LAPIN AMK
Lapland University of Applied Sciences

DEVELOPMENT OF A UNIVERSAL CRYOGENIC TEST FACILITY

Universal Cryogenic Test Facility

Jari Markkanen

Thesis
Technology, Communication and Transport
Mechanical and Production Engineering
Bachelor of Engineering

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Opinnäytetyön tiivistelmä

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Tämän opinnäytetyön aiheena oli kehittää olemassa olevaa yleiskäyttöistä materiaalintestauslaitteistoa, joka on käytössä CERNissä. Laitteistolla tehdään rikkovia materiaalinkoetustestejä hyvin kylmissä lämpötiloissa, jotta saadaan tietoa materiaalien käyttäytymisestä näissä olosuhteissa. Tavoitteena oli suunnitella laitteistolle lisäys niin, että sillä on tulevaisuudessa mahdollista tehdä myös puristustestejä.

Työn teoriaosuudessa käsiteltiin aiheita liittyen rikkovaan aineenkoetukseen, kylmätekniikkaan, käytettyihin suunnittelutyökaluihin ja olemassa olevan laitteiston esittelyyn. Työssä tarkasteltiin myös 3D-tulostusta, koska mallista tehtiin alustava prototyyppi Lapin AMK:n 3D-tulostimella.

Suunnittelutyö tehtiin yhteistyössä CERNin materiaalintestauslaboratorion henkilöstön kanssa, pääosin etätyönä. Tämän opinnäytetyön tulokseksi saatiin 3D-malli puristuslaitteistosta ja sen osista, sekä ensimmäinen prototyyppi, joiden pohjalta voidaan toteuttaa lopullinen laitteisto puristustestaukseen. Laitteisto tehdään ja testataan CERNissä, kun lopulliset piirustukset on laadittu.

Avainsanat 3D-mallinnus, suunnittelu, kylmätekniikka, aineenkoetus

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Abstract of Thesis

Technology, communication and transport
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Author	Jari Markkanen	Year	2017
Supervisor	Ari Pikkarainen, M.Eng		
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The subject of the thesis was the development of a universal cryogenic test facility used at CERN. With this facility, tensile tests are performed in very cold temperatures, to get information about materials behaviour in these conditions. The objective was to design an addition to the system, so that it could also support the compressive test method.

The theory of the thesis consists of material testing theory, cryogenics, used design tools and the introduction of the existing facility. 3D printing is included, because the first prototype was fabricated with LUAS's 3D printer.

The design was done in collaboration with the CERN MME group's staff, mostly as remote work. The final facility will be fabricated and tested at CERN, when the project is at that stage. The results of this thesis are the 3D model of the compression insert and its parts, and the first prototype, which are used in the future to fabricate and commission the compression testing method for the universal cryogenic test facility.

Key words 3D modeling, design, cryogenics, material testing

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FOREWORD

I want to thank all the people involved in the project at CERN and Lapland University of Applied Sciences. Thanks goes also to my family that supported me through the work.

9 May 2017, Kemi

Jari Markkanen

ABBREVIATIONS

ABS	Acrylonitrile Butadiene Styrene
CAD	Computer Aided Design
CERN	Conseil Européen pour la Recherche Nucléaire
EN	Engineering department
FDM	Fused Deposition Modeling
FEM	Finite Element Method
LEP	Large Electron-Positron Collider
LHC	Large Hadron Collider
LUAS	Lapland University of Applied Sciences
MME	Mechanical and Materials Engineering group
PLA	Polylactic Acid
PS	Proton Synchrotron
SC	Synchrocyclotron
SPS	Super Proton Synchrotron
UTS	Ultimate Tensile Strength

1 INTRODUCTION

This thesis project was done during my last year at Lapland University of Applied Sciences and during my traineeship in the summer of 2016. Mechanical testing for materials in extreme conditions is important at CERN, the biggest particle accelerator complex worldwide. EN-MME has a tensile testing system, which is needed to support the compressive material testing method in addition to the tensile testing. Taking the current tensile testing system to a more versatile level expands possibilities for testing materials in the future.

For me as a mechanical engineering student this was a great and interesting opportunity to expand my knowledge about engineering and design. Since I was going on internship at CERN, I could see and study the original tensile testing system on the spot.

1.1 Objectives

The main objective was to bring the current cryogenic tensile testing system to a new level of versatility, by integrating the compressive test method into the cryostat. Other objectives concerning the project were:

1. To develop familiarity in the testing of materials for cryogenic structural applications and testing techniques in cryogenic temperatures.
2. To acquire knowledge about the current tensile testing system.
3. To acquire knowledge about the technical aspects of the Ultimate Tensile Strength (UTS) testing system.
4. To make the final design and production of the upgraded test facility.

The subsequent objectives were the validation according to the standards and commissioning of the new test facility and the development of the experimental guidelines for the compression testing at cryogenic temperatures.

2 CERN

At the European Organization for Nuclear research, engineers and physicists study the basic structure of the universe. The world’s largest and most complex scientific apparatus is used to study fundamental particles. Particles are made to collide at close to the speed of light, and how the particles interact, it provides insight into the fundamental laws of nature. (CERN 2017.)

Particle accelerators and detectors used at CERN are built for precise purposes, to accelerate particles to high energies before beams are made to collide with each other or with stationary targets. Detectors like ATLAS or CMS are used to record and monitor the results of the collisions. (CERN 2017.)

Because our understanding goes much deeper than the nucleus, and CERN’s main area of research being particle physics, CERN operated laboratory is often referred as the European Laboratory for Particle Physics. Particle physics research at CERN studies the fundamental constituents of matter and the forces acting between them. (CERN 2017.)

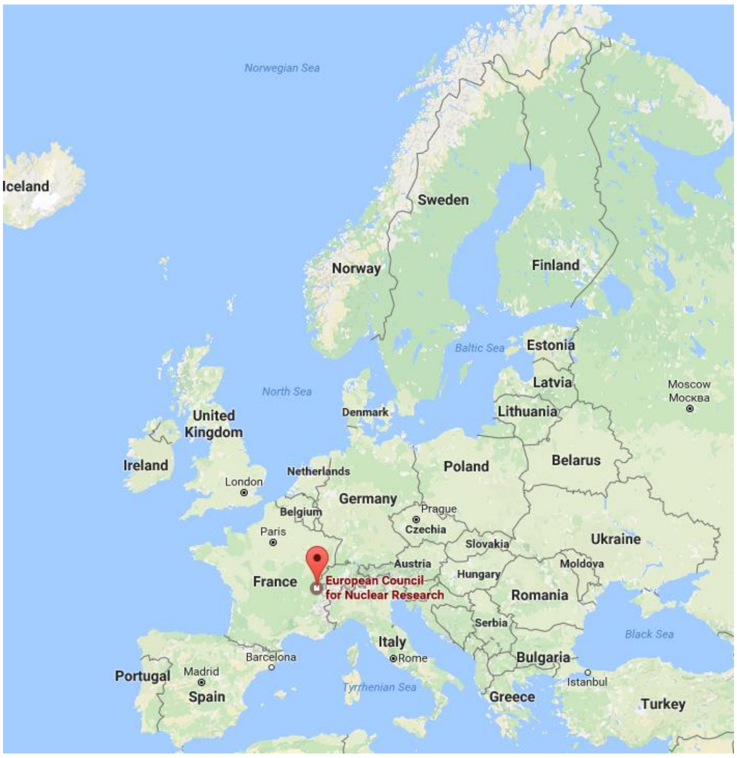


Figure 1. CERN’s Location in Europe (Google maps 2017.)

CERN was founded in 1954, and it was decided to be built at Franco-Swiss border near to Geneva. The location of CERN in Europe is in Figure 1. CERN has two main sites, one in France and the other in Switzerland. The main entrance (entrance B) can be found at the Meyrin site in Switzerland. (CERN 2017.)

The LHC tunnel and sites on Franco-Swiss border are presented in Figure 2.

Figure 2. The LHC Tunnel and Sites (CERN 2007.)

2.1 Organization

The highest authority of CERN is the CERN Council, which has the responsibility for all important decisions. The council controls CERN’s activities in a large scale. It accepts budgets, plans of activities and reviews expenditure. The scientific policy committee and Finance Committee assist the council. Appointed by the council, a Director-General manages the CERN laboratory. The Director-General is assisted by a directorate, who runs the laboratory through a structure of departments. (CERN 2017.)

CERN’s council consists of two delegates from each member countries. When writing this thesis, there were 22 member states. One of delegates represents his or her government administration while the other represent national scientific interests. The member states have one vote each, and most decisions require a simple majority of votes. In practice, The Council aims as close as possible at consensus in matters. (CERN 2017.)

The Scientific Policy Committee makes recommendations on CERN's scientific program and determines the scientific merits of activities suggested by the physicists. The members of the committee are elected by the committee colleagues and appointed by the council by basis of the scientific eminence. There are members elected from non-member states. The Finance Committee deals with issues concerning financial contributions by the member states and CERN's budget and expenditure. (CERN 2017.)

The Director-General is usually appointed for five years by the council. He manages CERN with assistance of the directorate. The Director-General reports directly to the council and can make necessary suggestions to the council, for evolving needs of the research programs. (CERN 2017.)

CERN's current organization chart for communications is presented in simplified form in Figure 3. More strategic method for communications is in use at CERN, because a regular corporate organization is not possible nor wanted. (CERN 2017.)

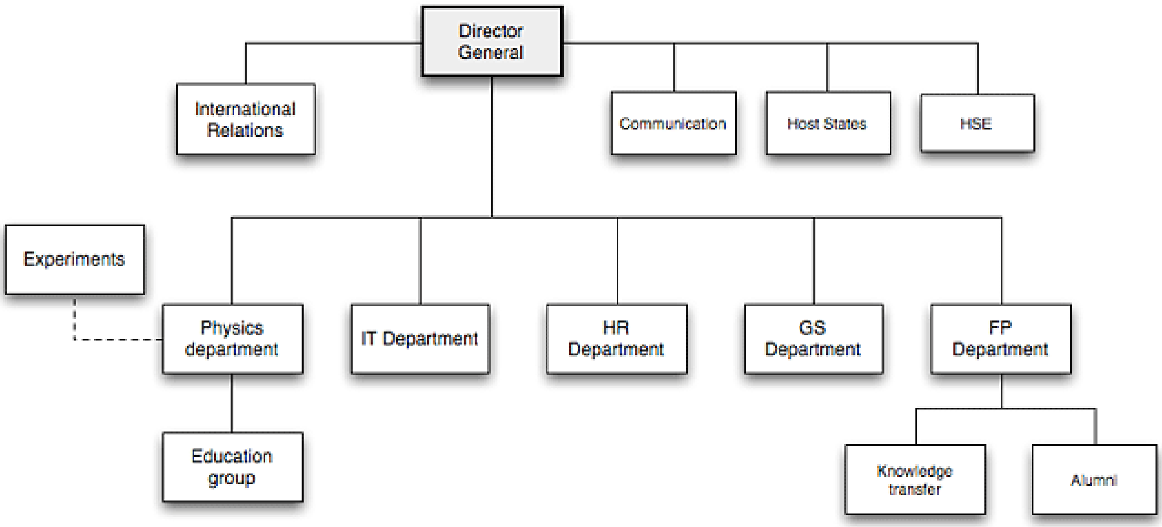


Figure 3. CERN's Organization Chart for Communications (CERN communication group 2016.)

2.2 History

The idea of creating a European atomic physics laboratory came from a handful of scientists, because European science was no longer world-class. The first official proposal for founding the laboratory came from Louis de Broglie in 1949 at the European Cultural Conference. The first conclusion to establish the European Council for Nuclear Research was made in 1951. The name CERN was born and shortly after it was decided to be built in Geneva. The construction started on 17 May 1954 and at that time there were 12 member states founding CERN. (CERN 2017.)

The first accelerator commissioned was the Synchrocyclotron (SC), which provided beams for the first experiments at CERN. When the much more powerful Proton Synchrotron (PS) was taken into action, SC started to focus on nuclear physics alone. The SC came to be an outstandingly long-lived machine, and its operations were shut down after 33 years of service. The Super Proton Synchrotron (SPS) commissioned in 1976 was CERN’s next workhorse and it is still in use, having handled many kinds of particles. (CERN 2017.)

The Large Electron-Positron Collider (LEP) which was built in the 27-kilometre circumference tunnel, was and is still the largest electron-positron accelerator ever built. The Large Hadron Collider (LHC) was built in the same cavern as the LEP after its shut down in 2000, and LHC started up in 2008. (CERN 2017.)

The LHC finds answers to the questions e.g. what gives matter its mass, how matter evolved from first moments of the Big Bang, why nature prefers matter to antimatter and what is the invisible 96% of the universe made of. (CERN 2017.)

CERN’s current accelerator complex is presented in Figure 4.

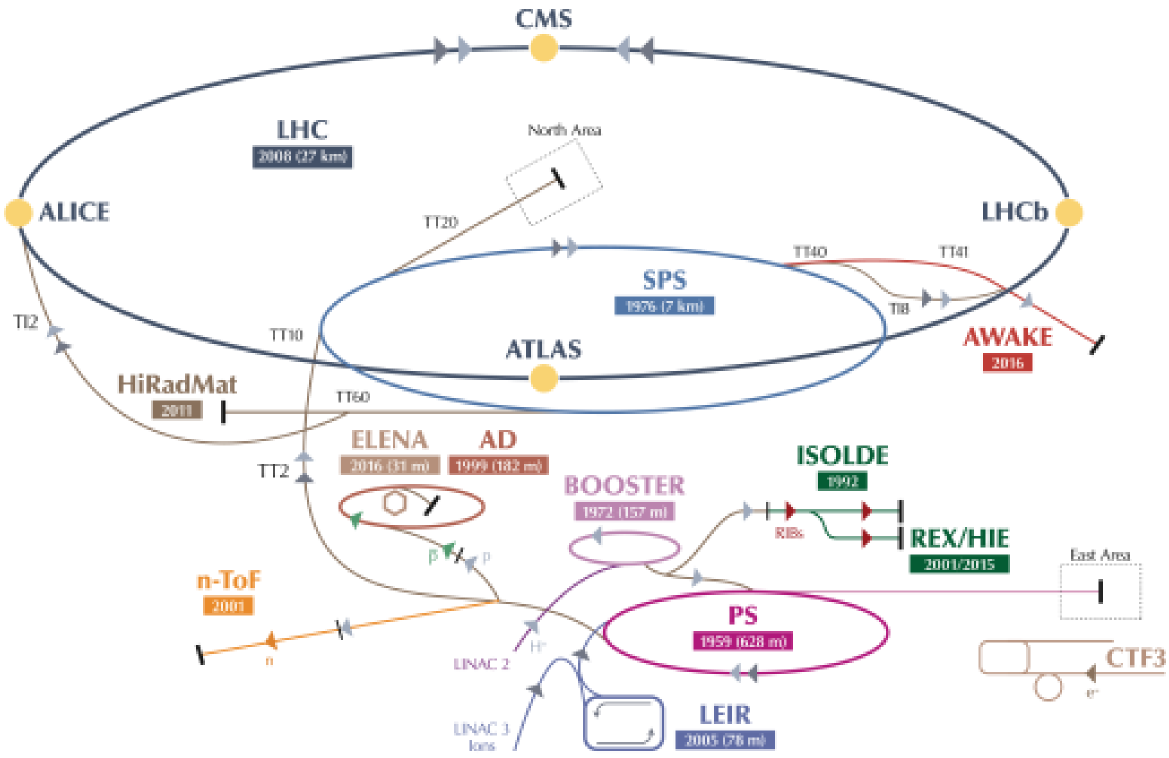


Figure 4. CERN’s Accelerator Complex (CERN 2013.)

2.3 Research

Around the LHC there are seven experiments which use detectors to analyze countless particles produced by collisions in the accelerator. The experiments are run in cooperation with the scientists from institutes all around the world. Each experiment is unique and the characteristics are determined by its detectors. (CERN 2017.)

The largest of experiments are ATLAS and CMS. Both are used to study the widest range of the physics as possible. Two independent detectors are crucial for making conclusions of any new discoveries, because the confirmation is needed from both of the stations. The second largest experiments are ALICE and LHCb, which both are located on the LHC ring along with CMS and ATLAS. ALICE and LHCb detectors focus on specific phenomena. (CERN 2017.)

LHC’s smaller experiments are TOTEM and LHCf. They focus on heavy ions or protons that brush past each other and do not collide head on when beams collide. TOTEM utilizes detectors located at either side of the CMS collision point, and LHCf uses detectors on either side of the ATLAS collision point. Although the focus of research being on the LHC for past years, there are also ongoing experiments on other accelerators and facilities. (CERN 2017.)

3 ENGINEERING DEPARTMENT AT CERN

The Engineering Department gives the CERN faculty to handle engineering competences, infrastructure systems and technical coordination needed for the installation, maintenance, design, operation and dismantling phases of the accelerator complex and its experimental facilities. (CERN 2017.)

The activities of the engineering department are for example in development, expertise on specific fields, mechanical and materials engineering for the design and technical coordination in the systems for day-to-day running. (CERN 2017.)

The structure of the engineering department is presented in Figure 5.

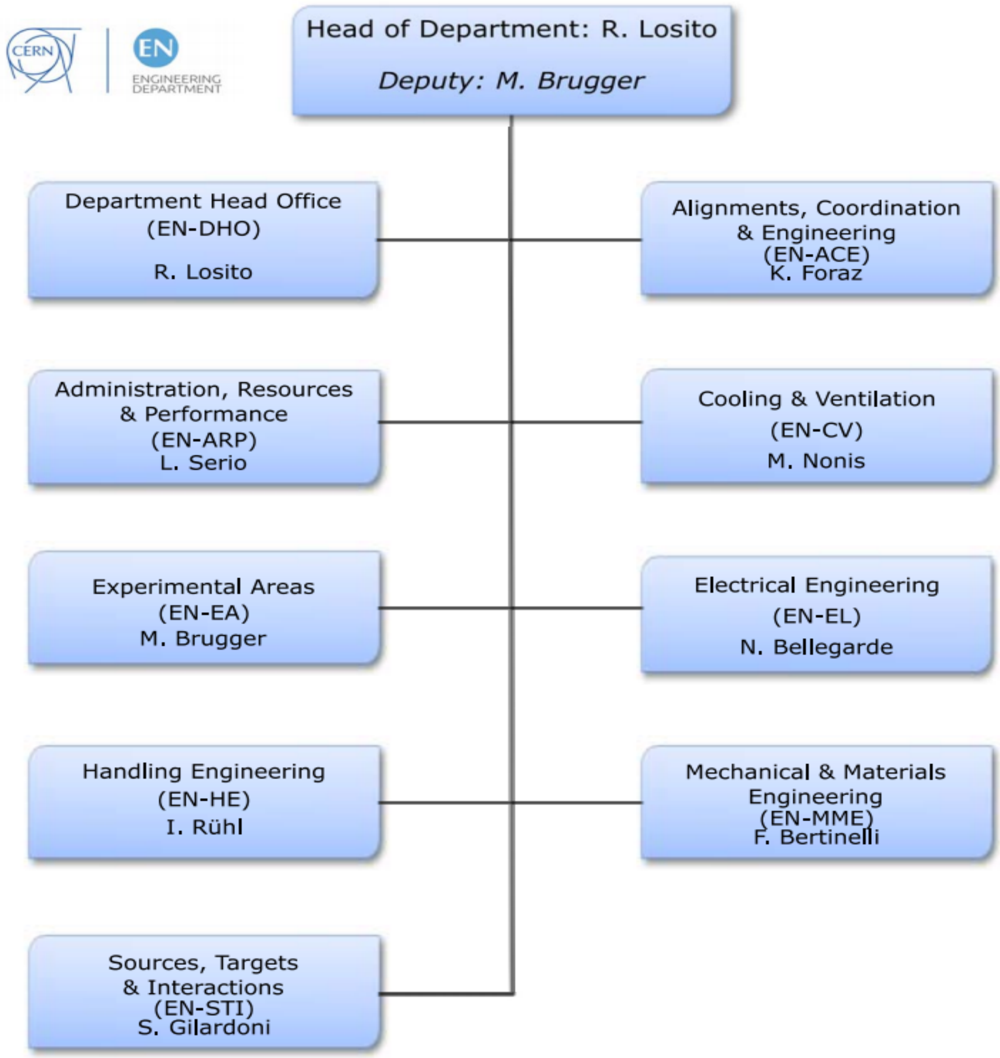


Figure 5. Engineering Department Structure (CERN Engineering Department 2017.)

3.1 Mechanical & Materials Engineering Group

The Mechanical and Materials Engineering (MME) group’s mandate is to provide specific solutions unifying mechanical design, fabrication and material sciences. Historically the group develops and maintains the know-how concerning the mechanical construction of physics detectors and beam accelerator components. The MME has a wide scale of highly specialized activities for example advanced calculations, CAD design, destructive and non-destructive material testing and metallurgical analysis. The group uses resources as integrated mix and provides support for a wide range of requests. The MME group responds quickly and professionally to challenging situations, having best effect with integrated approach starting at the conceptual state. (CERN 2017.)

EN-MME has seven sections:

1. EN-MME-EDM – Engineering Design & Measurements
2. EN-MME-EDS – Engineering Design & Simulations
3. EN-MME-FS – Fabrication Methods & Subcontracting
4. EN-MME-FW – Forming & Welding
5. EN-MME-MA – Machining & Maintenance
6. EN-MME-MM – Materials, Metrology & NDT

(CERN 2017.)

4 MECHANICAL TESTING OF MATERIALS

This thesis is associated with the destructive testing of materials. Tensile and compression testing are common destructive test methods. In the destructive testing a specimen is brought to a state where it fractures, while measuring the transforming of the specimen (Davis 2004, 1).

4.1 Tensile Testing

Tensile tests are made for many reasons. Tensile properties can provide information about the materials used in engineering applications. The tensile properties of the materials are usually included in material specifications to verify quality. During the development of the new materials and processes, materials tensile properties are measured to be compared with each other. With the tensile properties, materials behavior can be predicted under stress. (Davis 2004, 1.)

Materials strength is often the main concern. The strength can be measured from either the stress that a material starts to develop plastic deformation or the maximum stress that a material can withstand. These strengths are used in form of the safety factors in engineering design. Materials ductility is also an important measurement, it tells how much a material can deform before it takes damage. Ductility is rarely part of design, but it is usually included in the material specifications to ensure toughness and quality. Elastic properties are also measured, but special techniques must be used while tensile testing. More accurate elasticity measurements are made by using the ultrasonic techniques. (Davis 2004, 1-2.)

A typical tensile testing system is presented in Figure 6. With this system, the compression and the bending properties can also be measured.

Figure 6. Modern Tensile Testing Machine (Shimadzu Europa 2017.)

4.2 Strain-Stress Curves in Tensile Testing

In a tensile test, the specimen is mounted in a machine and subjected to tension. The tensile force and increase in the specimen length is recorded. These measurements can be produced to construct a function curve for a material. A typical curve for a ductile material is presented in Figure 7. (Davis 2004, 4.)

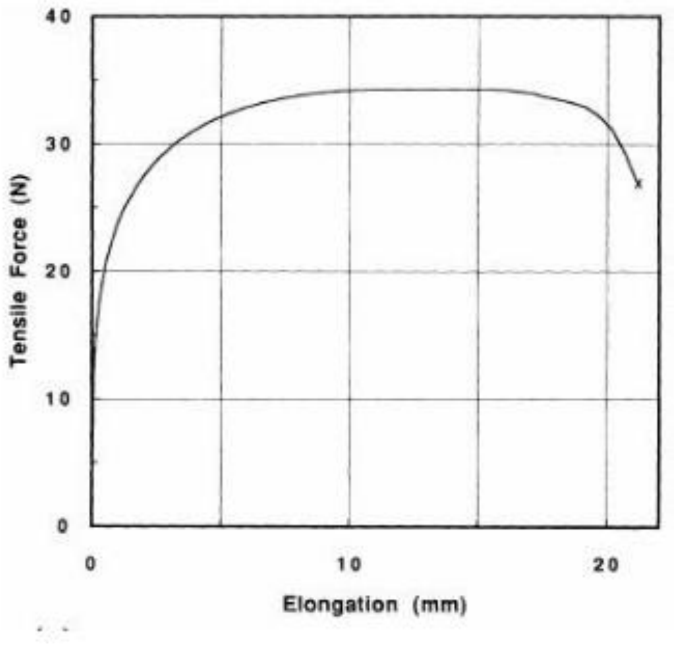


Figure 7. Typical Force-Elongation Curve (Davis 2004, 4.)

The nominal stress and strain are also known as the engineering stress and strain. Force-elongation data can be converted to the engineering stress and strain, and this way can be produced a curve identical to the shape of the force-elongation curve. The advantage in doing this is that the stress-strain curve is virtually independent of the specimen dimensions. The engineering strain-stress curve corresponding to the previous force-elongation curve is presented in Figure 8. (Davis 2004, 4.)

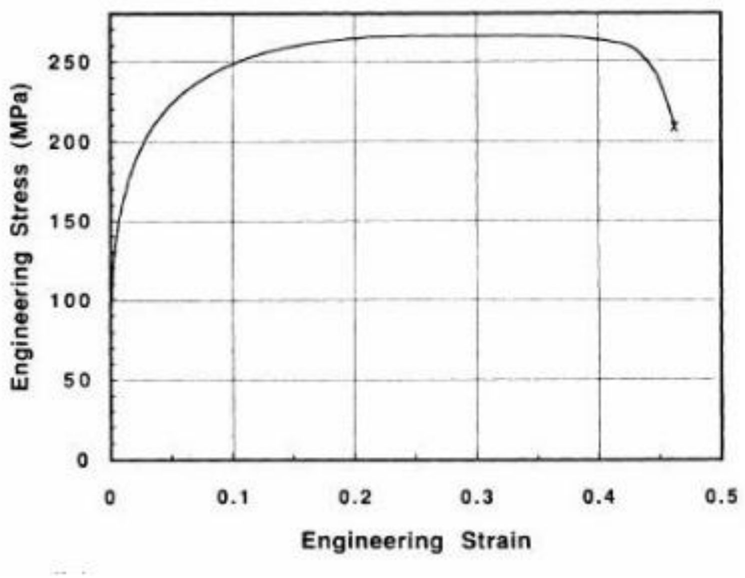


Figure 8. Strain-Stress Curve (Davis 2004, 4.)

If a solid material is brought under small stress, its bonds between the atoms are stretched. After removing stress, the bonds relax and the material returns to its original stage. This is called the elastic deformation. At greater stresses, a material will not return to its original stage due to the planes of atoms sliding over one another. This is called the plastic deformation. When the stress is high enough, in curves can be seen that the stress-strain behavior is no longer linear. The first plastic strain usually starts at the point where the curve differs the first time from linearity. (Davis 2004, 3-4.)

A typical tensile test specimen has enlarged ends for gripping, and the middle section is reduced so that deformation and the failure will occur in halfway of the specimen. (Davis 2004, 1-2).

The typical flat tensile test specimens are presented in Figure 9 and Appendix 2.

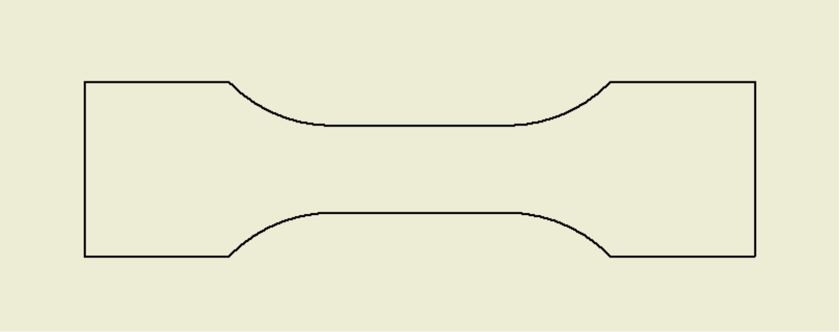


Figure 9. Typical Tensile Test Specimen

4.3 Terms Used in Compressive and Tensile Testing

In the compression and tensile testing there are some unique terms that are explained in next sentences. The terms are widely used in the compressive and tensile testing, but the tensile testing being the more common test method, most terms are used in it.

1. Compressive Strength - Maximum compressive stress a material can endure without fracture.
2. Elastic Limit - Maximum stress that a material can endure without permanent deformation.
3. Elongation - Length of extension on a specimen that has endured permanent deformation.
4. Modulus of Elasticity - Ratio of stress which measures stiffness of a metal.
5. Proportional Limit – The highest stress that material can reach being directly proportional to strain.
6. Reduction in Area – The difference between original and smallest area on the test specimen cross-sectional area after a fracture following the tensile test.
7. Strain - Change in test specimen size or shape caused by test.
8. Yield Point - Stress in a material in which strain occurs without an increase in stress.
9. Yield Strength - Stress in a material at which it expresses specified deviation from a linear stress-strain curve.
10. Ultimate Tensile Strength - The maximum tensile stress material can withhold without fracture. (MEE 2014.)

4.4 Compressive Testing

The compression test is a way to gain information about the behavior of a material under compressive stress. Compression tests are usually performed by loading the test specimen between two plates, which are then moved towards each other to apply force into the specimen, as seen in Figure 10. When the test specimen is compressed, its deformation and the applied load is recorded. The compression test can determine materials elastic limit, proportional limit, yield point, yield strength and compressive strength. (MEE 2014.)

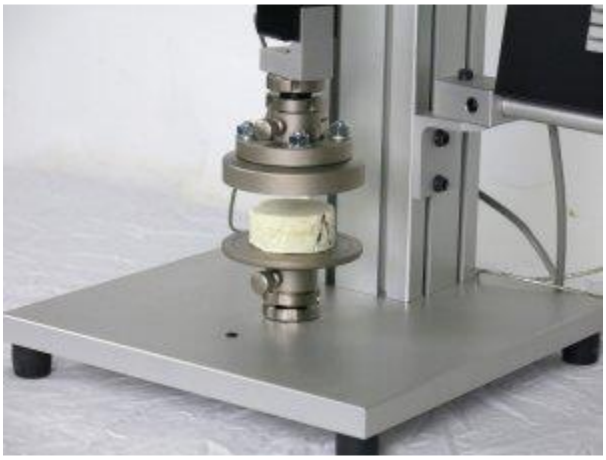


Figure 10. Compression Test Machine (Testresources 2017.)

Measurements gained from the compressive tests provide data on the integrity and safety of materials, products and components. The data helps to ensure that the materials and products are fit for their purposes and to ensure quality. The data acquired from the compression tests can be used in following ways:

1. Determining batch quality
2. Consistency in manufacture
3. Aid in the design process
4. Reducing material costs
5. Ensure compliance with the international and industry standards

(Mecmesin Limited 2010.)

In the mechanical testing of materials, axial compressive testing is a useful tool in determining a materials ductile fracture limits and plastic flow behavior (ASM International, 2000). In a general compressive testing machine, there are two forces opposing each other, so that the sample is compressed. There are also variations in the compressive test methods, for example testing more than one axis of the specimen or testing the specimen in cold or elevated temperature. (Testresources 2017.)

Normally materials that are tested in compressive tests, have a smaller tensile strength and higher compressive strength. All materials can experience compressive forces depending on their application, but the mostly tested materials in the compression testing are composites, concretes, polymers, plastics, metals, stone and brick for example. (Testresources 2017.)

Different metallic test specimen used in the compression testing are presented in Figure 11.

Figure 11. Compression Test Specimen (Khlystov, Lizardo, Matsushita, Zheng 2013.)

5 CRYOGENICS AND MATERIAL TESTING

In this thesis, the cryogenics and the material testing are combined in the developed apparatus. The material testing in cryogenic temperatures is needed when it is necessary to know materials behavior in these low temperatures, like in particle accelerators or other equipment associated with the cryogenics.

5.1 Cryogenics

The cryogenics is the study of production of very low temperatures and materials behavior in low temperatures. These temperatures that do not naturally occur on Earth, are used to study the human industry and study nature. Cryogenic temperature is also defined to limit temperature of 120K, which includes normal boiling points of the main atmospheric gases. The liquid natural gases are in use today with the application of cryogenics, in the transportation of gases, air separation plants, the propellants of rockets and even as automotive clean fuel. (Lebrun 2007.)

Cooling equipment with a cryogenic liquid is easiest when its latent heat of vaporization is exploited. Because of this, the useful temperature range is that where the latent heat of vaporization exists, in other words in the boiling point of the cryogenic liquid. From many cryogens, helium is the only liquid at very low temperature. Helium is used in the superconducting magnets of the particle accelerators, because of its lightness and low viscosity. Helium can infiltrate small channels in windings of magnets and this way stabilize the superconductor. (Lebrun 2007.)

5.2 Material Testing in Cryogenic Temperatures

Performing the compression or tensile testing in cryogenic temperatures, gives different results than the tests in ambient temperatures, so it can be concluded that the materials act differently in very low temperatures. Most test methods can be adapted to cryogenic temperatures, but there are some things that should be taken into account. Key points to consider are equipment capability, specimen design, temperature controls, instrumentation and fixture design. So far there is only one standard (ASTM E1450) made for cryogenic temperature testing. (Hipp, Fabian 2015.)

6 CRYOGENIC TEST FACILITY AT CERN

The mechanical testing of materials in cryogenic temperatures has always been of great importance at CERN. In the accelerator complex, high energy magnets, particle detectors, superconducting radiofrequency cavities and other hardware are working in close to absolute zero. The MME group has developed four cryogenic tensile testing systems to respond to the high demand of the mechanical characterization at cryogenic temperatures. (Aviles 2015.)

6.1 Current Tensile Testing System at MME

With the four cryogenic test systems results were obtained in sub-size samples. Because of new particle accelerators and improvement of existing ones, there is an increasing need of tensile tests made close to the operating temperature and with larger specimen. The MME group decided to fabricate and design in house 100kN cryostat, which is seen in Appendix 1, for standard-size specimen testing. (Aviles 2015.)

In figure 12, there is a cross section cut of the current tensile testing system. The specimen and inner parts are immersed in liquid helium, in steel dewar vessel. Helium is pumped through the top flanges inlet in to the vessel. The yellow colored components are taking the load train, blue is for instrumentation, pink is for the structural components and orange color represents the thermal components. (Aviles 2015.)

Because of the high volume of the cryostat, thermal performance becomes a very important aspect to minimize cryogen consumption. The steel dewar vessel as seen on right in Figure 12, is the main part ensuring the thermal performance of the system. The convolutions on the vessel are to ensure that no buckling will occur. The three thermal screens made of copper are used to minimize the heat transfer with a top flange, which is presented in Figure 13. (Aviles 2015.)

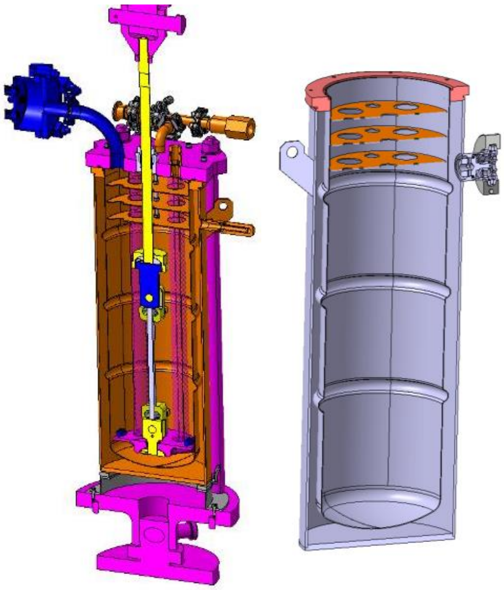


Figure 12. Tensile Testing System and Dewar Vessel (Aviles 2015.)

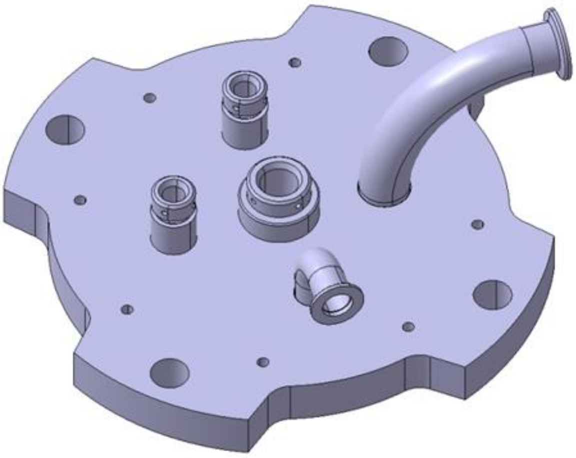


Figure 13. Top Flange of Tensile Testing System (Aviles 2015.)

The top flange is one of the structural components and contains the inlet and outlet for cryogenic fluids, transition to the instrumentation feedthrough and the transition to the safety overpressure systems. (Aviles 2015.)

The top flange was preferred to be kept as it is, because it contains the inlets and outlets for instrumentation. The new compressive method would also become more easily accessible when there is only the insert to change.

7 DESIGN PROCESS

The design process of a project is unique, but there are some basic principles that can help through the project. The engineering design process is often highly iterative, meaning that the parts of process must be repeated to gain the wanted outcome. (Ulrich, Eppinger 2012, 12.)

7.1 Product Development Process

The product development process is the series of steps or activities in which a product is conceived, designed and commercialized by a company. In the process, a series of inputs are changed into a set of outputs. As well as some of the steps are physical, many of the steps in process are intellectual and organizational. The other organization can follow strict development process, while the other cannot describe their process. All organizations have their own way of carrying out the process, and for every project there is a different kind of process. (Ulrich, Eppinger 2012, 12.)

In a generic product design process, there are six stages. These stages are shown in Figure 14. (Ulrich, Eppinger 2012, 14).

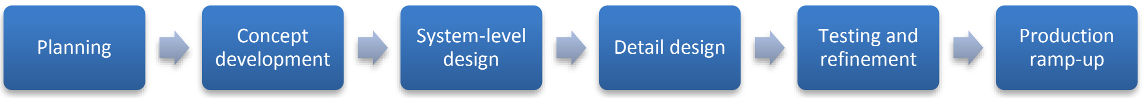


Figure 14. Generic Product Design Process (Ulrich, Eppinger 2012, 14.)

The first phase is often referred to be the” phase zero”, because it takes place before the projects approval and start of the true product development process. The concept development phase defines alternative product concepts and needs of the target market are identified. The main concepts are selected and carried out for further development and testing. In the system-level design, the preliminary design of the main components and final assembly are usually defined. In the detail design phase, the product is defined completely, materials, the unique parts and the standard parts are specified. The testing and refinement stage consists of the construction and testing of preproduction versions of the product. Early prototypes are built to test whether the product will work, although the production methods used in actual production are not necessarily used. The production ramp-up phase includes training workforce and figuring out any of the remaining problems in the production. (Ulrich, Eppinger 2012, 15-16.)

In this project, the steps are taken to the testing and refinement part of the product design process, since there are prototypes made. This projects apparatus is not going to large production, probably a couple prototypes and the final version are made.

7.2 Prototyping

Prototyping is the process of developing approximation of the product. This approximation can be a concept sketch, simulation, test component or fully operational preproduction version of the product. Any aspect of interest in product for the development team can be viewed as a prototype. (Ulrich, Eppinger 2012, 291.)

The prototypes can be divided into two dimensions. In the other dimension, prototype can be either analytical or physical, last being the concrete physical representation of the product, and analytical being the mathematical or visual representation of the product. For example, the physical prototype can be models which feel and work like the real product. The analytical prototype can be a computer simulation, which inspects useful aspects of the prototype by analyzing it. (Ulrich, Eppinger 2012, 291.)

In the second dimension, the prototype can be comprehensive in contrast to focused. The comprehensive prototype means a full-scale version of the product. This prototype can be given to customers to define any remaining flaws and it relates closely to the prototype word used most often. The focused prototype can be targeted to one or more specific features of the product. The focused prototype can examine just the electronic functionality or physical form of the product. (Ulrich, Eppinger 2012, 291.)

In this project, the first prototype will be 3D printed working version of the compressive insert integrated into the cryogenic test facility. This prototype is a physical representation as well as a focused prototype, since it is a tangible model and it is only an insert part of the entirety of the cryogenic test facility. This prototype is made so that it could be 3D printed and its size is half of the real size of the final apparatus.

7.3 Meetings

This project was carried out with cooperation of the MME staff. The meetings were held to discuss projects development. These sessions were mostly held as video meetings, although a few meetings were kept as normal meetings during my summer trainee period.

The meetings consisted of discussions and presentations about the matters in hand concerning the project and the compression apparatus design. Problems concerning the design were discussed, and sometimes solved right away. The process was iterative in nature. I presented solutions, which were either turned down or taken forward in next sessions.

8 3D PRINTING

3D printing makes solid parts layer by layer and this offers advantages compared to the traditional manufacturing methods. The 3D printing is unlikely to replace the traditional methods anytime soon, but there are many applications where the 3D printing can be used with a better effect. (Redwood 2017.)

8.1 FDM Printing

The Fused Deposition Modeling (FDM) is an additive manufacturing process and most affordable today. In the additive manufacturing process, material is built up to create a solid object. In the FDM printing, the string of a solid thermoplastic material is pushed through a heated nozzle. The nozzle and part being printed are seen in Figure 15. The nozzle moves continuously, making layers and building the object as it cools down and solidifies. It is a good choice for fast and low-cost prototyping. (Redwood 2017.)

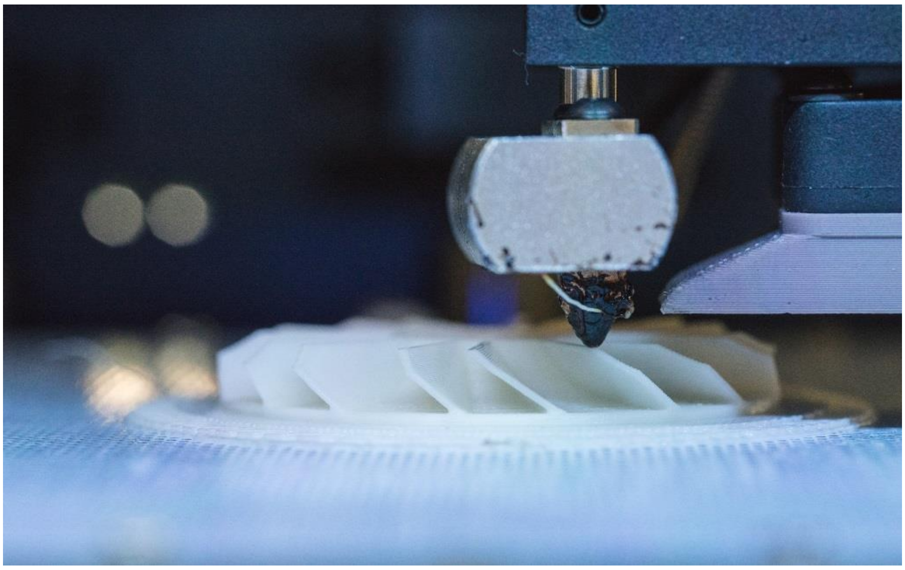


Figure 15. FDM Printer Nozzle (Redwood 2017.)

In this project, the Lapland University of Applied Sciences Innovator 3D -printer was used, and it is presented in Appendix 11. To make printing possible with this printer, the model was made in ratio of 1:2. The 3D models had to be modified for the FDM printing, e.g. vertical axis holes are often undersized. The material used was polylactic acid (PLA).

8.2 Common Materials

PLA and acrylonitrile butadiene styrene (ABS) are the most common printing materials in the FDM printing. ABS is normally in use in the injection molding industry, in applications like automotive bumper parts and electronic housings. PLA is biodegradable and used as most popular bioplastic in applications ranging from a medical implant to plastic cups. PLA is derived from renewable sources like sugarcane and corn starch. ABS is superior to PLA when the mechanical properties are compared, but PLA is easier to print. (Giang 2017.)

8.3 Design Considerations

One of the key considerations in designing model for the 3D printing, is that something digital is going to be turned into a real physical object. The design environment does not usually take the laws of physics into account, and there are instances of gravity, shrinking and expanding to be taken into account. (Brockotter 2017.)

Overhang means that the layer of the material is only partially supported by the layer below, or not at all. That is a problem since in the additive process, on which all printer technologies are based on, a layer requires a layer beneath it. The limit for the FDM printing is 45 degrees, and beyond that supports are needed for printing to be successful. The flat and long surfaces are possible to experience warping, which is caused by the heating and cooling down of the material. In addition, the wall thickness cannot be infinitely small, and too small details should be thought closely, since the FDM printing in confined to an accuracy of used printer and material. (Brockotter 2017.)

9 CAD SOFTWARES

Computer aided design (CAD) is in extensive use in the engineering design today. There are many companies like Autodesk and Dassault systems developing software for different fields of engineering. In this project, two CAD software from mentioned organizations were used.

9.1 Autodesk Inventor

Autodesk Inventor is a computer aided design software developed by Autodesk company. With the Inventor 3D modelling product can be visualized and simulated before production. In this project, the Inventor Professional 2017 with a student license was used.

The original model of cryogenic test facility was made in CAD application CATIA v5, since it is used by the Engineering department at CERN. Although this project was made using the Inventor, it was planned that this project model will be converted into the CATIA v5 format also.

The Inventor and CATIA v5 are similar in usability, both have the same principles in terms of usage. The parts are created by starting a sketch, in which a two or three -dimensional sketch of the part is constructed, as seen in Figure 16. The sketches are made by using regular geometrical shapes such as circles and squares. These shapes are then extruded, cut and shaped into desired geometries by making new sketches and using tools provided by the CAD application, seen in Figures 17 and 18. (Autodesk 2017.)

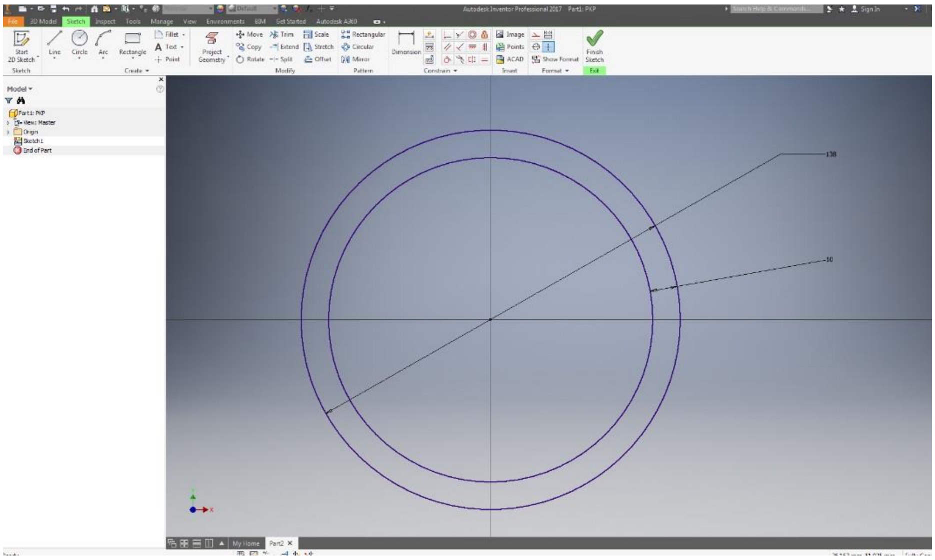


Figure 16. Inventor Sketch Tool

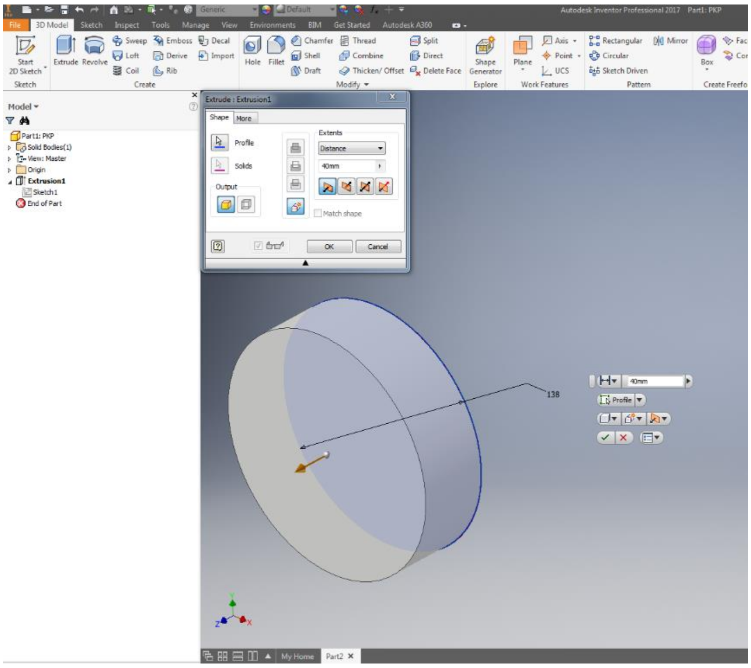


Figure 17. Inventor Extrude Feature

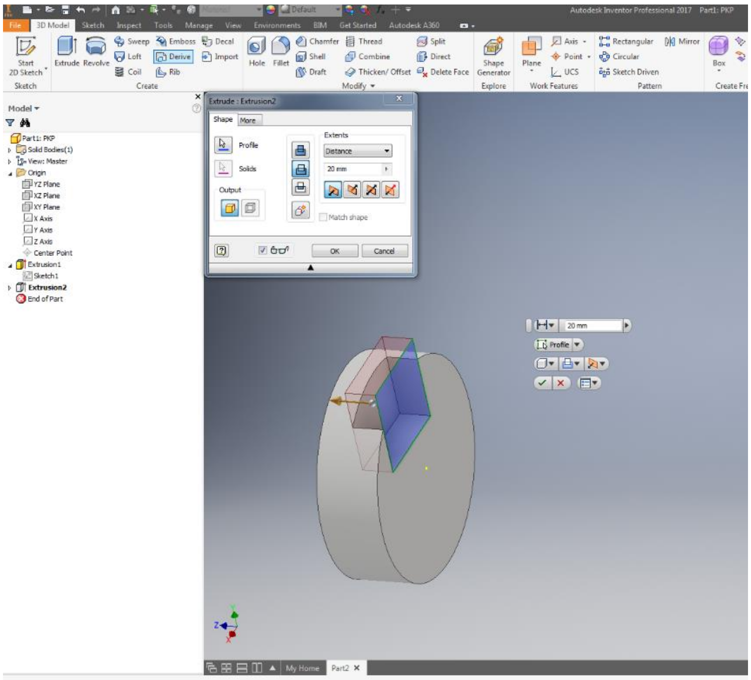
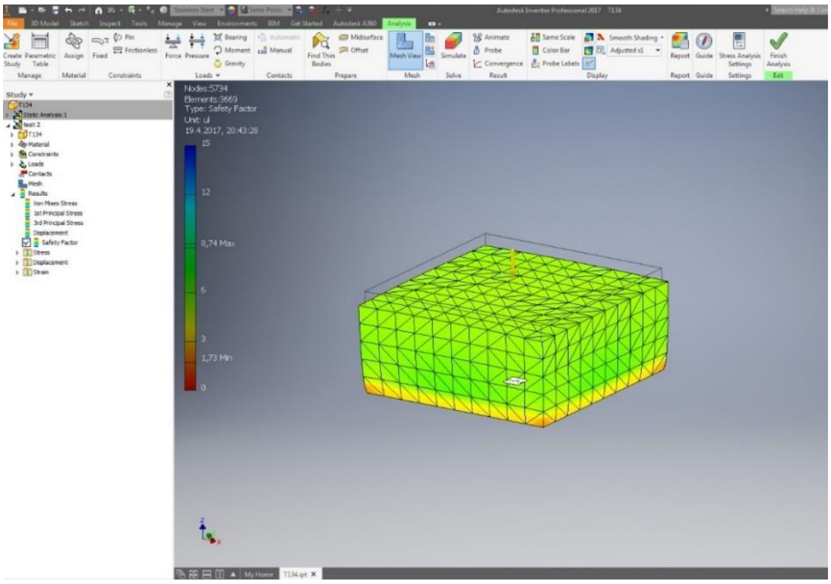


Figure 18. Inventor Cut Feature

All operations made are saved on the tree on left side of the screen. This makes the editing of parts afterwards easy. For example, a circular shapes diameter can be adjusted to a different value when a part is complete. (Autodesk 2017.)

9.2 Inventor Stress Analysis Environment

The inventor stress analysis environment, as seen in Figure 19, uses the Finite Element Method (FEM), which is a numerical calculation method that divides parts into smaller elements. These elements are then analyzed and calculated to get information about the part, and how will it behave in the real-world situations affected by forces. (Autodesk 2017.)



Nodes:5734
Elements:3669
Type: Safety Factor
Unit: ul
19.4.2017, 20:43:28

Figure 19. Inventor Stress Analysis

To begin the simulation, material, attachment constraints and forces are needed to be defined for each situation. It is important to get constrains right for correct the results. When dealing with assemblies or multiple parts simultaneously, contact constraints are used. These can be assigned automatically, but should be checked to make sure that they are correct. The simulation will calculate deformation, stresses and the safety factor for a part or assembly in hand. (Autodesk 2017.)

10 DESIGN CHOICES

The solutions of the compressive inserts design are presented in this chapter. The solutions were developed through the discussion in meetings with the personnel of the MME department in iterative manner.

10.1 Starting Point

The starting point of the project was the idea of integrating a compression testing system into the current measurement frame (Appendix 1). Its inner parts were to be designed to support the compressive test method for metallic materials by using the optimal available space inside the cryostat. The outer parts were to be kept as same as in the original tensile testing system, to ensure the usability of most parts also in the upcoming compression testing apparatus. Therefore, the design of the compressive mechanism needs to fit inside the dewar vessel and be connected to the top flange (Fig. 12, 13). This way the new compression testing part of the testing facility could be done with an identical top flange, and changing the test method by changing the insert will be easy. The previous tensile testing apparatus was assembled this way, by lowering the insert into the envelope (Appendix 3).

10.2 Design Challenges

As usually in design, there were some challenges to be solved. The first one was the question of how to convert a traction driven setup into a compressive load mechanism inside the confines of the designated area (Appendix 4). This is for the reuse of outer parts and the integrated envelope. (Langeslag 2015.)

Functionality while being immersed in cryogenic liquids is required, and it created some difficulties. Along with the safety requirements when working with cryogenic liquids, retaining specimens from boiling liquids and a closed system limiting monitoring of the test and the specimen introduce some difficulties. (Langeslag 2015.)

Alignment was requested to comply with the standard ASTM E1012 classification 5, which imposes a maximum percent bending over axial deformation of 5%. Cryogenic traction systems have shown alignment issues resulting from frictional components and tolerances on components. E.g. in tensile testing, it is found out that the bending is increased by a balljoint as can be seen from Figure 20. (Langeslag 2015.)

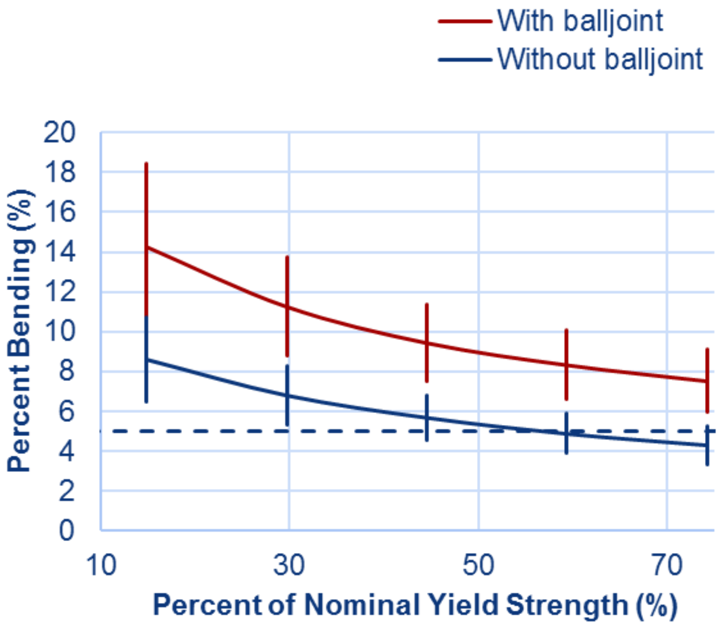


Figure 20. Bending with and without Balljoint (Langeslag 2015.)

10.3 Conversion Into Compressive Load

After a few different suggestions, the tubes on the columns concept was decided to be developed further (Appendices 5-7). With this system, a smaller amount of metal is used and less helium is spent for cooling inside the cryostat, due to a small volume of the design. The top flange (Fig 13, 21) is used as the base component of the insert, and four columns are connected to it.

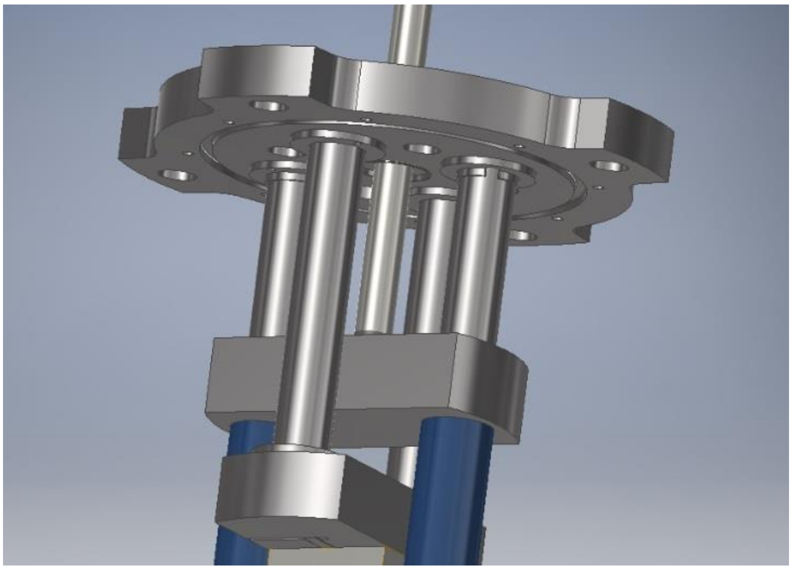


Figure 21. Top Flange and Upper Part

Two of the columns are shorter (Fig. 22) and they are connected by an upper end block which taking a compression force brought by a sliding frame. The short column is machined from a single part, unlike the longer column whose end flanges are welded on the upper part of the column. The flanges are solely in the purpose of keeping the columns in place when moving and preparing the system, they do not take any loads.

The moving frame (Fig. 25) consists of the two tubes, and the end blocks which are all welded together. The tubes slide on the two long columns which are on the same circumference with the two shorter columns. A titanium tension rod is connected to the upper block of the frame with a thread. When the titanium rod is moved upwards, the frame moves with it, sliding on the long columns and causing compression in the middle section of the system. On the long columns, to ensure good sliding, there will be thin tubes or coatings with a very low friction. A method of this kind is used at CERN in other similar applications, where the low friction is required.

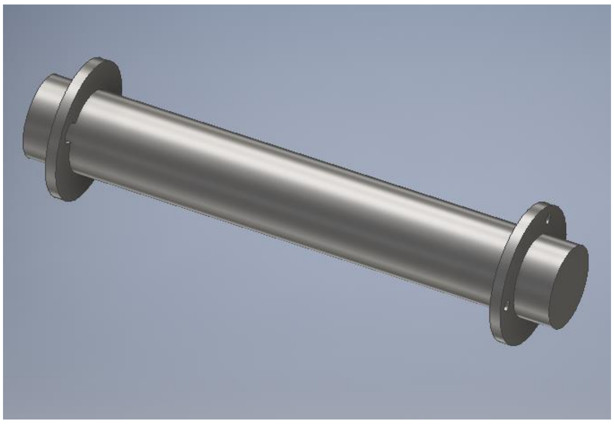


Figure 22. Short Column

The lowest plate connecting the two long columns does not experience any forces, it only ensures the alignment of the long columns. This plate is connected to the columns by a screw, which is attached from the bottom (Fig. 23).

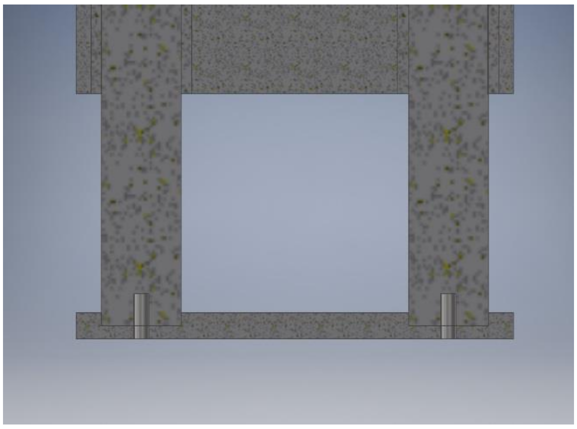


Figure 23. Bottom Part Plate

The colored picture (Fig. 24) presents different parts of the system. The red parts depict non-moving parts under compression, blue is for the tubes, yellow for the end blocks and violet is for the titanium rod.

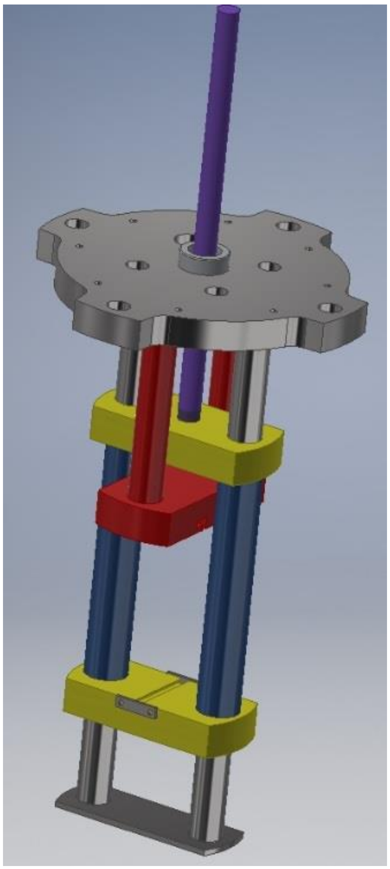


Figure 24. Compression Load Mechanism

Figure 25. Moving Frame

The tubes are brought through the end blocks, and welded from outer ends. This makes the alignment better and it saves space for the specimen fixture in the middle sections.

10.4 Sample Fixture

The sample fixture was decided to be made like a fixture already in use in tensile testing (Appendix 8) and the fixture in the standard ASTM D3410 (Appendix 9). The fixture is placed between the end blocks (Fig. 26). The fixture consists of a lower and upper housing, which both house two rectangular wedges. The pair of wedges work as a grip for the specimen (Appendix 10), and by changing the wedges, a different size test specimen can be used.

The housings are slid on place with rails, and movement is blocked by clamps at open sides. In the wedges, there are also a railing systems to ease the handling when setting up the system.

Figure 26. Fixture Placement

The upper and lower housings are similar, only the restriction of movement had to be made differently on the upper one. In the assembly of housing (Fig. 27), the lower housing with two gripping wedges in it can be seen, with the lateral movement restricted by the clamps. The clamps are fixed with bolts. Under the housing there is a rail which is bolted on the housing.

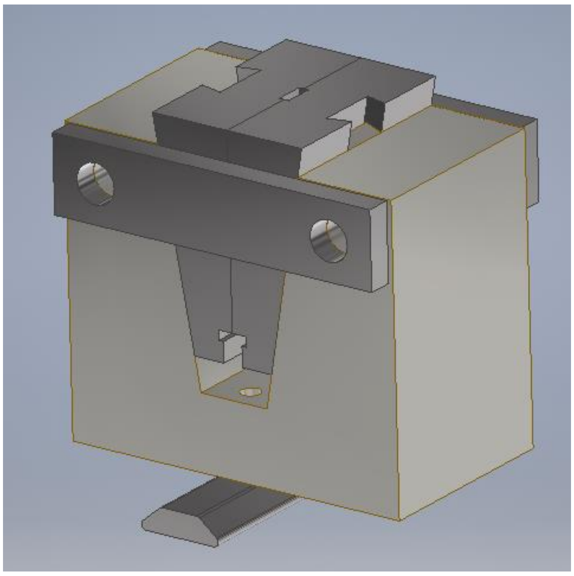


Figure 27. Lower Fixture

The upper housing is identical to the lower one with an exception of the mounting rail (Fig. 28). Because of the end block being perpendicular to lower end block, rail must be inserted on a longer axis of the block also. There is no space between the tubes for the clamping and a different solution had to be configured.

Figure 28. Upper Housing

The upper rail is slid into the upper block, to the end of the machined rail. From the side rail is blocked on place with a pin. After machining the rail to the upper block, the end would be circular, so another slot must be machined to ensure the correct place and alignment of the rails (Fig. 29).

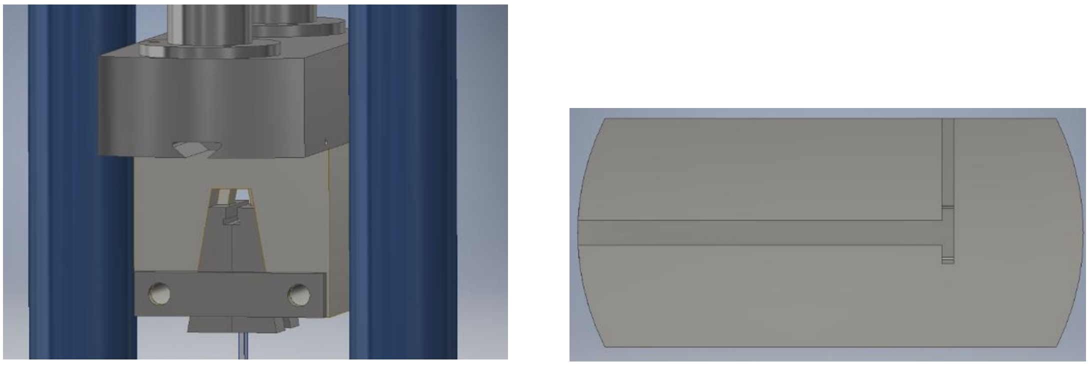


Figure 29. Upper Housing and End Block

The two wedges are fixed together with bolts, using four holes going through them. This ensures that the wedges are on same position compared to each other. The wedges (Fig. 30) are slid to place by the rails, which are machined to the housings. This helps the handling at the specimen placement stage. The slots in the wedges ensures that the specimen will not slide in the horizontal area between the wedges. The flat surface of the slot against the specimen is machined to have a better grip on the specimen.

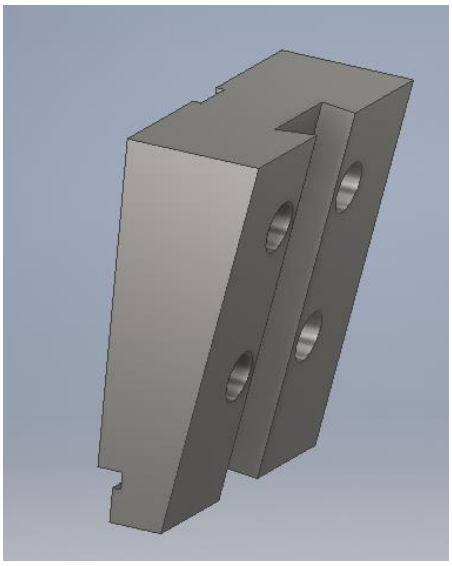


Figure 30. Wedge

10.5 Stress Analysis

The stress analysis of the parts were made so that the compression insert would withstand the testing force of 50 kN. The stress analysis can determine that the maximum stress does not exceed the materials yield strength, and not too much deformation takes place. This means the safety factor is on the safe side, preferably over two. The relevant structural parts were simulated with the stress analysis (Appendices 16-20). These are the tubes which are under tension, end blocks, short columns, housings and rectangular wedges. The short columns and fixture related parts are under compression. The force of the short columns, tubes and wedges is 25 kN, since the force divides through them.

11 3D PRINTED PROTOTYPE

It was decided that a 3D printed prototype was to be made, to see how the main mechanism of the insert would work. LUAS has a couple relatively new 3D printers and one was used to print parts for this project model. At LUAS campus Kosmos, there was also a possibility to work at a workshop to adjust and work on the printed parts.

11.1 Development of the First Prototype

In the FDM printing, the making of long columns is problematic, because melted plastic cannot hold a lot of weight. It was decided that the columns of this model are made from a plastic rod, bought directly from an industrial shop (Appendix 12). The tubes were also too long to be vertically printed, and they were integrated with the end blocks (Fig. 31). This frame was then printed horizontally, using removable supports inside the holes. The supports were however too strong to be removed by hand, and drilling the holes came to be the right course of action (Appendix 13).

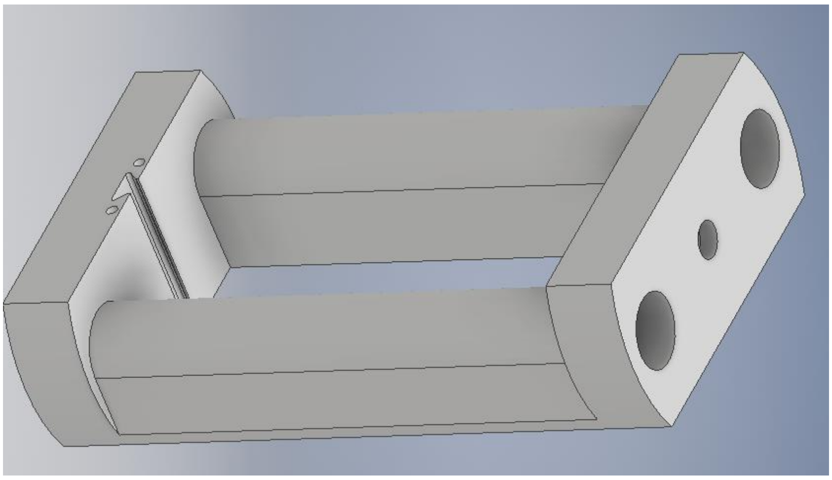


Figure 31. Frame Model for 3D -printing

There were no problem printing the other parts, the blocks and the top flange were printed with a good accuracy (Fig. 32). The holes for these were although too small for the rods to enter even with enlarged holes in 3D models, so there had to be another version of these parts made.

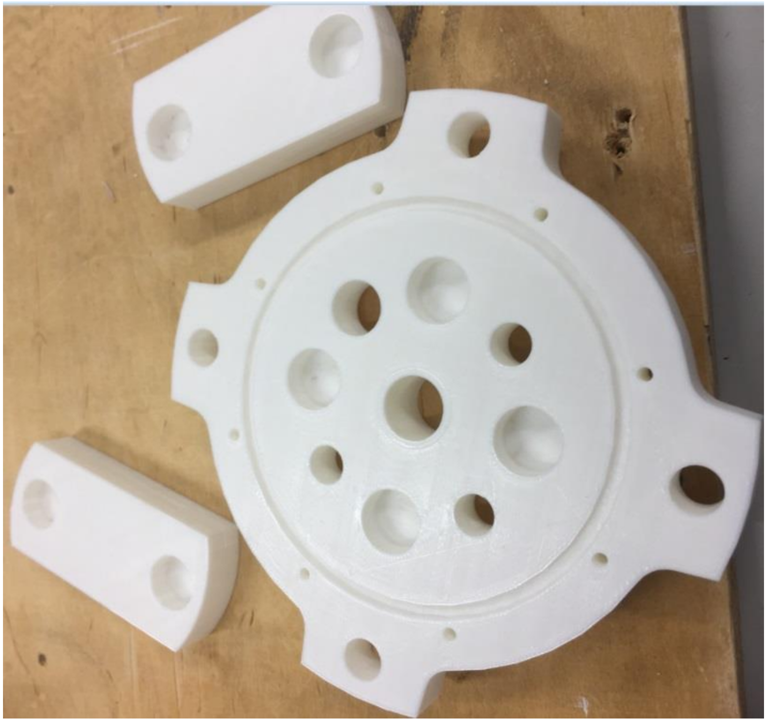


Figure 32. Flange and End Blocks

The first prototype was assembled using an adhesive putty, to be sure of the dimensions and to find errors in the model, without making the first assembly final. (Fig. 33).

Figure 33. First Prototype

11.2 Second Prototype

The second prototype (Appendices 14-15) was assembled by using two-compound epoxy adhesive. Epoxy is transparent and hard, and it made the second version more firm and usable. The frame could be moved as in the real compression apparatus. The inner specimen fixture is not up-to-date in this version, because the testing focus was on the load conversion part of the insert.

The next prototype will be done at CERN, and it will be done in their own workshop. This next prototype will be as close as possible to the final solution with the intended materials. The information about the future of the project and conclusions are discussed in the discussion chapter.

12 DISCUSSION

The goal of this project was to bring the cryogenic tensile testing facility to a new level of versatility, among the other objectives listed at the start of the thesis. In this thesis, a mechanical assembly for the functioning compressive insert was achieved and so this part of the project was successful. It was known that a project of this magnitude might not be covered fully by one bachelor thesis.

The project itself is continuing at CERN, with cooperation of Lapland UAS, since there are still tasks to be done to achieve the final working compression testing facility requirements, e.g. the standardization for the compressive test method in liquid helium temperature. In the future, there will probably be more theses concerning the compressive test method of this test facility with simulations and more calculations. Future studies can also include implementing different testing methods, which use an axial compressive test method to be integrated into this design.

The next continuing stage of this project will be confirming the technical producibility of the models and then manufacturing of the final blueprints. After this project continues to the first comprehensive prototype, which is a full-scale and operates as the final version will.

Doing the project in collaboration with the MME staff was very pleasant, and working on a project with people from different countries was very educational. Despite of the long-range communications, it did not appear much as a problem, although at times there were some delay is communication. Making the whole work in English was also a great learning opportunity, and my vocabulary experienced a great improvement in addition to learning more conversational skill in English through the meetings. At the start progression of the project was slower, but after getting other studies completed and making thorough scheduling of the work, it got a lot easier and started to advance faster. The scheduling could have been made more thorough from the start to make the progress of the project stable. An interesting aspect of the project was the fact, that there is not much research yet on the field of material testing in cryogenic temperature, especially with the compression testing. This brought a fascinating idea to work of doing something completely new.

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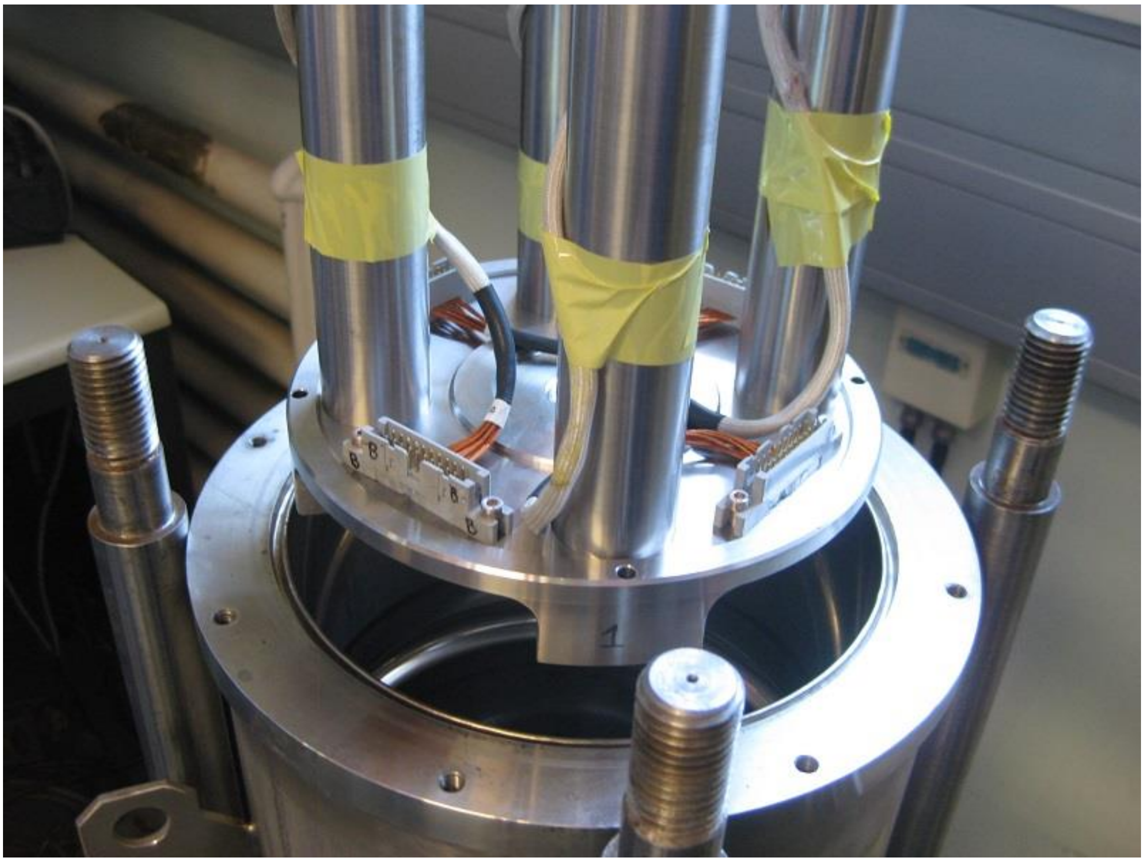
APPENDICES

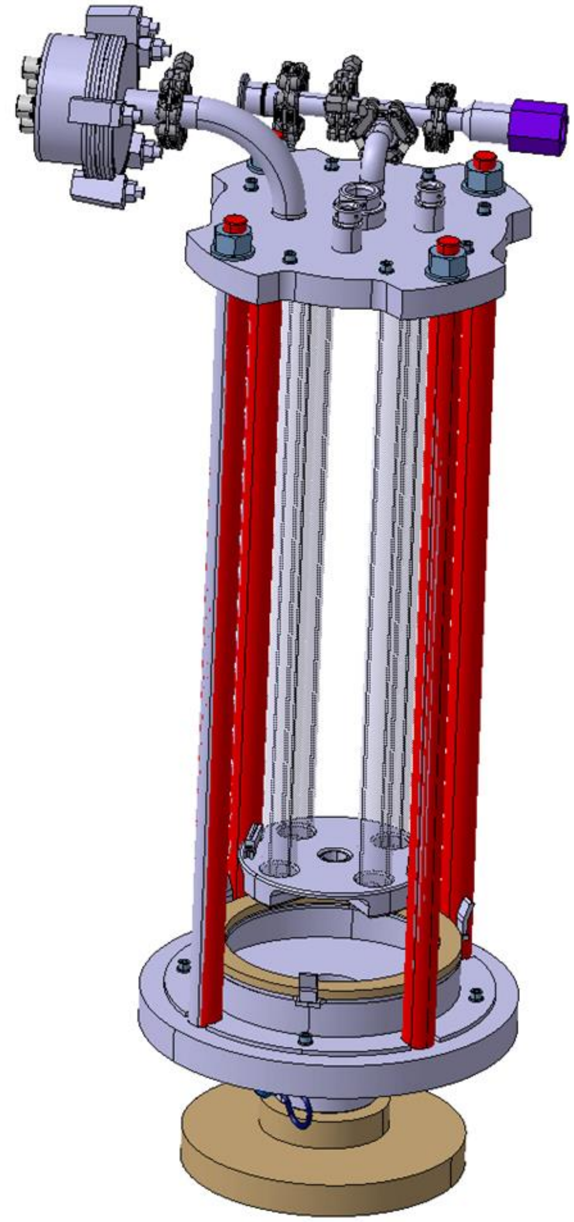
Appendix 1 1(20) Cryogenic Test Facility

Appendix 2 2 (20) Tensile Test Specimen

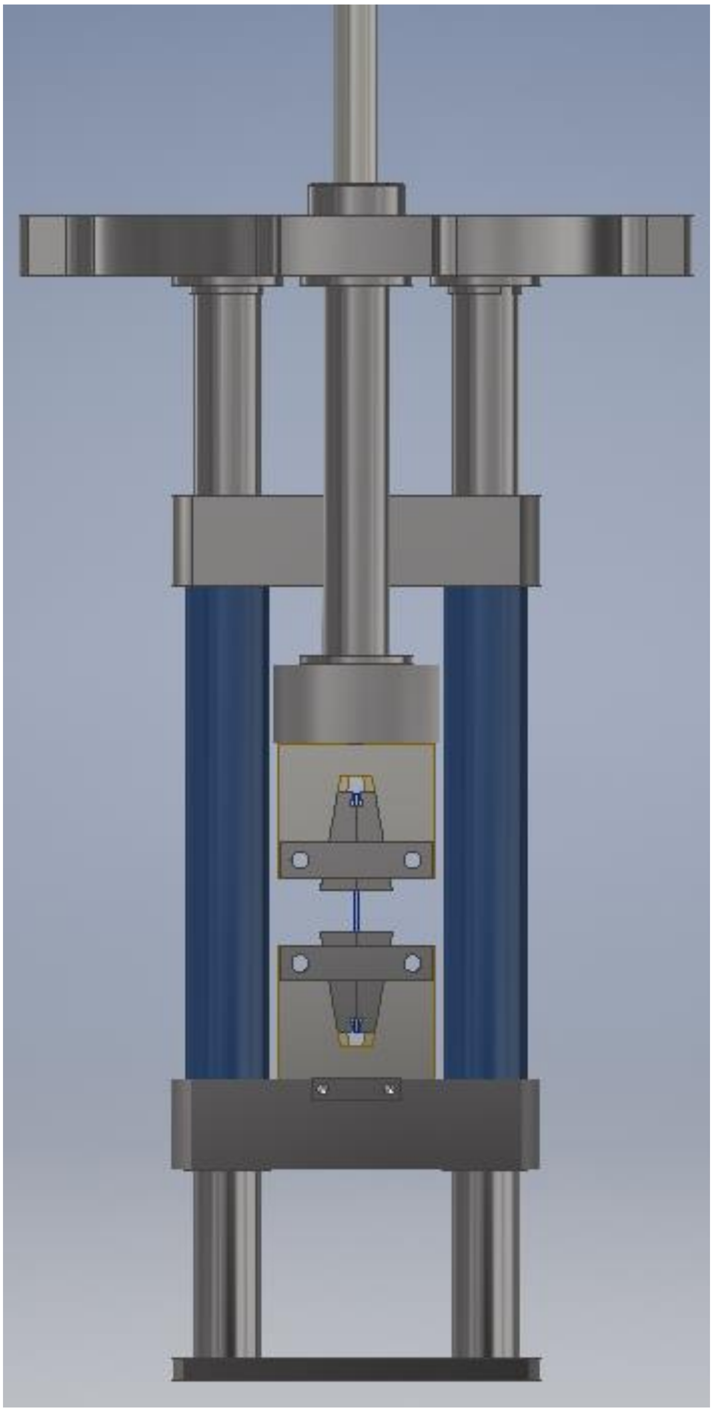
Appendix 3 3(20) Insert of Tensile Test Method



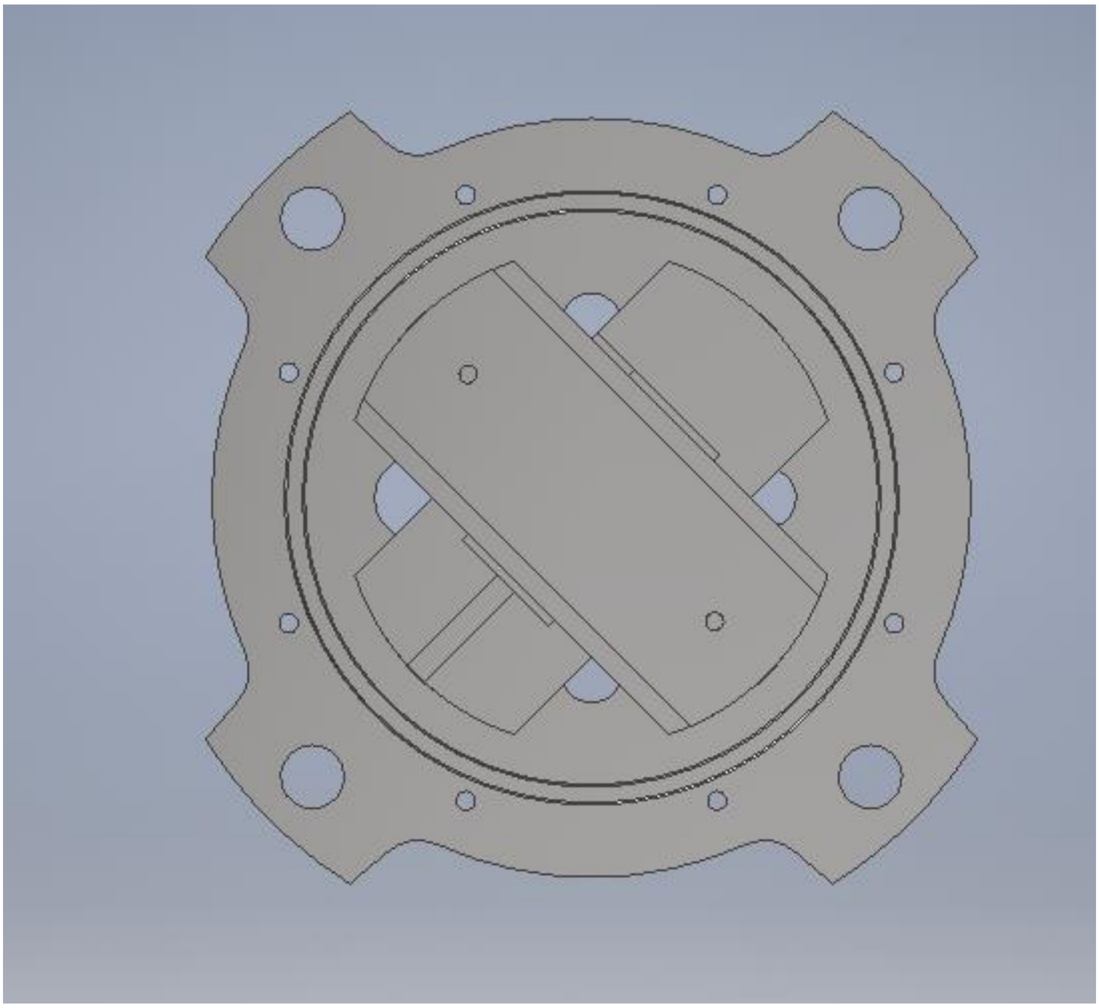
Appendix 4 4(20) Tensile Testing System Outer Structure (Langeslag 2015.)



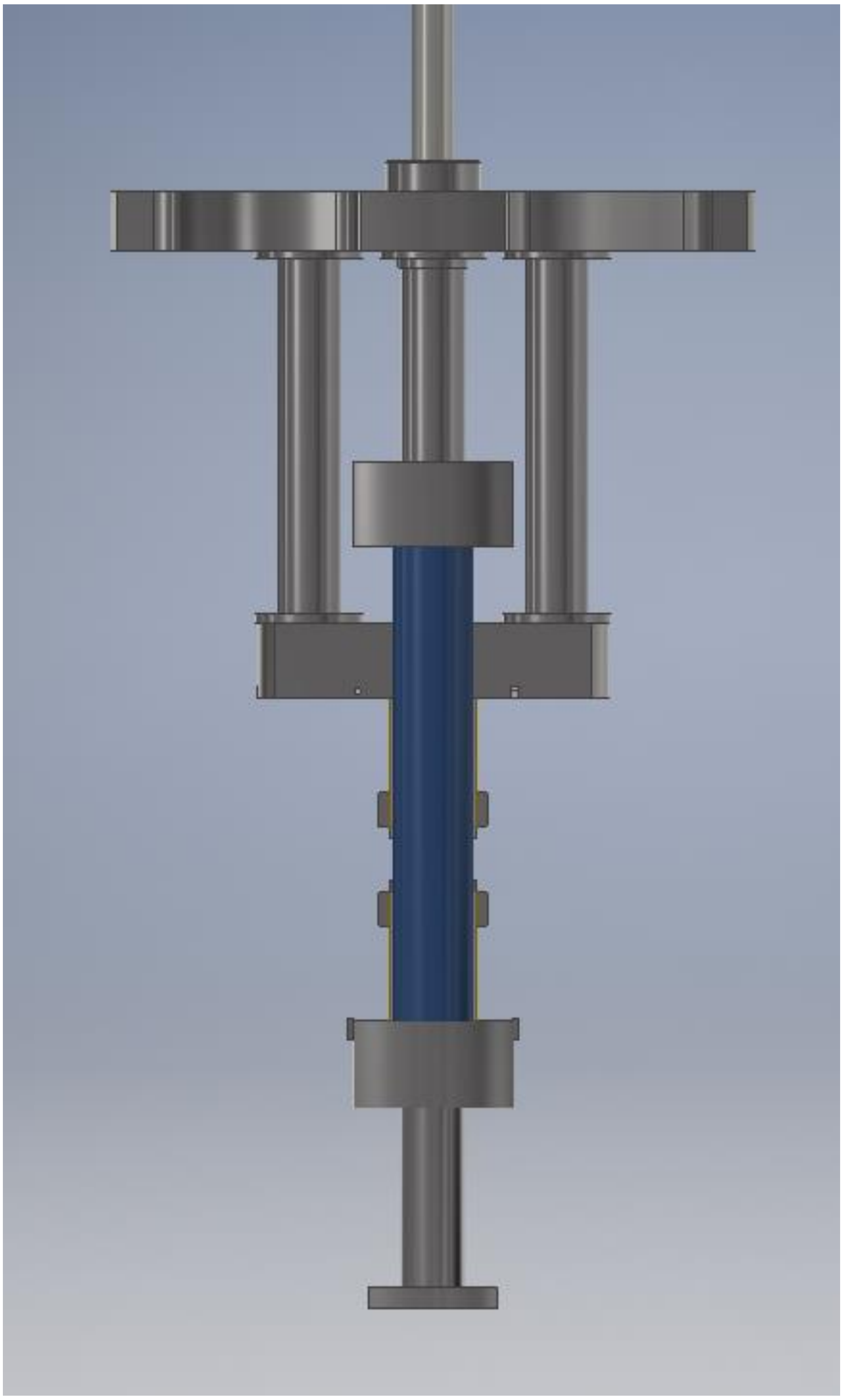
Appendix 5 5(20) Side view of the Compression Mechanism



Appendix 6 6(20) Bottom view of the Compression Mechanism

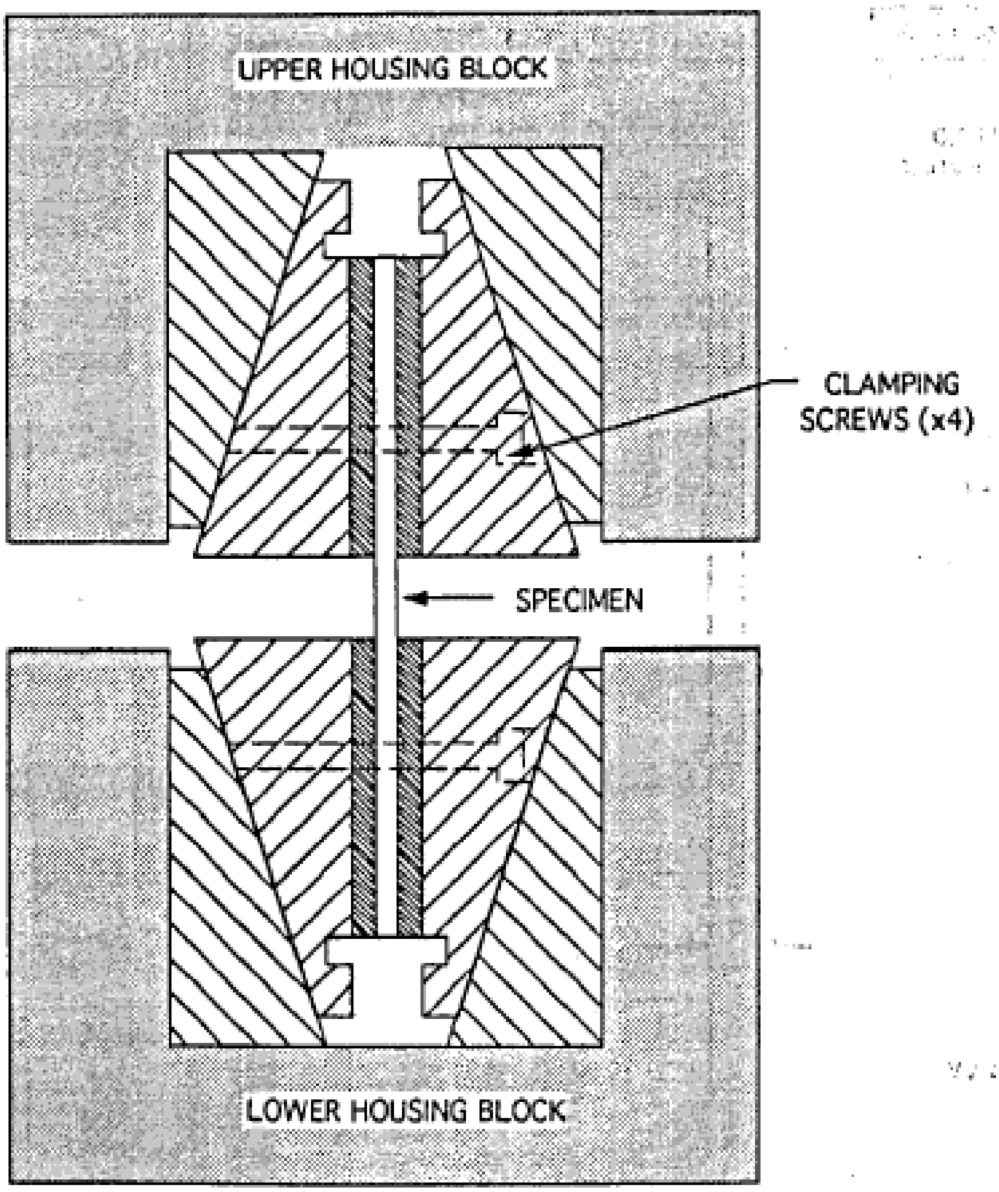


Appendix 7 7(20) Front view of the Compression Mechanism

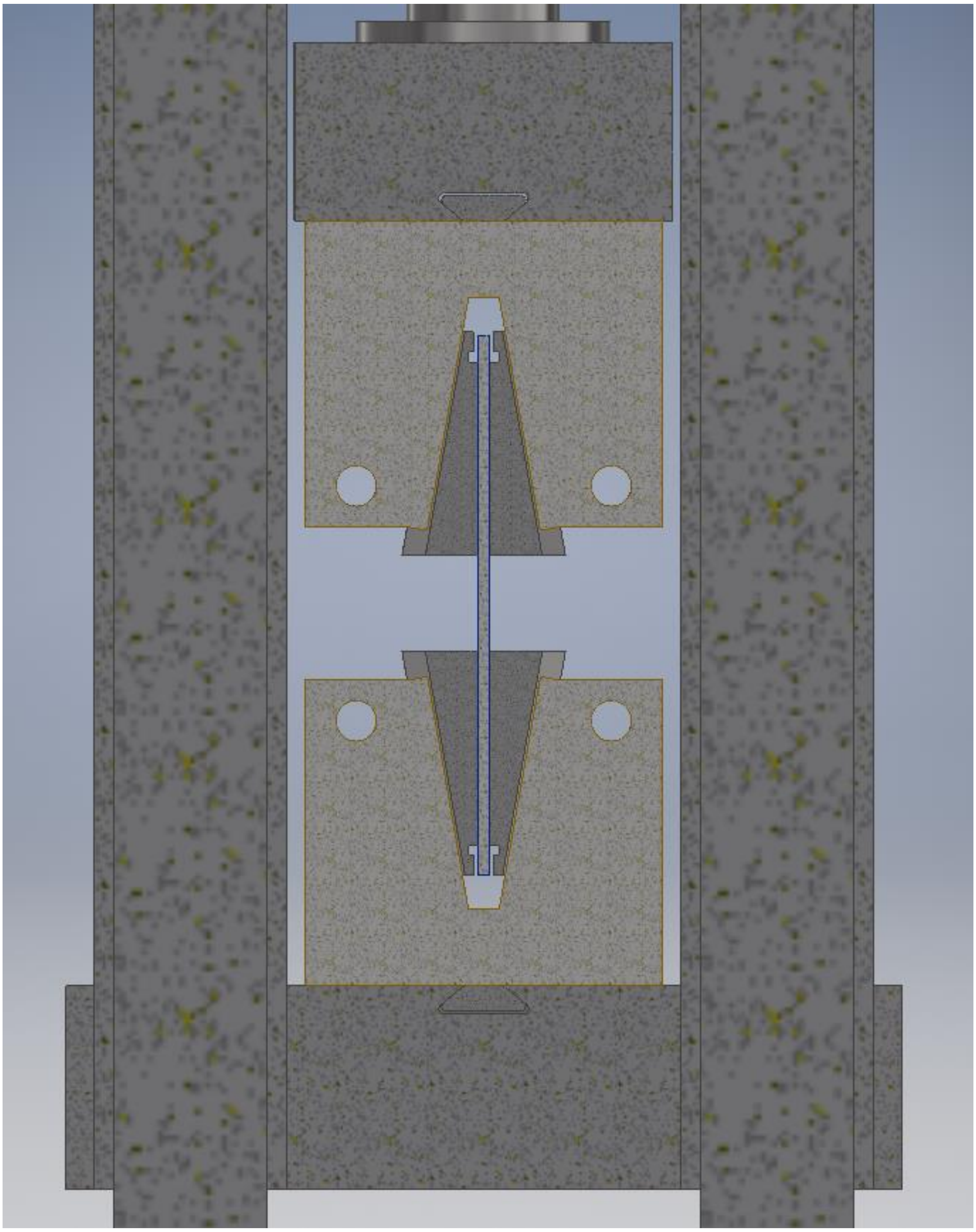


Appendix 8 8(20) Wedge fixture in use (Langeslag 2016.)

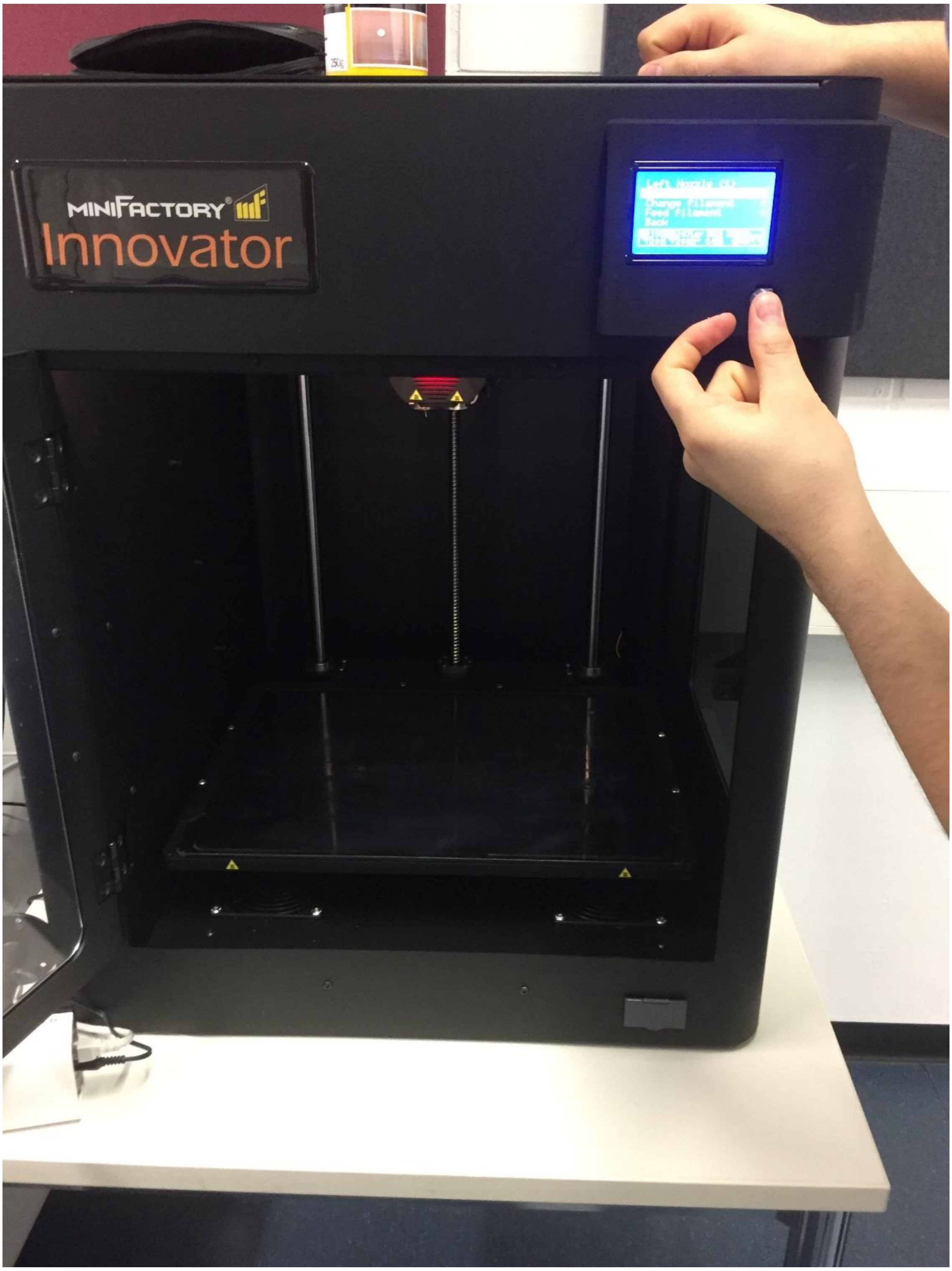
Appendix 9 9(20) ASTM 3410 Fixture



Appendix 10 10(20) Fixture Cross-Section



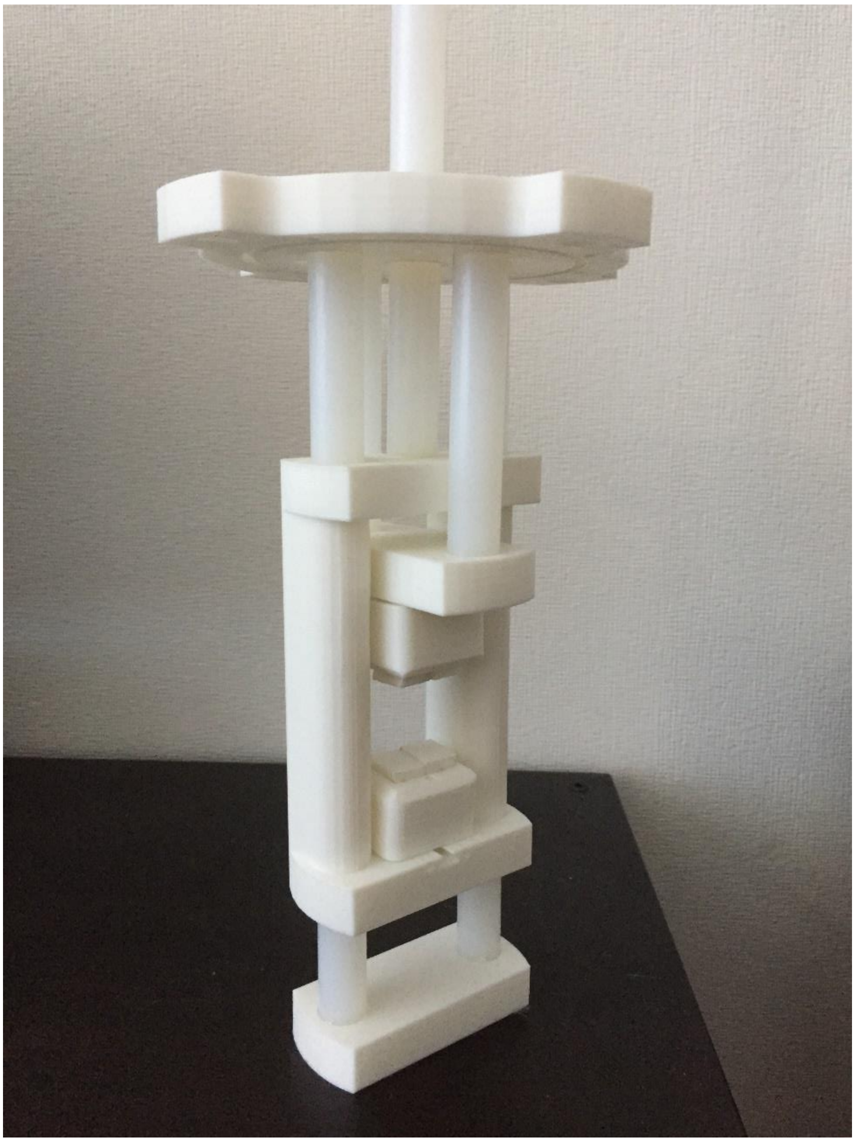
Appendix 11 11(20) Minifactory Innovator 3D printer



Appendix 12 12(20) Plastic Rods used as the Columns

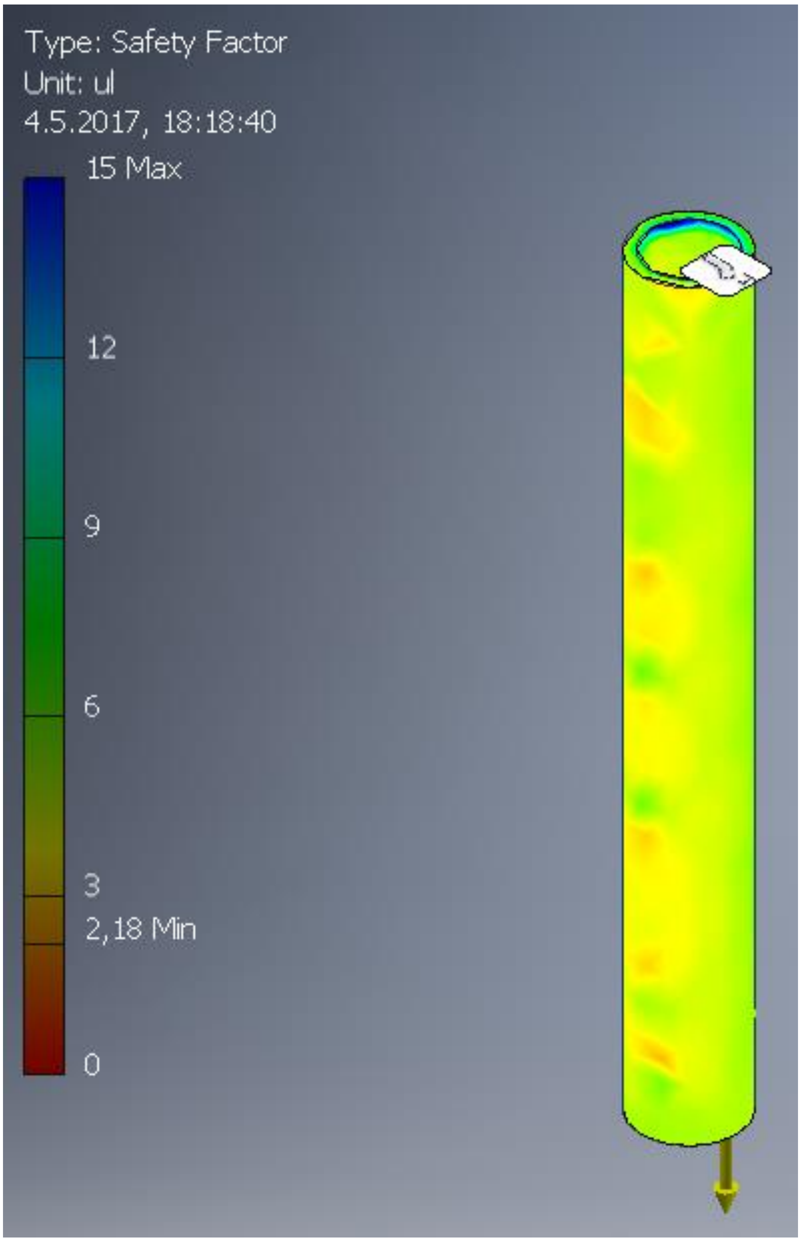
Appendix 13 13(20) Drilling of the Frame

Appendix 14 14(20) Second Prototype, Position 1

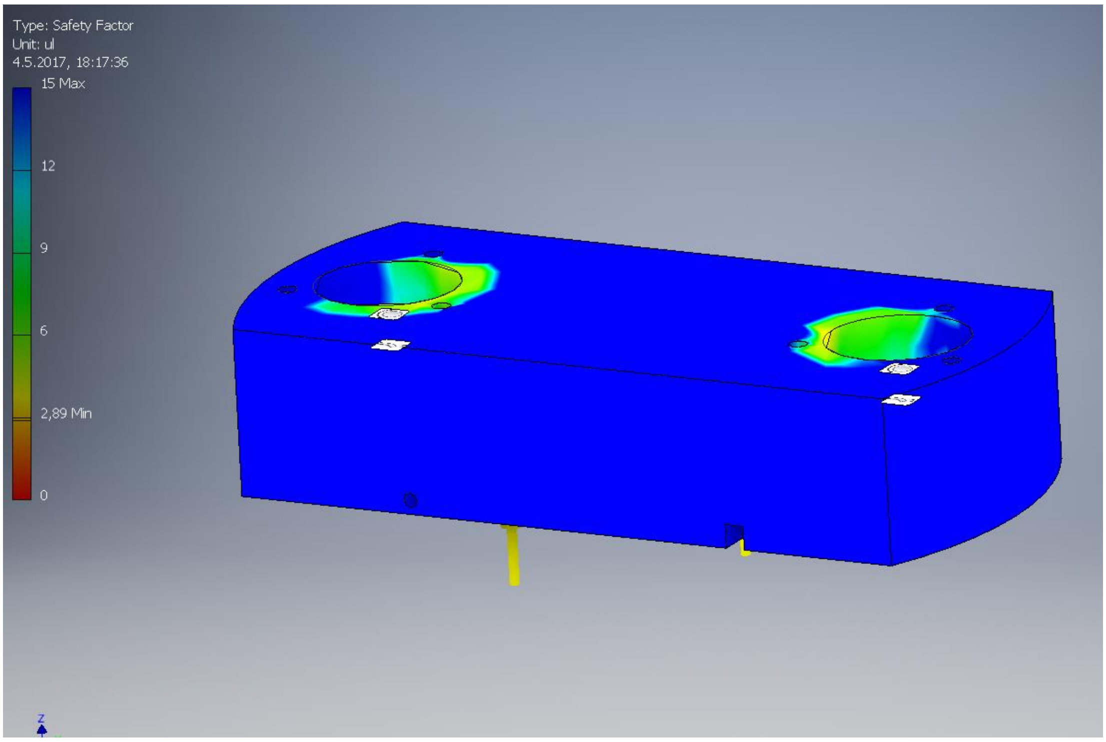


Appendix 15 15(20) Second Prototype, Position 2

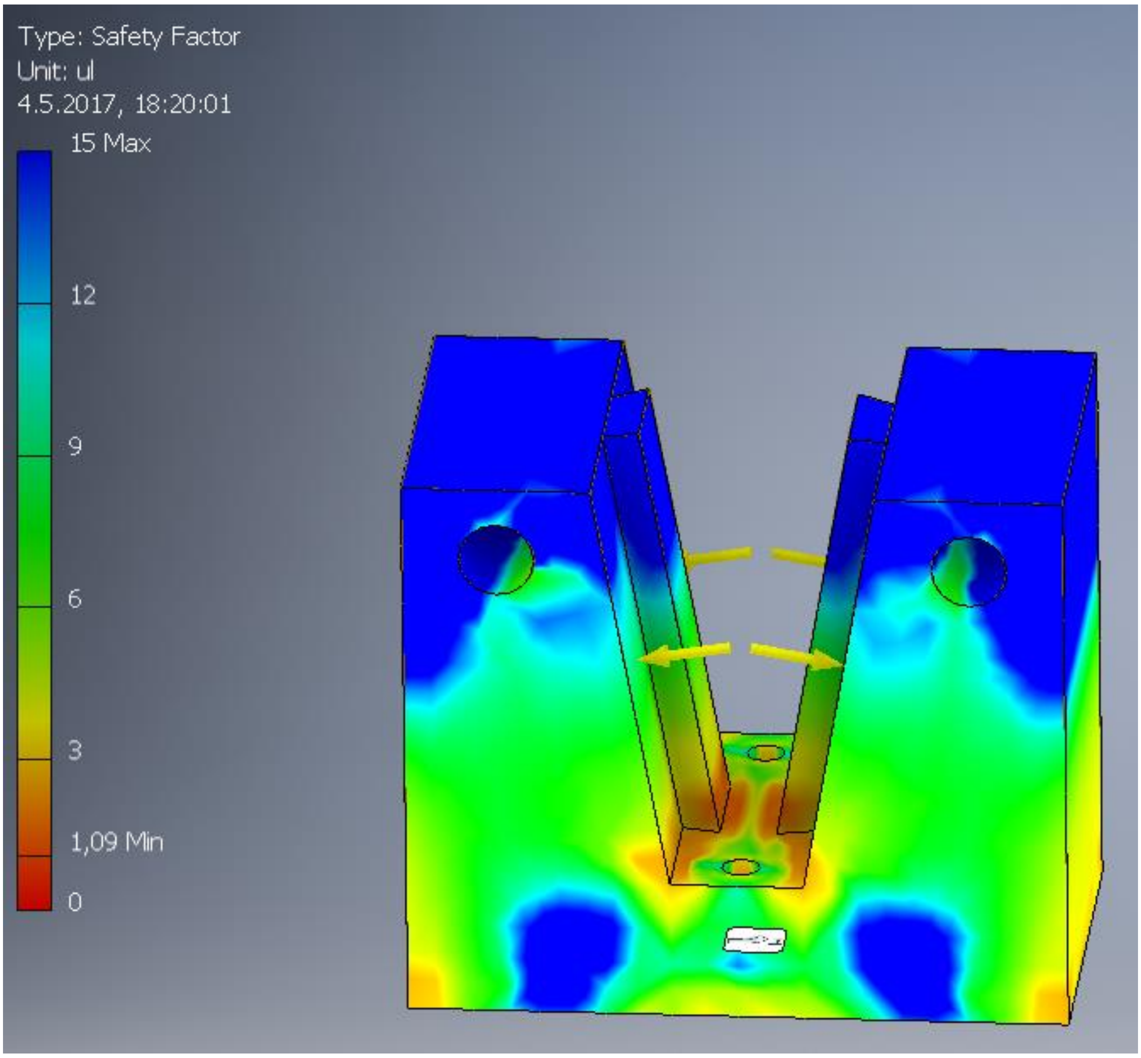
Appendix 16 16(20) Tube Under Tension



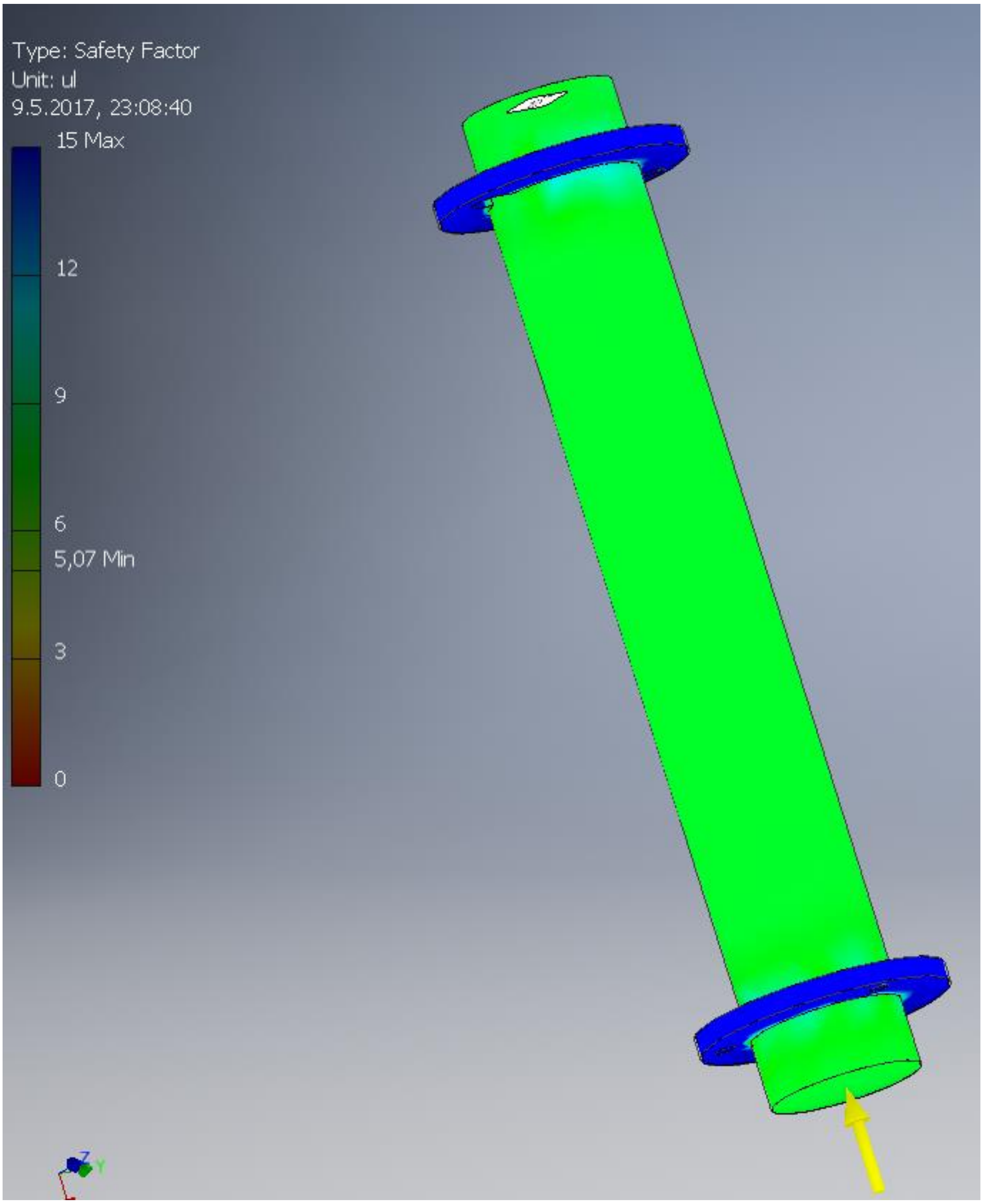
Appendix 17 17(20) Fixed End Block Under Compression



Appendix 18 18(20) Housing Under Compression



Appendix 19 19(20) Short Column Under Compression



Appendix 20 20(20) Wedge Under Compression