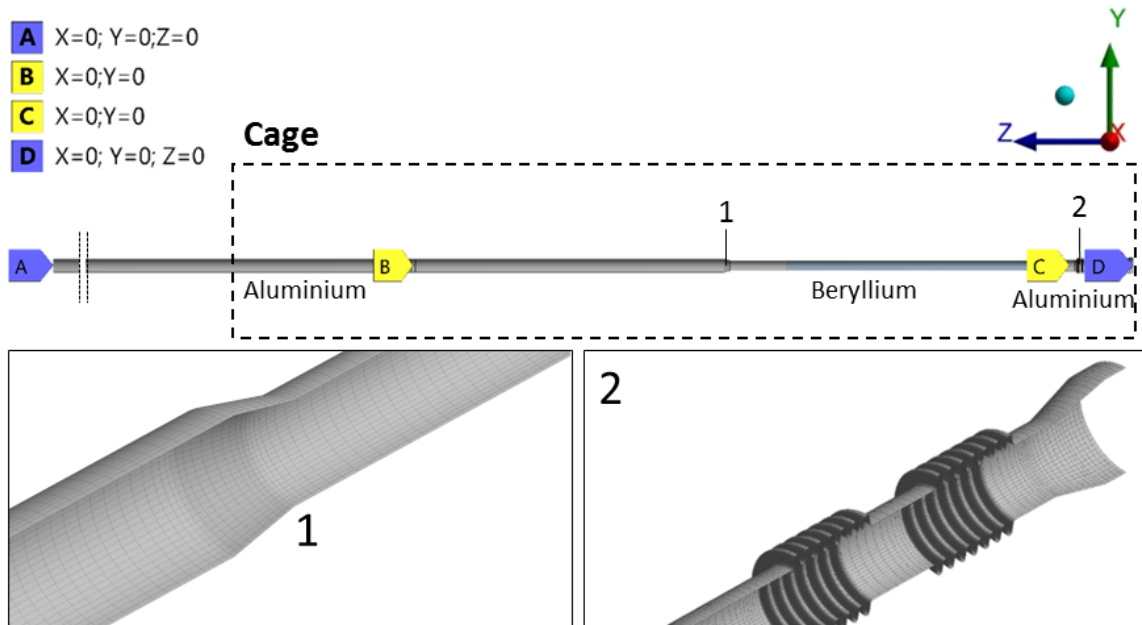


Figure 3.60: Beam pipe ideal case, mesh and boundary conditions.

Results

The beam pipe ideal case results show a maximum sag around 0.2mm in the beam pipe aluminium section ($D_o=52\text{mm}$), while near the interaction point (Beryllium part) the maximum sag is around 0.1mm.

The first natural frequency is around 40 Hz and while the second ones is around 50 Hz. All results are compatible with the other one of previous analysis for the Technical Design Report [5].

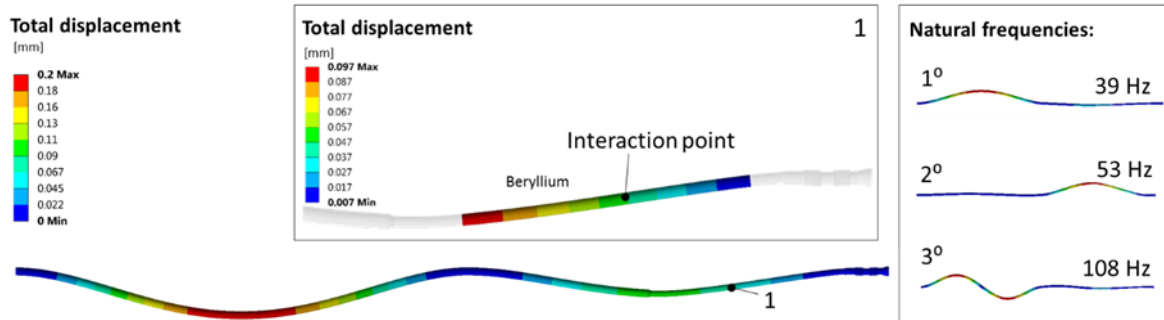


Figure 3.61: Beam pipe ideal case, results.

3.7.3 Baseline

Model

Quadratic solid elements SOLID186 and a mapped mesh have been used to simulate the supports.

The two material used are carbon fibre prepreg for the skins and Foam (Rohacell 51 IG) for the core; the carbon fibre material is simulated by using isotropic material properties ($E= 50 \text{ GPa}$, $\nu=0.3$, $\rho=1450\text{Kg/m}^3$) in a first approximation.

For contacts between supports and beam pipe No-separation ANSYS contact (based on pure-penalty contact) has been used (Appendix B.4). This contact left that the two surfaces in contact slip between them but they cannot detach between them.

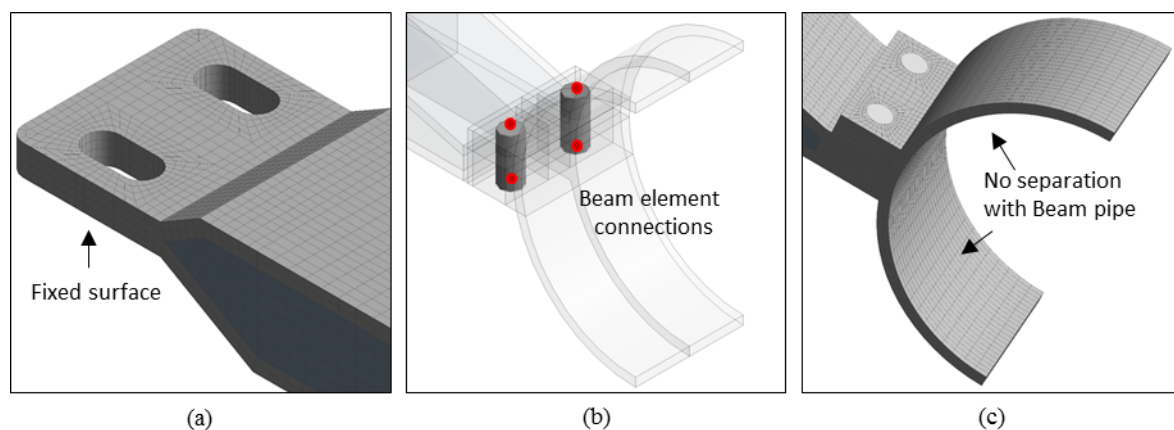


Figure 3.62: Beam pipe supports solid, boundary conditions.

(a) Fixed surface on the support; (b) Beam elements connection between up and down support B; (c) No separation contact between support B and beam pipe.

Results

Figure 3.63 shows a beam pipe maximum sag near the support B, due to the effect of the compliance of the support that is far from the ideal case of infinitely rigid constraint. A similar effect but of much lower entity is observed at the support C, where the limited length assure a larger stiffness.

A simulation with the support B under its own and without the beam pipe has been performed to understand its behaviour; the results (Figure 3.63 3) shows that its deformation is around 0.1mm; this provide the evidence of the compliance of this component.

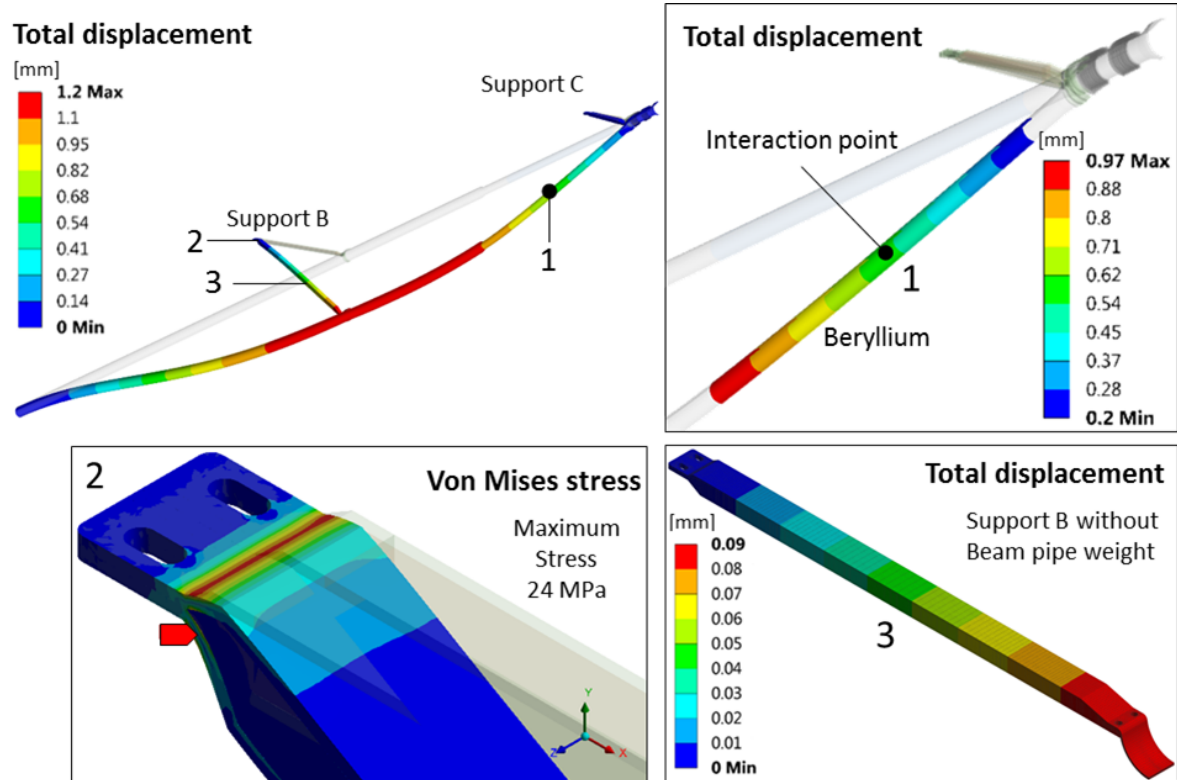


Figure 3.63: Beam pipe solid, results.

Detail 2 shown that the maximum stress is on the end of the support B while detail 3 signals how support B has an important deformation under own weight already.

3.7.4 Optimisation

In order to minimize the sag of the beam pipe, the optimization work has been focused on the support B that is the most critical due to its length and its limited thickness. Once the composite lay-up of the support B has been finalized the same lay-up could be adopted for the less critical support C.

A model of the support B fully based on shell elements has been used for this study.

The results obtained with the shell model and lay-up similar to the Baseline are compatible with those obtained with the solid model in a range of 10% of error (the maximum sag is 1.1 mm instead of 1.2mm).

The optimisation process based on thickness and materials tuning had to take into account the limit imposed by the geometrical layout of the detector that leaves a very limited volume for the development of the supports.

The support B has been divided in 5 main surfaces that have the same lay-up configurations, described in Figure 3.64 and the total thickness of the surface S2, S3, S4, S5 and S6 can't be changed as anticipated before.

The materials used can be divided by their location in three main categories: carbon skin, foam core and carbon central. A step by step optimisation of these three categories has been carried out and a final lay-up optimisation has been performed.

Materials with high elastic modulus have been considered such as carbon fabric prepreg and unidirectional prepreg with high modulus fibres (M46J, M55J and K13C2U [25]) and stiffer foam (Rohacell 110 IG and 300 WF [19] [22]). A correct elements orientation has been implemented such to account for the unidirectional material opposite properties in x and y direction. The use of unidirectional plies implies the use of at least a fabric ply to guaranty the external protection of the plies.

Results

Thanks to use of unidirectional material, an acceptable configuration has been found, the maximum displacement on the beryllium part is around 0.2mm, only 0.1mm more than the ideal support case. These results have been considered in a first mock up to verify if in the installation procedure the beam pipe achieve a good position. Further adjustments can be done by using shims on the fixation points of the supports. The modal analysis show a first natural frequency around 27 Hz, to be compared to 39 Hz of the ideal support. Another effect that can be seen from the results is the different modal shape of the beam pipe that reflects the more compliant real support.

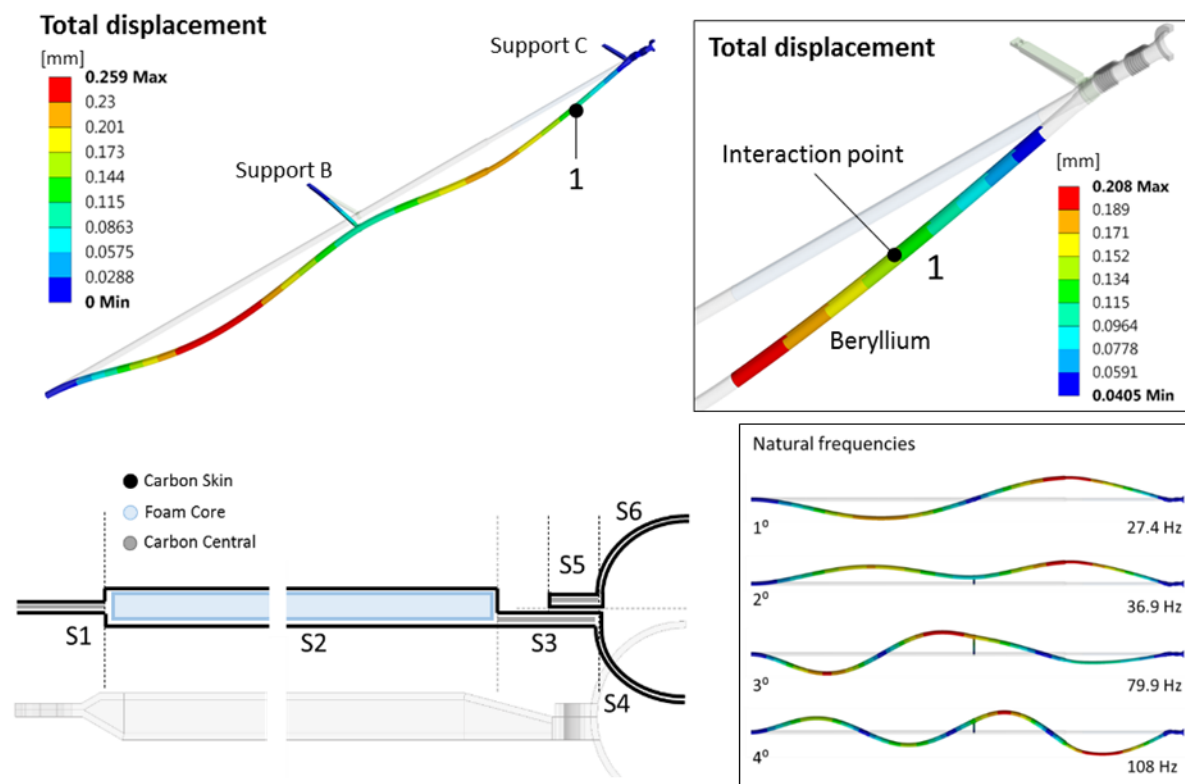


Figure 3.64: Support B optimization, results.

3.8 Cage analysis

3.8.1 Overview and aim

The Cage is the component that supports the weight of all the different Detector Barrels; the aim of this analysis is to verify that the maximum stress in the rail do not exceed the material strength, with a safety margin, and to predict the maximum sag.

The assembly of the Cage with the Detector Barrels is hold by the TPC detector rings. In order to limit the TPC deformation the Cage has to be as light as possible but at the same time has to fulfil the stiffness and strength requirements. For this reason the geometry of the rails and their material has to be optimized.

3.8.2 Model

Geometry

The geometry of the parts does not allow to use a light model (such as an entire shell and beam model), in particular the rail geometry has to be necessarily meshed by solid elements while for the other parts (Guide box, End cap, Barrel-up and Barrel-down) shells have been used. Half of the Cage has been considered based on the symmetric properties of the structure and of the applied loads. Elements used are SOLID186 and SHELL281.

Rail cannot be mapped and a particular procedure has been adopted to improve the mesh quality in the critical parts like the rails stops. Tetrahedrons elements have been used to cover the entire rail, the maximum element size is 10 mm; after that a detailed mesh of the rail stop parts have been created by using “sphere of influence” and “part element size” options with a respectively 1.5 and 1 mm as size elements and hexa elements (Appendix B.2).

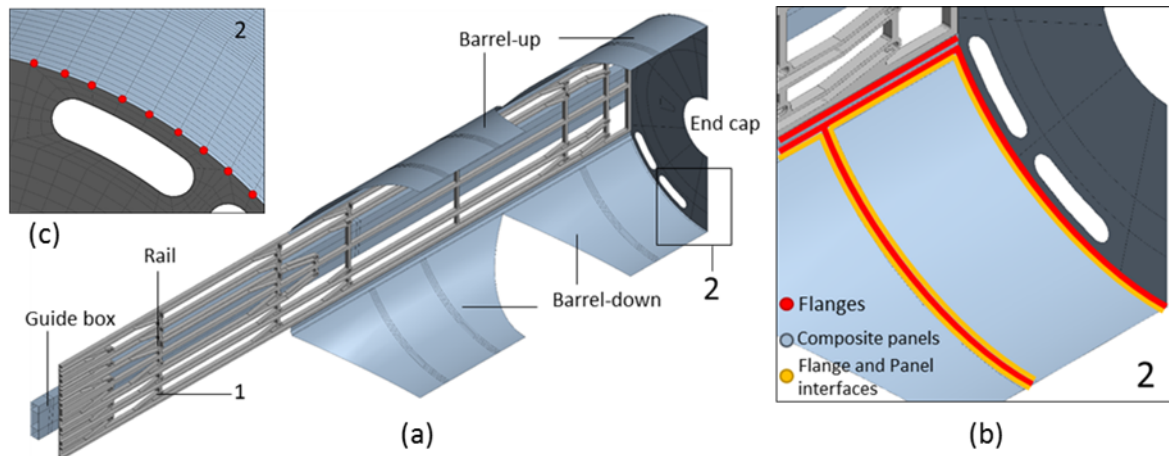


Figure 3.65: Cage model.

(a) Half Cage; (b) detail of different lay-ups in the Barrel-down; (c) detail of the mesh connection between Barrel-up and End Cap.

The shell elements have been mapped and a correct orientation and lay-up have been used. Materials and lay-ups used for Barrel-up, Barrel-down and End Cap are Rohacell 51 IG and T300 prepreg woven.

MPC contacts (Appendix B.4) have been used to connect shell elements with solid once while the nodes of shell parts such as Barrel-down and End Cap, have been merged.

Boundary conditions

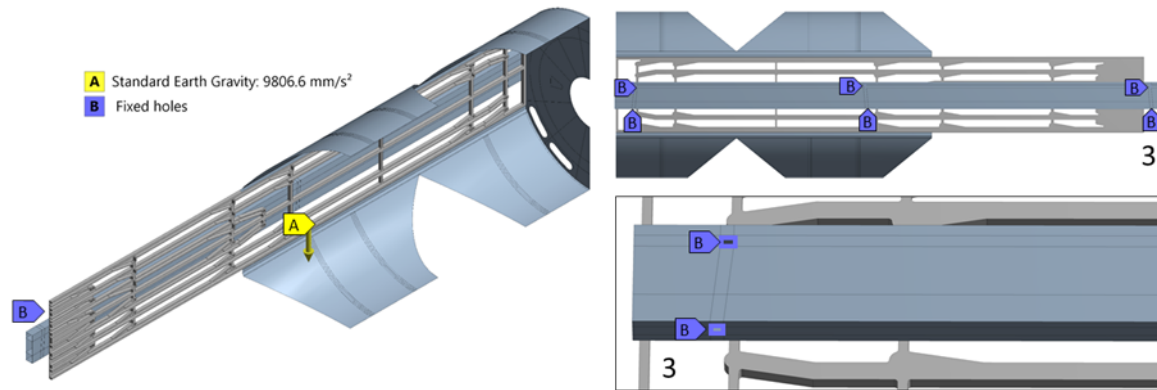


Figure 3.66: Cage boundary conditions.

The Guide boxes have been blocked at the holes positions where the Cage is in contact with TPC. The load condition consists in the Cage weight and in the loads of the barrels components. All the barrels weight is supported by the Cage and this has been simulated by applying the computed reaction forces on the surfaces of the rails support holes, where the barrel rollers are engaged.

The reaction forces have been calculated by an approach based on beam theory. A beam element has been used to simulate each Barrel, the barrel mass has been applied as distributed load, and the reaction force calculated at the rail stop. These forces have been applied in the Finite Element Model at the rail stops surfaces and displacements and local stress distribution have been evaluated. In Appendix D.5 the approximations and results of loads conditions described are shown.

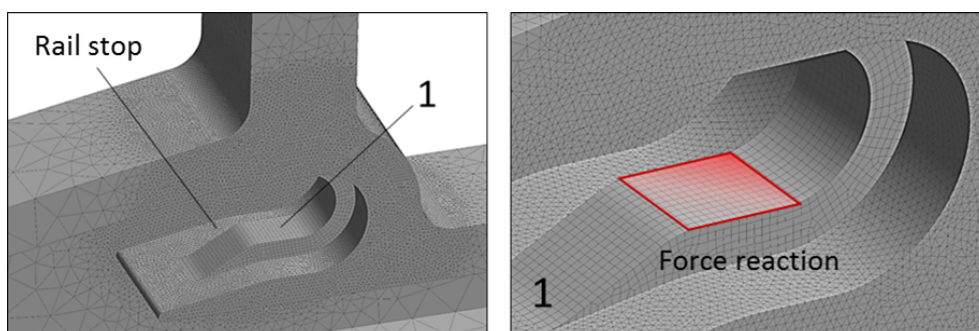


Figure 3.67: Rail stop, mesh.
(Left) Entire rail stop; (Right) Detail of rail stop.

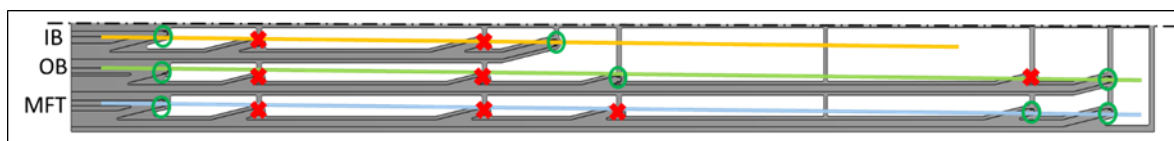


Figure 3.68: Position of reaction forces on the rail.

3.8.3 Results

Due to the mesh complexity an iterative solver has been used, PCG solver (Appendix B.5).

In Figure 3.69 the Cage displacements are shown. The largest deformations are predicted at the Barrel-up and Barrel-down parts, their entity is irrelevant from mechanical and functional point of view. The largest deformation of the rails is localised on the A-side. This is due to the fact that no flanges supports are in this side because of their interference with the TPC bore during the installation. The predicted displacements are acceptable and do not influence the Cage functionality.

For what concern the rails stops, the most critical point is the central rail stop of the Outer Barrel; this is due to the large weight of this barrel and to the fact that this is the support with the smaller thickness respect to the other ones. The maximum displacement and maximum stress (Von Mises stress) in this support are respectively $32\text{ }\mu\text{m}$ and 33 MPa . In the other supports of the barrel there are no relevant stress or deformations.

For a conservative analysis an additional load case has been considered assuming the full half Detector Barrel load (64 kg) applied to the cage critical rail stop. The results show a maximum stress around 95 MPa that considering the yield strength of the Aluminium 5052 (192 MPa) gives a margin of safety larger than 2.

The results indicate that the rail structure is oversized and it is possible then to reduce material thickness such to create a lighter Cage model. Other lighter materials, such as carbon peek, have not been considered due to the size of the component (not available on the market) and the necessity to machine the rails out of a single plate in order to avoid losing accuracy by assembling two or more plates.

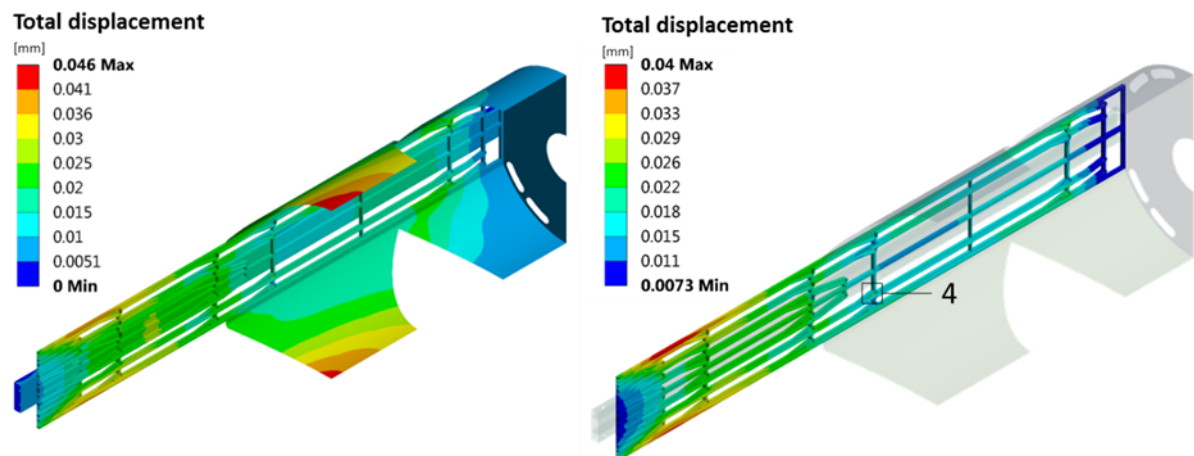


Figure 3.69: Cage displacement, results.
(Left) Entire Cage; (Right) Only rail.

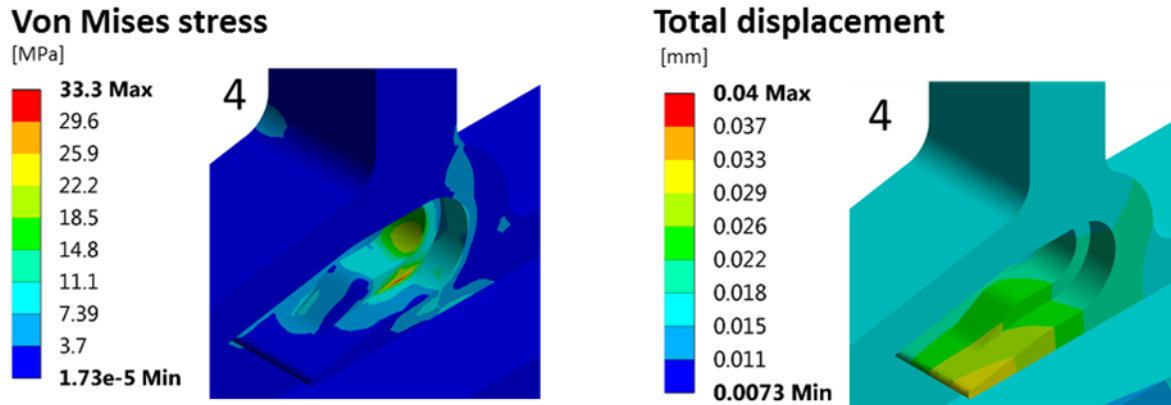


Figure 3.70: Critical rail stop, results.
(Left) Von Mises stress; (Right) total displacement.

3.8.4 Mock-up and light model

A Mock-up of the cage for the installation test has been realised. It is made by Aluminium 5052 and is shown in Figure 3.71.

The insertion in the Cage of the Inner Barrel and Outer Barrel mock-up has been tested. The sliding along the rails, the clearance with the beam pipe support and the final position stability have been exercised.

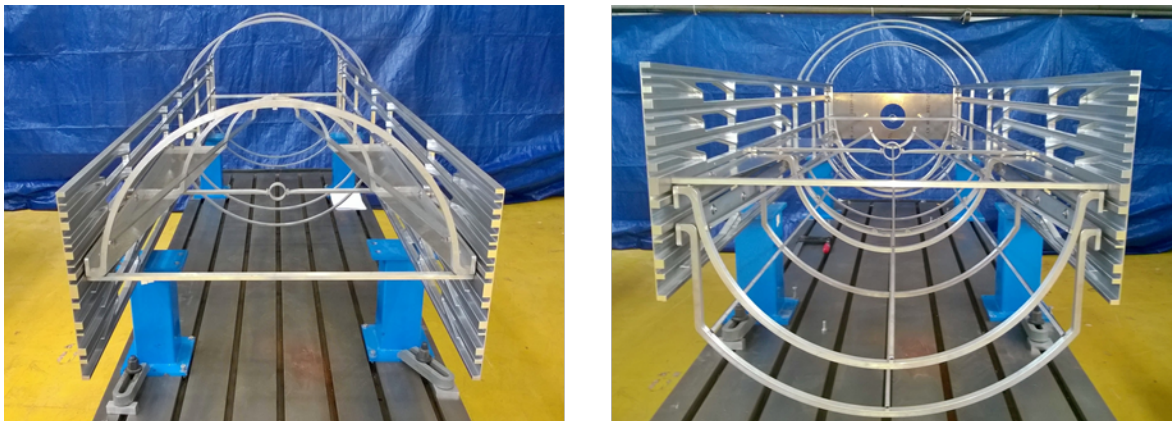


Figure 3.71: Cage mock-up.
(Left) IB Half Barrel inside the Cage in the Top position;
(Right) IB and OB Half Barrel inside the Cage in the Bottom position.

Summary

The accurate positioning of the chips and their final mapping are crucial aspects for the construction of the new Tracker.

In this thesis a semi-automatic program has been developed to control a measuring machine that will assist the chip positioning and survey. The program has been developed specifically for the Outer Barrel Staves that cover a length between 1000mm and 1500mm for a total number of chip per Stave that 102 and 196 respectively

The use of semi-automatic programs for the assembly and for the survey of the different components of the Outer Barrel Stave is crucial to guarantee the accuracy and the repeatability of the detector construction constituted by 192 Staves.

The program will permit to speed up the entire procedure and to avoid human errors such as crashes of the probe and accidental contacts between the parts to be assembled. Thanks to the use of dialog window and scheduled interruptions of the program the user is always guided along the different assembly steps such to avoid that any of them is skipped by mistake or a component is erroneously aligned. Any of this faulty step would result in rejecting the full Stave.

The program has been adopted to control the different CMM machines in the 5 assembly centres in Europe and in USA responsible for the construction of the Staves.

The Staves spatial distribution, to form a barrel of several layers, is realized by the detector mechanical support that has to fulfil conflicting requirement of high stiffness and minimum material.

The use of the most advanced structural materials, like carbon fibre composite laminate or sandwiches, has been preferred. The possibility to tailor the material properties in the maximum expected loaded direction permits to reduce the material thickness while achieving high mechanical stability.

In this thesis a detailed structural analysis has been performed to drive the design of the different mechanical parts, by individuating the most stressed component, by evaluating their deformation under the expected load and by optimising the fibre orientation and the plies stratification.

The analysis performed has led to the definition of the manufacturing drawings and to the final material choice, which have been used for the construction of the first prototypes.

The mechanical characterisation of these prototypes has permitted to verify the analysis performed and to further improve or to finally validate the proposed design.

Specific aspects of the design have required a deep investigation and several iterations, like for the Inner Barrel where the Detector Barrel is hold in position as a cantilever structure such to minimise the material in the detection area. The optimisation of the geometry at the connection of the Detector Barrel to the supporting Service Barrel, the minimisation of the weight of the Detector Barrel structure, and the choice of carbon prepreg as well foam with higher stiffness, represent some of the relevant subjects of the analysis of the Inner Barrel.

For the Outer Barrel the analysis has been used to define an optimised layout of the main cylindrical outer shell CYSS, as well to change the design of the EW at the interface with the Staves, such to increase the 1500mm Stave stability.

An optimisation of the Cage structure, where the rails for the insertion and positioning of the Detector Barrels are housed, has permitted to optimise the geometries and to sensibly reduce the material. The supports of the beam pipe inside the Cage, whose thickness and layout are heavily constrained by the minimum space available and minimum material budget requirement, have been optimised by increasing their stiffness through the choice of materials and through the optimisation of the lay-up.

The analysis has also provided a full modal characterisation of the different parts that precisely locate the first natural frequency of vibration of each of them. These characterisation will be used for a further step of verification that will be based on the acquisition of the environmental vibration in the ALICE cavern and the determination of the structure resonances that could affect the detector i.e. the sensor stability

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Appendix A

ITS Upgrade layers layout

A.1 Nomenclature

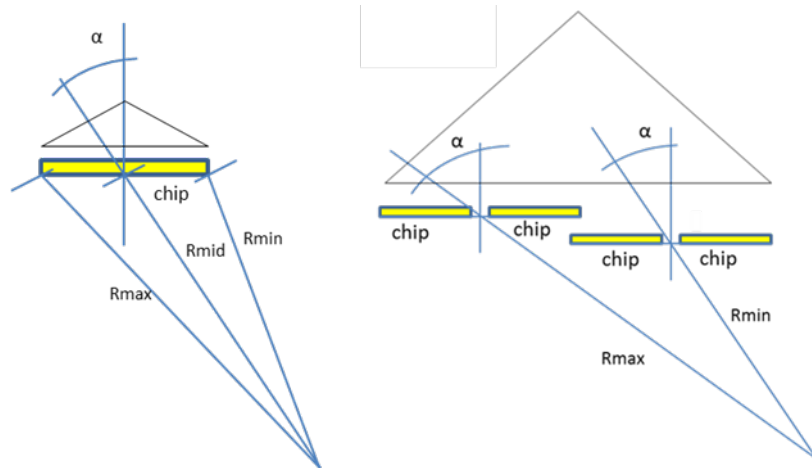


Figure A.1: Nomenclature of Stave radius and angle.
(Left) Inner Stave; (Right) Outer Stave.

A.2 Inner Layers layout (IB)

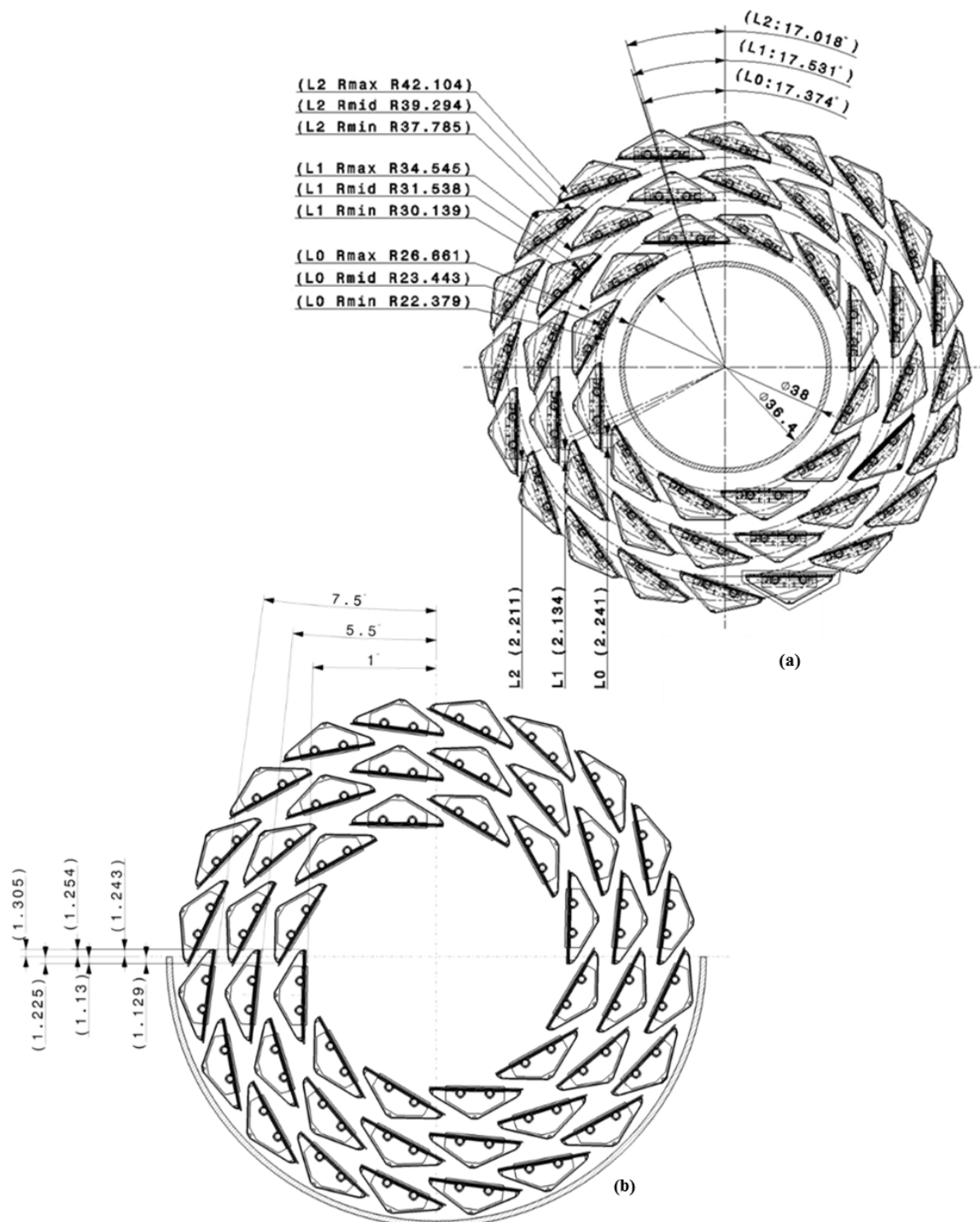


Figure A.2: Inner Barrel Stave layout.
Installation radius [mm], installation angles [rad].

A.3 Middle Layers layout (OB-ML)

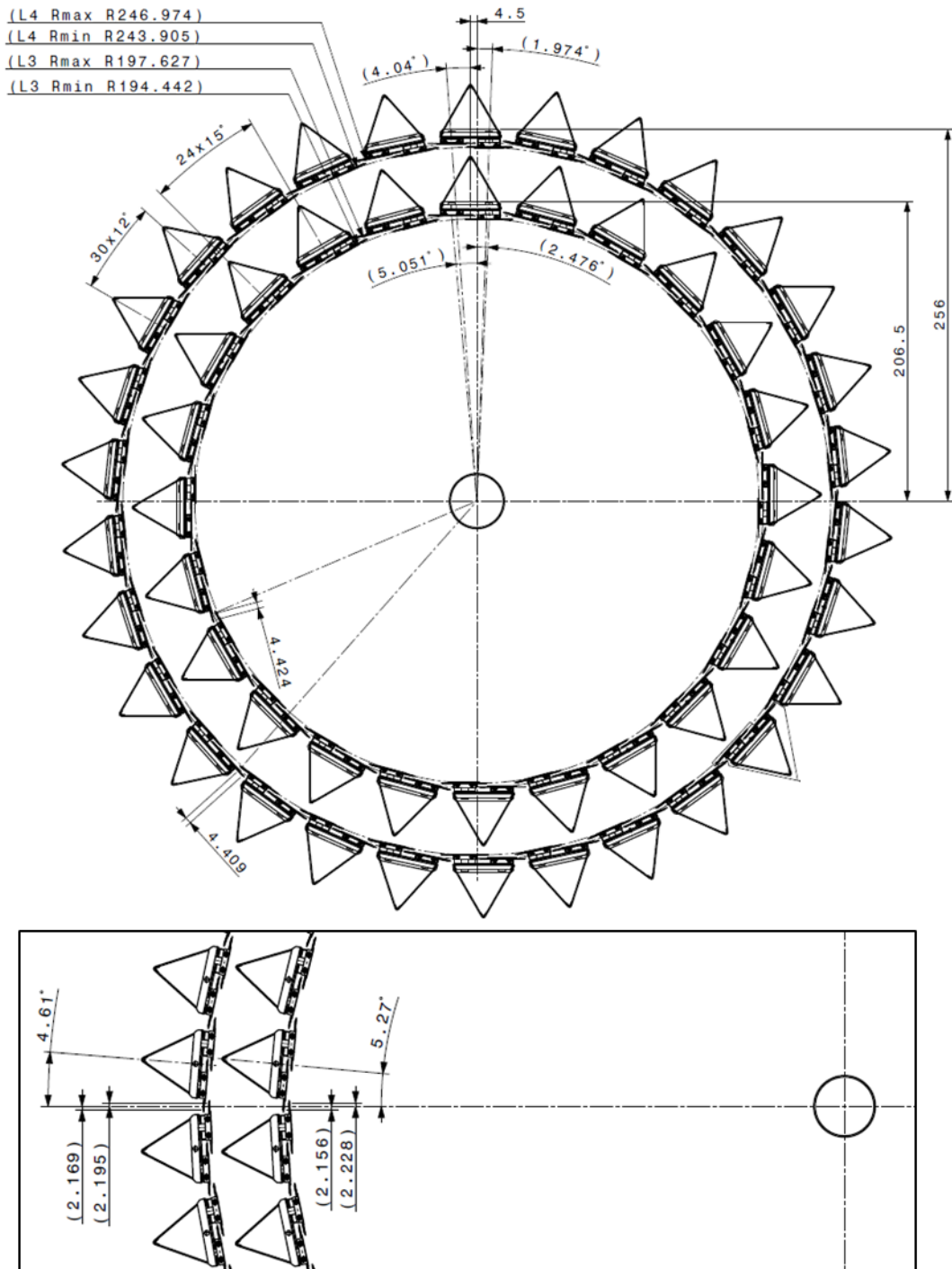


Figure A.3 : Middle layers layout.
Lengths [mm]; angles [rad].

A.4 Outer Layers layout (OB-OL)

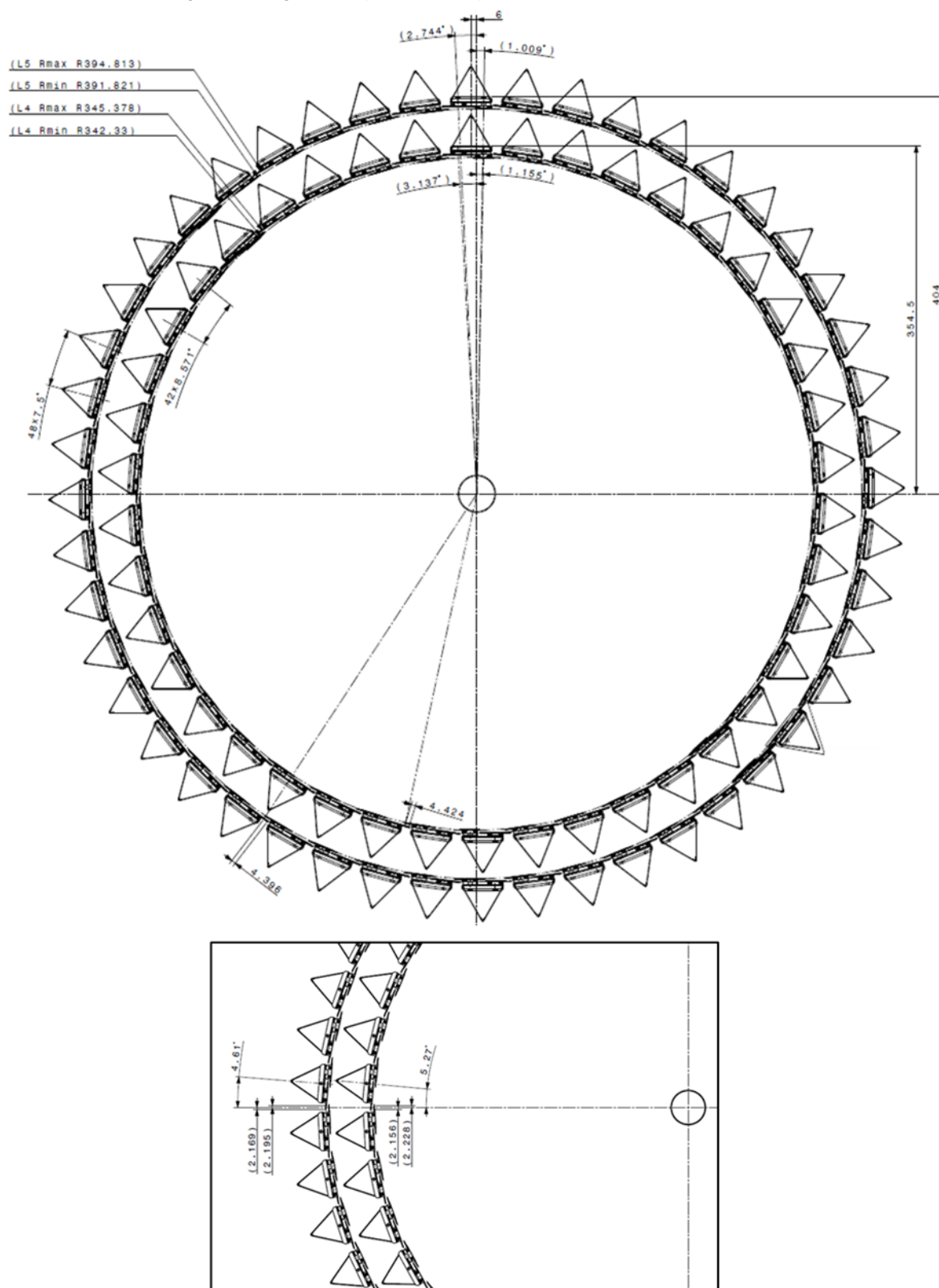


Figure A.4: Outer layers layout. Lengths [mm], angles [rad]

Appendix B

About ANSYS

B.1 From Elastic theory to FEM

The partial differential system equations Elastic theory are strong forms of the governing system of equations for solids. The strong form, in contrast to a weak form, requires strong continuity on the dependent field variables (the displacements u , v and w in this case). Whatever functions that define these field variables have to be differentiable up to the order of the partial differential equations that exist in the strong form of the system equations. Obtaining the exact solution for a strong form of the system equation is usually very difficult for practical engineering problems.

A weak form of the system equations Elastic theory is usually created using energy principle method.

The energy principle can be categorized as a special form of the variational principle which is particularly suited for problems of the mechanics of solids and structures. A more general mathematical tool applicable, in principle, for solving all kinds of partial differential equations is the weighted residual method.

The weak form is often an integral form and requires a weaker continuity on the field variables. Due to the weaker requirement on the field variables, and the integral operation, a formulation based on a weak form usually produces a set of discretized system equations that give accurate results, especially for problems of complex geometry.

The finite element method is a typical example of successfully using weak form formulations. Using the weak form usually leads to a set of well-behaved algebraic system equations, if the problem domain is discretized properly into elements (finite elements). Interpolation within the elements is achieved through shape functions, such as linear and quadratic shape functions to approximate the field variables.

An assembly of element-level equations is subsequently solved, in order to establish the response of the complete domain to a particular set of boundary conditions.

For more details see “The Finite Element Method, a practical course, 2003, G.R. Liu and S. S. Quek” [26]

B.2 Meshing process

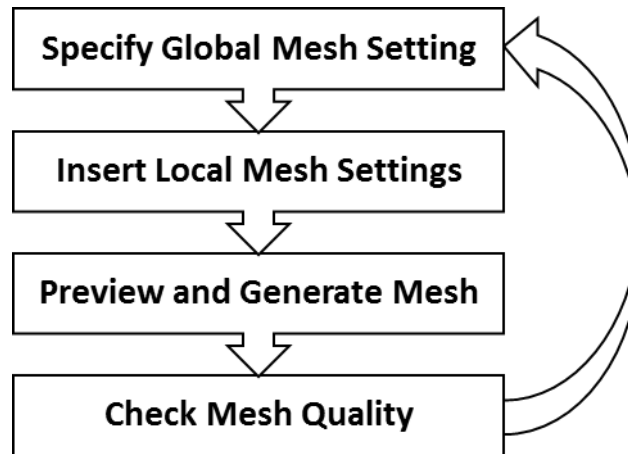


Figure B.1: Meshing process, flow chart.

A general Meshing Process in ANSYS Meshing is shown in the Figure above; the circle process has the aim to achieve a good mesh quality based on the studies to be done. Thanks to the Global Meshing Controls, the program can automatically calculate global element sizes based on the smallest geometric entity and smart default can be chosen based on physics preference selected. Then global adjustments has to be made for required level of mesh refinement.

Defaults

Physics Preference	Mechanical
Relevance	0

Advanced

Number of CPUs for Parallel Part Meshing	Program Controlled
Shape Checking	Standard Mechanical
Element Midside Nodes	Kept
Straight Sided Elements	No
Number of Retries	Default (4)
Extra Retries For Assembly	Yes
Rigid Body Behavior	Dimensionally Reduced
Mesh Morphing	Disabled

Sizing

Use Advanced Size Function	On: Proximity and Curvature
Use Fixed Size Function For Sheets	No
Relevance Center	Medium
Initial Size Seed	Full Assembly
Smoothing	Medium
Transition	Slow
Span Angle Center	Coarse
Curvature Normal Angle	20.0 °
Num Cells Across Gap	Default (3)
Proximity Size Function Sources	Faces and Edges
Min Size	1.0 mm
Proximity Min Size	1.0 mm
Max Face Size	5.0 mm
Max Size	5.0 mm
Growth Rate	Default
Minimum Edge Length	0.500340 mm

Figure B.2: Global Meshing Controls.

Local Meshing Controls are used to control the mesh locally, they depend on the mesh method used. The mesh could require just one or combination of methods.

For solid elements the mesh can be splitted in two main categories:

- *Tetrahedrons mesh*: the elements used are tetrahedrons, these mesh can be based on two main different algorithms. Patch Confirming Algorithm is a bottom up approach, meshing process starts from edges and faces to arrive in the volume; while Patch Independent approach is a top down approach, volume is meshed first and projected on to faces and edges.

- **Hexahedrons mesh:** The elements used are hexahedrons. This mesh reduces element count and then the run time. The elements can be well aligned reducing the numerical error. Hexahedrons mesh requires a clean geometry and could requires a geometrical decomposition first. Methods that belong to this category are: *Sweep Meshing*, *Multizone Meshing*.

Shell elements can be *Quadrilateral* or *Triangles* elements and methods are based on Patch conforming or Patch Independent again.

Local Meshing Controls are used to control and force the methods algorithms. It is possible to control the sizing of geometry elements.

There are different type of Sizing controls: *Element Size* type specifies average element edge length on bodies, faces or edges; *Number of Divisions* type specifies the number of elements on edge(s). To have a non-uniform division of edges (grading of elements towards one end, both end, or the centre) *Bias* option can be used. . Two different options to define Bias are available, one based on Bias Factor (the ratio of the largest element to the smallest element) and the other one based on Growth Rate (ratio between size of an element and size of the previous one). It is possible also to set the average element size around a selected vertex or point by defining a sphere radius and element size (*Sphere of Influence* option).

Mapped face meshing can be done by forcing the algorithm to build a mapped face with defined characteristic.



Figure B.3: Sizing controls.
Growth Rate = Bias Factor n^{-1} , with n number of divisions.

correction factors. The element uses an equivalent energy method to compute shear-correction factors. These factors are predetermined based on the section lay-up at the start of solution.

The element formulation is based on logarithmic strain and true stress measures. The element kinematics allow for finite membrane strains (stretching). However, the curvature changes within a time increment are assumed to be small.

SOLID186

SOLID186 is a higher order 3-D 20-node solid element that exhibits quadratic displacement behaviour. The element is defined by 20 nodes having three degrees of freedom per node: translations in the nodal x, y, and z directions. The element supports plasticity, hyperelasticity, creep, stress stiffening, large deflection, and large strain capabilities. It also has mixed formulation capability for simulating deformations of nearly incompressible elastoplastic materials, and fully incompressible hyperelastic materials.

SOLID186 Homogeneous Structural Solid is well suited to modelling irregular meshes (such as those produced by various CAD/CAM systems). The element may have any spatial orientation.

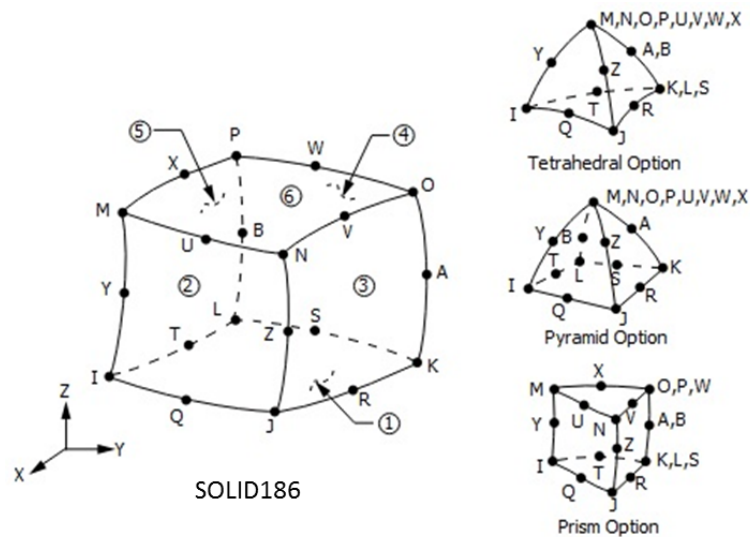


Figure B.5: SOLID186 element.

For more detailed information about these elements, see ANSYS Help Documentation; in the Mechanical APDL Theory Reference paragraph [27].

B.4 Contacts and connections used

ANSYS Contacts

Contact elements can be thought of as a “skin” covering the surfaces that are expected to interact with one another. One side of a contact pair is referred to as the “contact” and its mate as the “target”.

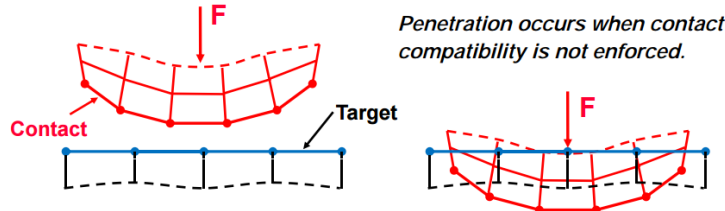


Figure B.6: Contact and target surfaces.

Bonded and No Separation contact are linear and require only one iteration.

- **Bonded:** surfaces are fixed to one another so no gaps can open and no sliding takes place.
- **No separation:** no gaps can open however small sliding can take place.

In order to enforce compatibility at the contact interface, Workbench Mechanical offers several different contact formulations. In our model two different contacts formulation have been used:

- **Pure penalty:** it is penalty-based contact formulation:

$$F_{\text{Normal}} = K_{\text{Normal}} X_{\text{penetration}} \quad (\text{Eq. 4})$$

The finite contact Force, F_n , is a concept of contact stiffness, k_{Normal} . The higher the contact stiffness, the lower the penetration, x_p , as illustrated in Figure B.7. Ideally, for an infinite k_{Normal} , one would get zero penetration. This is not numerically possible with penalty-based methods, but as long as x_p is small or negligible, the solution results are accurate.

- **Multi-Point Constraint (MPC):** MPC internally adds constraint equations to “tie” the displacements between contacting surfaces. This approach is not penalty-based or Lagrange multiplier-based. It is a direct, efficient way of relating surfaces of contact regions which are bonded. Large-deformation effects are supported with MPC-based bonded contact.

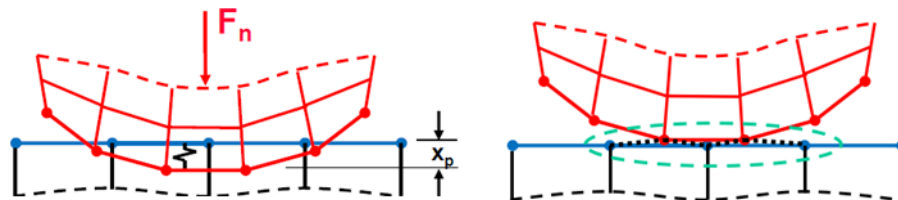


Figure B.7: Contact formulations, schematic view.
(Left) Pure penalty; (Right) Multi-Point Constraint.

Mesh Connection

The mesh connection feature allows to join the meshes of topologically disconnected surface bodies that may reside in different parts. With mesh connections, the connections are made at the mesh level and tolerance is based locally on mesh size. Connections are made edge-to-face or vertex-to-face; they connect edge(s) or vertices on face(s) to another face to pinch out the gap and create conformal mesh between the edge(s) and face(s).

Joint

The joint feature in ANSYS Mechanical provides an alternative to contact when simulating the interaction between bodies or to ground (fixed) locations. Joints are constraint equations useful to simulate different behaviour of coupling such as to block determinate displacements and maintain free others.

Beams

Beams elements are useful to connect parts without insert a so strong contact between them. In a first approximation bolt connections between different shell or thin elements are well simulate by using a beam and constraint equations between the beam nodes and the relatives nodes on the holes of the components.

B.5 ANSYS Solver

The direct solvers solves are based on a direct elimination of equation as opposed to iterative solvers, where the solution is obtained through an iterative process that successively refines an initial guess to a solution that is within an acceptable tolerance of the exact solution.

Iterative solvers do not require a matrix factorization and typically iterate towards the solution using a series of very sparse matrix-vector multiplications along with a preconditioning step, both of which require less memory and time per iteration than direct factorization. However, convergence of iterative methods is not guaranteed and the number of iterations required to reach an acceptable solution may be so large that direct methods are faster in some cases.

Direct solvers (such as the sparse direct solver) produce very accurate solutions. Iterative solvers, such as the Preconditioned Conjugate Gradient (PCG) solver, require that a PCG convergence tolerance be specified. Therefore, a large relaxation of the default tolerance may significantly affect the accuracy, especially of derived quantities.

With all iterative solvers you must verify that the model is appropriately constrained. No minimum pivot is calculated and the solver continues to iterate if any rigid body motion exists.

The solution time grows linearly with problems size for iterative methods so huge models can still be solved within very reasonable times.

Sparse direct Solver

The sparse direct solver (including the Block Lanczos method for modal and buckling analyses) is based on a direct elimination of equations. Direct elimination requires the factorization of an initial very sparse linear system of equations into a lower triangular matrix followed by forward and backward substitution using this triangular system. The space required for the lower triangular matrix factors is typically much more than the initial assembled sparse matrix, hence the large disk or in-core memory requirements for direct methods.

Sparse direct solvers seek to minimize the cost of factorizing the matrix as well as the size of the factor using sophisticated equation reordering strategies.

Because the sparse direct solver is based on direct elimination, poorly conditioned matrices do not pose any difficulty in producing a solution (although accuracy may be compromised). Direct factorization methods always give an answer if the equation system is not singular. When the system is close to singular, the solver can usually give a solution (although you must verify the accuracy).

The sparse solver can run completely in memory (also known as in-core) if sufficient memory is available. The sparse solver can also run efficiently by using a balance of memory and disk usage (also known as out-of-core).

The Preconditioned Conjugate Gradient (PCG) Solver

The PCG solver starts with element matrix formulation. Instead of factoring the global matrix, the PCG solver assembles the full global stiffness matrix and calculates the DOF solution by iterating to convergence (starting with an initial guess solution for all DOFs). The PCG solver uses a proprietary preconditioner that is material property and element-dependent.

This solver is available only for static or steady-state analyses and transient analyses, or for PCG Lanczos modal analyses. The PCG solver performs well on most static analyses and certain nonlinear analyses. It is valid for elements with symmetric, sparse, definite or indefinite matrices.

Because they take fewer iterations to converge, well-conditioned models perform better than ill-conditioned models when using the PCG solver.

Ill-conditioning often occurs in models containing elongated elements (i.e., elements with high aspect ratios) or contact elements.

The PCG solver primarily solves for displacements/rotations (in structural analysis), temperatures (in thermal analysis), etc. The accuracy of other derived variables (such as strains, stresses, flux, etc.) is dependent upon accurate prediction of primary variables. Therefore, the program uses a very conservative setting for PCG tolerance (defaults to 1.0E-8). The primary solution accuracy is controlled by the PCG. For most applications, setting the PCG tolerance to 1.0E-6 provides a very accurate displacement solution and may save considerable CPU time compared with the default setting.

For more detailed information about solvers, see ANSYS Help Documentation; in the Mechanical APDL Theory Reference paragraph [27].

Appendix C

Materials

C.1 Overview

Composite material

A composite material can be defined as a combination of two or more materials that results in better properties than those of the individual components used alone. In contrast to metallic alloys, each material retains its separate chemical, physical, and mechanical properties. The two constituents are a reinforcement and a matrix. The main advantages of composite materials are their high strength and stiffness, combined with low density, when compared with bulk materials, allowing for a weight reduction in the finished part. The reinforcing phase provides the strength and stiffness. [28]

The range of fibres is extensive. The graphs below highlight the main criteria for fibre selection.

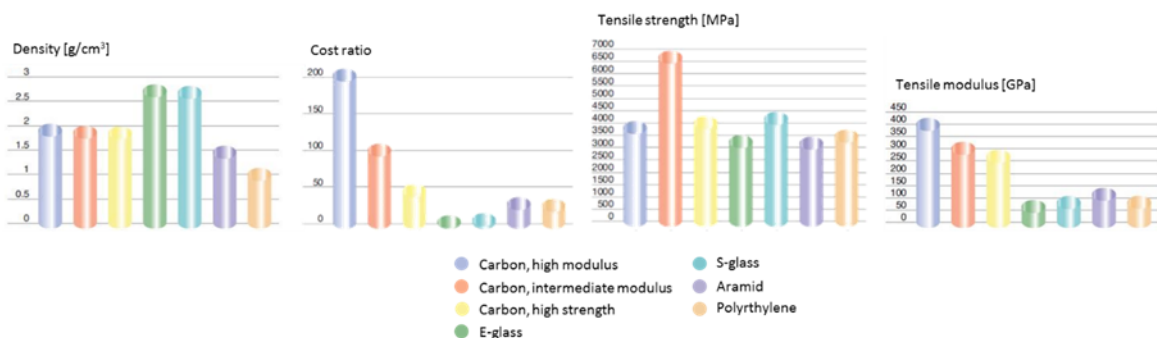


Figure C.1: Fibres properties, overview. [29]
The column charts highlight the main criteria for fibre selection.

Carbon Fibre Reinforced Polymer

Several thousand (12K, 6K, 3K, 1K) carbon filaments are bundled together to form a fibre (tow), which may be used by itself or together to form a Carbon Fibre Reinforced Polymer (CFRP).

The reinforcement types of the CFRP can be discontinuous type (Chopped, Mat) or continuous type (unidirectional, fabric or cloth and roving).

The type and quantity of the reinforcement determine the final properties. Discontinuous-fibre composites are normally somewhat random in alignment, which dramatically reduces their strength and modulus, the highest strength and modulus are obtained with continuous-fibre composites.

There is a practical limit of about 70 volume percent reinforcement that can be added to form a composite. The matrix contributes mainly to the service temperature, toughness, and environmental resistance of the composite.

Fibre composites generally fall under a category of anisotropic materials called orthotropic material. An orthotropic material is one that has two or three planes of rotational symmetry with regards to its elastic properties.

Unidirectional (UD) CFRP consist of long carbon fibres oriented in the same direction surrounded by a matrix of resin or other type of polymer. These materials permit to orient the fibres in the maximum loaded direction such to achieve the best mechanical properties and minimum weight. Bidirectional CFRP, like fabric prepreg woven (PW) consist of carbon fibres woven together, typically perpendicular to one another, surrounded by a polymer matrix.

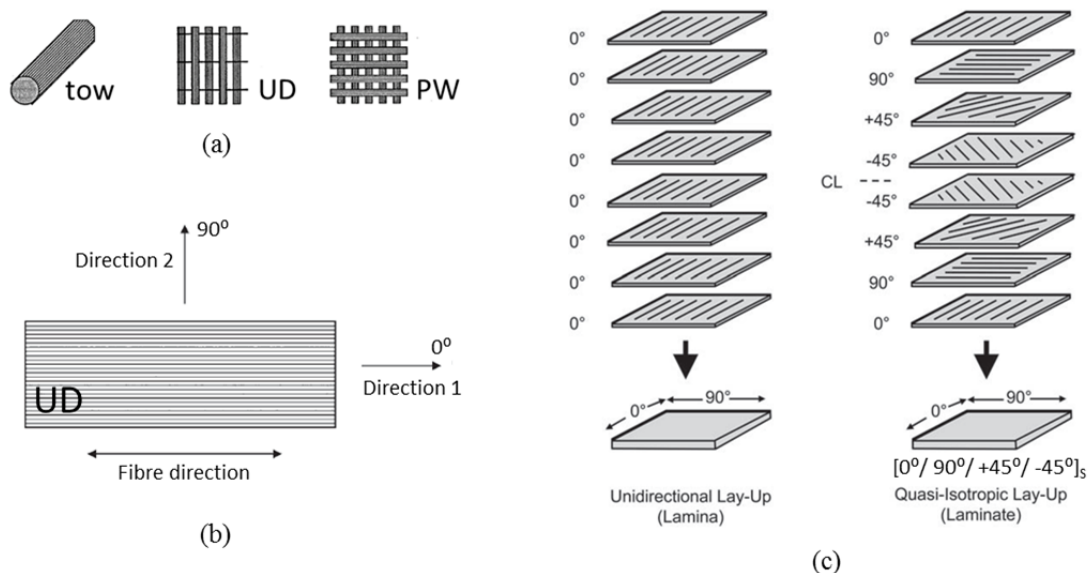


Figure C.2: CFRP, schematic view.

(a) Tow, unidirectional and prepreg woven; [30]

(b) Unidirectional continuous fibre lamina; (c) Lamina and laminate lay-ups. [28]

Lamina and laminate

When there is a single ply or a lay-up in which all of the layers or plies are stacked in the same orientation, the lay-up is called a lamina. When the plies are stacked at various angles, the lay-up is called a laminate. Continuous-fibre composites are normally laminated materials in which the individual layers, plies, or laminae are oriented in directions that will enhance the strength in the primary load direction. Unidirectional (0°) laminae are extremely strong and stiff in the 0° direction. However, they are very weak in the 90° direction because the load must be carried by the much weaker polymeric matrix.

The longitudinal tension and compression loads are carried by the fibres, while the matrix distributes the loads between the fibres in tension and stabilizes the fibres and prevents them from buckling in compression. The matrix is also the primary load carrier for interlaminar shear (i.e., shear between the layers) and transverse (90°) tension.

Because the fibre orientation directly impacts mechanical properties, it seems logical to orient as many of the layers as possible in the main load-carrying direction. While this approach may work for some structures, it is usually necessary to balance the load-carrying capability in a number of different directions, such as the 0° , 90° , $+45^\circ$, and -45° directions. A balanced laminate having equal numbers of plies in the 0° , 90° , $+45^\circ$, $-$ and 45° degrees directions is called a quasi-isotropic laminate, because it carries equal loads in all four directions. In a contracted notation: $[0^\circ/90^\circ/45^\circ/-45^\circ]_s$.

Sandwich construction

A sandwich construction consists of thin high strength skins bonded to a thicker honeycomb or foam core.

Most of the time skins are CFRP. The benefits of sandwich construction can be described as:

- Tensile and compression stresses are supported by the skins
- Shearing stress is supported by the honeycomb (or foam)
- The skins are stable across their whole length
- Excellent weight saving

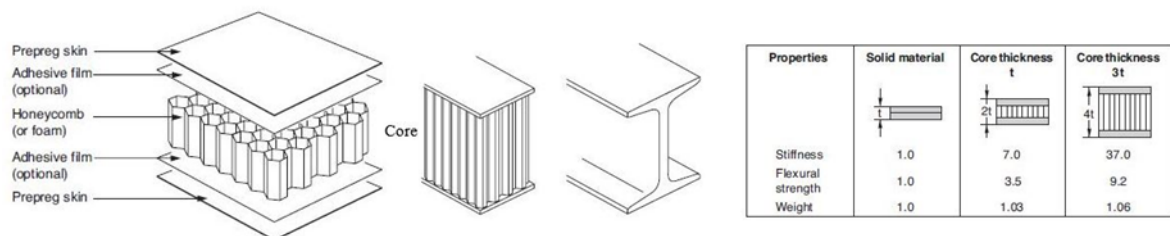


Figure C.3: Sandwich properties, schematic view. [29]

C.2 Theory

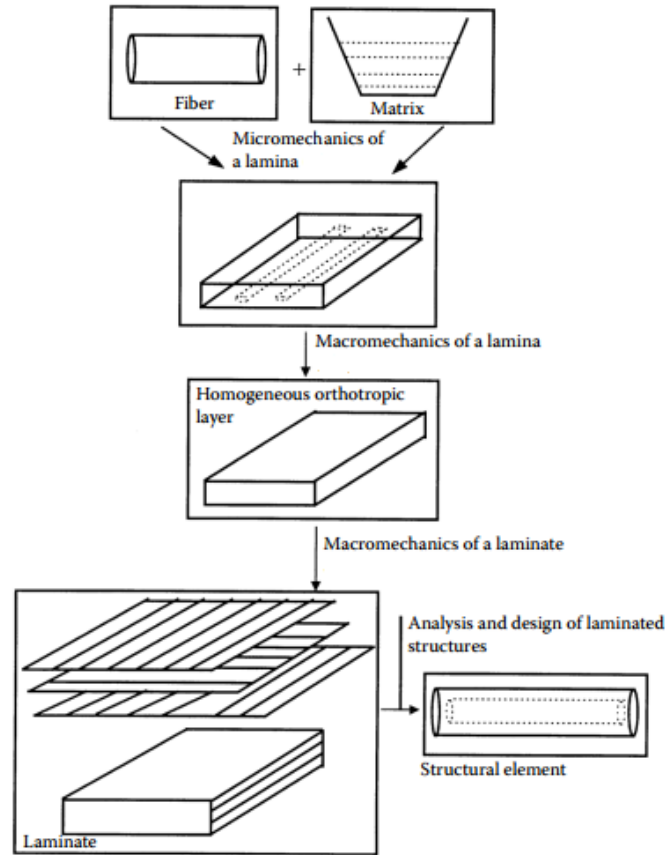


Figure C.4: Analysis of laminated composites, schematic view. [30]

Micromechanical behaviour of a lamina

When a unidirectional continuous-fibre lamina is loaded in a direction parallel to its fibres (0° or 11° direction), the longitudinal modulus E_{11} can be estimated from its constituent properties by using what is known as the rule of mixtures:

$$E_{11} = E_f V_f + E_m V_m \quad (\text{Eq. 5})$$

where E_f is the fibre modulus, V_f is the fibre volume percentage, E_m is the matrix modulus, and V_m is the matrix volume percentage.

The longitudinal tensile strength σ_{11} also can be estimated by the rule of mixtures:

$$\sigma_{11} = \sigma_f V_f + \sigma_m V_m \quad (\text{Eq. 6})$$

where σ_f and σ_m are the ultimate fibre and matrix strengths, respectively. Because the properties of the fibre dominate for all practical volume percentages, the values of the matrix can often be ignored; therefore:

$$E_{11} \approx E_f V_f \quad (\text{Eq. 7})$$

$$\sigma_{11} \approx \sigma_f V_f \quad (\text{Eq. 8})$$

Figure C.5. Left shows the dominant role of the fibres in determining strength and stiffness. When loads are parallel to the fibres (0°), the ply is much stronger and stiffer than when loads are transverse (90°) to the fibre direction. There is a dramatic decrease in strength and stiffness resulting from only a few degrees of misalignment off of 0° .

When the lamina shown in Fig. 1.11 is loaded in the transverse (90° or 22° -direction), the fibres and the matrix function in series, with both carrying the same load. The transverse modulus of elasticity E_{22} is given as:

$$\frac{1}{E_{22}} = \frac{V_f}{E_f} + \frac{V_m}{E_m} \quad (\text{Eq. 9})$$

Figure C.5. Right shows the variation of modulus as a function of fibre volume percentage. When the fibre percentage is zero, the modulus is essentially the modulus of the polymer, which increases up to 100 percent (where it is the modulus of the fibre). At all other fibre volumes, the E_{22} or 90° modulus is lower than the E_{11} or zero degrees modulus, because it is dependent on the much weaker matrix. Other rule of mixture expressions for lamina properties include those for the Poisson's ratio ν_{12} and for the shear modulus G_{12} :

$$\nu_{12} = \nu_f V_f + \nu_m V_m \quad (\text{Eq. 10})$$

$$\frac{1}{G_{12}} = \frac{V_f}{G_f} + \frac{V_m}{G_m} \quad (\text{Eq. 11})$$

These expressions are somewhat less useful than the previous ones, because the values for Poisson's ratio (ν_f) and the shear modulus (G_f) of the fibres are usually not readily available.

Physical properties, such as density (ρ), can also be expressed using rule of mixture relations:

$$\rho_{12} = \rho_f V_f + \rho_m V_m \quad (\text{Eq. 12})$$

While these micromechanics equations are useful for a first estimation of lamina properties when no data are available, they generally do not yield sufficiently accurate values for design purposes. For design purposes, basic lamina and laminate properties should be determined using actual mechanical property testing. [28]

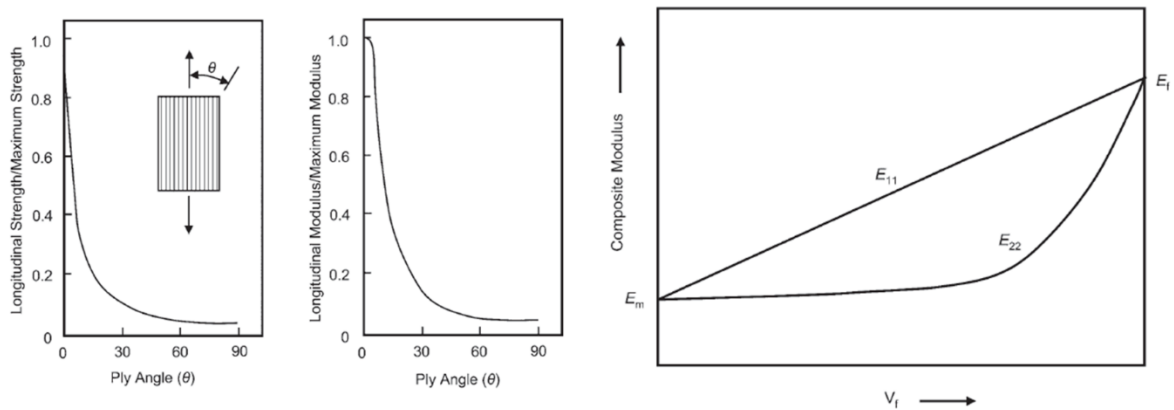


Figure C.5: Micromechanical behaviour of a lamina. [28]

(Left) Influence of ply angle (θ) on strength and modulus;

(Right) variation of composites modulus of a unidirectional 0° lamina as a function of fibre volume fraction.

Macromechanical behaviour of a lamina

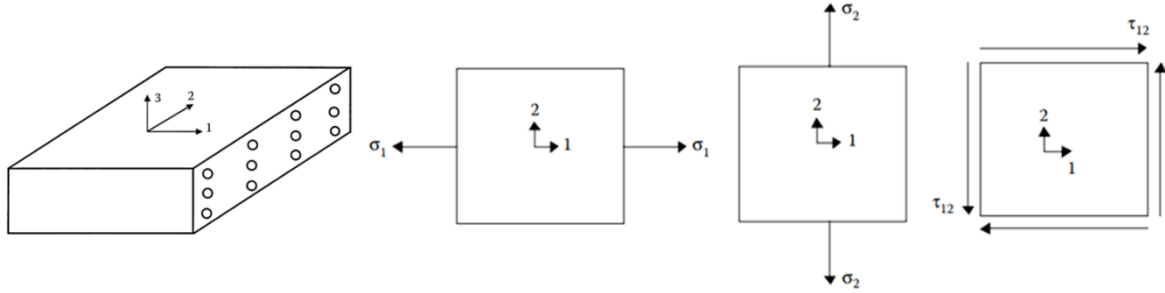


Figure C.6: Macromechanical behaviour of a lamina. [30]

The generalized Hooke's law relating stresses to strains can be written in contracted notation as

$$\sigma_i = C_{ij}\epsilon_j \quad i, j = 1, \dots, 6 \quad (\text{Eq. 13})$$

Where σ_i are the stress components, C_{ij} is the stiffness matrix, and ϵ_j are the strain components.

For a lamina:

- The stiffness matrix is symmetric (the order of differentiation of strain energy density⁸ is immaterial).
- There three orthogonal planes of material property symmetry.
- In 1-2 plane, a plane stress state is define by setting: $\sigma_3 = 0 \quad \tau_{23} = 0 \quad \tau_{31} = 0$.

The stress-strain relations in Figure C.6.Left reduce to

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \begin{Bmatrix} \epsilon_1 \\ \epsilon_2 \\ \gamma_{12} \end{Bmatrix} \quad (\text{Eq. 14})$$

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix} = [Q] \begin{Bmatrix} \epsilon_1 \\ \epsilon_2 \\ \gamma_{12} \end{Bmatrix} \quad (\text{Eq. 15})$$

$$[Q] = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \quad (\text{Eq. 16})$$

Where Q_{ij} , the so-called reduced stiffnesses, are (in terms of the engineering constants)

$$Q_{11} = \frac{E_1}{1 - \nu_{12}\nu_{21}} \quad (\text{Eq. 17})$$

$$Q_{12} = \frac{\nu_{12}E_2}{1 - \nu_{12}\nu_{21}} = \frac{\nu_{21}E_1}{1 - \nu_{12}\nu_{21}} \quad (\text{Eq. 18})$$

$$Q_{22} = \frac{E_2}{1 - \nu_{12}\nu_{21}} \quad (\text{Eq. 19})$$

$$Q_{66} = G_{12} \quad (\text{Eq. 20})$$

The isotropic relations can be obtained either from the orthotropic relations by equating $E_1 = E_2$ and $G_{12} = G$.

⁸ $\frac{\partial^2 W}{\partial \epsilon_j \partial \epsilon_i} = C_{ij}$ where $W = \sigma_i \epsilon_i$ is the strain energy density

The preceding strain-stress relations are the basis for the stiffness and stress analysis of an individual lamina subjected to forces in its own plane (in the principal material directions).

However, the principal directions of orthotropic often do not coincide with coordinate directions that are geometrically natural to the solution of the problem.

Then a method of transforming stress-strain relations from one coordinate to another is needed and from elementary mechanics

$$[T] = \begin{bmatrix} \cos^2 \theta & \sin^2 \theta & 2 \sin \theta \cos \theta \\ \sin^2 \theta & \cos^2 \theta & -2 \sin \theta \cos \theta \\ -\sin \theta \cos \theta & \sin \theta \cos \theta & \cos^2 \theta - \sin^2 \theta \end{bmatrix} \quad (\text{Eq. 21})$$

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = [T]^{-1} \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix} \quad (\text{Eq. 22})$$

$$\begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \frac{\gamma_{xy}}{2} \end{Bmatrix} = [T]^{-1} \begin{Bmatrix} \epsilon_1 \\ \epsilon_2 \\ \frac{\gamma_{12}}{2} \end{Bmatrix} \quad (\text{Eq. 23})$$

$$\begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{Bmatrix} = [R]^{-1} [T]^{-1} [R] \begin{Bmatrix} \epsilon_1 \\ \epsilon_2 \\ \gamma_{12} \end{Bmatrix} \quad [R] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 2 \end{bmatrix} \quad (\text{Eq. 24})$$

where θ is the angle from the x-axis to the 1-axis (Figure C.7), $[T]$ the transformation matrix and $[R]$ the Reuter matrix.

We obtain, in abbreviating form

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = [T]^{-1} \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix} = [T]^{-1} [Q] \begin{Bmatrix} \epsilon_1 \\ \epsilon_2 \\ \gamma_{12} \end{Bmatrix} = [T]^{-1} [Q] [R] [T] [R]^{-1} \begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{Bmatrix} \quad (\text{Eq. 25})$$

However, $[R][T][R]^{-1}$ can be shown to be $[T]^{-T}$ where the superscript T denotes the matrix transpose. Then, if we use the abbreviation

$$[\bar{Q}] = [T]^{-1} [Q] [T]^{-T} \quad (\text{Eq. 26})$$

The stress-strain relations in xy coordinates are

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = [\bar{Q}] \begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{Bmatrix}, \quad [\bar{Q}] = \begin{bmatrix} \bar{Q}_{11} & \bar{Q}_{12} & \bar{Q}_{16} \\ \bar{Q}_{12} & \bar{Q}_{22} & \bar{Q}_{26} \\ \bar{Q}_{16} & \bar{Q}_{26} & \bar{Q}_{66} \end{bmatrix}. \quad (\text{Eq. 27})$$

Where $\bar{Q}_{ij}$ is the transformed stiffness term. Same procedure for strain-stress relations. [31]

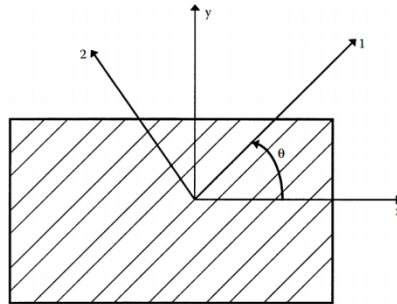


Figure C.7: Principal and coordinate axes of an angle lamina. [30]

Macromechanical behaviour of a laminate

The classical lamination theory is used to develop these relationships. The following assumptions are made in the classical lamination theory to develop the relationships (Kirchhoff-Love hypothesis):

- Each lamina is orthotropic.
- Each lamina is homogeneous.
- A line straight and perpendicular to the middle surface remains straight and perpendicular to the middle surface during deformation ($\gamma_{xz} = \gamma_{yz} = 0$).
- The laminate is thin and is loaded only in its plane (plane stress) ($\sigma_z = \tau_{xz} = \tau_{yz} = 0$).
- Displacements are continuous and small throughout the laminate ($|u|, |v|, |w| \ll |h|$), where h is the laminate thickness.
- Each lamina is elastic.
- No slip occurs between the lamina interfaces.

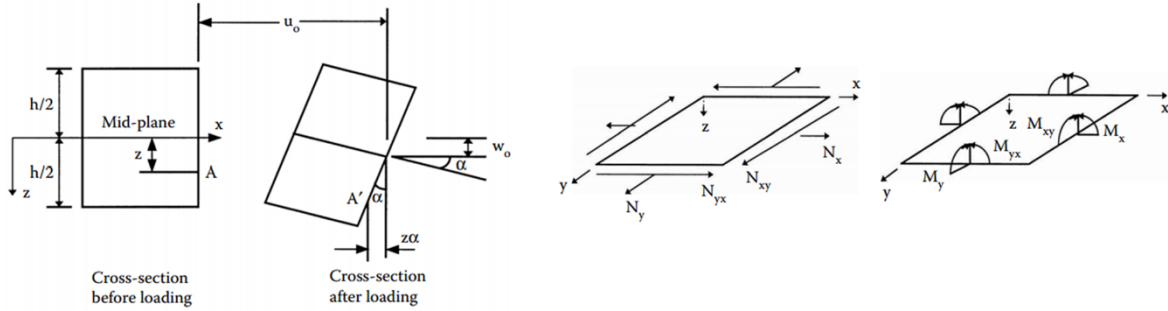


Figure C.8: Macromechanical behaviour of a laminate. [30]

(Left) Relationship between displacements through the thickness of a ply to midplane displacements and curvatures; (Right) Resultant forces and moments on a laminate.

Consider a side view of a plate in the Cartesian x - y - z coordinate system as shown in Figure C.8. The origin of the plate is at the midplane of the plate, that is, $z = 0$. Assume u_0 , v_0 , and w_0 to be displacements in the x , y , and z directions, respectively, at the midplane and u , v , and w are the displacements at any point in the x , y , and z directions, respectively. At any point other than the midplane, the two displacements in the x - y plane will depend on the axial location of the point and the slope of the laminate midplane with the x and y directions. For example, as shown in Figure C.8.Left,

$$u = u_0 - z\alpha, \quad \text{where } \alpha = \frac{\partial w_0}{\partial x}. \quad (\text{Eq. 28})$$

Thus, the displacement u in the x -direction is

$$u = u_0 - z \frac{\partial w_0}{\partial x}, \quad (\text{Eq. 29})$$

Similarly, taking a cross-section in the y - z plane would give the displacement in the y -direction as

$$v = v_0 - z \frac{\partial w_0}{\partial y}, \quad (\text{Eq. 30})$$

Now, from the definitions of the three strains in the x - y plane and the equation above

$$\epsilon_x = \frac{\partial u}{\partial x} = \frac{\partial u_0}{\partial x} - z \frac{\partial^2 w_0}{\partial x^2}, \quad (\text{Eq. 31})$$

$$\epsilon_y = \frac{\partial v}{\partial y} = \frac{\partial v_0}{\partial y} - z \frac{\partial^2 w_0}{\partial y^2}, \quad (\text{Eq. 32})$$

$$\gamma_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} = \frac{\partial u_0}{\partial y} + \frac{\partial v_0}{\partial x} - 2z \frac{\partial^2 w_0}{\partial x \partial y}. \quad (\text{Eq. 33})$$

The strain-displacement (Eq. 31, 32, 33) can be written in matrix form as

$$\begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{Bmatrix} = \begin{Bmatrix} \frac{\partial u_0}{\partial x} \\ \frac{\partial v_0}{\partial y} \\ \frac{\partial u_0}{\partial y} + \frac{\partial v_0}{\partial x} \end{Bmatrix} + z \begin{Bmatrix} -\frac{\partial^2 w_0}{\partial x^2} \\ -\frac{\partial^2 w_0}{\partial y^2} \\ -2\frac{\partial^2 w_0}{\partial x \partial y} \end{Bmatrix} \quad (\text{Eq. 34})$$

The two arrays on the right-hand sides are the definitions of the midplane strains and the midplane curvatures respectively.

$$\begin{Bmatrix} \epsilon_x^0 \\ \epsilon_y^0 \\ \gamma_{xy}^0 \end{Bmatrix} = \begin{Bmatrix} \frac{\partial u_0}{\partial x} \\ \frac{\partial v_0}{\partial y} \\ \frac{\partial u_0}{\partial y} + \frac{\partial v_0}{\partial x} \end{Bmatrix}, \quad \begin{Bmatrix} \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{Bmatrix} = \begin{Bmatrix} -\frac{\partial^2 w_0}{\partial x^2} \\ -\frac{\partial^2 w_0}{\partial y^2} \\ -2\frac{\partial^2 w_0}{\partial x \partial y} \end{Bmatrix} \quad (\text{Eq. 35})$$

Therefore, the laminate strains can be written as

$$\begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{Bmatrix} = \begin{Bmatrix} \epsilon_x^0 \\ \epsilon_y^0 \\ \gamma_{xy}^0 \end{Bmatrix} + z \begin{Bmatrix} \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{Bmatrix} \quad (\text{Eq. 36})$$

Eq.36 shows the linear relationship of the strains in a laminate to the curvatures of the laminate. It also indicates that the strains are independent of the x and y coordinates. [30]

Equation 27 can be thought of as stress-strain relations for the kth layer of a multi-layered laminate.

$$\{\sigma\}_k = [\bar{Q}]_k \{\epsilon\}_k \quad (\text{Eq. 37})$$

Substituting equation 36 into equation 27,

$$\{\sigma\}_k = [\bar{Q}]_k \{\epsilon^0\}_k + z[\bar{Q}]_k \{\kappa\}_k \quad (\text{Eq. 38})$$

From equation 36, the stresses vary linearly only through the thickness of each lamina (Figure C.9.Left). The stresses, however, may jump from lamina to lamina because the transformed reduced-stiffness matrix changes from ply to ply because depends on the material and orientation of the ply.

The resultant forces and moments acting on a laminate are obtained by integration of the stresses in each layer or lamina through the laminate thickness, for example:

$$N_x = \int_{-\frac{h}{2}}^{\frac{h}{2}} \sigma_x dz, \quad M_x = \int_{-\frac{h}{2}}^{\frac{h}{2}} \sigma_x z dz \quad (\text{Eq. 39})$$

The entire collection of force and moment resultants for a N-layered laminate is depicted in Figure C.8 and is defined as

$$\begin{Bmatrix} M_x \\ M_y \\ M_{xy} \end{Bmatrix} = \int_{-\frac{h}{2}}^{\frac{h}{2}} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix}_k z dz = \sum_{k=1}^N \int_{z_{k-1}}^{z_k} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix}_k z dz \quad (\text{Eq. 40})$$

Substituting the lamina stress-strain relations, equation 38, and due to the fact that midplane strains and the midplane curvatures are not functions of z but are middle surface values the equation 40 and can be written as

$$\begin{Bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{Bmatrix} = \begin{bmatrix} A_{ij} & B_{ij} \\ B_{ij} & D_{ij} \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \\ \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{Bmatrix} \quad (\text{Eq. 41})$$

Where

$$A_{ij} = \sum_{k=1}^N (\overline{Q}_{ij})_k (z_k - z_{k-1}) \quad (\text{Eq. 42})$$

$$B_{ij} = \frac{1}{2} \sum_{k=1}^N (\overline{Q}_{ij})_k (z_k^2 - z_{k-1}^2) \quad (\text{Eq. 43})$$

$$D_{ij} = \frac{1}{3} \sum_{k=1}^N (\overline{Q}_{ij})_k (z_k^3 - z_{k-1}^3) \quad (\text{Eq. 44})$$

The A_{ij} , B_{ij} , and D_{ij} matrices are called the extensional, coupling, and bending stiffness matrices, respectively. The extensional stiffness matrix A_{ij} relates the resultant in-plane forces to the in-plane strains, and the bending stiffness matrix D_{ij} relates the resultant bending moments to the plate curvatures. The coupling stiffness matrix B_{ij} couples the force and moment terms to the midplane strains and midplane curvatures. [31]

For a symmetric laminate, $B_{ij} = 0$.

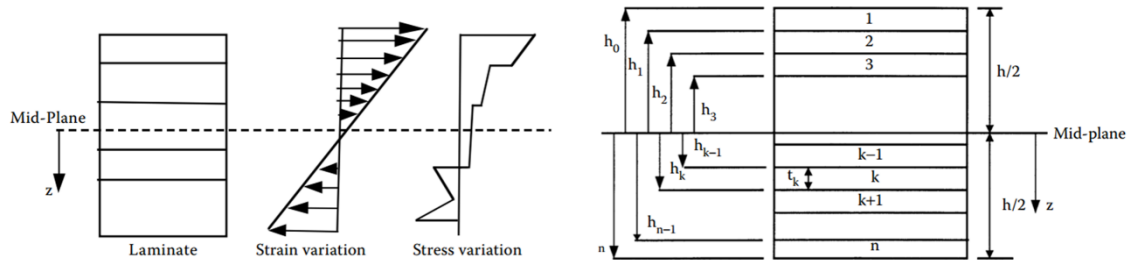


Figure C.9: Macromechanical behaviour of a laminate. [30]

(Left) Strain and stress variation of the laminate;

(Right) coordinate locations of plies in a laminate.

C.3 Materials used

Table C.1: Isotropic materials used.

Material	Type	ρ [kg/m ³]	E[GPa]	ν	G[GPa]	Datasheet
Aluminium 5052	Metal	2770	71	0.33	26.7	[8]
Beam test IB	/	1430	20	0.31	7.69	/
Beam test OB	/	1420	32.5	0.49	10.91	/
Beryllium	Metal	1850	303	0.3	116.5	ANSYS
Carbon Fleece	Carbon ply	750	98	0.3	37.7	theoretical
Carbon isotropic	/	1450	50	0.3	19.2	/
Carbon paper	Graphite	1600	10	0.3	3.85	theoretical
Carbon peek	Carbon	1410	7.7	0.37	2.81	[32]
Polyimide	Pyre LM	1420	2.5	0.34	0.933	theoretical
Rohacell 51 IG	Foam	52	0.065	0.47	22	[19]
Rohacell110 IG	Foam	110	0.160	0.454	55	[19]
Rohacell300 WF	Foam	300	0.578	0.003	288	[22]
Structural steel	Metal	7850	200	0.3	76.9	ANSYS

Table C.2: Carbon fibres used.

Material	ρ [kg/m ³]	E[GPa]	E[GPa]	E[GPa]	ν	ν	ν	G[GPa]	G[GPa]	G[GPa]
M55J	1620	340	6	6	0.25	0.25	0.25	2.4	2	2.4
M60J	1620	365	6	6	0.25	0.25	0.25	2.4	2	2.4

Datasheet [13] [12]

Table C.3: Carbon fabric prepreg woven (PW) used.

Material	ρ [kg/m ³]	E[GPa]	E[GPa]	E[GPa]	ν	ν	ν	G[GPa]	G[GPa]	G[GPa]
T300 1K PW	1420	68	68	6.9	0.04	0.3	0.3	19.5	2.7	2.7
M46J 6K PW	1420	120	120	9	0.04	0.3	0.3	19.5	3	3

Datasheet [21] [20]

Table C.4: Carbon unidirectional (UD) used.

Material	ρ [kg/m ³]	E[GPa]	E[GPa]	E[GPa]	ν	ν	ν	G[GPa]	G[GPa]	G[GPa]
M46J 6K	1540	213	7.6	7.6	0.27	0.4	0.27	5.5	3.9	5.5
M55J 6K	1540	321	6.2	6.2	0.27	0.4	0.27	4.7	3.9	4.7
K13C2U 6K	1540	556	4.8	4.8	0.27	0.4	0.27	4.7	3.9	4.7
K13D2U 2K	1860	560	5.4	5.4	0.23	0.25	0.23	4	2	4

Datasheet [25] [14]

* Theoretical or core properties (glue material) or values reported to ANSYS, for similar materials, have been used to fulfill the material data.

Appendix D

FEA Results

D.1 Inner Detector Barrel analysis

D.1.1 End-wheels lay-ups

A schematic view in Figure D.1 is helpful to understand which lay-up (L#) is inserted in which shell (red surface). Lay-ups are shown in Table D.1.

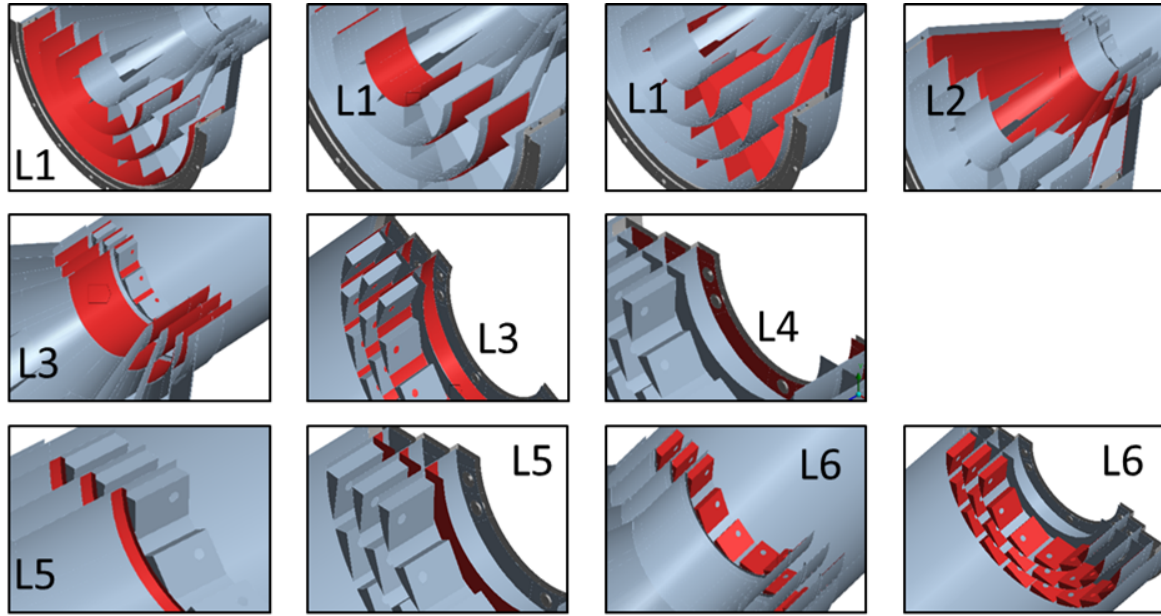


Figure D.1: End-wheels lay-ups.

Table D.1: Lay-ups of the End-wheels sheels.

#	Material	Thickness [mm]	Orientation [°]
L1			
10	T300 1K fabric prepreg	0.1	0
tot		1	
L2			
8	T300 1K fabric prepreg	0.1	[0,45,45,0] _s
tot		0.8	
L3			
6	T300 1K fabric prepreg	0.1	0
tot		0.6	
L4			
8	T300 1K fabric prepreg	0.1	0
tot		0.8	
L5			
4	T300 1K fabric prepreg	0.1	0
tot		0.4	
L6			
1	Carbon peek	1	0
tot		1	

D.1.2 Optimization CYSS results

Case.1 CYSS cylindrical part

Table D.2: cylindrical part optimization.

#	Thick. [mm]	Mat.	Orient. [°]	Sag [mm]	Freq [Hz]	#	Thick. [mm]	Mat.	Orient. [°]	Sag [mm]	Freq [Hz]	
1	0.1	C*	0		1	47.8	2	0.1	C	0	50.6	
1	1.8	F*	0		2	65.6	1	3	F	0	74.8	
1	0.1	C	0		3	128.7	2	0.1	C	0	136.9	
Tot.	2			0.126**	4	169.3	Tot.	3.4		0.115	4	178.7
2	0.1	C	0		1	47.7	3	0.1	C	0,0,0	1	51.5
1	1.6	F	0		2	67.1	1	3	F	0	2	77.7
2	0.1	C	0		3	127.6	3	0.1	C	0,0,0	3	140.6
Tot.	2			0.129	4	177.5	Tot.	3.6		0.113	4	182.3
3	0.1	C	0		1	47.1	2	0.1	C	0	1	49.7
1	1.4	F	0		2	67.5	1	2.6	F	0	2	72.7
3	0.1	C	0		3	125.2	2	0.1	C	0	3	133.7
Tot.	2			0.134	4	180.7	Tot.	3		0.119	4	178.4
2	0.1	C	0		1	48.0	3	0.1	C	0,0,0	1	50.3
1	1.8	F	0		2	68.2	1	2.6	F	0	2	75.3
2	0.1	C	0		3	128.6	3	0.1	C	0,0,0	3	136.1
Tot.	2.2			0.127	4	177.7	Tot.	3.2		0.118	4	182.0
3	0.1	C	0		1	48.1	2	0.1	C	0	1	48.8
1	1.8	F	0		2	70.2	1	2.2	F	0	2	70.5
3	0.1	C	0		3	128.3	2	0.1	C	0	3	130.9
Tot.	2.4			0.129	4	181.2	Tot.	2.6		0.123	4	178.1
1	0.05	C	0		1	47.2	3	0.1	C	0,0,0	1	49.1
1	1.9	F	0		2	63.6	1	2.2	F	0	2	72.8
1	0.05	C	0		3	127.5	3	0.1	C	0,0,0	3	132.0
Tot.	2			0.128	4	156.9	Tot.	2.8		0.123	4	181.6
1	0.1	C	0		1	48.0	3	0.1	C	0,45,0	1	51.3
1	2	F	0		2	66.3	1	3	F	0	2	78.6
1	0.1	C	0		3	129.0	3	0.1	C	0,45,0	3	144.9
Tot.	2.2			0.125	4	169.5	Tot.	3.6		0.113	4	181.9
1	0.1	C	0		1	48.2	3	0.1	C	0,45,0	1	48.0
1	2.2	F	0		2	67.0	1	1.8	F	0	2	71.1
1	0.1	C	0		3	129.5	3	0.1	C	0,45,0	3	130.5
Tot.	2.4			0.124	4	169.7	Tot.	2.4		0.129	4	180.8
1	0.1	C	0		1	48.7	3	0.1	C	0,45,0	1	50.1
1	2.6	F	0		2	68.5	1	2.6	F	0	2	76.3
1	0.1	C	0		3	130.6	3	0.1	C	0,45,0	3	139.7
Tot.	2.8			0.122	4	170.0	Tot.	3.2		0.118	4	181.5
1	0.1	C	0		1	49.1	3	0.1	C	0,45,0	1	49.0
1	3	F	0		2	70.1	1	2.2	F	0	2	75.8
1	0.1	C	0		3	132.1	3	0.1	C	0,45,0	3	134.8
Tot.	3.2			0.120	4	170.2	Tot.	2.8		0.124	4	181.2

*C= T300 1K fabric prepreg woven; F= Rohacell 51 IG.

** Results shown have been found by using different boundary conditions on the End-wheels with to the final ones describe in the model paragraph; however these different boundary conditions have been considerate to don't affect the optimization comparisons.

Red Colour highlights changing in the lay-up.

Case.2 CYSS conical part

Table D.3: Case.2 T1 optimization.

#	Thick. [mm]	Mat.	Orient. [°]	Sag [mm]	Freq. [Hz]
3	0.1	C	0		1 47.8
1	5	F	0		2 65.6
3	0.1	C	0		3 128.7
Tot.	5.6			0.126**	4 169.3
4	0.1	C	0		1 48.6
1	4.8	F	0		2 66
4	0.1	C	0		3 130.2
Tot.	5.6			0.122	4 172.3
5	0.1	C	0		1 49.2
1	4.6	F	0		2 66.4
5	0.1	C	0		3 131.4
Tot.	5.6			0.119	4 174.3
2	0.1	C	0		1 46.6
1	5.2	F	0		2 64.9
2	0.1	C	0		3 126.3
Tot.	5.6			0.133	4 164.2
4	0.1	C	0		1 49
1	5	F	0		2 66.2
4	0.1	C	0	Option1	3 131
Tot.	5.8			0.120	4 172.8
5	0.1	C	0		1 50
1	5	F	0		2 66.8
5	0.1	C	0	Option2	3 132.9
Tot.	6			0.115	4 175.2
6	0.1	C	0		1 50.9
1	5	F	0		2 67.2
6	0.1	C	0	Option3	3 134.6
Tot.	6.2			0.111	4 177
3	0.1	C	0		1 48.2
1	5.2	F	0		2 65.8
3	0.1	C	0		3 129.3
Tot.	5.8			0.124	4 169.8
3	0.1	C	0		1 48.6
1	5.4	F	0		2 66
3	0.1	C	0		3 130
Tot.	6			0.122	4 170.3
4	0.1	C	0		1 49.4
1	5.2	F	0		2 66.4
4	0.1	C	0		3 131.7
Tot.	6			0.118	4 173.2
4	0.1	C	0		1 49.84
1	5.4	F	0		2 66.6
4	0.1	C	0		3 132.4
Tot.	6.2			0.116	4 173.6
5	0.1	C	0		1 50.5
1	5.2	F	0		2 66.9
5	0.1	C	0		3 133.6
Tot.	6.2			0.113	4 175.6
5	0.1	C	0		1 50.9
1	5.4	F	0		2 67.1
5	0.1	C	0		3 134.4
Tot.	6.4			0.112	4 176

Table D.4: Case.2 T2 optimization.

#	Thick [mm]	Mat	Orient. [°]	Sag [mm]	Freq. [Hz]
Option1					
3	0.1	C	0		1 49
3	0.1	C	0		2 66.2
					3 131
Tot.	0.6			0.120	4 172.8
4	0.1	C	0		1 50
4	0.1	C	0		2 67.4
					3 131.1
Tot.	0.8			0.115	4 173.38
4	0.1	C	0		1 51.9
4	0.1	C	0		2 69.4
4	0.1	C	0		3 131.6
Tot.	1.2			0.107	4 174.3
4	0.1	C	[0,45] _s		1 52.1
4	0.1	C	0		2 69.4
4	0.1	C	[0,45] _s		3 132.5
Tot.	1.2		***	0.106	4 174.3
Option2					
3	0.1	C	0		1 50
3	0.1	C	0		2 66.8
					3 132.9
Tot.	0.6			0.115	4 175.2
5	0.1	C	0		1 52
5	0.1	C	0		2 68.9
					3 133.3
Tot.	1			0.107	4 176.2
5	0.1	C	0		1 53
2	0.1	C	0		2 69.9
5	0.1	C	0		3 133.5
Tot.	1.2			0.103	4 176.6
5	0.1	C	[0,45,0] _{as}		1 53.1
2	0.1	C	0		2 69.9
5	0.1	C	[0,45,0] _{as}		3 134.3
Tot.	1.2		***	0.102	4 176.7
Option3					
3	0.1	C	0		1 50.9
3	0.1	C	0		2 67.2
					3 134.6
Tot.	0.6			0.111	4 177
6	0.1	C	0		1 53.9
6	0.1	C	0		2 70.3
					3 135.2
Tot.	1.2			0.099	4 178.4
6	0.1	C	[0,45,0] _s		1 54
6	0.1	C	[0,45,0] _s		2 70.32
			***		3 135.9
Tot.	1.2			0.099	4 178.4

*** The same orientation has been applied for T1 skins.

Red Colour highlights changing in the lay-up.

D.2 Outer Barrel CYSS analysis

Table D.5: Outer Barrel CYSS analysis.

#	Thickness[mm]	Material	Orientation[°]	Displacement [mm]
Cylindrical laminate				
1	2	Carbon isotropic	0	
Tot.	2			7.30
4	0.25	T300 6K Prepreg Carbon Woven	0	
4	0.25	T300 6K Prepreg Carbon Woven	0	
Tot.	2			6.15
Cylindrical Sandwich				
2	0.25	T300 6K Prepreg Carbon Woven	0	
1	8	Rohacell 51 IG	0	
2	0.25	T300 6K Prepreg Carbon Woven	0	
Tot.	9			3.92
4	0.25	T300 6K Prepreg Carbon Woven	0	
1	8	Rohacell 51 IG	0	
4	0.25	T300 6K Prepreg Carbon Woven	0	
Tot.	10			2.21
2	0.25	T300 6K Prepreg Carbon Woven	0	
1	8	Rohacell 110 IG	0	
2	0.25	T300 6K Prepreg Carbon Woven	0	
Tot.	9			3.44
4	0.25	T300 6K Prepreg Carbon Woven	0	
1	8	Rohacell 110 IG	0	
4	0.25	T300 6K Prepreg Carbon Woven	0	
Tot.	10			1.84 R
Waved				
2	0.25	T300 6K Prepreg Carbon Woven	0	
2	0.25	T300 6K Prepreg Carbon Woven	0	
Tot.	2x0.5			6.99
4	0.25	T300 6K Prepreg Carbon Woven	0	
4	0.25	T300 6K Prepreg Carbon Woven	0	
Tot.	2x1			3.43

R= CYSS design chosen.

D.3 Inner Service Barrel

The C-Side Flange has not been considered under possible optimization; the material for C-Side Flange is aluminium. Details of the main configuration of the optimization are shown in Table D.6.

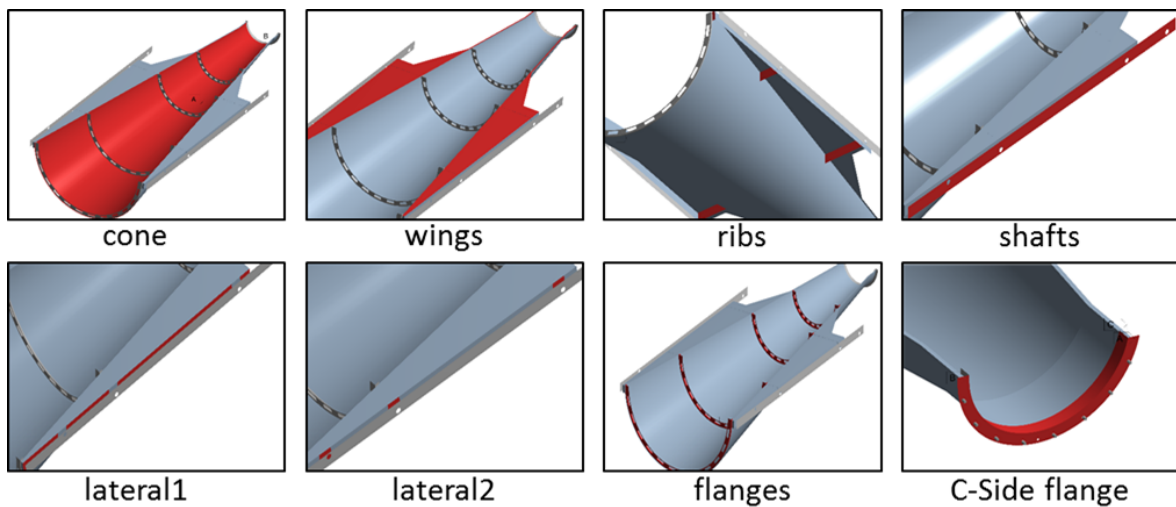


Figure D.2: Nomenclature of Inner Service Barrel shells.

Table D.6: Inner Service Barrel optimization results.

Comment	rib	Th. [mm]	Material	Orient.	Cone	Th. [mm]	Material	Orient
Base	1 tot	4 4	Carbon isotropic		1 tot	4 4	Carbon isotropic	
Sandwich lay-up	1	10	Carbon isotropic		3 1 3	0.1 8 0.1	T300 1K FABRIC ROHACELL 51 IG T300 1K FABRIC	0
	tot	10			tot	8.6		
	1	10	Carbon isotropic		3 1 3	0.1 8 0.1	T300 1K FABRIC ROHACELL 110 IG T300 1K FABRIC	0
	tot	10			tot	8.6		
	1	10	Carbon isotropic		6 1 6	0.2 8 0.2	T300 1K FABRIC ROHACELL 110 IG T300 1K FABRIC	0
	tot	10			tot	10.4		
Increase flanges	1 tot	10 10	Carbon isotropic		6 1 6	0.2 8 0.2	T300 1K FABRIC ROHACELL 110 IG T300 1K FABRIC	
Increase foam on the wings	1 tot	10 10	Carbon isotropic		6 1 6	0.2 8 0.2	T300 1K FABRIC ROHACELL 110 IG T300 1K FABRIC	0
Decrease shafts	1 tot	6 6	Carbon isotropic		6 1 6	0.2 8 0.2	T300 1K FABRIC ROHACELL 110 IG T300 1K FABRIC	0
Skins orientation	1 tot	6 6	Carbon isotropic		6 1 6	0.2 8 0.2	T300 1K FABRIC ROHACELL 110 IG T300 1K FABRIC	[0,45,0]s [0,45,0]s
Rib orientation	6 1 6 tot	0.2 3.6 0.2 6	T300 1K FABRIC T300 1K FABRIC T300 1K FABRIC	[0,45,0]s 0 [0,45,0]s	6 1 6 tot	0.2 8 0.2 10.4	T300 1K FABRIC ROHACELL 110 IG T300 1K FABRIC	[0,45,0]s [0,45,0]s [0,45,0]s
Change carbon fibres	6 1 6 tot	0.2 3.6 0.2 6	T300 1K FABRIC T300 1K FABRIC T300 1K FABRIC	[0,45,0]s 0 [0,45,0]s	6 1 6 tot	0.2 8 0.2 10.4	M46J 6K FABRIC ROHACELL 110 IG M46J 6K FABRIC	[0,45,0]s [0,45,0]s [0,45,0]s
Change foam	6 1 6 tot	0.2 3.6 0.2 6	T300 1K FABRIC T300 1K FABRIC T300 1K FABRIC	[0,45,0]s 0 [0,45,0]s	6 1 6 tot	0.2 8 0.2 10.4	M46J 6K FABRIC ROHACELL 300 WF M46J 6K FABRIC	[0,45,0]s [0,45,0]s [0,45,0]s
Change rib lay-up	6 1 6 tot	0.2 3.6 0.2 6	T300 1K FABRIC M55J 6K UD T300 1K FABRIC	[0,45,0]s 90 [0,45,0]s	6 1 6 tot	0.2 8 0.2 10.4	M46J 6K FABRIC ROHACELL 300 WF M46J 6K FABRIC	[0,45,0]s [0,45,0]s [0,45,0]s
	6 1 6 tot	0.2 8 0.2 10.4	M46J 6K FABRIC ROHACELL 300 WF M46J 6K FABRIC	[0,45,0]s 0 [0,45,0]s	6 1 6 tot	0.2 8 0.2 10.4	M46J 6K FABRIC ROHACELL 300 WF M46J 6K FABRIC	[0,45,0]s [0,45,0]s [0,45,0]s
	5 1 5 tot	0.2 8 0.2 10	M46J 6K FABRIC ROHACELL 300 WF M46J 6K FABRIC	[0,0,45]os 0 [0,0,45]os	5 1 5 tot	0.2 8 0.2 10.4	M46J 6K FABRIC ROHACELL 300 WF M46J 6K FABRIC	[0,0,45]os [0,0,45]os [0,0,45]os
	5 1 5 tot	0.2 8 0.2 10	M46J 6K FABRIC ROHACELL 300 WF M46J 6K FABRIC	[0,0,45]os 0 [0,0,45]os	5 1 5 tot	0.2 8 0.2 10	M46J 6K FABRIC ROHACELL 300 WF M46J 6K FABRIC	[0,0,45]os [0,0,45]os [0,0,45]os
	5 1 5 tot	0.2 8 0.2 10	M46J 6K FABRIC ROHACELL 300 WF M46J 6K FABRIC	[0,0,45]os 0 [0,0,45]os	5 1 5 tot	0.2 8 0.2 10	M46J 6K FABRIC ROHACELL 300 WF M46J 6K FABRIC	[0,0,45]os [0,0,45]os [0,0,45]os
	5 1 5 tot	0.2 8 0.2 10	M46J 6K FABRIC ROHACELL 300 WF M46J 6K FABRIC	[0,0,45]os 0 [0,0,45]os	5 1 5 tot	0.2 8 0.2 10	M46J 6K FABRIC ROHACELL 300 WF M46J 6K FABRIC	[0,0,45]os [0,0,45]os [0,0,45]os
Decrease carbon ply	5 1 5 tot	0.2 8 0.2 10	M46J 6K FABRIC ROHACELL 300 WF M46J 6K FABRIC	[0,0,45]os 0 [0,0,45]os	5 1 5 tot	0.2 8 0.2 10	M46J 6K FABRIC ROHACELL 300 WF M46J 6K FABRIC	[0,0,45]os [0,0,45]os [0,0,45]os
Decrease wings foam	5 1 5 tot	0.2 8 0.2 10	M46J 6K FABRIC ROHACELL 300 WF M46J 6K FABRIC	[0,0,45]os 0 [0,0,45]os	5 1 5 tot	0.2 8 0.2 10	M46J 6K FABRIC ROHACELL 300 WF M46J 6K FABRIC	[0,0,45]os [0,0,45]os [0,0,45]os
Decrease flanges	5 1 5 tot	0.2 8 0.2 10	M46J 6K FABRIC ROHACELL 300 WF M46J 6K FABRIC	[0,0,45]os 0 [0,0,45]os	5 1 5 tot	0.2 8 0.2 10	M46J 6K FABRIC ROHACELL 300 WF M46J 6K FABRIC	[0,0,45]os [0,0,45]os [0,0,45]os
Change foam	5 1 5 tot	0.2 8 0.2 10	M46J 6K FABRIC ROHACELL 110 IG M46J 6K FABRIC	[0,0,45]os 0 [0,0,45]os	5 1 5 tot	0.2 8 0.2 10	M46J 6K FABRIC ROHACELL 110 IG M46J 6K FABRIC	[0,0,45]os [0,0,45]os [0,0,45]os
Change orientation plies	5 1 5 tot	0.2 8 0.2 10	M46J 6K FABRIC ROHACELL 300 WF M46J 6K FABRIC	[0,45,0]os 0 [0,45,0]os	5 1 5 tot	0.2 8 0.2 10	M46J 6K FABRIC ROHACELL 300 WF M46J 6K FABRIC	[0,45,0]os [0,45,0]os [0,45,0]os
Insert UD in wings	5 1 5 tot	0.2 8 0.2 10	M46J 6K FABRIC ROHACELL 300 WF M46J 6K FABRIC	[0,45,0]os 0 [0,45,0]os	5 1 5 tot	0.2 8 0.2 10	M46J 6K FABRIC ROHACELL 300 WF M46J 6K FABRIC	[0,45,0]os [0,45,0]os [0,45,0]os

This table is the continuation of the previous one.

	Wings				Th. [mm]	Material	Orient	Later.	Th. [mm]	Material	Orient	Flanges	Th. [mm]	Material	Sag[mm]	
Base	1	4	Carbon isotropic				1	4	Carbon isotropic				1	5	alluminium	0.286
Sandwich lay-up	3	0.1	T300 1K FABRIC			0	3	0.1	T300 1K FABRIC			0	1	5	alluminium	0.447
	1	8	ROHACELL 51 IG				1	8	ROHACELL 51 IG							
	3	0.1	T300 1K FABRIC			0	3	0.1	T300 1K FABRIC			0				
	tot	8.6					tot	8.6					tot	5		
	3	0.1	T300 1K FABRIC			0	3	0.1	T300 1K FABRIC			0	1	5	alluminium	0.422
	1	8	ROHACELL 110 IG				1	8	ROHACELL 110 IG							
	3	0.1	T300 1K FABRIC			0	3	0.1	T300 1K FABRIC			0				
	tot	8.6					tot	8.6					tot	5		
	6	0.2	T300 1K FABRIC			0	6	0.2	T300 1K FABRIC			0	1	5	alluminium	0.291
	1	8	ROHACELL 110 IG				1	8	ROHACELL 110 IG							
	6	0.2	T300 1K FABRIC			0	6	0.2	T300 1K FABRIC			0				
	tot	10.4					tot	10.4					tot	5		
Increase flanges	6	0.2	T300 1K FABRIC			0	6	0.2	T300 1K FABRIC			0	1	7	aluminium	0.282
	1	8	ROHACELL 110 IG				1	8	ROHACELL 110 IG							
	6	0.2	T300 1K FABRIC			0	6	0.2	T300 1K FABRIC			0				
tot	10.4					tot	10.4					tot	7			
Increase foam on the wings	6	0.2	T300 1K FABRIC			0	6	0.2	T300 1K FABRIC			0	1	7	aluminium	0.27
	1	12.6	ROHACELL 110 IG				1	8	ROHACELL 110 IG							
	6	0.2	T300 1K FABRIC			0	6	0.2	T300 1K FABRIC			0				
tot	15					tot	10.4					tot	7			
Decrease shafts	6	0.2	T300 1K FABRIC			0	6	0.2	T300 1K FABRIC			0	1	7	aluminium	0.276
	1	12.6	ROHACELL 110 IG				1	6.6...17.6	ROHACELL 110 IG							
	6	0.2	T300 1K FABRIC			0	6	0.2	T300 1K FABRIC			0				
tot	15					tot	9...20					tot	7			
Skins orientation	6	0.2	T300 1K FABRIC			[0,45,0]s	6	0.2	T300 1K FABRIC			[0,45,0]s	1	7	aluminium	0.275
	1	12.6	ROHACELL 110 IG				1	6.6...17.6	ROHACELL 110 IG							0.266*
	6	0.2	T300 1K FABRIC			[0,45,0]s	6	0.2	T300 1K FABRIC			[0,45,0]s				
tot	15					tot	9...20					tot	7			
Rib orientation	6	0.2	T300 1K FABRIC			[0,45,0]s	6	0.2	T300 1K FABRIC			[0,45,0]s	1	7	aluminium	0.273
	1	12.6	ROHACELL 110 IG			[0,45,0]s	1	6.6...17.6	ROHACELL 110 IG			[0,45,0]s				0.264*
	6	0.2	T300 1K FABRIC			[0,45,0]s	6	0.2	T300 1K FABRIC			[0,45,0]s				
tot	15					tot	9...20					tot	7			
Change carbon fibres	6	0.2	M46J 6K FABRIC			[0,45,0]s	6	0.2	M46J 6K FABRIC			[0,45,0]s	1	7	aluminium	0.234
	1	12.6	ROHACELL 110 IG				1	6.6...17.6	ROHACELL 110 IG							
	6	0.2	M46J 6K FABRIC			[0,45,0]s	6	0.2	M46J 6K FABRIC			[0,45,0]s				
	tot	15					tot	9...20					tot	7		
Change foam	6	0.2	M46J 6K FABRIC			[0,45,0]s	6	0.2	M46J 6K FABRIC			[0,45,0]s	1	7	aluminium	0.202
	1	12.6	ROHACELL 300 WF			[0,45,0]s	1	6.6...17.6	ROHACELL 300 WF			[0,45,0]s				
	6	0.2	M46J 6K FABRIC			[0,45,0]s	6	0.2	M46J 6K FABRIC			[0,45,0]s				
tot	15					tot	9...20					tot	7			
Change rib lay-up	6	0.2	M46J 6K FABRIC			[0,45,0]s	6	0.2	M46J 6K FABRIC			[0,45,0]s	1	7	aluminium	0.199
	1	12.6	ROHACELL 300 WF			[0,45,0]s	1	6.6...17.6	ROHACELL 300 WF			[0,45,0]s				
	6	0.2	M46J 6K FABRIC			[0,45,0]s	6	0.2	M46J 6K FABRIC			[0,45,0]s				
	tot	15					tot	9...20					tot	7		
	6	0.2	M46J 6K FABRIC			[0,45,0]s	6	0.2	M46J 6K FABRIC			[0,45,0]s	1	7	aluminium	0.205
	1	12.6	ROHACELL 300 WF			[0,45,0]s	1	6.6...17.6	ROHACELL 300 WF			[0,45,0]s				
6	0.2	M46J 6K FABRIC			[0,45,0]s	6	0.2	M46J 6K FABRIC			[0,45,0]s					
tot	15					tot	9...20					tot	7			
Decrease carbon ply	6	0.2	M46J 6K FABRIC			[0,45,0]s	6	0.2	M46J 6K FABRIC			[0,45,0]s	1	7	aluminium	0.206
	1	12.6	ROHACELL 300 WF			[0,45,0]s	1	6.6...17.6	ROHACELL 300 WF			[0,45,0]s				
	6	0.2	M46J 6K FABRIC			[0,45,0]s	6	0.2	M46J 6K FABRIC			[0,45,0]s				
	tot	15					tot	9...20					tot	7		
	6	0.2	M46J 6K FABRIC			[0,45,0]s	6	0.2	M46J 6K FABRIC			[0,45,0]s	1	7	aluminium	0.209
	1	12.6	ROHACELL 300 WF			[0,45,0]s	1	6.6...17.6	ROHACELL 300 WF			[0,45,0]s				
	6	0.2	M46J 6K FABRIC			[0,45,0]s	6	0.2	M46J 6K FABRIC			[0,45,0]s				
	tot	15					tot	9...20					tot	7		
	5	0.2	M46J 6K FABRIC			[0,0,45]os	5	0.2	M46J 6K FABRIC			[0,45,0]s	1	7	aluminium	0.212
	1	12	ROHACELL 300 WF			[0,45,0]s	1	6.6...17.6	ROHACELL 300 WF			[0,45,0]s				
	5	0.2	M46J 6K FABRIC			[0,45,0]s	5	0.2	M46J 6K FABRIC			[0,45,0]s				
	tot	14					tot	9...20					tot	7		
5	0.2	M46J 6K FABRIC			[0,0,45]os	5	0.2	M46J 6K FABRIC			[0,45,0]s	1	7	aluminium	0.213	
1	12	ROHACELL 300 WF			[0,45,0]s	1	7...18	ROHACELL 300 WF			[0,45,0]s					
5	0.2	M46J 6K FABRIC			[0,0,45]os	5	0.2	M46J 6K FABRIC			[0,45,0]s					
tot	14					tot	9...20					tot	7			
Decrease wings foam	5	0.2	M46J 6K FABRIC			[0,0,45]os	5	0.2	M46J 6K FABRIC			[0,45,0]s	1	7	aluminium	0.216
	1	10	ROHACELL 300 WF			[0,45,0]s	1	7...18	ROHACELL 300 WF			[0,45,0]s				
	5	0.2	M46J 6K FABRIC			[0,0,45]os	5	0.2	M46J 6K FABRIC			[0,45,0]s				
	tot	12					tot	9...20					tot	7		
Decrease flanges	5	0.2	M46J 6K FABRIC			[0,0,45]os	5	0.2	M46J 6K FABRIC			[0,45,0]s	1	7	aluminium	0.22
	1	8	ROHACELL 300 WF			[0,45,0]os	1	7...18	ROHACELL 300 WF			[0,45,0]s				
	5	0.2	M46J 6K FABRIC			[0,0,45]os	5	0.2	M46J 6K FABRIC			[0,45,0]s				
	tot	10					tot	9...20					tot	7		
Change foam	5	0.2	M46J 6K FABRIC			[0,0,45]os	5	0.2	M46J 6K FABRIC			[0,45,0]s	1	3	aluminium	0.266
	1	8	ROHACELL 110 IG				1	7...18	ROHACELL 110 IG							
	5	0.2	M46J 6K FABRIC			[0,0,45]os	5	0.2	M46J 6K FABRIC			[0,45,0]s				
tot	10					tot	9...20					tot	3			
Change orientation plies	5	0.2	M46J 6K FABRIC			[0,45,0]os	5	0.2	M46J 6K FABRIC			[0,45,0]os	1	3	aluminium	0.227
	1	8	ROHACELL 300 WF				1	7...18	ROHACELL 300 WF							
	5	0.2	M46J 6K FABRIC			[0,45,0]os	5	0.2	M46J 6K FABRIC			[0,45,0]os				
tot	10					tot	9...20					tot	3			
Insert UD in wings	5	0.2	M46J 6K FABRIC			[0,45,0]os	5	0.2	M46J 6K FABRIC			[0,45,0]os	1	3	aluminium	0.218
	2	0.25	M55J 6K UD			0	1	7...18	ROHACELL 300 WF							
	1	8	ROHACELL 300 WF				5	0.2	M46J 6K FABRIC			[0,45,0]os				
	2	0.25	M55J 6K UD			0										
	5	0.2	M46J 6K FABRIC			[0,45,0]os										
tot	11					tot	9...20					tot	3			

Table D.8: Specifics lay-ups for the skins.

(*)	Thickness[mm]	(**)	Thickness[mm]
T300 1K fabric	0.2	T300 1K fabric	0.2
M55J 6K UD	0.2	M55J 6K UD	0.2
M55J 6K UD	0.2	M55J 6K UD	0.2
T300 1K fabric	0.2	M55J 6K UD	0.2
M55J 6K UD	0.2	M55J 6K UD	0.2
M55J 6K UD	0.2	M55J 6K UD	0.2
T300 1K fabric	0.2	M55J 6K UD	0.2
M55J 6K UD	0.2	M55J 6K UD	0.2
M55J 6K UD	0.2	M55J 6K UD	0.2
T300 1K fabric	0.2	M55J 6K UD	0.18
		Carbon fleece	0.02
Total	2		2

This table is the continuation of the previous one.

	S4 Material	Thickness [mm]	S5 Material	Thickness [mm]	S6 Material	Thickness [mm]	Sag [mm]	Beryllium
Base	Carbon Isotropic Carbon Isotropic	2 2	Carbon Isotropic	2	Carbon Isotropic	2	1.1	0.89
change carbon	T300 1K fabric T300 1K fabric	2 2	T300 1K fabric	2	T300 1K fabric	2	0.97	0.79
	M46J 6K FABRIC M46J 6K FABRIC	2 2	M46J 6K FABRIC	2	M46J 6K FABRIC	2	0.72	0.62
	M46J 6K UD M46J 6K UD	2 2	M46J 6K UD	2	M46J 6K UD	2	0.53	0.47
	M46J 6K UD M46J 6K UD	2 2	M46J 6K UD	2	M46J 6K UD	2	0.55	0.49
change foam	M46J 6K UD M46J 6K UD	2 2	M46J 6K UD	2	M46J 6K UD	2	0.436	0.4
	M46J 6K UD M46J 6K UD	2 2	M46J 6K UD	2	M46J 6K UD	2	0.37	0.35
	M46J 6K UD M46J 6K UD	2 2	M46J 6K UD	2	M46J 6K UD	2	0.3	0.29
	M46J 6K UD M46J 6K UD	2 2	M46J 6K UD	2	M46J 6K UD	2	0.29	0.27
Carbon in S1	M46J 6K UD M46J 6K UD	2 2	M46J 6K UD	2	M46J 6K UD	2	0.29	0.26
	M46J 6K UD M46J 6K UD	2 2	M46J 6K UD	2	M46J 6K UD	2	0.3	0.28
	M46J 6K UD M46J 6K UD	2 2	M46J 6K UD	2	M46J 6K UD	2	0.29	0.28
	M46J 6K UD M46J 6K UD	2 2	M46J 6K UD	2	M46J 6K UD	2	0.31	0.3
change skin thickness	M46J 6K UD M46J 6K UD	2 2	M46J 6K UD	2.8	M46J 6K UD	2.8	0.29	0.27
	M46J 6K UD M46J 6K UD	1.4 1.4	M46J 6K UD	2.8	M46J 6K UD	2.8	0.29	0.27
	M55J 6K UD M55J 6K UD	2 2	M55J 6K UD	2	M55J 6K UD	2	0.29	0.27
	K13C2U 6K UD K13C2U 6K UD	2 2	K13C2U 6K UD	2	K13C2U 6K UD	2	0.26	0.23
change Carbon	(**)M55J 6K UD (**)M55J 6K UD	2 2	(**)M55J 6K UD	2	(**)M55J 6K UD	2	0.33	0.31
	(**)M55J 6K UD (**)M55J 6K UD	2 2	(**)M55J 6K UD	2	(**)M55J 6K UD	2	0.3	0.29
	(**)M55J 6K UD (**)M55J 6K UD	2 2	(**)M55J 6K UD	2	(**)M55J 6K UD	2	0.293	0.275
	(**)M55J 6K UD (**)M55J 6K UD	2 2	(**)M55J 6K UD	2	(**)M55J 6K UD	2	0.282	0.261
Insert fabric and fleece	(**)K12C2U 6K UD (**)K12C2U 6K UD	2 2	(**)K12C2U 6K UD	2	(**)K12C2U 6K UD	2	0.255	0.229
	(**)K12C2U 6K UD (**)K12C2U 6K UD	2 2	(**)K12C2U 6K UD	2	(**)K12C2U 6K UD	2	0.259	0.208 R
	(**)K12C2U 6K UD (**)K12C2U 6K UD	2 2	(**)K12C2U 6K UD	2	(**)K12C2U 6K UD	2	0.35	0.329
	(**)K12C2U 6K UD (**)K12C2U 6K UD	2 2	(**)K12C2U 6K UD	2	(**)K12C2U 6K UD	2		

R= optimized lay-up chosen and inserted in the support C. Red Colour highlights changing in the lay-up.

D.5 Cage reaction forces

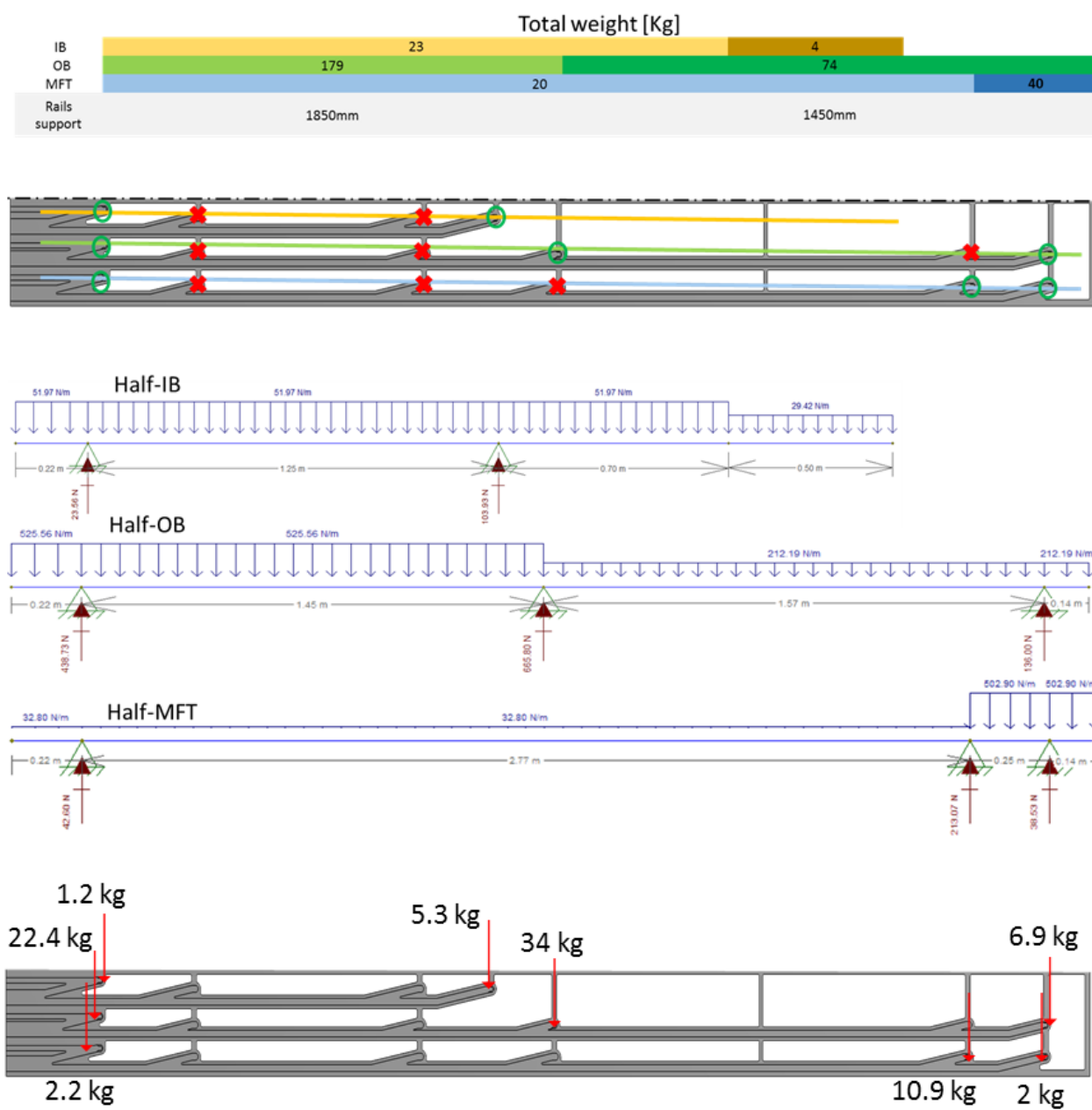


Figure D.4: Weights of barrels on the rail stops.

Appendix E

MCOSMOS programs

E.1 Overview

In the following sections the programs based on MCOSMOS software and developed for the OB Stave assembly are reported.

The programs show for each line the action name and the main parameters associated to the action, while Secondary parameters are not listed

For example for the action *Misurazione ottico manual*, the coordinate of the desired probe focus are listed (most of the time $x=0$, $y=0$, $z=0$); not listed are the actual position of the probe but also the light and the other settings of the measurement.

The parameter *Combinazione* =2 in the action *Cambia combinazione tastatore* means the optical probe is used, while *Combinazione*=1 means the touch trigger probe.

The action *Cambia tastatore* means the position of the probe chosen; 1 means perpendicular to the Marble table.

The action *CNC* if it is “*acceso*” means that the automatic movement are on; while “*spento*” are off and the User can move the probe.

E.2 Half-Stave reference system programs

E.2.3 Localization base1

The program computes RS-200 from itself with an indirect procedure.

Main program

1	Cambia combinazione tastatore	Combinazione n° = 2
2	Cambia tastatore	1
3	Interruzione programmata	Check carefully if the stroke is free.
4	CNC acceso e parametri CNC	Velocità di spostamento = 300.0000 Velocità di misura = 3.0000 Distanza di sicurezza = 1.0000
5	Richiama	200
6	Punto intermedio Spostamento assoluto	X = 0.0000 Y = 0.0000 Z = 200.0000
7	Formula di calcolo	mem = 0
8	Linea di commento	****start measure****
9	Formula di calcolo	Y = -600
10	Formula di calcolo	Z = 10
11	Formula di calcolo	y_jump = 400
12	Define Label	start
13	Inizio Loop	Numero di ripetizioni = 4
14	Formula di calcolo	X = -23
15	Sottoprogramma	point Libreria = No
16	Formula di calcolo	X = 23
17	Sottoprogramma	point Libreria = No
18	Formula di calcolo	Y = Y+y_jump
19	Fine Loop	
20	Trasla e ruota sistema coordinate	Asse Y X = 0.0000 Y = 0.0000 Z = -30.0000, Angolo = 0.0000
21	Ente di connessione Piano	Plane_b1 (1); Gauss
22	Tolleranza Planarità	Ente = Plane_b1 (1) Ampiezza tolleranza = 0.0500
23	Orientamento piano	Plane_b1 (1) Piano XY, Origine su ente
24	Formula di calcolo	X = 22.2
25	Formula di calcolo	Y = 733
26	Formula di calcolo	Z = 0
27	Punto intermedio Spostamento assoluto	X = X Y = Y Z = 200.0000
28	Punto intermedio Spostamento assoluto	X = X Y = Y Z = Z
29	CNC acceso/spento	Spento
30	Interruzione programmata	Check if the position is similar to the image and then click Confirm
31	Posizione attuale in variabile Sistema Coordinate attuali	X = X, Y = Y, Z = Z
32	CNC acceso/spento	Acceso
33	Cerchio	hole 9 (2) Gauss
34	Misurazione ottico Messa a fuoco	X = 0.4000 Y = -0.4000 Z = 0.0000
35	Posizione attuale in variabile Sistema Coordinate attuali	Z = Z
36	Misurazione ottico Muovi traccia automatica	X = 0.0000 Y = 0.0000 Z = 0.0000
37	Ente completato	
38	Punto intermedio Spostamento incrementale	X = 0.0000 Y = 0.0000 Z = 200.0000
39	Formula di calcolo	Y = -737
40	Formula di calcolo	Z = 0
41	Punto intermedio Spostamento assoluto	X = X Y = Y Z = 200.0000
42	Punto intermedio Spostamento assoluto	X = X Y = Y Z = Z
43	CNC acceso/spento	Spento

44	Interruzione programmata	Check if the position is similar to the image and then click Confirm
45	Posizione attuale in variabile Sistema Coordinate attuali	X = X, Y = Y, Z = Z
46	CNC acceso/spento	Acceso
47	Cerchio	hole 1 (1) Gauss
48	Misurazione ottico Messa a fuoco	X = 0.4000 Y = -0.4000 Z = 0.0000
49	Posizione attuale in variabile Sistema Coordinate attuali	Z = Z
50	Misurazione ottico Muovi traccia automatica	X = 0.0000 Y = 0.0000 Z = 0.0000
51	Ente completato	
52	Punto intermedio Spostamento incrementale	X = 0.0000 Y = 0.0000 Z = 200.0000
53	Ente di connessione Punto	middlepoint19(11) Nessuna proiezione
54	Ente di connessione Retta	line_hole19(1) Nessuna proiezione
55	Allineamento asse parallelo ad asse	line_hole19(1) Asse Y
56	Crea origine	middlepoint19(11) XY
57	Ente teorico Punto	point00_teor (12) X = -22.0205 Y = 0.0609 Z = 0.0000
58	Ente teorico Punto	point01000_teor (13) X = -22.0395 Y = 1000.0609 Z = 0.0000
59	Ente di connessione Retta	Line_points_teor(2) Nessuna proiezione
60	Allineamento asse parallelo ad asse	Line_points_teor(2) Asse Y
61	Crea origine	point00_teor(12) XY
62	Memorizza sistema coordinate	200

Subprogram: point

1	Formula di calcolo	mem = mem+1
2	Punto intermedio Spostamento assoluto	X = X Y = Y Z = 200.0000
3	Punto intermedio Spostamento assoluto	X = X Y = Y Z = Z
4	CNC acceso/spento	Spento
5	Interruzione programmata	Check if Focus is OK and then click Confirm
6	CNC acceso/spento	Acceso
7	Posizione attuale in variabile Sistema Coordinate attuali	X = X, Y = Y, Z = Z
8	Punto	plane_b1_@(mem) (MEM) Punto compensato
9	Misurazione ottico Messa a fuoco	X = 0.0000 Y = 0.0000 Z = 0.0000
10	Posizione attuale in variabile Sistema Coordinate attuali	Z = Z
11	Misurazione ottico Manuale	X = 1.9700 Y = 1.9700 Z = 0.0000
12	Ente completato	
13	Punto intermedio Spostamento incrementale	X = 0.0000 Y = 0.0000 Z = 200.0000

E.2.4 Alignment Base1

The program computes RS-202 from RS-200 with an indirect procedure

Main program

1	Cambia combinazione tastatore	Combinazione n° = 2
2	Cambia tastatore	1
3	Richiama	200
4	Interruzione programmata	Check carefully if the stroke is free.
5	CNC acceso e parametri CNC	Velocità di spostamento = 300.0000 Velocità di misura = 3.0000 Distanza di sicurezza = 1.0000
6	Punto intermedio Spostamento assoluto	X = -23.0000 Y = -650.0000 Z = 150.0000
7	Formula di calcolo	mem = 0
8	Linea di commento	***Start measure*****
9	Formula di calcolo	X = -23
10	Formula di calcolo	Y = -650
11	Formula di calcolo	y_jump = 300
12	Define Label	start
13	Inizio Loop	Numero di ripetizioni = 3
14	Formula di calcolo	X = -23
15	Sottoprogramma	point Libreria = No
16	Formula di calcolo	X = 23
17	Sottoprogramma	point Libreria = No
18	Formula di calcolo	Y = Y+y_jump
19	Fine Loop	
20	If	If Y > 600
21	Goto	Numero di decimali = 0
22	Formula di calcolo	Y = 50
23	Goto	start
24	Define Label	end
25	Trasla e ruota sistema coordinate	Asse Y X = 0.0000 Y = 0.0000 Z = -10.0000, Angolo = 0.0000
26	Ente di connessione Piano	plane_BASE1 (1); Gauss
27	Orientamento piano	plane_BASE1 (1) Piano XY, Origine su ente
28	Tolleranza Planarità	Ente = plane_BASE1 (1) Ampiezza tolleranza = 0.0500
29	Formula di calcolo	X = 22.2
30	Formula di calcolo	Y = -737
31	Formula di calcolo	y_jump = 735
32	Formula di calcolo	mem = 0
33	Inizio Loop	Numero di ripetizioni = 3
34	Punto intermedio Spostamento assoluto	X = X Y = Y Z = 0.0000
35	Sottoprogramma	hole Libreria = No
36	Formula di calcolo	Y = Y+y_jump
37	Fine Loop	
38	Formula di calcolo	Y = 0
39	Formula di calcolo	X = 0
40	Punto intermedio Spostamento assoluto	X = X Y = Y Z = 200.0000
41	Ente di connessione Retta Nessuna proiezione	line_holes159 (1)
42	Ente di connessione Punto Nessuna proiezione	middlepoint1-5 (13)
43	Ente di connessione Punto Nessuna proiezione	middlepoint5-9 (14)
44	Ente di connessione Punto Nessuna proiezione	MIDDLEpoint15-59 (15)
45	Allineamento asse parallelo ad asse	line_holes159 (1) Asse Y
46	Crea origine XY	MIDDLEpoint15-59 (15)
47	Ente teorico Punto	point00_teor (16) X = -22.0205 Y = 0.0609 Z = 0.0000
48	Ente teorico Punto	point01000_teor (17) X = -22.0395 Y = 1000.0609 Z = 0.0000
49	Ente di connessione	line_points_ric (2)

	Retta	Nessuna proiezione
50	Allineamento asse parallelo ad asse	line_points_ric (2) Asse Y
51	Crea origine	Punto00_teor
52	Memorizza Sistema coordinate	202

Subprogram: point

1	Formula di calcolo	mem = mem+1
2	Punto	point(MEM) Punto
3	Misurazione Ottico Messa a fuoco	X = 0.0000 Y = 0.0000 Z = 0.0000
4	Misurazione ottico Manuale	X = 1.9777 Y = 1.9702 Z = 0.0022
5	Ente completato	

Subprogram: hole

1	Formula di calcolo	mem = mem+1
2	Cerchio	hole(MEM) GAUSS
3	Misurazione Ottico Messa a fuoco	X = 0.3237 Y = -0.0778 Z = 0.0001
4	Misurazione ottico Muovi traccia automatica	X = 0.0000 Y = 0.0000 Z = 0.0000
5	Ente completato	

E.3 Stave reference system programs

E.3.5 Localization Ruby

The program computes RS-210 from itself with an indirect procedure.

Main program

1	Cambia combinazione tastatore	Combinazione n° = 2
2	Cambia tastatore	1
3	Richiama	210
4	CNC accesso e parametri CNC	Velocità di spostamento = 300.0000 Velocità di misura = 3.0000 Distanza di sicurezza = 1.0000
5	Punto intermedio Spostamento assoluto	X = 0.0000 Y = 0.0000 Z = 100.0000
6	Formula di calcolo	mem = 0
7	Formula di calcolo	i = -1
8	Linea di commento	****parametricdata****
9	Formula di calcolo	Y1 = 780
10	Formula di calcolo	Y2 = 788
11	Formula di calcolo	X = 10
12	Formula di calcolo	Z1 = 40,5
13	Formula di calcolo	Z_sec = 50
14	Linea di commento	****Start measure****
15	Inizio Loop	Numero di ripetizioni = 2
16	Formula di calcolo	Y1 = Y1*i
17	Formula di calcolo	Y2 = Y2*i
18	Formula di calcolo	Y = Y1
19	Punto intermedio Spostamento assoluto	X = X Y = Y Z = 100.0000
20	Inizio Loop	Numero di ripetizioni = 2
21	Formula di calcolo	Z = Z1+10
22	Formula di calcolo	Y = Y1
23	Punto intermedio Spostamento assoluto	X = X Y = Y Z = Z
24	CNC acceso/spento	Spento
25	Interruzione programmata	Check if Focus is OK and then click Confirm
26	CNC acceso/spento	Acceso
27	Posizione attuale in variabile Sistema Coordinate attuali	X = X, Y = Y, Z = Z
28	Sottoprogramma	point_platelet Libreria = No
29	Formula di calcolo	Y = Y2
30	Punto intermedio Spostamento assoluto	X = X Y = Y Z = Z
31	CNC acceso/spento	Spento
32	Interruzione programmata	Check if Focus is OK and then click Confirm
33	CNC acceso/spento	Acceso
34	Posizione attuale in variabile Sistema Coordinate attuali	X = X, Y = Y, Z = Z
35	Sottoprogramma	point_platelet Libreria = No
36	Formula di calcolo	X = X*i
37	Fine Loop	
38	Punto intermedio Spostamento incrementale	X = 0.0000 Y = 0.0000 Z = Z_SEC
39	Fine Loop	
40	Trasla e ruota sistema coordinate	Asse Y X = 0.0000 Y = 0.0000 Z = -100.0000, Angolo = 0.0000
41	Ente di connessione Piano	plane_platelets (1); Gauss punti_piastrina (1); Numero di enti = 8
42	Orientamento piano	Plane_platelets (1) Piano XY, Origine su ente
43	Formula di calcolo	mem = 0
44	Formula di calcolo	X = 0,63
45	Formula di calcolo	Y = 782,1
46	Formula di calcolo	Z = 0
47	Punto intermedio Spostamento assoluto	X = X Y = Y Z = Z_SEC
48	Punto intermedio Spostamento assoluto	X = X Y = Y Z = Z
49	CNC acceso/spento	Spento
50	Interruzione programmata	Check if the position is similar to the image and then click Confirm
51	CNC acceso/spento	Acceso
52	Posizione attuale in	X = X, Y = Y, Z = Z

	variabile Sistema Coordinate attuali	
53	Sottoprogramma	hole Libreria = No
54	Punto intermedio Spostamento incrementale	X = 0.0000 Y = 0.0000 Z = Z_SEC
55	Formula di calcolo	X = 0,74
56	Formula di calcolo	Y = -786,2
57	Punto intermedio Spostamento assoluto	X = X Y = Y Z = Z_SEC
58	Punto intermedio Spostamento assoluto	X = X Y = Y Z = Z
59	CNC acceso/spento	Spento
60	Interruzione programmata	Check if the position is similar to the image and then click Confirm
61	CNC acceso/spento	Acceso
62	Posizione attuale in variabile Sistema Coordinate attuali	X = X, Y = Y, Z = Z
63	Sottoprogramma	hole Libreria = No
64	Punto intermedio Spostamento incrementale	X = 0.0000 Y = 0.0000 Z = 50.0000
65	Distanza	Distance(1)
66	Ente di connessione Retta	line_holes_platelets (1) Nessuna proiezione
67	Allineamento asse parallelo ad asse	line_holes_platelets (1) Asse Y
68	Ente di connessione Punto	middlepoint_platelets (9) Nessuna proiezione
69	Crea origine	middlepoint_platelets (9) XY
70	Ente teorico Punto	point_000_teo (10) X = -0.5340 Y = 0.0098 Z = -40.5033
71	Ente teorico Punto	point_01000_teo (11) X = -0.4542 Y = 1000.0098 Z = -40.4768
72	Ente teorico Punto	point_100000_teo (12) X = 999.4636 Y = 0.0700 Z = -42.7067
73	Trasla e ruota sistema coordinate	Asse Y X = 0.0000 Y = 0.0000 Z = -100.0000, Angolo = 0.0000
74	Ente di connessione Piano	plane_point_teo (2); Gauss
75	Orientamento piano	plane_point_teo (2) Piano XY, Origine su ente
76	Ente di connessione Retta	line_points_teo (2) Nessuna proiezione
77	Allineamento asse parallelo ad asse	line_points_teo (2) Asse Y
78	Crea origine	point_000_teo (10) XY
79	Punto intermedio Spostamento assoluto	X = 0.0000 Y = 0.0000 Z = 100.0000
80	Memorizza sistema di coordinate	210

Subprogram: point_platelet

1	Formula di calcolo	mem = mem+1
2	Punto	Point_platelet(MEM) Punto compensato
3	Misurazione Ottico Messa a fuoco	X = 0.0000 Y = 0.0000 Z = 0.0000
4	Posizione attuale in variabile Sistema coordinate attuali	Z=Z
5	Misurazione ottico Manuale	X = 1.9784 Y = 1.9596 Z = 0.0036
6	Ente completato	

E.3.6 Alignment Ruby

The program computes RS-212 from RS-210 with an indirect procedure.

Main program

1	Cambia combinazione tastatore	Combinazione n° = 2
2	Cambia tastatore	1
3	Richiama	210
4	Interruzione programmata	Check carefully if the stroke is free.
5	CNC accesso e parametri CNC	Velocità di spostamento = 300.0000 Velocità di misura = 3.0000 Distanza di sicurezza = 1.0000
6	Punto intermedio Spostamento assoluto	X = 0.0000 Y = 0.0000 Z = 100.0000
7	Formula di calcolo	mem = 0
8	Formula di calcolo	i = -1
9	Linea di commento	****parametric data****
10	Formula di calcolo	Y1 = 780
11	Formula di calcolo	Y2 = 788
12	Formula di calcolo	X = 10
13	Linea di commento	****start measure****
14	Inizio Loop	Numero di ripetizioni = 2
15	Formula di calcolo	Y1 = Y1*i
16	Formula di calcolo	Y2 = Y2*i
17	Formula di calcolo	Y = Y1
18	Punto intermedio Spostamento assoluto	X = X Y = Y Z = 100.0000
19	Inizio Loop	Numero di ripetizioni = 2
20	Formula di calcolo	Y = Y1
21	Sottoprogramma	point_platelet Libreria = No
22	Formula di calcolo	Y = Y2
23	Sottoprogramma	point_platelet Libreria = No
24	Formula di calcolo	X = X*i
25	Fine Loop	
26	Punto intermedio Spostamento incrementale	X = 0.0000 Y = 0.0000 Z = 50.0000
27	Fine Loop	
28	Trasla e ruota sistema coordinate	Asse Y X = 0.0000 Y = 0.0000 Z = -100.0000, Angolo = 0.0000
29	Ente di connessione Piano	plane_platelets(1);Gauss point_platelet(1);Numero di enti = 8
30	Orientamento piano	plane_platelets (1) Piano XY, Origine su ente
31	Formula di calcolo	mem = 0
32	Formula di calcolo	X = 0,63
33	Formula di calcolo	Y = 782,1
34	Sottoprogramma	hole Libreria = No
35	Punto intermedio Spostamento incrementale	X = 0.0000 Y = 0.0000 Z = 50.0000
36	Formula di calcolo	X = 0,74
37	Formula di calcolo	Y = -786,2
38	Sottoprogramma	hole Libreria = No
39	Punto intermedio Spostamento incrementale	X = 0.0000 Y = 0.0000 Z = 50.0000
40	Distanza	Distance (1)
41	Ente di connessione Retta	line_holes_platelets (1) Nessuna proiezione
42	Allineamento asse parallelo ad asse	line_holes_platelets (1) Asse Y
43	Ente di connessione Punto	middlepoint_platelets (9) Nessuna proiezione
44	Crea origine	middlepoint_platelets (9) XY
45	Ente teorico Punto	point_000_teo (10) X = -0.5340 Y = 0.0098 Z = -40.5033
46	Ente teorico Punto	point_01000_teo (11) X = -0.4542 Y = 1000.0098 Z = -40.4768
47	Ente teorico Punto	point_100000_teo (12) X = 999.4636 Y = 0.0700 Z = -42.7067
48	Trasla e ruota sistema coordinate	Asse Y X = 0.0000 Y = 0.0000 Z = -100.0000, Angolo = 0.0000
49	Ente di connessione Piano	plane_point_teo (2); Gauss

50	Orientamento piano	plane_point_teo (2) Piano XY, Origine su ente
51	Ente di connessione Retta	line_points_teo (2) Nessuna proiezione
52	Allineamento asse parallelo ad asse	line_points_teo (2) Asse Y
53	Crea origine	punto_000_teo (10) XY
54	Punto intermedio Spostamento assoluto	X = 0.0000 Y = 0.0000 Z = 100.0000
55	Memorizza sistema di coordinate	212

Subprogram: point_platelet

1	Formula di calcolo	mem = mem+1
2	Cerchio	hole(MEM) Gauss
3	Misurazione Ottico Messa a fuoco	X = 0.0000 Y = -0.2000 Z = 0.0000
4	Misurazione ottico Muovi traccia automatica	X = 0.0000 Y = 0.0000 Z = 0.0000
5	Ente completato	

Subprogram: hole

1	Formula di calcolo	mem = mem+1
2	Cerchio	hole(MEM) Gauss
3	Misurazione Ottico Messa a fuoco	X = 0.0000 Y = -0.2000 Z = 0.0000
4	Misurazione ottico Muovi traccia automatica	X = 0.0000 Y = 0.0000 Z = 0.0000
5	Ente completato	

E.4 Base1_2pt_rif

The program computes with trigger probe the 2 points used to pass from RS-202temp to RS-202 in Alignment Base1 program.

Main program

1	Cambia combinazione tastatore	Combinazione n° = 1
2	Cambia tastatore	1
3	Richiama	100
4	CNC acceso e parametri CNC	Velocità di spostamento = 300.0000 Velocità di misura = 3.0000 Distanza di sicurezza = 1.0000
5	Punto intermedio Spostamento assoluto	X = 0.0000 Y = -650.0000 Z = 300.0000
6	Piano	piano_base1_aut(1) Gauss
7	Punto di misura Sul pezzo con direzione	X = 23.0000 Y = -650.0000 Z = 0.0000 I = 0.0000 J = 0.0000 K = -1.0000
8	Punto di misura Sul pezzo con direzione	X = -23.0000 Y = -650.0000 Z = 0.0000 I = 0.0000 J = 0.0000 K = -1.0000
9	Punto di misura Sul pezzo con direzione	X = -23.0000 Y = -350.0000 Z = 0.0000 I = 0.0000 J = 0.0000 K = -1.0000
10	Punto di misura Sul pezzo con direzione	X = 23.0000 Y = -350.0000 Z = 0.0000 I = 0.0000 J = 0.0000 K = -1.0000
11	Punto di misura Sul pezzo con direzione	X = 23.0000 Y = -50.0000 Z = 0.0000 I = 0.0000 J = 0.0000 K = -1.0000
12	Punto di misura Sul pezzo con direzione	X = -23.0000 Y = -50.0000 Z = 0.0000 I = 0.0000 J = 0.0000 K = -1.0000
13	Punto di misura Sul pezzo con direzione	X = -23.0000 Y = 50.0000 Z = 0.0000 I = 0.0000 J = 0.0000 K = -1.0000
14	Punto di misura Sul pezzo con direzione	X = 23.0000 Y = 50.0000 Z = 0.0000 I = 0.0000 J = 0.0000 K = -1.0000
15	Punto di misura Sul pezzo con direzione	X = 23.0000 Y = 350.0000 Z = 0.0000 I = 0.0000 J = 0.0000 K = -1.0000
16	Punto di misura Sul pezzo con direzione	X = -23.0000 Y = 350.0000 Z = 0.0000 I = 0.0000 J = 0.0000 K = -1.0000
17	Punto di misura Sul pezzo con direzione	X = -23.0000 Y = 650.0000 Z = 0.0000 I = 0.0000 J = 0.0000 K = -1.0000
18	Punto di misura Sul pezzo con direzione	X = 23.0000 Y = 650.0000 Z = 0.0000 I = 0.0000 J = 0.0000 K = -1.0000
19	Ente completato	
20	Punto intermedio Spostamento incrementale	X = 0.0000 Y = 0.0000 Z = 200.0000
21	Trasla e ruota sistema coordinate	Asse Y X = 0.0000 Y = 0.0000 Z = -10.0000, Angolo = 0.0000
22	Orientamento piano	piano_base1_aut(1) Piano XY, Origine su ente
23	Punto intermedio Spostamento assoluto	X = 0.0000 Y = 755.0000 Z = 10.0000
24	Cerchio	Spina2(1)
25	Misura automatica Cerchio	N° di Punti = 6 Piano di proiezione = Piano XY X = 0.0000 Y = 755.0000 Z = -6.0000 Diametro = 4.0000
26	Ente completato	
27	Punto intermedio Spostamento incrementale	X = 0.0000 Y = 0.0000 Z = 200.0000
28	Punto intermedio Spostamento incrementale	X = 0.0000 Y = -1510.0000 Z = 0.0000
29	Cerchio	Spina1(2)
30	Misura automatica Cerchio	N° di Punti = 6 Piano di proiezione = Piano XY X = 0.0000 Y = -755.0000 Z = -6.0000 Diametro = 4.0000
31	Ente completato	
32	Punto intermedio Spostamento incrementale	X = 0.0000 Y = 0.0000 Z = 200.0000

33	Ente di connessione Retta	Retta Y_aut(1) Nessuna proiezione
34	Allineamento asse parallelo ad asse	Retta Y_aut(1) Asse Y
35	Crea origine	spina2 (1) XY
36	Trasla e ruota sistema coordinate	Asse Y X = 0.0000 Y = -755.0000 Z = 0.0000, Angolo = 0.0000
37	Memorizza sistema coordinate	101
38	Ente teorico Punto	punto0,0 (1) X = 0.0000 Y = 0.0000 Z = 0.0000
39	Ente teorico Punto	punto0,1000 (2) X = 0.0000 Y = 1000.0000 Z = 0.0000
40	Punto intermedio Spostamento assoluto	X = 22.0000 Y = -735.0000 Z = 200.0000
41	Tolleranza Planarità	Ente = piano_base1_aut (1) Ampiezza tolleranza = 0.0000
42	Distanza	Distanza (1)
43	Cerchio	cerchio1 (3) Gauss
44	Misura automatica cerchio	N° di Punti = 6 Piano di proiezione = Piano XY X = 22.0000 Y = -735.0000 Z = -3.0000 Diametro = 4.0000
45	Punto intermedio Spostamento incrementale	X = 0.0000 Y = 0.0000 Z = 200.0000
46	Punto intermedio Spostamento assoluto	X = 22.0000 Y = 0.0000 Z = 200.0000
47	Ente completato	
48	Cerchio	cerchio5 (4) Gauss
49	Misura automatica Cerchio	N° di Punti = 6 Piano di proiezione = Piano XY X = 22.0000 Y = 0.0000 Z = -3.0000 Diametro = 4.0000
50	Ente completato	
51	Punto intermedio Spostamento incrementale	X = 0.0000 Y = 0.0000 Z = 200.0000
52	Punto intermedio Spostamento assoluto	X = 22.0000 Y = 735.0000 Z = 200.0000
53	Cerchio	Cerchio9 (5) Gauss
54	Misura automatica Cerchio	N° di Punti = 6 Piano di proiezione = Piano XY X = 22.0000 Y = 735.0000 Z = -3.0000 Diametro = 4.0000
55	Ente completato	
56	Punto intermedio Spostamento incrementale	X = 0.0000 Y = 0.0000 Z = 200.0000
57	Ente di connessione Retta	retta_fori159(2) Nessuna proiezione
58	Ente di connessione Punto	puntomedio1-5(3) Nessuna proiezione
59	Ente di connessione Punto	puntomedio5-9(4) Nessuna proiezione
60	Ente di connessione Punto	puntoMEDIO15-59(5) Nessuna proiezione
61	Allineamento asse parallelo ad asse	Retta_fori159(2) Asse Y
62	Crea origine	puntoMEDIO15-59(5) XY
63	Ricalcolato da memoria Punto	punto00_ric (6) punto0,0 (1); Projection from selected element
64	Ricalcolato da memoria Punto	punto01000_ric (7) punto0,1000 (2); Projection from selected element

E.5 Ruby_3pt_rif

The program computes with trigger probe the 3 points used to pass from RS-212temp to RS-212 in Alignment Ruby program.

Main program

1	Cambia combinazione tastatore	Combinazione n° = 1
2	Cambia tastatore	1
3	Richiama	110
4	CNC accesso e parametri CNC	Velocità di spostamento = 300.0000 Velocità di misura = 3.0000 Distanza di sicurezza = 1.0000
5	Punto intermedio Spostamento assoluto	X = 0.0000 Y = 0.0000 Z = 200.0000
6	Cambia tastatore	5
7	Punto intermedio Spostamento assoluto	X = 0.0000 Y = 0.0000 Z = 0.0000
8	Punto intermedio Spostamento assoluto	X = 0.0000 Y = 760.0000 Z = 0.0000
9	Punto intermedio Spostamento incrementale	X = 0.0000 Y = 0.0000 Z = -5.0000
10	Sfera	Rubino_2 (1) Gauss
11	Punto di misura Sul pezzo con direzione	X = 0.0000 Y = 770.0000 Z = -5.5000 I = 0.0000 J = 0.0000 K = 1.0000
12	Misura automatica cerchio	N° di Punti = 6 Piano di proiezione = Piano XY X = 0.0000 Y = 770.0000 Z = -3.5000 Diametro = 4.0000
13	Ente completato	
14	Punto intermedio Spostamento incrementale	X = 0.0000 Y = -20.0000 Z = 0.0000
15	Punto	punti_pianonero_5 (1) Punto compensato
16	Punto di misura Sul pezzo con direzione	X = -17.0000 Y = 775.0000 Z = 0.0000 I = 0.0000 J = 0.0000 K = 1.0000
17	Ente completato	
18	Punto	punti_pianonero_6 (2) Punto compensato
19	Punto di misura Sul pezzo con direzione	X = -17.0000 Y = 765.0000 Z = 0.0000 I = 0.0000 J = 0.0000 K = 1.0000
20	Ente completato	
21	Punto intermedio Spostamento incrementale	X = 0.0000 Y = 0.0000 Z = -10.0000
22	Punto intermedio Spostamento incrementale	X = 34.0000 Y = 0.0000 Z = 0.0000
23	Punto	punti_pianonero_7 (3) Punto compensato
24	Punto di misura Sul pezzo con direzione	X = 17.0000 Y = 765.0000 Z = 0.0000 I = 0.0000 J = 0.0000 K = 1.0000
25	Ente completato	
26	Punto	punti_pianonero_8 (4) Punto compensato
27	Punto di misura Sul pezzo con direzione	X = 17.0000 Y = 775.0000 Z = 0.0000 I = 0.0000 J = 0.0000 K = 1.0000
28	Ente completato	
29	Punto intermedio Spostamento incrementale	X = 0.0000 Y = -50.0000 Z = 0.0000
30	Punto intermedio Spostamento assoluto	X = 0.0000 Y = 0.0000 Z = 200.0000
31	Cambia tastatore	3
32	Punto intermedio Spostamento assoluto	X = 0.0000 Y = -700.0000 Z = 200.0000
33	Punto intermedio Spostamento assoluto	X = 0.0000 Y = -700.0000 Z = -10.0000
34	Sfera	Rubino_1 (2) Gauss
35	Punto di misura Sul pezzo con direzione	X = 0.0000 Y = -770.0000 Z = -5.5000 I = 0.0000 J = 0.0000 K = 1.0000
36	Misura automatica cerchio	N° di Punti = 6 Piano di proiezione = Piano XY X = 0.0000 Y = -770.0000 Z = -3.5000 Diametro = 4.0000
37	Ente completato	
38	Punto intermedio Spostamento incrementale	X = 0.0000 Y = 0.0000 Z = -10.0000
39	Punto	punti_pianonero_1 (5) Punto compensato
40	Punto di misura Sul pezzo con direzione	X = -17.0000 Y = -775.0000 Z = 0.0000 I = 0.0000 J = 0.0000 K = 1.0000
41	Ente completato	
42	Punto	punti_pianonero_2 (6) Punto compensato
43	Punto di misura Sul pezzo con direzione	X = -17.0000 Y = -765.0000 Z = 0.0000 I = 0.0000 J = 0.0000 K = 1.0000
44	Ente completato	
45	Punto intermedio Spostamento incrementale	X = 0.0000 Y = 0.0000 Z = -10.0000
46	Punto	punti_pianonero_3 (7) Punto compensato
47	Punto di misura Sul pezzo con direzione	X = 17.0000 Y = -765.0000 Z = 0.0000 I = 0.0000 J = 0.0000 K = 1.0000
48	Ente completato	
49	Punto	punti_pianonero_4 (4) Punto compensato
50	Punto di misura Sul pezzo con direzione	X = 17.0000 Y = -775.0000 Z = 0.0000 I = 0.0000 J = 0.0000 K = 1.0000
51	Ente completato	
52	Punto intermedio Spostamento incrementale	X = 0.0000 Y = 0.0000 Z = -10.0000
53	Punto intermedio Spostamento incrementale	X = 0.0000 Y = 770.0000 Z = 100.0000
54	Trasla e ruota sistema coordinate	Asse Y X = 0.0000 Y = 0.0000 Z = -10.0000, Angolo = 0.0000
55	Ente di connessione Piano	piano_neromedio_aut (1); Gauss
56	Orientamento piano	piano_neromedio_aut (1) Piano XY, Origine su ente
57	Ente di connessione Retta	retta_rubini1-2 aut (1) Piano XY
58	Allineamento asse parallelo ad asse	retta_rubini1-2 aut (1) Asse Y
59	Crea origine	Rubino_2 (1) XY
60	Trasla e ruota sistema coordinate	Asse Y X = 0.0000 Y = -770.0000 Z = 0.0000, Angolo = 0.0000
61	Memorizza sistema coordinate	111
62	Ente teorico Punto	punti_000 (9) X = 0.0000 Y = 0.0000 Z = 0.0000
63	Ente teorico Punto	punti_010000 (10) X = 0.0000 Y = 1000.0000 Z = 0.0000
64	Ente teorico Punto	punti_100000 (11) X = 1000.0000 Y = 0.0000 Z = 0.0000
65	Punto intermedio Spostamento assoluto	X = 0.0000 Y = -780.0000 Z = 200.0000
66	Cambia tastatore	1
67	Piano	piano_piastrina (2) Gauss
68	Punto di misura Sul pezzo con direzione	X = -11.0000 Y = -780.0000 Z = 42.0000 I = 0.0000 J = 0.0000 K = -1.0000
69	Punto di misura Sul pezzo con direzione	X = -11.0000 Y = -788.0000 Z = 42.0000 I = 0.0000 J = 0.0000 K = -1.0000
70	Punto di misura Sul pezzo con direzione	X = 11.0000 Y = -788.0000 Z = 42.0000 I = 0.0000 J = 0.0000 K = -1.0000
71	Punto di misura Sul pezzo con direzione	X = 11.0000 Y = -780.0000 Z = 42.0000 I = 0.0000 J = 0.0000 K = -1.0000

72	Punto intermedio Spostamento assoluto	X = 11.0000 Y = 780.0000 Z = 42.0000
73	Punto di misura Sul pezzo con direzione	X = 11.0000 Y = 780.0000 Z = 42.0000 I = 0.0000 J = 0.0000 K = -1.0000
74	Punto di misura Sul pezzo con direzione	X = 11.0000 Y = 788.0000 Z = 42.0000 I = 0.0000 J = 0.0000 K = -1.0000
75	Punto di misura Sul pezzo con direzione	X = -11.0000 Y = 788.0000 Z = 42.0000 I = 0.0000 J = 0.0000 K = -1.0000
76	Punto di misura Sul pezzo con direzione	X = -11.0000 Y = 780.0000 Z = 42.0000 I = 0.0000 J = 0.0000 K = -1.0000
77	Ente completato	
78	Orientamento piano	piano_piastrina (2) Piano XY, Origine su ente
79	Punto intermedio Spostamento assoluto	X = 1.0000 Y = 784.0000 Z = 10.0000
80	Cerchio	spina_piastrina_2 (1) Gauss
81	Misura automatica cerchio	N° di Punti = 6 Piano di proiezione = Piano XY X = 1.0000 Y = 784.0000 Z = - 2.0000 Diametro = 4.0000
82	Ente completato	
83	Punto intermedio Spostamento incrementale	X = 0.0000 Y = 0.0000 Z = 20.0000
84	Punto intermedio Spostamento assoluto	X = 1.0000 Y = -784.0000 Z = 10.0000
85	Cerchio	spina_piastrina_1 (2) Gauss
86	Misura automatica cerchio	N° di Punti = 6 Piano di proiezione = Piano XY X = 1.0000 Y = -784.0000 Z = - 2.0000 Diametro = 4.0000
87	Ente completato	
88	Punto intermedio Spostamento incrementale	X = 0.0000 Y = 0.0000 Z = 20.0000
89	Ente di connessione Retta	retta_piastrina1-2 aut (4) Nessuna proiezione
90	Allineamento asse parallelo ad asse	retta_piastrina1-2 aut (4) Asse Y
91	Ente di connessione Punto	punto medio fori piastrina (12) Nessuna proiezione
92	Crea origine	punto medio fori piastrina (12) XY
93	Ricalcolato da memoria Punto	punto_000_ric (13) punti_000 (9); Projection from selected element
94	Ricalcolato da memoria Punto	punto_010000_ric (14) punti_010000 (10); Projection from selected element
95	Ricalcolato da memoria Punto	punto_100000_ric (15) punti_100000 (11); Projection from selected element

E.6 Module alignment program

The program permits to align the modules on the Half-Stave.

Main program

1	Cambia combinazione tastatore	Combinazione n° = 2	
2	Cambia tastatore	1	
3	Richiama	202	
4	CNC acceso e parametri CNC	Velocità di spostamento = 300.0000 Velocità di misura = 3.0000 Distanza di sicurezza = 1.0000	
5	Punto intermedio Spostamento assoluto	X = 0.0000 Y = 0.0000 Z = 200.0000	
6	Formula di calcolo	month = Sys.Date.M	
7	Formula di calcolo	day = Sys.Date.D	
8	Formula di calcolo	year = Sys.Date.Y	
9	Linea di commento	****parametric data***	
10	Formula di calcolo	module_cross_size = 210,46	
11	Formula di calcolo	module_cross_dista = 0,24	
12	Formula di calcolo	X1 = 14,98	
13	Formula di calcolo	Z = 1	
14	Formula di calcolo	mem1 = 0	
15	Formula di calcolo	mem = 0	
16	Linea di commento	*****	
17	Define Label	start_align	
18	Inserisci variabile Dal file dialogo	D:\Alice Upgrade\Dialog\dialog_all_modulo.udl Alignment_module	
19	Linea di commento	****module****	
20	CNC acceso/spento	Acceso	
21	If	If MODULE_ALIGN = 10 Numero di decimali = 0	
22	Goto	end	
23	If	If MODULE_ALIGN = 3 Numero di decimali = 0	
24	Goto	start_script	
25	Formula di calcolo	Y0 = (mod-4)* (module_cross_size+module_cross_dista)	
26	Formula di calcolo	Y1 = Y0+module_cross_size/2	
27	Formula di calcolo	Y2 = Y0- module_cross_size/2	
28	Punto intermedio Spostamento assoluto	X = 0.0000 Y = Y0 Z = 200.0000	
29	Linea di commento	****marker****	
30	Formula di calcolo Definizione locale	X = (mark=1) *X1+(mark=2) *X1-(mark=3)*X1-(mark=4)*X1	
31	Formula di calcolo	Y = (mark=3)*Y1 +(mark=2)*Y1+(mark=1) *Y2+(mark=4)*Y2	
32	Punto intermedio Spostamento assoluto	X = X Y = Y Z = Z	
33	CNC acceso/spento	Spento	
34	If	If MODULE_ALIGN = 1 Numero di decimali = 0	
35	Testo output	first of all control rotation around Z , and then translation in Y and Z	
36	If	If MODULE_ALIGN = 2 Numero di decimali = 0	
37	Inizio		
38	Formula di calcolo	mem1 = mem1+1 punto_mod@(mod)_(mark) (MEM1) Punto compensato	
40	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000	
41	Ente completato		
42	End		
43	CNC acceso/spento	Acceso	
44	Punto intermedio Spostamento incrementale	X = 0.0000 Y = 0.0000 Z = 200.0000	
45	Goto	start_align	
46	Define Label	start_script	
47	Inserimento stringa variabile Dal file dialogo	D:\Alice Upgrade\Dialog\dialog_all_modulo.udl, CP	
48	Apri protocollo	GEOPAK\Mitutoyo\Mitutoyo	
			Standard Report D:\Alice Upgrade\POS_MARKS\POS_MARK_@(year)_(month)_(day)_[CP].xls
49	Define Label	start_loop_script	
50	Inserisci variabile Dal file dialogo	D:\Alice Upgrade\Dialog\dialog_all_modulo.udl Position_markers	
51	If	If EXIT = 1 Numero di decimali = 0	
52	Goto	end_script	
53	Linea di commento	****module****	
54	Formula di calcolo	Y0 = (mod-4)* (module_cross_size+module_cross_dista)	
55	Formula di calcolo	Y1 = Y0+module_cross_size/2	
56	Formula di calcolo	Y2 = Y0- module_cross_size/2	
57	Linea di commento	****marker****	
58	Formula di calcolo	mark = 0	
59	CNC acceso/spento	Acceso	
60	Inizio Loop	Numero di ripetizioni = 4	
61	Punto intermedio Spostamento assoluto	X = 0.0000 Y = Y0 Z = 200.0000	
62	Formula di calcolo	mark = mark+1	
63	Formula di calcolo Definizione locale	X = (mark=1)*X1+(mark=2)*X1- (mark=3)*X1-(mark=4)*X1	
64	Formula di calcolo	Y = (mark=3)*Y1+(mark=2)*Y1 +(mark=1)*Y2+(mark=4)*Y2	
65	Punto intermedio Spostamento assoluto	X = X Y = Y Z = 0.4	
66	Formula di calcolo	mem = 10*mod+mark	
67	Punto	point_mod@(mod)_(mark) (MEM) Punto compensato	
68	Misurazione Ottico Messa a fuoco	X = 0.0000 Y = 0.0000 Z = 0.0000	
69	CNC acceso/spento	Spento	
70	Misurazione Ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000	
71	Ente completato		
72	CNC acceso/spento	Acceso	
73	Punto intermedio Spostamento incrementale	X = 0.0000 Y = 0.0000 Z = 200.0000	
74	Fine Loop		
75	Goto	start_loop_script	
76	Define Label	end_script	
77	Chiudi protocollo		
78	CNC acceso/spento	Acceso	
79	Punto intermedio Spostamento assoluto	X = 0.0000 Y = 0.0000 Z = 200.0000	
80	Define Label	end	

E.7 Half-Stave alignment programs

The program permits the alignment of the Half-Stave.

Main program

1	Cambia combinazione tastatore	Combinazione n° = 2
2	Cambia tastatore	1
3	CNC acceso e parametri CNC	Velocità di spostamento = 300.0000 Velocità di misura = 3.0000 Distanza di sicurezza = 1.0000
4	Interruzione programmata	Check carefully if the stroke is free.
5	Linea di commento	****DATA****
6	Linea di commento	****Generic Data****
7	Formula di calcolo	month = Sys.Date.M
8	Formula di calcolo	day = Sys.Date.D
9	Formula di calcolo	year = Sys.Date.Y
10	Formula di calcolo	Z_safety_202 = 200.0000
11	Formula di calcolo	Z_safety_212 = 100.0000
12	Inserimento stringa variabile Inserimento guidato	Nome della variabile = CP
13	Inserimento stringa variabile Inserimento guidato	Nome della variabile = HS
14	Inserisci variabile Dal file dialogo	D:\Alice Upgrade\Dialog\dialog_all_halfstave.udl UL
15	Linea di commento	****Parametric data for FPC_holes_positions****
16	Formula di calcolo	dista_mod = 0.2
17	Formula di calcolo	length_mod = 210.9
18	Formula di calcolo	width_FPC = 33
19	Formula di calcolo	dista_hole_yedge = 1
20	Formula di calcolo	dista_hole_xedge = 1
21	Formula di calcolo	Y1 = 3.5*length_mod+3*dista_mod- dista_hole_yedge
22	Formula di calcolo	Y2 = 0.5*length_mod- dista_hole_yedge
23	Formula di calcolo	X1 = width_FPC/2- dista_hole_xedge
24	Formula di calcolo	X2 = -X1
25	Linea di commento	****Parametric data for Tolerance HS_Plane Data****
26	Formula di calcolo	X_plan_offset = 100
27	Formula di calcolo	X_planarity_dist = 12
28	Formula di calcolo	X1_planarity = X_plan_offset-X_planarity_dist
29	Formula di calcolo	X2_planarity = X_plan_offset
30	Formula di calcolo	X3_planarity = X_plan_offset+X_planarity_dist
31	Formula di calcolo	Y_start_planarity = -740
32	Formula di calcolo	Y_step_planarity = 740
33	Formula di calcolo	Y_end_planarity = -Y_start_planarity
34	Formula di calcolo	Z_planarity = -16,3
35	Linea di commento	****Parametric data for Alignment HS ****
36	Formula di calcolo	X_HS_offset = 12.9

37	Formula di calcolo	X_HS_offset_real = (X_HS_offset) *(- 1*(UL=1)+(UL=2))
38	Formula di calcolo	X_HS_offset_side = (X_HS_offset+15.2) *(- 1*(UL=1)+(UL=2))
39	Formula di calcolo	X_focus_pos = ((UL=1)- (UL=2))*0.5
40	Formula di calcolo	Z_align_HS = -16
41	Formula di calcolo	Z_focus_X4 = Z_align_HS
42	Formula di calcolo	Z_focus_X1 = Z_align_HS
	Formula di calcolo	Z_nominal = -11.9 *(UL=2)- 9.3*(UL=1)
43	Linea di commento	****Alignment HS data shift Z ****
44	Linea di commento	**** position of suction elements ****
45	Formula di calcolo	Y_shift_mod1 = -633,3
46	Formula di calcolo	Y_shift_mod7 = - Y_shift_mod1
47	Formula di calcolo	Y_shift_step = 211,1
48	Formula di calcolo	Y_shift_start = -740
49	Formula di calcolo	Y_shift_end = -Y_shift_start
50	Linea di commento	****START MAIN PROGRAM****
51	Define Label	start_main
52	Inserisci variabile Dal file dialogo	D:\Alice Upgrade\Dialog\dialog_all_halfstave.ud l STAVE_ASSEM LY
53	If	If SELECT_SUBPROGRAM = 10 Numero di decimali = 0
54	Goto	end_main
55	If	If SELECT_SUBPROGRAM = 1 Numero di decimali = 0
56	Sottoprogramm a	FPC_hole_subprg Libreria = No
57	If	If SELECT_SUBPROGRAM = 2 Numero di decimali = 0
58	Sottoprogramm a	HS_plane_subprg Libreria = No
59	If	If SELECT_SUBPROGRAM = 3 Numero di decimali = 0
60	Sottoprogramm a	HS_alignment_subprg Libreria = No
61	Goto	start_main
62	Define Label	end_main

E.7.7 FPC_hole_sbprg

1	Richiama	202
2	Formula di calcolo	Z_S = Z_safety_202
3	Punto intermedio Spostamento assoluto	X = 0.0000 Y = 0.0000 Z = Z_S
4	Formula di calcolo	mem = 0
5	Formula di calcolo	Z = 0.400
6	Linea di commento	****Measure FPC****
7	Apri protocollo	GEOPAK\Mitutoyo\Mitutoyo Standard Report D:\Alice Upgrade\FPC_holes\FPC_holes_@(year)_@(month)_@(day)_@[CP].xls
8	Define Label	start_FPC_hole_meas
9	CNC acceso/spento	Spento
10	Inserisci variabile Dal file dialogo	D:\Alice Upgrade\Dialog\dialog_all_halfstave.udl Measure_FPC_hole_on_Base
11	CNC acceso/spento	Acceso
12	Punto intermedio asse singolo	Asse Z = Z_S
13	If	If RETURN_MAIN = 1 Numero di decimali = 0
14	Inizio	
15	Formula di calcolo	return_main = 0
16	Goto	end_FPC_hole_meas
17	End	
18	Formula di calcolo	mem = select_base_bar*100
19	Sottoprogramma	FPC_hole_mov Libreria = No
20	Punto intermedio Spostamento assoluto	X = 0.0000 Y = 0.0000 Z = Z_S
21	Goto	start_FPC_hole_meas
22	Define Label	end_FPC_hole_meas
23	Inizio Loop	Numero di ripetizioni = 8
24	Distanza	Distance (1)&
25	Fine Loop	
26	Inizio Loop	Numero di ripetizioni = 8
27	Tolleranza - Distanza Distance (1)&	Distanza Y 0.0000 0.0500 -0.0500 Distanza X 0.0000 0.0500 -0.0500
28	Fine loop	
29	Interruzione programmata	Check in the small window if the tolerances are green
30	Chiudi protocollo	
31	Formula di calcolo	mem = 0
32	Esporta enti	DMIS D:\Alice Upgrade\FPC_holes\FPC_holes_@(year)_@(month)_@(day)_@[CP]

Subprogram: FPC_hole_subprg

1	Richiama	202
2	Formula di calcolo	Z_S = Z_safety_202
3	Punto intermedio Spostamento assoluto	X = 0.0000 Y = 0.0000 Z = Z_S
4	Formula di calcolo	mem = 0
5	Formula di calcolo	Z = 0.400
6	Linea di commento	****Measure FPC****
7	Apri protocollo	GEOPAK\Mitutoyo\Mitutoyo Standard Report D:\Alice Upgrade\FPC_holes\FPC_holes_@(year)_@(month)_@(day)_@[CP].xls
8	Define Label	start_FPC_hole_meas
9	CNC	Spento

	acceso/spento	
10	Inserisci variabile Dal file dialogo	D:\Alice Upgrade\Dialog\dialog_all_halfstave.udl Measure_FPC_hole_on_Base
11	CNC acceso/spento	Acceso
12	Punto intermedio asse singolo	Asse Z = Z_S
13	If	If RETURN_MAIN = 1 Numero di decimali = 0
14	Inizio	
15	Formula di calcolo	return_main = 0
16	Goto	end_FPC_hole_meas
17	End	
18	Formula di calcolo	mem = select_base_bar*100
19	Sottoprogramma	FPC_hole_mov Libreria = No
20	Punto intermedio Spostamento assoluto	X = 0.0000 Y = 0.0000 Z = Z_S
21	Goto	start_FPC_hole_meas
22	Define Label	end_FPC_hole_meas
23	Inizio Loop	Numero di ripetizioni = 8
24	Distanza	Distance (1)&
25	Fine Loop	
26	Inizio Loop	Numero di ripetizioni = 8
27	Tolleranza - Distanza Distance (1)&	Distanza Y 0.0000 0.0500 -0.0500 Distanza X 0.0000 0.0500 -0.0500
28	Fine loop	
29	Interruzione programmata	Check in the small window if the tolerances are green
30	Chiudi protocollo	
31	Formula di calcolo	mem = 0
32	Esporta enti	DMIS D:\Alice Upgrade\FPC_holes\FPC_holes_@(year)_@(month)_@(day)_@[CP]

Subprogram: FPC_hole_mov

1	Formula di calcolo	i = 0
2	Inizio Loop	Numero di ripetizioni = 4
3	Formula di calcolo	i = i+1
4	Formula di calcolo	Y = -Y1*(i=1)-Y2*(i=2)+Y2*(i=3)+Y1*(i=4)
5	Formula di calcolo	X = X1
6	Punto intermedio Spostamento assoluto	X = X Y = Y Z = Z_S
7	Punto intermedio Spostamento assoluto	X = X Y = Y Z = Z
8	Formula di calcolo	X_F = 0.000
9	Sottoprogramma	hole_manual Libreria = No
10	Punto intermedio Spostamento assoluto	X = X Y = Y Z = Z_S
11	Formula di calcolo	X = X2
12	Punto intermedio Spostamento assoluto	X = X Y = Y Z = Z_S
13	Punto intermedio Spostamento assoluto	X = X Y = Y Z = Z
14	Formula di calcolo	X_F = 0.000
15	Sottoprogramma	hole_manual Libreria = No
16	Punto intermedio Spostamento assoluto	X = X Y = Y Z = Z_S
17	Fine Loop	
18	Formula di calcolo	Y = 0

E.7.8 HS_plan_subprg

1	Richiama	212
2	Formula di calcolo	Z_S = Z_safety_212
3	Punto intermedio Spostamento assoluto	X = 0.0000 Y = 0.0000 Z = Z_S
4	CNC accesso e parametri CNC	Velocità di spostamento = 300.0000 Velocità di misura = 3.0000 Distanza di sicurezza = 1.0000
5	Linea di commento	****HS Planaritymeasure****
6	Punto intermedio Spostamento assoluto	X = X2_PLANARITY Y = 0.0000 Z = Z_S
7	Punto intermedio Spostamento assoluto	X = X2_PLANARITY Y = 0.0000 Z = Z_PLANARITY
8	Interruzione programmata	Check if the light is in the middle of HS
9	Punto intermedio Spostamento assoluto	X = X2_PLANARITY Y = Y_START_PLANARITY Z = Z_PLANARITY
10	Interruzione programmata	Check and rotate till the light is in the middle of HS
11	Define Label	start_plan
12	Formula di calcolo	mem = 400
13	Formula di calcolo	Z = Z_planarity
14	Apri protocollo	GEOPAK\Mitutoyo\Mitutoyo Standard Report D:\Alice Upgrade\HS_plane\HS_plane_@(year) _@(month)_@(day)_@[HS].xls
15	Sottoprogramma	HS_plan_check Libreria = No
16	Formula di calcolo	Z = Z_planarity
17	Formula di calcolo	Y = 0.0000
18	Ente di connessione Piano	Plane (1); Gauss Punto (401)&; Numero di enti = mem-400
19	Tolleranza Planarità	Ente = Plane (1) Ampiezza tolleranza = 0.0500
20	Variabile Si/No Definizione locale	Nome della variabile = Plan_yn; Testo = The planarity of HS is ok?
21	If	If PLAN_YN = 0 Numero di decimali = 0
22	Inizio	
23	Formula di calcolo	X = X2_planarity
24	Formula di calcolo	Z_SE = Z_planarity
25	Formula di calcolo	mem = 480
26	Sottoprogramma	SE_mov Libreria = No
27	Goto	start_plan
28	End	
29	Chiudi protocollo	

Subprogram: HS_plan_check

1	Formula di calcolo	Y = Y_start_planarity
2	Define Label	start_plan_movement
3	If	If Y > Y_END_PLANARITY Numero di decimali = 4
4	Goto	end_plan_check
5	Formula di calcolo	X = X1_planarity
6	Punto intermedio Spostamento assoluto	X = X Y = Y Z = Z
7	Sottoprogramma	point_auto Libreria = No
8	Formula di calcolo	X = X2_planarity
9	Punto intermedio Spostamento assoluto	X = X Y = Y Z = Z
10	Sottoprogramma	point_auto Libreria = No
11	Formula di calcolo	X = X3_planarity
12	Punto intermedio Spostamento assoluto	X = X Y = Y Z = Z
13	Sottoprogramma	point_auto Libreria = No
14	Formula di calcolo	Y = Y +Y_step_planarity
15	Goto	start_plan_check
16	Define Label	end_plan_check
17	Punto intermedio Spostamento incrementale	X = 0.0000 Y = 0.0000 Z = Z_S
18	Punto intermedio Spostamento assoluto	X = X2_PLANARITY Y = 0.0000 Z = Z_S

Subprogram: point_auto

1	Posizione attuale in variabile Sistema Coordinate attuali	X = X, Y = Y, Z = Z
2	Formula di calcolo	mem = mem+1 point (MEM)
3	Punto	Punto compensato
4	Misurazione ottico Messa a fuoco	X = 0.0000 Y = 0.0000 Z = 0.0000
5	Posizione attuale in variabile Sistema Coordinate attuali	Z = Z
6	Misurazione ottico Manuale	X = 1.9000 Y = 1.9000 Z = 0.0000
7	Ente completato	

Subprogram: SE_mov

1	Linea di commento	*****
2	Interruzione programmata	Start correction Z nominal positions
3	Formula di calcolo	Y = Y_shift_start
4	Sottoprogramma	SE_corr Libreria = No
5	Formula di calcolo	Y = Y_shift_mod1
6	Inizio Loop	Numero di ripetizioni = 7
7	Sottoprogramma	SE_corr Libreria = No
8	Formula di calcolo	Y = Y+Y_shift_step
9	Fine Loop	
10	Formula di calcolo	Y = Y_shift_end
11	Sottoprogramma	SE_corr Libreria = No
12	Punto intermedio Spostamento assoluto	X = X Y = 0.0000 Z = Z_S

Subprogram: SE_corr

1	Define Label	start_SE_corr
	Formula di calcolo	Z = Z_SE
2	Punto intermedio Spostamento assoluto	X = X Y = Y Z = Z_S
3	Punto intermedio Spostamento assoluto	X = X Y = Y Z = Z
4	Interruzione programmata	Adjust HS to Z nominal position to focus the point
5	Sottoprogramma	point_auto Libreria = No
6	Punto intermedio Spostamento incrementale	X = 0.0000 Y = 0.0000 Z = Z_S
7	Variabile Si/No Definizione locale	Nome della variabile = Z_correct; Testo = Is Z correct?
8	If	If Z_CORRECT = 0 Numero di decimali = 0
9	Inizio	
10	Formula di calcolo	mem = mem-1
11	Goto	Start_SE_corr
12	End	

Subprogram: hole manual

1	CNC accesso/spento	Spento
2	Interruzione programmata	Check hole position ,on focus and correct light then click confirm
3	Posizione attuale in variabile Sistema Coordinate attuali	X = X, Y = Y, Z = Z
4	CNC accesso/spento	Acceso
5	Interruzione programmata	Take four point of FPC hole
6	Formula di calcolo	mem = mem+1
7	Cerchio	hole (MEM) Gauss
8	Misurazione ottico Messa a fuoco	X = X_F Y = 0.0000 Z = 0.0000
9	Posizione attuale in variabile Sistema Coordinate attuali	Z = Z
10	Misurazione ottico Manuale	X = 0.0 Y = 0.0 Z = 0.0
11	Misurazione ottico Manuale	X = 0.0 Y = 0.0 Z = 0.0
12	Misurazione ottico Manuale	X = 0.0 Y = 0.0 Z = 0.0
13	Misurazione ottico Manuale	X = 0.0 Y = 0.0 Z = 0.0
14	Ente completato	

E.7.9 HS_alignment_subprg

1	Richiama	212
	Formula di calcolo	Z_S = Z_safety_212
	Punto intermedio Spostamento assoluto	X = 0.0000 Y = 0.0000 Z = Z_S
2	CNC accesso e parametri CNC	Velocità di spostamento = 300.0000 Velocità di misura = 3.0000 Distanza di sicurezza = 1.0000
4	Linea di commento	****Parametric Data****
5	Inserisci variabile Dal file dialogo	D:\Alice Upgrade\Dialog\dialog_all_halfstave.udl INPUT_DATA
6	Linea di commento	****UL upper=1 lower=2****
7	Linea di commento	****manually****
8	If	If LOAD_MANUALLY = 1 Numero di decimali = 0
9	Inizio	
10	If	If UL = 1 Numero di decimali = 0
11	Inserisci variabile Dal file dialogo	D:\Alice Upgrade\Dialog\dialog_all_halfstave.udl Load_FPC_Ho es_UPPER
12	If	If UL = 2 Numero di decimali = 0
13	Inserisci variabile Dal file dialogo	D:\Alice Upgrade\Dialog\dialog_all_halfstave.udl Load_FPC_Ho es_LOWER
14	End	
15	Linea di commento	****automatic****
16	If	If LOAD_MANUALLY = 0 Numero di decimali = 0
17	Inizio	
18	Richiama	202
19	If	If UL = 1 Numero di decimali = 0
20	Inizio	
21	Formula di calcolo	X1_load = CR[301].X
22	Formula di calcolo	Y1_load = CR[301].Y
23	Formula di calcolo	X2_load = CR[302].X
24	Formula di calcolo	Y2_load = CR[302].Y
25	Formula di calcolo	X3_load = CR[303].X
26	Formula di calcolo	Y3_load = CR[303].Y
27	Formula di calcolo	X4_load = CR[304].X
28	Formula di calcolo	Y4_load = CR[304].Y
29	End	
30	Else	
31	Inizio	
32	Formula di calcolo	X1_load = CR[302].X
33	Formula di calcolo	Y1_load = CR[302].Y
34	Formula di calcolo	X2_load = CR[303].X
35	Formula di calcolo	Y2_load = CR[303].Y
36	Formula di calcolo	X3_load = CR[304].X
37	Formula di calcolo	Y3_load = CR[304].Y
38	Formula di calcolo	X4_load = CR[305].X
39	Formula di calcolo	Y4_load = CR[305].Y
40	End	
41	Richiama	212
42	End	
43	Linea di commento	****transform on 212****
44	If	If UL = 1 Numero di decimali = 0
45	Inizio	
46	Formula di calcolo	FPC_hole_X1 = - X1_load - x_HS_offset
47	Formula di calcolo	FPC_hole_Y1 = Y1_load
48	Formula di calcolo	FPC_hole_X2 = - X2_load - x_HS_offset
49	Formula di calcolo	FPC_hole_Y2 = Y2_load
50	Formula di calcolo	FPC_hole_X3 = - X3_load - x_HS_offset
51	Formula di calcolo	FPC_hole_Y3 = Y3_load
52	Formula di calcolo	FPC_hole_X4 = - X4_load - x_HS_offset
53	Formula di calcolo	FPC_hole_Y4 = Y4_load
54	End	
55	Else	
56	Inizio	
57	Formula di calcolo	FPC_hole_X1 + x_HS_offset = - X1_load
58	Formula di calcolo	FPC_hole_Y1 = Y1_load
59	Formula di calcolo	FPC_hole_X2 = - X2_load + x_HS_offset

60	Formula di calcolo	FPC_hole_Y2 = Y2_load
61	Formula di calcolo	FPC_hole_X3 = - X3_load + x_HS_offset
62	Formula di calcolo	FPC_hole_Y3 = Y3_load
63	Formula di calcolo	FPC_hole_X4 = - X4_load + x_HS_offset
64	Formula di calcolo	FPC_hole_Y4 = Y4_load
65	End	
66	Linea di commento	****HS Positioning****
67	Punto intermedio Spostamento assoluto	X = X_HS_OFFSET_SIDE Y = 0.0000 Z = Z_S
68	Punto intermedio Spostamento assoluto	X = X_HS_OFFSET_SIDE Y = 0.0000 Z = Z_ALIGN_HS
69	Interruzione programmata	MOVE THE HS on focus with the light in the center
70	Interruzione programmata	MOVE THE HS on focus with the light on side
71	Punto intermedio Spostamento incrementale	X = 0.0000 Y = 0.0000 Z = Z_S
72	Linea di commento	****Alignment Procedure****
73	Define Label	start_alignment
74	Inserisci variabile Dal file dialogo	D:\Alice Upgrade\Dialog\dialog_all_halfstave.udl Alignment_Procedure
75	If	If REPEAT = 10 Numero di decimali = 0
76	Goto	end_alignment
77	If	If REPEAT = 1 Numero di decimali = 0
78	Sottoprogramma	HS_Rotation Libreria = No
79	If	If REPEAT = 2 Numero di decimali = 0
80	Sottoprogramma	HS_Translation_XY Libreria = No
81	If	If REPEAT = 3 Numero di decimali = 0
82	Sottoprogramma	HS_Shift_Z Libreria = No
83	If	If REPEAT = 4 Numero di decimali = 0
84	Sottoprogramma	HS_verify_save Libreria = No
85	Goto	start_alignment
86	Define Label	end_alignment

Subprogram: HS_Rotation

1	Linea di commento	****Rotation Z****
2	Punto intermedio Spostamento assoluto	X = 0.0000 Y = 0.0000 Z = Z_S
3	Formula di calcolo	mem = 500
4	Interruzione programmata	START ALIGNMENT IN ROTATION Z
5	Punto intermedio Spostamento assoluto	X = FPC_HOLE_X4 Y = FPC_HOLE_Y4 Z = Z_S
6	Punto intermedio Spostamento assoluto	X = FPC_HOLE_X4 Y = FPC_HOLE_Y4 Z = Z_FOCUS_X4
7	Interruzione programmata	MOVE THE HS FPC HOLE TO THIS POINT ONLY
8	Formula di calcolo	X_F = X_focus_pos
9	Sottoprogramma	hole_manual Libreria = No
10	Posizione attuale in variabile Sistema Coordinate attuali	Z = Z_focus_X4
11	Punto intermedio Spostamento incrementale	X = 0.0000 Y = 0.0000 Z = Z_S
12	Punto intermedio Spostamento assoluto	X = FPC_HOLE_X1 Y = FPC_HOLE_Y1 Z = Z_S
13	Punto intermedio Spostamento assoluto	X = FPC_HOLE_X1 Y = FPC_HOLE_Y1 Z = Z_FOCUS_X1
14	CNC accesso/spento	Spento
15	Interruzione programmata	MOVE THE VIDEO PROBE TO HS FPC HOLE ONLY
16	CNC accesso/spento	Acceso
17	Sottoprogramma	hole_manual Libreria = No
18	Linea di commento	****compute value of X for rotation and alignment****

19	Posizione attuale in variabile Sistema Coordinate attuali	Z = Z_focus_X1
20	Formula di calcolo	X_middle_rotation = (CR[501].X + CR[502].X)/2
21	Posizione attuale in variabile Sistema Coordinate attuali	Y = Y_X1_rotated
22	Punto intermedio Spostamento assoluto	X = X_MIDDLE_ROTATION Y = Y_X1_ROTATED Z = Z_FOCUS_X1
23	Interruzione programmata	Move HS using only Rotation movement to the correct X
25	Punto intermedio Spostamento incrementale	X = 0.0000 Y = 0.0000 Z = Z_S
26	Punto intermedio Spostamento assoluto	X = X_MIDDLE_ROTATION Y = FPC_HOLE_Y4 Z = Z_S
27	Punto intermedio Spostamento assoluto	X = X_MIDDLE_ROTATION Y = FPC_HOLE_Y4 Z = Z_FOCUS_X4
28	Interruzione programmata	Control the correct X position (only the vertical line of the green cross)
29	Punto intermedio Spostamento incrementale	X = 0.0000 Y = 0.0000 Z = Z_S
30	Punto intermedio Spostamento assoluto	X = 0.0000 Y = 0.0000 Z = Z_S

Subprogram: HS_Translation_XY

1	Linea di commento	****Translation X Y****
2	Punto intermedio Spostamento assoluto	X = 0.0000 Y = 0.0000 Z = Z_S
3	Interruzione programmata	START ALIGNMENT TRASLATION IN X Y
4	Punto intermedio Spostamento assoluto	X = FPC_HOLE_X4 Y = FPC_HOLE_Y4 Z = Z_S
5	Punto intermedio Spostamento assoluto	X = FPC_HOLE_X4 Y = FPC_HOLE_Y4 Z = Z_FOCUS_X4
6	Interruzione programmata	MOVE THE HS FPC HOLE TO THIS POINT
7	Linea di commento	****Check position relatives points ****
8	Punto intermedio Spostamento incrementale	X = 0.0000 Y = 0.0000 Z = Z_S
9	Punto intermedio Spostamento assoluto	X = FPC_HOLE_X1 Y = FPC_HOLE_Y1 Z = Z_S
10	Punto intermedio Spostamento assoluto	X = FPC_HOLE_X1 Y = FPC_HOLE_Y1 Z = Z_FOCUS_X1
11	Interruzione programmata	Control the correct HS FPC hole position
12	Punto intermedio Spostamento incrementale	X = 0.0000 Y = 0.0000 Z = Z_S
13	Punto intermedio Spostamento assoluto	X = 0.0000 Y = 0.0000 Z = Z_S

Subprogram: HS_Shift_Z

1	Interruzione programmata	START ALIGNMENT in nominal Z
2	Punto intermedio Spostamento assoluto	X = X_HS_OFFSET_REAL Y = 0.0000 Z = Z_S
3	Punto intermedio Spostamento assoluto	X = X_HS_OFFSET_REAL Y = 0.0000 Z = Z_ALIGN_HS
4	CNC acceso/spento	Spento
5	Interruzione programmata	Move Video probe and HS till Z=-11.9 (LOWER HS) or Z=-9.3 (U PER HS)
6	CNC acceso/spento	Acceso
7	Punto intermedio Spostamento assoluto	X = X_HS_OFFSET_REAL Y = 0.0000 Z = Z_NOMINAL
8	Interruzione programmata	Move HS to Z nominal position until is on focus
9	Interruzione programmata	Start Planarity control of HS
10	Define Label	start_shift_control
11	Formula di calcolo	mem = 600
12	Formula di calcolo	X = X_HS_OFFSET_REAL
13	Formula di calcolo	Z_SE = Z_NOMINAL
14	Sottoprogramma	SE_check Libreria = No

15	Ente di connessione Piano	Plane (2); Gauss Punto (601)&; Numero di enti = mem-600
16	Tolleranza Planarità	Ente = Plane (2) Ampiezza tolleranza = 0.0500
17	Ente teorico Retta	line_Z_nominal (1) Lunghezza = 1500.0000; X = X_HS_offset_real Y = -750.0000 Z = Z_NOMINAL;
18	Inizio Loop	Numero di ripetizioni = 9
19	Distanza	Distance (601)&
20	Fine Loop	
21	Inizio Loop	Numero di ripetizioni = 9
22	Tolleranza - Distanza (601)&	Distanza 0.0000 0.1000 - Distanza Z 0.0000 0.1000 - 0.1000
23	Fine Loop	
24	Interruzione programmata	Check Data Results
25	Variabile Si/No Definizione locale	Nome della variabile = Plan2_yn; Testo = The planarity and parallelism with Z_nominal plane of HS is ok?
26	If	If PLAN2_YN = 0 Numero di decimali = 0
27	Inizio	
28	Formula di calcolo	X = X_HS_OFFSET_REAL
29	Formula di calcolo	Z_SE = Z_NOMINAL
30	Formula di calcolo	mem = 680
31	Sottoprogramma	SE_mov Libreria = No
32	Goto	start_shift_control
33	End	
34	Interruzione programmata	Glue the U legs and relax

Subprogram: SE_check

1	Linea di commento	*****
2	Interruzione programmata	Start check Z nominal positions
3	Formula di calcolo	Y = Y_shift_start
4	Formula di calcolo	Z = Z_SE
5	Punto intermedio Spostamento assoluto	X = X Y = Y Z = Z_S
6	Punto intermedio Spostamento assoluto	X = X Y = Y Z = Z
7	Sottoprogramma	Point_auto Libreria = No
8	Punto intermedio Spostamento incrementale	X = 0.0000 Y = 0.0000 Z = Z_S
9	Formula di calcolo	Y = Y_shift_mod1
10	Inizio Loop	Numero di ripetizioni = 7
11	Formula di calcolo	Z = Z_SE
12	Punto intermedio Spostamento assoluto	X = X Y = Y Z = Z_S
13	Punto intermedio Spostamento assoluto	X = X Y = Y Z = Z
14	Sottoprogramma	Point_auto Libreria = No
15	Punto intermedio Spostamento incrementale	X = 0.0000 Y = 0.0000 Z = Z_S
16	Formula di calcolo	Y = Y+Y_shift_step
17	Fine Loop	
18	Formula di calcolo	Y = Y_shift_end
19	Formula di calcolo	Z = Z_SE
20	Punto intermedio Spostamento assoluto	X = X Y = Y Z = Z_S
21	Punto intermedio Spostamento assoluto	X = X Y = Y Z = Z
22	Sottoprogramma	Point_auto Libreria = No
23	Punto intermedio Spostamento incrementale	X = 0.0000 Y = 0.0000 Z = Z_S
24	Punto intermedio Spostamento assoluto	X = X Y = 0.0000 Z = Z_S

Subprogram: HS_verify_save

1	Linea di commento	**** verify and save FPC hole position****
2	Punto intermedio Spostamento assoluto	X = 0.0000 Y = 0.0000 Z = Z_S
3	Formula di calcolo	mem = 800
4	Apri protocollo	GEOPAK\Mitutoyo\Mitutoyo Standard Report D:\Alice Upgrade\HS_final_position\HS_final_posi

		tion_@(year)_@(month)_@[HS].xls
5	Sottoprogramma	HS_verify_mov Libreria = No
6	Punto intermedio Spostamento assoluto	X = 0.0000 Y = 0.0000 Z = Z_S
7	Chiudi protocollo	
8	Ente teorico Punto	point (901) X = FPC_HOLE_X1 Y = FPC_HOLE_Y1 Z = Z_NOMINAL
9	Ente teorico Punto	point (902) X = FPC_HOLE_X2 Y = FPC_HOLE_Y2 Z = Z_NOMINAL
10	Ente teorico Punto	point (903) X = FPC_HOLE_X3 Y = FPC_HOLE_Y3 Z = Z_NOMINAL
11	Ente teorico Punto	point (904) X = FPC_HOLE_X4 Y = FPC_HOLE_Y4 Z = Z_NOMINAL
12	Inizio Loop	Numero di ripetizioni = 4
13	Distanza	Distance (901)&
14	Fine Loop	
15	Inizio Loop	Numero di ripetizioni = 4
16	Tolleranza - Distanza Distance (901)&	Distanza 0.0000 0.0500 - 0.0500 Distanza X Y 0.0000 0.0500 -0.0500
17	Fine Loop	

Subprogram: HS_verify_mov

1	Formula di calcolo	i = 0
2	Inizio Loop	Numero di ripetizioni = 4
3	Formula di calcolo	i = i+1
4	Formula di calcolo	Y = FPC_hole_Y1*(i=1)+FPC_hole_Y2 *(i=2)+FPC_Hole_Y3*(i=3)+FPC_ hole_Y4*(i=4)
5	Formula di calcolo	X = FPC_hole_X1*(i=1)+FPC_hole_X2 *(i=2)+FPC_Hole_X3*(i=3)+FPC_ hole_X4*(i=4)
6	Formula di calcolo	Z = Z_nominal
7	Formula di calcolo	X_F = X_focus_pos
8	Punto intermedio Spostamento assoluto	X = X Y = Y Z = Z_S
9	Punto intermedio Spostamento assoluto	X = X Y = Y Z = Z
10	Sottoprogramma	hole_manual Libreria = No
11	Punto intermedio Spostamento incrementale	X = 0.0000 Y = 0.0000 Z = Z_S
12	Fine Loop	

E.8 Mask_position

The program measures the position of the gluing mask windows, to find longitudinal and lateral final variations.

Main program

1	Cambia combinazione tastatore	Combinazione n° = 2
2	Cambia tastatore	1
3	Richiama	202
4	CNC accesso e parametri CNC	Velocità di spostamento = 300.0000 Velocità di misura = 3.0000 Distanza di sicurezza = 1.0000
5	Inserimento stringa variabile Inserimento guidato	Nome della variabile = codice
6	Formula di calcolo	step = 30,1
7	Formula di calcolo	distanza_moduli = 210,7
8	Formula di calcolo	w = 1
9	Formula di calcolo	k = 1
10	Formula di calcolo	year = Sys.Date.Y
11	Formula di calcolo	month = Sys.Date.M
12	Formula di calcolo	day = Sys.Date.D
13	Apri protocollo	GEOPAK\Mitutoyo\Mitutoyo Standard Report D:\Alice Upgrade\MASCHERE\maschera_@(ye ar)_@(month)_@(day)_@[c
14	Define Label	inizio modulo
15	Inserisci variabile Inserimento guidato	Nome della variabile = mod; Testo = numero modulo Massimo = 8; Predefinito = 1-8; Minimo = 1
16	If	If MOD = 8 Numero di decimali = 0
17	Goto	fine modulo
18	Linea di commento	*****inizio misura_altezza*****
19	If	If MOD <= 4 Numero di decimali = 0
20	Inizio	
21	Sottoprogramma	MISURA_alt_mod1-4 Libreria = No
22	End	
23	If	If MOD > 4 Numero di decimali = 0
24	Inizio	
25	Sottoprogramma	MISURA_alt_mod5-7 Libreria = No
26	End	
27	Linea di commento	*****inizio misura_larghezza*****
28	Formula di calcolo	w = 1
29	Formula di calcolo	Y = -722,4+(mod- 1)*distanza_moduli
30	Define Label	inizio_larghezza
31	Formula di calcolo	X = -14,55
32	If	If W = 8 Numero di decimali = 0
33	Goto	fine_larghezza
34	Punto intermedio Spostamento assoluto	X = X Y = Y Z = 0.2500
35	Sottoprogramma	misure_larghezza Libreria = No
36	Formula di calcolo	Y = Y+step
37	Formula di calcolo	w = w+1
38	Goto	inizio_larghezza
39	Define Label	fine_larghezza
40	Goto	inizio modulo
41	Define Label	fine modulo
42	Chiudi protocollo	

Subprogram: misura_alt_mod1-4

1	Formula di calcolo	Y1 = -736,9+(mod- 1)*distanza_moduli
2	Formula di calcolo	Y2 = -527,3+(mod- 1)*distanza_moduli
3	Formula di calcolo	mem = 100*mod+85
4	Formula di calcolo	Z = 0.35
5	Punto intermedio Spostamento assoluto	X = -7.5000 Y = Y1 Z = Z
6	Punto	MOD_@(mod)_punto_bas_sx (MEM) Punto compensato

7	Misurazione ottico Messa a fuoco	X = 0.0000 Y = 0.0000 Z = 0.0000
8	Posizione attuale in variabile Sistema di coordinate attuali	Z = Z
9	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
10	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
11	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
12	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
13	Ente completato	
14	Punto intermedio Spostamento incrementale	X = 15.0000 Y = 0.0000 Z = 0.0000
15	Formula di calcolo	mem = 100*mod+95
16	Punto	MOD_@(mod)_punto_bas_dx (MEM) Punto compensato
17	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
18	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
19	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
20	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
21	Ente completato	
22	Punto intermedio Spostamento assoluto	X = -7.5000 Y = Y2 Z = Z
23	Formula di calcolo	mem = 100*mod+86
24	Punto	MOD_@(mod)_punto_alt_sx (MEM) Punto compensato
25	Misurazione ottico Messa a fuoco	X = 0.0000 Y = 0.0000 Z = 0.0000
26	Posizione attuale in variabile Sistema di coordinate attuali	Z = Z
27	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
28	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
29	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
30	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
31	Ente completato	
32	Formula di calcolo	mem = 100*mod+87
33	Punto	MOD_@(mod)_punto_end_dx (MEM) Punto compensato
34	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
35	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
36	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
37	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
38	Ente completato	
39	Formula di calcolo	mem = 100*mod+96
40	Punto intermedio Spostamento incrementale	X = 15.0000 Y = 0.0000 Z = 0.0000
41	Punto	MOD_@(mod)_punto_alt_dx (MEM) Punto compensato
42	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
43	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000

44	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
45	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
46	Ente completato	
47	Formula di calcolo	mem = 100*mod+97
48	Punto	MOD_@(mod)_punto_end_dx (MEM) Punto compensato
49	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
50	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
51	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
52	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
53	Ente completato	

Subprogram: misura_alt_mod5-7

1	Formula di calcolo	Y1 = 736.9+(mod-7)*distanza_moduli
2	Formula di calcolo	Y2 = 527.3+(mod-7)*distanza_moduli
3	Formula di calcolo	mem = 100*mod+85
4	Formula di calcolo	Z = 0.35
5	Punto intermedio Spostamento assoluto	X = -7.5000 Y = Y2 Z = Z
6	Punto	MOD_@(mod)_punto_iniz_sx (MEM) Punto compensato
7	Misurazione ottico Messa a fuoco	X = 0.0000 Y = 0.0000 Z = 0.0000
8	Posizione attuale in variabile Sistema di coordinate attuali	Z = Z
9	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
10	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
11	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
12	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
13	Ente completato	
14	Formula di calcolo	mem = 100*mod+86
15	Punto	MOD_@(mod)_punto_bas_sx (MEM) Punto compensato
16	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
17	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
18	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
19	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
20	Ente completato	
21	Punto intermedio Spostamento incrementale	X = 15.0000 Y = 0.0000 Z = 0.0000
22	Formula di calcolo	mem = 100*mod+95
23	Punto	MOD_@(mod)_punto_iniz_dx (MEM) Punto compensato
24	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
25	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
26	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
27	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
28	Ente completato	
29	Formula di calcolo	mem = 100*mod+96
30	Punto	MOD_@(mod)_punto_bas_dx (MEM) Punto compensato
31	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
32	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
33	Misurazione ottico	X = 0.0000 Y = 0.0000 Z =

	Manuale	0.0000
34	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
35	Ente completato	
36	Formula di calcolo	mem = 100*mod+87
37	Punto intermedio Spostamento assoluto	X = -7.5000 Y = Y1 Z = Z
38	Punto	MOD_@(mod)_punto_alt_sx (MEM) Punto compensato
39	Misurazione ottico Messa a fuoco	X = 0.0000 Y = 0.0000 Z = 0.0000
40	Posizione attuale in variabile Sistema di coordinate attuali	Z = Z
41	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
42	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
43	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
44	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
45	Ente completato	
46	Punto intermedio Spostamento incrementale	X = 15.0000 Y = 0.0000 Z = 0.0000
47	Formula di calcolo	mem = 100*mod+97
48	Punto	MOD_@(mod)_punto_alt_dx (MEM) Punto compensato
49	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
50	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
51	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
52	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
53	Ente completato	

Subprogram: misure_larghezza

1	Formula di calcolo	X = -14,55
2	Formula di calcolo	k = 1
3	Punto intermedio Spostamento assoluto	X = X Y = Y Z = 0.2500
4	Formula di calcolo	Z = 0.35
5	Formula di calcolo	mem = 100*mod+10*w+k
6	Punto	punto_@(mem)(MEM) Punto compensato
7	Misurazione ottico Messa a fuoco	X = -0.500 Y = 0.2500 Z = 0.0000
8	Posizione attuale in variabile Sistema di coordinate attuali	Z = Z
9	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
10	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
11	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
12	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
13	Ente completato	
14	Formula di calcolo	k = 2
15	Formula di calcolo	mem = 100*mod+10*w+k
16	Formula di calcolo	X = -0,55
17	Punto intermedio Spostamento assoluto	X = X Y = Y Z = Z
18	Punto	punto_@(mem)(MEM) Punto compensato
19	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
20	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
21	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
22	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000
23	Ente completato	
24	Formula di calcolo	k = 3
25	Formula di calcolo	mem =

		100*mod+10*w+k	
26	Formula di calcolo	X	= 0,55
27	Punto intermedio Spostamento assoluto	X = X Y = Y Z = Z	
28	Punto	punto_@(mem)(MEM) Punto compensato	
29	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000	
30	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000	
31	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000	
32	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000	
33	Ente completato		
34	Formula di calcolo	k	= 4
35	Formula di calcolo	mem	=

		100*mod+10*w+k	
36	Formula di calcolo	X	= 14,55
37	Punto intermedio Spostamento assoluto	X = X Y = Y Z = Z	
38	Punto	punto_@(mem)(MEM) Punto compensato	
39	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000	
40	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000	
41	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000	
42	Misurazione ottico Manuale	X = 0.0000 Y = 0.0000 Z = 0.0000	
43	Ente completato		

E.9 CP_planarity

The program measures the CP planarity; the results are stored in an Excel file and then analyzed.

1	Cambia combinazione tastatore	Combinazione n° = 1
2	Cambia tastatore	1
3	Richiama	102
4	CNC acceso e parametri CNC	Velocità di spostamento = 300.0000 Velocità di misura = 3.0000 Distanza di sicurezza = 1.0000
5	Punto intermedio asse singolo	Asse Z = 200.0000
6	Formula di calcolo	month = Sys.Date.M
7	Formula di calcolo	day = Sys.Date.D
8	Formula di calcolo	year = Sys.Date.Y
9	Inserimento stringa variabile Inserimento guidato	Nome della variabile = codice
10	Apri protocollo	GEOPAK\Mitutoyo\Mitutoyo Standard Report D:\Alice Upgrade\CP\CPtast_@(\year)_@(month)_@(\day)_@[codice].xls
11	Formula di calcolo	X = 13
12	Formula di calcolo	Ystart = -740
13	Formula di calcolo	Yend = 740
14	Formula di calcolo	stepY = 20
15	Formula di calcolo	mem = 0
16	Formula di calcolo	Z = 0,15
17	Formula di calcolo	Ycurrent = Ystart-stepY
18	Define Label	inizio
19	Formula di calcolo	Ycurrent = Ycurrent+stepY
20	If	If YCURRENT >= YEND Numero di decimali = 4
21	Goto	fine
22	Sottoprogramma	misura Libreria = No
23	Goto	inizio
24	Define Label	fine
25	Formula di calcolo	Ycurrent = Yend
26	Sottoprogramma	misura Libreria = No
27	Punto intermedio asse singolo	Asse Z = 200.0000
28	Chiudi protocollo	

Subprogram: misura

1	Formula di calcolo	mem = mem+1
2	Punto	punto_dx (MEM) Punto compensato
3	Punto di misura Sul pezzo con direzione	X = X Y = YCURRENT Z = Z Angolo X = 90:00:00 Angolo Y = 90:00:00 Angolo Z = 180:00:00
4	Ente completato	
5	Formula di calcolo	mem = mem+1
6	Punto	punto_centrale (MEM) Punto compensato
7	Punto di misura Sul pezzo con direzione	X = 0.0000 Y = YCURRENT Z = Z Angolo X = 90:00:00 Angolo Y = 90:00:00 Angolo Z = 180:00:00
8	Ente completato	
9	Formula di calcolo	mem = mem+1
10	Punto	punto_sx (MEM) Punto compensato
11	Punto di misura Sul pezzo con direzione	X = -X Y = YCURRENT Z = Z Angolo X = 90:00:00 Angolo Y = 90:00:00 Angolo Z = 180:00:00
12	Ente completato	

E.10 Handling_bar_planarity

The program measures the planarity and parallelism of the feet of the HS Handling Bar respect to XY plane of SR-212.

Main program

1	Cambia combinazione tastatore	Combinazione n° = 2
2	Cambia tastatore	1
3	Richiama	212
4	CNC acceso e parametri CNC	Velocità di spostamento = 300.0000 Velocità di misura = 3.0000 Distanza di sicurezza = 1.0000
5	Punto intermedio Spostamento assoluto	X = 60.0000 Y = 0.0000 Z = 100.0000
6	Formula di calcolo	mem = 0
7	Linea di commento	*****start measure*****
8	Formula di calcolo	Xdiff = 20
9	Formula di calcolo	Xmedio = -12,9
10	Formula di calcolo	Y = -707
11	Formula di calcolo	Z = -9,3
12	Formula di calcolo	y_jump1 = 400
13	Formula di calcolo	y_jump2 = 307
14	Sottoprogramma	x_dx_sx Libreria = No
15	Formula di calcolo	Y = Y+y_jump1
16	Sottoprogramma	x_dx_sx Libreria = No
17	Formula di calcolo	Y = Y+y_jump2
18	Sottoprogramma	x_dx_sx Libreria = No
19	Formula di calcolo	Y = Y+y_jump2
20	Sottoprogramma	x_dx_sx Libreria = No
21	Formula di calcolo	Y = Y+y_jump1
22	Sottoprogramma	x_dx_sx Libreria = No
23	Ente di connessione Piano	Plane_bar (1); Gauss Punto (1)&; Numero di enti = 10
24	Tolleranza Planarità	Ente = Plane_bar (1) Ampiezza tolleranza = 0.0500 Plane_000 (2)
25	Ente teorico Piano	Distanza = 0.0000; I = 0.0000 J = 0.0000 K = 1.0000

26	Tolleranza Parallelismo	Ente = Plane_bar (1) Ampiezza tolleranza = 0.1000 Ente di riferimento = Plane_000 (2)
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Supprogram: x_dx_sx

1	Formula di calcolo	X = Xmedio-Xdiff
2	Sottoprogramma	bar_point Libreria = No
3	Formula di calcolo	X = Xmedio+Xdiff
4	Sottoprogramma	bar_point Libreria = No

Subprogram: bar_point

1	Formula di calcolo	mem = mem+1
2	Punto intermedio Spostamento assoluto	X = X Y = Y Z = 100.0000
3	Punto intermedio Spostamento assoluto	X = X Y = Y Z = Z
4	CNC acceso/spento	Spento
5	Interruzione programmata	Take a point near the hole
6	CNC acceso/spento	Acceso
7	Posizione attuale in variabile Sistema Coordinate attuali	X = X, Y = Y, Z = Z
8	Punto	plane_b1_@(mem)(MEM) Punto compensato
9	Misurazione ottico Messa a fuoco	X = 0.0000 Y = 0.0000 Z = 0.0000
10	Posizione attuale in variabile Sistema Coordinate attuali	Z = Z
11	Misurazione ottico Manuale	X = 1.9700 Y = 1.9700 Z = 0.0000
12	Ente completato	
13	Punto intermedio Spostamento incrementale	X = 0.0000 Y = 0.0000 Z = 100.0000