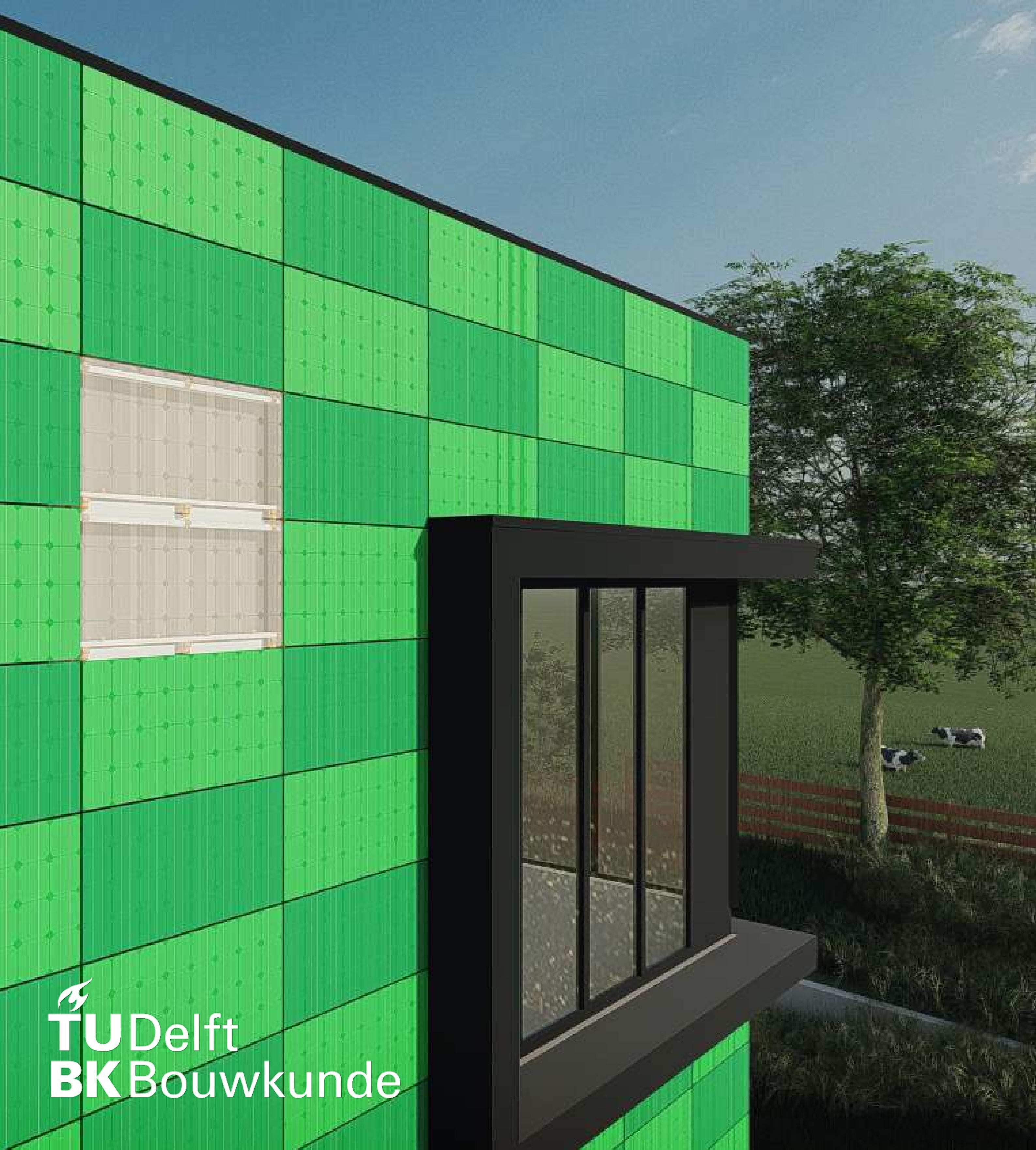
HIGH PRESSURE LAMINATE BUILDING-INTEGRATED PHOTOVOLTAICS FACADE SYSTEM



TU Delft
BK Bouwkunde

COLOPHON

TITLE
High Pressure Laminate Building-Integrated
PhotoVoltaics Facade System

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I would also like to thank Dr. ir. Fred Veer for supervising the structural testing of the facade system in the laboratory.

Finally, I would like to thank my parents, brother, sister, friends, roommates and fellow students for supporting me during this journey.

Dion van Vlerken
Rotterdam, June 2021

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SUMMARY

In the National Climate Agreement, the Dutch government has set the goal of reducing Netherlands' greenhouse gas emissions by 49% in 2030 compared to 1990 levels. By 2050, this number should even have risen to 95%. Part of the greenhouse gas emissions is the generation of electricity by means of coal and natural gas. In order to contribute to the reduction of greenhouse gas emissions, the Dutch government has set a target that 70% of electricity must be generated from renewable sources by 2030. Last year, 18% of electricity was generated from renewable sources. 24% of this was generated by solar power.

Solar power can be generated through solar panels on roofs, on the ground, and on the facade. Solar panels on the roof are often sufficient for a single-family dwelling to generate enough energy for their own use. However, there are many buildings where the roof surface is limited in relation to the user surface. The facade surface is often larger than the roof surface.

In order to make optimal use of the energy potential of facades, new facade claddings are needed that make it possible to generate energy through the facade. One of the possibilities is the integration of PhotoVoltaics in a High Pressure Laminate (HPL) facade panel. However, this has an impact on the installation of the product and has other requirements.

In this master thesis, research has been done into the requirements, design and development of an easy-to-use facade system for mounting High Pressure Laminate facade panels with integrated PhotoVoltaics on the facade.

The research is divided into several phases. In the first phase, the requirements for the High Pressure Laminate Building-Integrated facade system are researched trough literature research. This included the properties of the material High Pressure Laminate and the relevant aspects of solar panels, but also the regulations for facade claddings. Furthermore, research has been done into comparable systems for mounting High Pressure Laminate and solar panels.

The program of requirements has been formulated based on the result of the literature research. First, the systems from the literature research were evaluated against the program of requirements. However, none of the systems met all the requirements. Additions were made to the program of requirements and these were used as a guideline for the development of the new system.

In the second phase, the concept for the facade system has been developed. The design problems of the facade system are subdivided into different aspects. For each aspect different designs were made that were tested against the different criteria of the program of requirements. For each aspect, a design got the highest score and combined the designs with the highest score form the concept proposal.

In the third phase of the research, prototypes were made for each aspect of the concept development. These prototypes were made with a 3D printer. This allowed the prototypes to be analysed in terms of their functionality. Because this method was very accessible, there was the possibility to make many prototypes.

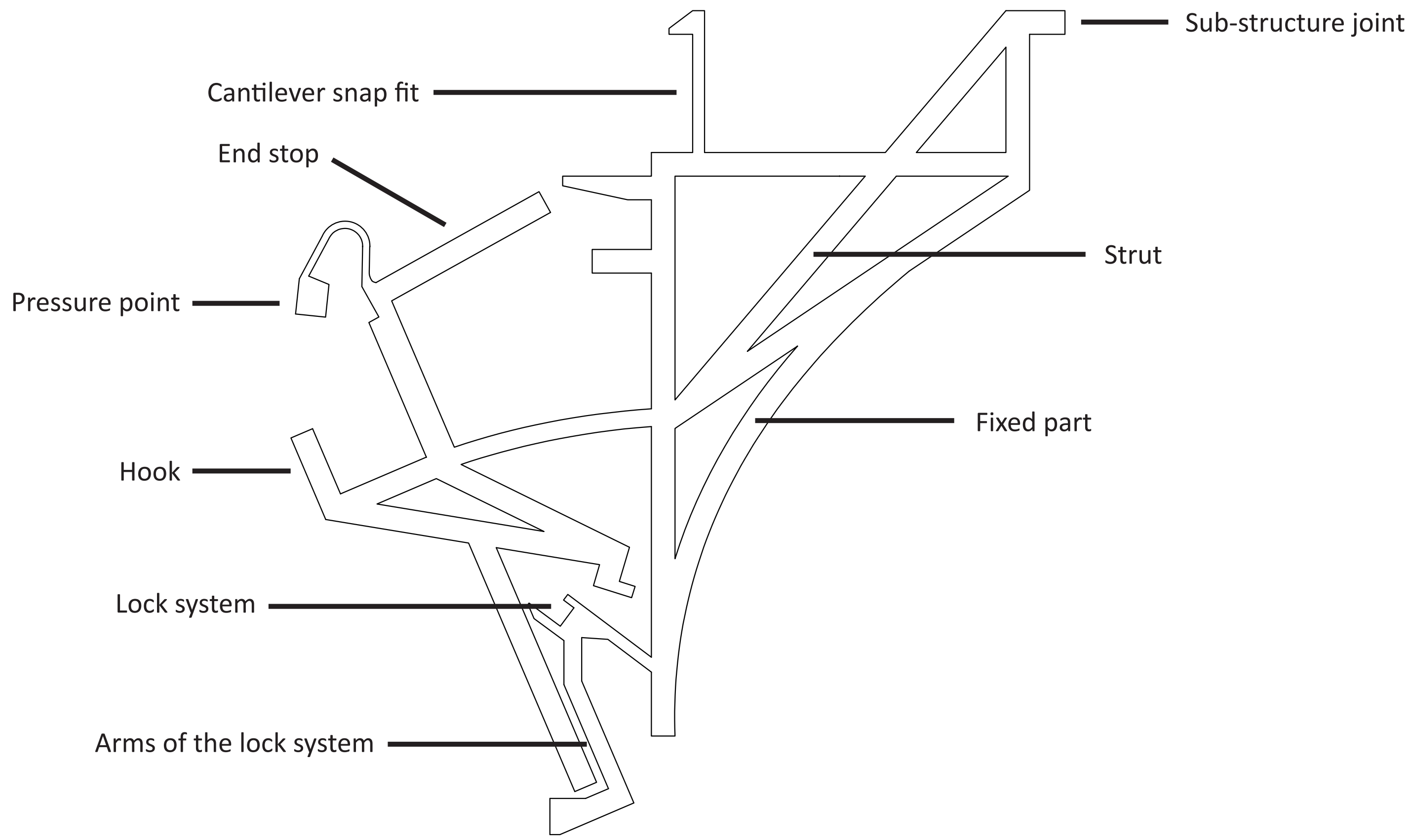
Next, a material analysis was made to determine the most suitable materials for the facade system. The material PLA, used to develop the prototypes, did not meet all the durability properties. In the material analysis, only materials that satisfied the durability properties were analysed.The mechanical characteristics of these materials were then compared with those of PLA, and the materials with approximately the same characteristics as PLA were selected to be used in the facade system.

After that, the prototypes were structurally tested. This was done by means of a Finite Element Analysis. The first analysis was with the final prototype from the chapter 'prototyping'. Next, several iterations were made until the design met all the requirements. The last iteration was used to do a practical test. This practical test gave a good insight into the actual structural strength of the design. With the information from the practical test, the design was adjusted again and analysed by means of a Finite Element Analysis.

After all parts met the functional and structural requirements, they were combined into the final design of the High Pressure Laminate Building-Integrated PhotoVoltaics facade system. The system is functioning, the tolerances have been taken into account and there are technical drawings of all components of the high pressure laminate building integrated photovoltaics facade system.

LIST OF DEFINITIONS

BIPV – Building-integrated photovoltaics
Compliant mechanism – Is a flexible mechanism that achieves force and motion transmission through elastic body deformation.
Eurocode – Are the ten European standards specifying how structural design should be conducted within the European Union (EU).
FEA – Finite element analysis
HPL – High pressure laminate
Linear elastic isotropic composite – A material that has the same properties in every direction.



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1 INTRODUCTION

1.1 PROBLEM STATEMENT

In the National Climate Agreement, the Dutch government has set the goal of reducing Netherlands' greenhouse gas emissions by 49% in 2030 compared to 1990 levels. By 2050, this number should even have risen to 95% (Ministerie van Economische Zaken en Klimaat, 2019). Part of the greenhouse gas emissions is the generation of electricity by means of coal and natural gas. In order to contribute to the reduction of greenhouse gas emissions, the Dutch government has set a target that 70% of electricity must be generated from renewable sources by 2030. Last year, 18% of electricity was generated from renewable sources. 24% of this was generated by solar power (CBS, 2020).

Solar power can be generated through solar panels on roofs, on the ground, and on the facade. Solar panels on the roof are often sufficient for a single-family dwelling to generate enough energy for their own use. However, there are many buildings where the roof surface is limited in relation to the user surface (Zonatlas, 2020). The facade surface is often larger than the roof surface.

Research shows that in the city of Senne in Germany, the solar energy potential in the facade is even twice as high as on the roofs. Despite the barriers and obstacles, roughly 20% of the facades are suitable for the installation of solar panels (Tetraeder, 2020).

In order to make optimal use of the energy potential of facades, new facade claddings are needed that make it possible to generate energy through the facade. One of the possibilities is the integration of PhotoVoltaics in a High Pressure Laminate (HPL) facade panel. However, this has an impact on the installation of the product and has other requirements. The system should be easy to use, so the panels should be easy to mount on the facade and to connect and conceal the electrical cables of the BIPV system. It is also not possible to saw or drill into the product after it has been manufactured. It must be possible to carry out maintenance behind the panels and in order to prevent theft, a hidden system will be better. A traditional facade system will not be able to meet these requirements.

1.2 GOAL OF THE RESEARCH

It is clear that there is a lot of potential in generating electricity via the facade. The aim of this graduation project is to develop an easy-to-use facade system that makes it possible to mount the High Pressure Laminate facade panels with integrated PhotoVoltaics (BIPV) on the facade.

Before developing a new facade system, research must be done into the design of the system. Research must also be carried out into which materials will be used for the system. The strength, fire safety and production process are important for this.

1.3 RESEARCH QUESTION

What are the requirements for a High Pressure Laminate Building-Integrated PhotoVoltaics facade system and how can these requirements be satisfied in the design and development of an easy-to-use facade system for mounting High Pressure Laminate Building-Integrated Photovoltaics to the facade?

1.4 LITERATURE QUESTIONS

- **What is High Pressure Laminate?**
- **What is the process from raw material to facade cladding?**
- **Which aspects of solar panels are relevant for the facade system?**
- **What are the regulations regarding the installation of facade cladding?**
- **Which mounting systems are currently used to mount PV and BIPV?**
- **Which mounting systems are currently used to mount HPL to the facade?**

1.5 METHODOLOGY

The research is divided into different phases. In the first phase, literature research will take place on all aspects of HPL facade cladding and solar panels. The purpose of this literature research is to gain insights into the mentioned topics and to build a framework for the research from here. Based on the conclusions of the literature research, the design criteria for the design of the new facade system can be formulated.

Concept development is planned in the second phase. Various designs have been made on every aspect of the facade system, which will be tested against the design criteria resulting from the literature research and some additions to it. The design criteria were compared with each other and given a certain weighting. Next, various designs per aspect were tested against these design criteria and the scores were summed up. For each aspect, one design received the highest score and together these designs form the concept proposal.

The design will be developed in the third phase. First, various prototypes will be developed based on the concept proposal. The prototype with the most potential will then be used further in the research.

A material analysis will be done for the prototype and the prototype will be tested for structural strength. This will be done by means of simulations and 3D printing. The prototype will be optimized to create the final design.

In the fourth and final phase, the research will be evaluated and conclusions will be made. Recommendations will also be made for further research into HPL facade systems with integrated solar cells.

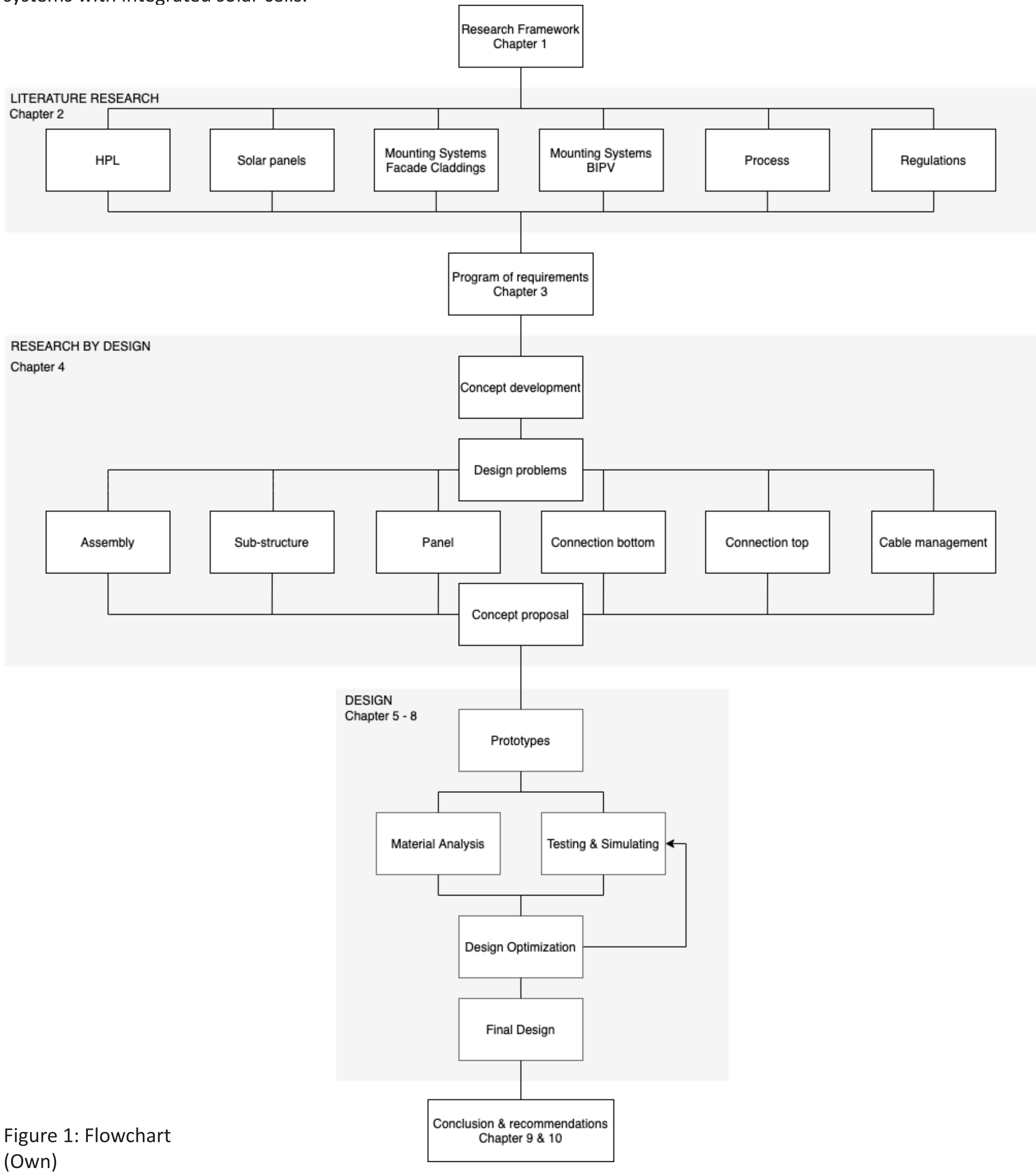


Figure 1: Flowchart
(Own)

2 LITERATURE RESEARCH

2.1 HIGH PRESSURE LAMINATE

High Pressure Laminate is a sheet material that can be used both indoors and outdoors. Well-known manufacturers include Trespa, Plastica and Duropal. The panel is built up of a core and a top layer. The core is made of wood fibres or paper impregnated with thermosetting resin, which are pressed together under high pressure. The top layer is located on both outer sides of the core. This is necessary because otherwise the panel may warp. The top layer ensures that the panel is resistant to UV radiation and moisture. The panel is also durable, wear-resistant and highly impact-resistant (Plastica, 2021).

The most common thicknesses of HPL panels are 6 and 8 millimeters. There are also HPL panels with a thickness of 10 and 13 millimeters. The HPL panel with a thickness of 6 millimeters has a weight of 8.4 kg per square meter, a panel of 8 millimeters 11,2 kg per square meter, a panel of 10 millimeters 14 kg per square meter and a panel of 13 millimeters 18,2 kg per square meter. More material properties can be found in appendix I.

The maximum span of the HPL panels depends on the thickness of the panels, the wind load and whether it is a single or multiple span. See appendix II. It must be noted that from top to bottom, only single span is possible. This is due to the limitations of the system.

The assembly of the HPL panels is normally done by two people. Dutch Health and Safety legislation states that the maximum weight that can be moved by hand is 50 kg (Ministerie van Sociale Zaken en Werkgelegenheid, 2021). This means that the maximum weight of the HPL BIPV panels may not exceed 50 kg.

Combining solar cells with the High Pressure Laminate facade panel creates a High Pressure Laminate Building Integrated PhotoVoltaics facade panel.

2.2 RAW MATERIAL TO FACADE CLADDING

The process starts with the request of a customer who has a project where a new facade must be designed and built. The architect makes a design and the customer contacts a facade builder to make the facade.

The facade builder needs the facade panels to make the facade. The panels will be ordered from a manufacturer of HPL cladding. The panels are made from various raw materials and delivered to the facade builder in standard sizes. The facade builder still has to cut the panels to size themselves.

For mounting the facade panels on the facade, the facade builder must purchase a mounting system from a mounting system manufacturer. The correct mounting system is selected based on the wishes of the customer. The facade builder then mounts the facade panels using the mounting system on the facade.

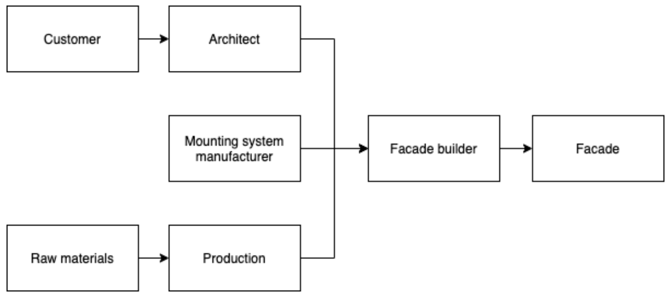


Figure 2: Process
(Own)

The development of the facade system is best left to the mounting system manufacturer. They have all the knowledge to design and develop the facade system. The HPL manufacturer is less familiar with this and it is not part of their field of expertise. However, it is advisable for HPL manufacturers to cooperate with a mounting system manufacturer in order to contribute to the development of the final product.

2.3 RELEVANT ASPECTS OF SOLAR PANELS

The way in which solar panels are connected has an influence on the space required for the cavity behind the facade cladding. This is because the thickness of the cables can change or that additional equipment may have to be placed behind the facade cladding. The number of solar panels also influences this. It is also important to know the reliability of the system. This affects how dismountable the system must be.

SERIES, PARALLEL OR OPTIMIZERS?

There are various options for connecting the solar panels, each with its advantages and disadvantages. The most common option is to connect the panels in series. The panels are connected one after the other. This is also referred to as a string. A solar panel usually supplies between 30 and 40 volts. 10 solar panels in series therefore deliver 300 to 400 volts. The Amperage remains the same. Through the central inverter, the electricity from the solar panels, which is in DC voltage, is converted to 230 Volt AC. A disadvantage of series connection is that when one panel is shaded and the voltage is only 10 volts, the other panels that are in the sun also only have a maximum voltage of 10 volts (Borrias, 2019). Another disadvantage is that the central inverter has a lifespan of 10 to 15 years, which means that the lifespan of the central inverter is shorter than the panels themselves (Solar bouwmarkt, 2020).

Another option is to connect the solar panels in parallel. The panels are not connected one after the other like the series connection, but next to each other. The pluses are connected to the pluses and the minuses to the minuses. Due to the high currents that are released, micro-inverters are used in a parallel circuit. A micro-inverter converts the DC voltage to AC voltage per panel (Borrias, 2019). Furthermore, a micro-inverter is about the size of an A5 and has a thickness of about 30 millimeters. The advantage of a micro-inverter is that if one panel produces less power, it has no effect on the yield of the other panels. Another advantage is that the system does not need a central inverter and that the yield can be analyzed per panel. Possible poorly performing panels will surface. Also, the life of the micro-inverters is about as long as the panels, namely 25 years. The disadvantage of a parallel connection is that the cables often have to be made thicker. This is because with a parallel connection not the voltage but the current strength (Ampere) per panel increases. Another disadvantage is that because each panel has its own micro-inverter, the system is more expensive than a series connection (Solar bouwmarkt, 2020).

The last option is a system with optimizers. Basically this system is the same as a series connection. The difference is that with this system each panel has an optimizer. Just like with a parallel connection with micro-inverters, this optimizer ensures that if one panel produces less power, it does not affect the yield of the other panels (Borrias, 2019). However, an optimizer works differently then a microinverter. Where a micro-inverter converts the DC voltage to AC voltage, an optimizer ensures that the power of the panels remains the same by playing with the voltage. An optimizer is about the size of an A6 paper and a thickness of 25 mm. The advantage of this system is that, just like the parallel connection, it is possible to monitor the yield per panel. Also, the cables do not need to be made thicker because the Amperage is the same as a normal series connection. Furthermore, the power optimizers, just like the micro-inverters, have a lifespan of about 25 years. A disadvantage of this system is that a central inverter is still required (Solar bouwmarkt, 2020).

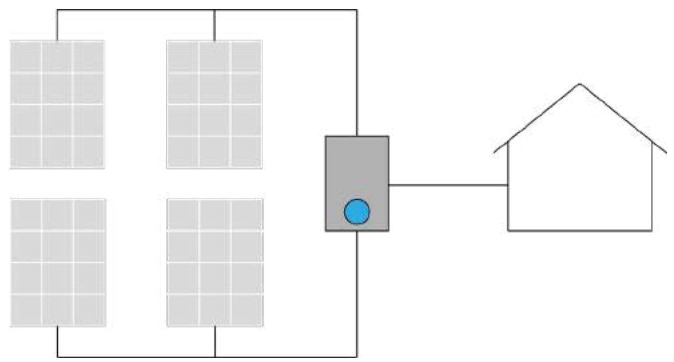


Figure 3: Series or parallel connection with inverter
(Own)

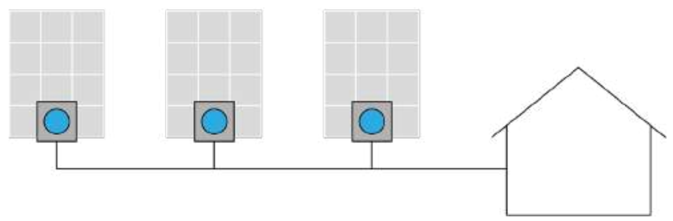


Figure 4: Micro-inverter
(Own)

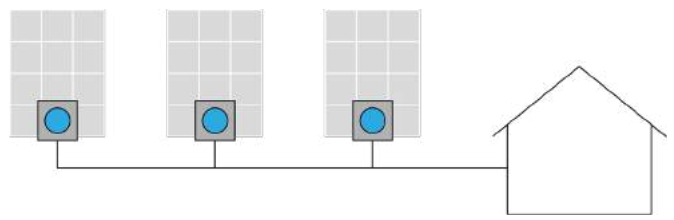


Figure 5: Optimizers
(Own)

AMOUNT OF PANELS PER GROUP

The amount of panels that can be connect per group depends on the maximum number of Amps of the group in question. The standard main fuse in a house has a current maximum of 25 Amps. However, it is possible to install a larger main fuse up to 80 Amps. For companies it is even possible to have a main fuse up to 250 Amps (Stedin, 2020). According to the rule of thumb, the fuse in the group fuse box must be 1,6 times smaller than the main fuse (Zonnepanelen.net, 2020). This means that for a standard connection in the fuse box, the current can be a maximum of 16 Amps per group. With a connection of 80 or 250 Amps, this is a maximum of 50 or 156 Amps per group.

The inverter converts the electricity generated by the panels from direct current to 230 Volt alternating current. The formula for calculating the maximum power (Watt) is the voltage (Volts) times the amperage (Ampere) (Rijnberk, 2020). This means that for a standard home connection, the voltage of the current (230 Volt) times the current of the group (16 Amps) must be done to calculate the maximum allowable power of the solar panel installation. In this case, the maximum power of the solar panel installation is 3680 Watt peak.

LOSS OF YIELD & DEFECTS

Despite the fact that solar panels benefit from a high amount of sunshine, it is important that the temperature does not exceed 25 degrees Celsius. For each degree that it is warmer, the panel's power output decreases by 0,35%. It also turns out that 5% of the panels have defects. Even if they have just been installed. This is caused by poor welds, and bird droppings can also cause damage to the panels (Claes, 2010).

It is important for the efficiency of the solar panels that the cavity behind the panels is ventilated. If solar panels are fixed vertically to the facade without ventilation, the yield loss can be as much as about 10% (Kooning & Depreeuw, 2010).

SIZE & WEIGHT OF THE PANELS

A standard solar panel consists of 6 solar cells in one direction and 10 solar cells in the other. In total, there are 60 solar cells per panel. These solar cells have a dimension of 156 by 156 millimeters. With the space between the solar cells and the space at the edges, a standard solar panel measures approximately 1650 by 1000 millimeters. The weight of a panel is around 18 kg. This converts to 0,3 kg per solar cell (Matasci, 2020).

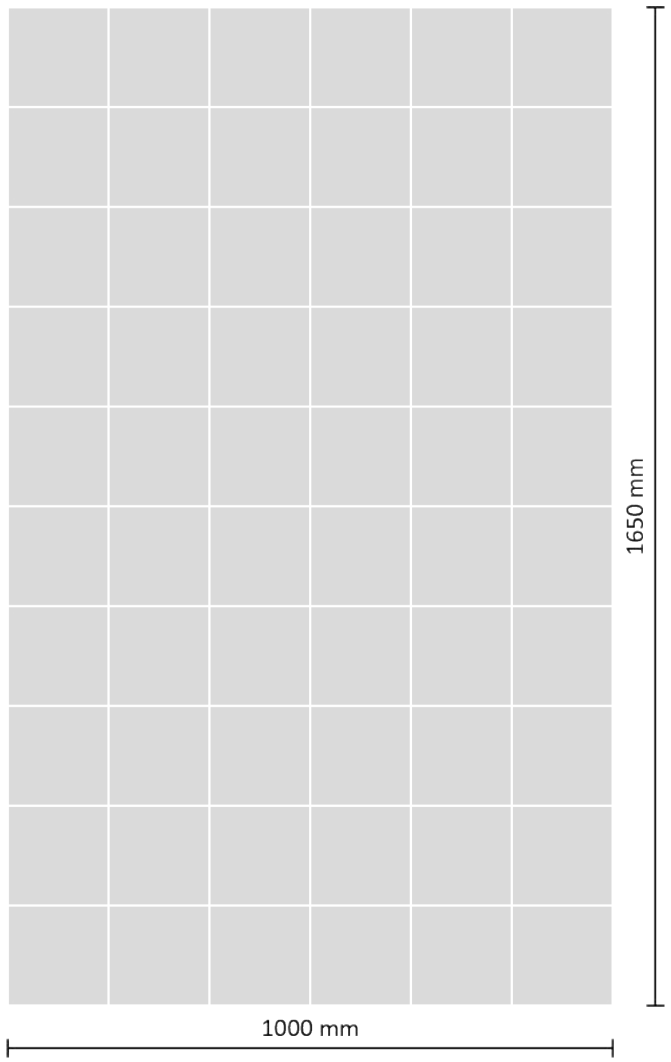


Figure 6: Dimensions solar panel
(Own)

2.4 REGULATIONS FACADE CLADDINGS

If the facade cladding is installed, it must be certain that it is structurally strong enough. Therefore, the facade must be strong enough to withstand the load of the wind, and safety factors are taken into account in order to build in extra security. There are also regulations on the fire safety of the facades.

CONCEQUENCE CLASSES

The consequence classes are described in the NEN-EN 1990. This describes that a structure must be designed and built in such a way that it is sufficiently reliable during the specified design life that it meets the criteria of safety and usability, without excessive maintenance. The consequence classes are divided into 3 categories (NEN, 2019). See table 1.

Consequences class	Discription	Examples of buildings and civil engineering works
CC3	**High** consequence for loss of human life, or economic, social or environmental consequences **very great**	Grandstands, public buildings where consequences of failure are high (e.g. a concert hall)
CC2	**Medium** consequence for loss of human life, economic, social or environmental consequences **considerable**	Residential and office buildings, public buildings where consequences of failure are medium (e.g. an office building)
CC1	**Low** consequence for loss of human life, and economic social or environmental consequences **small or negligible**	Agricultural buildings where people do not normally enter (e.g. storage buldings), greenhouses

Table 1: Consequences classes
(NEN, 2019)

For each consequence class there are corresponding safety factors (NEN, 2019), see table 2.

Consequences class	Safety factor permanent actions	Safety factor variable actions
CC3	1,10	1,35
CC2	1,20	1,50
CC1	1,30	1,65

Table 2: Safety factors consequences classes
(NEN, 2019)

FIRE SAFETY

NEN-EN 13501-1 (Fire classification of construction products and building elements) describes the minimum fire classification to be met by the exterior of the facade. The minimum fire classification that applies to facades is fire classification B. The material has a very limited contribution to the development of the fire (NEN, 2019). The fire classification of HPL is even better with fire classification A2. In this case, the material has hardly any contribution to the development of the fire.

However, the fire classification does not only apply to the facade cladding, but to the entire facade construction. As a result, the mounting system must also meet at least fire classification B.

WIND LOAD

A Eurocode has been drawn up for the maximum wind load on the facades, namely the NEN-EN 1991, Wind actions. This describes the calculation method used to calculate the wind load for each individual country. In this report the wind zones in the Netherlands will be used. In the Netherlands three wind zones have been designated. In wind area I, the most stringent requirements apply. This area is situated on the coast and has the highest wind speeds in the Netherlands. Wind area II is also situated on the coast, but here the wind speeds are less high. Wind area III is inland and has the lowest wind speeds (NEN, 2020).

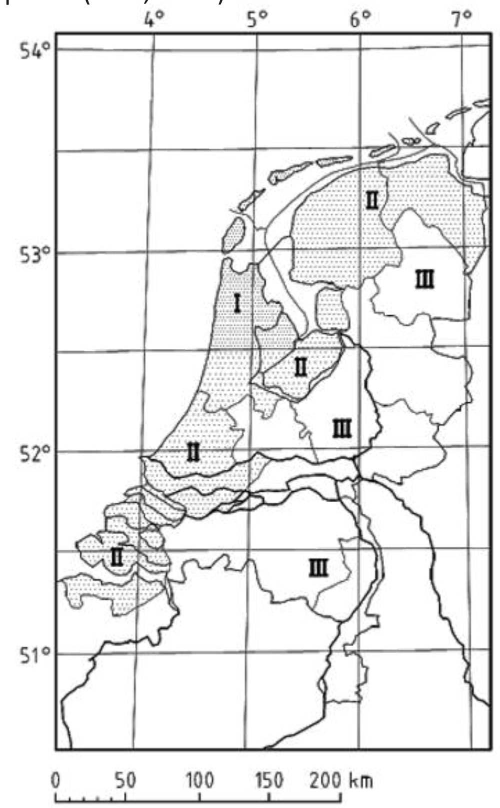


Figure 7: Wind areas in the Netherlands
(NEN, 2020)

These areas are divided into three terrain categories. Namely whether the building is in a sea or coastal area, a built-up area or an undeveloped area. The height of the building is also important for the wind load per square meter. See table 3.

Height	Area I			Area II			Area III	
m	Coast	Undeveloped	Built-up	Coast	Undeveloped	Built-up	Undeveloped	Built-up
1	0,93	0,71	0,69	0,78	0,60	0,58	0,49	0,48
2	1,11	0,71	0,69	0,93	0,60	0,58	0,49	0,48
3	1,22	0,71	0,69	1,02	0,60	0,58	0,49	0,48
4	1,30	0,71	0,69	1,09	0,60	0,58	0,49	0,48
5	1,37	0,78	0,69	1,14	0,66	0,58	0,54	0,48
6	1,42	0,84	0,69	1,19	0,71	0,58	0,58	0,48
7	1,47	0,89	0,69	1,23	0,75	0,58	0,62	0,48
8	1,51	0,94	0,73	1,26	0,79	0,62	0,65	0,51
9	1,55	0,98	0,77	1,29	0,82	0,65	0,68	0,55
10	1,58	1,02	0,81	1,32	0,85	0,68	0,70	0,56
15	1,71	1,16	0,96	1,43	0,98	0,80	0,80	0,66
20	1,80	1,27	1,07	1,51	1,07	0,90	0,88	0,74
25	1,88	1,36	1,16	1,57	1,14	0,97	0,94	0,80
30	1,94	1,43	1,23	1,63	1,20	1,03	0,99	0,85
35	2,00	1,50	1,30	1,67	1,25	1,09	1,03	0,89
40	2,04	1,55	1,35	1,71	1,30	1,13	1,07	0,93
45	2,09	1,60	1,40	1,75	1,34	1,17	1,11	0,97
50	2,12	1,65	1,45	1,78	1,38	1,21	1,14	1,00
55	2,16	1,69	1,49	1,81	1,42	1,25	1,17	1,03
60	2,19	1,73	1,53	1,83	1,45	1,28	1,19	1,05
65	2,22	1,76	1,57	1,86	1,48	1,31	1,22	1,08
70	2,25	1,80	1,60	1,88	1,50	1,34	1,24	1,10
75	2,27	1,83	1,63	1,90	1,53	1,37	1,26	1,13
80	2,30	1,86	1,66	1,92	1,55	1,39	1,28	1,15
85	2,32	1,88	1,69	1,94	1,58	1,42	1,30	1,17
90	2,34	1,91	1,72	1,96	1,60	1,44	1,32	1,18
95	2,36	1,93	1,74	1,98	1,62	1,46	1,33	1,20
100	2,38	1,96	1,77	1,99	1,64	1,48	1,35	1,22
110	2,42	2,00	1,81	2,03	1,68	1,52	1,38	1,25
120	2,45	2,04	1,85	2,05	1,71	1,55	1,41	1,28
130	2,48	2,08	1,89	2,08	1,74	1,59	1,44	1,31
140	2,51	2,12	1,93	2,10	1,77	1,62	1,46	1,33
150	2,54	2,15	1,96	2,13	1,80	1,65	1,48	1,35
160	2,56	2,18	2,00	2,15	1,83	1,67	1,50	1,38
170	2,59	2,21	2,03	2,17	1,85	1,70	1,52	1,40
180	2,61	2,24	2,06	2,19	1,88	1,72	1,54	1,42
190	2,63	2,27	2,08	2,20	1,90	1,75	1,56	1,44
200	2,65	2,29	2,11	2,22	1,92	1,77	1,58	1,46
225	2,70	2,35	2,17	2,26	1,97	1,82	1,62	1,50
250	2,74	2,40	2,23	2,30	2,01	1,86	1,66	1,54
275	2,78	2,45	2,28	2,33	2,05	1,91	1,69	1,57
300	2,82	2,50	2,32	2,36	2,09	1,95	1,72	1,60

Table 3: Wind load per square meter
(NEN, 2020)

LITERATURE RESEARCH

2.5 CURRENT MOUNTING SYSTEMS PV/BIPV

There are various systems on the market for mounting normal PhotoVoltaics (PV) panels and Building Integrated PhotoVoltaics (BIPV). Standard PV panels are usually placed on roofs using clamps on a rail system, as shown in figure 8.

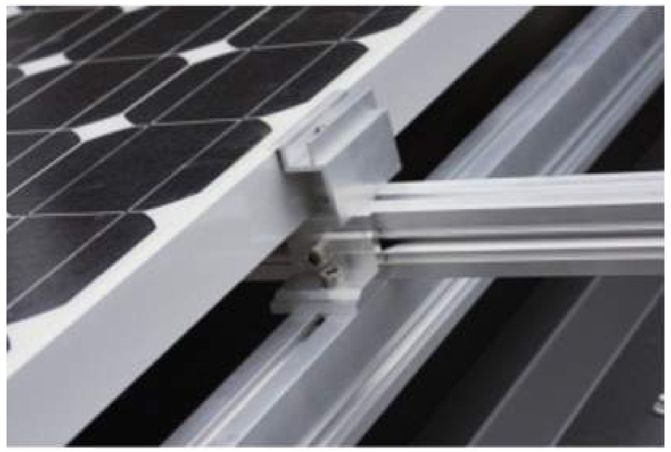


Figure 8: PV panels mounted with clamps on a rail system
(Zonnepanelen-Voordelig, 2020)

For the mounting of BIPV there is more variation. This is because BIPV is a collective name for various products in which solar cells are integrated. A good example of this are solar cells integrated in roof tiles, as shown in figure 9 and figure 10. The roof tiles with integrated solar cells are mounted in the same way as normal roof tiles.

Figure 9: Monier V90 – integrated PV-system
(Monier, 2021)

Figure 10: Tesla Solar Roof
(Tesla, 2020)

Another example are these BIPV panels (figure 11) in the facade of a building. The BIPV panels are fixed to the facade using clamps.

Figure 11: BIPV facade
(Hanjin, 2013)

The last example are solar cells integrated in glass, which can be seen on figure 12. The great thing about this system is that daylight still comes in and electricity is generated. The glass with the integrated solar cells is placed in a frame just like normal glass panels.

Figure 12: Solar cells integrated in glass
(Mashriq energy, sd)

LITERATURE RESEARCH

2.6 CURRENT MOUNTING SYSTEMS HPL

The most commonly used methods of mounting HPL facade panels are by mechanical and chemical mounting methods. Mechanical mounting methods are both visible and invisible on the outside of the facade. Chemical mounting methods are not visible. Manufacturers of HPL facade systems include ECO Cladding, GIP GmbH, Ipex Group and NVELOPE Rainscreen Systems.

These mounting methods are all attached to a sub-structure. The sub-structure is made of wood or aluminium. The depth of the sub-structure depends on whether the wall still needs to be insulated or not.

MECHANICAL MOUNTING METHODS

SCREWS & BLIND RIVETS

With these mounting methods, the panels are fixed to the sub-structure by means of screws or blind rivets. Before the panels can be fixed to the sub-structure, they must first be pre-drilled. This must be measured in advance. The panels are then fixed to the sub-structure using spacers. Because the panels are fastened with screws or blind rivets, the panels are fixed immediately and therefore cannot move horizontally. The panels are mounted separately from each other, so that maintenance can be carried out per panel if necessary.

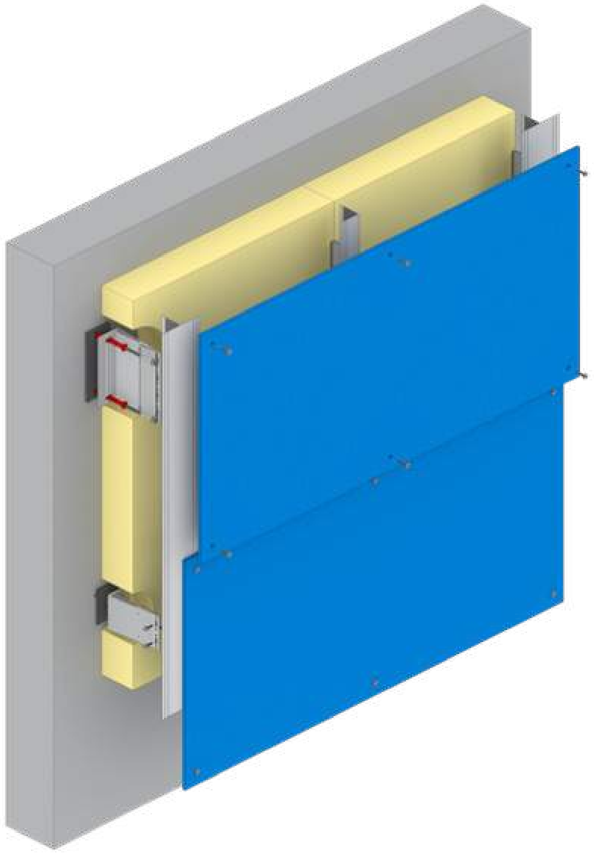


Figure 13: Screws and blind rivets
(Ipex Group, 2020)

CLAMP WITH BRACKETS

With this mounting method, the panels are fastened by means of a clamp with hooks. First, the clamp is attached to the bottom of the sub-structure. Subsequently, the panel is first placed with the bottom in the clamp. Next, the clamp is placed at the top of the panel and then attached to the sub-structure. There is a component in the clamp to prevent it from moving horizontally. The panels are connected to each other using the fastening method. As a result, maintenance on a single panel is not possible.

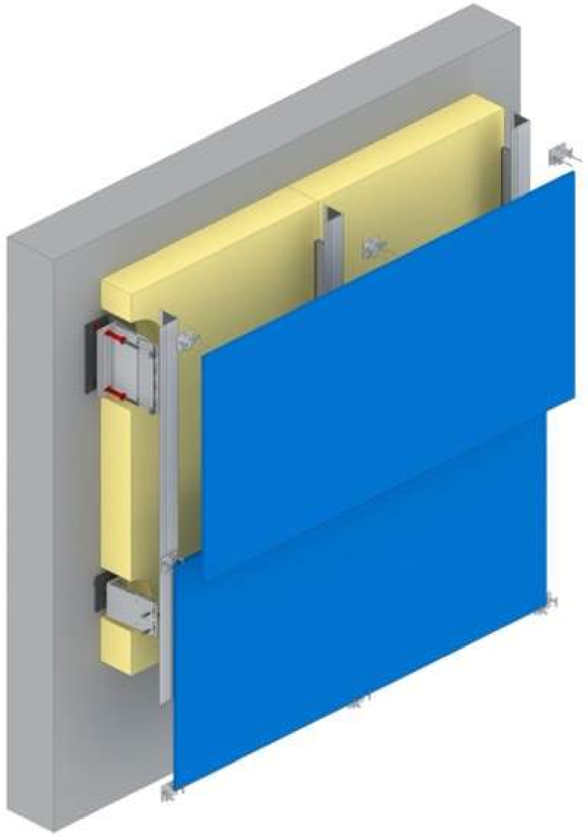


Figure 14: Clamp with brackets
(Ipex Group, 2020)

METAL TONGUES WITH PROFILED EDGES

In this mounting method, the panels are fixed to the sub-structure by means of metal springs. A groove must be milled on all sides of the panel. The panels are then fixed to the sub-structure by means of the metal springs. Furthermore, a countersunk hole must be drilled in the panel to fix the panel. Because the panels are connected to each other by means of the metal springs, it is not possible to carry out maintenance on a single panel.

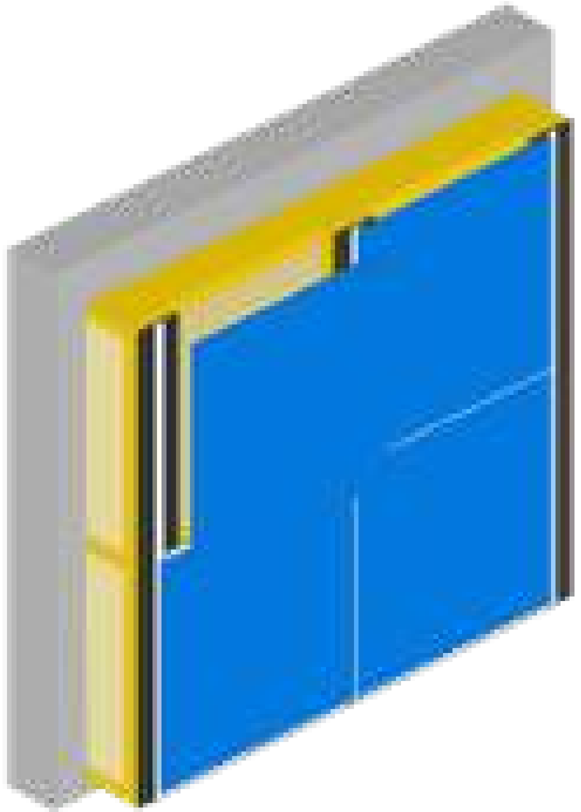


Figure 15: Metal tongues with profiled edges
(Own)

HANGERS ON HORIZONTAL PROFILE

With this method of mounting, plate hooks are attached to the back of the panel. The horizontal rails are attached to the sub-structure, into which the panels are hung by using the plate hooks. The panel hooks are then attached to the rails with a screw. This ensures that the panel is directly fixed and no horizontal movement can occur. Despite the fact that the panels are installed separately from each other, it is not possible to detach a single panel for maintenance purposes. It is not possible to unscrew the screw that attaches the panel hook to the rails when there is a panel on top.

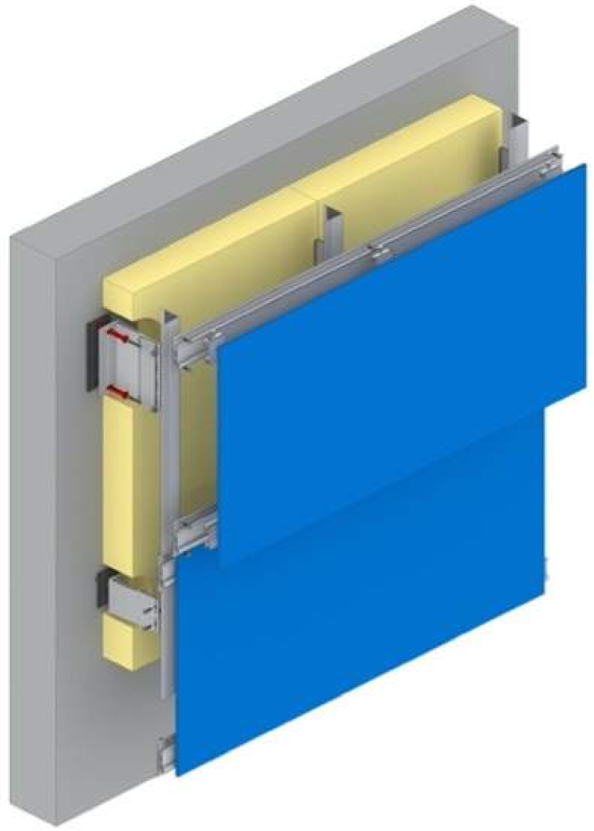


Figure 16: Hangers on horizontale profile
(Ipex Group, 2020)

PROFILED EDGES

In this method, a groove is milled locally or completely at the top and bottom of the panel. The panels are then fastened by using hooks in the horizontal rails or through continuous horizontal profiles where the panels are retracted and glued. Because there are local grooves in the case of the hooks, the panels cannot move horizontally. The other system does not allow horizontal movement either, as the panels are glued together. With both systems it is not possible to separate a panel for maintenance.

Figure 17: Profiled edges
(Ipex Group, 2020)

CHEMICAL MOUNTING METHODS

ADHESIVE

With this mounting method, the panels are glued directly to the sub-structure. Double-sided foam tape is used to ensure that the panels remain in position during the curing process. The panels are fixed automatically because they are glued. It is not possible to perform maintenance behind the panels.

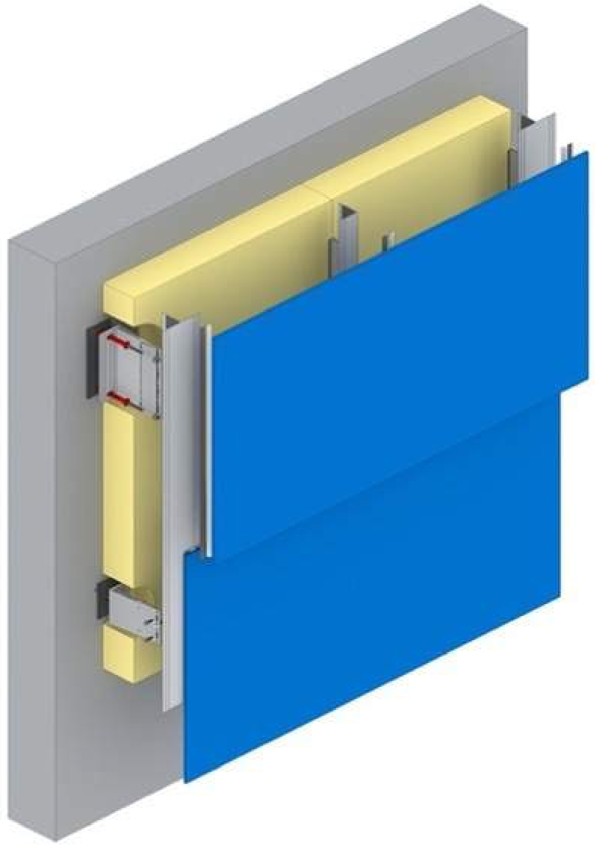


Figure 18: Adhesive
(Ipex Group, 2020)

MECHANICAL & CHEMICAL COMBINED

GLUED ON A PROFILE

In this method, a profile is glued to the back of the panel. The panel is then attached with the profile to the horizontal rails of the sub-frame. As the fixing is done by using a screw, the panels are fixed in place. It is not possible to carry out maintenance behind a single panel.

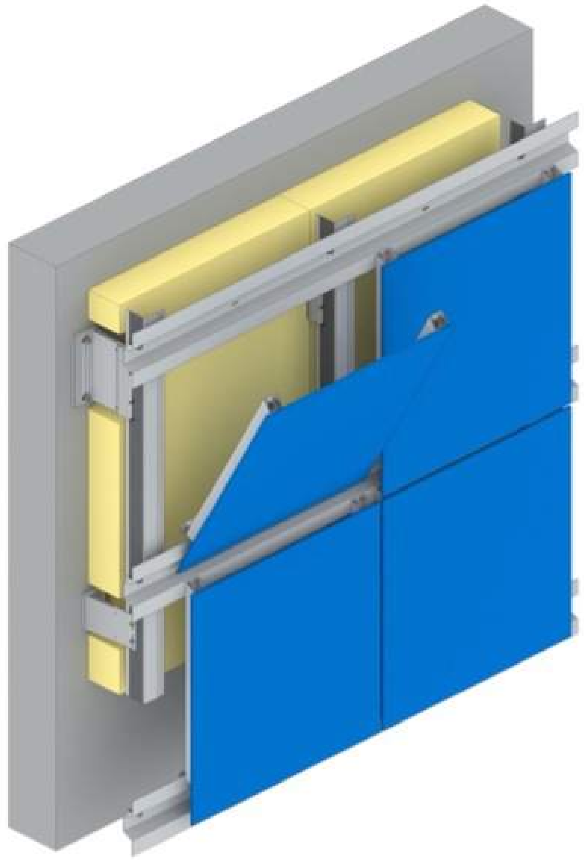


Figure 19: Glued on a profile
(Ipex Group, 2020)

3 PROGRAM OF REQUIREMENTS

The program of requirements has been formulated based on the results of the literature research. It also incorporates certain preferences.

3.1 REQUIREMENTS

- The system should not be visible from the outside
- The system must allow the panels to be disassembled separately for maintenance
- The system should have as few parts as possible
- No adjustments on site
- Multi-step assembly
- Installation space behind the panels

3.2 MATRIX

	Invisible 1	**Separately demountable for maintenance** 3	**Amount of parts** 1	**No adjustments on site** 2	**Multi-step assembly** 3	**Installation space** 2	**Result**
Screws & blind rivets	-	+	+	-	-	+	0
Clamp with brackets	-	-	+	+	+	+	4
Metal tongues	0	-	+	-	-	+	-5
Hangers on horizontal profile	+	-	0	-	-	+	-5
Profiled edges	+	-	0	-	+	+	1
Adhesive	+	-	+	+	-	+	0
Glued on a profile	+	-	0	-	+	+	1

Table 4: Matrix mounting systems (Own)

PROGRAM OF REQUIREMENTS

CONCLUSION

The results from the matrix show that none of the facade systems examined meets all the requirements of the program of requirements. All systems have their weaknesses and strengths. For the new design it is necessary to merge the strengths of the existing systems in order to meet the program of requirements.

3.3 ADDITIONS PROGRAM OF REQUIREMENTS

In addition to the program of requirements, there are some additional requirements for the new facade system to be developed.

- It should be easy to mount the panels. With as few actions as possible;
- Easy production method;
- Risk of errors in production and the resulting residual waste;
- The structure of the system should be safe;
- Possibility of adding additional components;
- Adjustment possibility to compensate for tolerances;
- The possibility of changing parts;
- Easy to disassemble and reuse.

For the structural calculations of the system, it is important that structural assumptions are made. For the maximum wind load, a building with a height of 20 meters has been taken into account which is located at the coast in wind area I. This results in a wind load of 1,8 kN/m^2. The system will be mainly intended for residential, office and public use where the consequences of failure are medium. The corresponding consequence class is CC2. Furthermore, the facade system is only suitable for vertical installation of the HPL panels.

The HPL BIPV facade panels are made of an HPL panel with integrated solar cells. The dimensions of the HPL BIPV panels are derived from the dimensions of the solar cells, which have a size of 156 by 156 millimeters. In order to have a space between the solar cells, the dimensions of the solar cells are rounded off to 160 by 160 millimeters. The dimensions of an HPL BIPV facade panel are a multiple of 160 millimeters. However, a joint of at least 10 millimeters wide between the panels must also be taken into account. Therefore, the width and height of the panel will be a multiple of 160 millimeters minus a joint thickness of 10 millimeters. The centre-to-centre distance between the joints is a multiple of 160 millimeters.

In addition to the size of the solar cells, the thickness and weight of the facade panels also influence the maximum size of the facade panels. The panel thickness affects the maximum free span between the support points of the panel. This free span also depends on the wind load on the facade. Furthermore, the panel must not weight more than 50 kilograms in order to make it is possible to install the panel with 2 people. Figure 20 shows the optimum size per panel thickness. The calculations can be found in appendix III.

In order to achieve the highest possible yield from the system, it is important that the system is placed somewhere where there are no shadow obstructions. Since this can in principle always be assumed, a series connection of the panels will be taken into account in the remainder of the research.

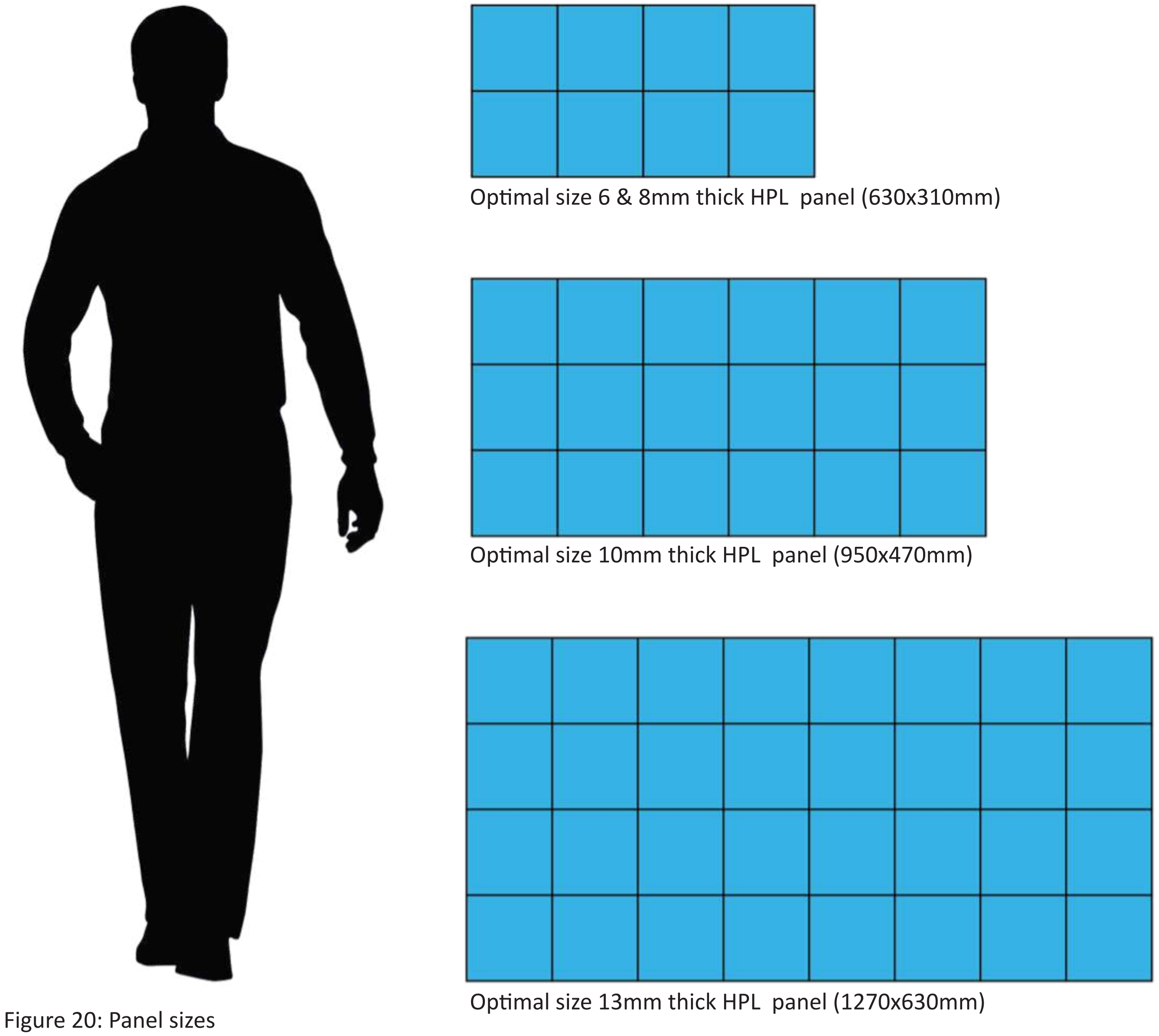


Figure 20: Panel sizes
(Own)

A panel with a thickness of 13 millimeters was used for the further development of the system.

4 CONCEPT DEVELOPMENT

This chapter describes the development of the concept for the facade system. First, the design problems of the facade system are divided into different aspects. Different designs will be made for each aspect and will then be tested against different criteria arising from the program of requirements. These criteria are subdivided into 'boundary conditions' and 'other criteria'. The designs must in any case satisfy the boundary conditions and for the other criteria, a distinction is made between important and less important criteria with the aid of a matrix. The criteria are also explained in more detail. All design solutions were then tested against the criteria that were relevant to the design solution in a multi-criteria analysis.

4.1 ASPECTS

Assembly
In the aspect of assembly, the various sequences for mounting the panels on the facade are assessed against the established criteria.

Sub-structure
The sub-structure is the connection between the wall and the cladding.

Panel
In this aspect, various modifications to the panel for connecting to the sub-structure are assessed.

Top & bottom connection
This aspect is the connection of the panel to the sub-structure at the top and bottom of the panel.

Cable management
The cable management ensures that the cables of the BIPV system can be concealed in an organized manner.

4.2 WEIGHT

In order to decide which design will be used for each aspect, various criteria have been formulated to assess the designs. There are boundary conditions that the design must satisfy in any case. These come from the program of requirements. There are also specific criteria for each aspect.

In order to distinguish between important and less important criteria, each criterion has been given a certain weighting. The important criteria are given a weighting of 3, while the less important criteria are given a weighting of 1 or 2. The weight valuation method is used to determine this value. The score matrix on the next page is used to compare all criteria one by one. If one criterion is more important than the other, it gets the value of 1. If the criteria are less important, it gets the value of 0.

		Production method	Risk of errors	Amount of parts	Easy to mount	Multi-step assembly	Expandable	Resilience to tolerance	Physical ergonomics	Maintenance	Adaptability	Disassembly	Total	Weight
	Production method		1	1	0	0	0	0	0	0	0	0	2	o
Production	Risk of errors	0		1	0	0	0	0	0	0	0	0	1	o
	Amount of parts	0	0		0	0	0	0	0	0	0	0	0	o
	Easy to mount	1	1	1		0	1	0	1	1	1	1	8	ooo
Assembly	Multi-step assembly	1	1	1	1		1	0	1	1	1	1	9	ooo
	Expandable	1	1	1	0	0		0	1	1	1	1	8	ooo
	Resilience to tolerance	1	1	1	1	1	1		1	1	1	1	10	ooo
	Physical ergonomics	1	1	1	0	0	0	0		0	1	1	5	oo
Use	Maintenance	1	1	1	0	0	0	0	1		1	1	6	oo
	Adaptability	1	1	1	0	0	0	0	0	0		0	3	o
End-of-life	Disassembly	1	1	1	0	0	0	0	0	0	1		4	oo

Table 5: Score matrix
(Own)

The criteria with a score between 0 and 3 are given a weighting of 1. The criteria with a score between 4 and 7 are given a weighting of 2 and the criteria with a score between 8 and 10 are given a weighting of 3. Green means that the design is satisfactory, orange means that the design is average and red means that the design is unsatisfactory.

4.3 EXPLANATION CRITERIA

Boundary conditions:

• **Visibility**	O O O	The visibility of the mounting system on the outside of the facade.
• **Demountability**	O O	The system must allow the panels to be disassembled separately for maintenance.
• **No adjustments on building site**	O O	The panels must not be adjusted on the building site.
• **Structural safety**	O O O	The structure of the system should be safe.

Production:

• Production method	O	Using simple production techniques.
• Risk of errors	O	Minimize residual waste in production.
• Amount of parts	O	Minimize human labour, thus assembly errors.

Assembly:

• Easy to mount	OOO	Easy and quick handling methods.
• Multi-step assembly	OOO	Multi-step assembly ensures that there is one step between the assembly of the bottom and top profile. This allows the wiring of the BIPV system to be connected.
• Expandable	OOO	Possibility of adding additional components.
• Resilience to tolerance	OOO	Adjustment possibility to compensate for tolerances.
• Physical ergonomics	OO	Minimize use of heavy equipment

Use:

• Maintenance	OO	The possibility of doing maintenance.
• Adaptability	O	The possibility of replacing the panels.

End-of-life:

• Disassembly	OO	Easy to disassemble and reuse.

4.4 CRITERIA & ASPECTS

Not all criteria and boundary conditions are relevant to every aspect. Therefore, each aspect has been assigned the applicable criteria and boundary conditions.

Assembly:
- **Structural safety**
- Easy to mount
- Multi-step assembly
- Physical ergonomics
- Maintenance
- Adaptability

Sub-structure:
- **Structural safety**
- Risk of errors
- Amount of parts
- Easy to mount
- Resilience to tolerance
- Physical ergonomics
- Maintenance
- Adaptability
- Disassembly

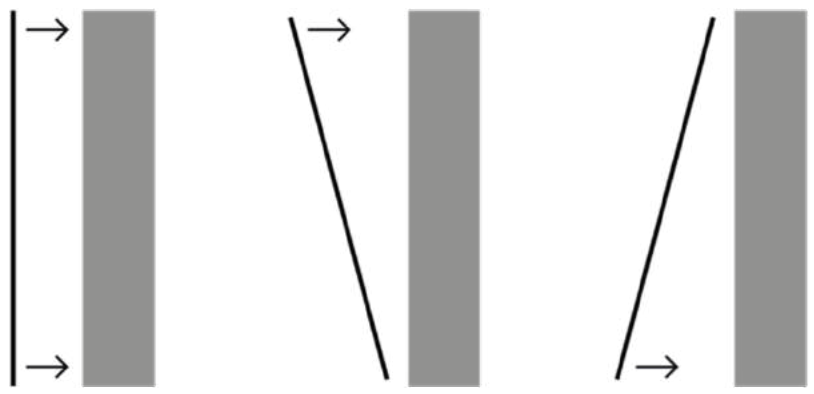
Panel:
- **Visibility**
- **No adjustments on site**
- **Structural safety**
- Production method
- Risk of errors
- Easy to mount
- Resilience to tolerance
- Maintenance
- Adaptability
- Disassembly

Top & bottom connection:
- **Visibility**
- **Demountability**
- **Structural safety**
- Production method
- Risk of errors
- Easy to mount
- Resilience to tolerance
- Physical ergonomics
- Maintenance
- Adaptability
- Disassembly

Cable management:
- **Visibility**
- **Demountability**
- Production method
- Risk of errors
- Easy to mount
- Expandable
- Maintenance
- Adaptability
- Disassembly

For each aspect, different design solutions have been developed. Some design solutions are based on existing solutions, while other design solutions are self-generated. The solutions are not discussed in depth, but on a conceptual level to speed up the process. Subsequently, the solutions of the various aspects are assessed according to the criteria drawn up. In addition to the weighting of the criteria, a score of 1 to 3 can be achieved. In appendix IV the explanation of the score per criteria can be found. If the criteria is not applicable in the design solution, a dash is added. By adding up the scores of the criteria, the best design solution per aspect emerges.

ASSEMBLY



1 2 3

Structural safety	O O O	O	O	O
Easy to mount	OOO	1	2	3
Multi-step assembly	OOO	-	3	3
Physical ergonomics	OO	2	3	3
Maintenance	OO	1	3	3
Adaptability	O	3	3	3
	Total:	12	30	33

1. Simultaneously

In this design solution, there is no multi-step assembly and the top and bottom of the panel are installed simultaneously. Assembly is quite difficult, as both top and bottom must be in the right position at the same time. From an ergonomic point of view, installation is fairly easy to do. Maintenance is difficult because the panel has to be loosened at both the top and the bottom. The panel must be completely removed from the facade. In case of a defect or something similar, it is easy to change the panels.

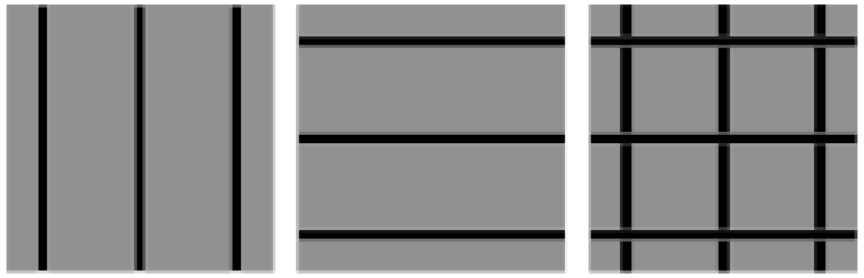
2. Bottom first

This design first mounts the panel at the bottom. Then the weight of the panel is already supported and the panel must be held to connect the cabling of the BIPV system. This can be done from the side of the panel. If the cabling is connected, the panel can also be connected from the top. By loosening the connection at the top and holding the panel up, maintenance of the system can be carried out. It is also possible to remove the panel in this way.

3. Top first

The panel is first hung on the top. The cabling can then be connected through the side of the panel. The panel is then mounted to the wall at the bottom. Because the panel is suspended, it already hangs in the right position and does not need to be held back. Maintenance can easily be done by loosening the bottom panel. The panels can be replaced if necessary by loosening the bottom panel and then also loosening the top panel.

SUB-STRUCTURE



1 2 3

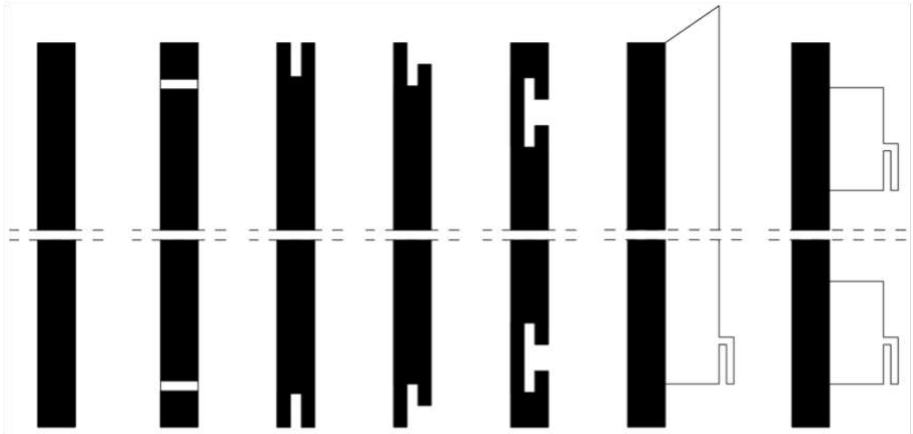
Structural safety	O O O	O	O	O
Risk of errors	O	3	3	3
Amount of parts	O	3	3	1
Easy to mount	OOO	1	1	2
Resilience to tolerance	OOO	1	1	3
Physical ergonomics	OO	3	3	3
Maintenance	OO	3	3	3
Adaptability	O	3	3	3
Disassembly	OO	3	3	3
	Total:	33	33	40

1. Vertical
The vertical sub-structure is not easy to mount. This is because it is difficult to precisely measure the distance between the sub-structures. This also affects the resilience of tolerance, because it is not possible to eliminate any unevenness. The vertical sub-structure also meets the other criteria.

2. Horizontal
The same applies to the horizontal sub-structure as to the vertical sub-structure. It is difficult to get the intermediate distances right and the adjustment possibilities are limited. Apart from that, it meets the other criteria.

3. Vertical/horizontal
With this method, first the vertical profiles are mounted on the structure behind. Then, the horizontal profiles are attached to the vertical profiles. This connection makes it possible to make adjustments if necessary, and therefore it is resilient of tolerance. A disadvantage of the system is that it consists of several parts. Otherwise, it meets the other criteria.

PANEL



1 2 3 4 5 6 7

Visibility	O O O	O	O	O	O	O	O	O
No adjustments on site	O O	O	O	O	O	O	O	O
Structural safety	O O O	O	O	O	O	O	O	O
Production method	O	3	3	2	2	2	1	1
Risk of errors	O	3	3	2	2	2	2	2
Amount of parts	O	3	3	3	3	3	1	1
Easy to mount	OOO	1	1	2	2	3	2	1
Resilience to tolerance	OOO	3	3	1	1	1	3	2
Maintenance	OO	1	2	3	3	3	3	2
Adaptability	O	1	3	3	3	3	3	3
Disassembly	OO	1	2	3	3	3	1	2
	Total:	26	30	31	31	34	30	24

1. Without adjustments
The first design solution is the panel without adjustments. The advantages are that the mounting system is not visible and no adjustments have to be made on site. What is more difficult is to check whether the chemical fixing at the back has reached the right strength. The production method is simple and the risk of errors is low. Mounting the panel on the facade is quite difficult. This is because the cables must first be connected before the panel can be attached to the facade. Maintenance of the system is not possible because it is fixed to the sub-structure by the chemical fixation. This also makes it difficult to change panels as damage may occur to the panel itself and the sub-structure. This makes it impossible to reuse the system.

2. Drilled holes
In the second design solution, holes are drilled in the panel at the building site. There is no risk of errors occurring. Installation is difficult because the cabling must first be connected before the panel can be attached to the sub-structure with screws. Because the holes are only made at the construction site, they can be drilled in exactly the right place. However, care must be taken not to drill into the solar cells. It is possible to carry out maintenance, but it is necessary to remove the entire panel from the facade. Swapping panels is easy and it is possible to reuse the panels. The ''damage'' of the holes will, however, be visible.

3. Ends milled locally (even)
With this design, a hole is milled locally at the top and bottom of the panel. The ends are even. This makes the mounting system semi-invisible. Milling is a reasonably simple production method, with a small risk of errors. Mounting this design is done by first mounting the bottom, then connecting the cabling and then connecting the panel on top. Because the holes are already milled in the factory, the resilience of tolerance depends on the sub-structure. Furthermore, maintenance is easy by loosening the top of the panel and the panels can be exchanged in the same way. The panels can also be easily reused.

4. End milled locally (uneven)

For design 4, the same applies as for design 3, except for one criterion. In this design, the ends are uneven. Because of this, the mounting system will become invisible.

5. Undercut locally

This design has local undercuts on the back of the panel. This is done in the factory and has little risk of errors. The attachment is mechanical, so the structural safety can be checked. The design is suitable for fixation in different ways. The panel can be attached to the sub-structure either from the bottom or the top. The advantage of attaching the panel at the top is that the weight of the panel is already taken care of, which makes it easy to connect the cables on the bottom of the panel. Next, the panel is attached to the sub-structure with its underside. Because the holes are already milled in the factory, the resilience of tolerance depends on the sub-structure. Furthermore, maintenance is easy by loosening the top of bottom of the panel and the panels can be exchanged in the same way. The panels can also be easily reused.

6. Profile glued on panel

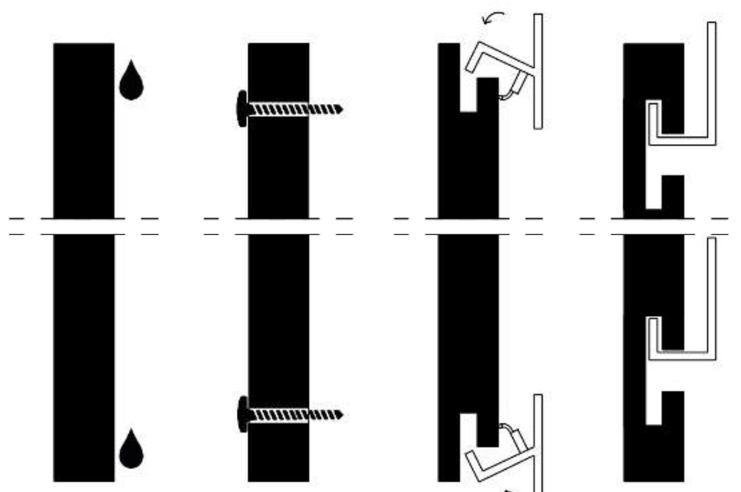
Design 6 has a profile glued to the back of the panel. The profile is applied in the factory and requires several actions. Although the gluing is done in the factory, it is not possible to guarantee structural safety because it cannot be checked when it is attached to the facade. Another disadvantage is that it consists of several parts. The assembly is carried out by first attaching the bottom to the sub-structure, then the cabling, and then the top. The slotted hole at the top provides the resilience of tolerance. By detaching the top side, maintenance can be carried out and the panels can be replaced if necessary. Reusing the panels is difficult due to the presence of the profile.

7. Plate hook

The last design solution has plate hooks on the back of the panel. These are attached to the panel using an undercut anchor. The production process involves several operations with little risk of error. The system consists of several parts and the cabling must be connected before the panel can be attached to the facade. The adjustment possibilities of the design solution are limited and are mainly in the sub-structure. When carrying out maintenance, the entire panel must be dismantled. Changing the panels is easy and the panels can be reused. However, the panel hooks would then have to be removed.

CONCEPT DEVELOPMENT

TOP & BOTTOM CONNECTION



1 2 3 4

		1	2	3	4
Visibility	O O O	O	O	O	O
Demountability	O O	O	O	O	O
Structural safety	O O O	O	O	O	O
Production method	O	3	3	1	3
Risk of errors	O	1	3	1	3
Easy to mount	OOO	1	3	2	2
Multi-step assembly	OOO	1	1	2	1
Resilience to tolerance	OOO	3	3	3	2
Physical ergonomics	OO	3	2	3	3
Maintenance	OO	1	1	3	2
Adaptability	O	1	3	3	3
Disassembly	OO	1	3	3	3
	Total:	30	42	44	40

1. Glued

The first option is to attach the panel to the sub-structure by means of glue. The disadvantage of this method is that it is impossible to check whether the glue has hardened correctly and is still strong enough after some time. The assembly is quite tricky as preparations have to be made. Both the plate and the sub-structure must be degreased. Furthermore, foam tape must be applied to temporarily support the panel until the adhesive is strong enough to support the panel. Since the panel is attached to the sub-structure from all sides at the same time, multi-step assembly is not possible. Furthermore, maintenance is not possible because the panel cannot be removed from the facade without damaging it.

2. Screwed

In this design, the panel is fixed to the facade by screws. The panels can be removed from the facade independently to carry out maintenance. However, all screws must be unscrewed in order to be able to work behind the panel. A screw machine is required to mount the panels to the facade. Multi-step assembly is not possible, and because of the screwdriver, the physical ergonomics are slightly less good.

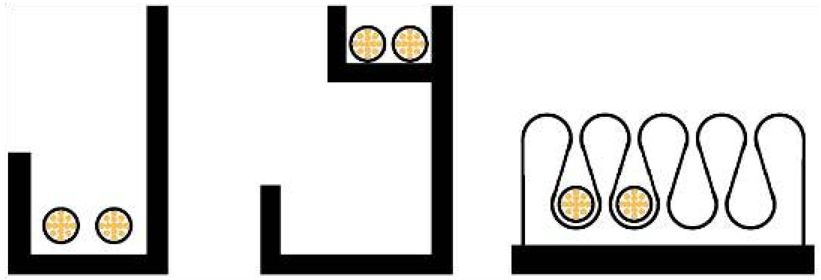
3. Compliant mechanism

The third option is to fix the panel with a compliant mechanism. A compliant mechanism consists of one component in which movements are possible. The production of this is very precise and there is a risk of errors. The assembly is reasonably simple by pressing the panel against the compliant mechanism. The mechanism then ‘clicks’ shut. No further tools are required to attach the panel and maintenance is simple. The compliant mechanism can also be ‘clicked’ open again.

4. Fixed profile

The last option is to mount the panel on a fixed profile. This is easy to produce and the risk of errors is low. Mounting the panel is fairly simple. First, the cabling must be connected before the panel is attached to the top and bottom simultaneously. This means that a multi-step assembly is not possible. Any deviations must be compensated for by means of the sub-structure. When carrying out maintenance, the panel must first be removed from the top and bottom.

CABLE MANAGEMENT



1 2 3

Visibility	O O O	O	O	O
Demountability	O O	O	O	O
Production method	O	3	3	3
Risk of errors	O	3	3	3
Easy to mount	OOO	2	3	3
Expandable	OOO	2	1	3
Maintenance	OO	3	3	3
Adaptability	O	2	1	3
Disassembly	OO	3	1	3
	Total:	32	27	39

1. Cable tray

The first option is to place a cable tray against the sub-structure. The cable tray can be easily extruded, and the risk of errors is low. The cable tray is installed by means of screws against the sub-structure. There is a possibility to add additional cable trays if required. The cable tray is open at the top, so any maintenance of the system can be done. It is possible to replace the cable tray. But because the cable tray is attached by screws and runs behind all the panels, all the panels will have to be detached to replace the cable tray. Reusing the cable tray is simple.

2. Cable tray integrated with sub-structure

With this option, the cable duct is integrated with the sub-structure. This ensures that the cable tray cannot be dismantled separately. It is also not possible to extend or replace the system. Re-use of only the cable tray is therefore not possible. Production is simple with little risk of errors. The cable tray is open at the top, so doing maintenance is not a problem.

3. Cable clamp

The last option is a cable clamp. It can be easily clicked onto the sub-structure at any position and is easily expandable due to the male-female connection. This is an existing system and therefore the production method is reliable and there is no risk of errors. Maintenance is possible and the clamping bracket can be dismantled separately.

4.5 CONCEPT PROPOSAL

The designs that achieved the highest score per aspect in the multi-criteria analysis together form the concept proposal.

Assembly

Figure 21: Top first (Own)

Sub-structure

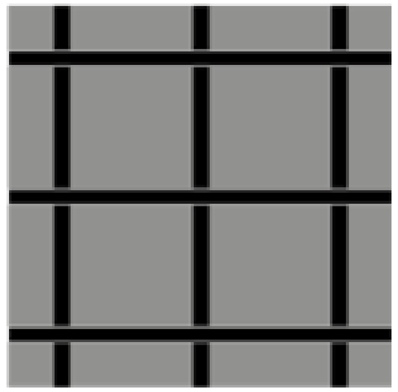


Figure 22: Vertical/horizontal (Own)

Panel

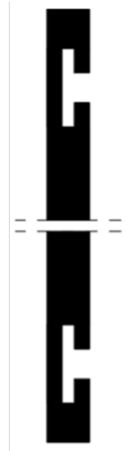


Figure 23: Undercut locally (Own)

Connection bottom/top

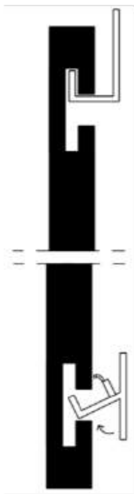


Figure 24: Fixed profile/compliant mechanism (Own)

Cable management

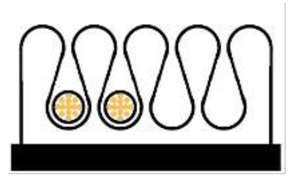


Figure 25: Cable clamp (Own)

5 PROTOTYPING

In the previous chapter, choices were made for each aspect in terms of design solutions on the basis of a multi-criteria analysis. In this chapter, these design solutions are translated into prototypes that together will form the facade system. To give a better idea of the facade system, first an overview is given of the final prototype.Then it focuses on how the system works and finally, the development of the prototypes are discussed and represented.

5.1 OVERVIEW FACADE SYSTEM

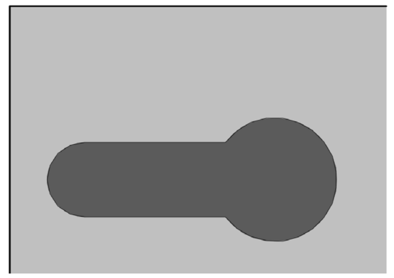


Figure 26: Undercut locally
(Own)

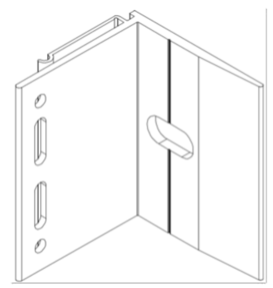


Figure 27: Wall bracket
(Hilti, 2021)

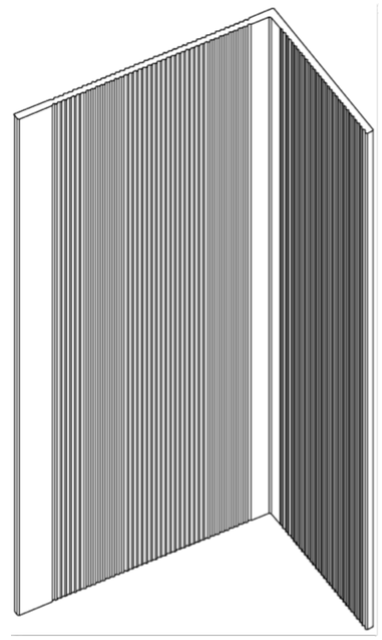


Figure 28: L-profile
(Hilti, 2021)

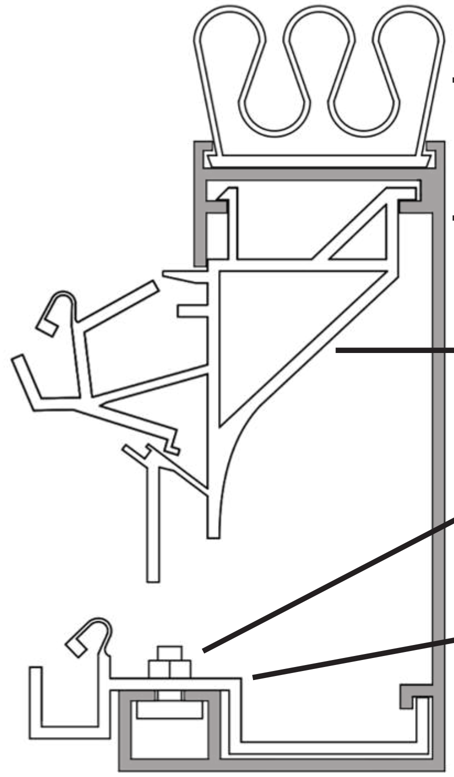


Figure 29: Cable clamp
(Own)

Figure 30: Horizontale profile
(Own)

Figure 31: Compliant mechanism
(Own)

Figure 32: Hammerhead bolt
(Own)

Figure 33: Hook
(Own)

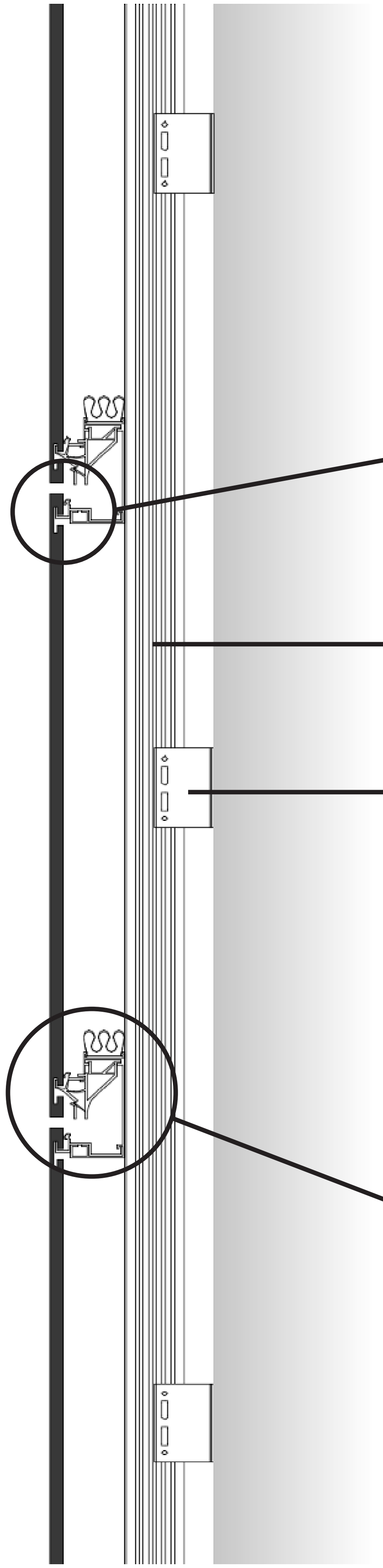
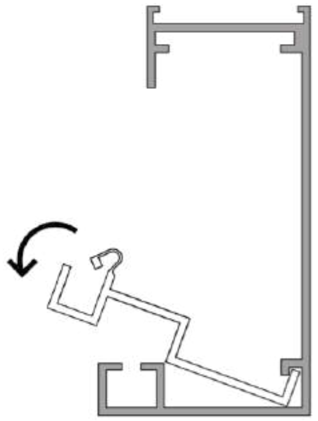


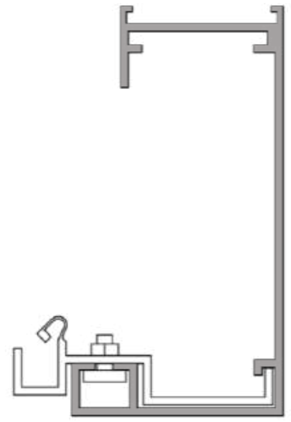
Figure 34: Overview facade system
(Own)

5.2 EXPLANATION OF THE SYSTEM

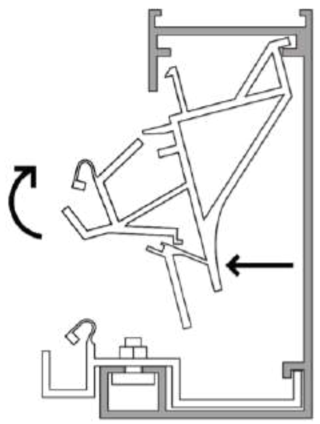
INSTALLATION OF PARTS IN HORIZONTAL PROFILE



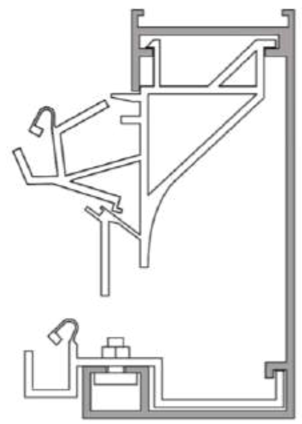
Step 1: Turn the hook into the horizontal profile.



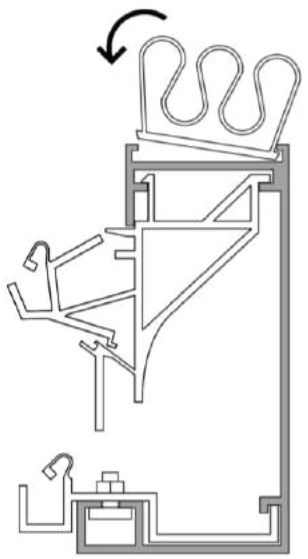
Step 2: Use a hammer head bolt to mount the hook to the horizontal profile.



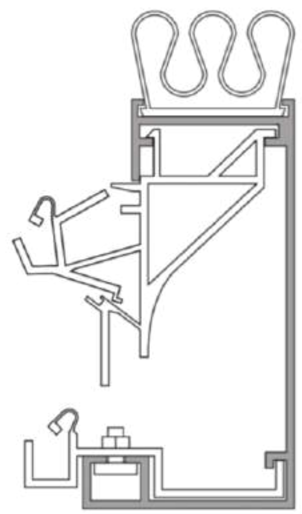
Step 3: Insert the compliant mechanism into the rear side of the horizontal profile and turn it into the front side of the horizontal profile.



Step 4: Result step 3

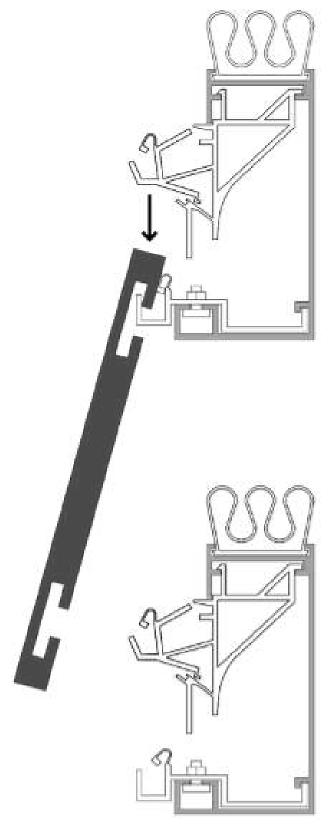


Step 5: Place the cable clamp with one side in the horizontal profile and turn it in the other side of the horizontal profile.

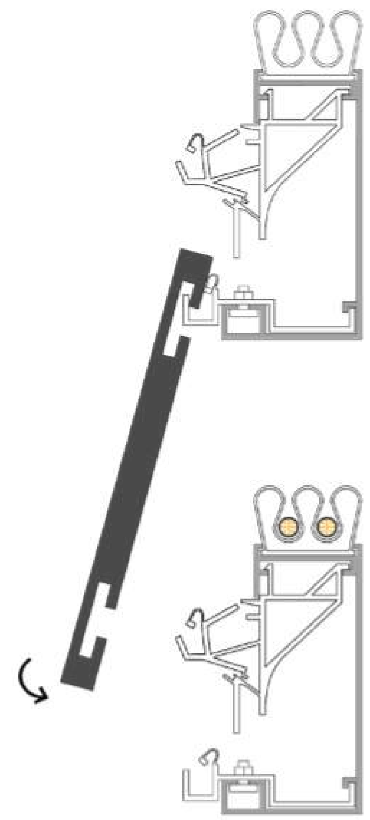


Final step: Result

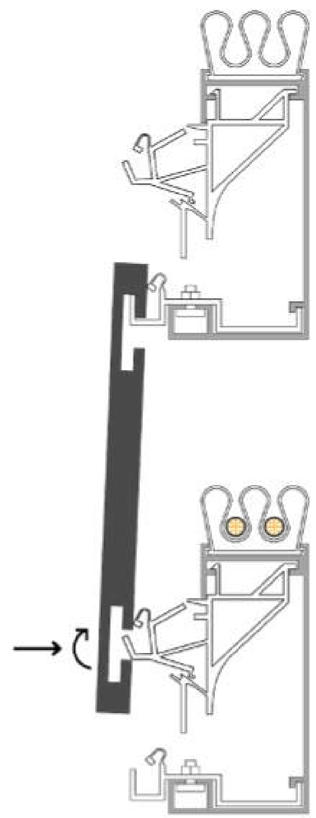
ASSEMBLY OF THE HPL BIPV PANEL



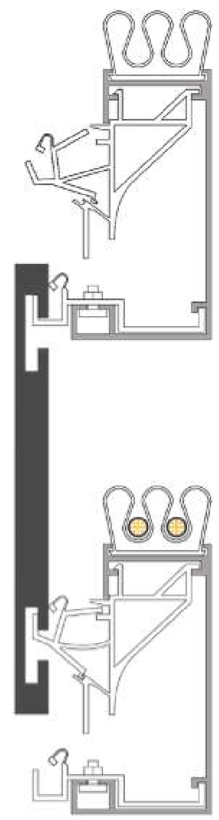
Step 1: Place the panel with the top on the hook.



Step 2: Connect the cables of the HPL BIPV panel and turn the panel towards the compliant mechanism.

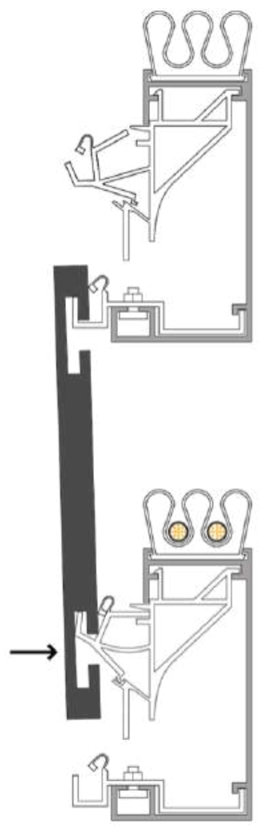


Step 3: Press the panel against the compliant mechanism. The compliant mechanism will rotate into the panel and lock system.

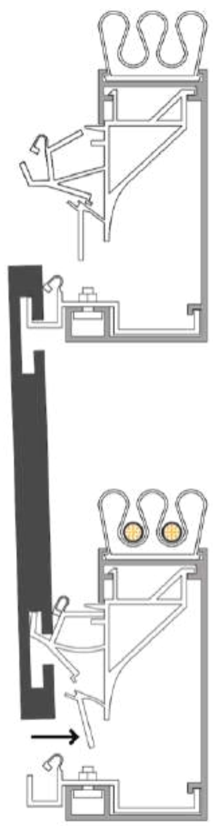


Final step: Result

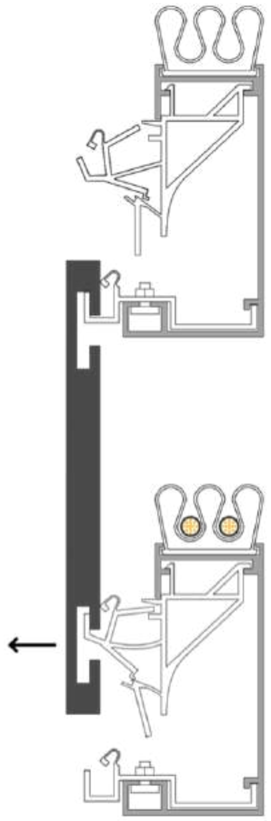
DISASSEMBLY OF THE HPL BIPV PANEL



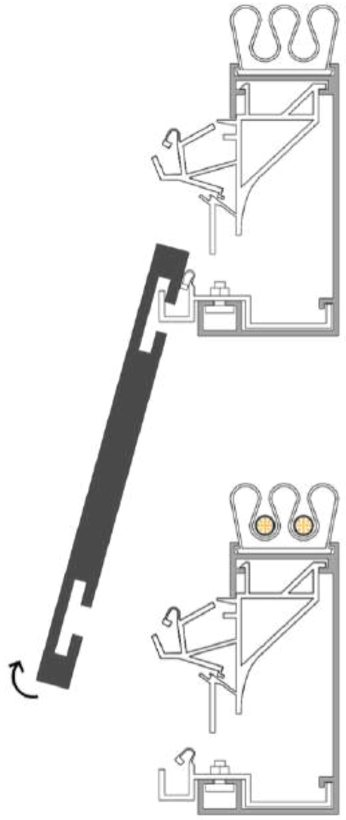
Step 1: Press against the panel. The compliant mechanism will continue to rotate and the lock system will open.



Step 2: Press against the arm of the lock system will open.



Step 3: Release the panel. The panel and compliant mechanism will return to its original position.



Step 4: Pull the panel out of the compliant mechanism and remove it from the hook.

5.3 SUB-STRUCTURE

From the multi-criteria analysis of the concept development, the sub-structure with horizontal and vertical profiles combined emerged as the best. Prototypes were made for both profiles. However, for the vertical profile, there are already solutions on the market that are fully optimized. These will therefore be used for the facade system. For the horizontal profile, a completely new profile has been developed that has been optimized for the facade system.

VERTICAL PROFILE

The vertical profile is the connection between the wall construction and the facade system. It consists of a wall bracket and an L-profile.

PROTOTYPE 1

Prototype 1 is based on the existing system that was also chosen as the final prototype. The idea of this prototype is that by inserting slotted holes, a measuring principle is created and there are many adjustment possibilities. This is important because there are no adjusting possibilities in the compliant mechanism. However, the operation of this prototype is highly dependent on the straightness of the wall construction and the precision of the placement. If the slotted holes are not in the right location, the entire system has to be dismantled and reinstalled.

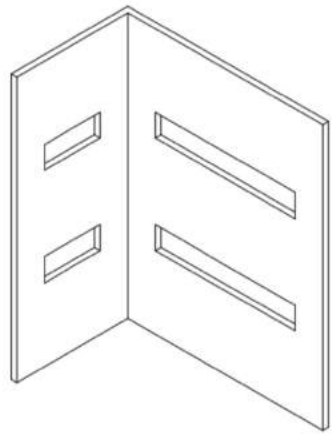


Figure 35: Wall bracket (Own)

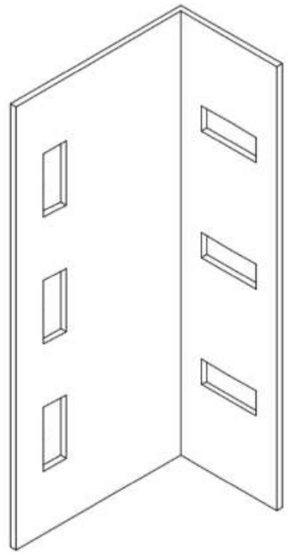


Figure 36: L-profile (Own)

FINAL PROTOTYPE

The final prototype is an existing system from the manufacturer Hilti. They have a wide range of wall brackets and L-profiles. Figure 37 and Figure 38 are examples of this. The reason for choosing an existing system over the self-developed prototype is because the self-developed prototype had too many limitations. The system from Hilti is fully optimized and has already proven that it works.

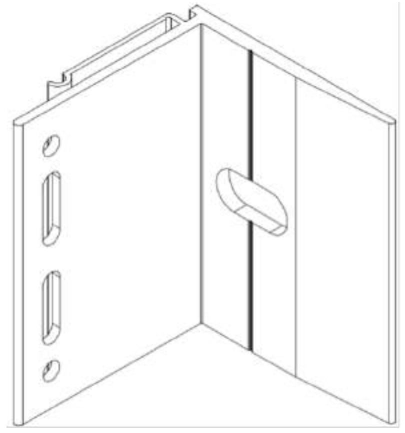


Figure 37: Hilti MFT-MF 060 M 11 (Hilti, 2021)

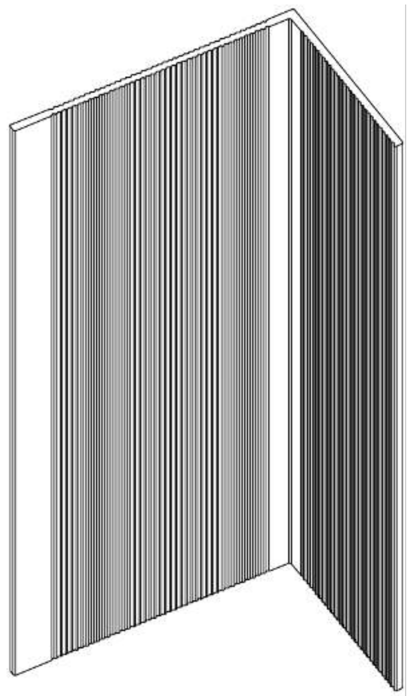


Figure 38: Hilti MFT-L 60x40x2 (Hilti, 2021)

HORIZONTAL PROFILE

The basic shape of the horizontal profile is a C-profile and is mounted against the vertical L-profile. It is designed so that the compliant mechanism, the hook and the cable management can be attached to it. This was tested by 3D printing the various prototypes.

PROTOTYPE 1

On the top of the prototype there are two slots where the cable management can be clicked in. There is also a notch on the top and a moving part where the compliant mechanism is clicked into the C-profile. The standard shape of a C-profile is applied to the bottom. An extra gripping point has been added to prevent the hook from rotating.

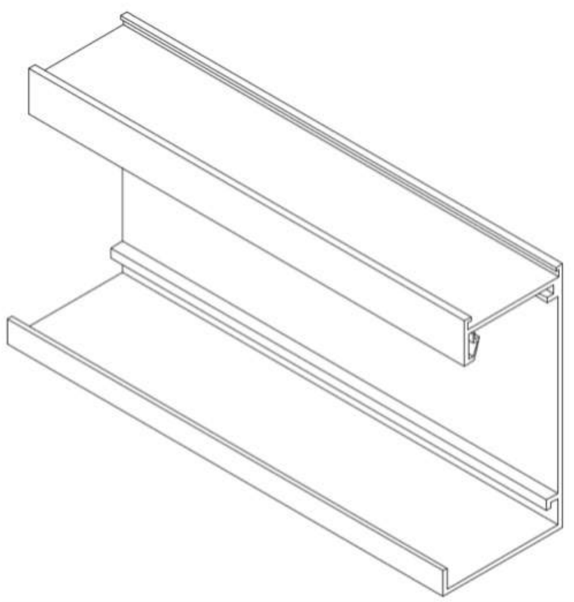


Figure 39: Prototype 1 isometrics (Own)

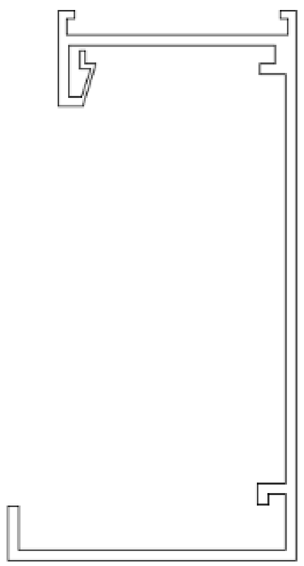


Figure 40: Prototype 1 cross section (Own)

PROTOTYPE 2

Prototype 2 is basically the same as prototype 1. However, at the bottom a moving part has been added so the hook can be clicked in so that it cannot be detached. In this prototype is tried to create a measuring principle and adjustment possibilities with slotted holes and recesses, just like prototype 1 of the vertical profile. However, the same problems arise here. If the parts does not fit, the entire system must be dismantled and reinstalled.

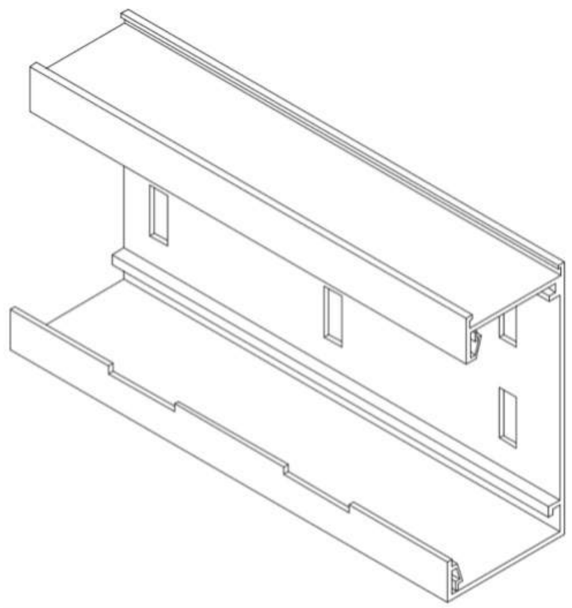


Figure 41: Prototype 2 isometrics (Own)

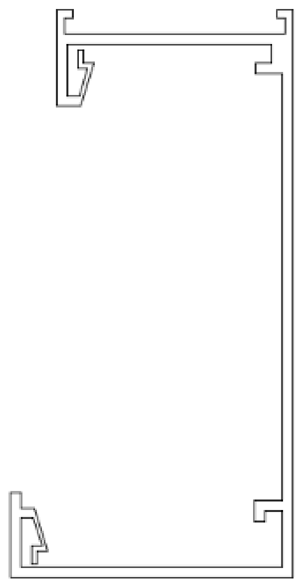


Figure 42: Prototype 2 cross section (Own)

FINAL PROTOTYPE

In the final prototype, the measuring principle has been removed due to its disadvantages. The moving parts have been replaced by static parts. This was done to make the horizontal profile as clean as possible. To attach the hook at the bottom of the profile, a nut track was added. The hook is attached to the horizontal profile with a hammerhead bolt.

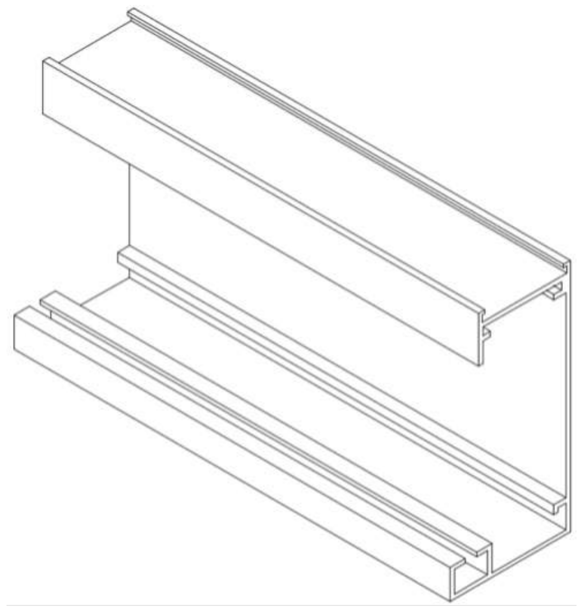


Figure 43: Final prototype isometrics (Own)

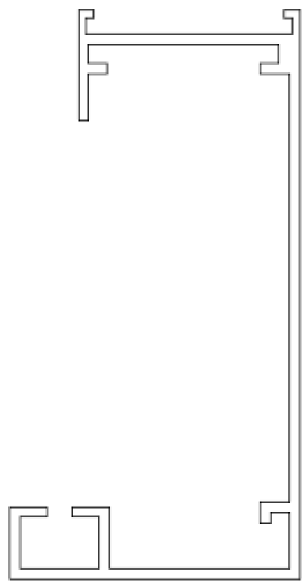


Figure 44: Final prototype cross section (Own)

5.4 COMPLIANT MECHANISM

For the compliant mechanism, prototypes were made for two different concepts and tested for the movement of the compliant mechanism. This was done by printing the prototypes with a 3D printer. The first concept is based on a compliant mechanism that is under tension in the end position. The second concept is based on a compliant mechanism that is relaxed in the end position.

For the development of the concepts, many prototypes were made. Some prototypes had a development in the design of the compliant mechanism. While in some prototypes, only minor adjustments were made in terms of dimensions. Therefore, only the most important prototypes are shown below with the biggest steps in the development where the design was changed.

CONCEPT 1: TENSED POSITION

In this concept, the compliant mechanism is in the relax position at the starting position. By pushing the panel against the compliant mechanism, a movement takes place in the compliant mechanism and the compliant mechanism 'clicks' into its end position. The compliant mechanism is under tension in its end position.

PROTOTYPE 1.1

The first prototype is based on the compliant mechanism developed during the Bucky Lab. The design of the Bucky Lab can be found in Appendix V. What has changed in this prototype is that the design is reversed. This is because in the Bucky Lab design, the connection of the HPL panel with the compliant mechanism was at the top. While the connection for the BIPV HPL panel with the compliant mechanism is at the bottom. Furthermore, 2 fixed connection points were used for the connection with the horizontal profile.

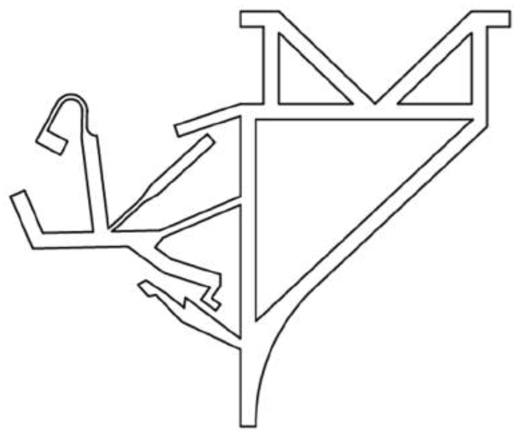


Figure 45: Prototype 1.1 starting position (Own)

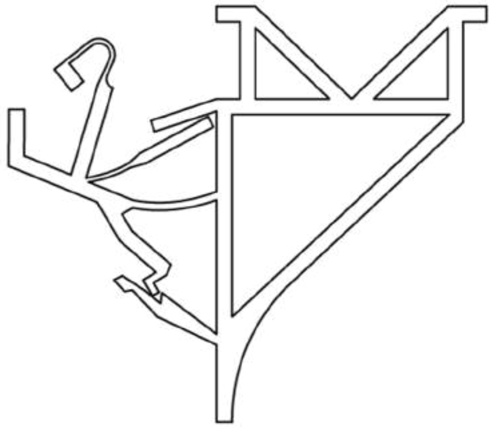


Figure 46: Prototype 1.1 end position
(Own)

PROTOTYPE 1.2

In this prototype, the end stop that ensures that the compliant mechanism cannot deform too much has been moved to the top of the pressure point that ensures that the compliant mechanism can rotate. This ensures that the forces of the wind load are passed on to the underlying structure in a more efficient manner. Also, the bending part has been extended so that the compliant mechanism can rotate more easily.

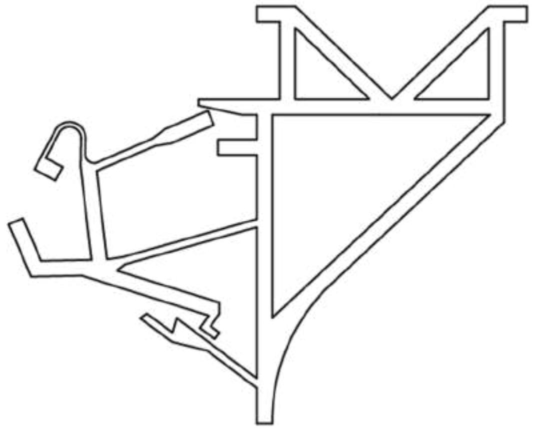


Figure 47: Prototype 1.2 starting position
(Own)

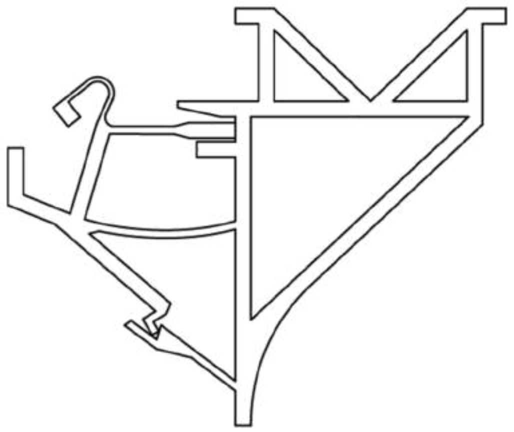


Figure 48: Prototype 1.2 end position
(Own)

PROTOTYPE 1.3

In prototype 1.3, the arm of the lock system has been added so that the panel can be removed from the compliant mechanism. This can be done by pushing the panel through and then pressing the hook at the bottom. The unlock system is designed in such a way that it is not easy for thieves to remove the panel from the facade. It should always be done by two people.

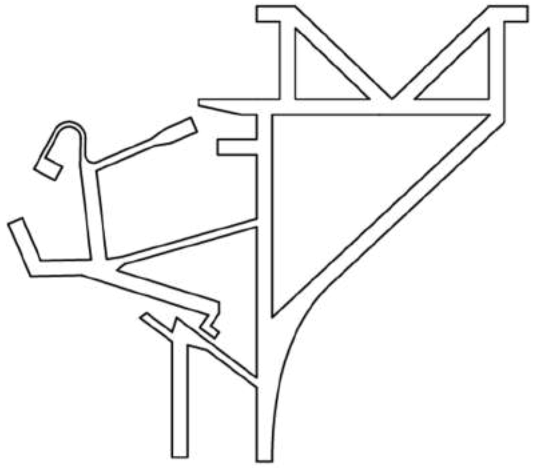


Figure 49: Prototype 1.3 start position
(Own)

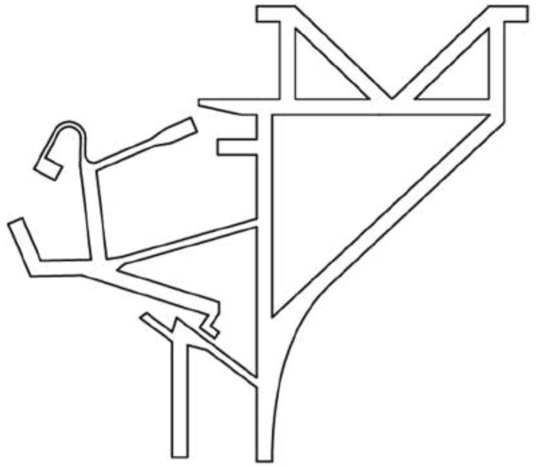


Figure 50: Prototype 1.3 end position
(Own)

PROTOTYPE 1.4

In prototype 1.4, the end stop that prevents the compliant mechanism from rotating too far has been thickened to make it stronger.

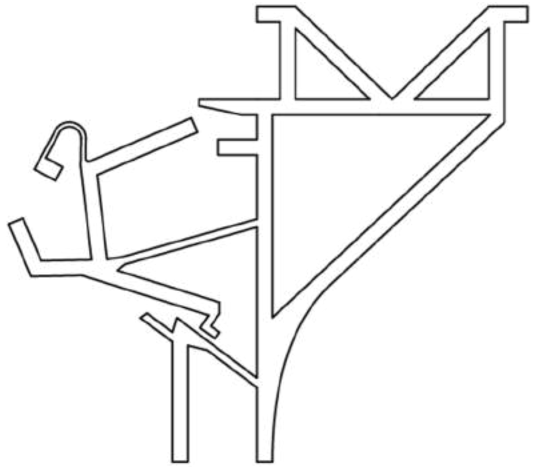


Figure 51: Prototype 1.4 start position
(Own)

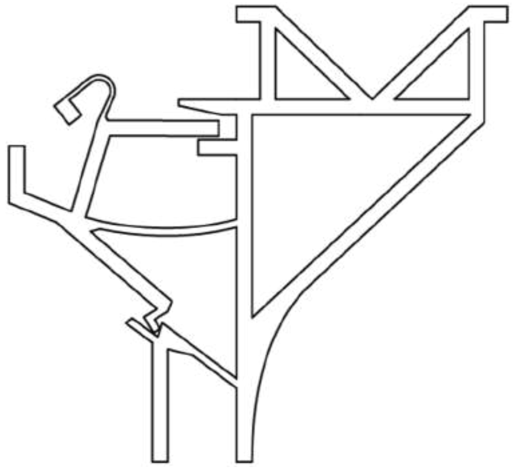


Figure 52: Prototype 1.4 end position
(Own)

PROTOTYPE 1.5

In the last prototype of concept 1, a cantilever snap-fit has been added so the compliant mechanism can be clicked into the horizontal profile. The bending part is thickened, the arm of the lock system has been made longer, and the hook has been made longer too. The lock system has also been restyled.

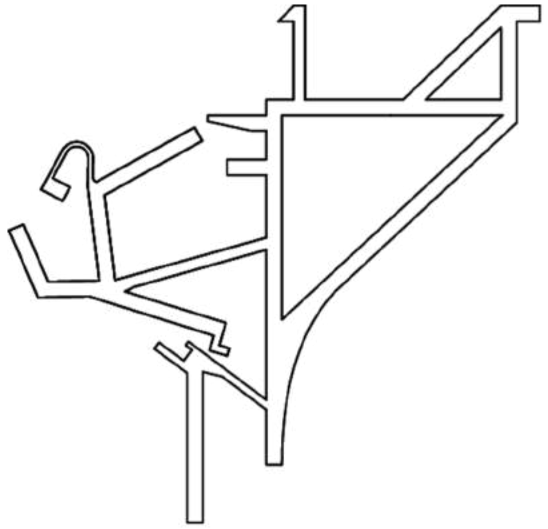


Figure 53: Prototype 1.5 start position
(Own)

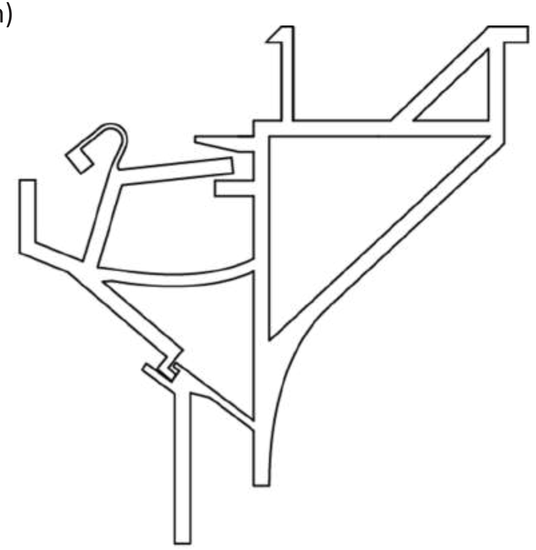


Figure 54: Prototype 1.5 end position
(Own)

CONCEPT 2: RELAXED POSITION

In concept 2, the compliant mechanism is under tension in the starting position. By pushing the panel against the compliant mechanism, a movement takes place in the compliant mechanism and the compliant mechanism 'clicks' into its end position. The compliant mechanism is relaxed in its end position.

PROTOTYPE 2.1

The design of this prototype is based on prototype 1.1. The prototype is produced in the end position. By rotating the compliant mechanism, the prototype will be locked in the starting position. Then, by pushing the panel against the pressure point, the compliant mechanism will be released and go back to the end position.

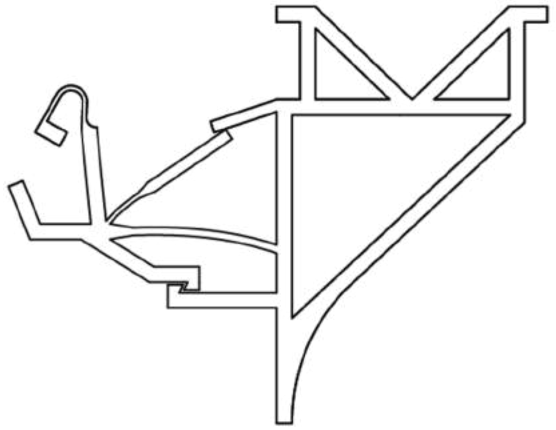


Figure 55: Prototype 2.1 starting position (Own)

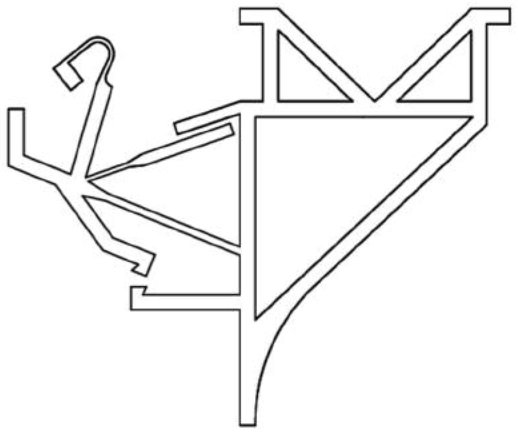


Figure 56: Prototype 2.1 end position (Own)

PROTOTYPE 2.2

In this prototype, the end stop that prevents the compliant mechanism from rotating too far is moved to the pressure point so that the horizontal forces can be transferred more efficiently.

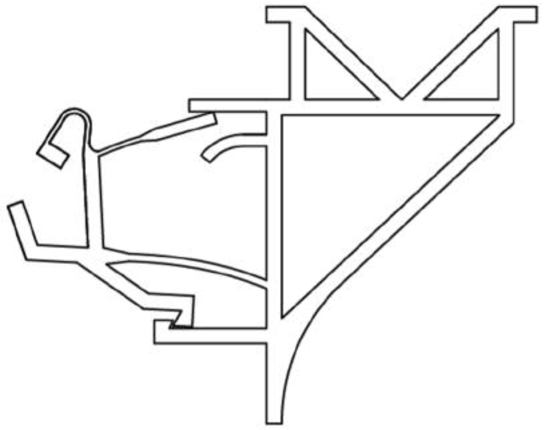


Figure 57: Prototype 2.2 start position (Own)

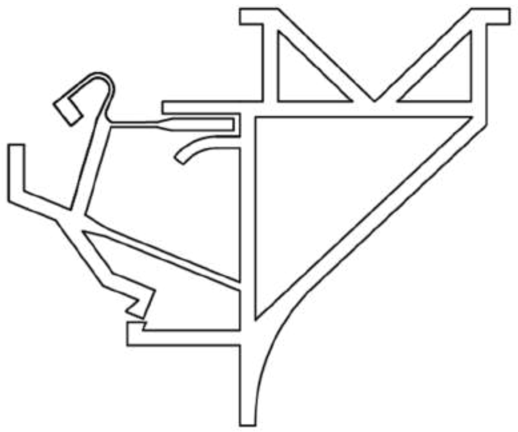


Figure 58: Prototype 2.2 end position (Own)

PROTOTYPE 2.3

In prototype 2.3, the bending part has been moved upwards so that the panel in the end position is less likely to slip out of the hook.

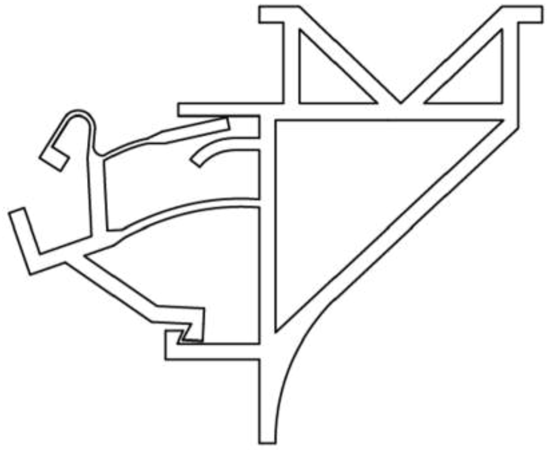


Figure 59: Prototype 2.3 start position (Own)

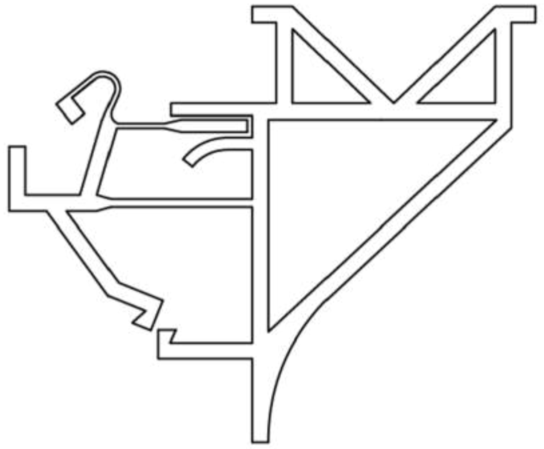


Figure 60: Prototype 2.3 end position (Own)

PROTOTYPE 2.4

Practical tests showed that the panel still slip out in prototype 2.3. By placing the bending part a little further up, an attempt was made to prevent this from happening.

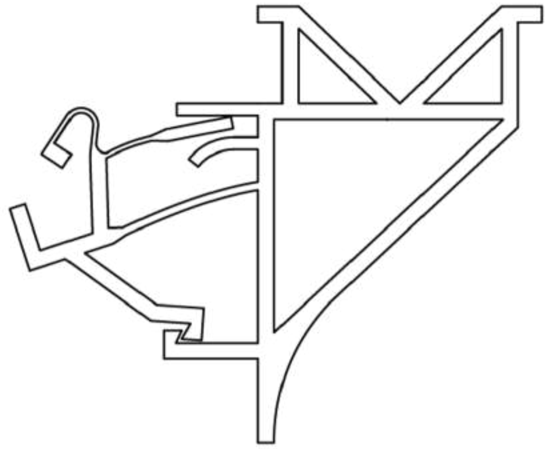


Figure 61: Prototype 2.4 start position (Own)

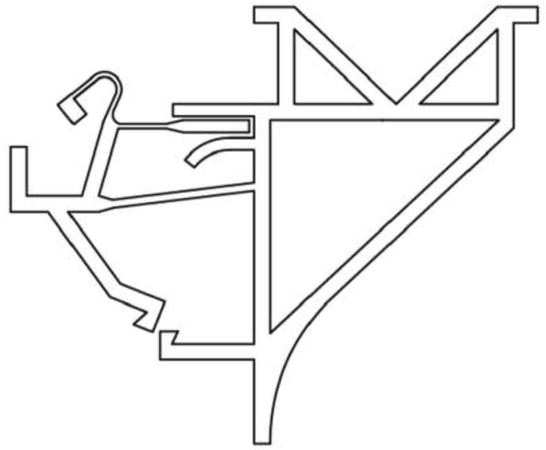


Figure 62: Prototype 2.4 end position (Own)

PROTOTYPE 2.5

In this prototype, the part that ensures that the compliant mechanism is locked in the starting position has been moved to the top of the prototype. The old part that provides the lock is used in this prototype to better resist tensile forces. However, practical tests show that the prototype does not work properly, and the panel can still click out of the hook.

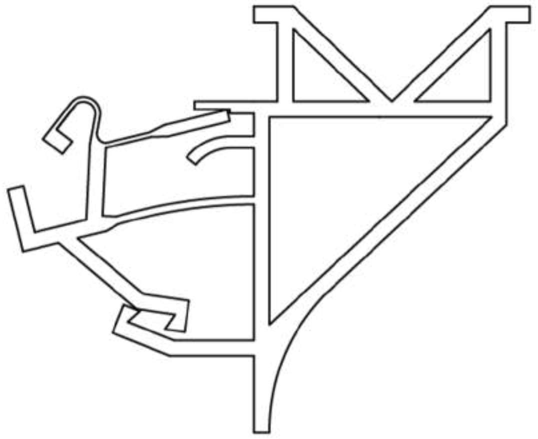


Figure 63: Prototype 2.5 starting position (Own)

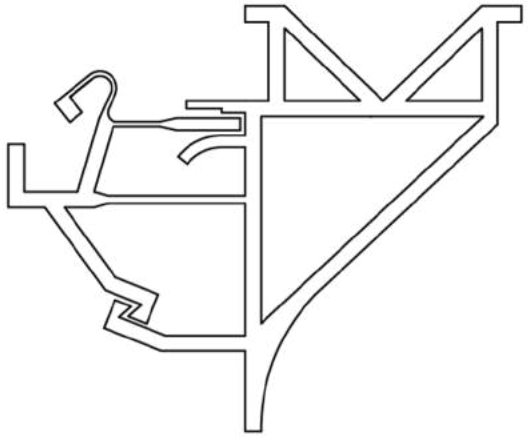


Figure 64: Prototype 2.5 end position (Own)

FINAL PROTOTYPE

After both concepts have been extensively tested with 3D printed prototypes, prototype 1.5 of concept 1 comes out on top. The reason that concept 1 works better than concept 2 is mainly due to the fact that the compliant mechanism in concept 1 is locked in the end position. Because of this the panel cannot slip out of the compliant mechanism without any action. Whereas in concept 2, the compliant mechanism is not locked and can therefore be loosened more quickly under, for example, wind load.

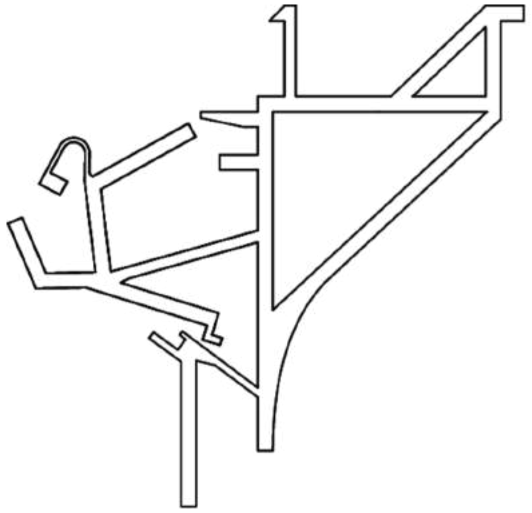


Figure 65: Final prototype start position (Own)

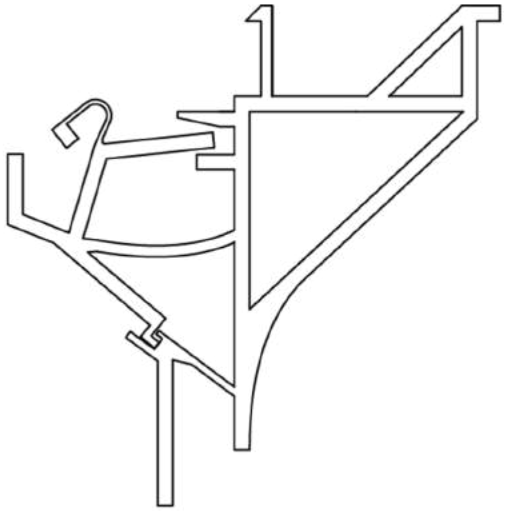


Figure 66: Final prototype end position (Own)

5.5 HOOK

The hook is mounted in the horizontal profile and then the HPL panel can be hung on the hook from the top.

PROTOTYPE 1

The hook has a pressure point just like the compliant mechanism. This ensures that the panel cannot simply shift. The hook is first inserted at the rear into the horizontal profile and then rotated over the lip of the horizontal profile.

Figure 67: Prototype 1 hook (Own)

PROTOTYPE 2

The hook is modified on prototype 2 of the horizontal profile. This allows the hook to be clicked onto the horizontal profile.

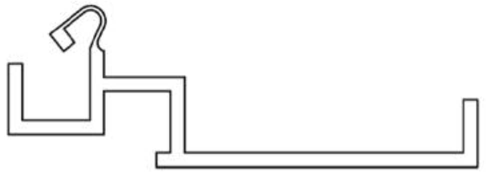


Figure 68: Prototype 2 hook (Own)

FINAL PROTOTYPE

The final prototype of the hook is also adapted to the final prototype of the horizontal profile. By using a hammerhead bolt, the hook is mounted in the nut track of the horizontal profile.

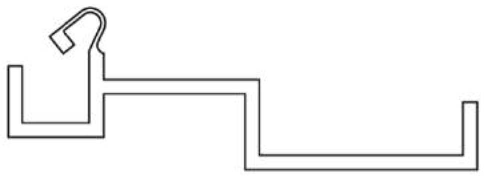


Figure 69: Final prototype hook (Own)

5.6 CABLE MANAGEMENT

For cable management, a cable clamp has been designed that can be mounted on the horizontal profile.

PROTOTYPE 1

In this prototype, space has been made for 4 cables with a maximum diameter of 5 millimeters.

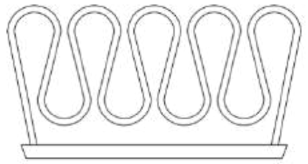


Figure 70: Prototype 1 cable management (Own)

FINAL PROTOTYPE

Since only two cables with a maximum diameter of 9 millimeters are required for a BIPV system, the cable clamp has been adapted to this.

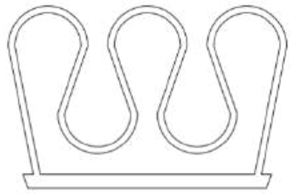


Figure 71: Final prototype cable management (Own)

5.7 PANEL

The panel treatment that scored the highest in the concept development was the undercut locally. The undercut is always modified according to the dimensions of the compliant mechanism and the hook. The principle remained the same, so only one prototype was made.

FINAL PROTOTYPE

The undercut is made using a milling machine. It makes a hole to reach the right depth in the panel and then mills a slot in it.

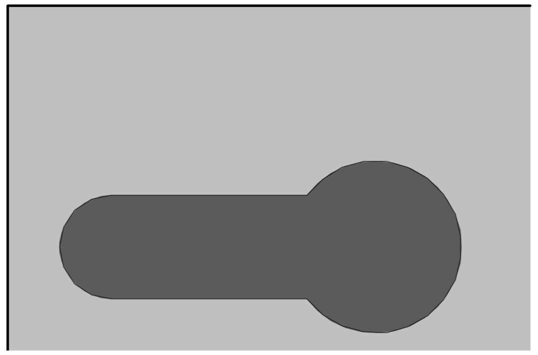


Figure 72: Final prototype panel (Own)

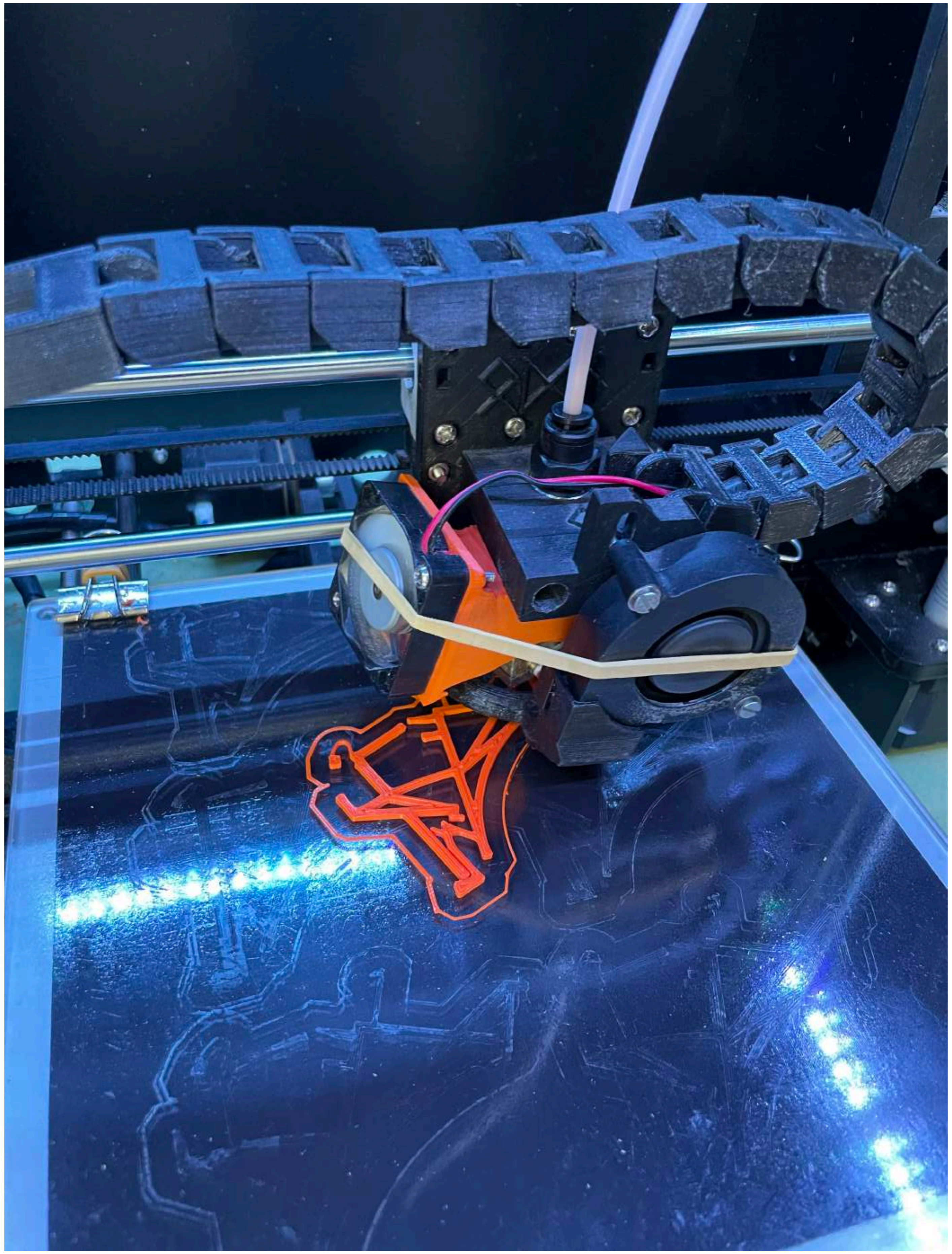


Figure 73: 3D printer

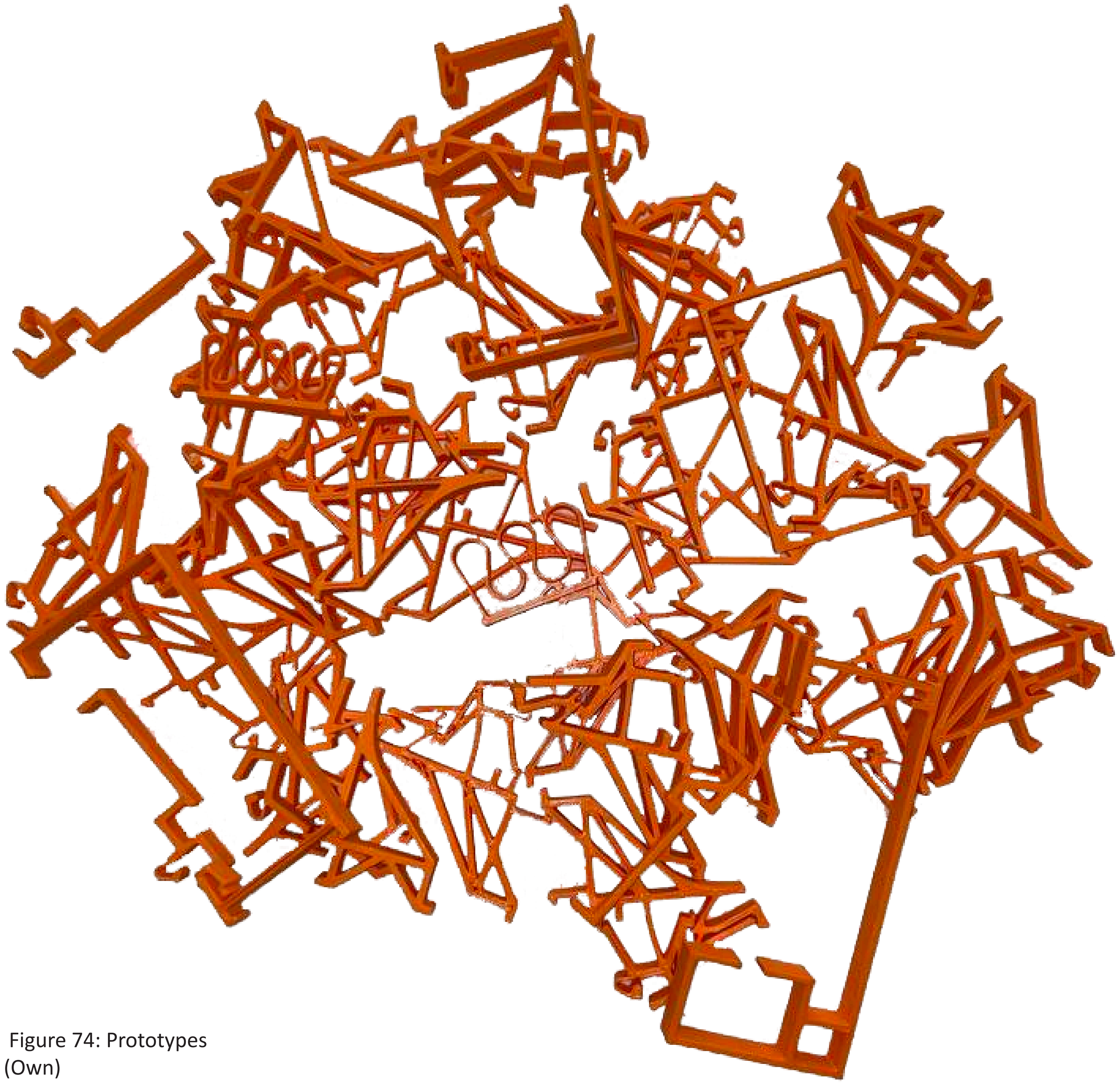


Figure 74: Prototypes (Own)

6 MATERIAL ANALYSIS

The material PLA is used to make the prototypes of the facade system, because it is extremely suitable for 3D printing. However, this material does not meet all the established properties rquired for a facade system. Therefore, with the help of the computer program CES EduPack 2019, a material analysis has been made in which a material has been determined that meets the established properties.

The material analysis applies to the compliant mechanism, the hook and the cable clamp. For the horizontal profile, a material that is always used for this type of sub-structures, aluminium, is used. Further research can be done to find out which alloy of aluminium suits best.

Since the prototypes were made with PLA plastic and this material has proven to work, it is important that the mechanical properties of the material are similar to those of PLA. For this reason is searched for a material in the material family ‘plastics’. Other material families, such as metals, will not be suitable because of the high rigidity of the materials in this material family.

In terms of durability, there are various requirements. The material must be able to resist both fresh and salt water. The material must also be resistant to UV radiation. Furthermore, it is important that the material is suitable for the high temperatures that can occur in the cavity and that the material meets the fire regulations.

The properties:
- Material family: Plastics;
- Water (fresh): Acceptable or excellent;
- Water (Salt): Acceptable or excellent;
- Flammability: Self-extinguishing or non-flammable;
- UV radiation: good or excellent;
- Maximum service temperature at least 80 °C.

The material must comply with the above-mentioned properties in all cases. Materials that do not meet these requirements have been excluded from the analysis. In addition to the various mechanical properties, properties such as embodied energy, recyclability and price per kg were also included in the analysis. Furthermore, it is important that the material is suitable for the production method polymer injection molding or polymer extrusion, so the various parts of the system can actually be produced.

The matrix on the next page shows all the materials that meet the specified properties. The data from PLA have also been added so that the materials that resulted from the analysis can be compared with the mechanical properties of PLA.

The analysis revealed three materials whose mechanical properties are more or less in line with PLA. These materials are PC+PBT, PEI and PPSU. All three materials meet the specified properties and are recyclable. However, the embodied energy and also the price per kg of both PEI and PPSU are considerably higher than PC+PBT. Also, in terms of production method, PC+PBT scores better than the other two. This is why PC+PBT is determined as the material for the compliant mechanism and the cable clamp. PEI was determined for the hook, because the structural analysis showed that the properties of PC+PBT were not sufficient.

Figure 75: PC+PBT
(AZ Reptec, 2021)

Figure 76: PEI
(Eriks, 2021)

Although this analysis has been done with due care and the materials meet the requirements on paper, the actual production of facade systems requires cooperation with the industry. They can further help to determine the right production method and material.

MATERIAL ANALYSIS

Material	Production method		Maximum service temperature (°C)	Young's modulus (N/mm2)	Specific stiffness (MN.m/kg)	Compressive strength (N/mm2)	Tensile strength (N/mm2)	Embodied energy (MJ/kg)	Recycle	Price (€/kg)
	Polymer injection molding	Polymer extrusion								
PLA (High impact)	Acceptable	Acceptable	45 - 60	2300 - 2600	1,96 - 2,27	45,6 - 81,6	29 - 52	64,1 - 70,6	Yes	2,89 - 3,55
LCP (Unfilled)	Excellent	Limited use	157 - 227	15000 - 15400	10,6 -10,9	85 - 95	120 - 127	209 - 231	Yes	9,93 - 11,1
PCT (15% glass fiber)	Excellent	Unsuitable	250 - 270	5450 - 5720	4,09 - 4,31	86,4 -95,2	90 - 99,2	116 - 128	No	8,65 - 9,08
PC+PBT (Flame retarded)	Excellent	Acceptable	120	2150 - 2600	1,68 - 2,04	60 - 75,6	42 - 59	110-121	Yes	4,08 - 4,62
PEI (Unfilled)	Acceptable	Acceptable	161 - 179	2890 - 3040	2,27 - 2,4	144 - 159	91,9 - 101	197 - 217	yes	15,1
PEKK (Unfilled, amorphous)	Acceptable	Limited use	233 - 287	3360 - 3530	2,62 - 2,77	97,8 - 108	85,1 - 94,1	302 - 333	Yes	74,5 - 83,1
PF (Glass and/or mineral filled, heat resistant, molding)	Acceptable	Unsuitable	196 - 215	16100 - 17000	8,97 - 11,5	155 - 248	41,4 - 69	54,3 - 59,9	No	1,59 - 1,74
PFA (Unfilled)	Acceptable	Limited use	250 - 271	471 - 495	0,219 - 0,231	23 - 25,3	27,6 - 29,6	244 - 269	Yes	18,8 - 25,7
PPSU (Unfilled)	Acceptable	Limited use	168 - 186	2290 - 2400	1,77 - 1,85	63,6 - 70,2	66,3 - 73,1	222 - 245	Yes	17,1 - 34,3
PTT (30% glass fiber, flame retarded)	Acceptable	Limited use	166 - 170	11700 - 12100	6,97 - 7,51	124 - 149	103 - 124	68,1 - 75	No	3,05 - 4,5
PVDF (Copolymer, wire and cable jacketing)	Acceptable	Acceptable	120 - 150	2000 - 2500	1,13 - 1,41	55,2 - 110	24,1 - 50	98,7 - 109	Yes	9,42 - 13,7
PARA (50% glass fiber, flame retarded)	Limited use	Acceptable	187 - 199	17000 - 21200	9,6 - 12	230 - 254	182 - 222	80,9 - 89,2	No	4,82 - 5,35
PEEK (Unfilled)	Limited use	Acceptable	239 - 260	3760 - 3950	2,87 - 3,95	118 - 130	70,3 - 103	286 - 315	Yes	84,9

Table 6: Material analysis
(Own)

7 STRUCTURAL ANALYSIS

In this chapter the prototypes of the compliant mechanism and the hook are structurally optimized so that they will be able to withstand the wind- and permanent loads. This has been done by means of a structural analysis in DIANA FEA and a practical test has been done for the compliant mechanism.

7.1 HAND CALCULATIONS

For the hand calculation, the data set out in the program of requirements was used. These requirements are the following. The height of the building may not exceed 20 meters and is located on the coast in wind area I. The wind load in that case is 1,8 kN/m^2. The consequence class is CC2 and the panel has a thickness of 13 millimeters and a dimension of 1270 by 630 millimeters.

The panel, measuring 1270 by 630 millimeters, has 3 hooks at the top and 3 compliant mechanisms at the bottom. Redundancy is included to ensure that if one of the connections fails, the panel does not fall off the facade. This means that the horizontal wind load on the panel will be divided by 5 connections instead of 6. The vertical loads will be divided by 2 instead of 3.

The compliant mechanism will only have variable loads in the form of wind loads. These are only horizontal. In addition to the variable wind load, the hook will be loaded with the permanent load of the panel. This will be in the vertical direction.

Data					
	Wind load:	1,8	kN/m2		
	Safety factor permament actions:	1,2			
	Safety factor variable actions:	1,5			
	Size panel:	1,27	x	0,63	m
	Thickness panell:	13	mm		
	Weight m2:	18,2	kg/m2		
	Area panel:	0,80	m2		
Horizontal forces					
	Permanent load:	0	N		
	Variable load:	2160,3	N		
	Total:	2160,3	N		
	Per connection (amount of connections (6) - 1):	432,1	N		
Vertical forces					
	Permanent load:	174,7	N		
	Variable load:	0	N		
	Total:	174,7	N		
	Per connection (amount of connections (3) - 1):	87,4	N		

Table 7: Hand calculation connections (Own)

7.2 FINITE ELEMENT ANALYSIS

In order to structurally optimize the compliant mechanism and the hook, a finite element analysis has been made in the program DIANA FEA. In this analysis the compliant mechanism and the hook are tested on both pressure and tensile forces. Several iterations of both parts were made and further optimized to obtain the strongest possible design.

COMPLIANT MECHANISM

The designs are in 2D and were created in the program Rhinoceros and exported as STEP-file. These files were imported into DIANA. A material is assigned to the imported geometry. In this case the material PLA, as this was also used in the development of the prototypes. This material is a linear elastic isotropic composite and has a Young's modulus of 2300 N/mm^2, a Poisson's ratio of 0.4 and a density of 1224 kg/m^3. Next, the loads and supports are linked to the geometry. The loads are taken from the manual calculation. Also, a depth must be given to the geometry. For this analysis, the depths of 15, 30 and 50 millimeters were used. Then the geometry is converted to meshes with a mesh size of 0,5 millimeters. Next, a structural linear static analysis is made, resulting in the displacement, normal stresses and shear stresses. For the normal stresses and shear stresses, the maximum compressive and tensile strength of PLA has been taken into account in the colour scale.

The results of the analyses in which the geometry has a depth of 30 millimeters were ultimately leading. This was determined because this depth is an excellent compromise between depth and strength. Appendix VI shows the other results of the analyses.

ANALYSIS 1: PROTOTYPE 1.4

The first analysis made of the compliant mechanism is prototype 1.4 from the prototyping chapter. What is notable from the results is that the maximum displacement in the case of the tensile test is enormous. The displacement in the compression test is relatively small and already meets expectations. Also, in the geometry there are too high tensile stresses present, which the material cannot withstand. This can be seen in figure 78.

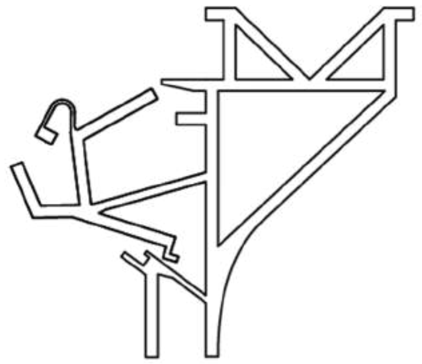


Figure 77: Geometry prototype 1.4 (Own)

Tensile

Thickness	Maximum displacement
15 mm	48,07 mm
30 mm	24,03 mm
50 mm	14,42 mm

Compression

Thickness	Maximum displacement
15 mm	2,07 mm
30 mm	1,04 mm
50 mm	0,62 mm

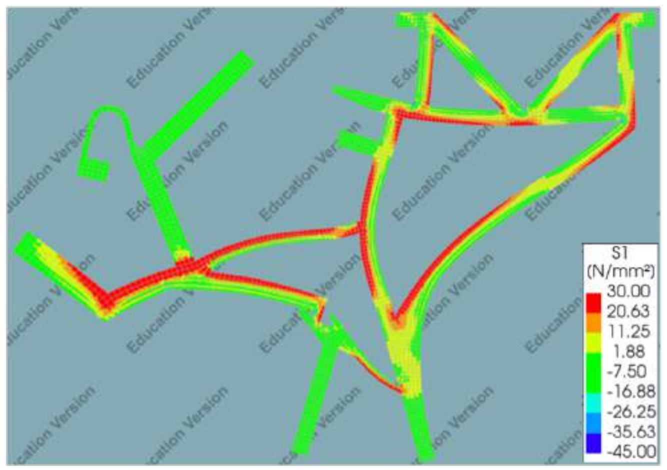


Figure 78: Stresses tensile test prototype 1.4 30mm (Own)

ANALYSIS 2: ITERATION 1

In the first iteration, a strut was placed in the fixed part of the geometry. This creates an extra triangle that provides more stiffness in the geometry. This is also reflected in the maximum displacement. This was reduced by almost 40% in the tensile test. Also, the tensile stresses in the fixed part are now within the norms. However, the tensile stresses in the hook and the bending part are still too high.

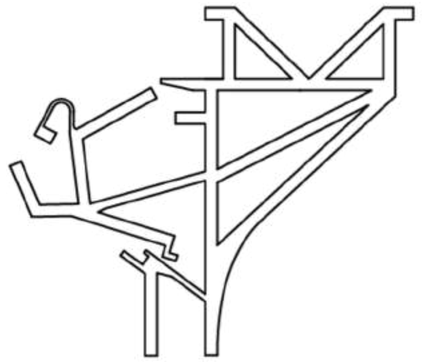


Figure 79: Geometry iteration 1 (Own)

Tensile

Thickness	Maximum displacement
15 mm	28,66 mm
30 mm	14,33 mm
50 mm	8,6 mm

Compression

Thickness	Maximum displacement
15 mm	1,75 mm
30 mm	0,87 mm
50 mm	0,52 mm

Figure 80: Stresses tensile test iteration 1 30mm (Own)

ANALYSIS 3: ITERATION 2

In the second iteration, reinforcement was added to the hook. This reduces the maximum displacement by 25% in the tensile test compared to iteration 1. However, the tensile stresses at the hook and bending part are still too high.

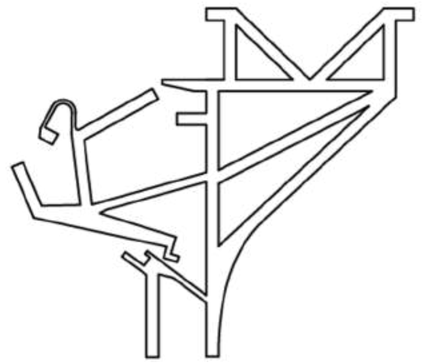


Figure 81: Geometry iteration 2 (Own)

Tensile

Thickness	Maximum displacement
15 mm	21,22 mm
30 mm	10,61 mm
50 mm	6,36 mm

Compression

Thickness	Maximum displacement
15 mm	1,9 mm
30 mm	0,95 mm
50 mm	0,57 mm

Figure 82: Stresses tensile test iteration 2 30mm (Own)

ANALYSIS 4: ITERATION 3

In iteration 3, the new mounting system from the final prototype was integrated into the design. An extra strut has been added for more rigidity. In terms of displacement, there is only a small difference with iteration 2. Also, the tensile stresses are more or less the same.

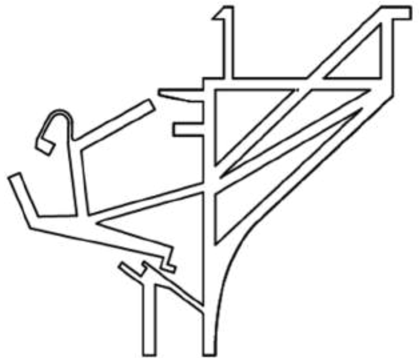


Figure 83: Geometry iteration 3 (Own)

Tensile

Thickness	Maximum displacement
15 mm	20,94 mm
30 mm	10,47 mm
50 mm	6,28 mm

Compression

Thickness	Maximum displacement
15 mm	1,96 mm
30 mm	0,98 mm
50 mm	0,59 mm

Figure 84: Stresses tensile test iteration 3 30mm (Own)

ANALYSIS 5: ITERATION 4

Iteration 4 is a variant in which the bending part is made 10 millimeters longer and 0,5 millimeters thicker. Unfortunately, this did not have the desired result. The maximum displacement in the tensile test is actually a lot larger than in iteration 3. There is also no improvement in terms of the tensile stresses in the geometry.

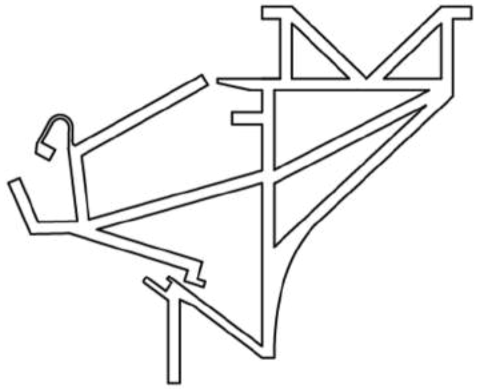


Figure 85: Geometry iteration 4 (Own)

Tensile

Thickness	Maximum displacement
15 mm	29,34 mm
30 mm	14,67 mm
50 mm	8,8 mm

Compression

Thickness	Maximum displacement
15 mm	2,06 mm
30 mm	1,03 mm
50 mm	0,62 mm

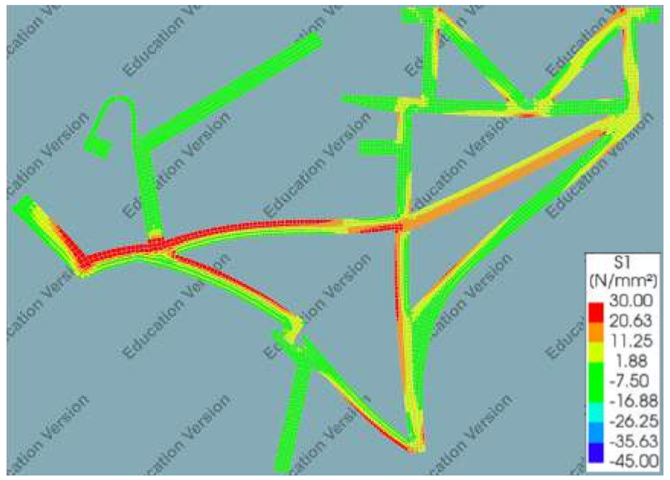


Figure 86: Stresses tensile test iteration 4 30mm (Own)

ANALYSIS 6: ITERATION 5

In iteration 5 the bending part is produced with an arc. As soon as the compliant mechanism is rotated into its end position, the bending part becomes straight. Because of this, the maximum displacement has become less. Also, the tensile stresses in the geometry are reduced.

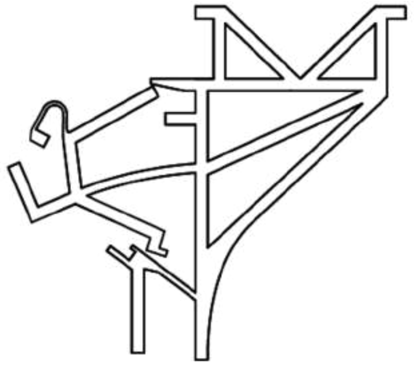


Figure 87: Geometry iteration 5 (Own)

Tensile

Thickness	Maximum displacement
15 mm	15,17 mm
30 mm	7,63 mm
50 mm	4,58 mm

Compression

Thickness	Maximum displacement
15 mm	1,86 mm
30 mm	0,93 mm
50 mm	0,56 mm

Figure 88: Stresses tensile test iteration 5 30mm (Own)

ANALYSIS 7: ITERATION 6

In iteration 6, the hook has been strengthened. As a result, the displacement in the tensile test was reduced by almost 50% compared to iteration 5. The displacement in the compression test has remained the same. Furthermore, the tensile stresses have been reduced compared to iteration 5.

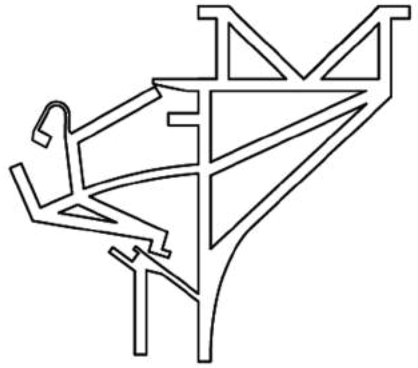


Figure 89: Geometry iteration 6 (Own)

Tensile

Thickness	Maximum displacement
15 mm	7,55 mm
30 mm	3,77 mm
50 mm	2,26 mm

Compression

Thickness	Maximum displacement
15 mm	1,86 mm
30 mm	0,93 mm
50 mm	0,56 mm

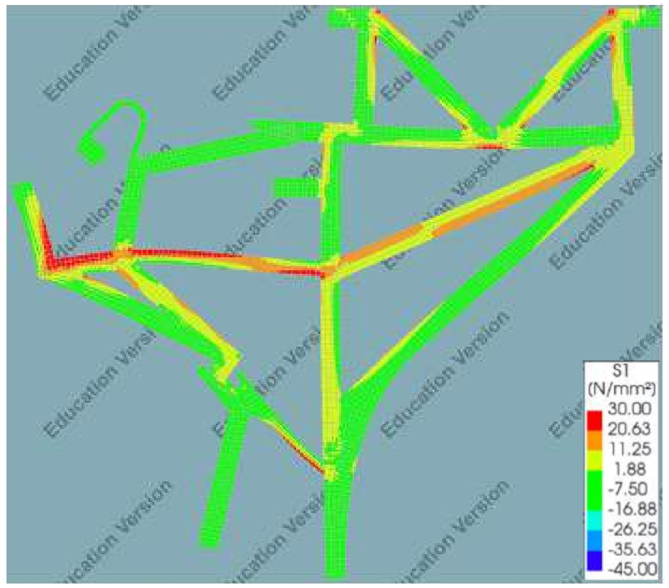


Figure 90: Stresses tensile test iteration 6 30mm (Own)

ANALYSIS 8: ITERATION 7

Iteration 7 has the new mounting system of the final prototype of the chapter prototyping. This has a small impact on the maximum displacement in the tensile test. In the compression test the maximum displacement has increased relatively much but is still within the norms. The tensile stresses in the geometry remain almost the same.

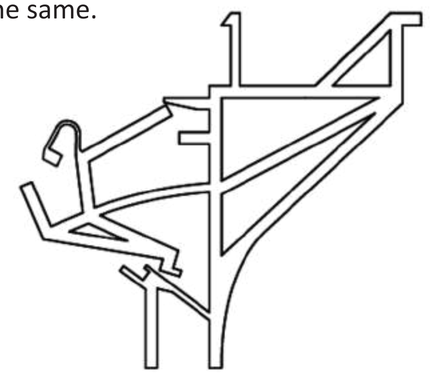


Figure 91: Geometry iteration 7 (Own)

Tensile

Thickness	Maximum displacement
15 mm	6,9 mm
30 mm	3,45 mm
50 mm	2,07 mm

Compression

Thickness	Maximum displacement
15 mm	2,69 mm
30 mm	1,35 mm
50 mm	0,81 mm

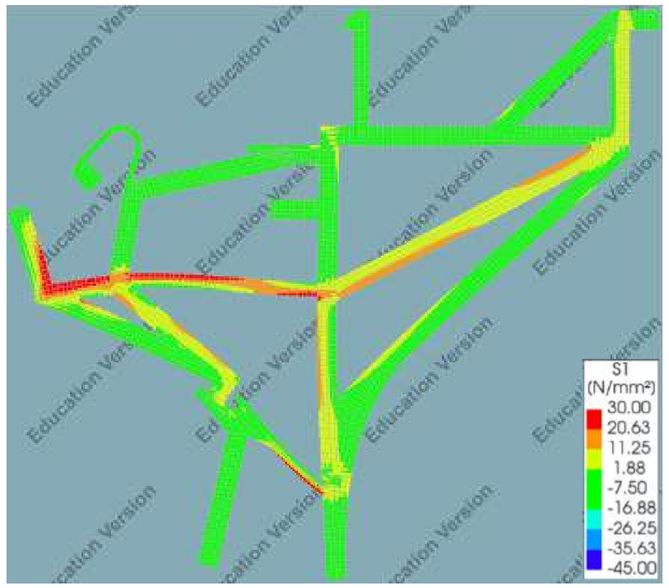


Figure 92: Stresses tensile test iteration 7 30mm (Own)

ANALYSIS 9: ITERATION 8

In iteration 8, another strut is added in the fixed part to generate more stiffness. This gives a negligible difference in the maximum displacement in the tensile test. The maximum displacement in the compression test is reduced by almost 25% compared to iteration 7. The tensile stresses in the geometry remain almost the same.

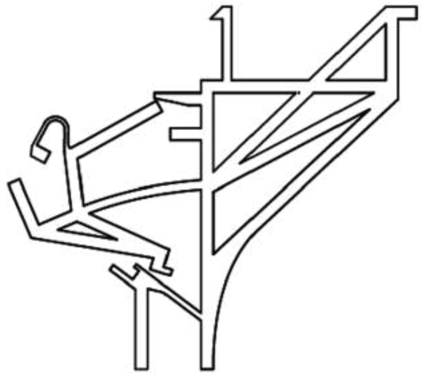


Figure 93: Geometry iteration 8 (Own)

Tensile

Thickness	Maximum displacement
15 mm	6,76 mm
30 mm	3,38 mm
50 mm	2,03 mm

Compression

Thickness	Maximum displacement
15 mm	2,02 mm
30 mm	1,01 mm
50 mm	0,61 mm

Figure 94: Stresses tensile test iteration 8 30mm (Own)

STRUCTURAL ANALYSIS

HOOK

For the first analysis the same settings were used in DIANA FEA as for the analysis of the compliant mechanisms. For the second and third analysis other settings were used as the first analysis showed that the material properties of PLA were not sufficient for the hook. It was replaced by PEI. PEI is also a linear elastic isotropic composite and has a Young's modulus of 2890 N/mm², a Poisson's ratio of 0.4 and a density of 1260 kg/m³. PEI mainly has a high tensile strength and compressive strength compared to PLA.

Since the depth of 30 millimeters was used in the analysis of the compliant mechanism, the depth used in the analyses of the hook is only 30 millimeters.

ANALYSIS 1: FINAL PROTOTYPE

The first analysis of the hook is from the final prototype in the prototyping section. The maximum displacement is large and also the tensile forces in the geometry are much higher than the material can handle.

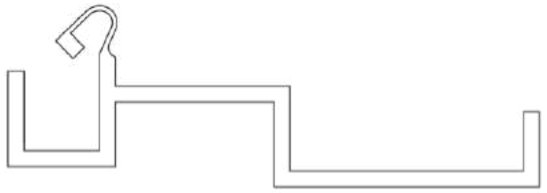


Figure 95: Geometry final prototype (Own)

Tensile

Thickness	Maximum displacement
30 mm	15,99 mm

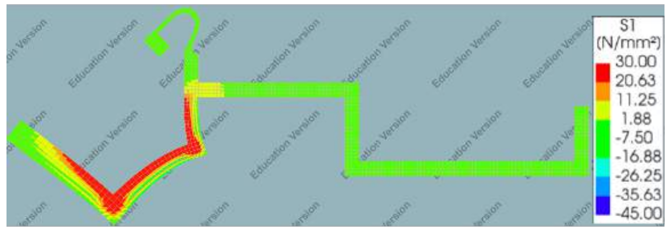


Figure 96: Stresses tensile test final prototype 30mm (Own)

ANALYSIS 2: ITERATION 1

The geometry of iteration 1 was completely changed from the final prototype. Knowledge gained during the analysis of the iterations of the compliant mechanisms was used to change the geometry of the hook. The material of the hook has also been changed, since the forces were so high that they could not be absorbed with the material properties of PLA. The maximum displacement of 4,63 millimeters in the tensile test is still slightly too much. No compressive test was carried out because virtually no displacement can take place in this design. The new material PEI has a positive effect on the absorption of stresses in the geometry.

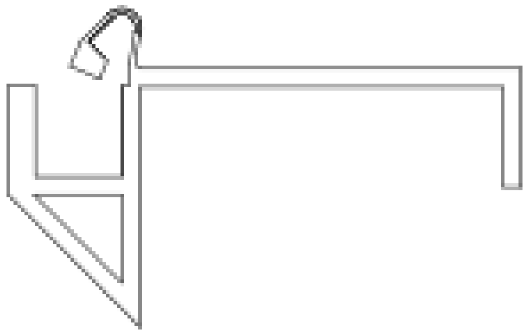


Figure 97: Geometry iteration 1 (Own)

Tensile

Thickness	Maximum displacement
30 mm	4,63 mm

Figure 98: Stresses tensile test iteration 1 30mm (Own)

ANALYSIS 3: ITERATION 2

Iteration 2 has a slight modification compared to iteration 1. The thickness at the back of the hook has been changed from 2 to 3 millimeters in order to create more rigidity in the geometry. As a result, the maximum displacement has been reduced by about 40% to 2,7 millimeters. The tensile forces in the geometry have been significantly reduced.

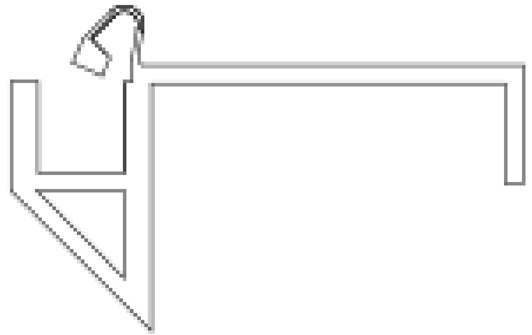


Figure 99: Geometry iteration 2
(Own)

Tensile

Thickness	Maximum displacement
30 mm	2,7 mm

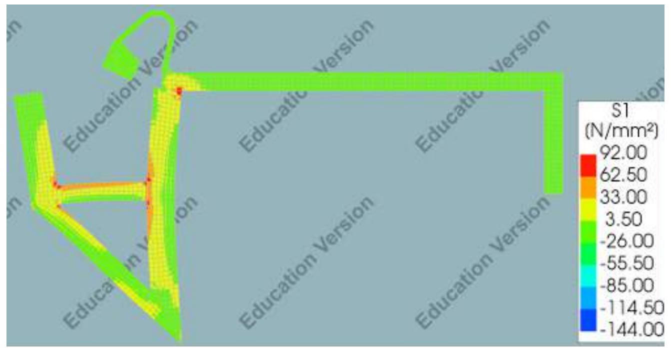


Figure 100: Stresses tensile test iteration 2 30mm
(Own)

7.3 PRACTICAL TEST

In order to verify the results of the analysis in DIANA, several practical tests were done with the compliant mechanism. The designs of iteration 3 and iteration 8 were used for this. A normal tensile test was done, a tensile test where the compliant mechanism was out of the lock system and a compression test.

The samples were made using a 3D printer and all have a depth of 30 millimeters. The material used to make the samples is PLA Signal White from MakerPoint. The attachments were also made using a 3D printer and the material is PLA Orange from the brand REAL. A dogbone tensile test was used to compare the properties of these materials.

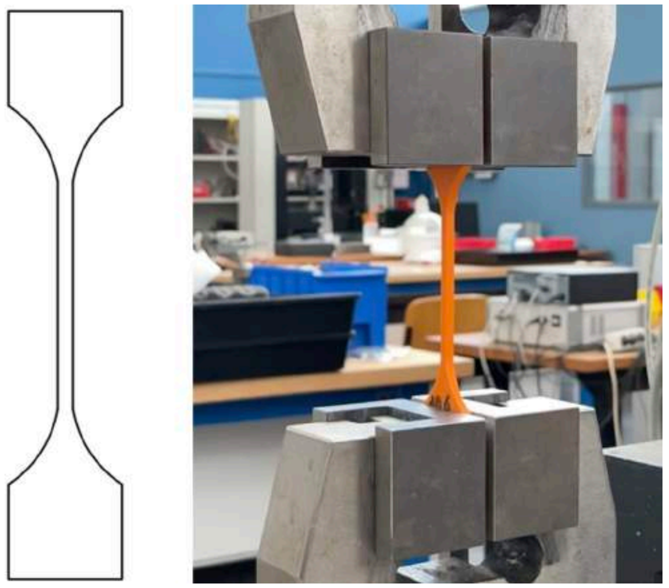


Figure 102: Geometry - test set up
(Own)

TEST 1: DOGBONE TENSILE TEST

The dogbone test was done to find out how much difference there is in the properties of PLA from different manufacturers. The gauge length of the dogbone is 60 millimeters and the width and thickness are 4 millimeters. The results show that REAL PLA has a higher ultimate stress than MakerPoint PLA. The failure stress of the MakerPoint PLA is much higher than the failure stress of the REAL PLA. It can also be seen that the REAL PLA stretches a lot more than the PLA from MakerPoint in both the ultimate stress and the failure stress. The strain is calculated with the formula ΔL/L (change in length/original length). It can be concluded that MakerPoint's PLA is much more brittle than REAL's PLA. While the PLA from REAL is a lot tougher than the PLA from MakerPoint.

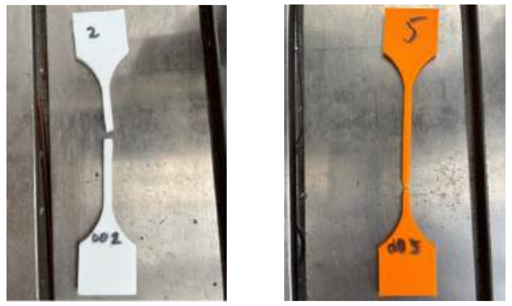
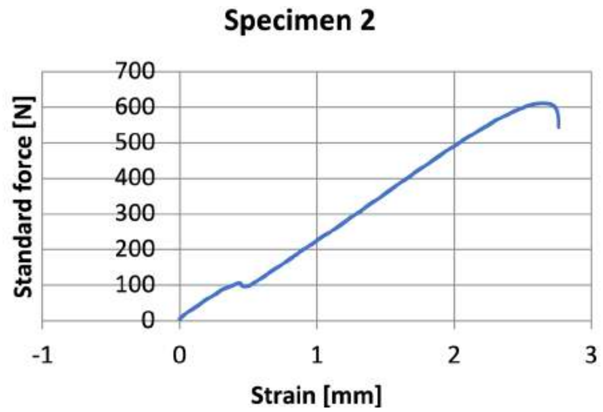
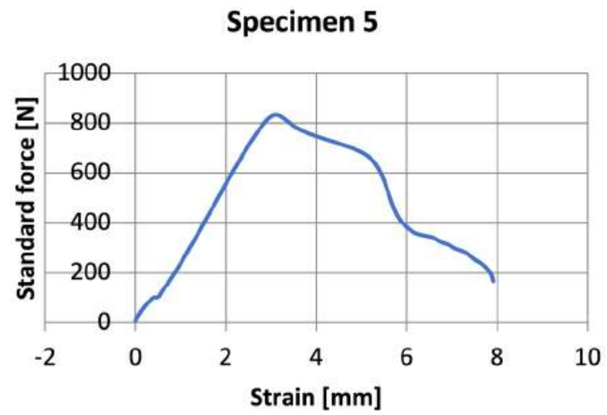


Figure 101: Specimen 2 - Specimen 5
(Own)





Test	Material	Ultimate stress	Strain	Failure stress	Strain
Specimen 1	PLA MakerPoint	37,7 N/mm²	1,04	35,0 N/mm²	1,05
Specimen 2	PLA MakerPoint	38,2 N/mm²	1,04	34,1 N/mm²	1,05
Specimen 3	PLA MakerPoint	35,5 N/mm²	1,05	34,5 N/mm²	1,05
Specimen 4	PLA REAL	51,7 N/mm²	1,08	10,3 N/mm²	1,15
Specimen 5	PLA REAL	52,1 N/mm²	1,05	10,4 N/mm²	1,13
Specimen 6	PLA REAL	51,6 N/mm²	1,06	10,3 N/mm²	1,12

table 8: Results dogbone tensile test
(Own)

TEST 2: TENSILE TESTS COMPLIANT MECHANISM

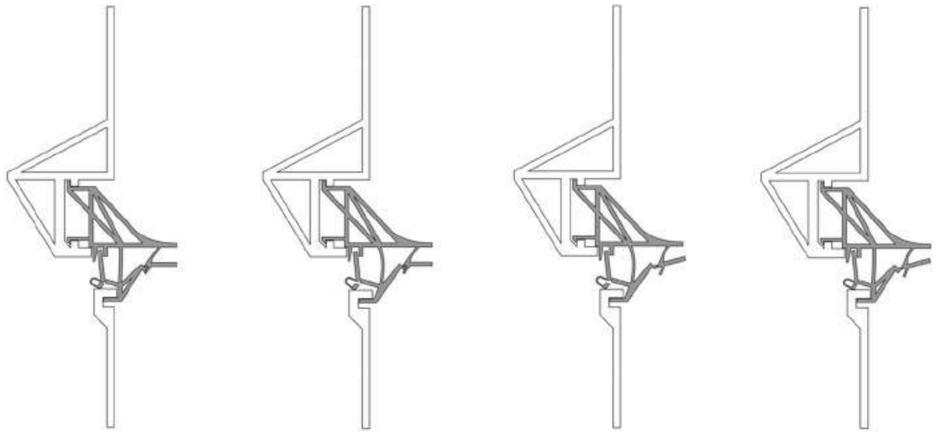


Figure 103: Test set up, specimen 7 & 8 - specimen 9 & 10 - specimen 11 - specimen 12
(Own)

To find out how much tensile strength the compliant mechanisms can withstand, a tensile test was performed. A tensile test was performed of iteration 3 and iteration 8 with the compliant mechanism in the lock system and a tensile test was also performed of both designs with the compliant mechanism out of the lock system. The results in table 9 show that the ultimate strength of the specimens from iteration 8 is considerably higher than the ultimate strength of the specimens from iteration 3. It is also noticeable that the ultimate strength almost corresponds to the failure stress. This is because the specimen shot out of the attachment almost every time, see figure 104. In the one test in which the ultimate strength does not correspond with the failure strength, the attachment has failed, see figure 105. The specimens themselves were still intact after each test.

The strain is mainly explained by the deformation of the attachments and not by the deformation of the specimens. The only small difference in displacement that can be seen between the iterations is because in iteration 3 the bending part is under a curve, while in iteration 8 the bending part is straight.
Interesting to note is that in the test of specimen 12, where the complaining mechanism was out of the lock system, the tensile stresses are still higher than the values from the manual calculation.

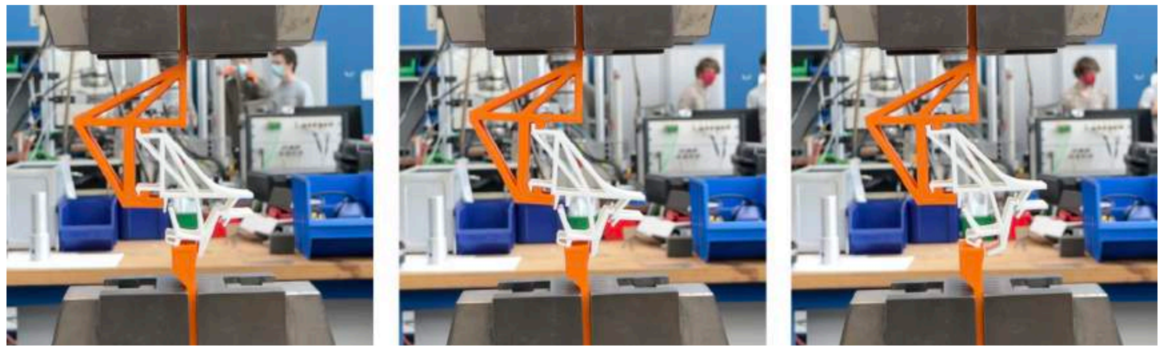


Figure 104: Tensile test specimen 11, starting position - ultimate strength - end position
(Own)

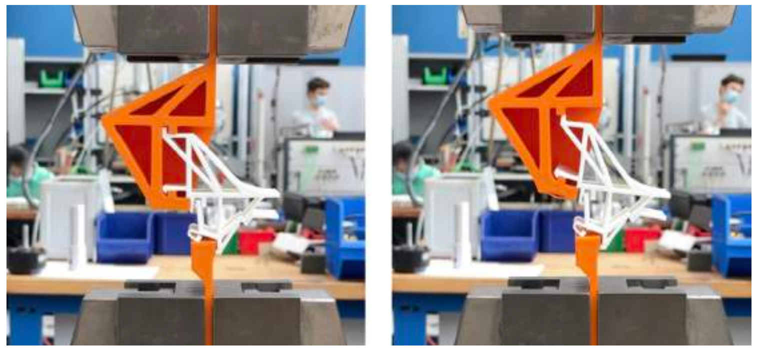


Figure 105: Tensile test specimen 8, starting position - failure attachment
(Own)

STRUCTURAL ANALYSIS

Test	Type	Ultimate strength	Displacement	Failure strength	Displacement
Specimen 7	Iteration 8 normal	641,7 N	5,50 mm	641,7 N	5,50 mm
Specimen 8	Iteration 8 normal	819,2 N	6,75 mm	263,9 N	9,10 mm
Specimen 9	Iteration 3 normal	576,9 N	7,11 mm	573,9 N	7,12 mm
Specimen 10	Iteration 3 normal	436,3 N	5,60 mm	419,9 N	5,61 mm
Specimen 11	Iteration 3 out of the lock system	291,5 N	3,81 mm	291,5 N	3,81 mm
Specimen 12	Iteration 8 out of the lock system	587,2 N	7,55 mm	586,6 N	7,57 mm

table 9: Results tensile tests
(Own)

TEST 3: COMPRESSION TESTS COMPLIANT MECHANISM

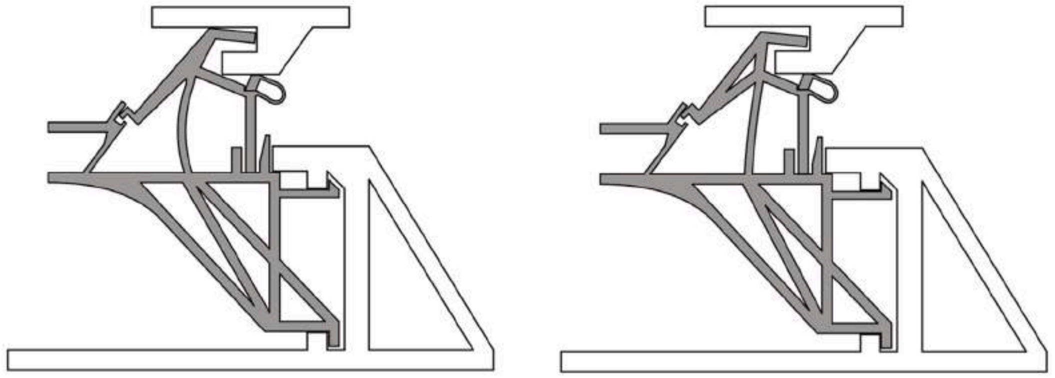


Figure 106: Test set up, iteration 3 - iteration 8
(Own)

The last test done was the compression test. Three specimens of iteration 8 and two specimens of iteration 3 were tested. Because it was not easy to determine from the test results when exactly the specimens failed, only the ultimate strength is shown in table 9. Appendix VII contains all the graphs of the tests. The displacement is shown, but cannot be compared 1 to 1. This is because the two pressure points of the compression machine first had to drop quite a bit before there was real pressure on the specimens.

The ultimate strengths of all iterations are fairly similar. This can be explained by the fact that the fixed part of iteration 3 and iteration 8 are exactly the same. In specimens 13, 15 and 16, it was first the pressure point that buckled. Then all the forces were applied to the hook and a bigger bending moment developed in the compliant mechanism, after which the cantilever snap fit failed. The pressure point of specimen 14 even broke off completely. In specimen 17 the pressure point also buckled, after which the bending part broke off.

Test	Type	Ultimate strength	Type of failure	Displacement
Specimen 13	Iteration 8	782,9 N	Pressure point buckled	5,68 mm
Specimen 14	Iteration 8	704,4 N	Pressure point broken	5,03 mm
Specimen 15	Iteration 8	753,9 N	Pressure point buckled	6,81 mm
Specimen 16	Iteration 3	1051,7 N	Pressure point buckled	6,96 mm
Specimen 17	Iteration 3	721,7 N	Bending part broken	7,22 mm

Table 10: Results compression test
(Own)

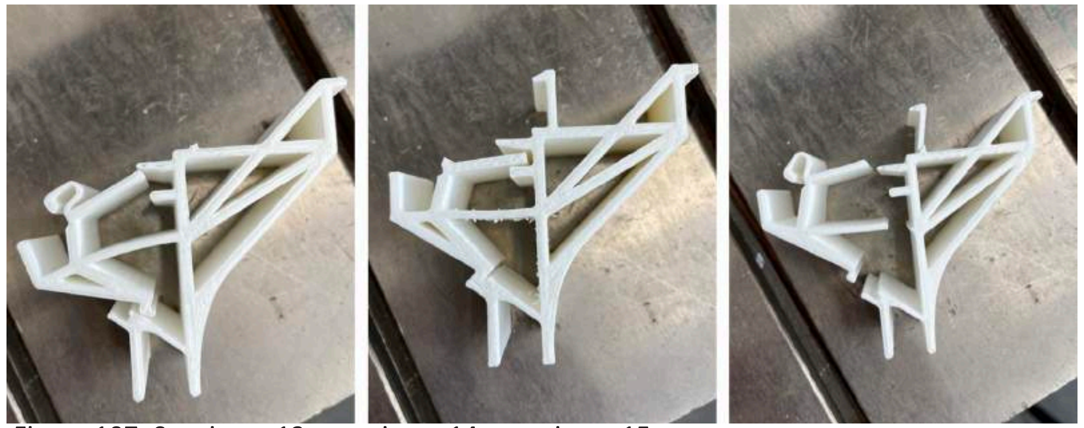


Figure 107: Specimen 13 - specimen 14 - specimen 15
(Own)

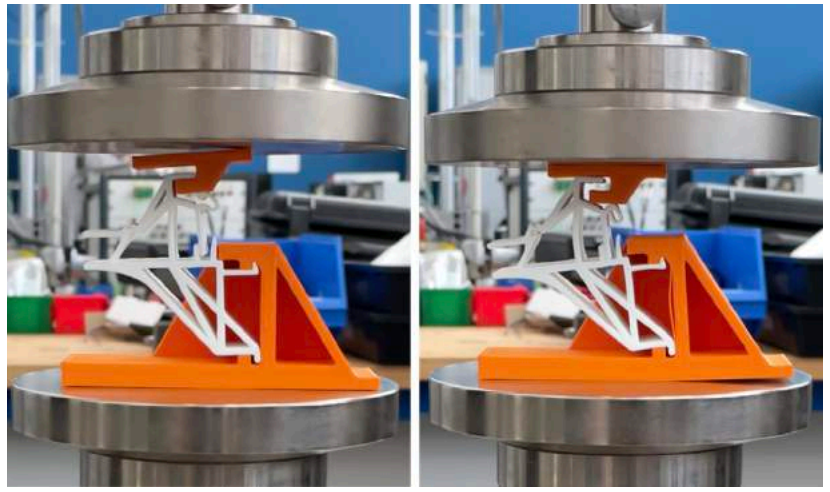


Figure 108: Compression test specimen 13, starting position - second before failure
(Own)

RECOMMEND IMPROVEMENTS

Based on the results of the practical test, final adjustments must be made to the design of the compliant mechanism. In the tensile tests, both iteration 3 and iteration 8 scored higher than the minimum values from the hand calculation. The results do however show that iteration 8 is a lot stronger than iteration 3. In terms of tensile strength, iteration 8 is sufficient and no improvements need to be made to the design. The only aspect in which the design can be improved is the unlocking of the lock system. The results show that a force of almost 600 N is needed per connection to pull the panel out of the compliant mechanism. Apart from that, no improvements in the design are necessary with regard to the tensile forces.

From the results of the compressive test, it can be concluded that there are still some improvements to be made in the design. In every specimen, the problem was that the pressure point either started to bend or broke off. Although a change was made to the pressure point before the practical test, it was still not sufficient.

In the modified specimen, the load was not centred in relation to the end stop. This must be changed in a new design. Also, in specimen 17 of iteration 3, the bending part broke off. The compressive test shows that in this case iteration 8 also is better than iteration 3. Furthermore, the arm of the pressure point must be lengthened in order to create a larger moment of inertia, which makes the compliant mechanism easier to rotate.

The last adjustment to be made to the design is the thickness of the cantilever snap fit. In iteration 3 and iteration 8 the thickness of the cantilever snap fit was 1,5 millimeters. However, it turned out that it was not possible to click the specimens into the attachments because the cantilever snap fit was too stiff. This part has to be made thinner.

What is interesting to note is that despite the 3D printed prototypes not being completely solid, such good results have emerged. The production version that is completely solid will therefore perform even better.

7.4 FINAL DESIGN FINITE ELEMENT ANALYSIS

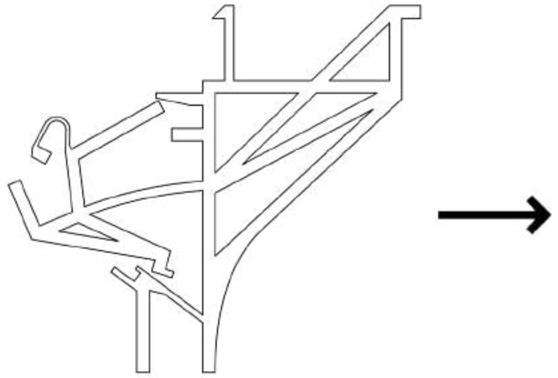


Figure 109: Iteration 8 with improved pressure point
(Own)

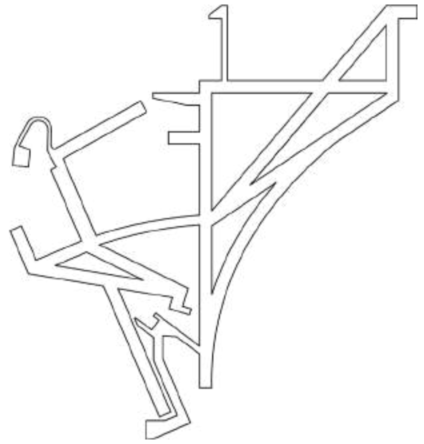


Figure 110: Final design
(Own)

The adjustments that were recommended on the basis of the results of the practical tests have been applied in the final design, see figure 110. The pressure point has been changed so that the loads can be better transmitted to the fixed part and the pressure point will bend less easily. The lock system has been modified so that the compliant mechanism can be more easily rotated out of the panel and the thickness of the cantilever snap fit has been reduced from 1,5 to 1 millimeter. The arm of the pressure point has also been extended by 5 mm, resulting also in a change of the fixed part. Furthermore, the hook has been shortened by 2 mm.

For the finite element analysis of the final design, the same steps were taken as for the previous finite element analysis. The only change is the material of the design. This has been changed from PLA to PC+PBT. This material is a linear elastic isotropic composite and has a Young's modulus of 2600 N/mm^2, a Poisson's ratio of 0,397 and a density of 1250 kg/m^3. The maximum tensile strength of the material is 59 N/mm^2 and the maximum compressive strength is 75,6 N/mm^2. Since a depth of 30 millimeters was chosen for the design, the analysis of the final prototype was made with this depth only.

The results of the analysis of the final design are very good. The values for the maximum displacement in the tensile test gives a distorted view, because this displacement is in the arm of the lock system and not in the hook as in the other analyses. The displacement in the compression test is strongly reduced and, partly because a different material is used, there are far less stresses in the geometry that fall outside the maximum tensile strength and compressive strength.

It should be noted that the external pressure coefficient has not yet been taken into account in the wind loads used for the calculations. These depend on the dimensions of the building and will result in lower wind loads, so the maximum displacement will be less.

Tensile

Thickness	**Maximum displacement**
30 mm	2,54 mm

Compression

Thickness	**Maximum displacement**
30 mm	1,04 mm

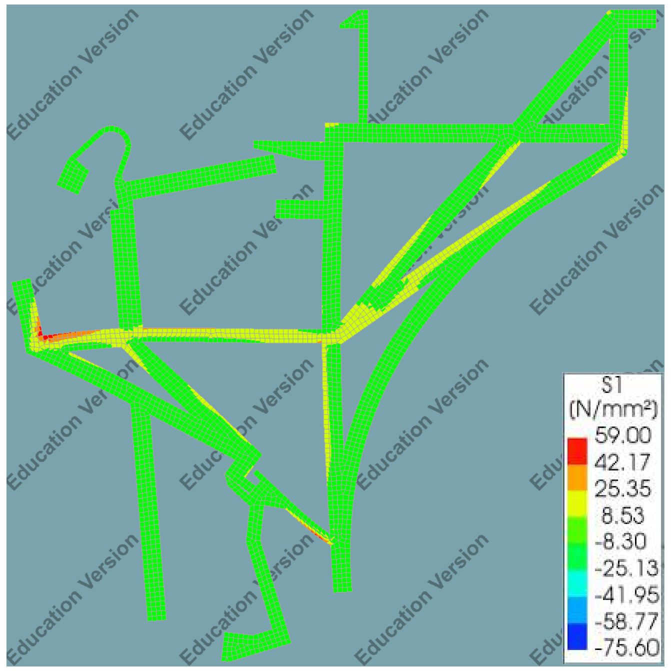


Figure 111: Stresses tensile test iteration 4 30mm
(Own)

8 FINAL DESIGN

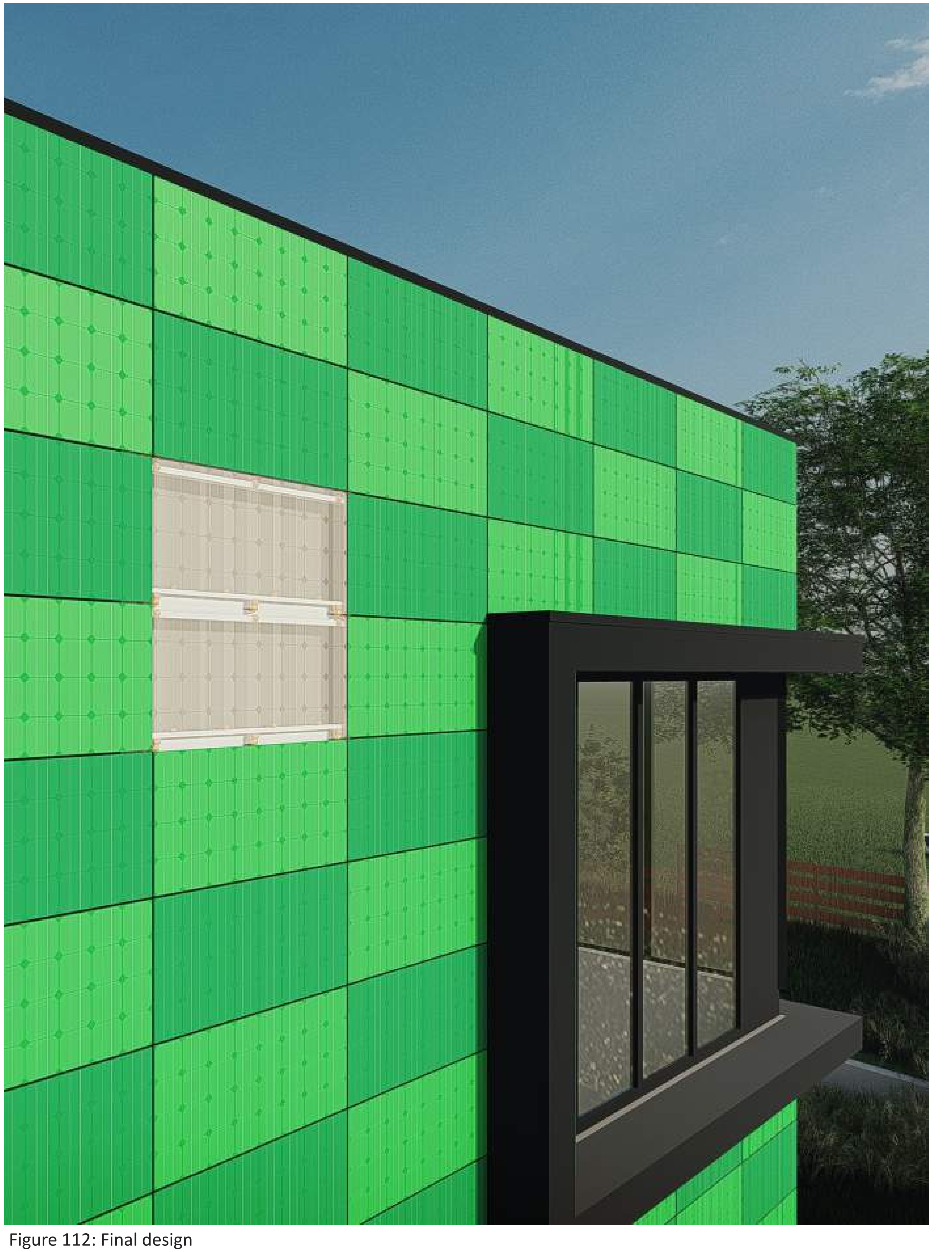


Figure 112: Final design
(Own)

8.1 OVERVIEW FACADE SYSTEM

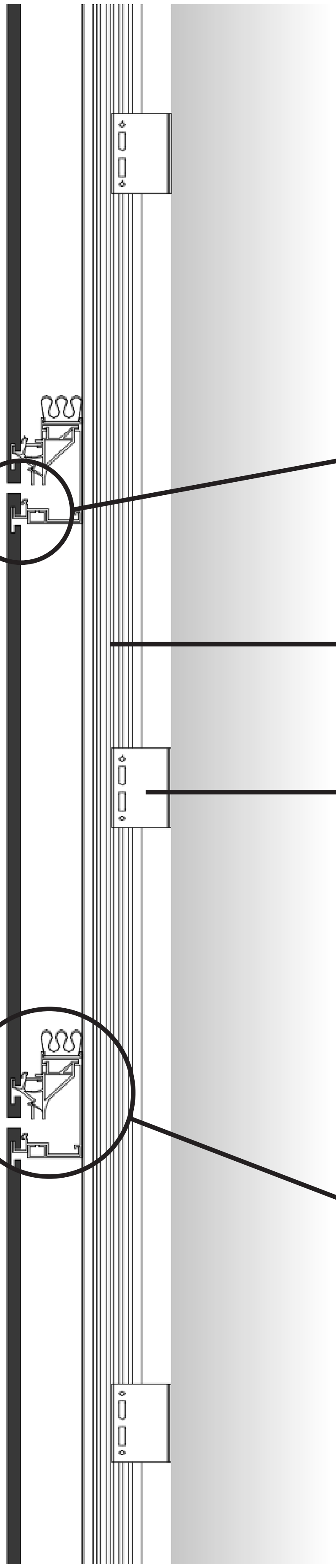


Figure 121: Overview facade system
(Own)

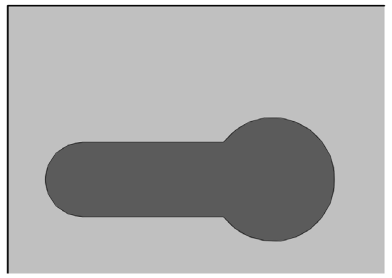


Figure 113: Undercut locally
(Own)

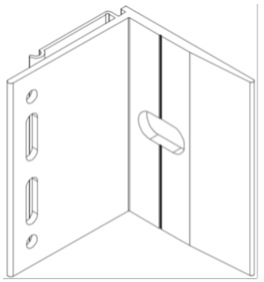


Figure 114: Wall bracket
(Hilti, 2021)

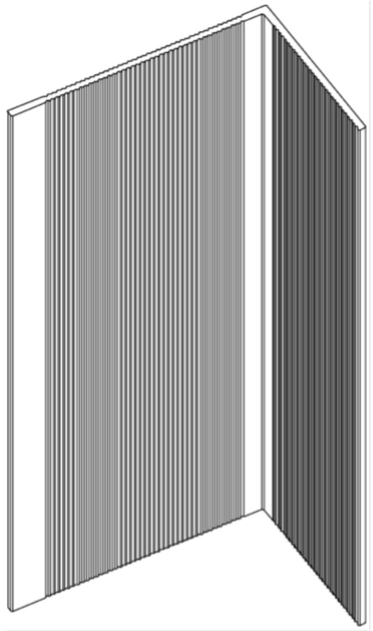


Figure 115: L-profile
(Hilti, 2021)

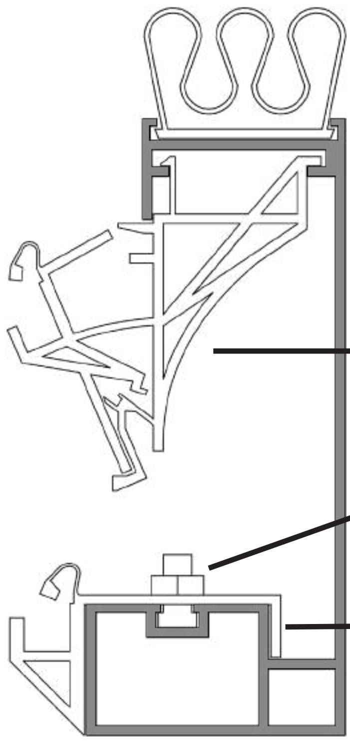


Figure 116: Cable clamp
(Own)

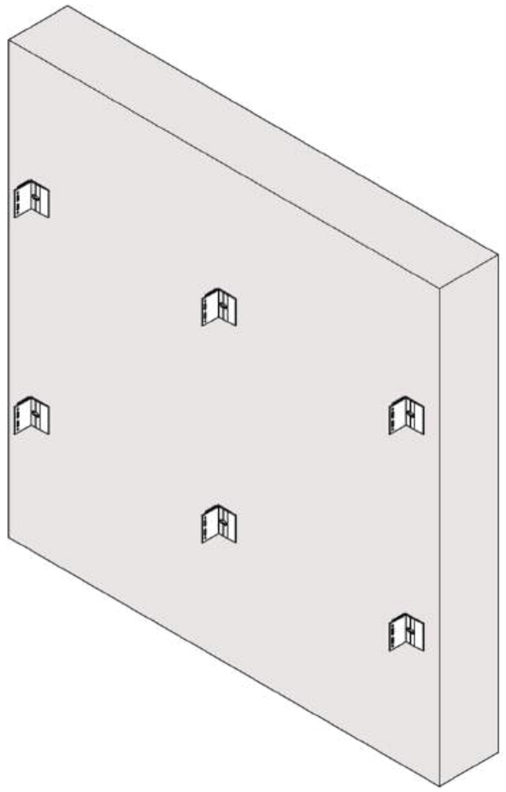
Figure 117: Horizontale profile
(Own)

Figure 118: Compliant mechanism
(Own)

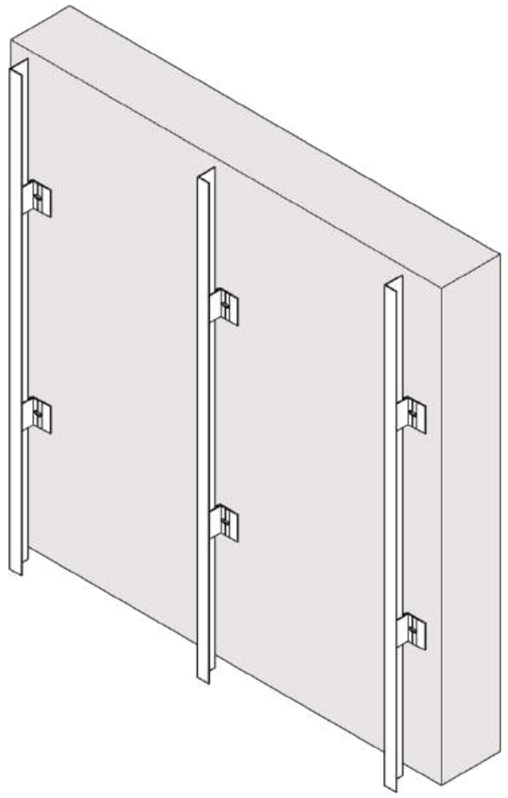
Figure 119: Hammerhead bolt
(Own)

Figure 120: Hook
(Own)

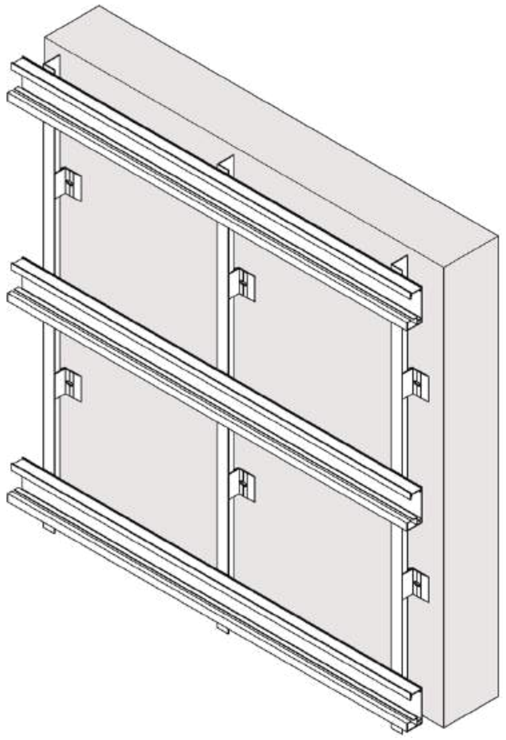
8.2 ASSEMBLY



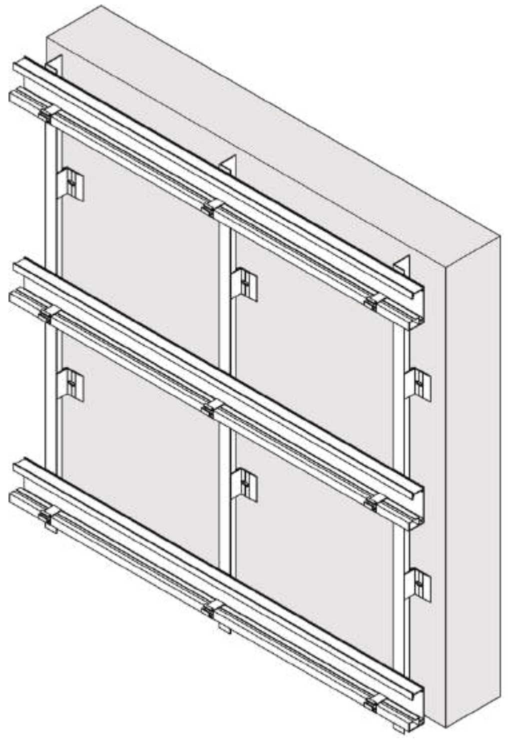
Step 1: Install the wall brackets on the wall behind



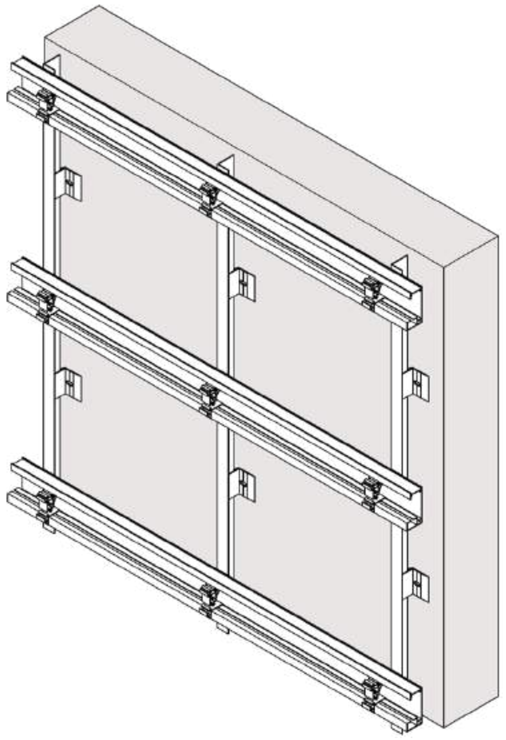
Step 2: Mount the L-profile to the wall brackets



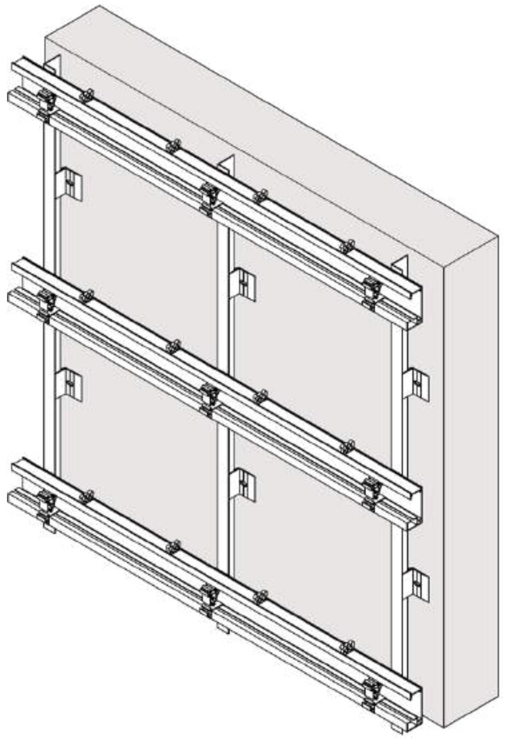
Step 3: Attach the horizontal profile to the L-profile



Step 4: Hang the hooks in the horizontal profile and fas-
ten them with the hammerhead bolt

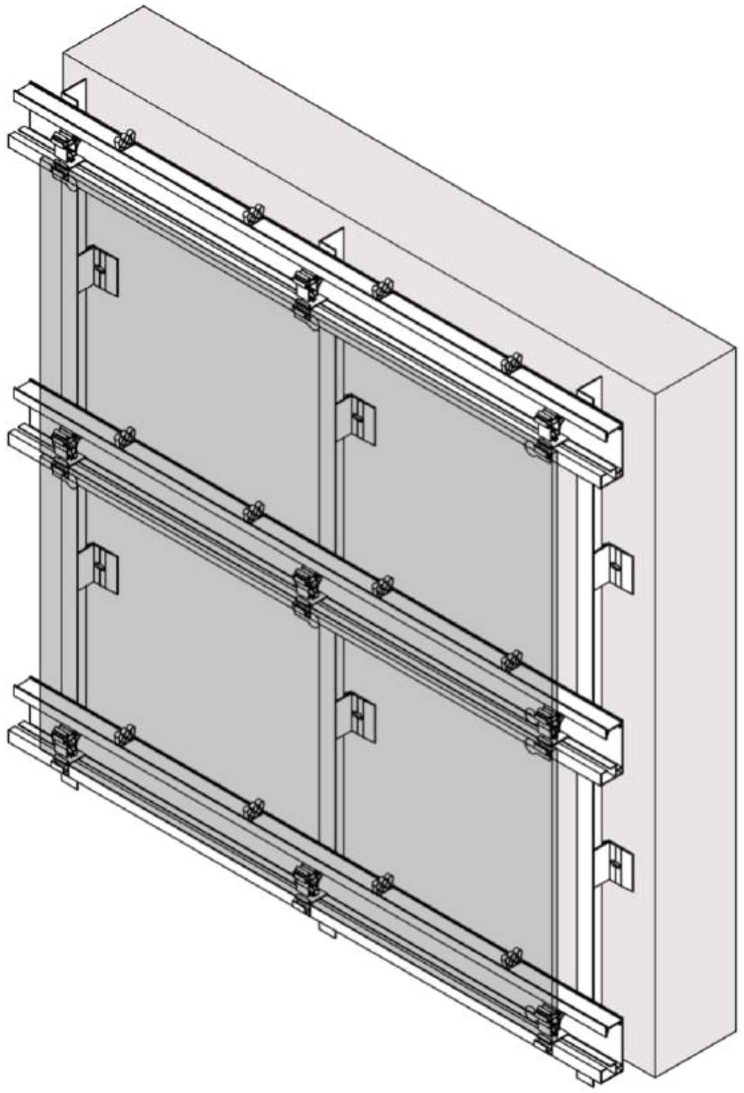


Step 5: Click the compliant mechanism into the horizontal profile



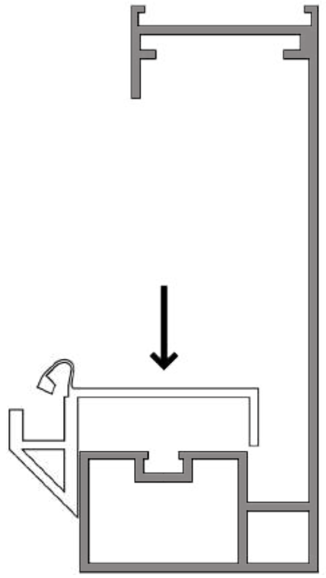
Step 6: Click the cable clamp into the horizontal profile

Final step: Hang the panel in the hook, connect the cables and click the panel into the compliant mechanism

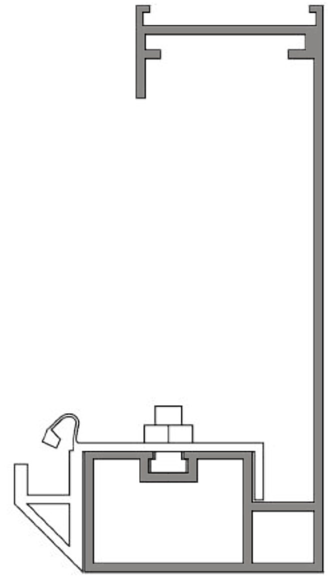


8.3 EXPLANATION OF THE SYSTEM

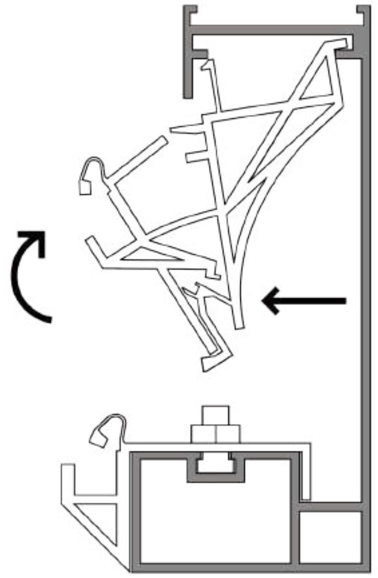
INSTALLATION OF THE SYSTEM



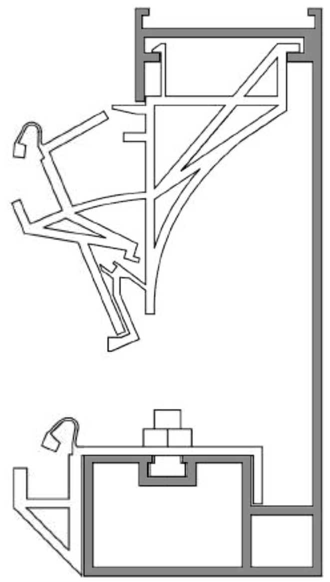
Step 1: Insert the hook into the horizontal profile



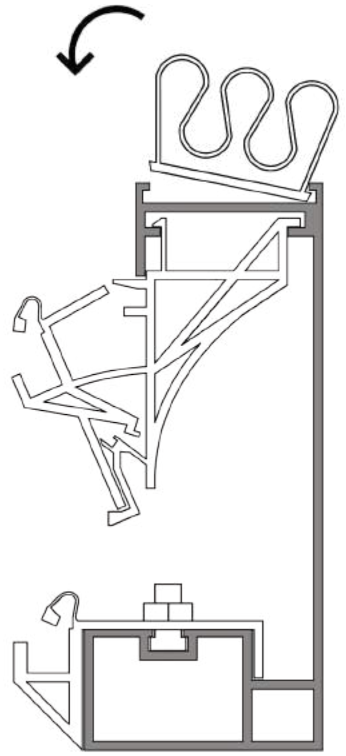
Step 2: Use a hammerhead-bolt to mount the hook to the horizontal profile



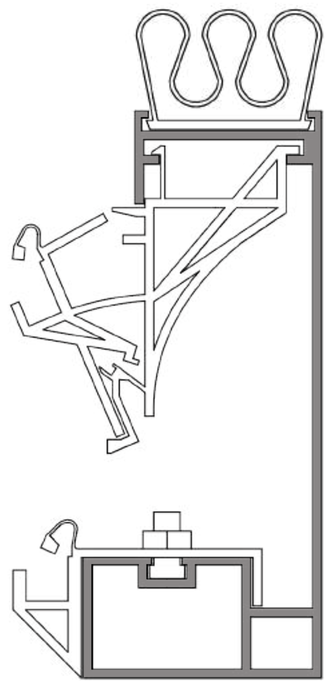
Step 3: Insert the compliant mechanism into the rear side of the horizontal profile and turn it into the front side of the horizontal profile



Step 4: Result step 3

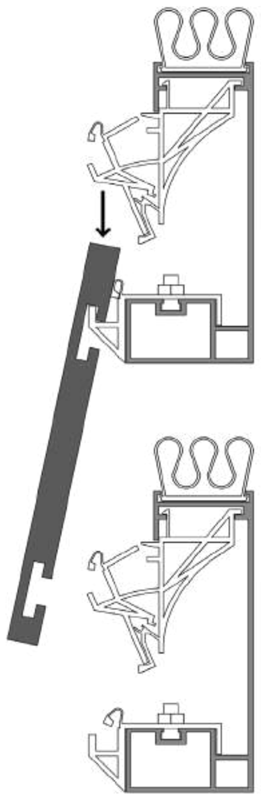


Step 5: Place the cable clamp with one side in the horizontal profile and turn it in the other side of the horizontal profile

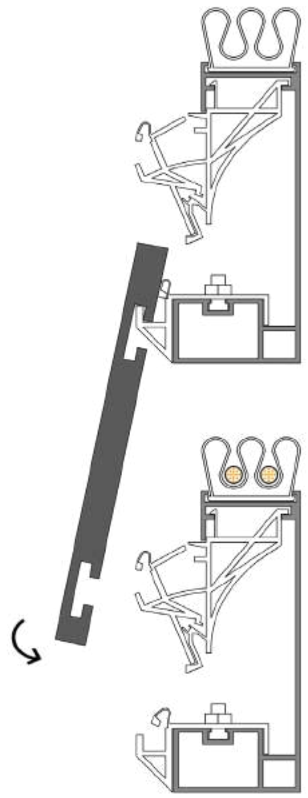


Final step: Result

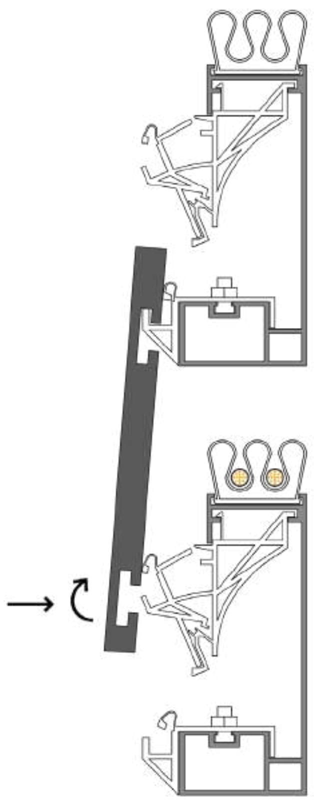
ASSEMBLY OF THE HPL BIPV PANEL



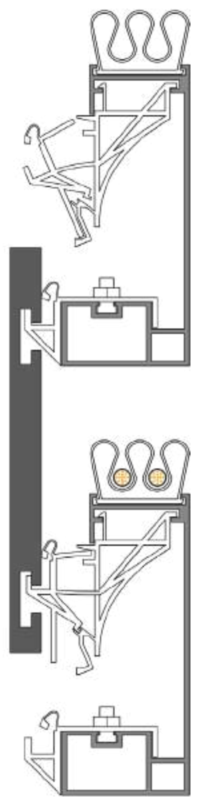
Step 1: Place the panel with the top on the hook



Step 2: Connect the cables of the HPL BIPV panel and turn the panel towards the compliant mechanism

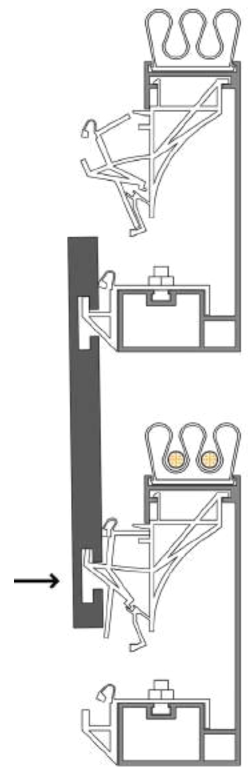


Step 3: Press the panel against the compliant mechanism. The compliant mechanism will rotate into the panel.

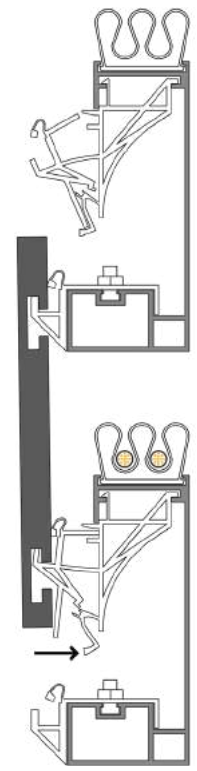


Final step: Result

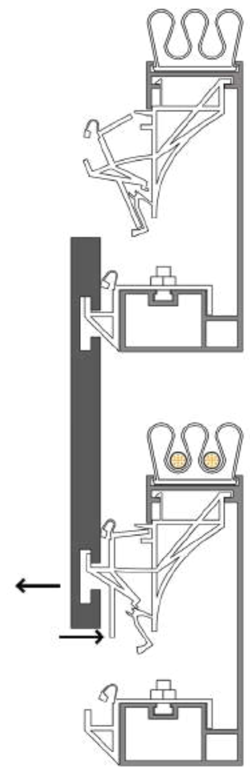
DISASSEMBLY OF THE HPL BIPV PANEL



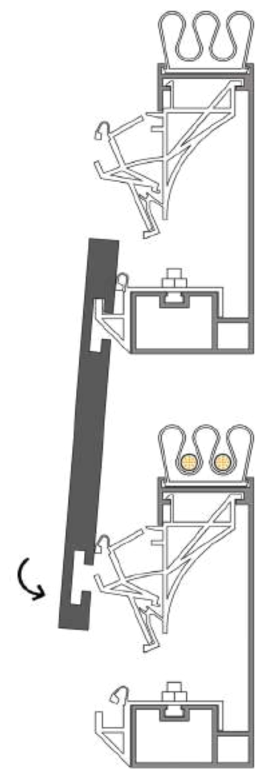
Step 1: Press against the panel. The compliant mechanism will continue to rotate and the lock system will open



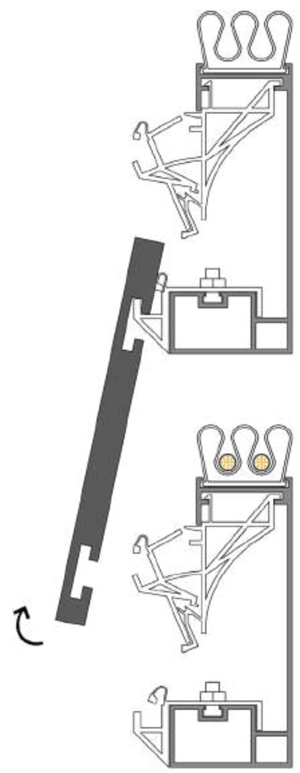
Step 2: Press with a screwdriver or similar against the arm of the lock system



Step 3: Release the panel. Press with a screwdriver or similar against the other arm of the lock system



Step 4: The compliant mechanism will rotate out of the panel



Final step: Pull the panel out of the compliant mechanism and take it off the hook

8.4 TOLERANCES

The maximum expansion of High Pressure Laminate under the influence of moisture and temperature changes is 2,5 mm/m. A HPL panel also has a dimensional tolerance of 5 mm in length and 5 mm in width. The thickness of the panel may also contain a small tolerance of -0,6 to +0,6 mm (KOMO, 2016).

There are also tolerances in the sub-frame that need to be taken into account. This starts with the facade behind. The NEN 2886 states that the maximum allowable dimensional deviation of a facade is calculated using the formula 1,4 x L. In this report a building with a maximum height of 20 meters is assumed. If this value is used in the formula it means that the maximum allowable dimensional deviation in the facade may be a maximum of 28 millimeters (NEN, 1990).

Aluminium is recommended for the horizontal profile, PEI for the hook and PC+PBT for the compliant mechanism and cable clamp. The thermal expansion coefficient of aluminium is 22,5 μm/(m °C), of PEI 84,6 μm/(m °C) and of PC+PBT 88 μm/(m °C).

8.4 TECHNICAL DRAWINGS

COMPLIANT MECHANISM

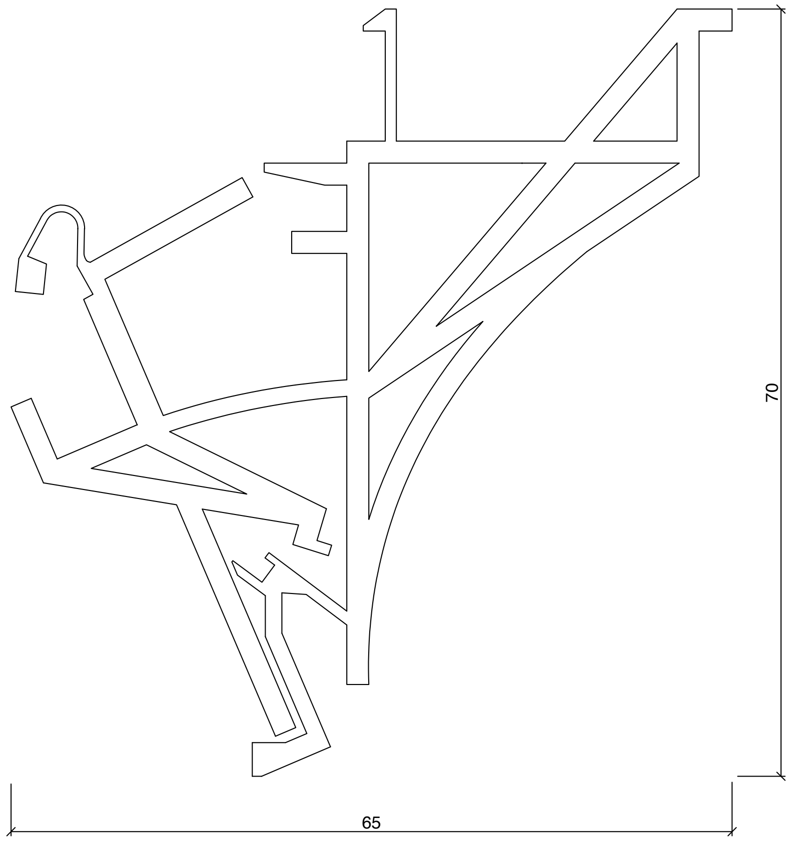


Figure 122: Technical drawing compliant mechanism (Own)

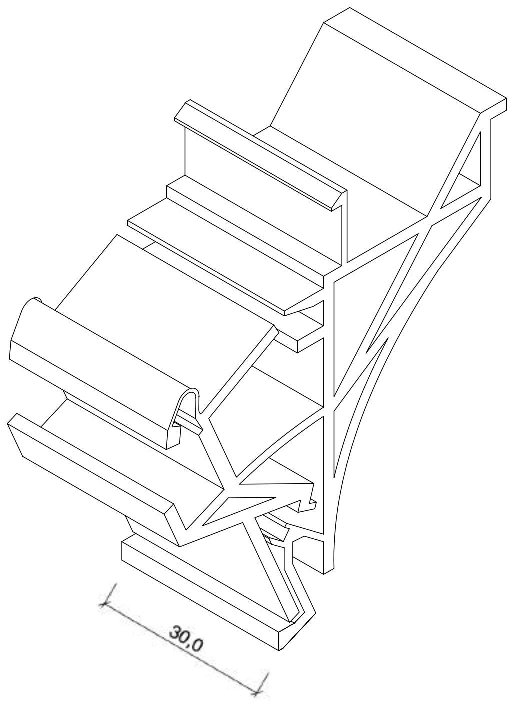


Figure 123: Isometric compliant mechanism (Own)

FINAL DESIGN

HORIZONTAL PROFILE

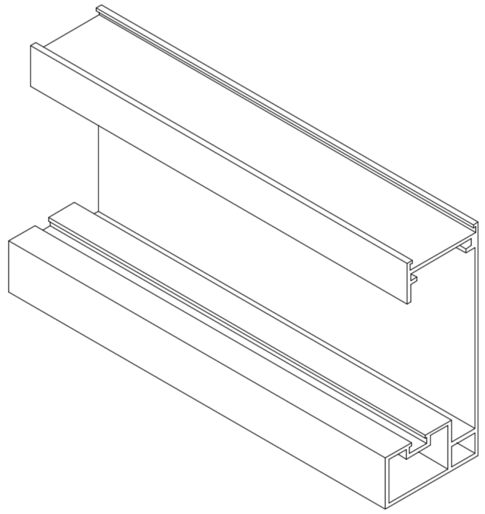


Figure 124: Isometric horizontal profile (Own)

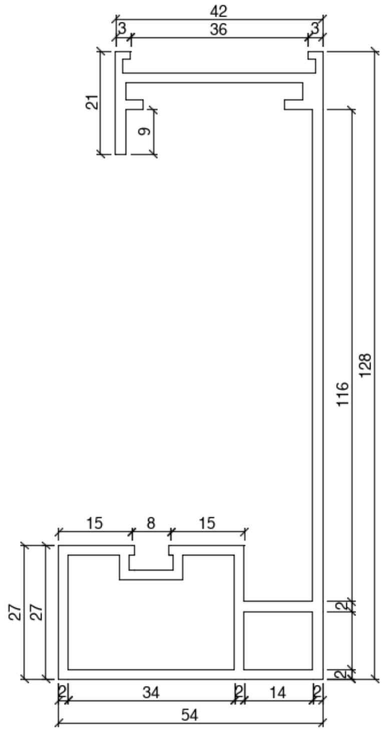


Figure 125: Technical drawing horizontal profile (Own)

CABLE CLAMP

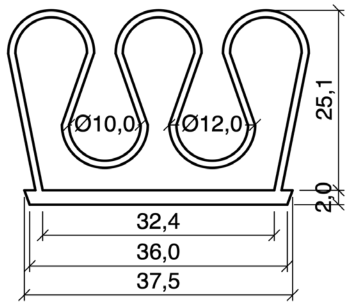


Figure 126: Technical drawing cable clamp (Own)

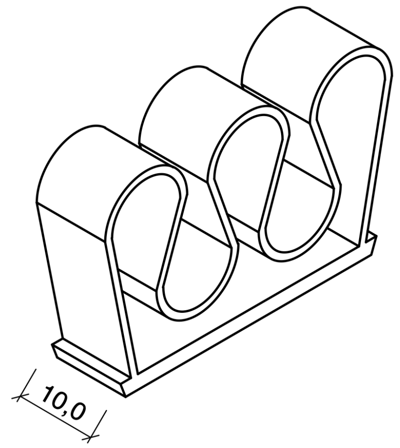


Figure 127: Isometric cable clamp (Own

HOOK

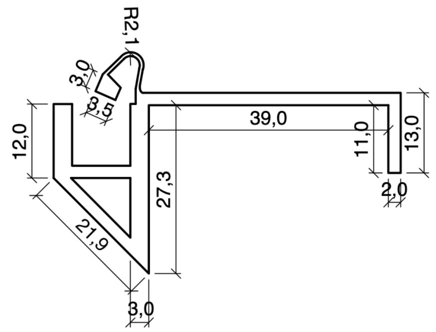


Figure 128: Technical drawing hook (Own)

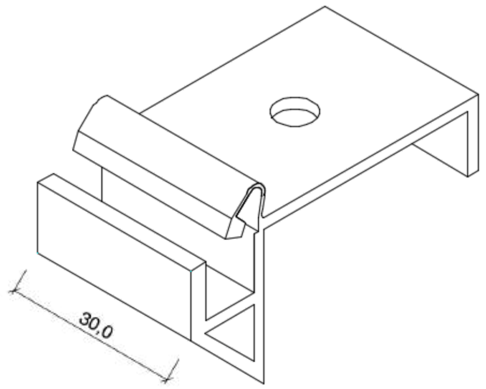


Figure 129: Isometric hook (Own)

PANEL & UNDERCUT LOCALLY

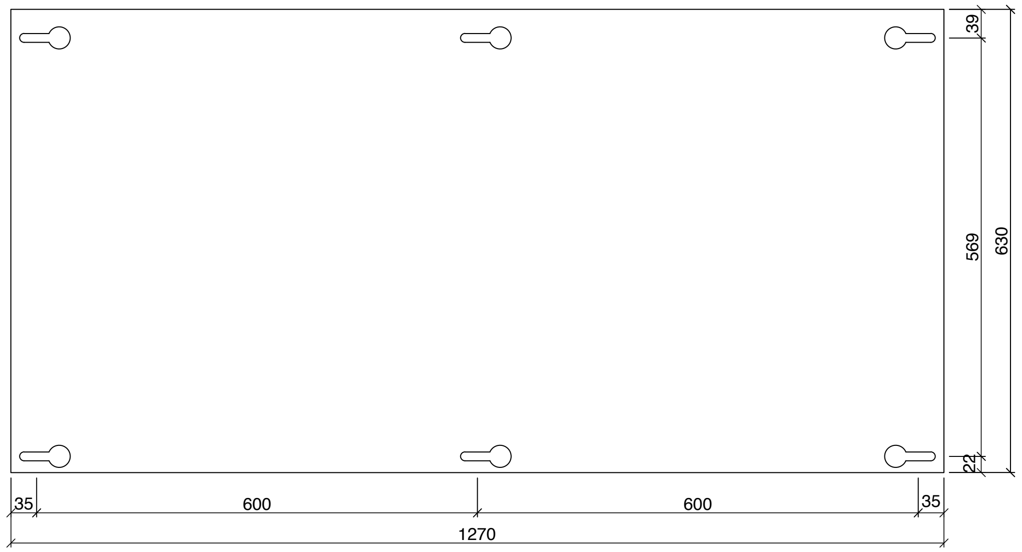


Figure 130: Rear view panel
(Own)

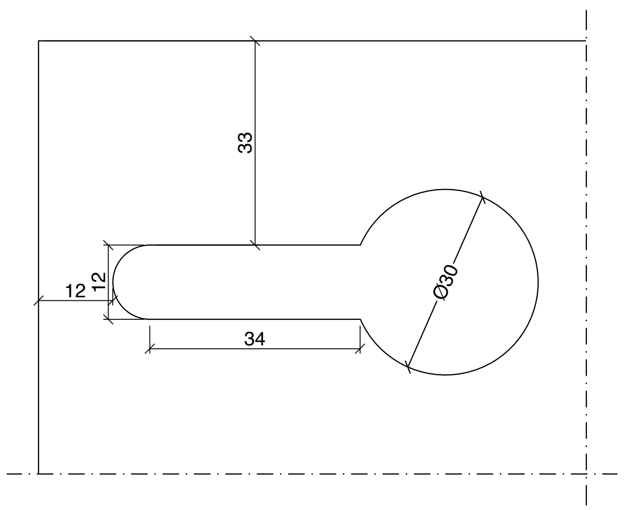


Figure 131: Undercut locally rear view
(Own)

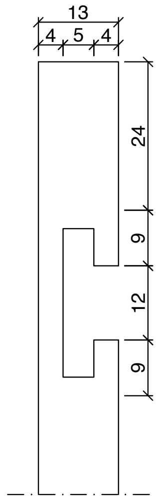


Figure 132: Undercut locally side view
(Own)

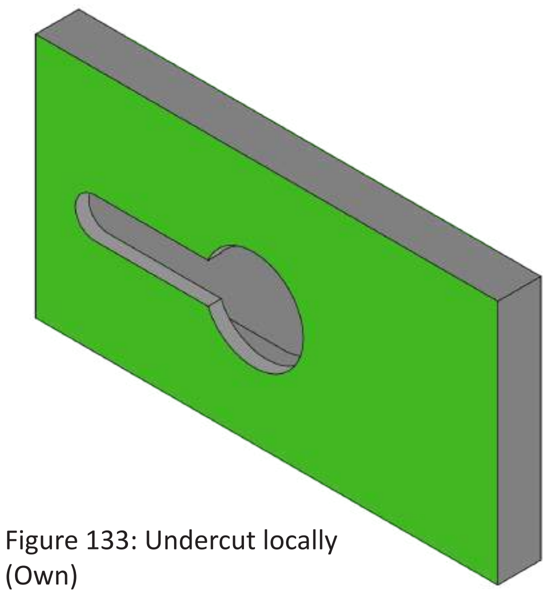


Figure 133: Undercut locally
(Own)


Figure 134: Close-up mock-up
(Own)


Figure 135: Mock-up
(Own)

9 CONCLUSION

In this thesis, research was done into the design and development of an easy-to-use facade system for mounting high pressure laminate building-integrated photovoltaics to the facade. The following main research question was formulated:

'What are the requirements for a High Pressure Laminate Building-Integrated PhotoVoltaics facade system and how can these requirements be satisfied in the design and development of an easy-to-use facade system for mounting High Pressure Laminate Building-Integrated Photovoltaics to the facade?'

To find an answer to the main research question, the thesis was divided into several phases. In the first phase of the thesis, literature research was done on all aspects of HPL facade cladding and solar panels. This was done to set up guidelines for the new facade system. The maximum dimensions of the HPL BIPV panels were investigated and it was determined that a series connection is used for connecting the panels. The literature research also established the regulations for wind loads, consequence classes and fire safety. All guidelines can be found in the program of requirements.

In the second phase of the thesis, the concept for the facade system was developed. This was done by means of a multi-criteria analysis in which the facade system was split up in different aspects. For each aspect different designs were made. These designs were tested against the various criteria set out in the schedule of requirements. In the end, for each aspect there was a design with the highest score and together these aspects formed the concept proposal. This method has made it possible to make decisions in a structured way.

In phase three, the designs of each aspect from the concept proposal were used to develop prototypes. The development of these prototypes was done by 3D printing. This was a very useful method for the entire process. But especially for the development of the compliant mechanism. Because there is a certain movement in a compliant mechanism, the 3D printed prototypes ensured that this movement could be optimized.

The material PLA was used for 3D printing the prototypes. However, this material does not meet the requirements for a facade system. Therefore, a material analysis was done for the compliant mechanism, the hook and the cable clamp. Various requirements were set for the material. The most important thing was that the material had to have approximately the same flexibility as PLA, to ensure that the movements of the prototypes with the new material were still possible. The material that will be used for the compliant mechanism and the cable clamp is PC+PBT, for the hook PEI and for the horizontal profile aluminium has been chosen because this material is usually used for these kinds of applications.

The compliant mechanism and hook have been subjected to finite element analysis. This analysis was a linear static analysis and the prototypes were analyzed and optimized to ensure that they were structurally strong enough to meet the requirements of the facade system. A practical test was also carried out for the compliant mechanism. For this practical test, two prototypes were tested for compressive and tensile strength. The prototypes were made of PLA material and were produced using a 3D printer. The results of the practical test were very good. On both compressive and tensile strength, the prototypes scored better than in the finite element analysis. By analyzing the results, some further improvements to the design were proposed. These improvements have been implemented in the design and have been subject to a second finite element analysis. The material from the material analysis was also taken into account in this analysis. The results of the finite element analysis of the final design showed that the design meets the requirements.
The method used in this thesis for the structural development of the compliant mechanism has been very useful. By first making designs and 3D printing them, followed by a finite element analysis and finally a practical test, the prototypes were completely optimised. In the finite element analysis, big steps have been made in the development of the compliant mechanism. The results of the two designs in the practical test verify the results of the finite element analysis and show that the finite element analysis has had an added value.

In the final chapter, all prototypes are brought together and form the final design of the High Pressure Laminated Building-Integrated PhotoVoltaics facade system. The system is functioning, the tolerances have been taken into account and there are technical drawings of all components of the high pressure laminate building integrated photovoltaics facade system.

10 RECOMMENDATIONS

In this thesis, much has already become clear about the development of a high pressure laminate building-integrated photovoltaics facade system. However, there are still elements that require additional research.

The first recommendation is to do more research on the materials and production methods resulting from the material analysis. This involves the manufacturability of the designs. It will also be an added value to produce the prototypes in the material resulting from the material analysis. This allows the design to be developed even better.

A limitation in the system is the maximum height of the panels. This is due to the maximum free span that is possible between the connection points of the panel. Further research could be done into how these panels can be strengthened in such way that the maximum height of the panels can be increased significantly. This would also increase the design freedom of the system.

The system has now only been developed for the application of high pressure laminate building-integrated photovoltaics facade panels. However, there are many more facade claddings on the market and it would be interesting to investigate whether this system could also be applied to other facade claddings.

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Appendix I: Material properties high pressure laminate

Properties	Test method	Property or attribute	Unit	Result [A] [B] Grade: EDS (Meteon®) Standard: EN 438-6 Colour/Decor: All [B]	Grade: EDF (Meteon® FR) Standard: EN 438-6 Colour/Decor: All [B]
Surface quality					
Surface quality	EN 438-2 : 4	Spots, dirt, similar surface defects	mm²/m²	≤ 2	
			in²/ft²	≤ 0.0003	
		Fibres, hairs & scratches	mm/m²	≤ 20	
			in/ft²	≤ 0.073	
Dimensional tolerances					
Dimensional tolerances	EN 438-2 : 5	Thickness	mm	6.0 ≤ t < 8.0: +/- 0.40	
				8.0 ≤ t < 12.0: +/- 0.50	
				12.0 ≤ t < 16.0: +/- 0.60	
			in	0.2362 ≤ t < 0.3150: +/- 0.0157	
				0.3150 ≤ t < 0.4724: +/- 0.0197	
				0.4724 ≤ t < 0.6299: +/- 0.0236	
	EN 438-2 : 9	Flatness	mm/m	≤ 2	
			in/ft	≤ 0.024	
	EN 438-2 : 6	Length & width	mm	+ 5 / - 0	
			in	+ 0.1968 / - 0	
	EN 438-2 : 7	Straightness of edges	mm/m	≤ 1	
			in/ft	≤ 0.012	
	Trespa Standard	Squareness	mm	2550 x 1860 = max. difference between diagonals (x-y) = 4	
				3050 x 1530 = max. difference between diagonals (x-y) = 4	
				3650 x 1860 = max. difference between diagonals (x-y) = 5	
				4270 x 2130 = max. difference between diagonals (x-y) = 6	
			in	100.39 x 73.23 = max. difference between diagonals (x-y) = 0.1575	
				120.08 x 60.24 = max. difference between diagonals (x-y) = 0.1575	
				143.70 x 73.23 = max. difference between diagonals (x-y) = 0.1969	
				168.11 x 83.86 = max. difference between diagonals (x-y) = 0.2362	
		Curved Elements [C]	Radius inside/ outside corner mm	n.a.	970/980 +/- 5%
					1290/1300 +/- 5%
			Radius inside/ outside corner in		38.19 / 38.58 +/- 5%
					50.79 / 51.18 +/- 5%
			Max. height mm	n.a.	r 970 / 980: 1300 (-0/+5)
					r 1290 / 1300: 1300 (-0/+5)
			Max. height in		r 38.19 / 38.58: 51.18 (-0/+5)
					r 50.79 / 51.18: 51.18 (-0/+5)
			Max. angle (°)	n.a.	90 +/- 0.5°
Physical properties					
Resistance to impact by large diameter ball	EN 438-2 : 21	Indentation diameter - 6 ≤ t mm with drop height 1.8 m	mm	≤ 10	
Impact resistance	ASTM D5420-04	Mean failure height	ft	1.0466	
		Mean failure energy	J	11.3	
Dimensional stability at elevated temperature	EN 438-2 : 17	Cumulative dimensional change	Longitudinal %	≤ 0.25	
			Transversal %	≤ 0.25	
Resistance to wet conditions	EN 438-2 : 15	Mass increase	%	≤ 3	
		Appearance	Rating	≥ 4	
	ASTM D2247-02	Water resistance	Rating	No change	
	ASTM D2842-06	Water absorption	%	0.5	
Modulus of elasticity	EN ISO 178	Stress	MPa	≥ 9000	
					Curved Elements: ≥ 8000
	ASTM D638-08	Stress	psi	≥ 1305000	
Flexural strength	EN ISO 178	Stress	MPa	≥ 120	
	ASTM D790-07	Stress	psi	≥ 17500	
Tensile strength	EN ISO 527-2	Stress	MPa	≥ 70	
	ASTM D638-08	Stress	psi	≥ 10150	
Density	EN ISO 1183	Density	g/cm³	≥ 1.35	
	ASTM D792-08	Density	g/cm³	≥ 1.35	
Resistance to fixings	ISO 13894-1	Pull out strength	N	6 mm: ≥ 2000	
				8 mm: ≥ 3000	
				≥ 10 mm: ≥ 4000	
				0.2362 in: ≥ 2000	
				0.3150 in: ≥ 3000	
				≥ 0.3937 in: ≥ 4000	
Other properties					
Thermal resistance / conductivity	EN 12524	Thermal resistance / conductivity	W/mK	0.3	

[A] Due to conversion from metric values, the US values provided are approximate.
[B] All data are related to the products mentioned in the Trespa® Meteon® standard delivery programme.
[C] Availability limited – contact your local Trespa representative for more details.

(Trespa, 2020)

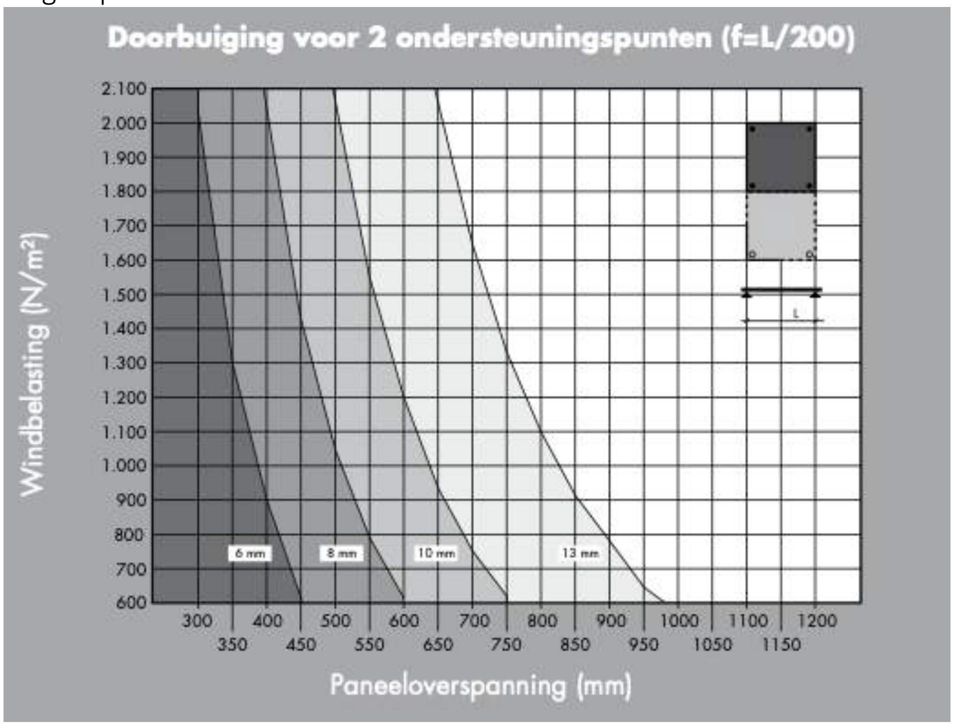
Properties	Test method	Property or attribute	Unit	Result [A] [B]	
				Grade: EDS (Meteon®) Standard: EN 438-6 Colour/Decor: All [B]	Grade: EDF (Meteon® FR) Standard: EN 438-6 Colour/Decor: All [B]
Weather resistance properties					
Resistance to climatic shock	EN 438-2 : 19	Flexural strength index (Ds)	Index	≥ 0.95	
		Flexural modulus index (Dm)	Index	≥ 0.95	
		Appearance	Rating	≥ 4	
Resistance to artificial weathering (incl. Light fastness) *West European cycle*	EN 438-2 : 29	Contrast	Grey scale ISO 105 A02	4-5 [E]	
		Contrast	Grey scale ISO 105 A03	4-5	
		Appearance	Rating	≥ 4	
Resistance to artificial weathering (incl. Light fastness) [D] *Florida cycle 3000hrs*	Trespa Standard	Contrast	Grey scale ISO 105 A02	4-5 [E]	
		Contrast	Grey scale ISO 105 A03	4-5	
		Appearance	Rating	≥ 4	
Resistance to SO_2	DIN 50018	Contrast	Grey scale ISO 105 A02	4-5 [E]	
		Contrast	Grey scale ISO 105 A03	4-5	
		Appearance	Rating	≥ 4	
Fire performance					
Europe					
Reaction to Fire	EN 438-7	Classification t ≥ 6 mm / 0.2362 in	Euroclass		B-s2, d0
		Classification t ≥ 8 mm / 0.3150 in (Metal Frame)	Euroclass	D-s2, d0	B-s1, d0
Reaction to Fire (Germany)	DIN 4102-1	Classification	Class	B2	B1
Reaction to Fire (France)	NF P 92-501	Classification	Class	M3	M1
North America					
Material Surface Burning Characteristics [F]	ASTM E84/UL 723	Classification	Class	n.a.	A
		Flame Spread Index	FSI	n.a.	0-25
		Smoke Developed Index	SDI	n.a.	0-450
Asia Pacific					
Reaction to Fire (China)	GB 8624	Classification	Class	D-s2, d0	B-s1, d0, t1

[A] Due to conversion from metric values, the US values provided are approximate.
[B] All data are related to the products mentioned in the Trespa® Meteon® standard delivery programme.
[D] Not valid for following colours: A04.0.1/A10.1.8/A20.2.3/A17.3.5/A12.3.7.
For other applications/colours such as project colours, please contact your local Trespa representative.
[E] For more information on Delta E values, please contact the Technical Service Department of Trespa North America at 1-800-487-3772.
[F] Laboratory test results are not intended to represent hazards that may be present under actual fire conditions.
For multi-story applications, where local or national building codes may require full-scale fire testing in accordance with NFPA 285(U.S.) or Can/ULC-S134 (Canada), please visit our website www.trespa.info or contact the Technical Service Department of Trespa North America at 1-800-487-3772 for installation information.

(Trespa, 2020)

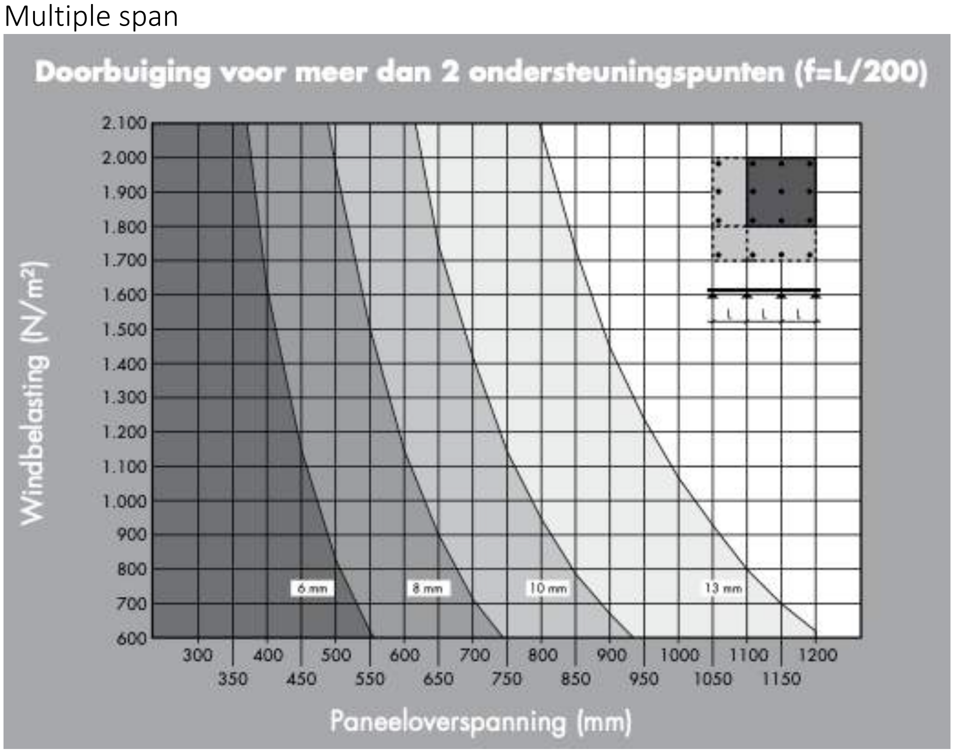
Appendix II: Span graphs

Single span



(Trespa, 2020)

Multiple span



(Trespa, 2020)

Appendix III: Calculations weight & size panel

Wind area I, maximum height 20 meters at the coast

maximum windload: 1,8 kN/m2

6mm panel

Weight HPL:	8,4	kg/m2	
Weight cell:	0,3	kg/cell	(0,16 x 0,16m)
maximum weight:	50	kg	

size panel	maximum (single-span)			minimum (multiple span)			optimal			maximum (multispan)		
x-direction:	2	cells		2	cells		4	cells		48	cells	
y-direction (maximum):	2	cells		2	cells		2	cells		2	cells	
Weight cells:	1,2	kg		1,2	kg		2,4	kg		28,8	kg	
Weight panel:	0,86	kg		0,86	kg		1,72	kg		20,64	kg	
Total weight:	2,06	kg		2,06	kg		4,12	kg		49,44	kg	
size panel (m):	0,32	x	0,32	0,32	x	0,32	0,64	x	0,32	7,68	x	0,32
	X		Y	X		Y	X		Y	X		Y

8mm panel

Weight HPL:	11,2	kg/m2	
Weight cell:	0,3	kg/cell	(0,16 x 0,16m)
maximum weight:	50	kg	

size panel	maximum (single-span)			minimum (multiple span)			optimal			maximum (multispan)		
x-direction:	2	cells		3	cells		4	cells		42	cells	
y-direction (maximum):	2	cells		2	cells		2	cells		2	cells	
Weight cells:	1,2	kg		1,8	kg		2,4	kg		25,2	kg	
Weight panel:	1,15	kg		1,72	kg		2,29	kg		24,08	kg	
Total weight:	2,35	kg		3,52	kg		4,69	kg		49,28	kg	
size panel (m):	0,32	x	0,32	0,48	x	0,32	0,64	x	0,32	6,72	x	0,32
	X		Y	X		Y	X		Y	X		Y

10mm panel

Weight HPL:	14	kg/m2	
Weight cell:	0,3	kg/cell	(0,16 x 0,16m)
maximum weight:	50	kg	

size panel	maximum (single-span)			minimum (multiple span)			optimal			maximum (multispan)		
x-direction:	3	cells		4	cells		6	cells		25	cells	
y-direction (maximum):	3	cells		3	cells		3	cells		3	cells	
Weight cells:	2,7	kg		3,6	kg		5,4	kg		22,5	kg	
Weight panel:	3,23	kg		4,30	kg		6,45	kg		26,88	kg	
Total weight:	5,93	kg		7,90	kg		11,85	kg		49,38	kg	
size panel (m):	0,48	x	0,48	0,64	x	0,48	0,96	x	0,48	4	x	0,48
	X		Y	X		Y	X		Y	X		Y

13mm panel

Weight HPL:	18,2	kg/m2	
Weight cell:	0,3	kg/cell	(0,16 x 0,16m)
maximum weight:	50	kg	

size panel	maximum (single-span)			minimum (multiple span)			optimal			maximum (multispan)		
x-direction:	4	cells		5	cells		8	cells		16	cells	
y-direction (maximum):	4	cells		4	cells		4	cells		4	cells	
Weight cells:	4,8	kg		6	kg		9,6	kg		19,2	kg	
Weight panel:	7,45	kg		9,32	kg		14,91	kg		29,82	kg	
Total weight:	12,25	kg		15,32	kg		24,51	kg		49,02	kg	
size panel(m):	0,64	x	0,64	0,8	x	0,64	1,28	x	0,64	2,56	x	0,64
	X		Y	X		Y	X		Y	X		Y

Wind area III, maximum height 20 metres at the coast

maximum windload: 0,74 kN/m2

6mm panel

Weight HPL:	8,4	kg/m2	
Weight cell:	0,3	kg/cell	(0,16 x 0,16m)
maximum weight:	50	kg	

size panel	maximum (single-span)			minimum (multiple span)			optimal			maximum (multispan)		
x-direction:	2	cells		3	cells		4	cells		48	cells	
y-direction (maximum):	2	cells		2	cells		2	cells		2	cells	
Weight cells:	1,2	kg		1,8	kg		2,4	kg		28,8	kg	
Weight panel:	0,86	kg		1,29	kg		1,72	kg		20,64	kg	
Total weight:	2,06	kg		3,09	kg		4,12	kg		49,44	kg	
size panel:	0,32	x	0,32	0,48	x	0,32	0,64	x	0,32	7,68	x	0,32
	X		Y	X		Y	X		Y	X		Y

8mm panel

Weight HPL:	11,2	kg/m2	
Weight cell:	0,3	kg/cell	(0,16 x 0,16m)
maximum weight:	50	kg	

size panel	maximum (single-span)			minimum (multiple span)			optimal			maximum (multispan)		
x-direction:	3	cells		4	cells		6	cells		28	cells	
y-direction (maximum):	3	cells		3	cells		3	cells		3	cells	
Weight cells:	2,7	kg		3,6	kg		5,4	kg		25,2	kg	
Weight panel:	2,58	kg		3,44	kg		5,16	kg		24,08	kg	
Total weight:	5,28	kg		7,04	kg		10,56	kg		49,28	kg	
size panel:	0,48	x	0,48	0,64	x	0,48	0,96	x	0,48	4,48	x	0,48
	X		Y	X		Y	X		Y	X		Y

10mm panel

Weight HPL:	14	kg/m2	
Weight cell:	0,3	kg/cell	(0,16 x 0,16m)
maximum weight:	50	kg	

size panel	maximum (single-span)			minimum (multiple span)			optimal			maximum (multispan)		
x-direction:	4	cells		5	cells		8	cells		18	cells	
y-direction (maximum):	4	cells		4	cells		4	cells		4	cells	
Weight cells:	4,8	kg		6	kg		9,6	kg		21,6	kg	
Weight panel:	5,73	kg		7,17	kg		11,47	kg		25,80	kg	
Total weight:	10,53	kg		13,17	kg		21,07	kg		47,40	kg	
size panel:	0,64	x	0,64	0,8	x	0,64	1,28	x	0,64	2,88	x	0,64
	X		Y	X		Y	X		Y	X		Y

13mm panel

Weight HPL:	18,2	kg/m2	
Weight cell:	0,3	kg/cell	(0,16 x 0,16m)
maximum weight:	50	kg	

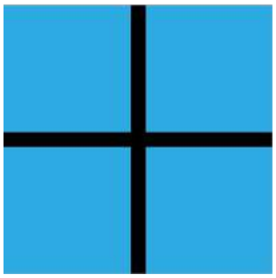
size panel	maximum (single-span)			minimum (multiple span)			optimal			maximum (multispan)		
x-direction:	5	cells		6	cells		10	cells		13	cells	
y-direction (maximum):	5	cells		5	cells		5	cells		5	cells	
Weight cells:	7,5	kg		9	kg		15	kg		19,5	kg	
Weight panel:	11,65	kg		13,98	kg		23,30	kg		30,28	kg	
Total weight:	19,15	kg		22,98	kg		38,30	kg		49,78	kg	
size panel:	0,8	x	0,8	0,96	x	0,8	1,6	x	0,8	2,08	x	0,8
	X		Y	X		Y	X		Y	X		Y

Appendix IV: Criteria score explanation

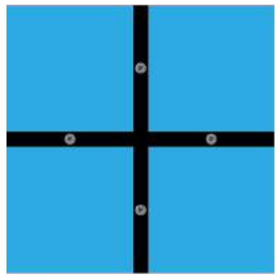
Boundary conditions

Visibility

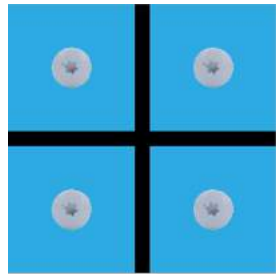
The visibility of the mounting system on the outside of the façade.



o Invisible



o Semi-invisible



o Visible

Demountability

The demountability of the panels for maintenance purposes.

- o Separately demountable
- o Not separately demountable

No adjustments on building site

The panels must not be adjusted on the building site.

- o No adjustments
- o Adjustments

Structural safety

The construction of the system should be (visible) safe.

- o Mechanically fixed
- o Mechanical and chemical fixing combined
- o Chemically fixed

Production

Production method

The difficulty of the production method.

Complicated •————————•————————• Easy
1 2 3

Risk of errors

Risk of errors in production and the resulting residual waste.

High •————————•————————• Low
1 2 3

Amount of parts

The amount of parts affects the number of production lines and the costs.

A lot •————————•————————• One
1 2 3

Assembly

Easy to mount

Easy and quick handling methods.

Complicated •————————•————————• Easy
1 2 3

Multi-step assembly

Multi-step assembly ensures that there is one step between the assembly of the bottom and top profile. This allows the wiring of the BIPV system to be connected.

Single-step •————————•————————• Multi-step
1 2 3

Expandable

Possibility of adding additional components.

Not possible •————————•————————• Possible
1 2 3

Resilience of tolerance
Adjustment possibility to compensate for tolerances.

Non-adjustable •————————•————————• Adjustable
1 2 3

Physical ergonomics
The weight of the product must not exceed 50 kilograms. No heavy tools. Enough space to manoeuvre.

Difficult •————————•————————• Easy
1 2 3

Use

Maintenance
The possibility of doing maintenance.

Hard •————————•————————• Easy
1 2 3

Adaptability
The possibility of changing parts.

Hard •————————•————————• Easy
1 2 3

End-of-life

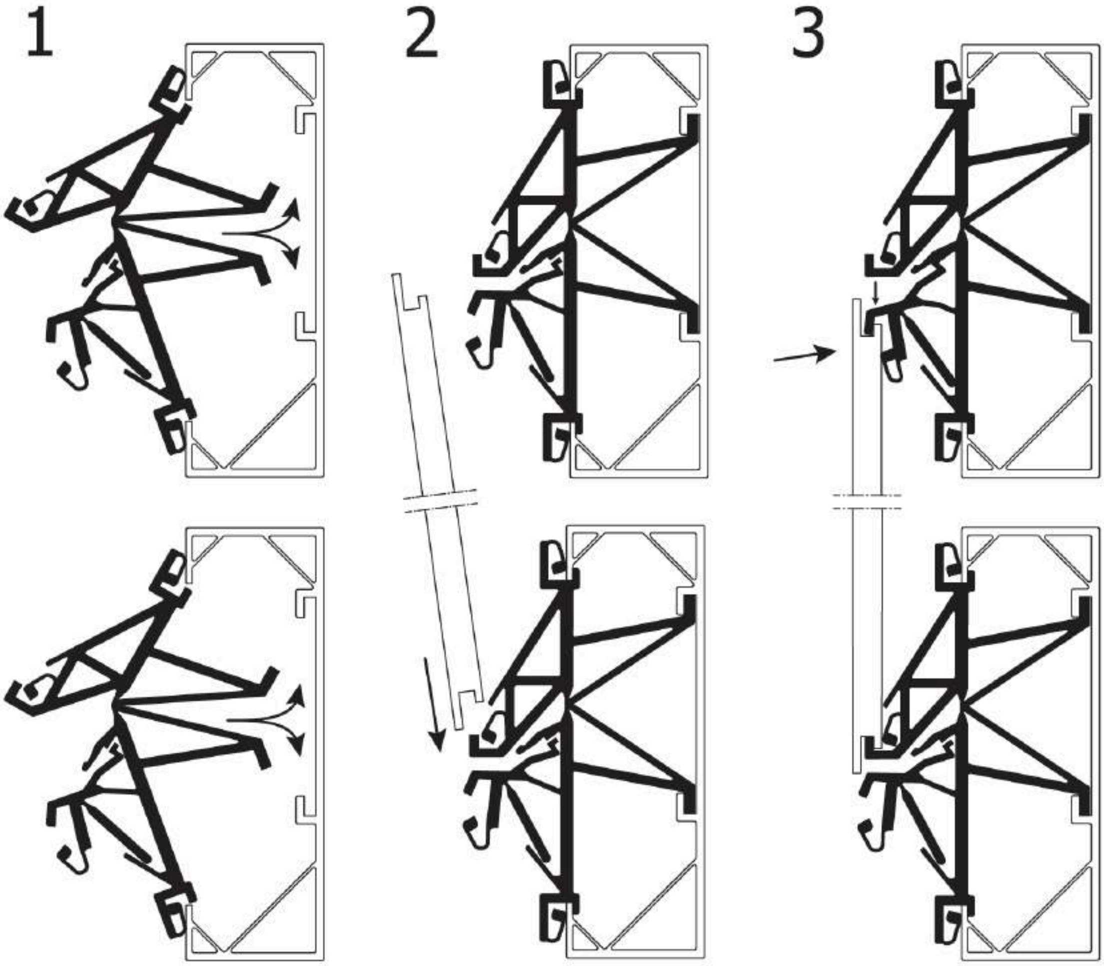
Disassembly
Easy to disassemble and reuse.

Hard •————————•————————• Easy
1 2 3

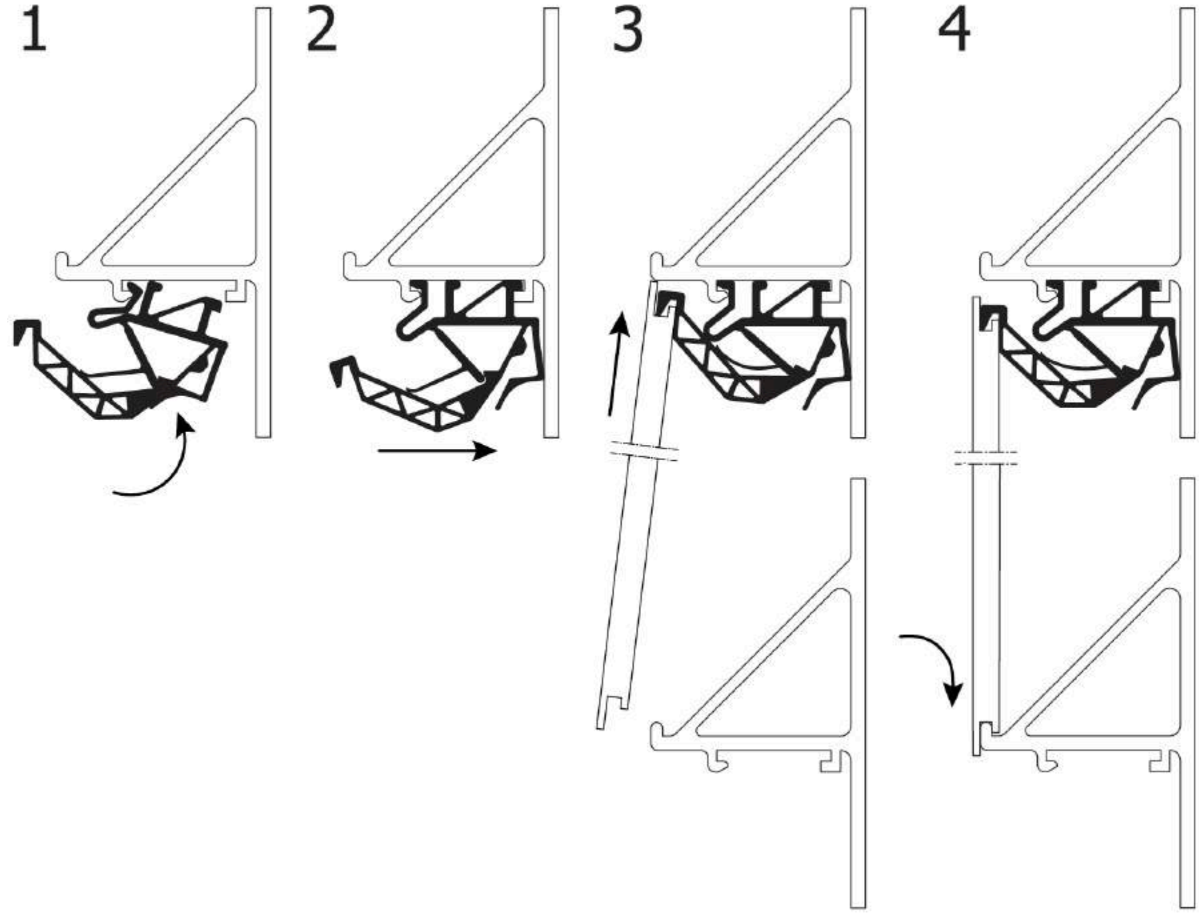
Appendix V: Bucky Lab project concepts

Concept 1

Concept 2



Concept 1: Functioning of the system



Concept 2: Functioning of the system

Appendix VI: Results finite element analysis

Analysis 1: Prototype 1.4

Results tensile analysis

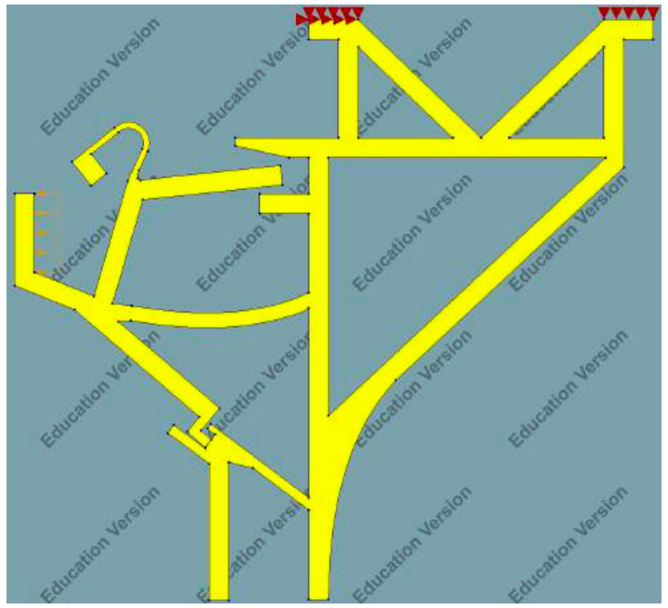


Figure 1: Geometry

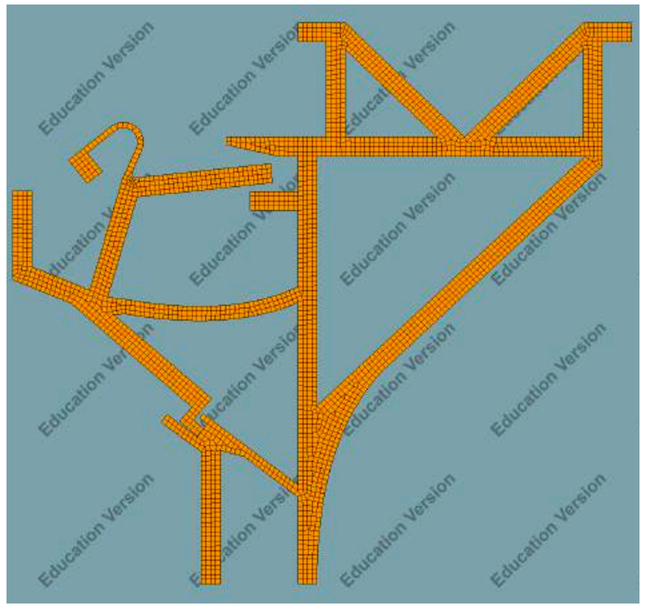


Figure 2: Mesh geometry

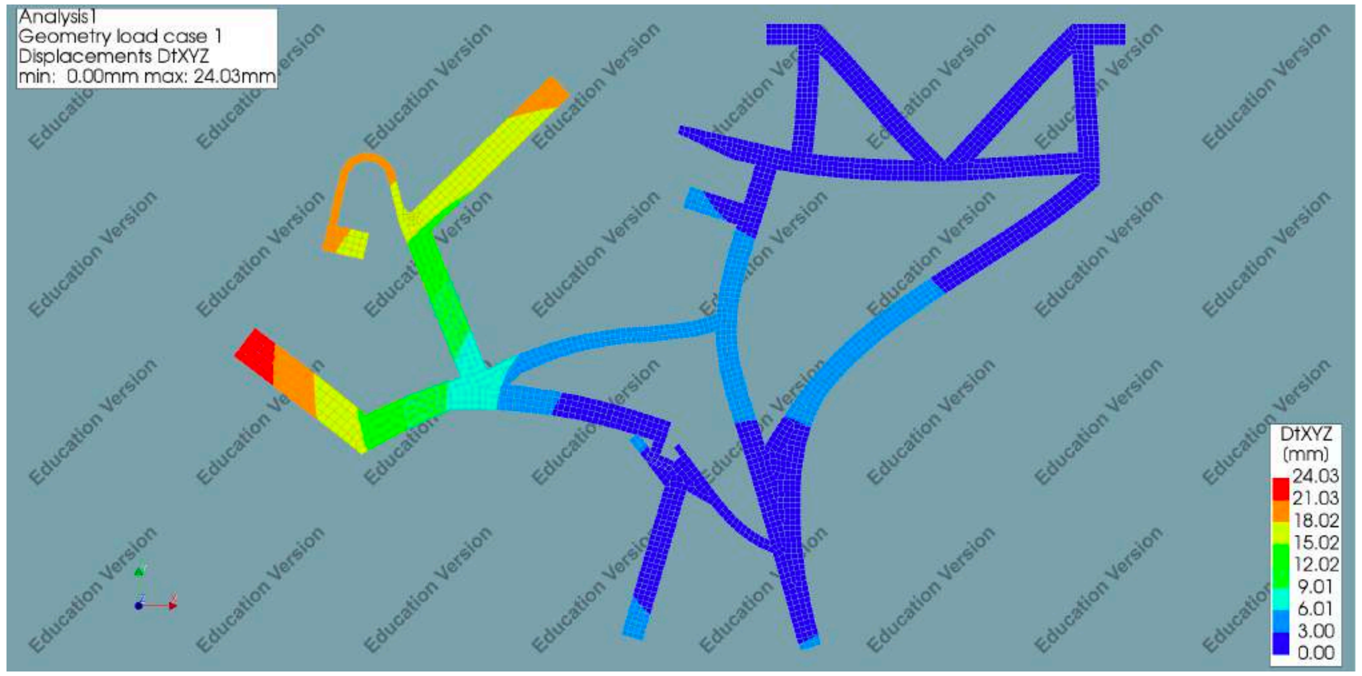


Figure 4: Displacement 30mm depth

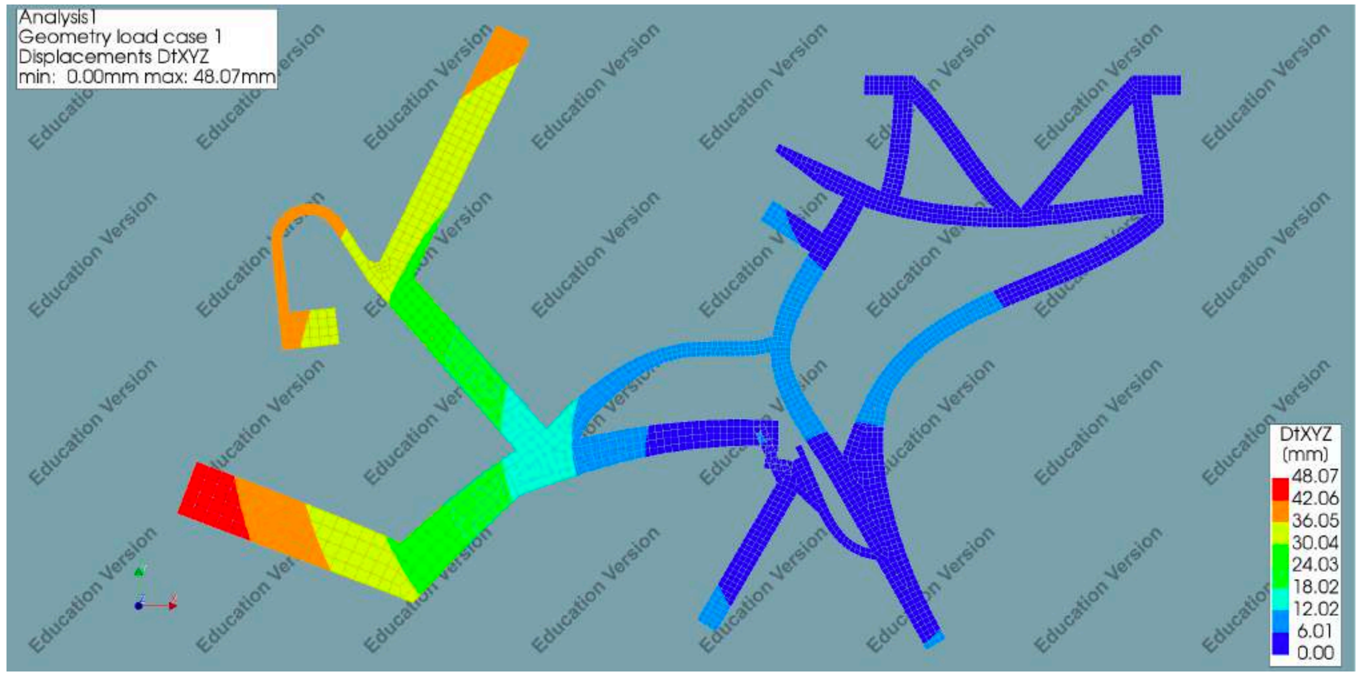


Figure 3: Displacement 15mm depth

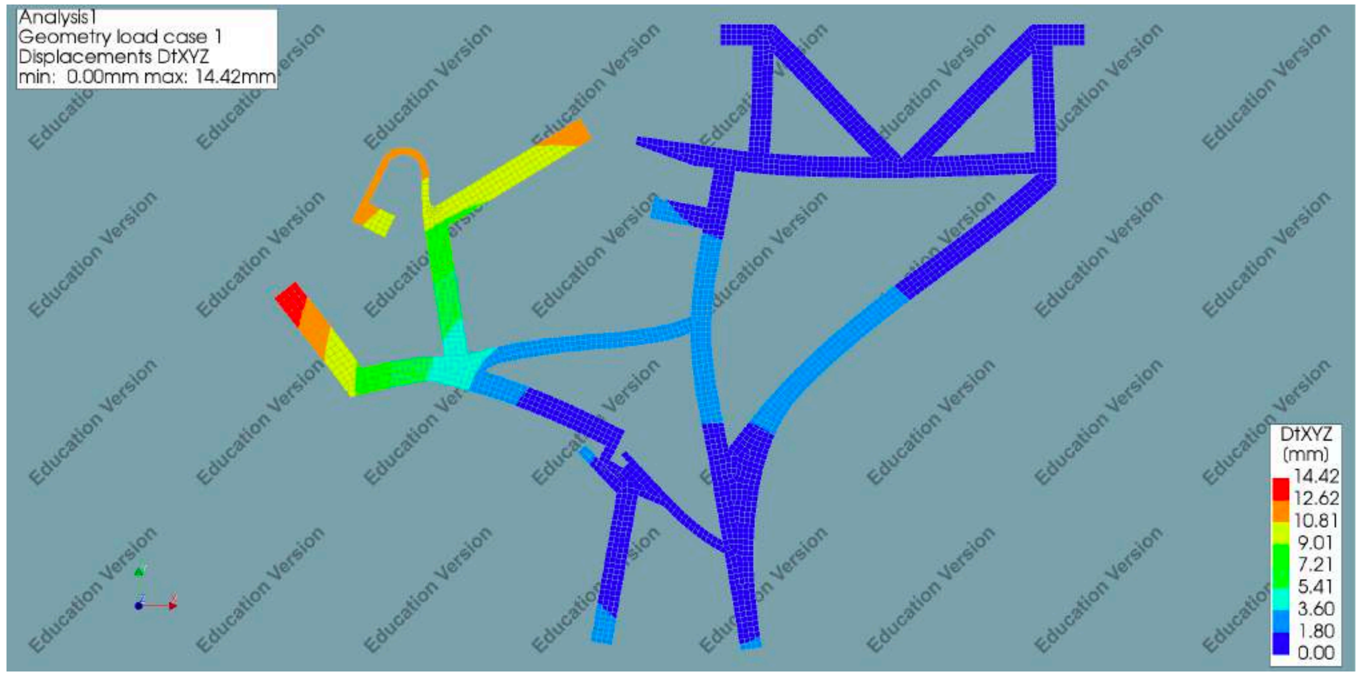


Figure 5: 50mm depth

Figure 6: Tensile stresses 15mm depth

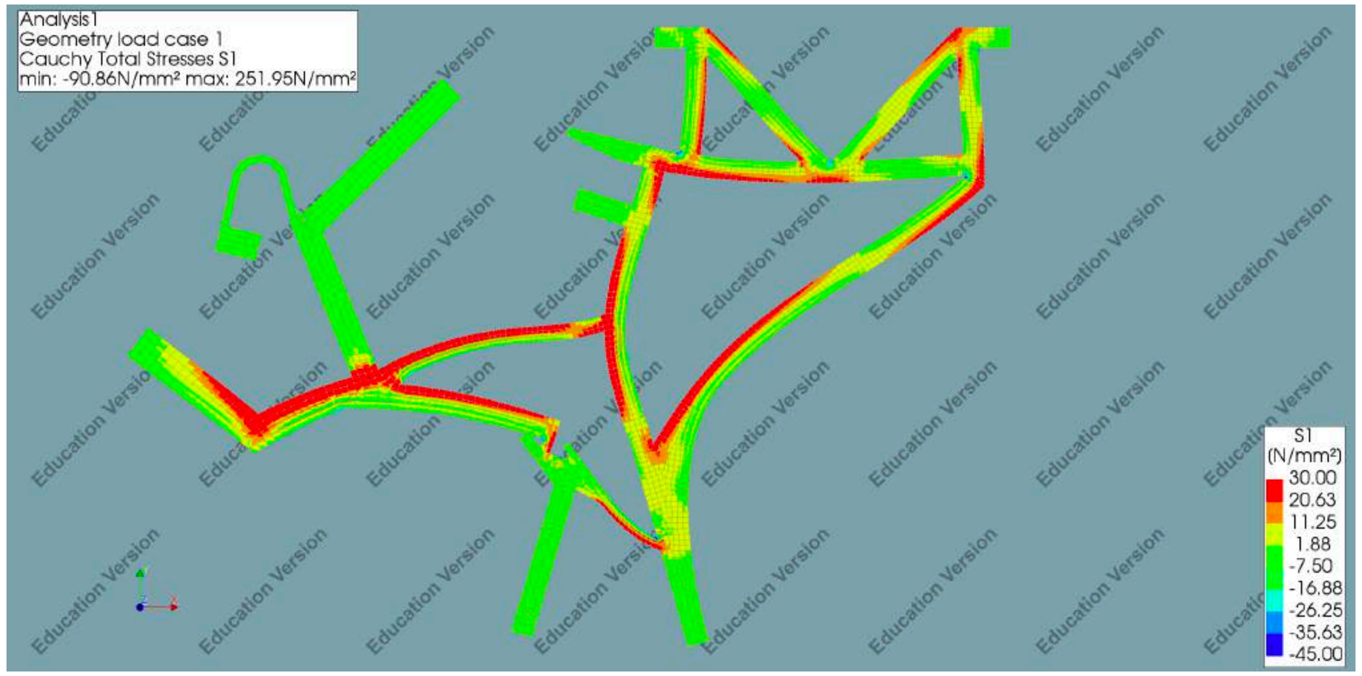


Figure 7: Tensile stresses 30mm depth

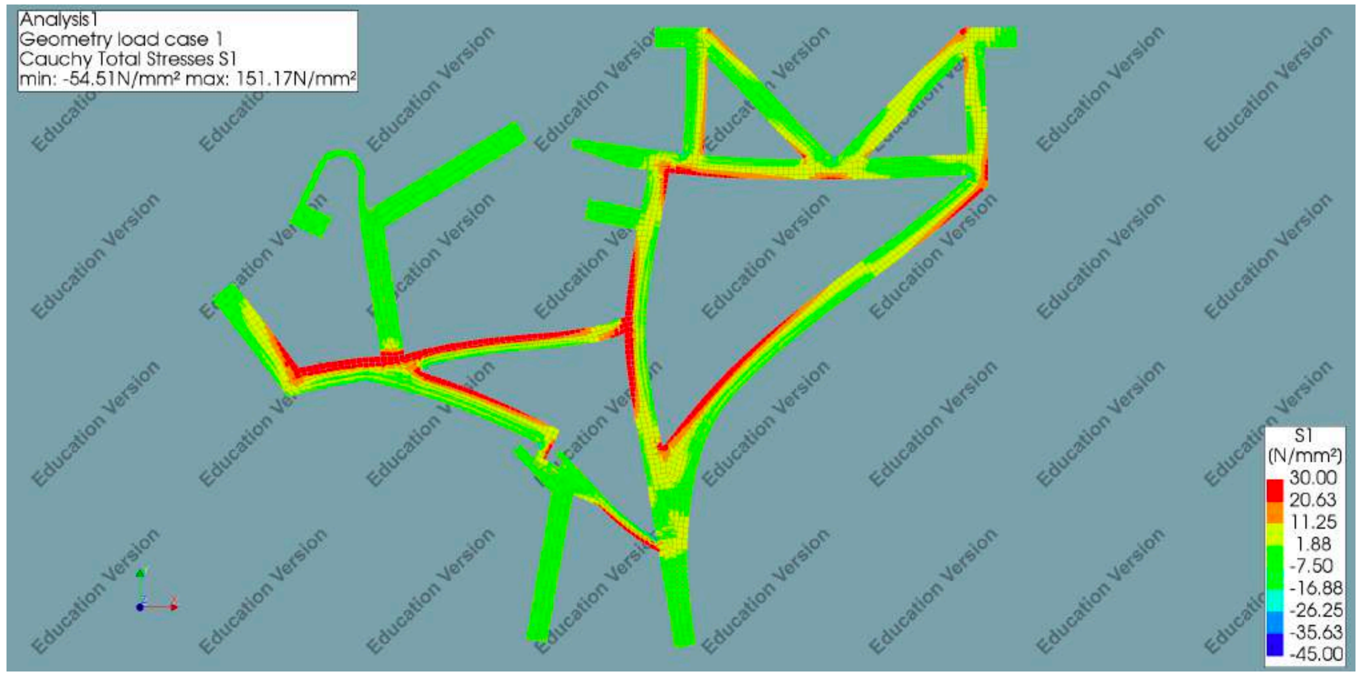


Figure 8: Tensile stresses 50mm depth

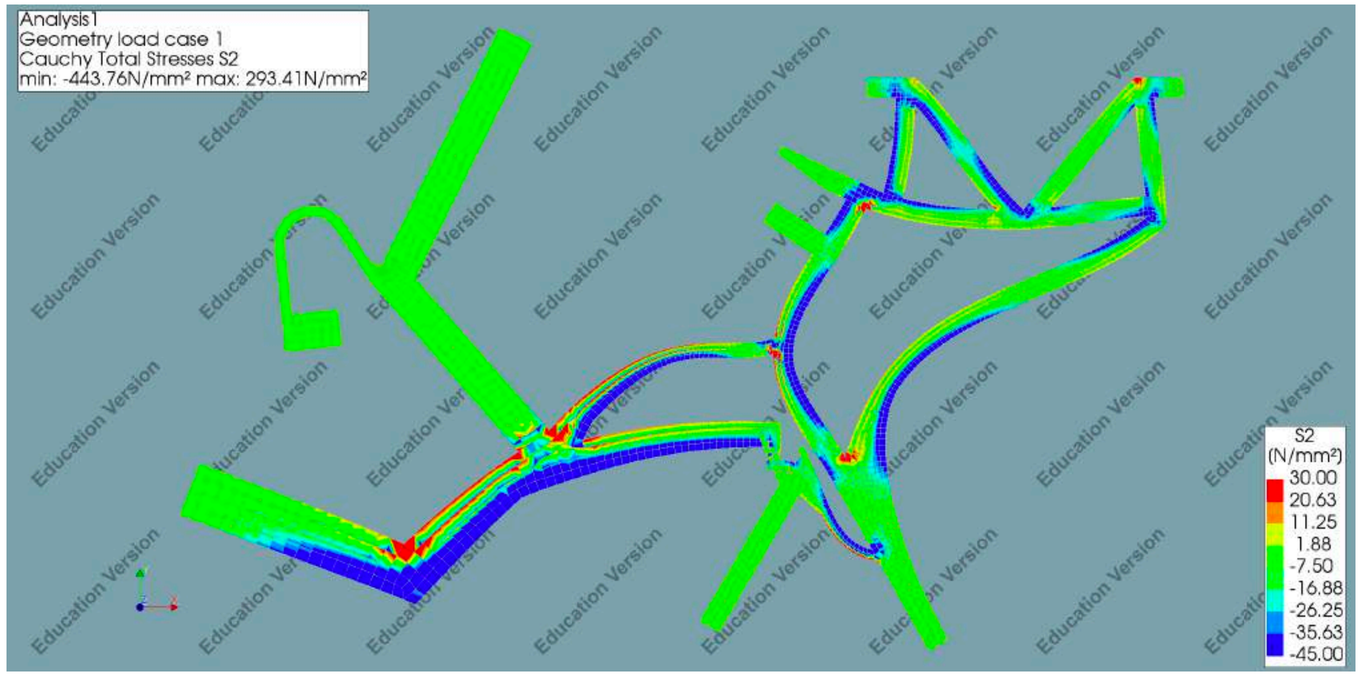


Figure 9: Compressive stresses 15mm depth

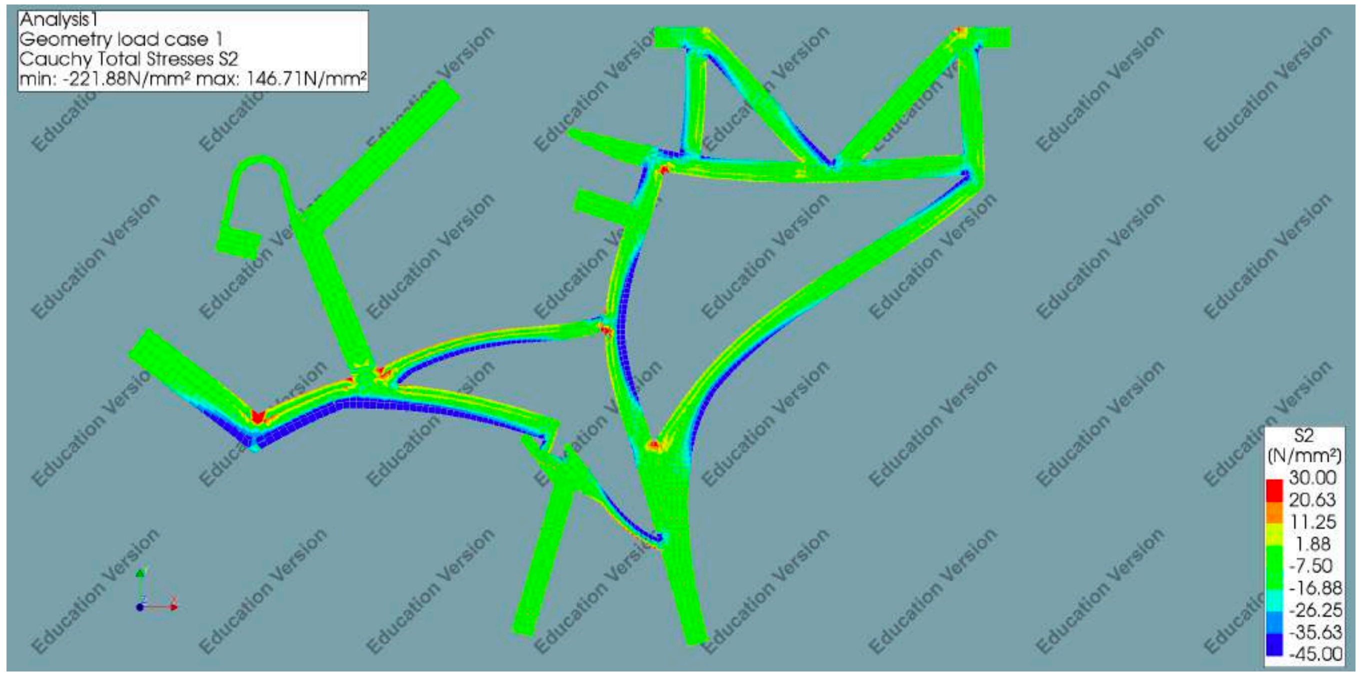


Figure 10: Compressive stresses 30mm depth

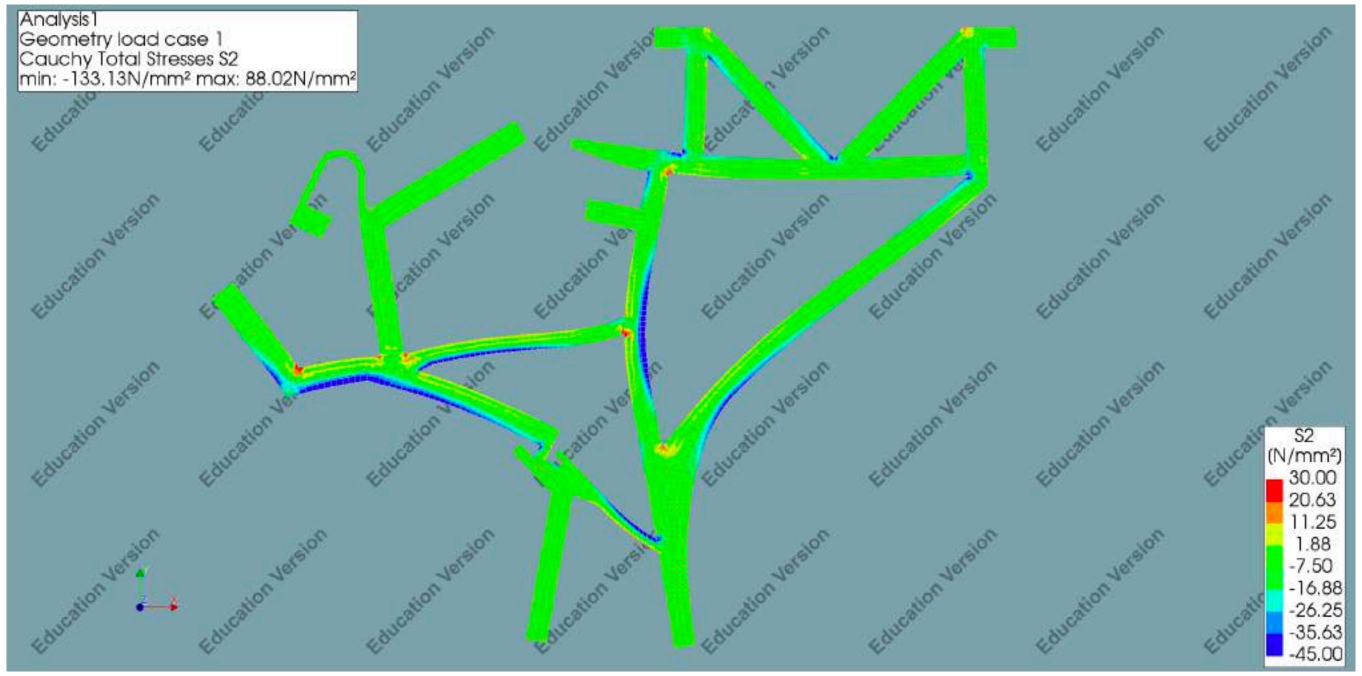


Figure 11: Compressive stresses 50mm depth

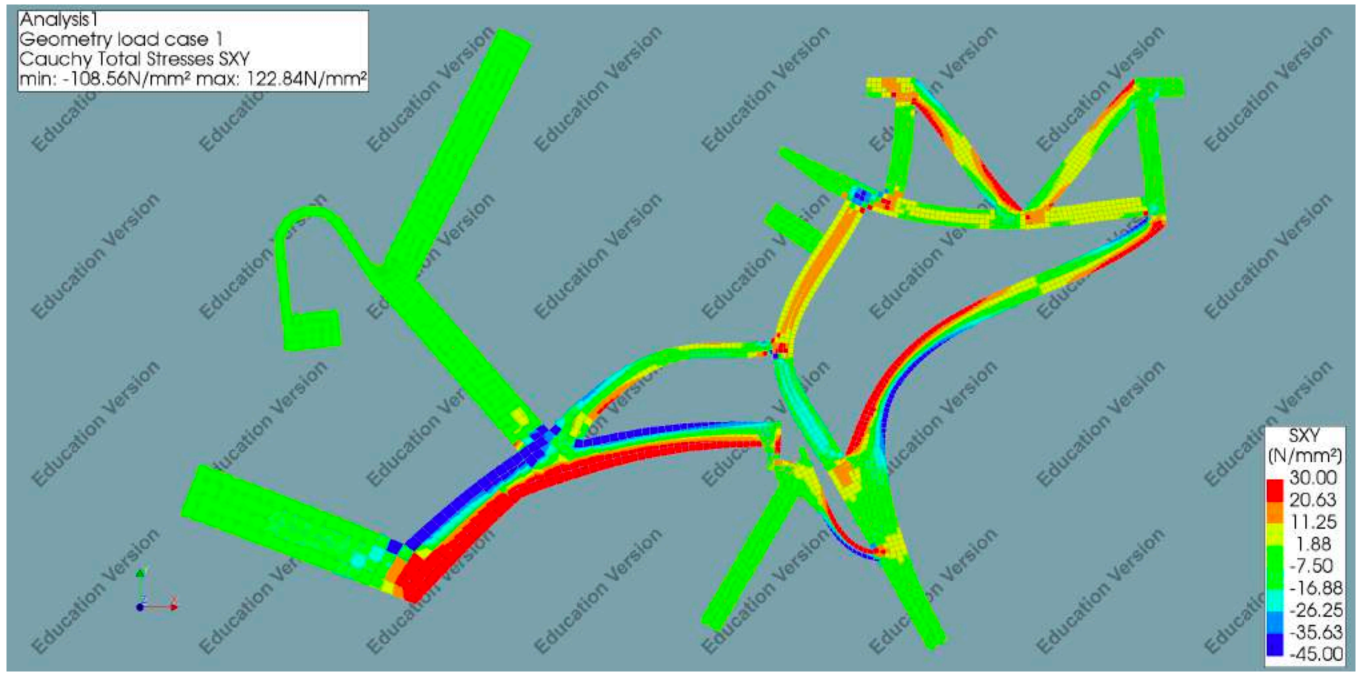


Figure 12: Shear stresses 15mm depth

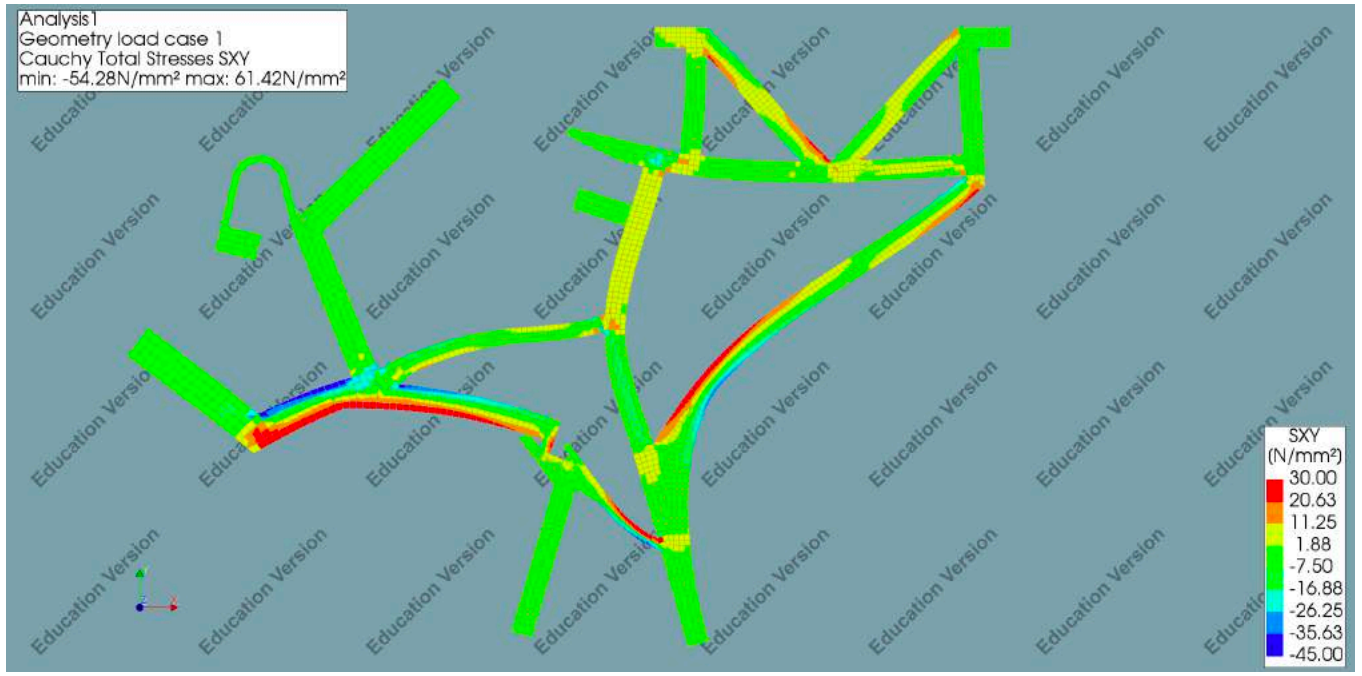


Figure 13: Shear stresses 30mm depth

Figure 14: Shear stresses 50mm depth

<u>Results compressive analysis</u>

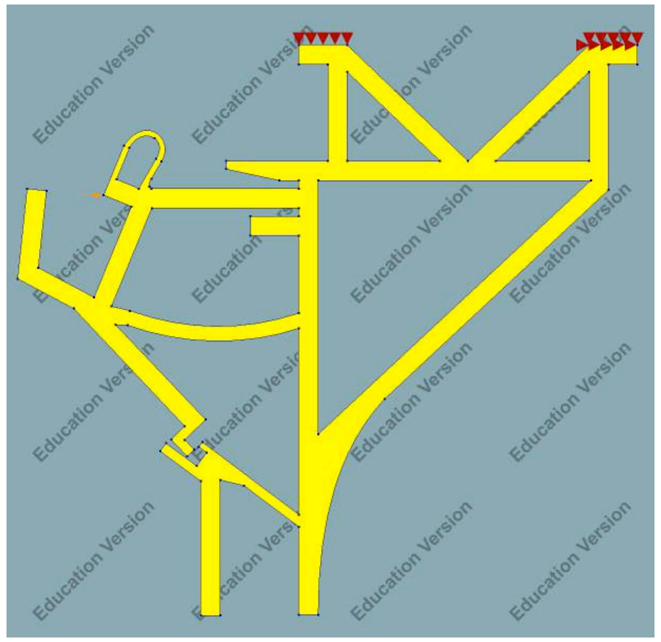


Figure 15: Geometry

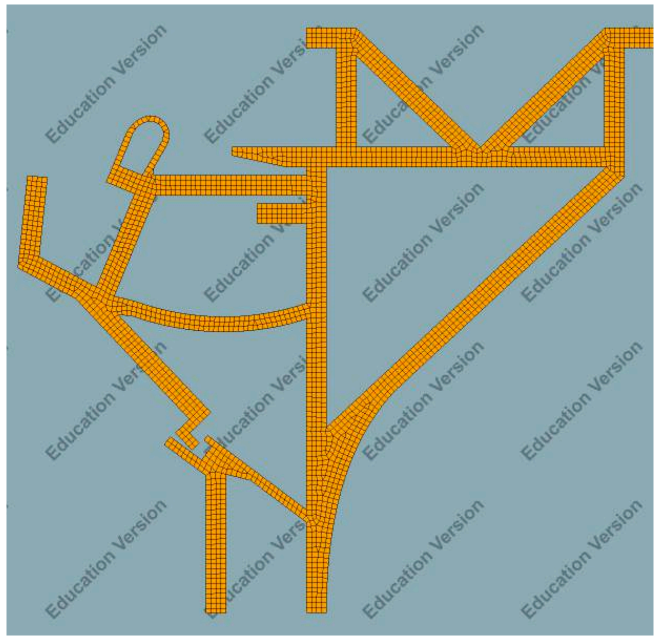


Figure 16: Mesh geometry

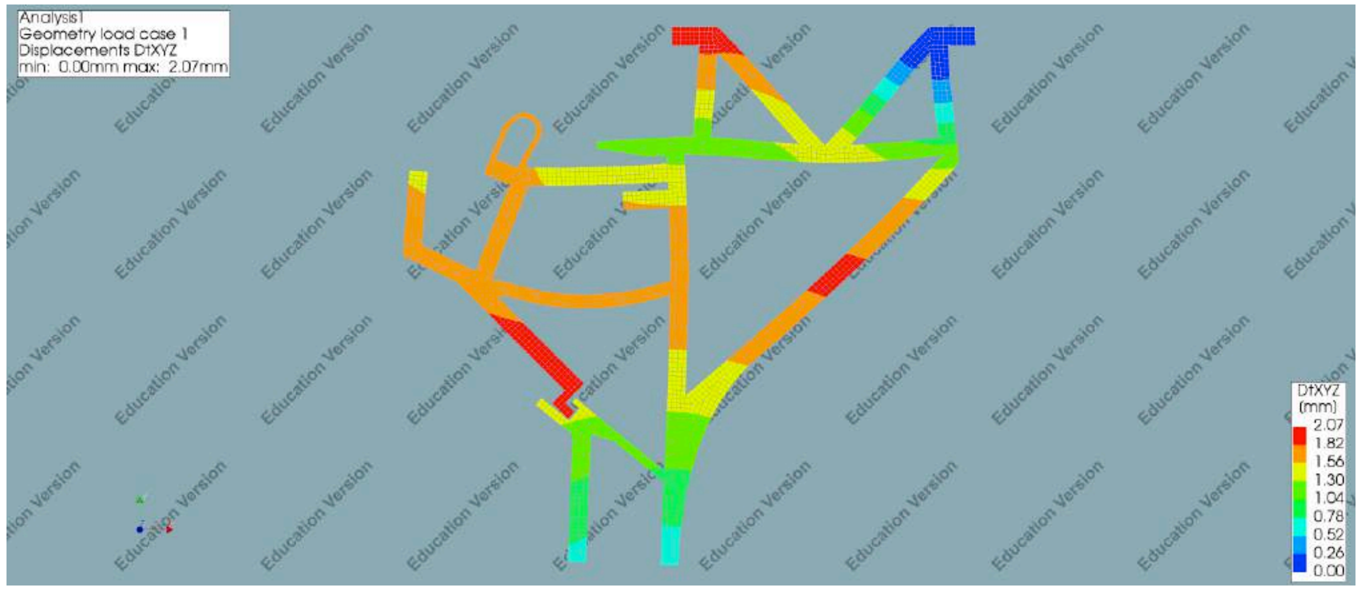


Figure 17: Displacement 15mm depth

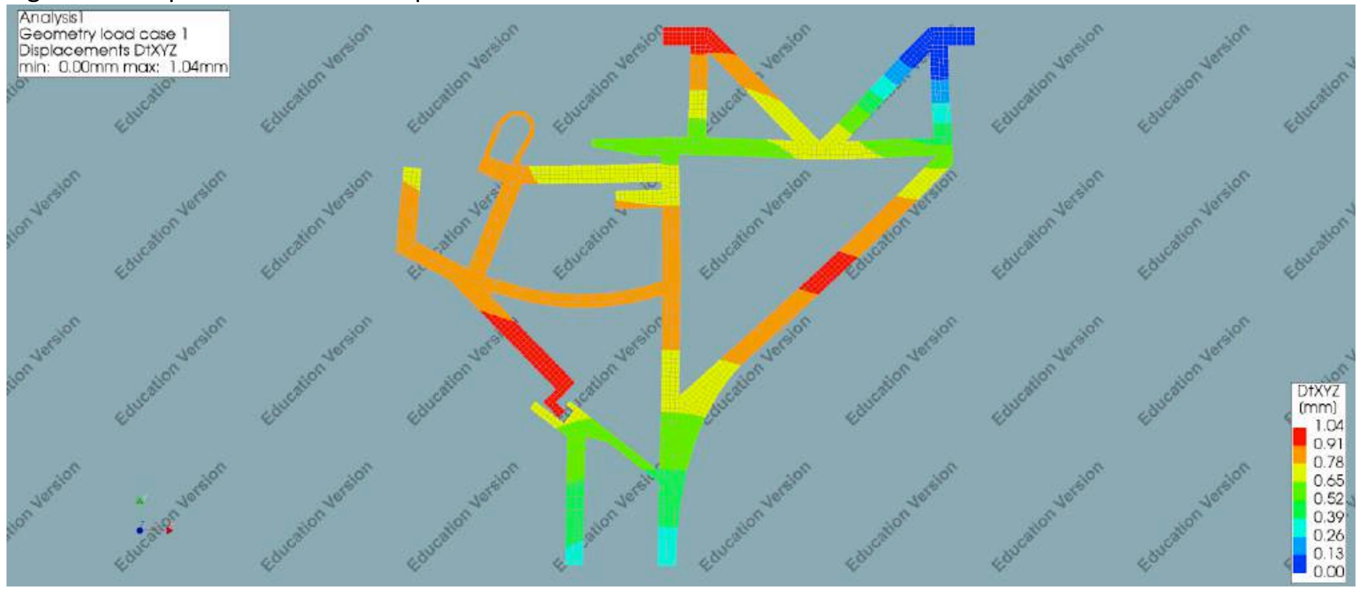


Figure 18: Displacement 30mm depth

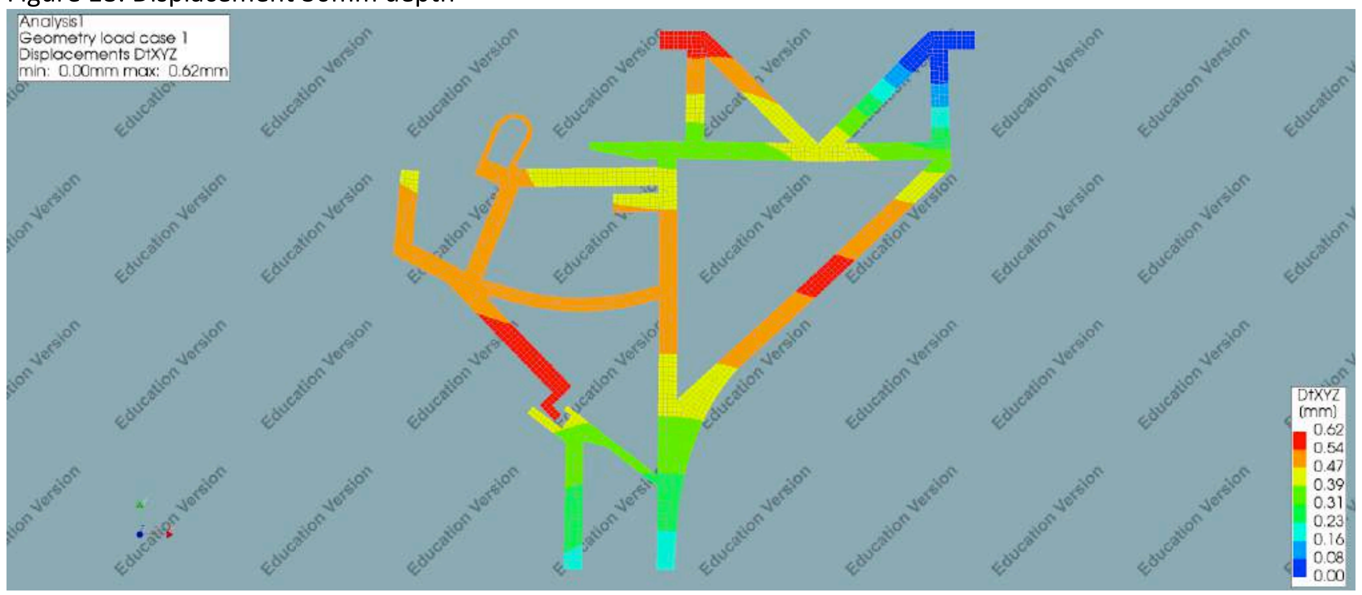


Figure 19: Displacement 50mm depth

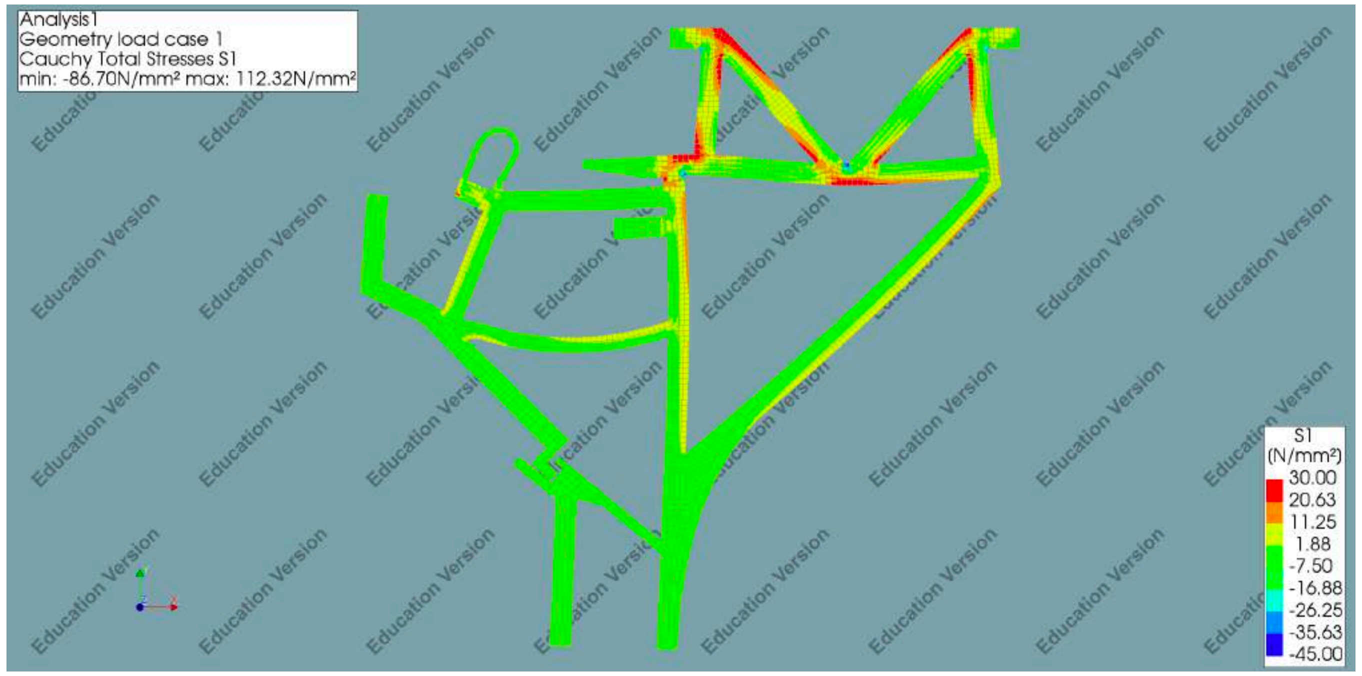


Figure 20: Tensile stresses 15mm depth

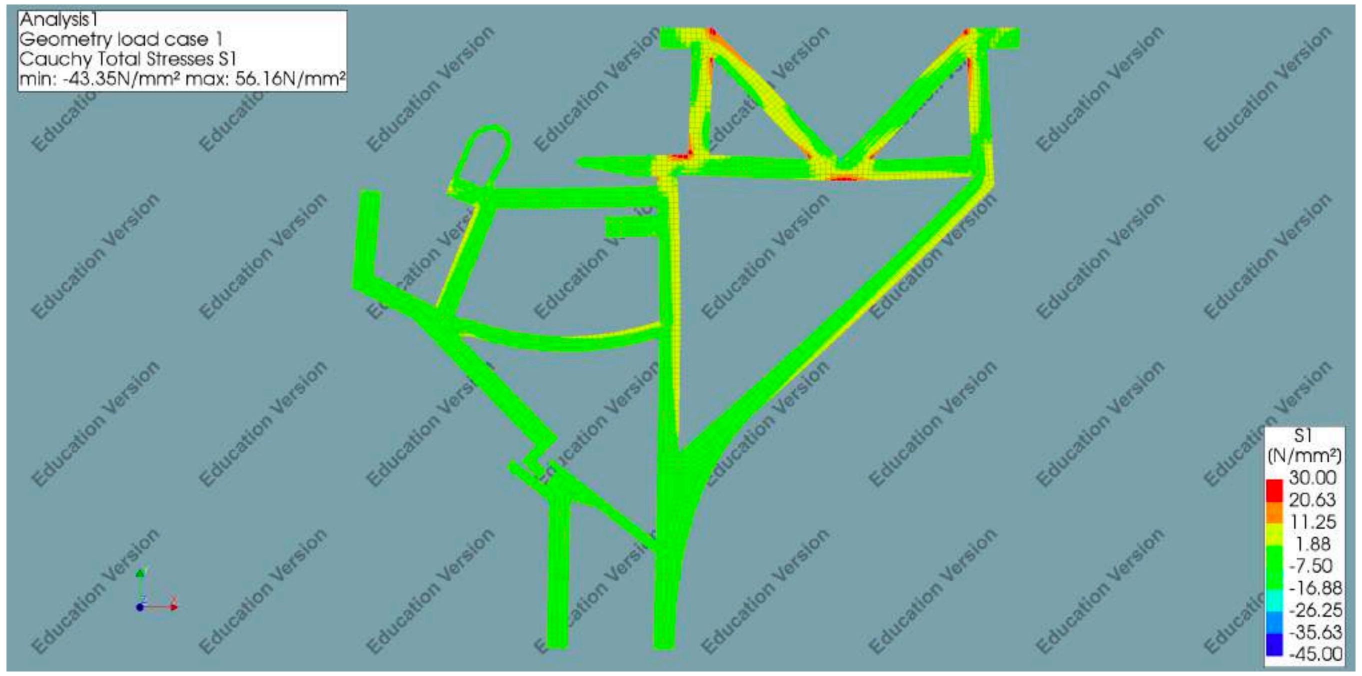


Figure 21: Tensile stresses 30mm depth

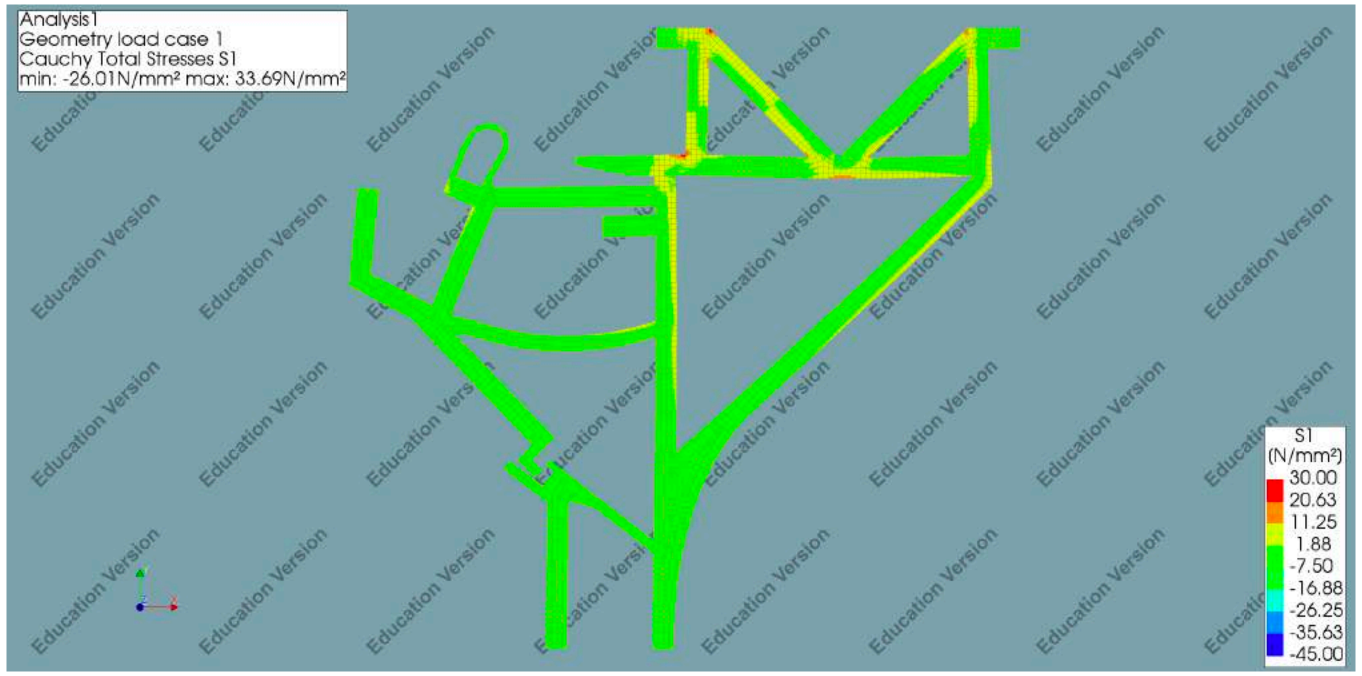


Figure 22: Tensile stresses 50mm depth

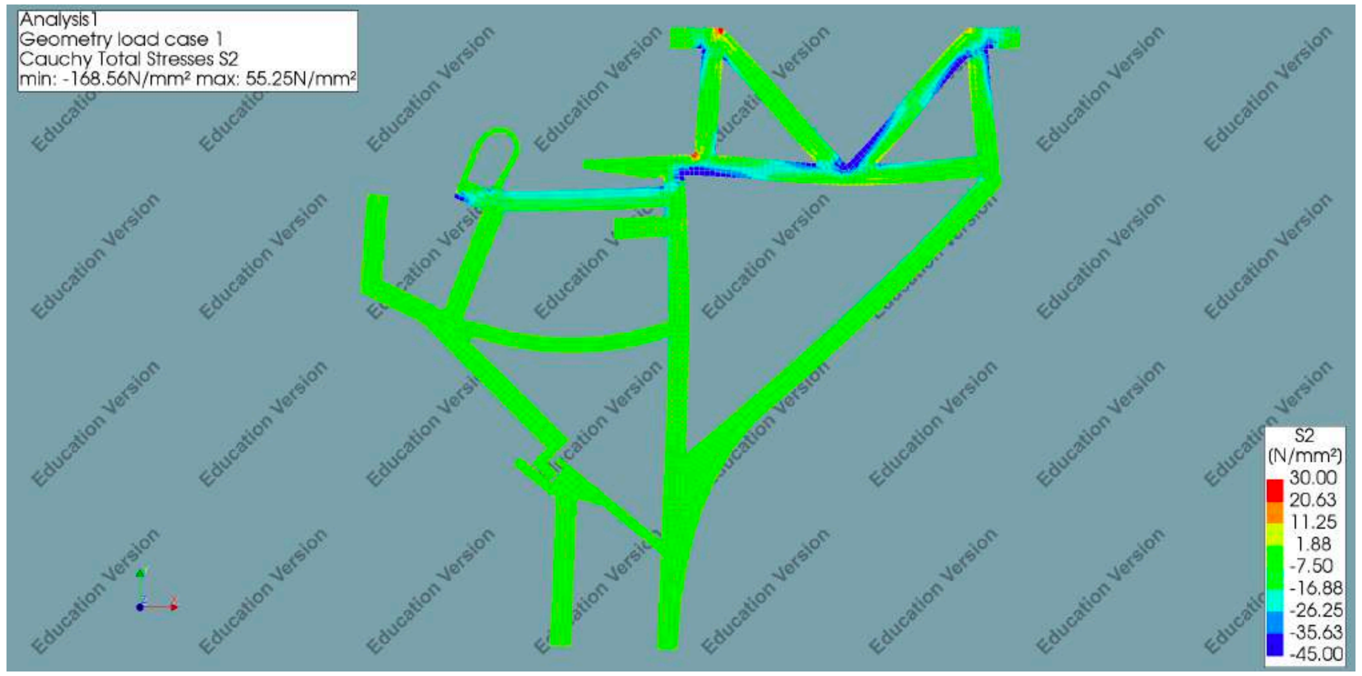


Figure 23: Compressive stresses 15mm depth

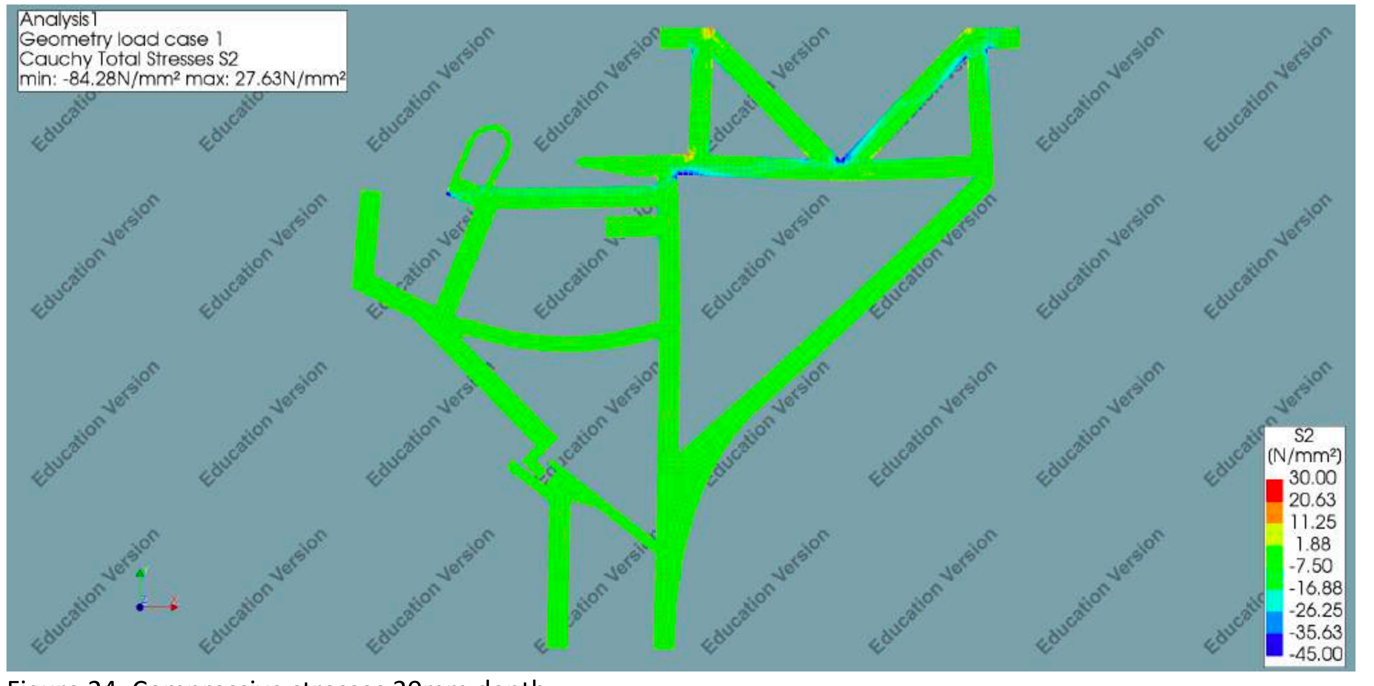


Figure 24: Compressive stresses 30mm depth

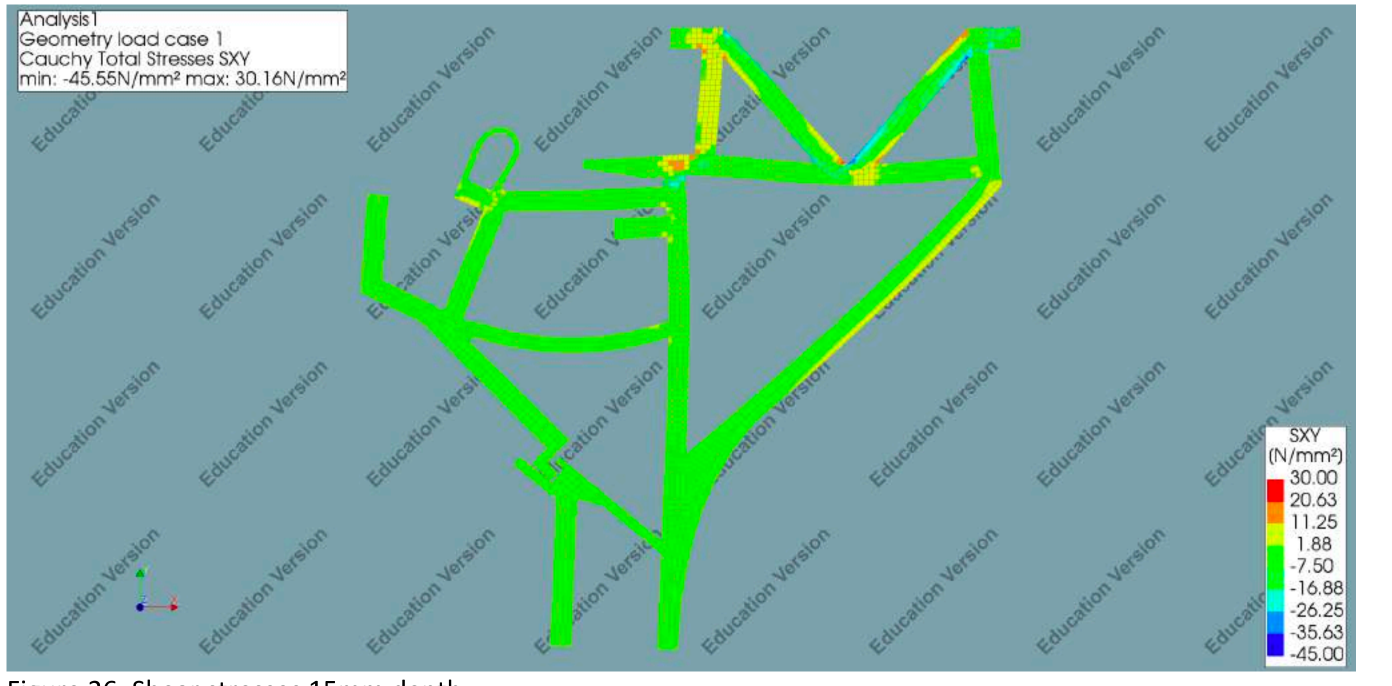


Figure 26: Shear stresses 15mm depth

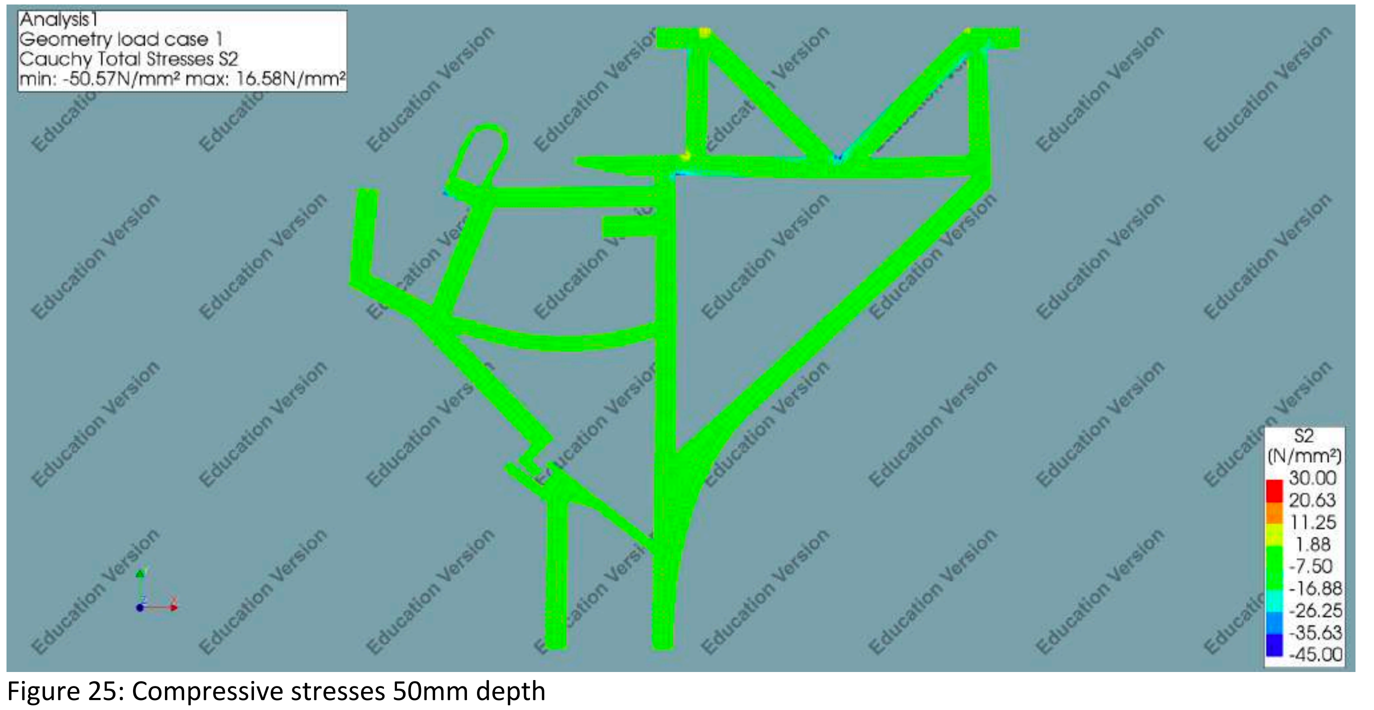


Figure 25: Compressive stresses 50mm depth

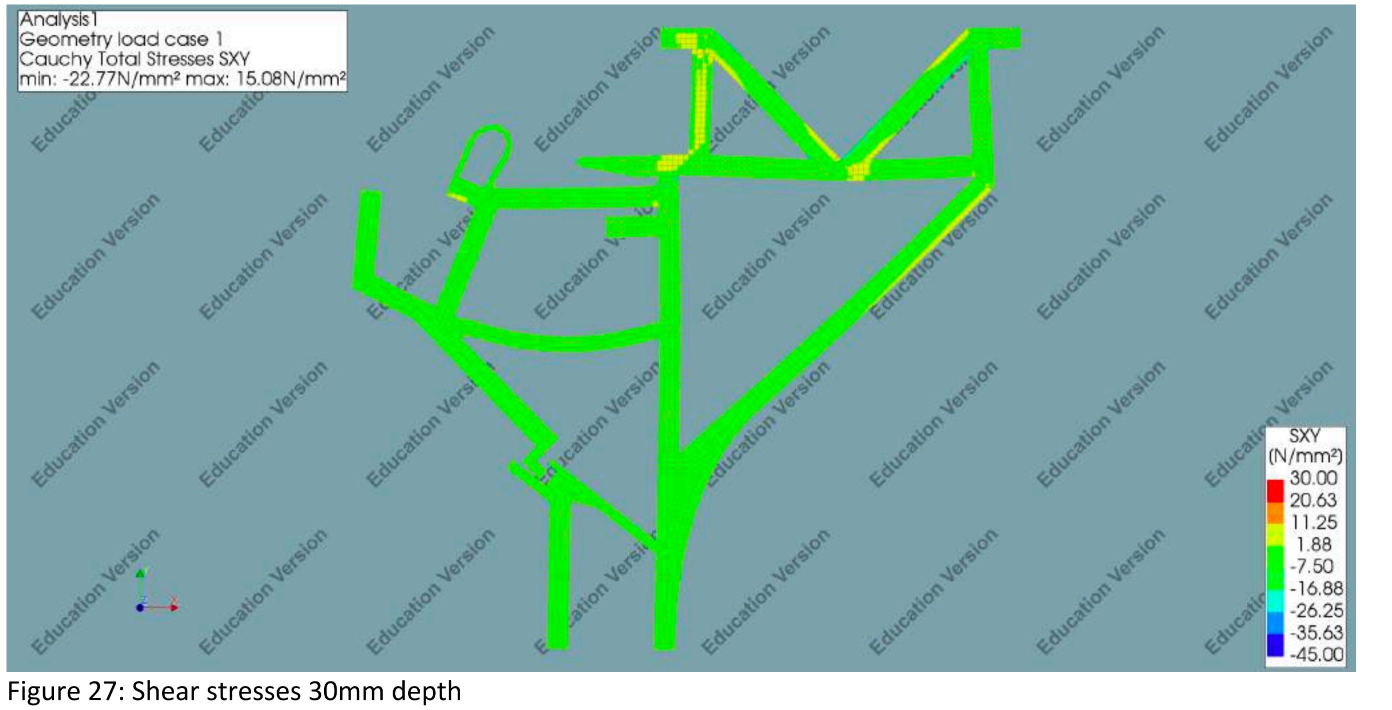


Figure 27: Shear stresses 30mm depth

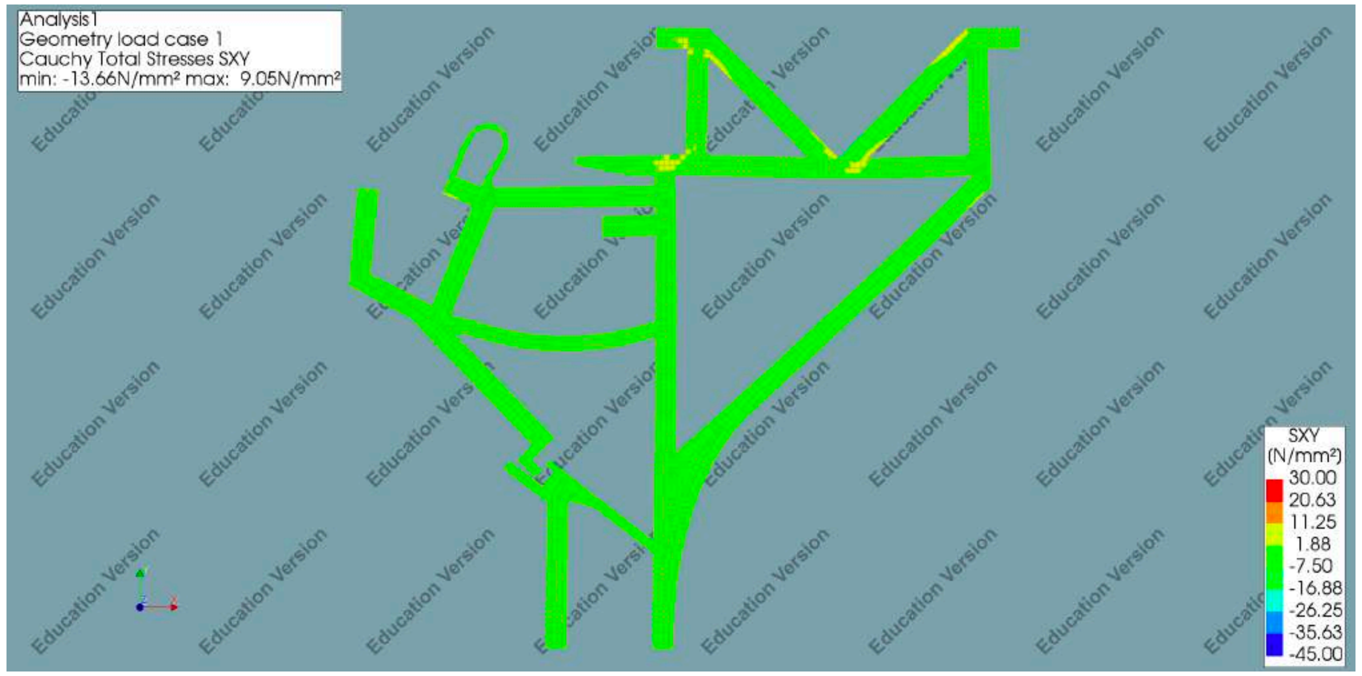


Figure 28: Shear stresses 50mm depth

Analysis 2: Iteration 1

<u>Results tensile analysis</u>

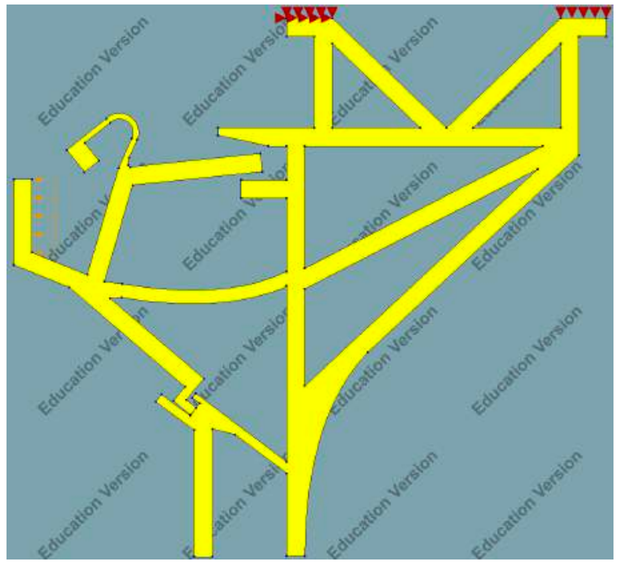


Figure 29: Geometry

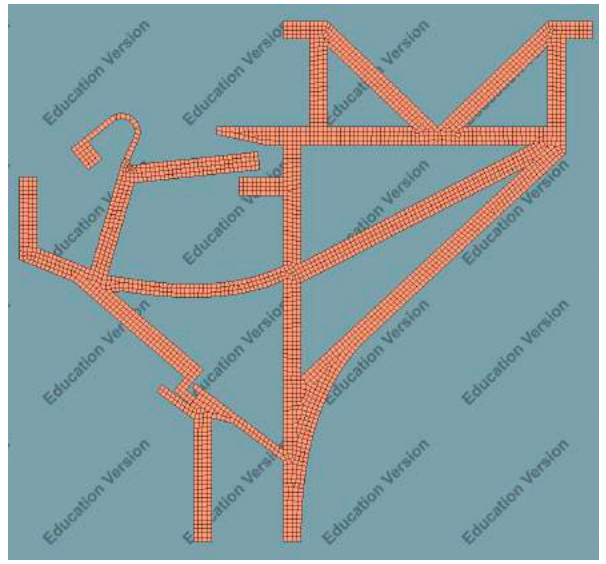


Figure 30: Mesh geometry

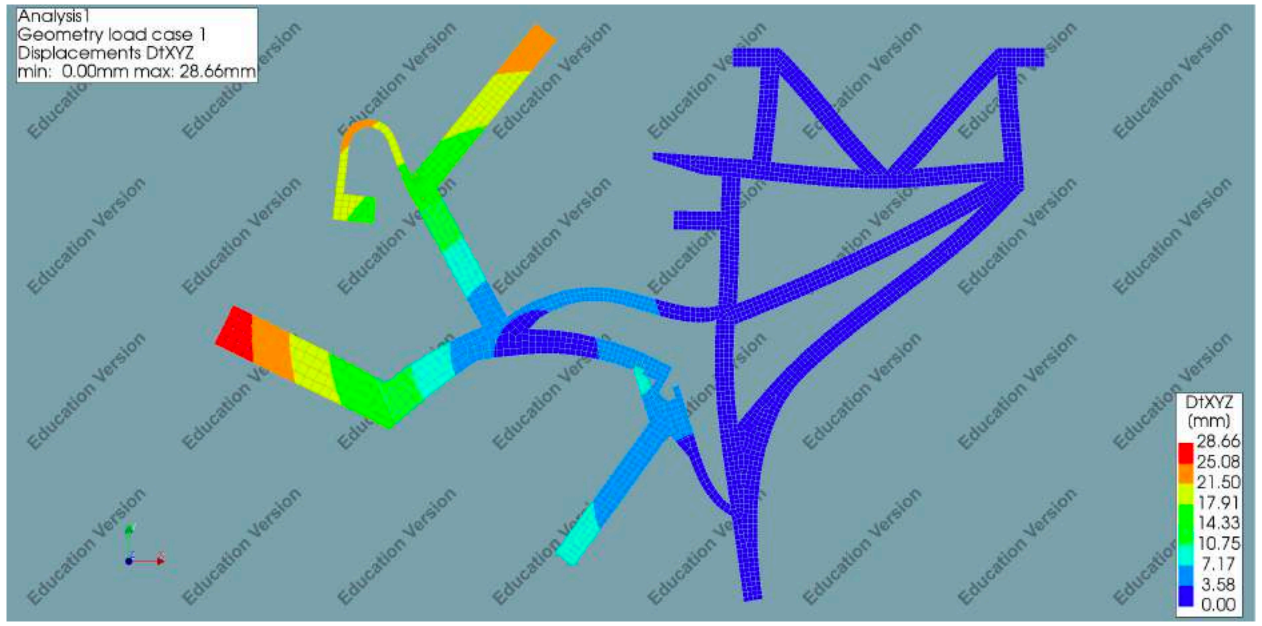


Figure 331: Displacement 15mm depth

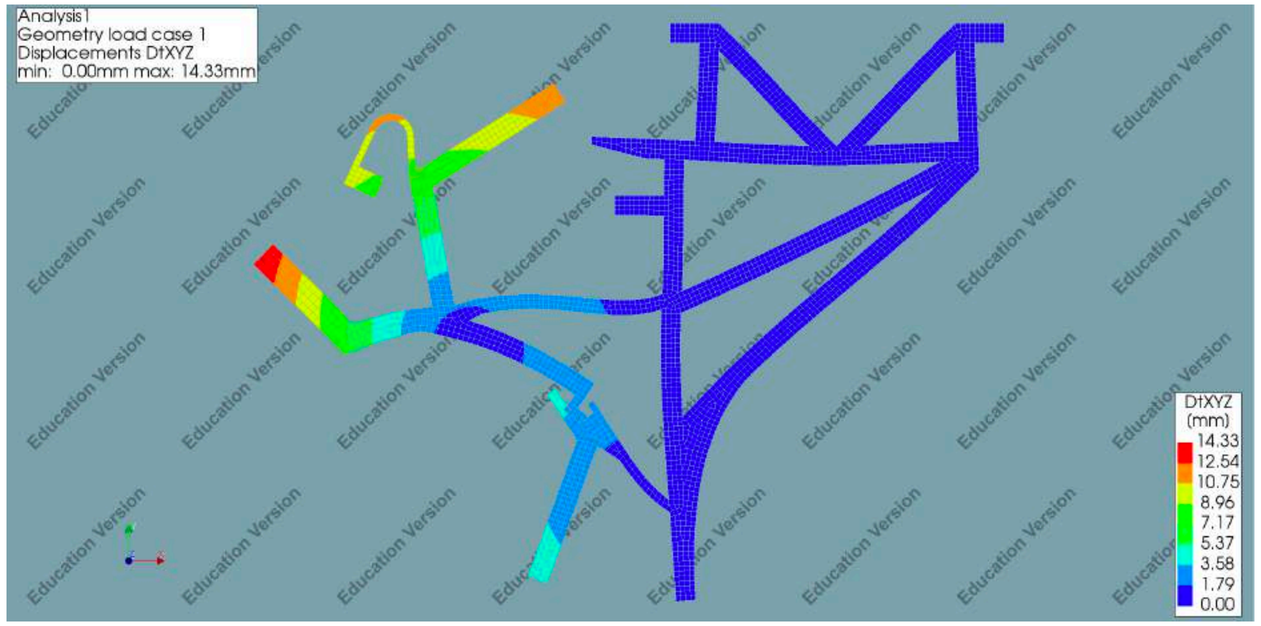


Figure 32: Displacement 30mm depth

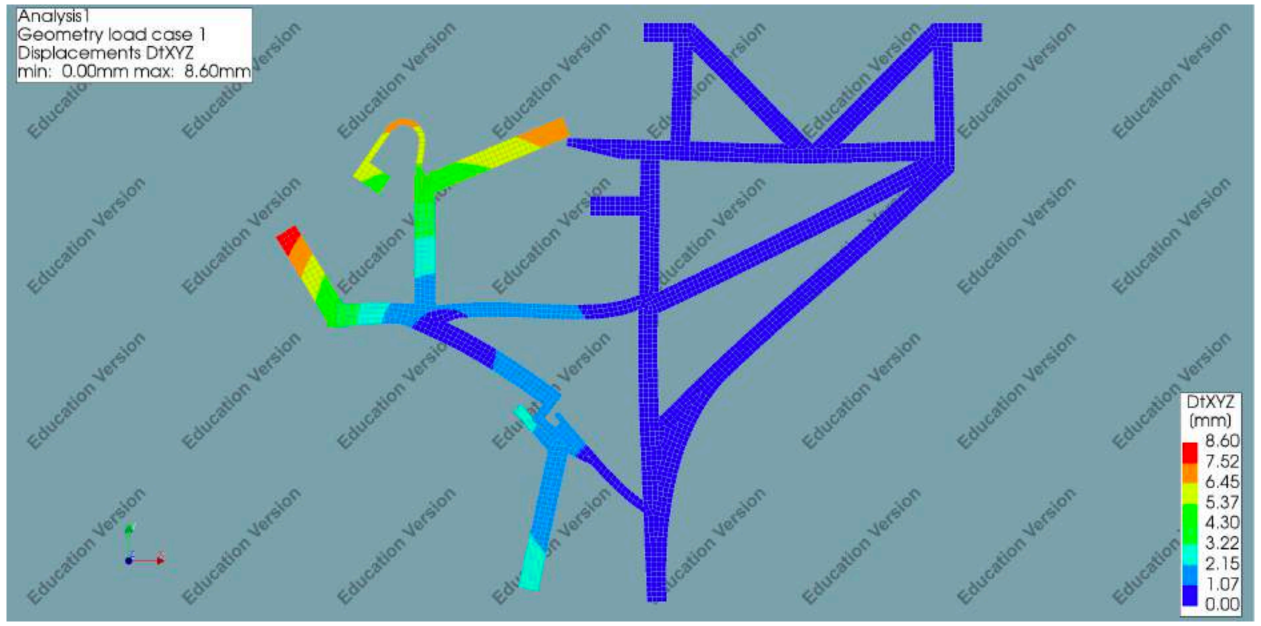


Figure 33: 50mm depth

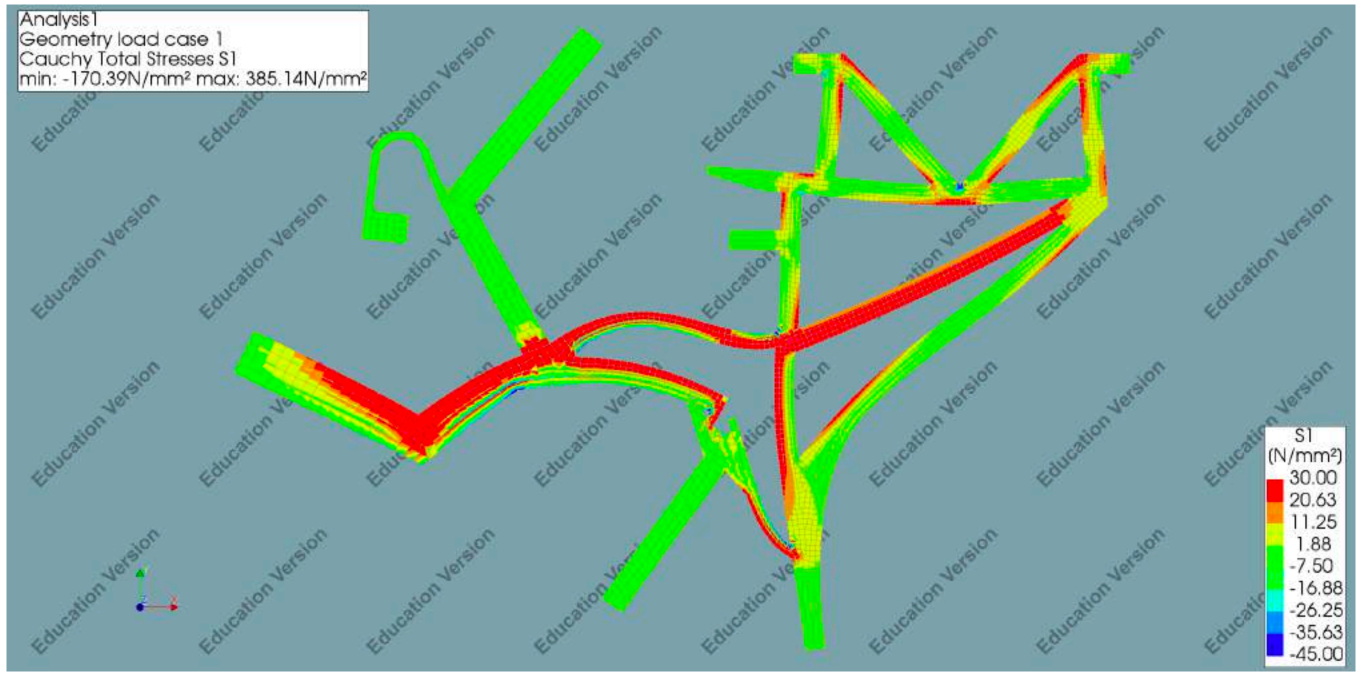


Figure 34: Tensile stresses 15mm depth

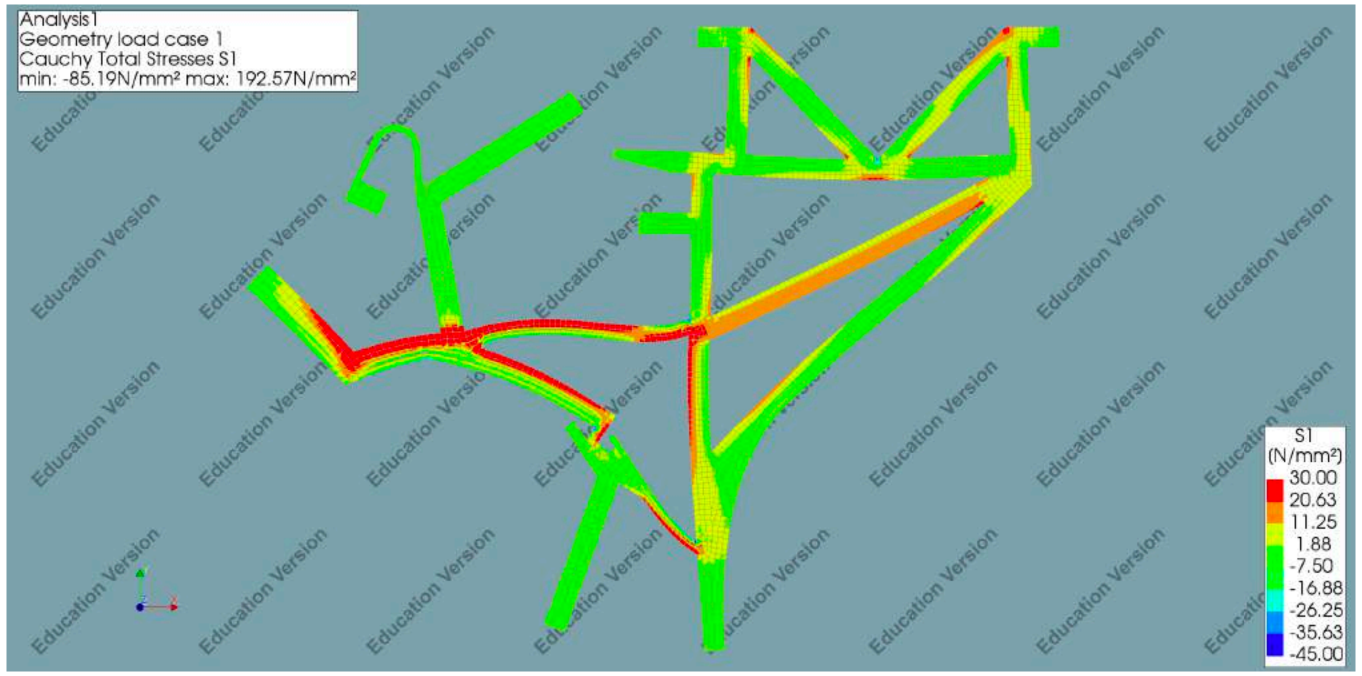


Figure 35: Tensile stresses 30mm depth

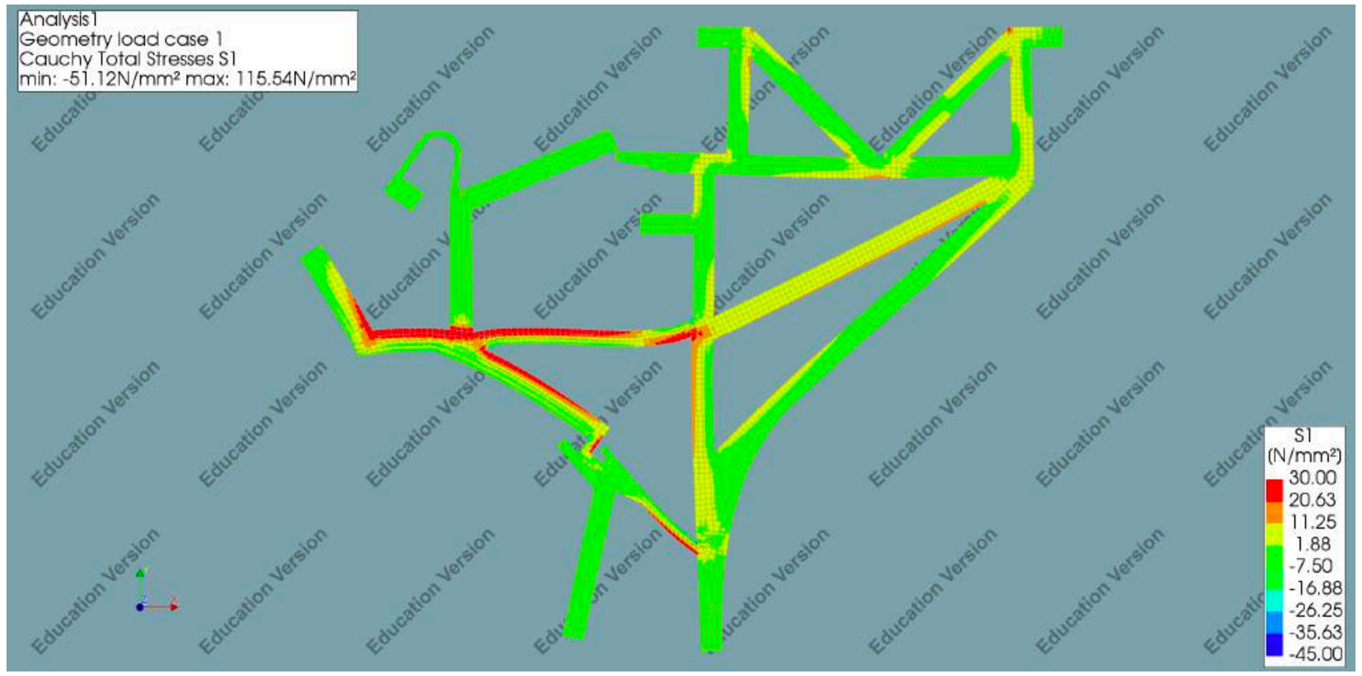


Figure 36: Tensile stresses 50mm depth

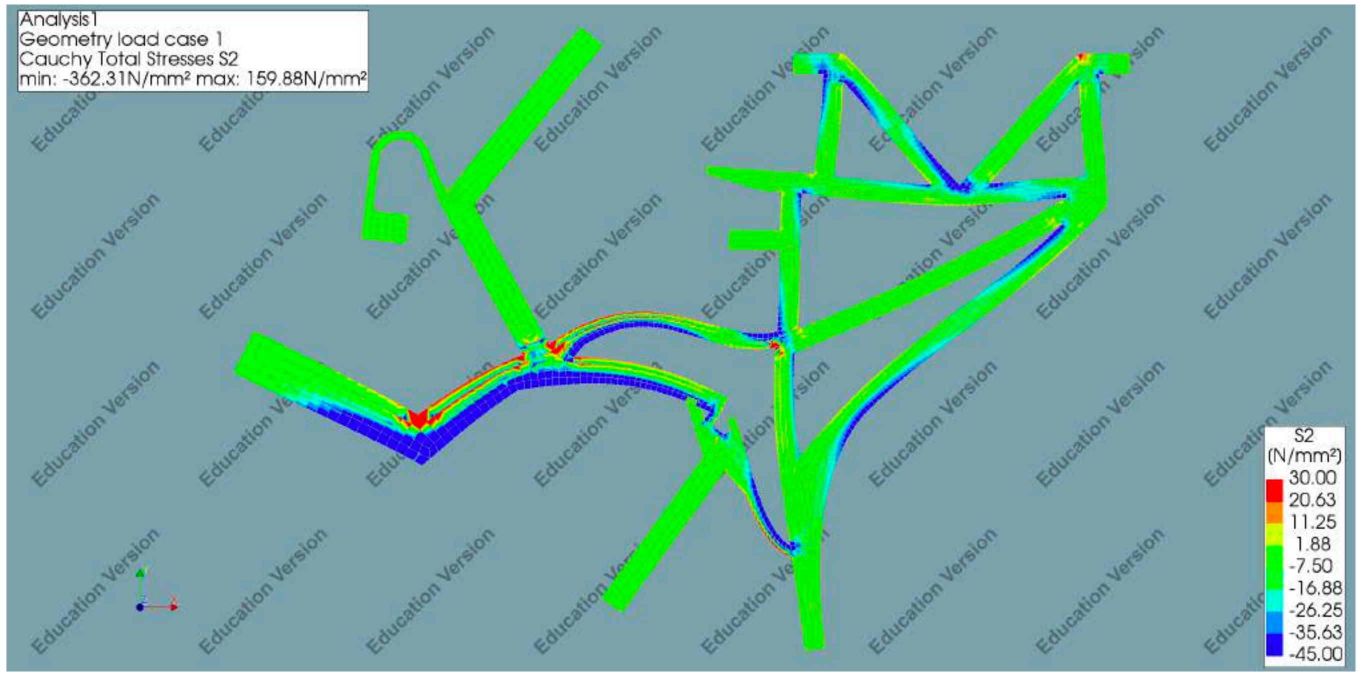


Figure 37: Compressive stresses 15mm depth

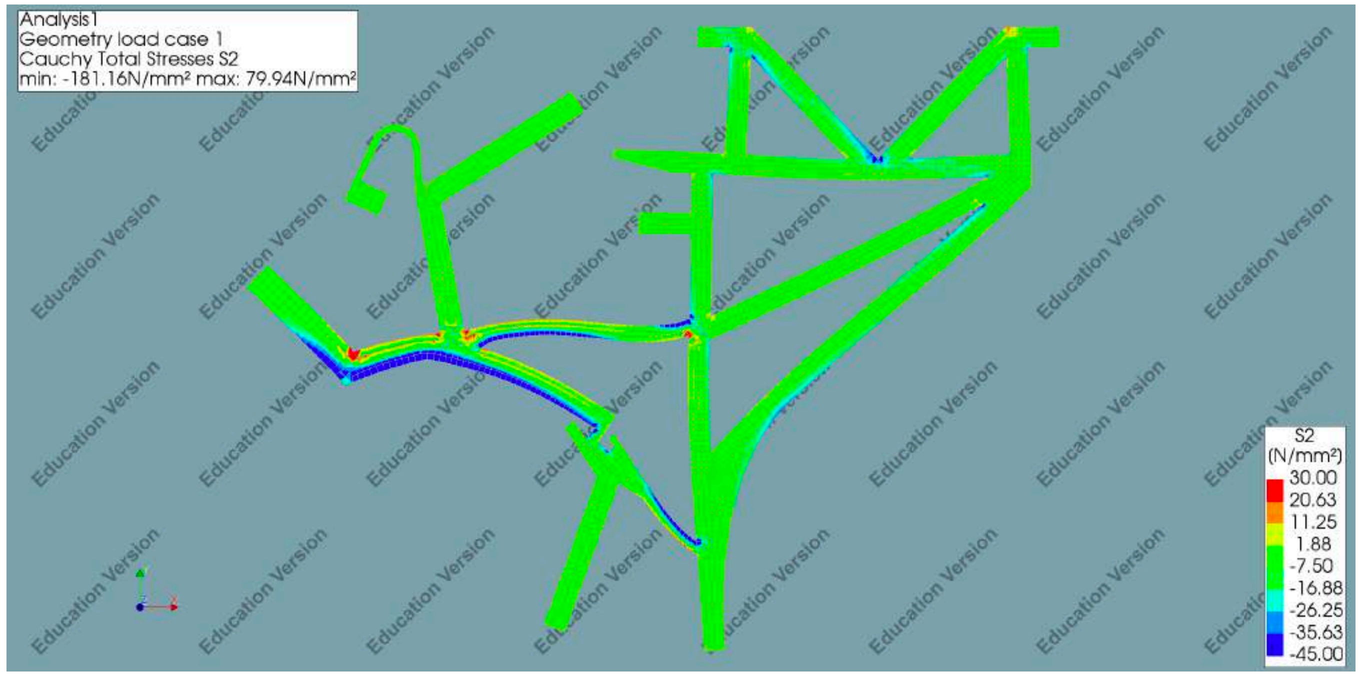


Figure 38: Compressive stresses 30mm depth

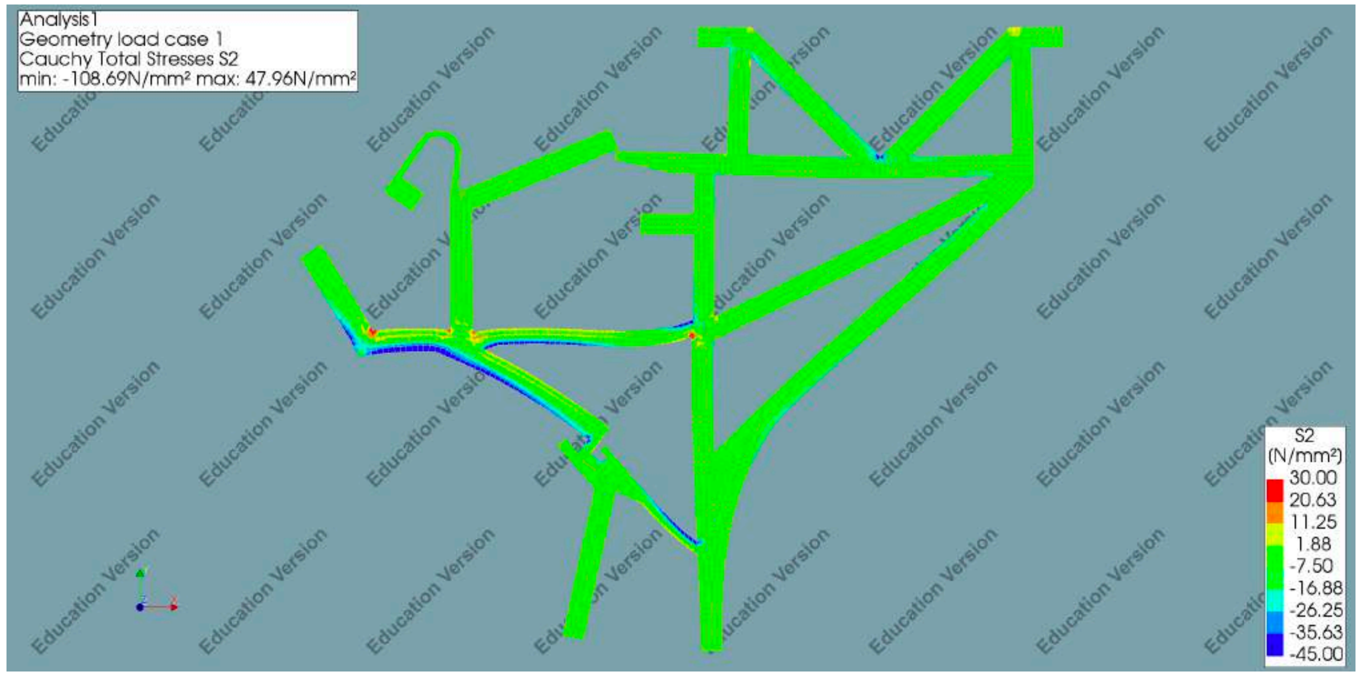


Figure 39: Compressive stresses 50mm depth

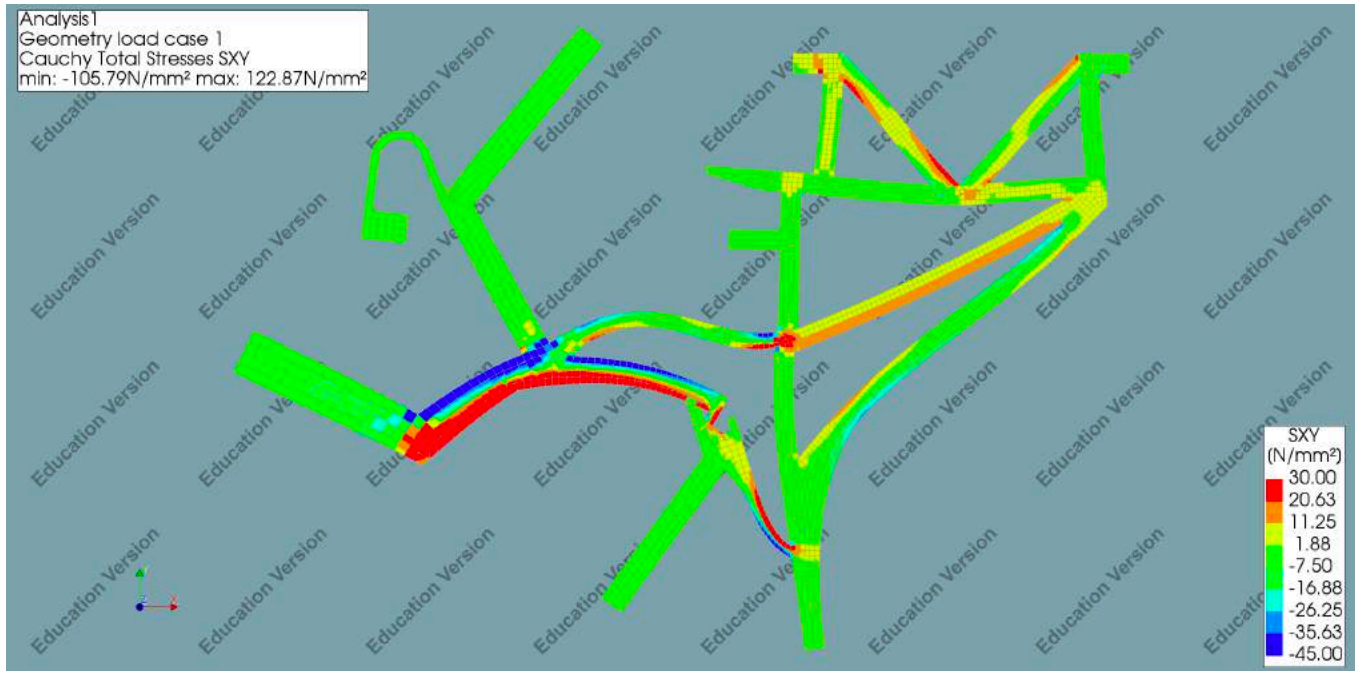


Figure 40: Shear stresses 15mm depth

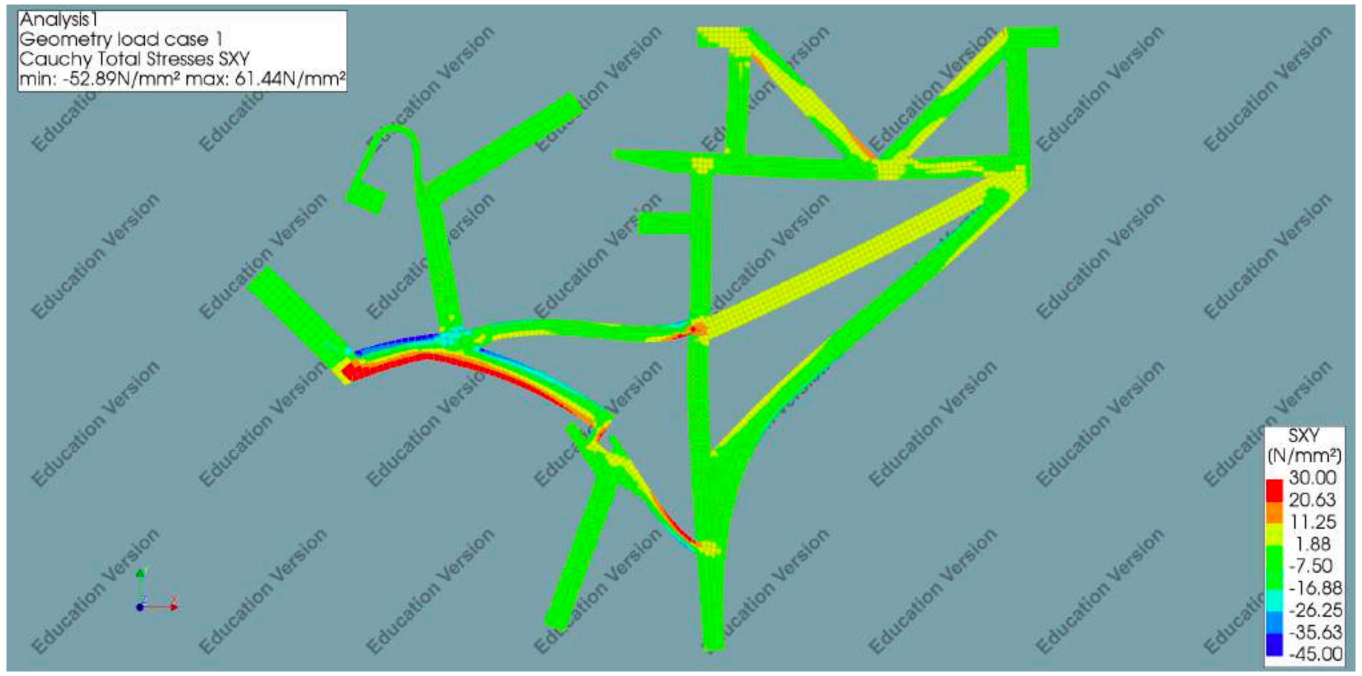


Figure 41: Shear stresses 30mm depth

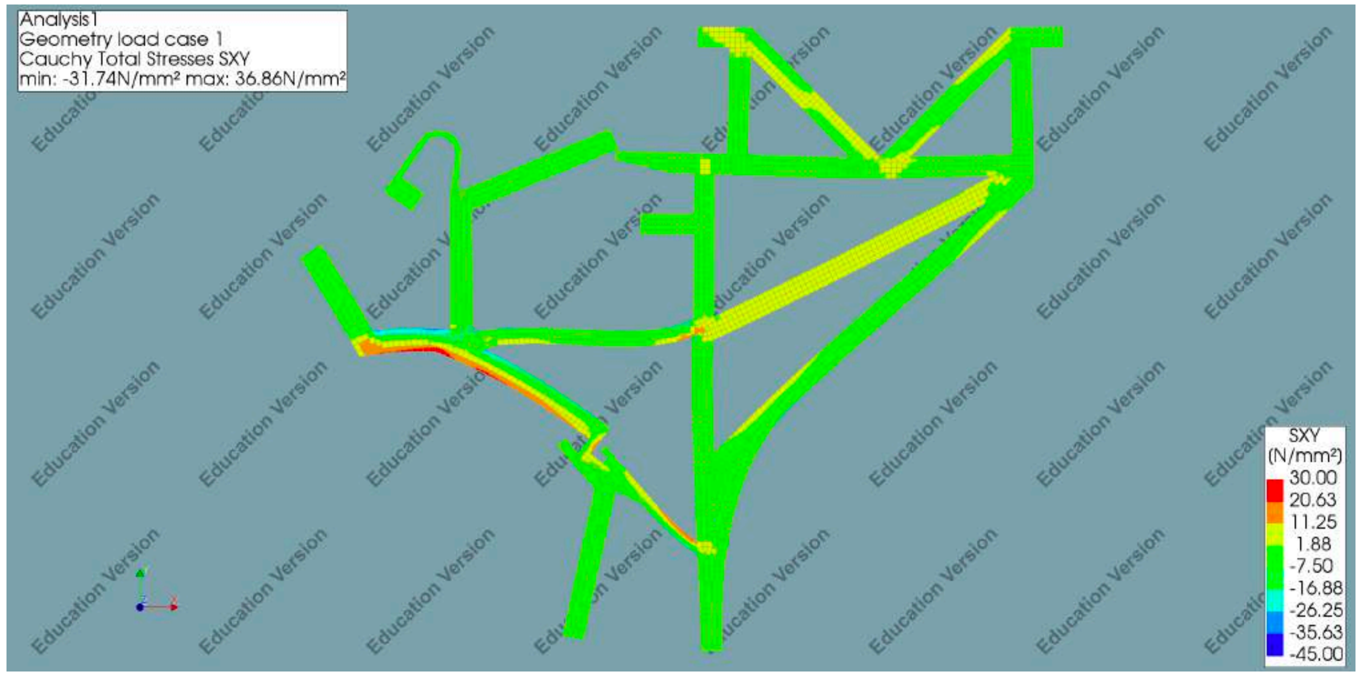


Figure 42: Shear stresses 50mm depth

<u>Results compressive analysis</u>

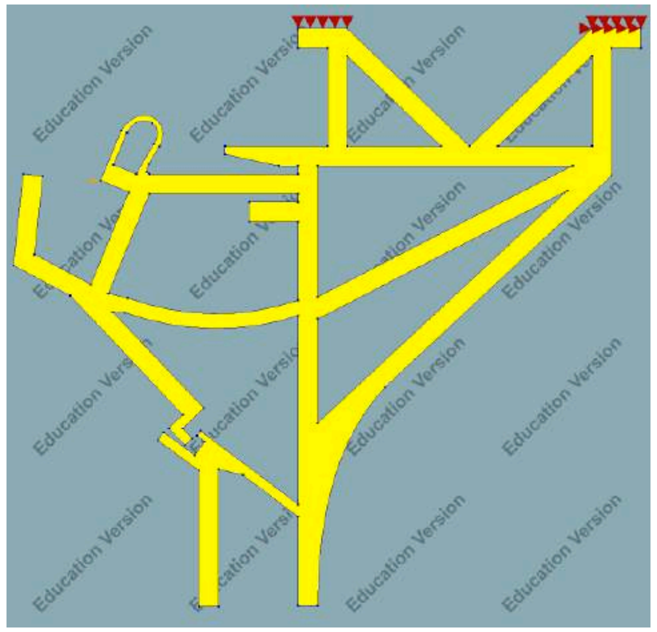


Figure 43: Geometry

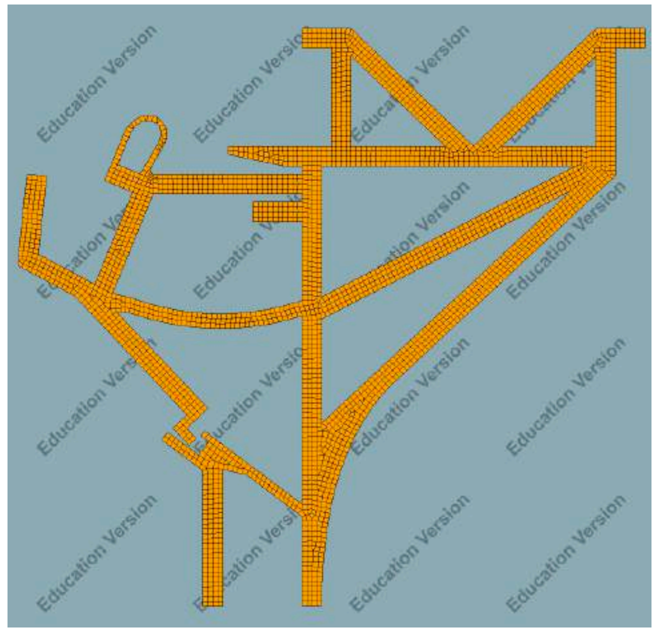


Figure 44: Mesh geometry

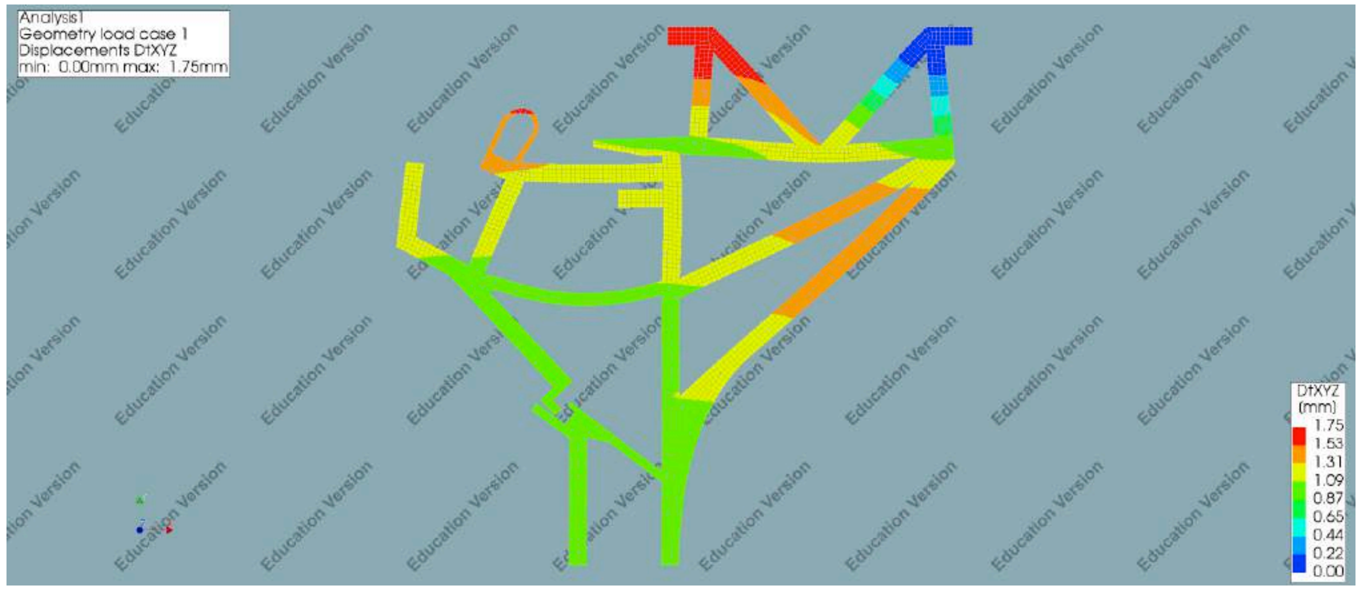


Figure 45: Displacement 15mm depth

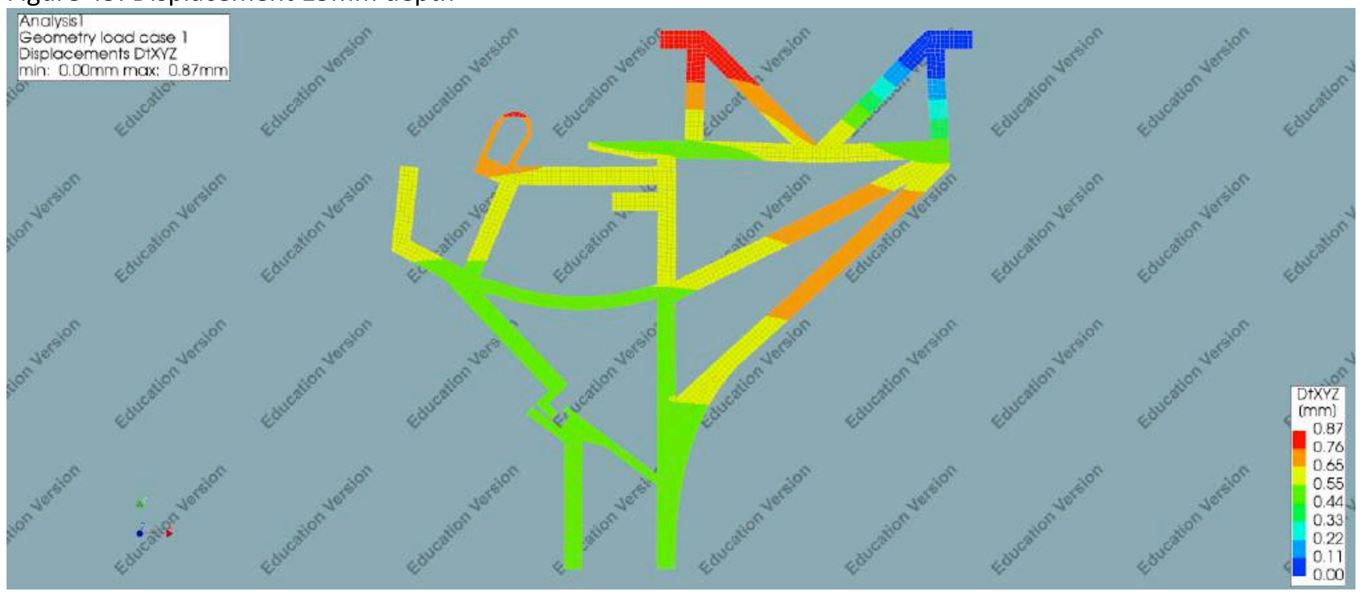


Figure 46: Displacement 30mm depth

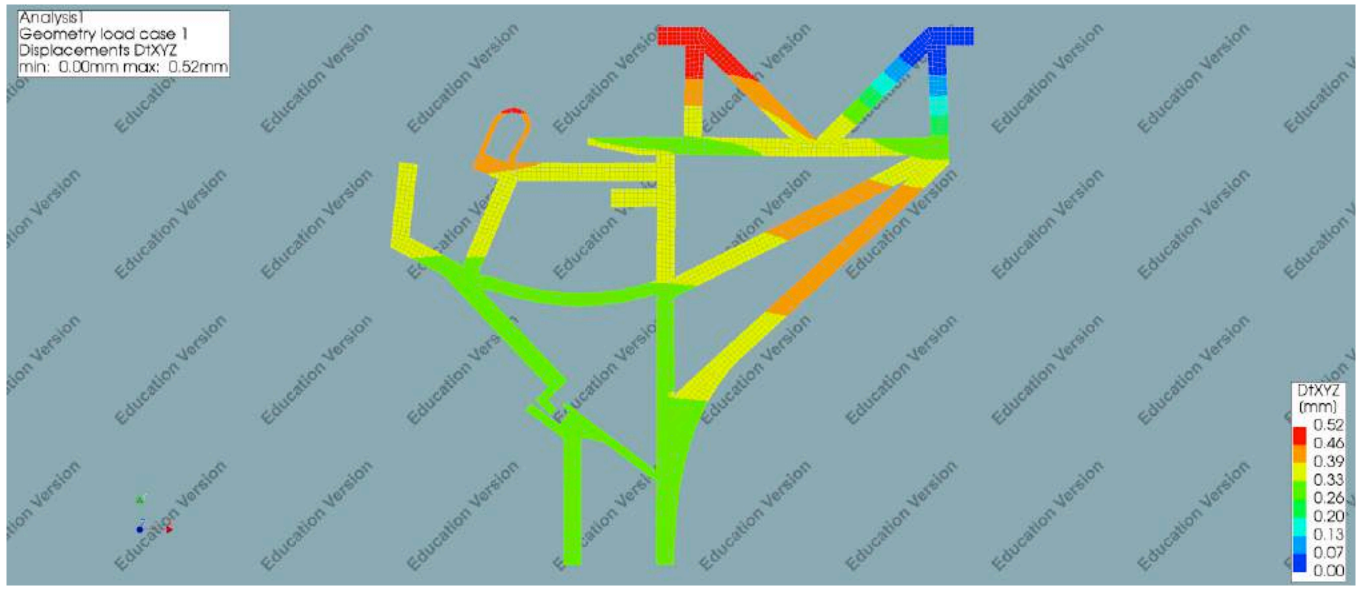


Figure 47: Displacement 50mm depth

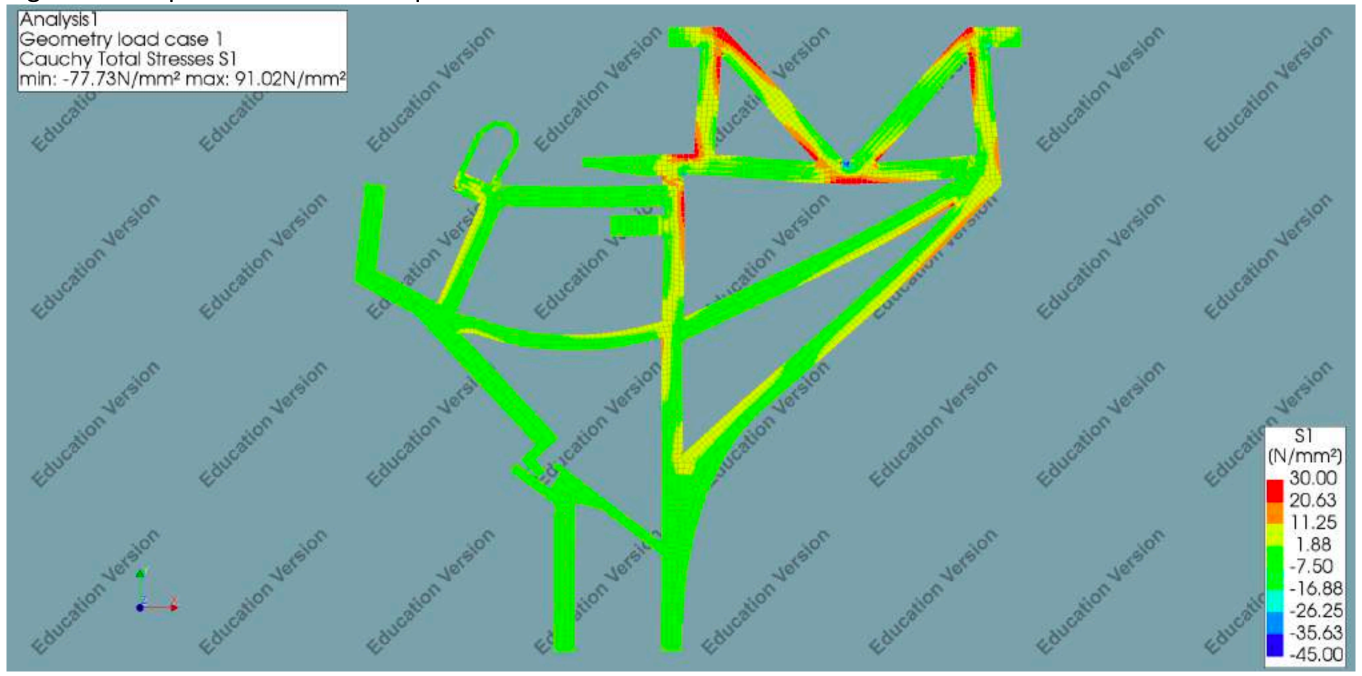


Figure 48: Tensile stresses 15mm depth

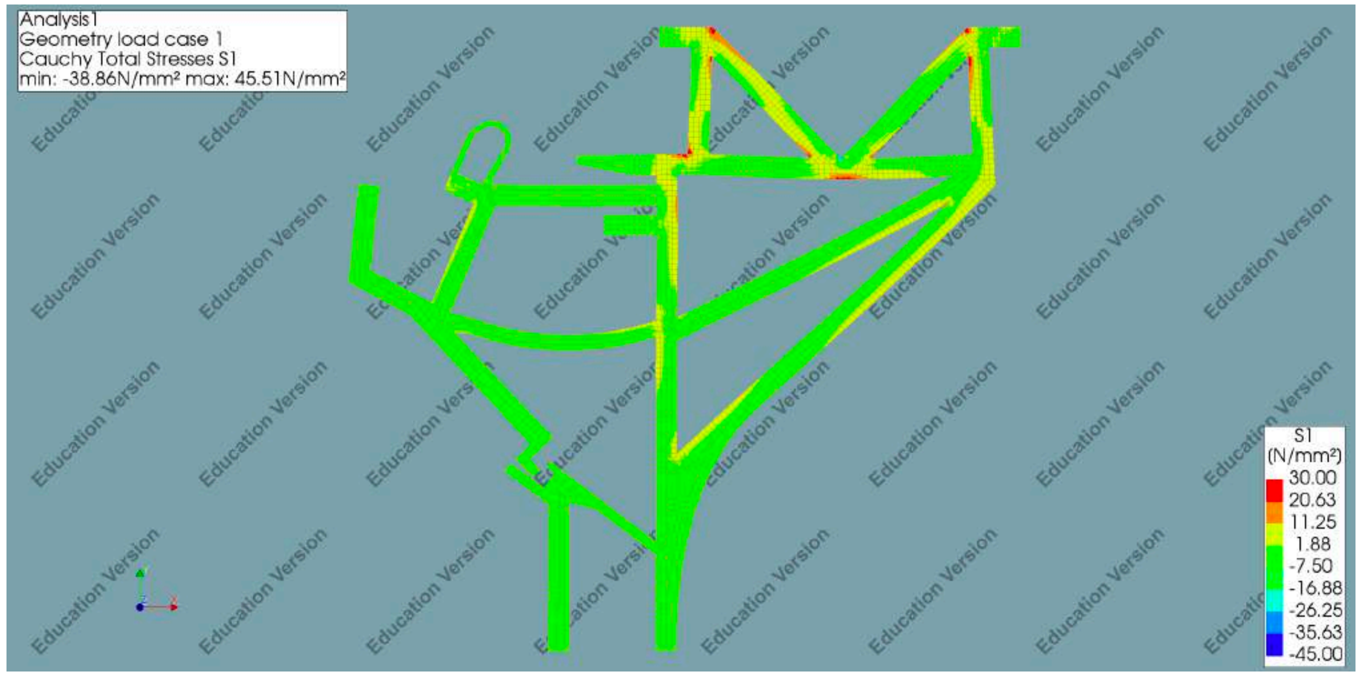


Figure 49: Tensile stresses 30mm depth

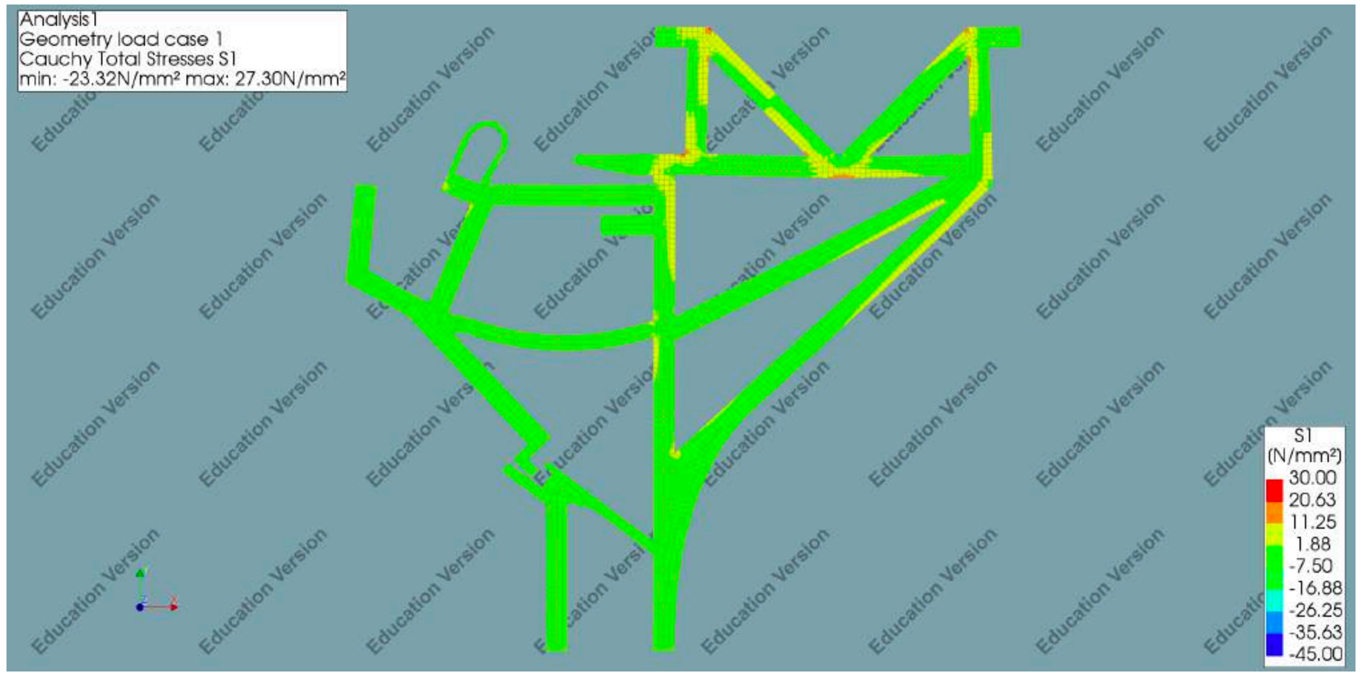


Figure 50: Tensile stresses 50mm depth

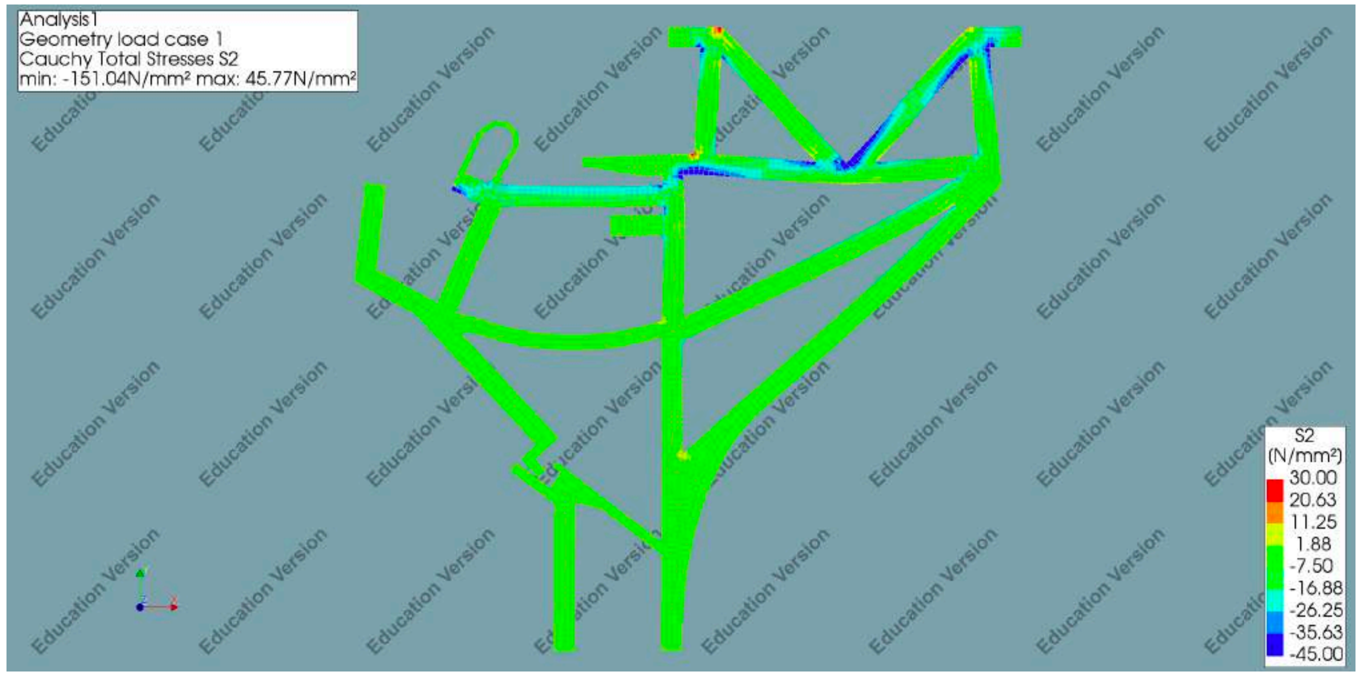


Figure 51: Compressive stresses 15mm depth

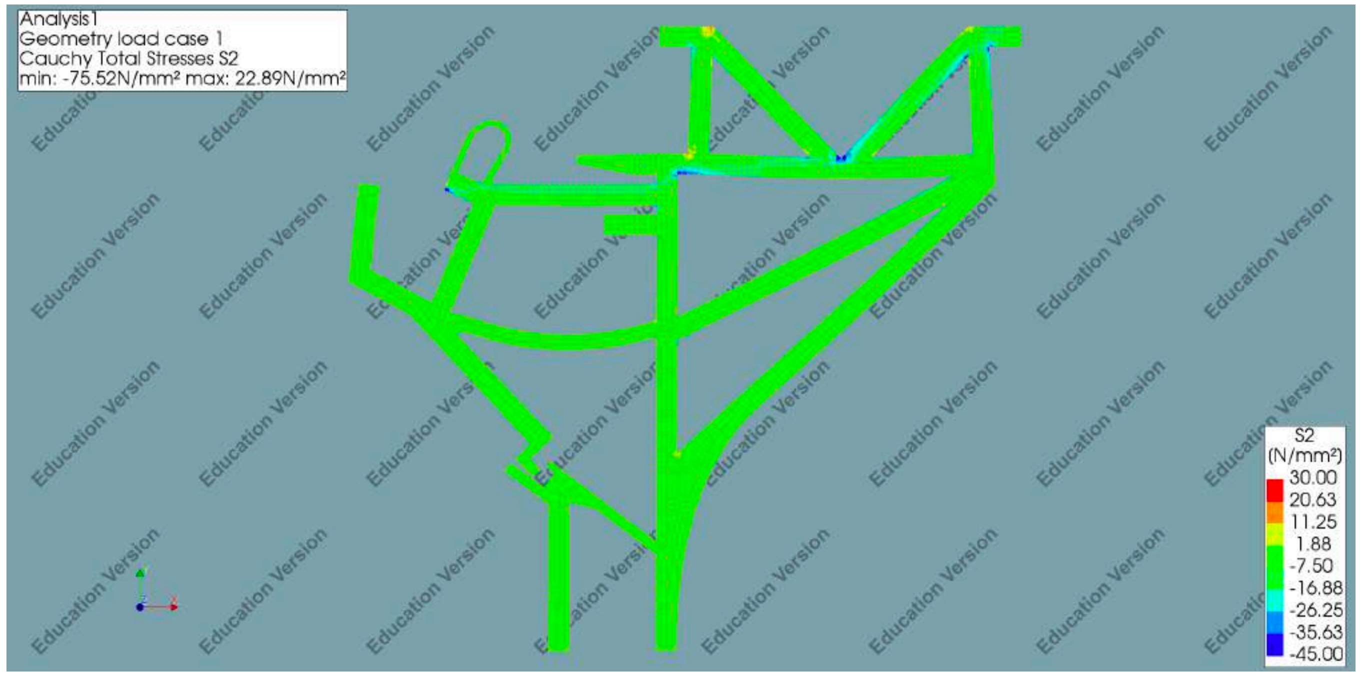


Figure 52: Compressive stresses 30mm depth

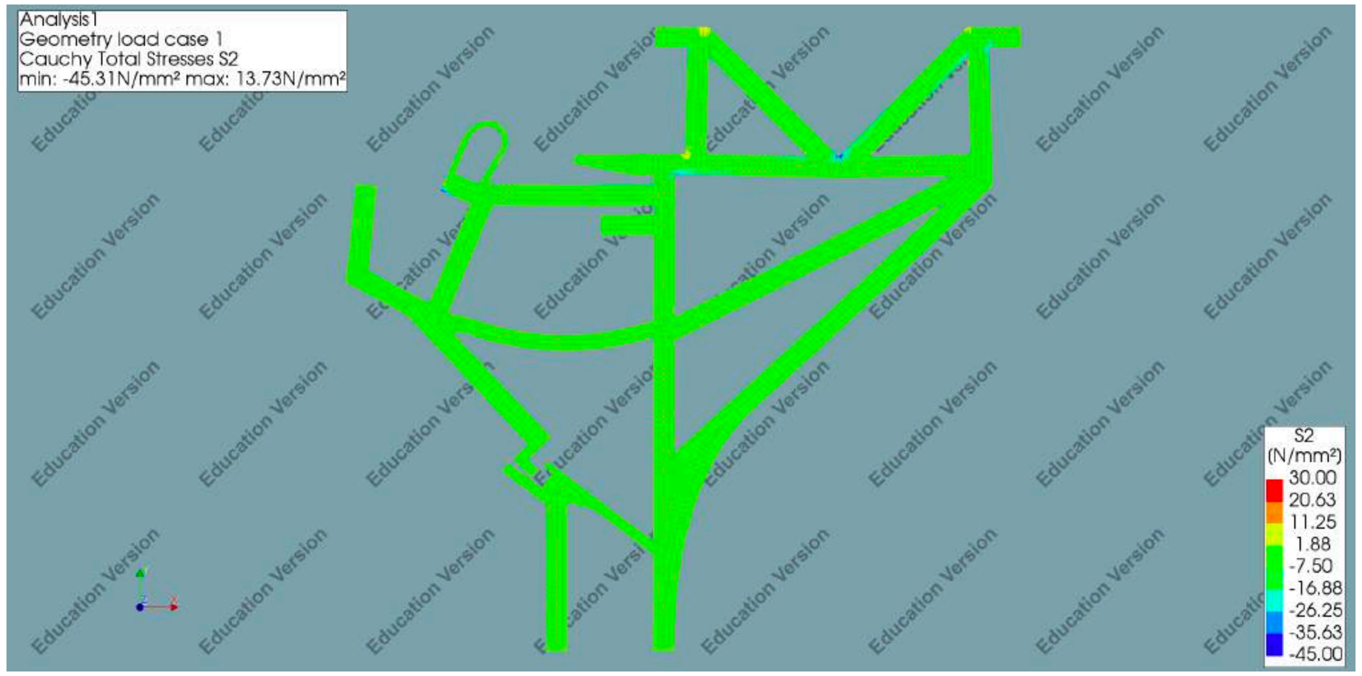


Figure 53: Compressive stresses 50mm depth

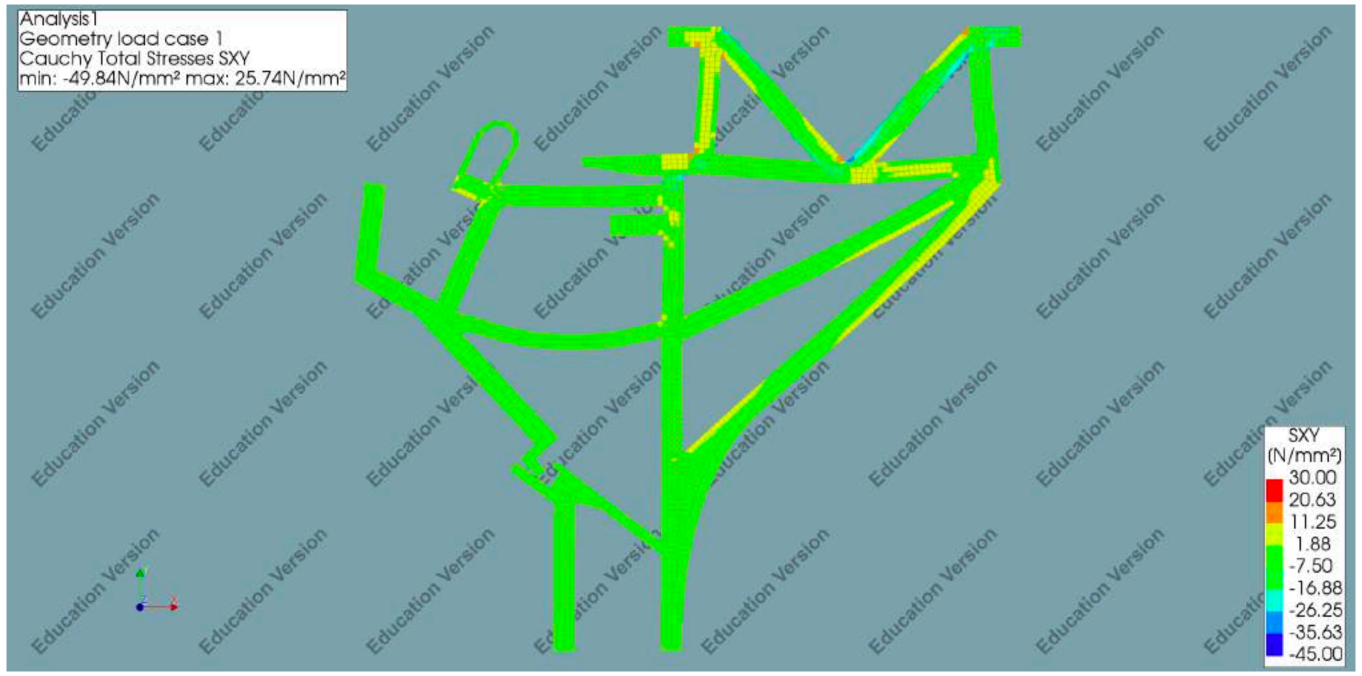


Figure 54: Shear stresses 15mm depth

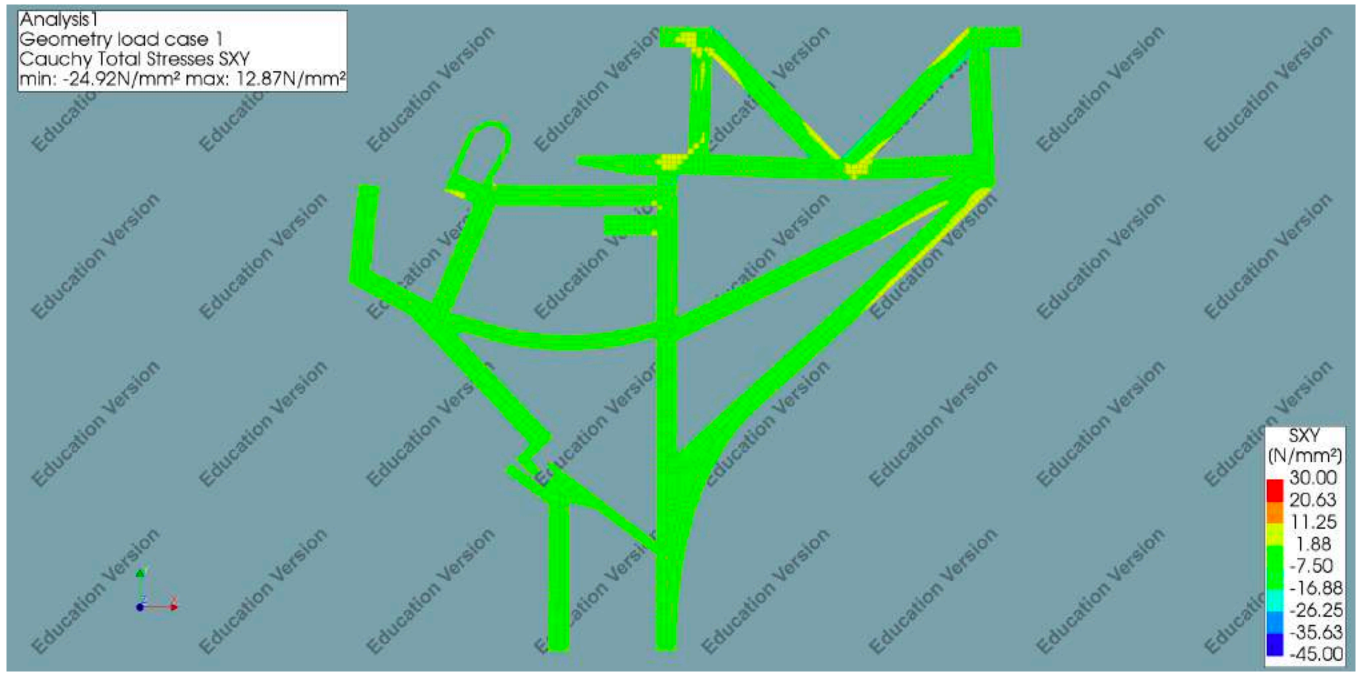


Figure 55: shear stresses 30mm depth

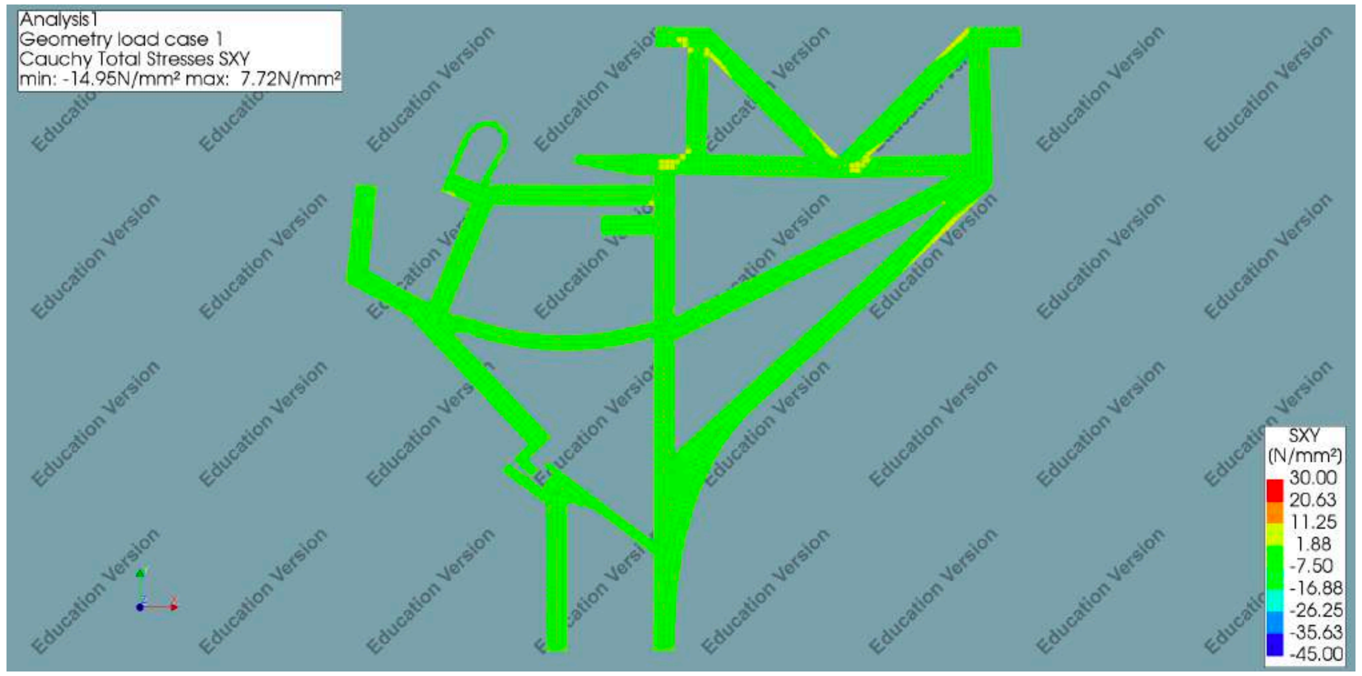


Figure 56: shear stresses 50mm depth

Analysis 3: Iteration 2

<u>Results tensile analysis</u>

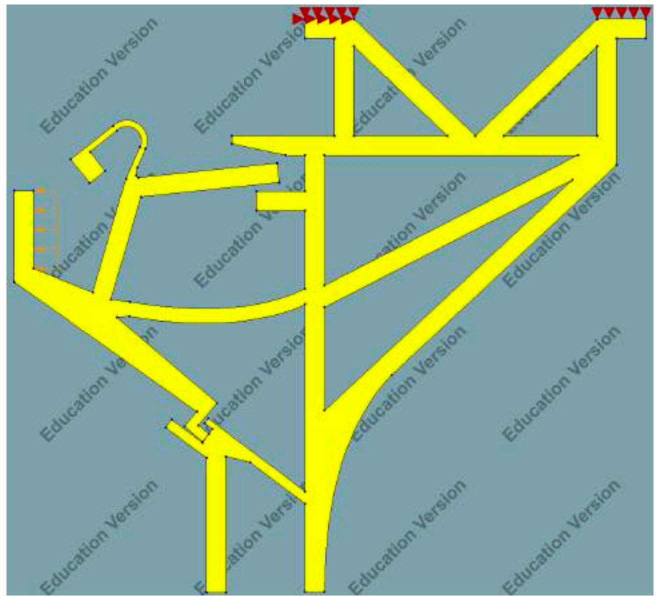


Figure 57: Geometry

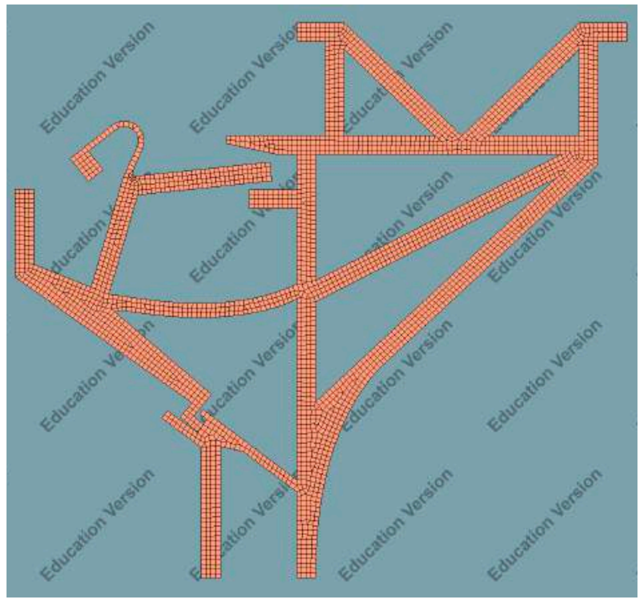


Figure 58: Mesh geometry

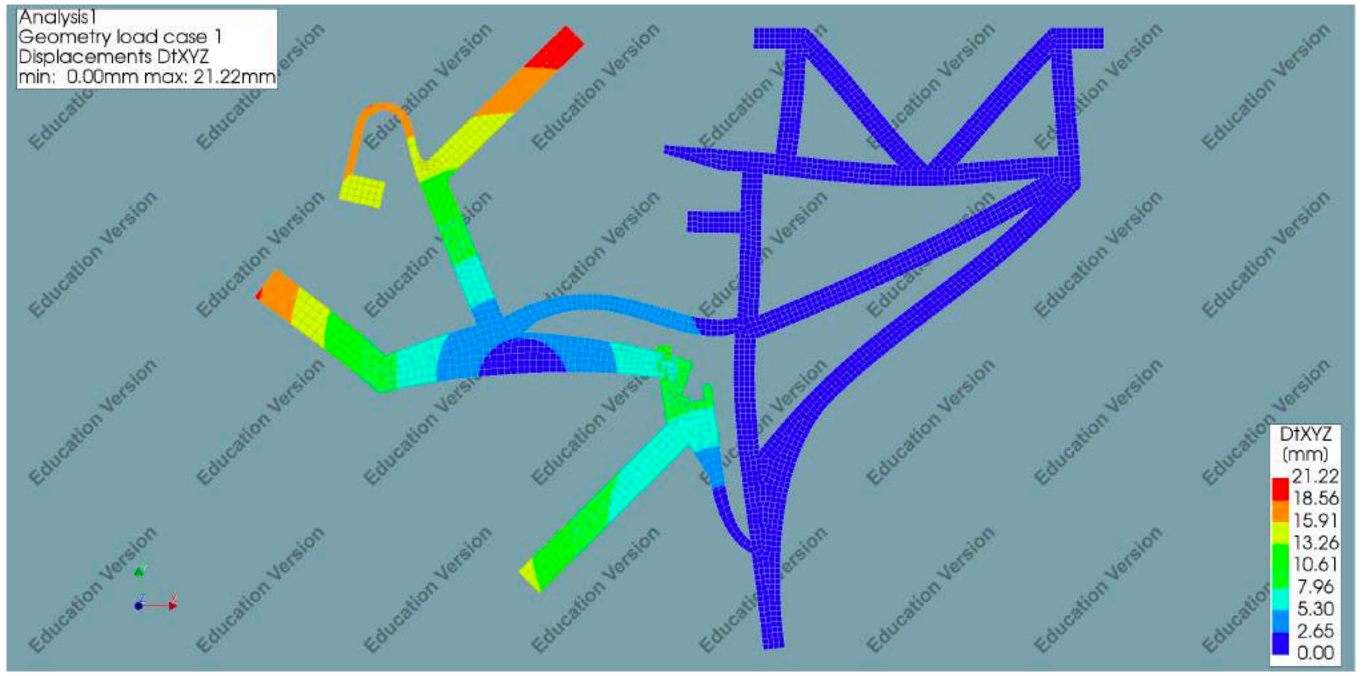


Figure 59: Displacement 15mm depth

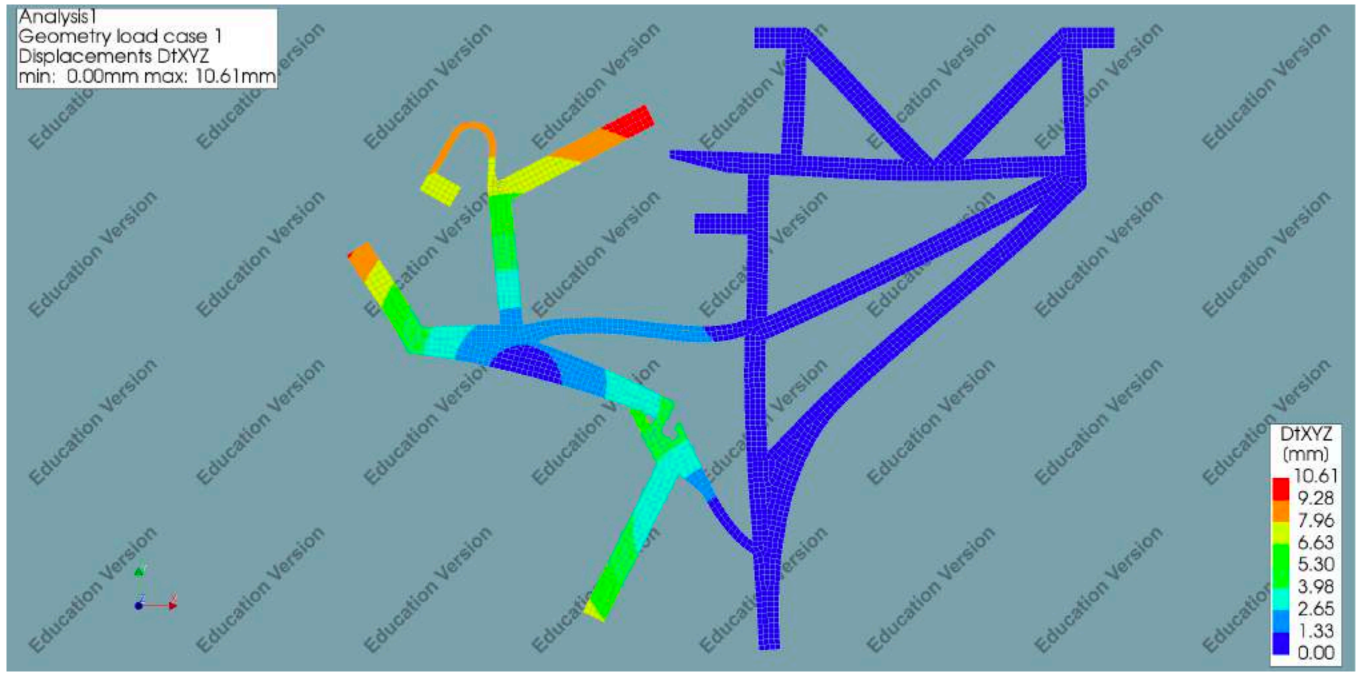


Figure 60: Displacement 30mm depth

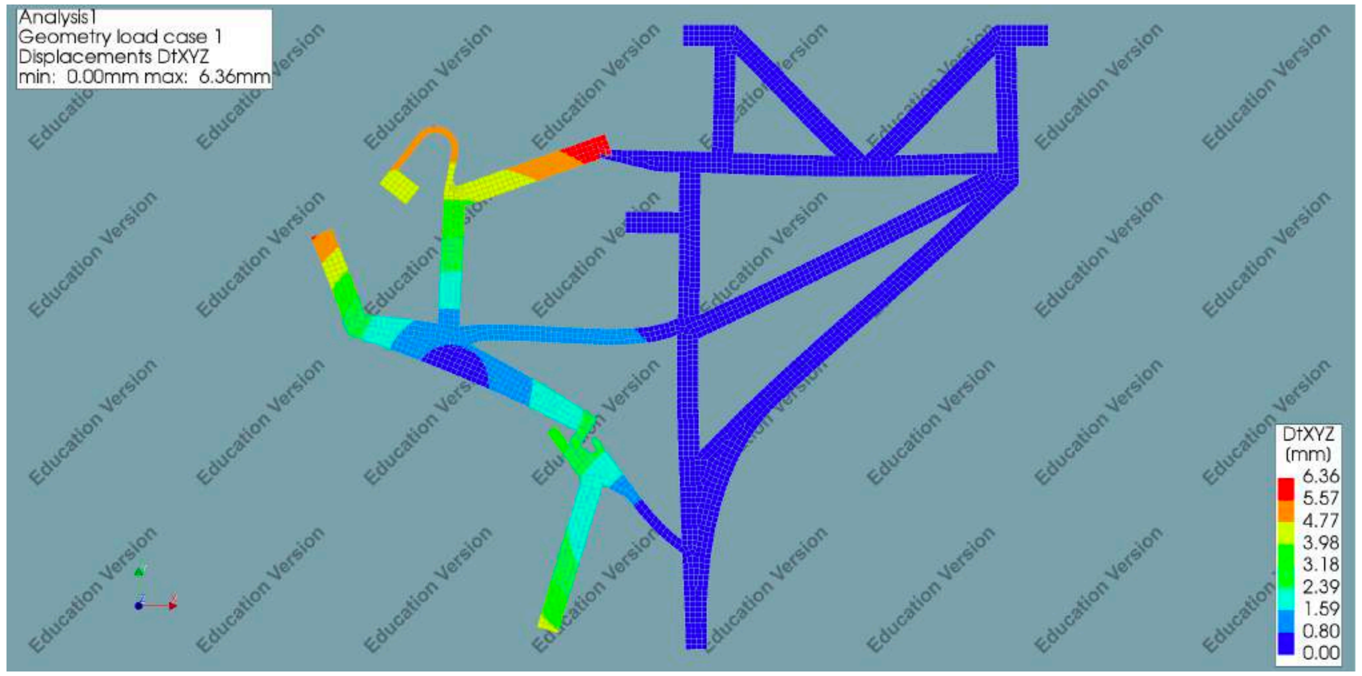


Figure 61: 50mm depth

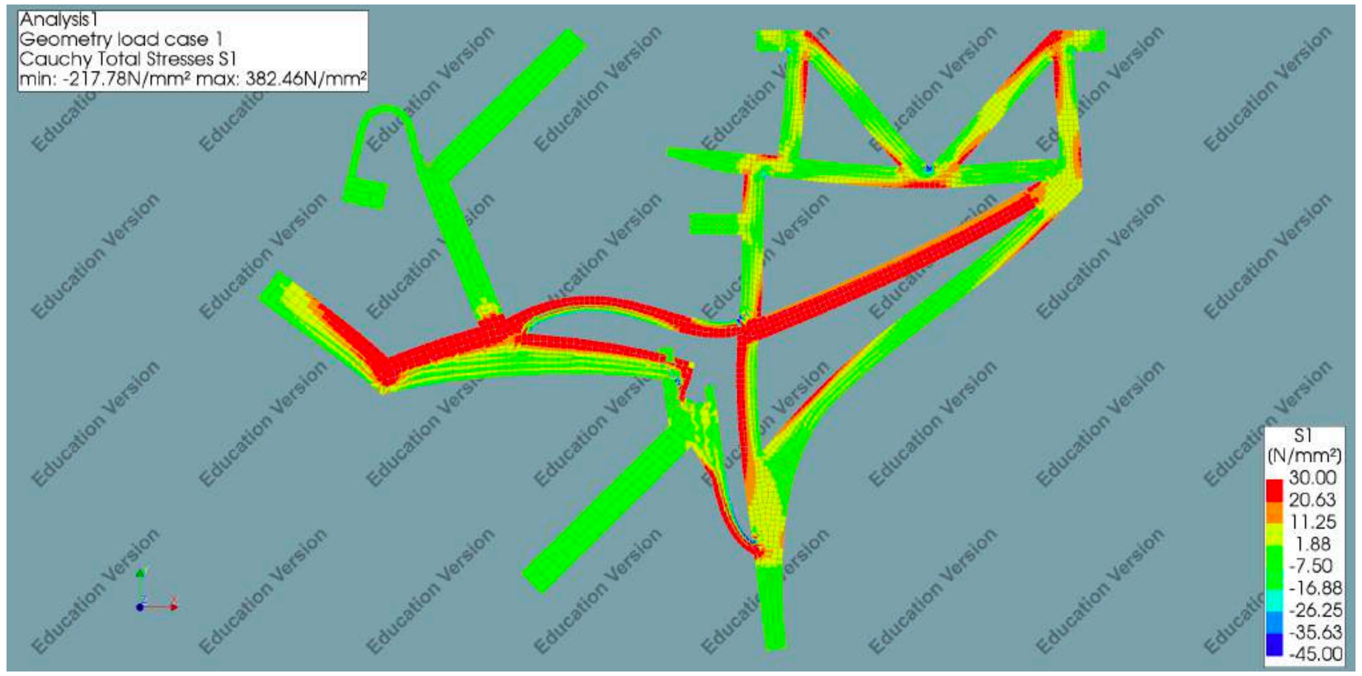


Figure 62: Tensile stresses 15mm depth

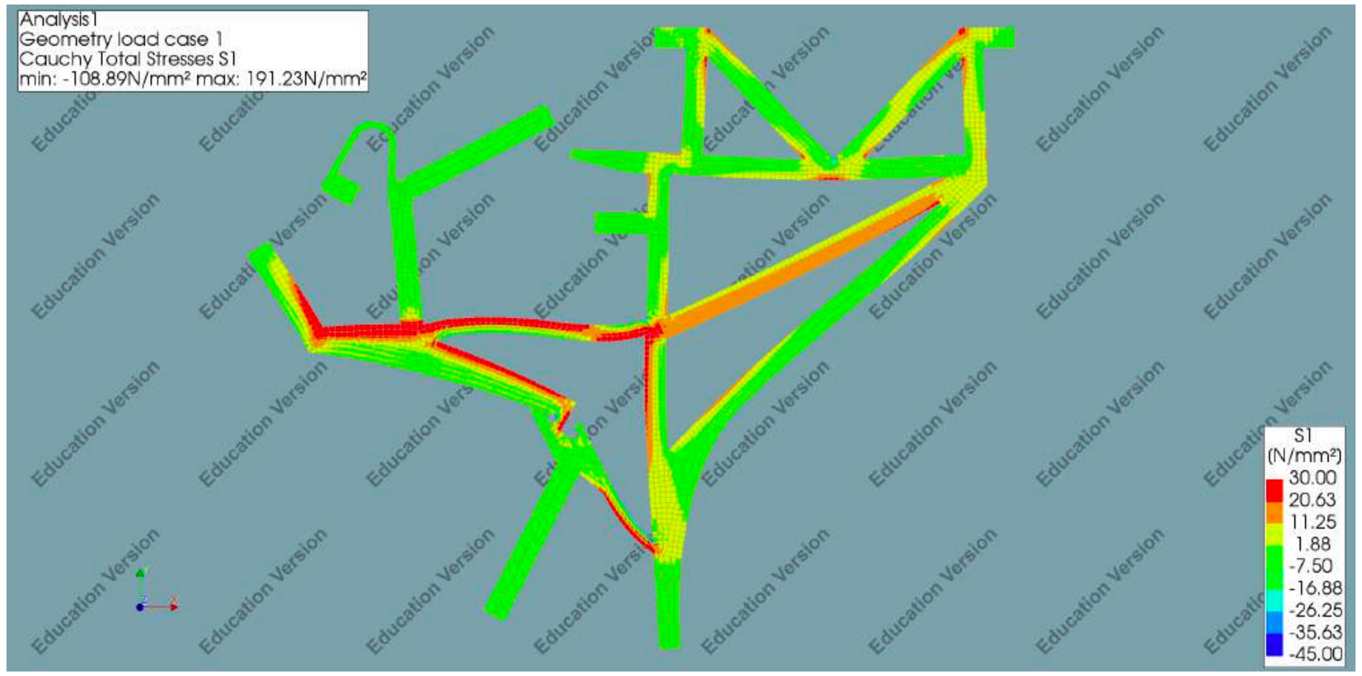


Figure 63: Tensile stresses 30mm depth

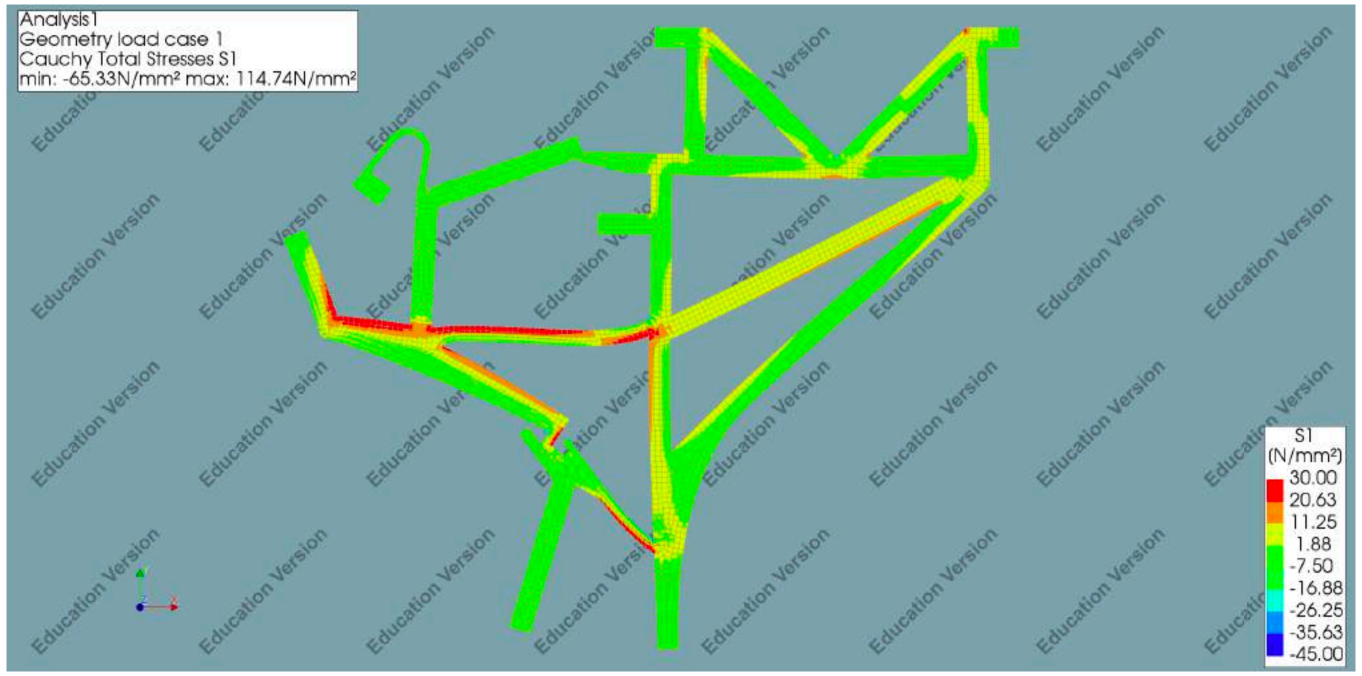


Figure 64: Tensile stresses 50mm depth

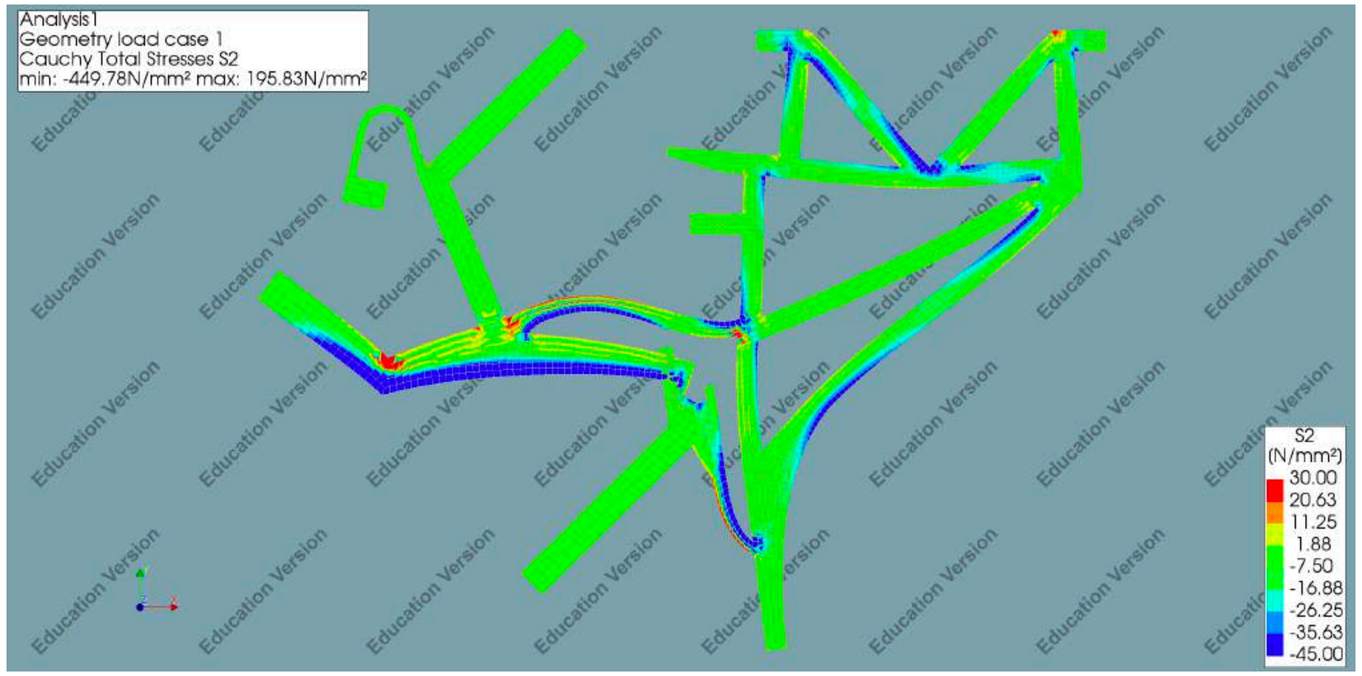


Figure 65: Compressive stresses 15mm depth

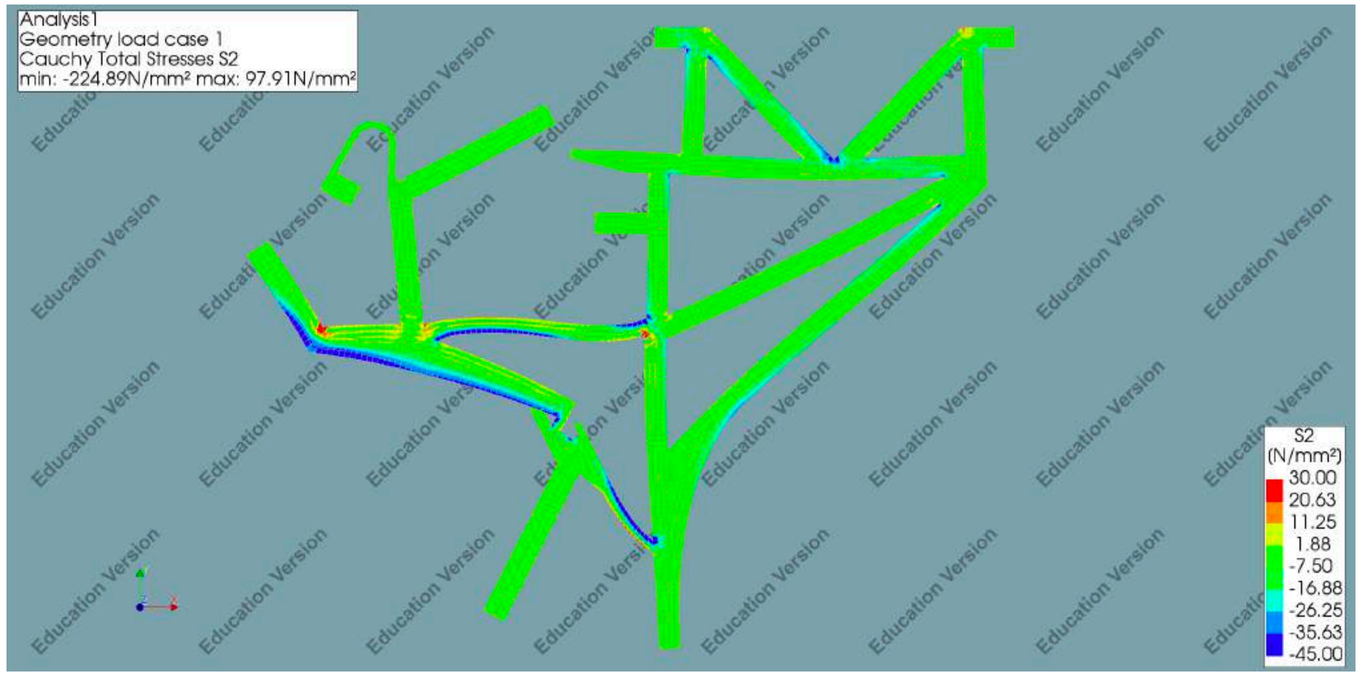


Figure 66: Compressive stresses 30mm depth

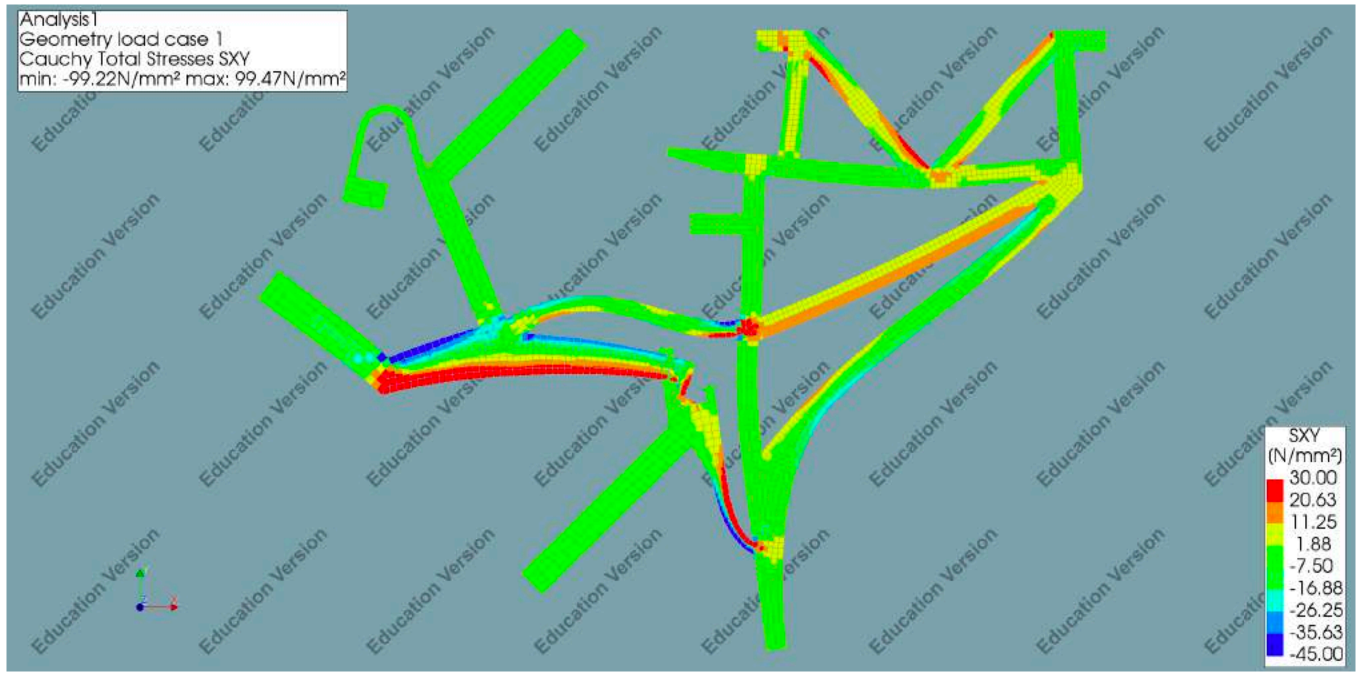


Figure 68: Shear stresses 15mm depth

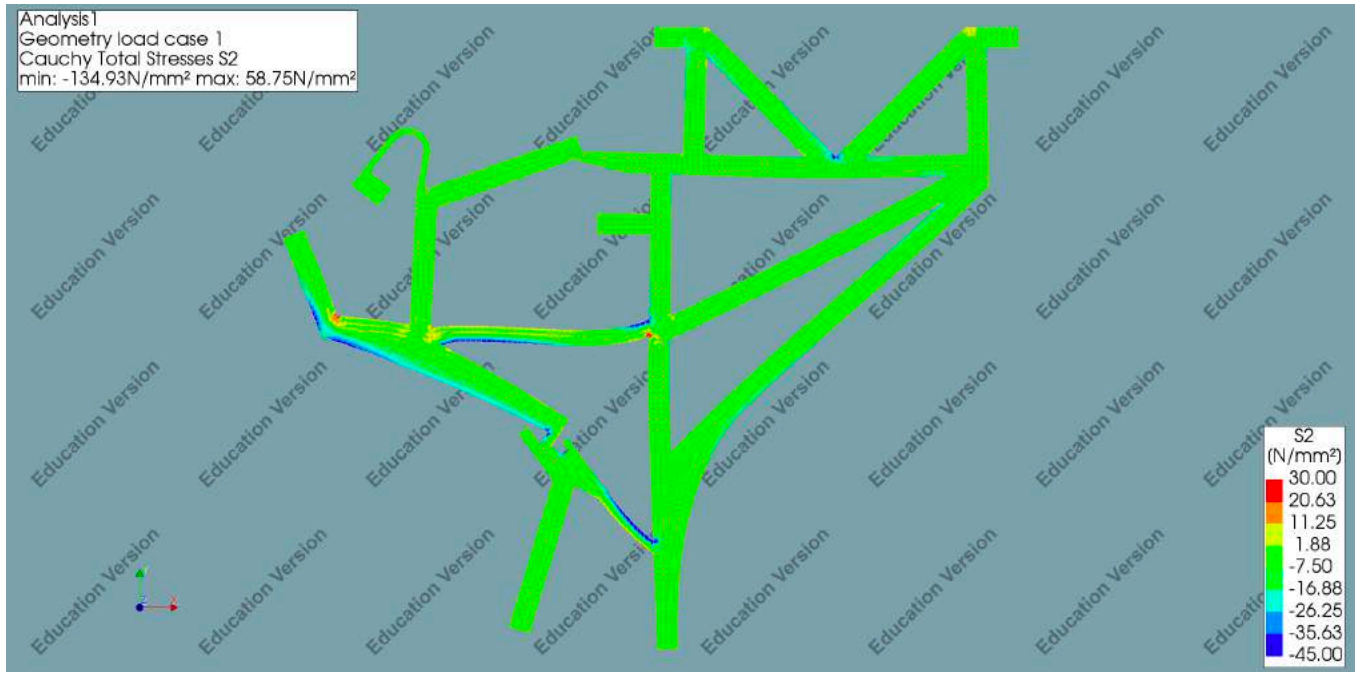


Figure 67: Compressive stresses 50mm depth

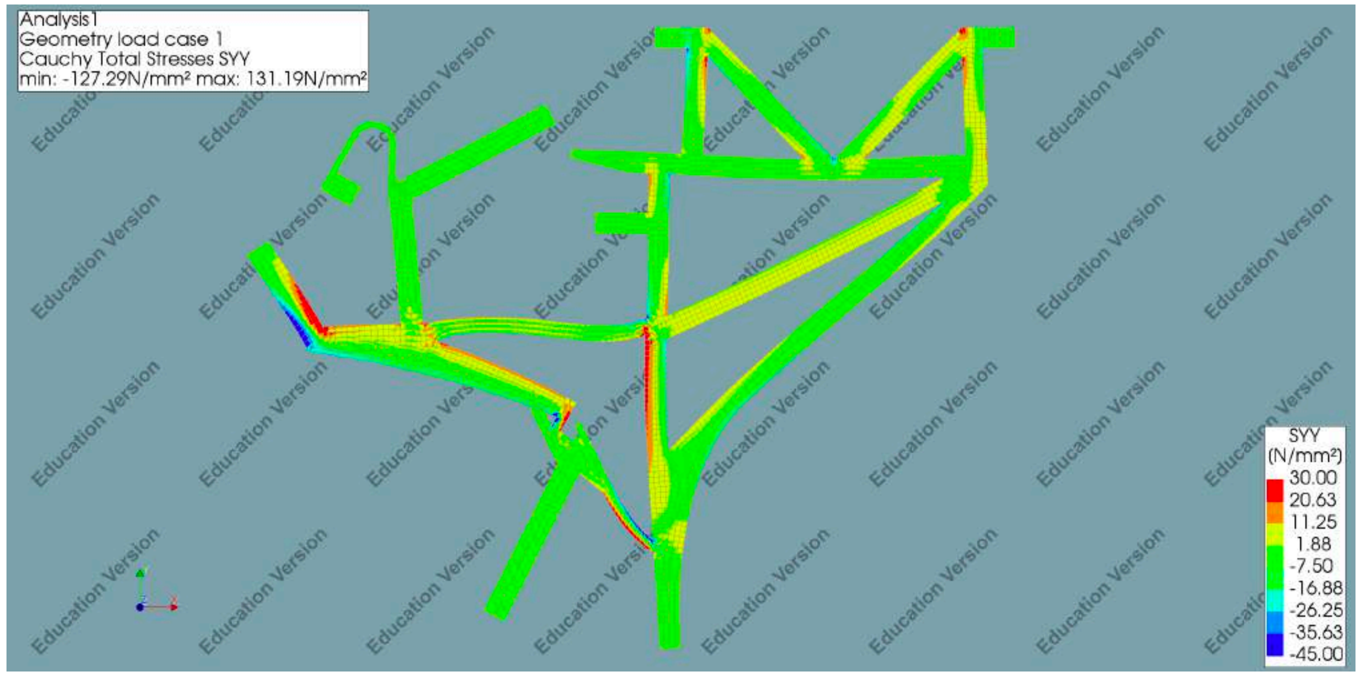


Figure 69: Shear stresses 30mm depth

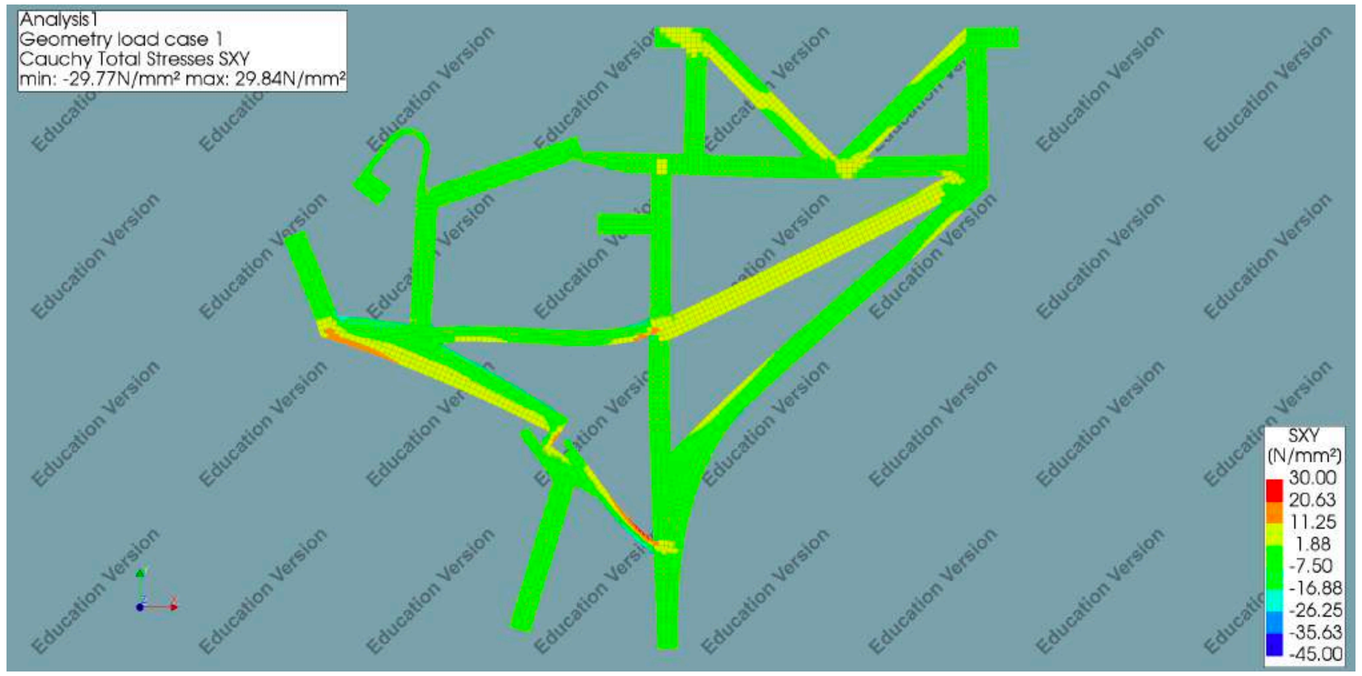


Figure 70: Shear stresses 50mm depth

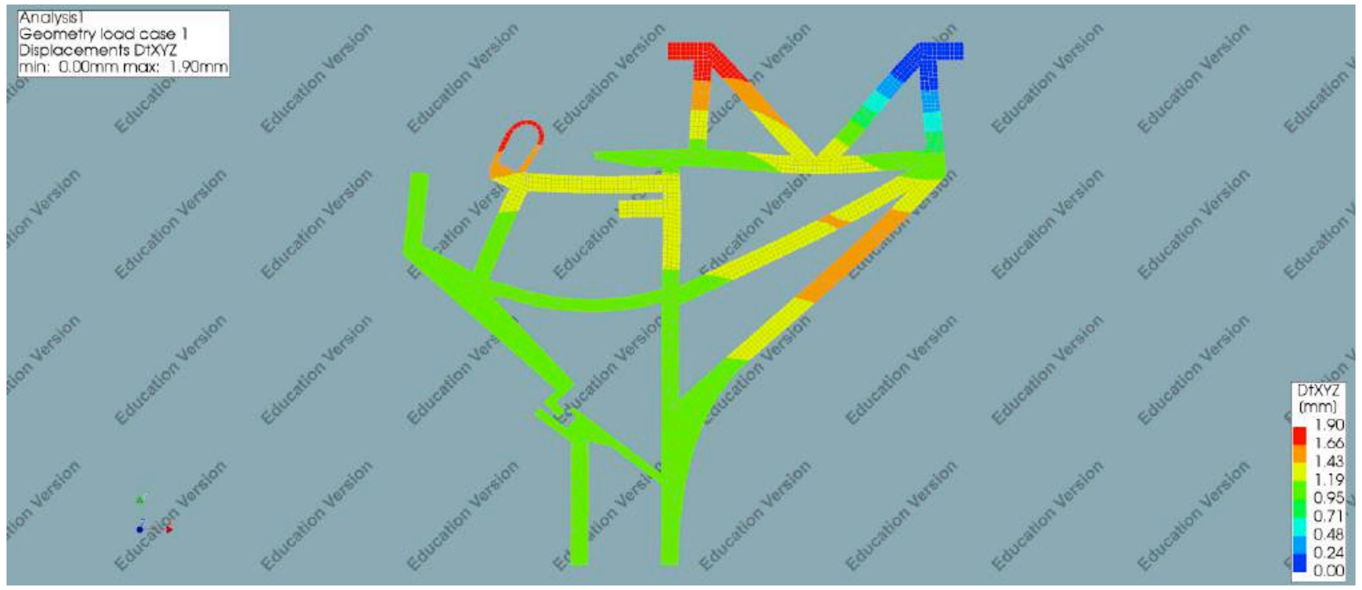


Figure 73: Displacement 15mm depth

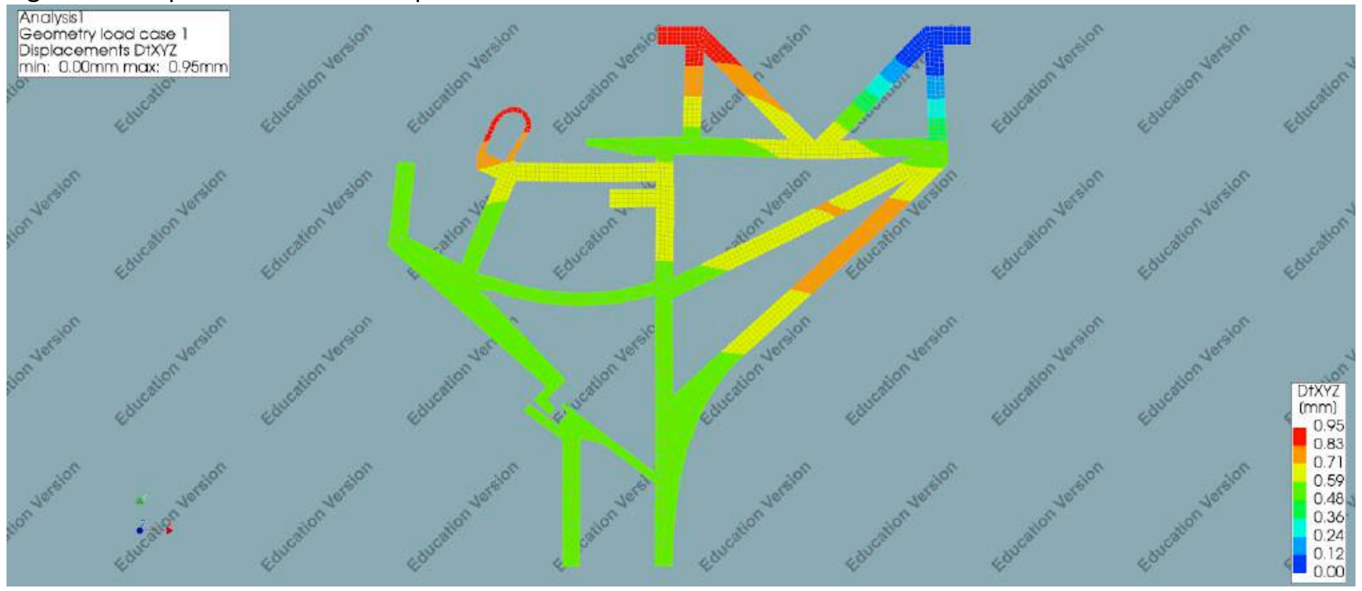


Figure 74: Displacement 30mm depth

<u>Results compressive analysis</u>

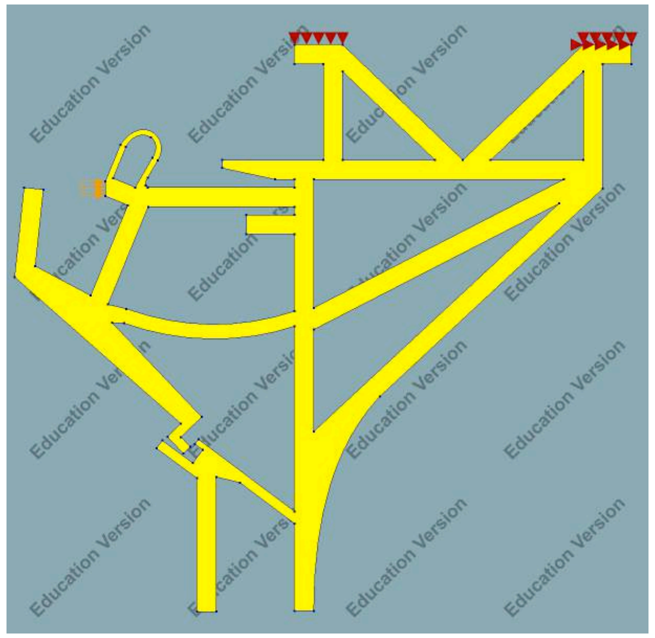


Figure 71: Geometry

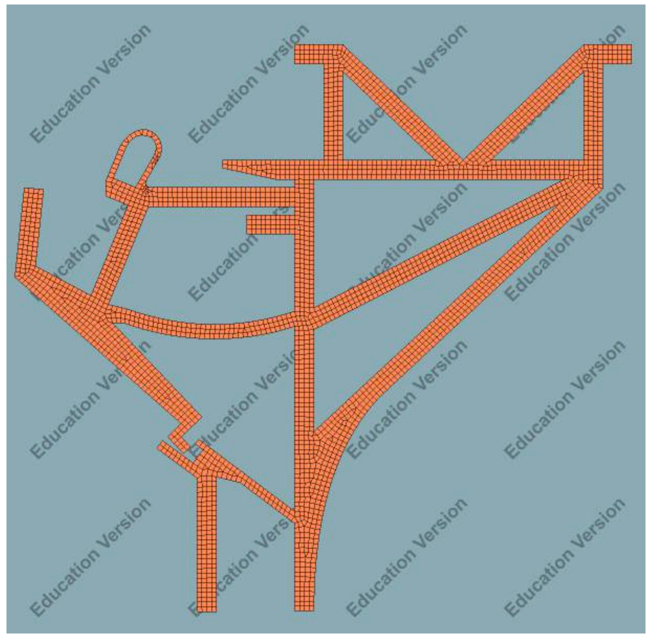


Figure 72: Mesh geometry

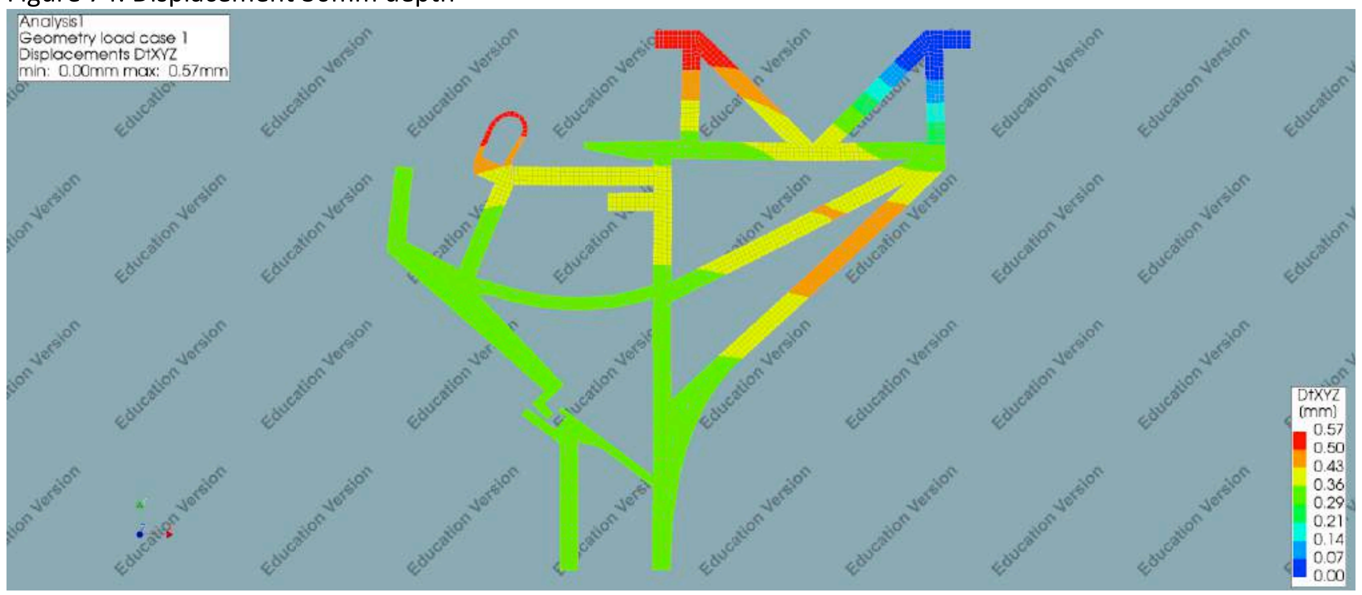


Figure 75: Displacement 50mm depth

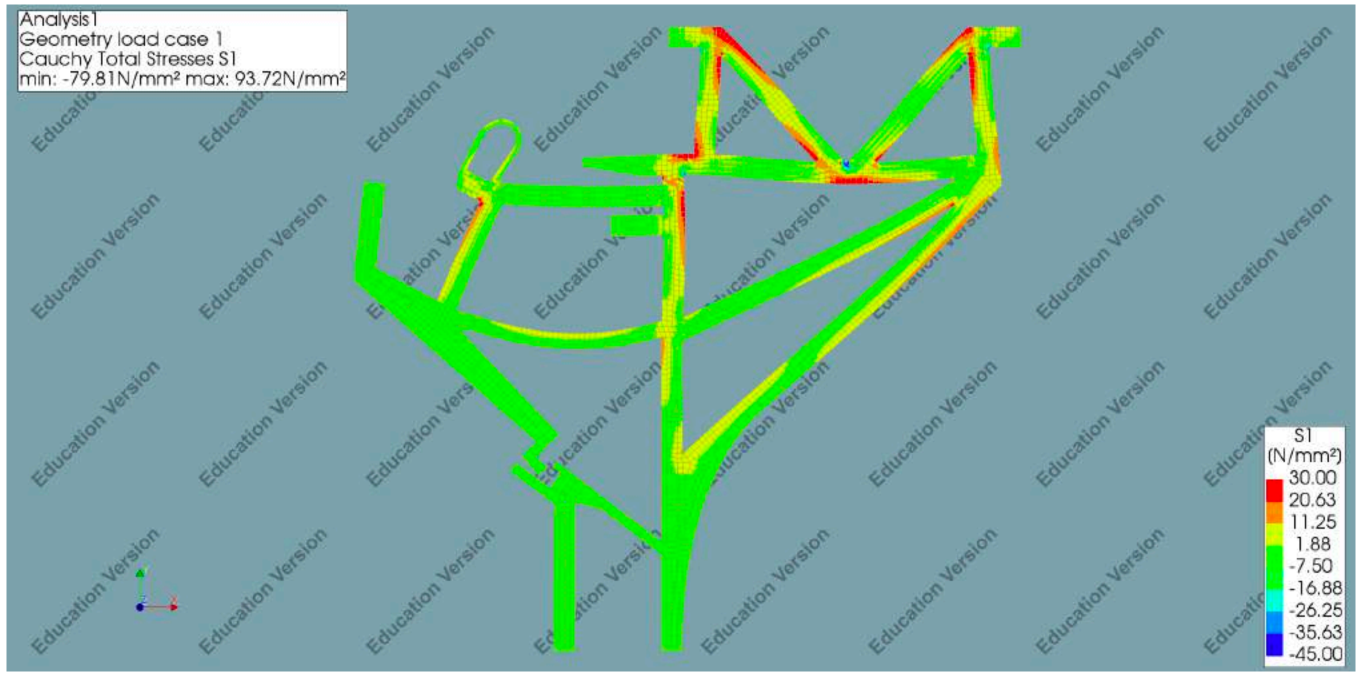


Figure 76: Tensile stresses 15mm depth

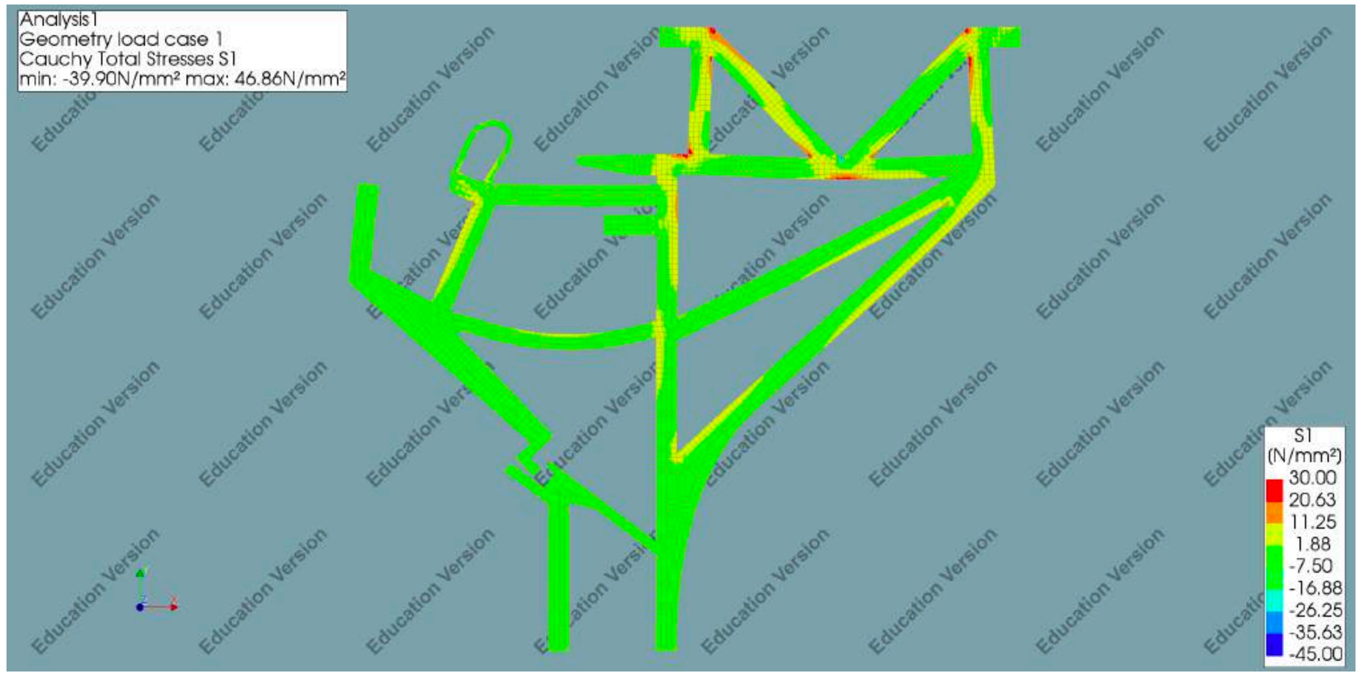


Figure 77: Tensile stresses 30mm depth

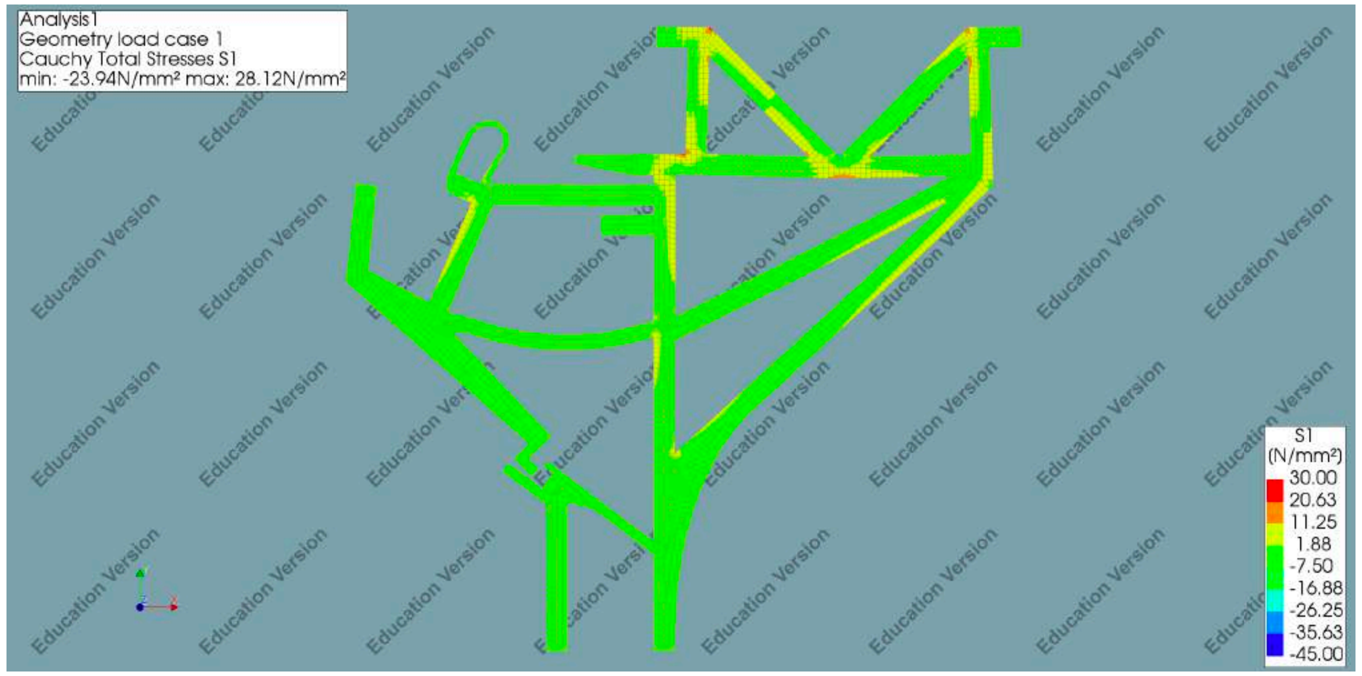


Figure 78: Tensile stresses 50mm depth

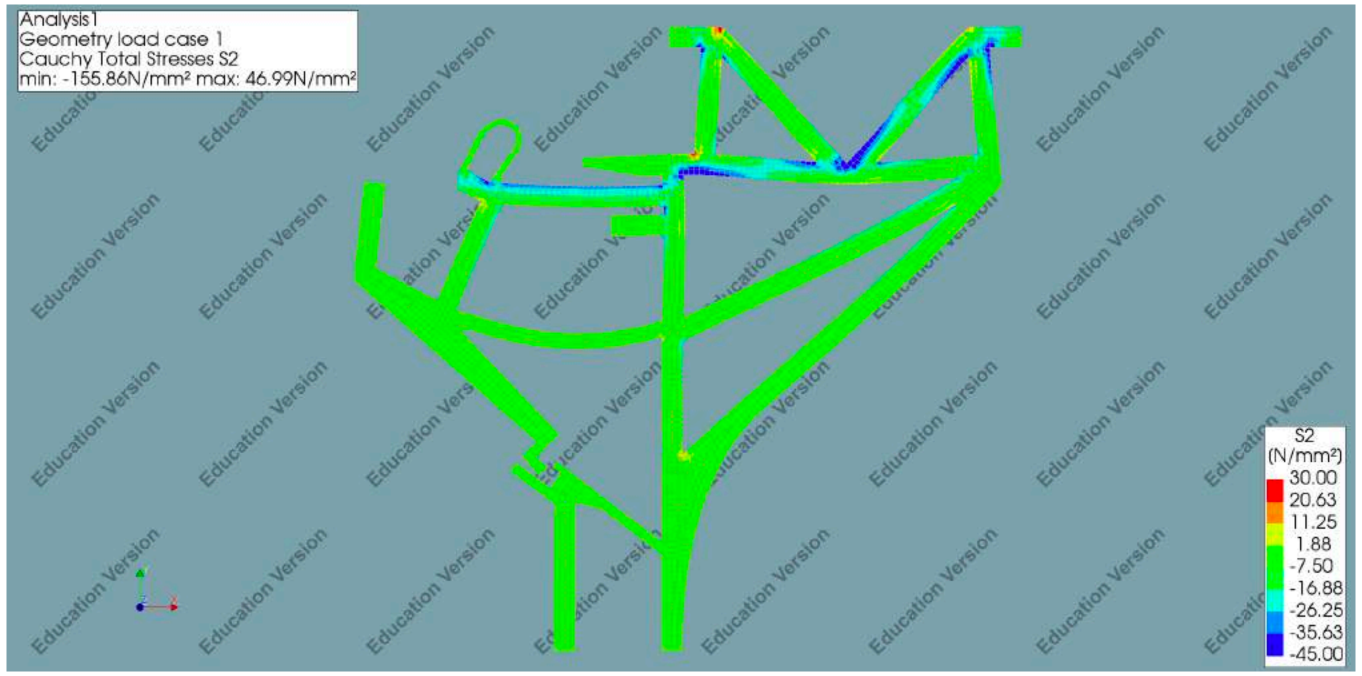


Figure 79: Compressive stresses 15mm depth

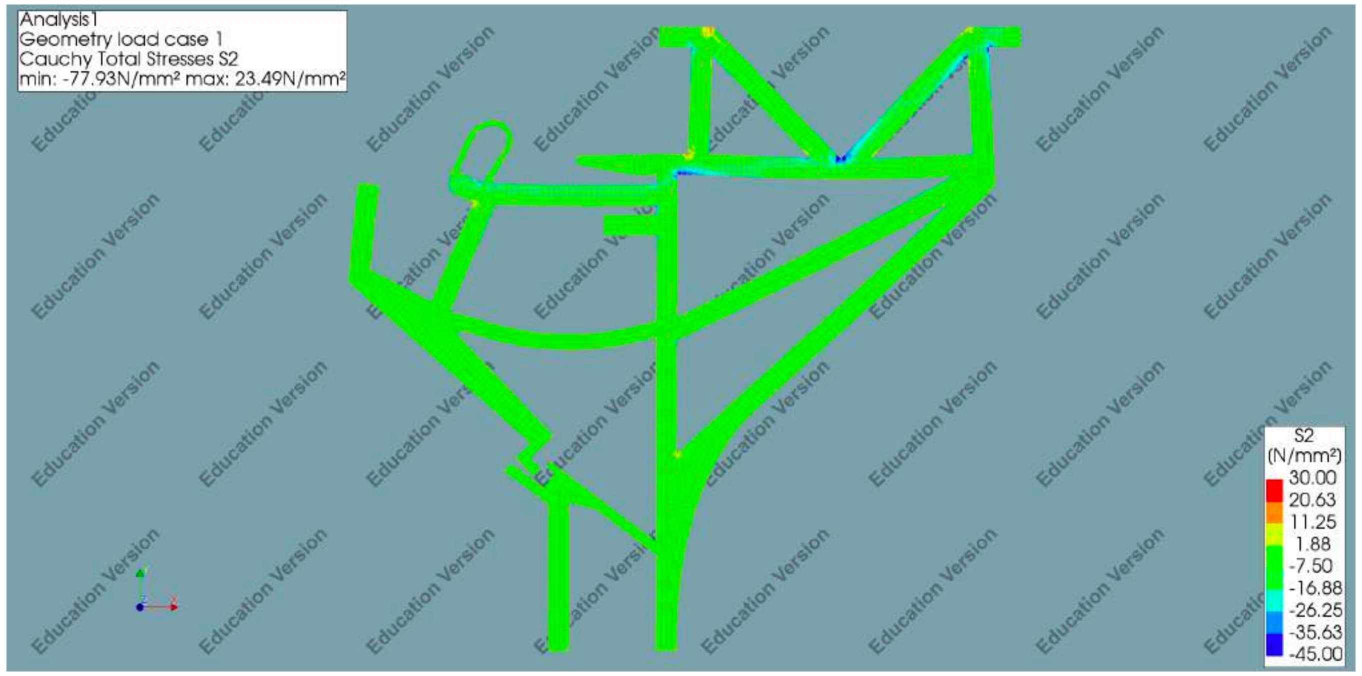


Figure 80: Compressive stresses 30mm depth

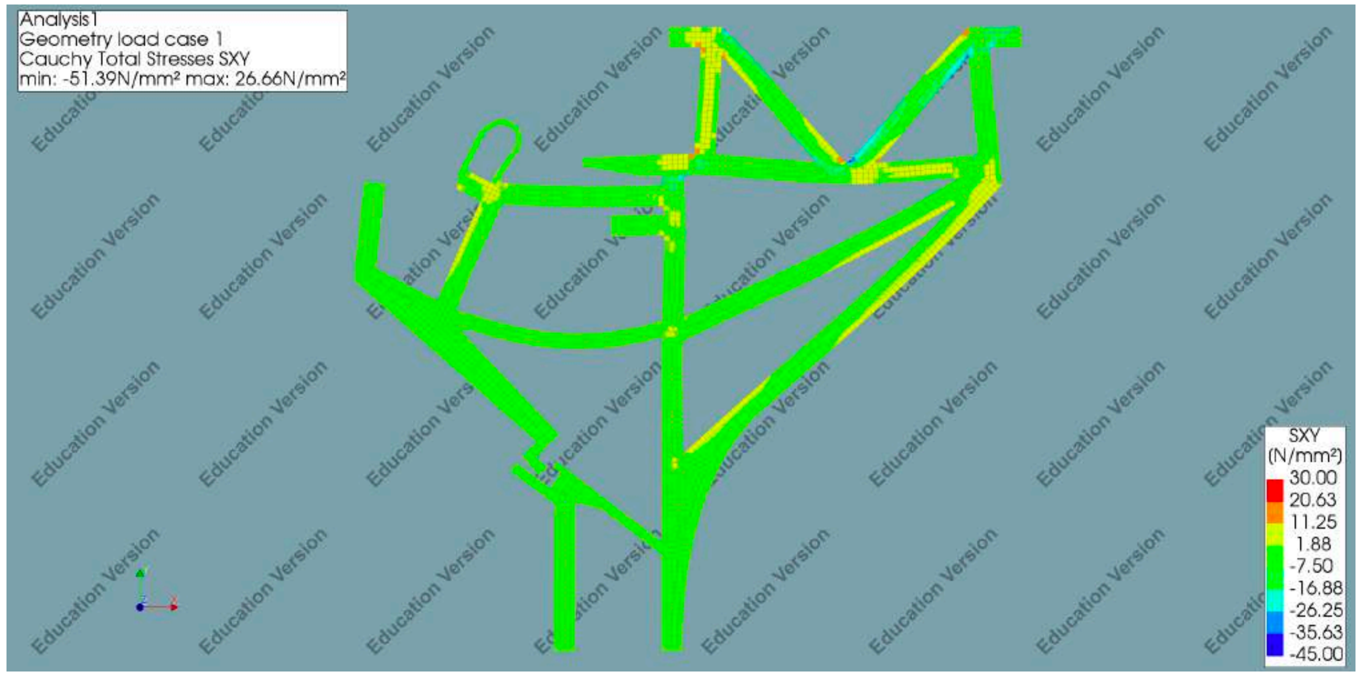


Figure 82: shear stresses 15mm depth

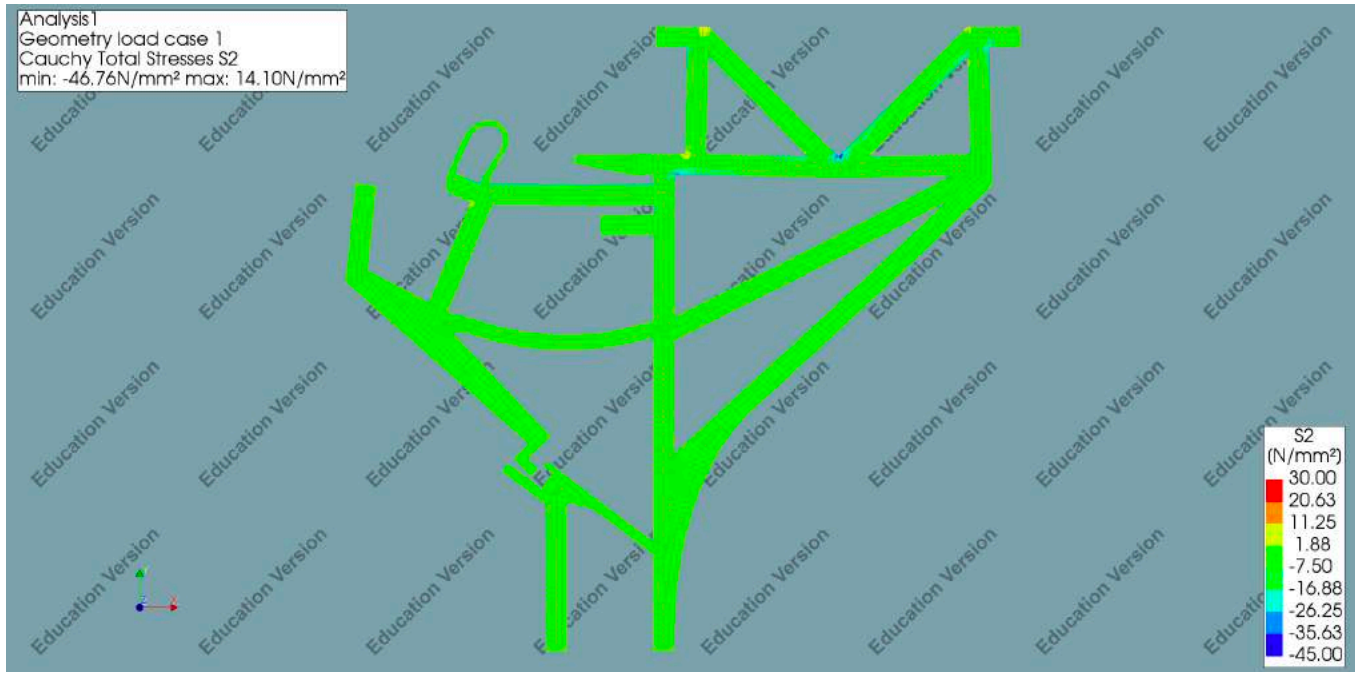


Figure 81: Compressive stresses 50mm depth

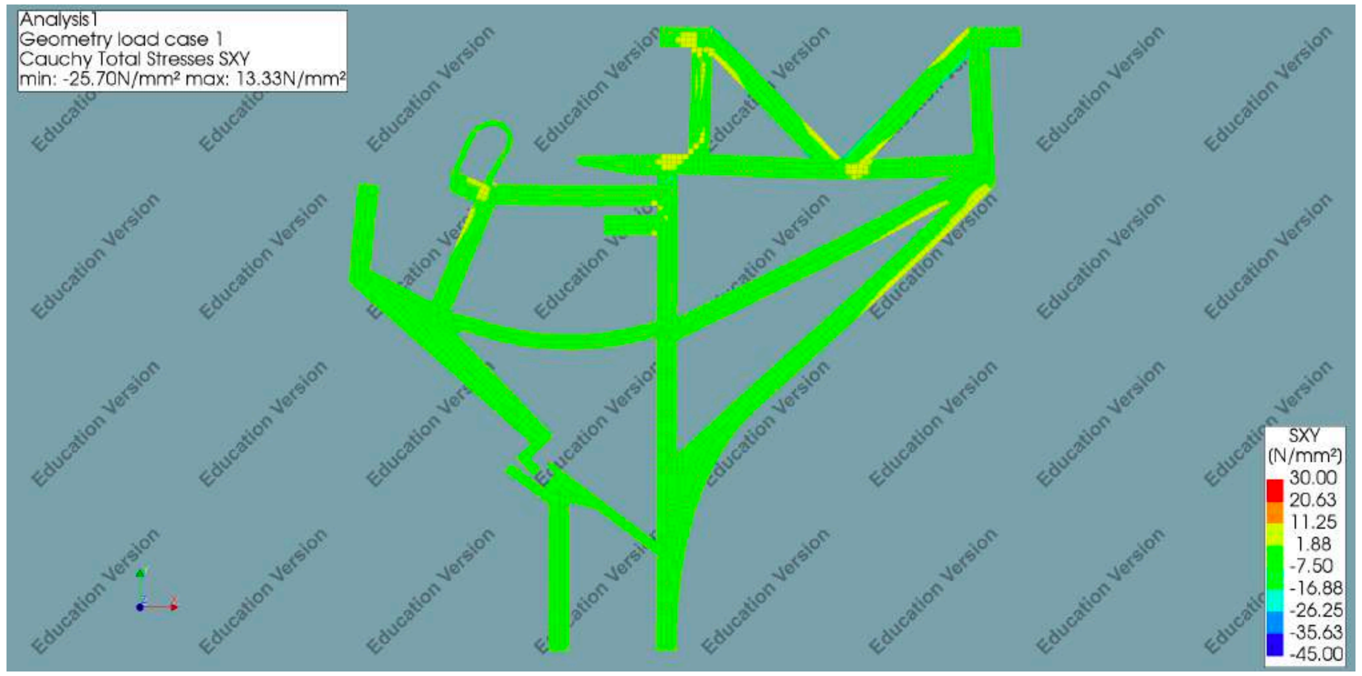


Figure 83: shear stresses 30mm depth

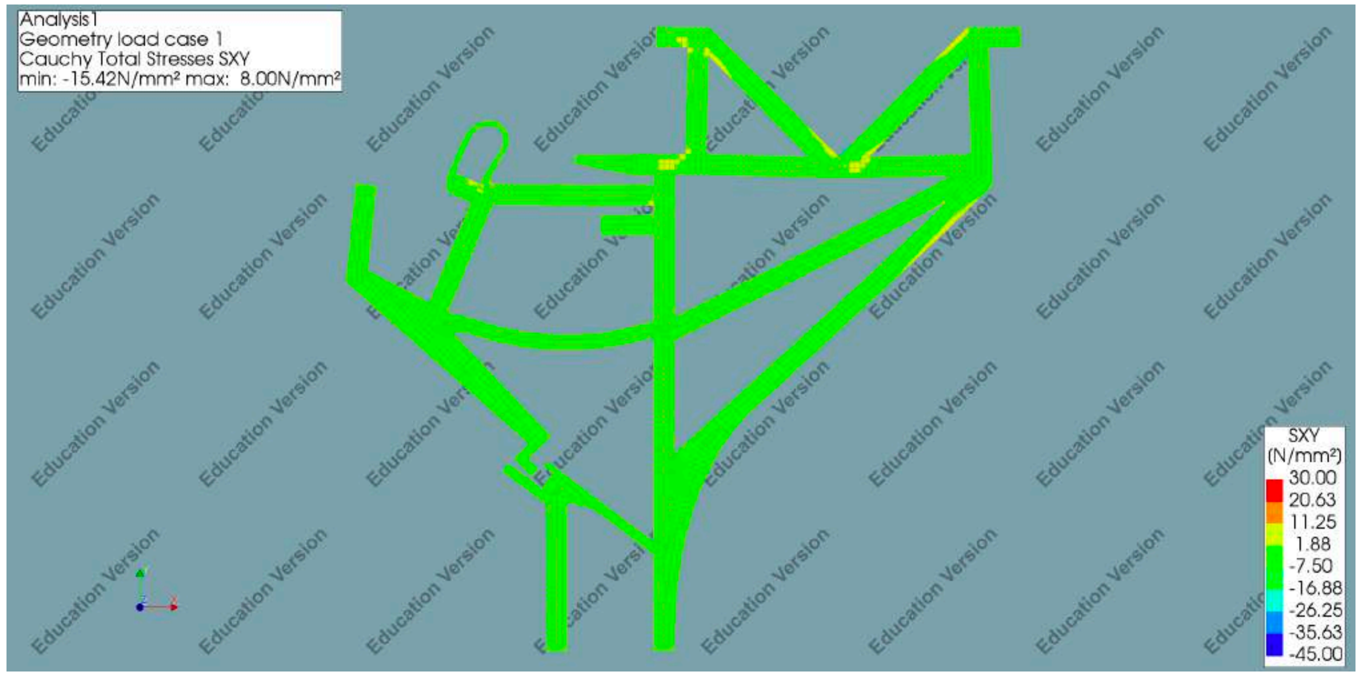


Figure 84: shear stresses 50mm depth

Analysis 4: Iteration 3

<u>Results tensile analysis</u>

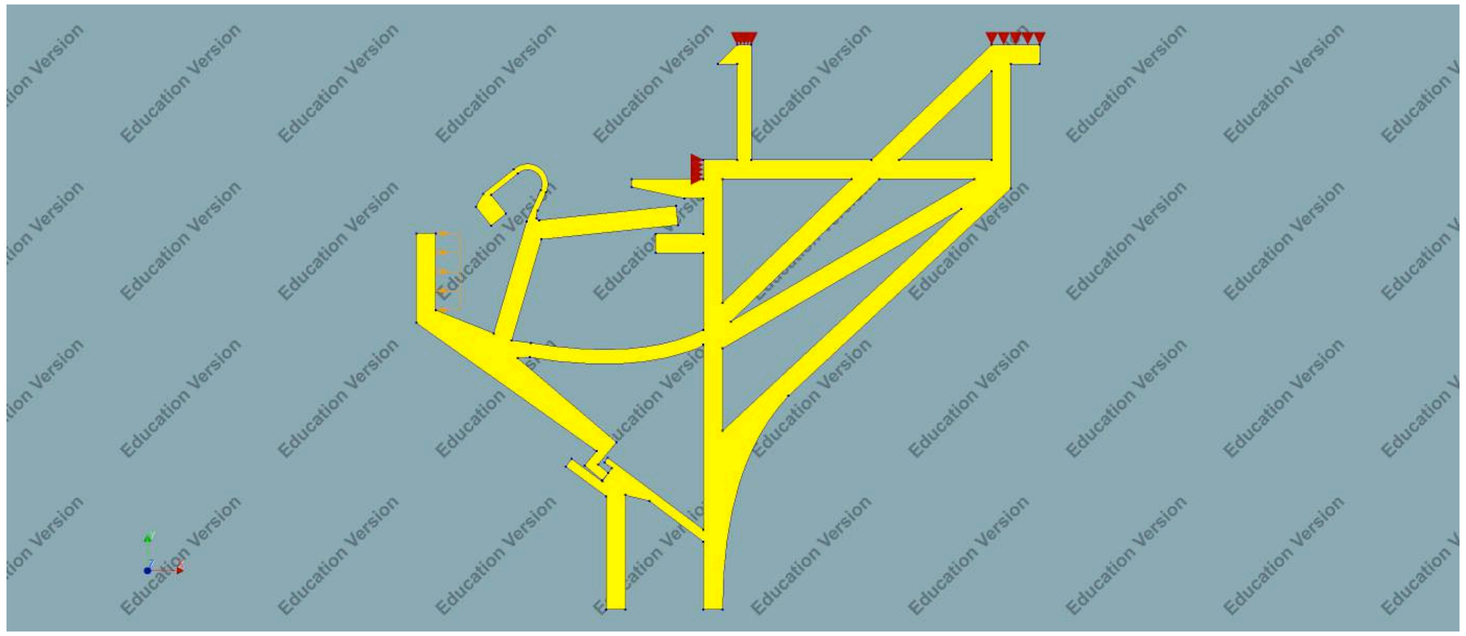


Figure 85: Geometry

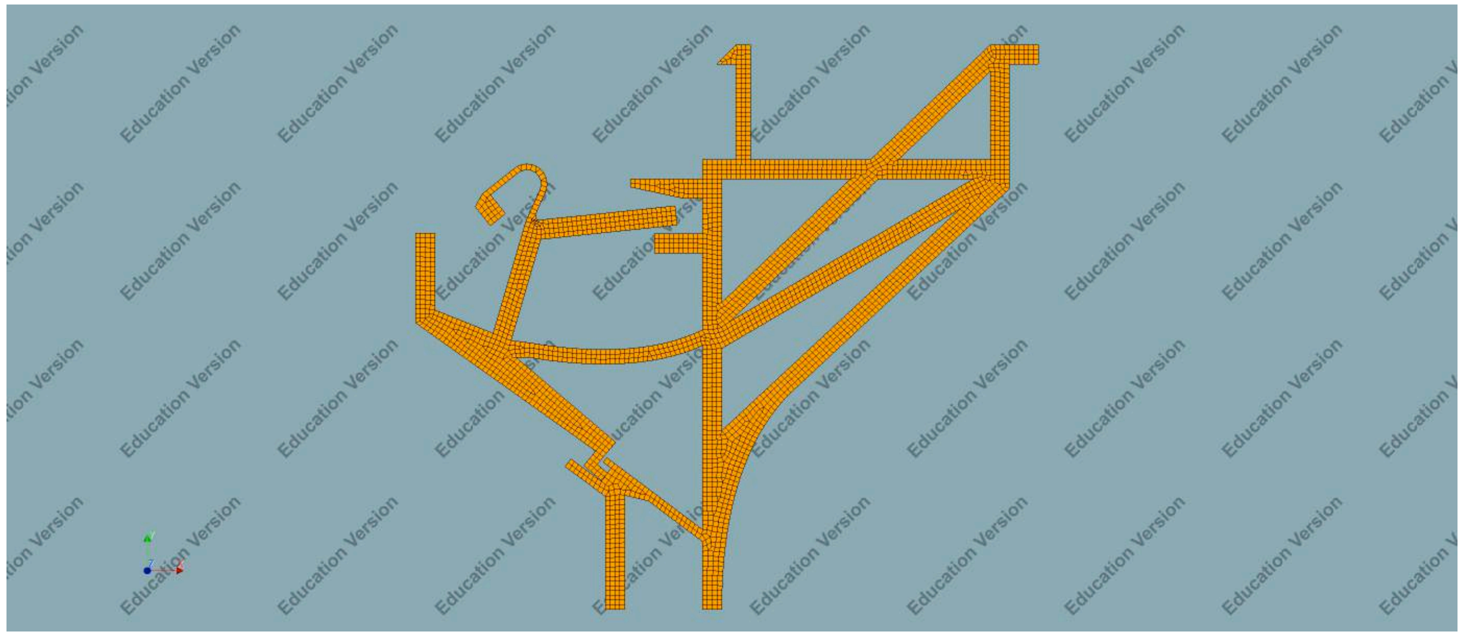


Figure 86: Mesh geometry

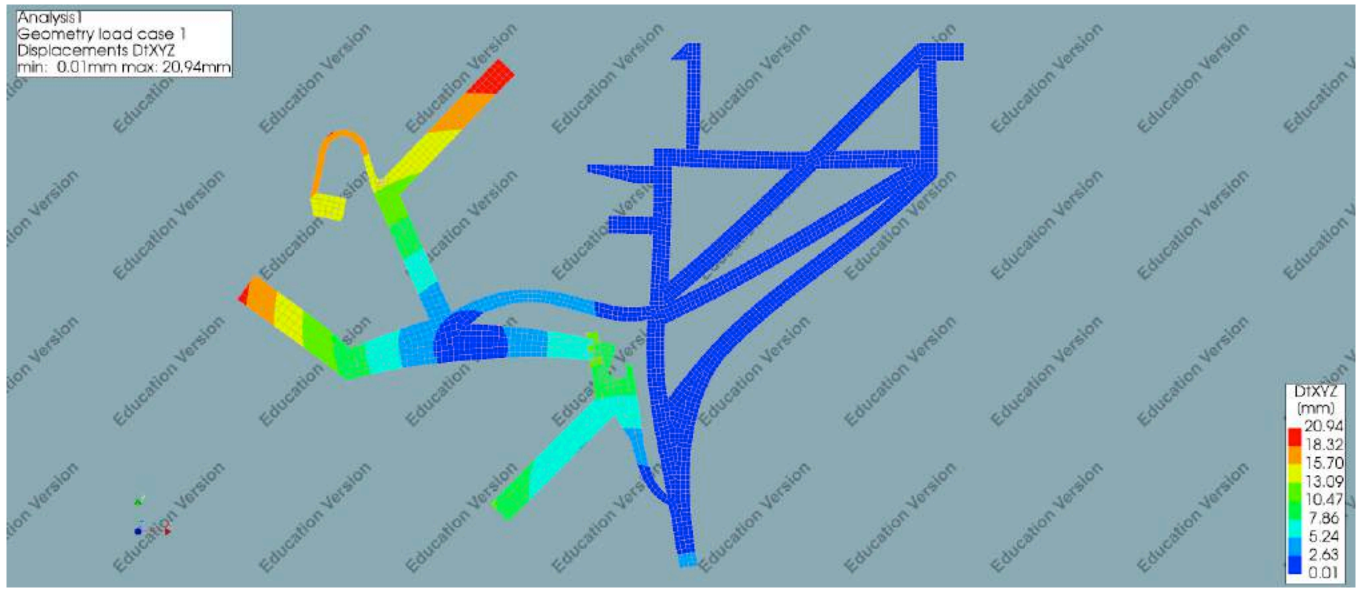


Figure 87: Displacement 15mm depth

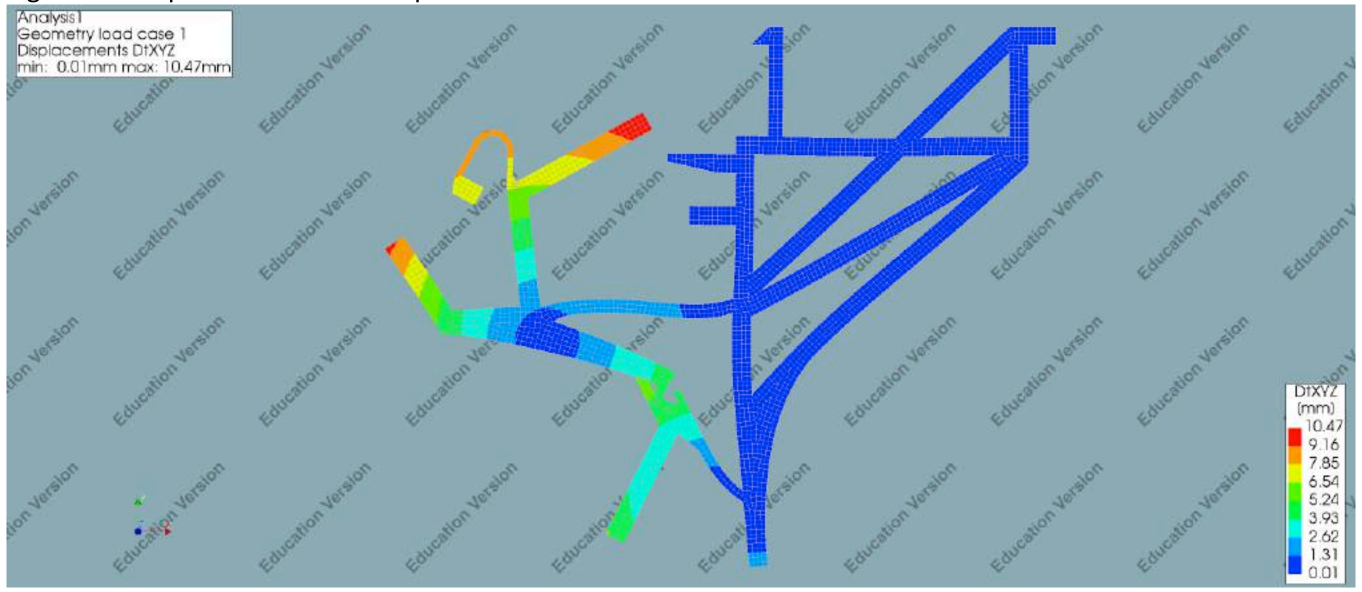


Figure 88: Displacement 30mm depth

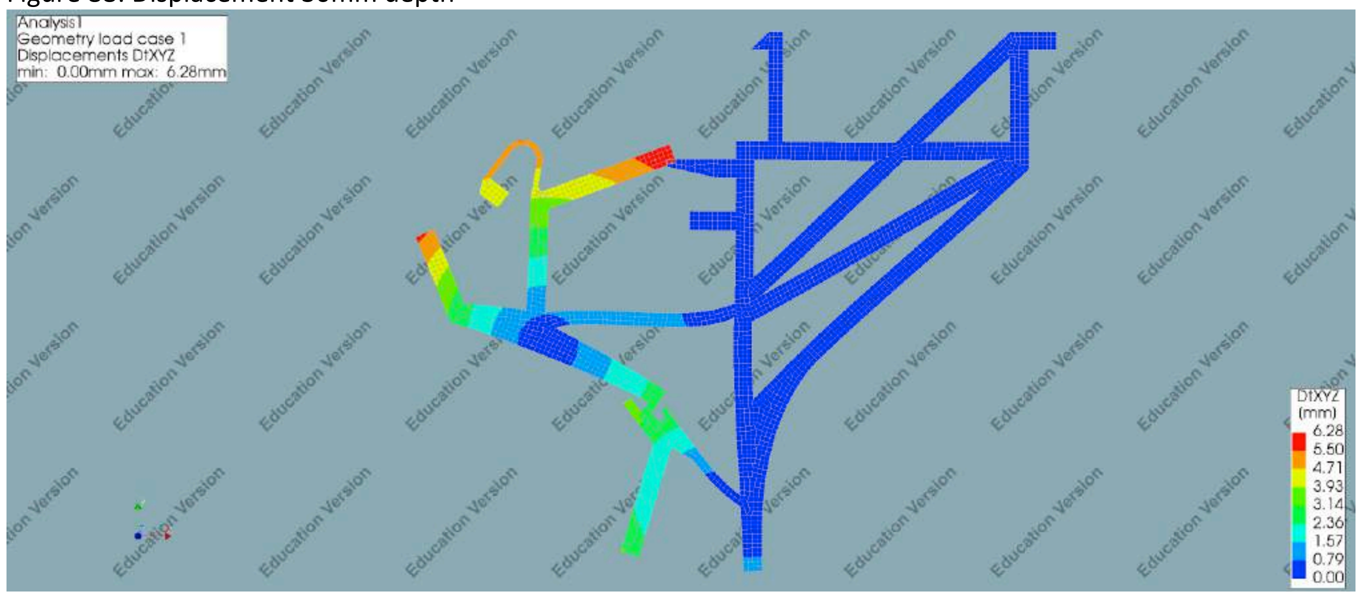


Figure 89: 50mm depth

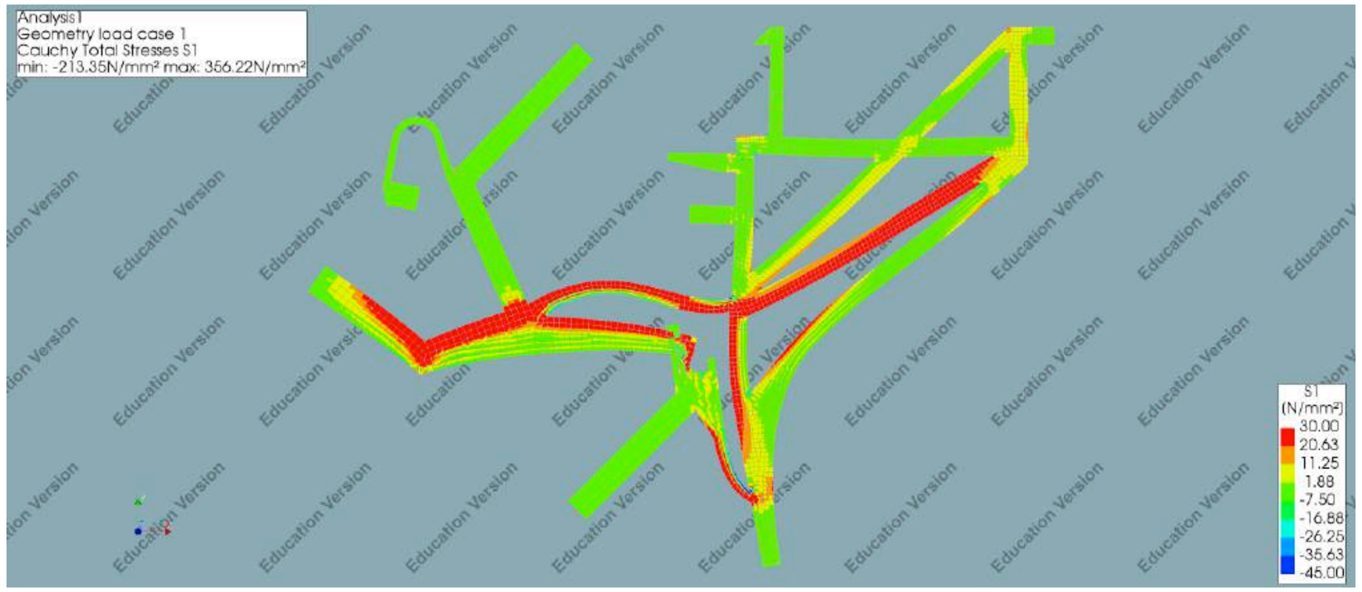


Figure 90: Tensile stresses 15mm depth

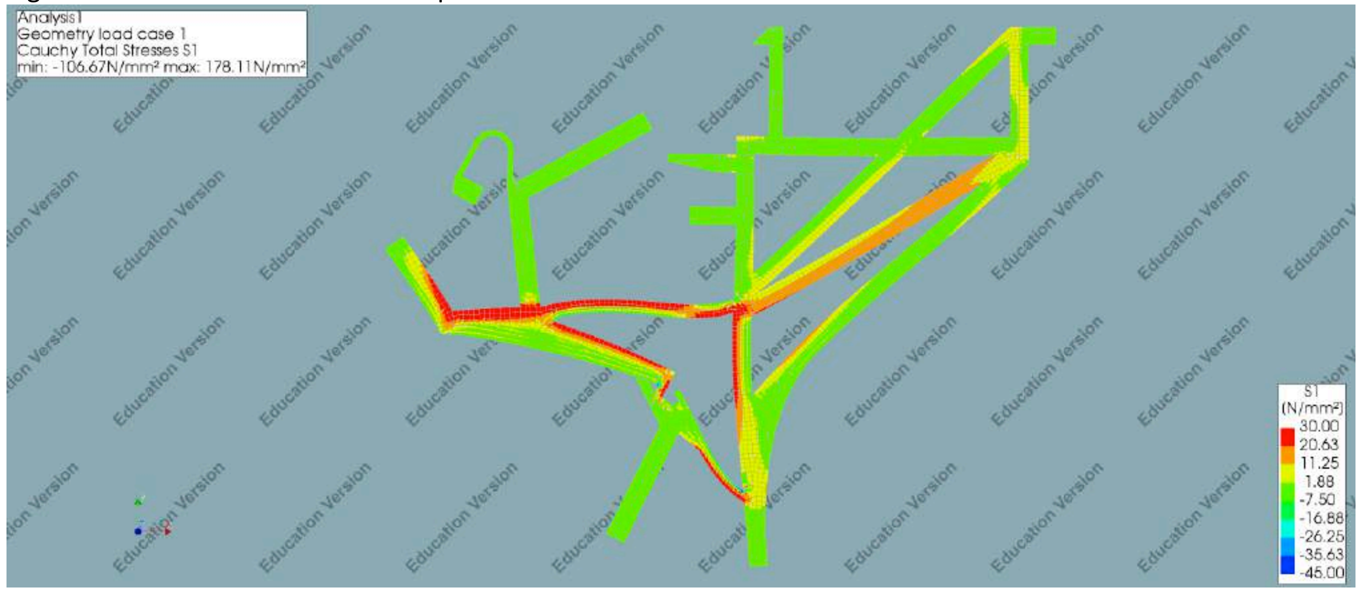


Figure 91: Tensile stresses 30mm depth

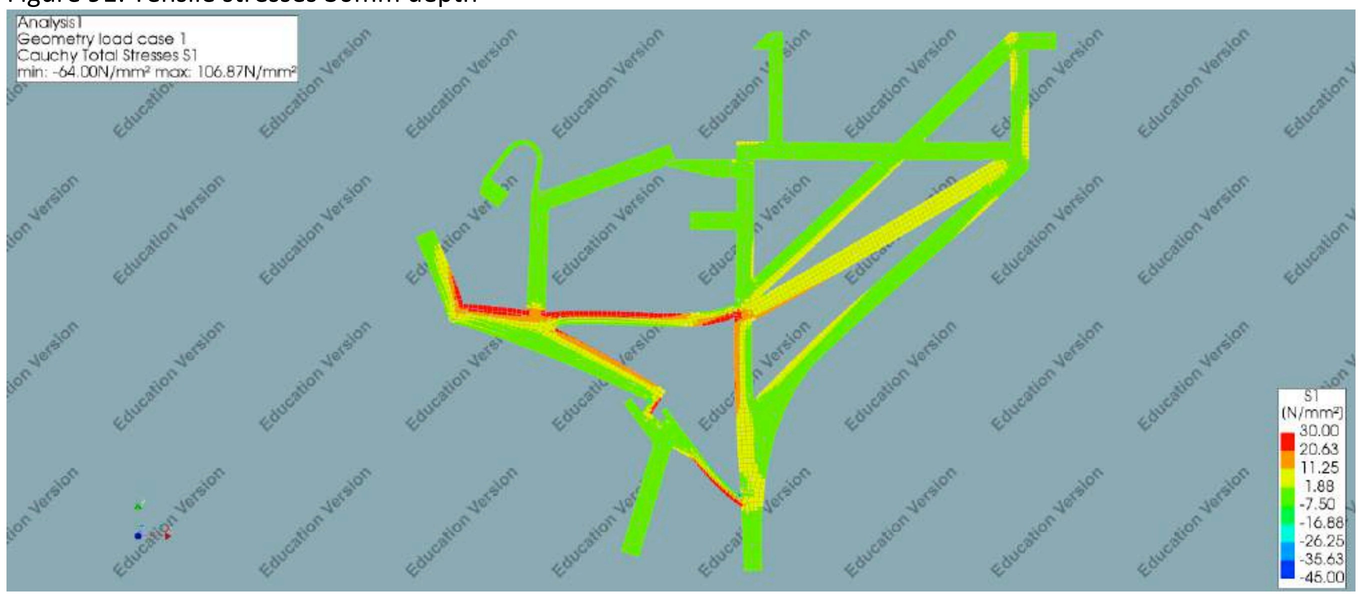


Figure 92: Tensile stresses 50mm depth

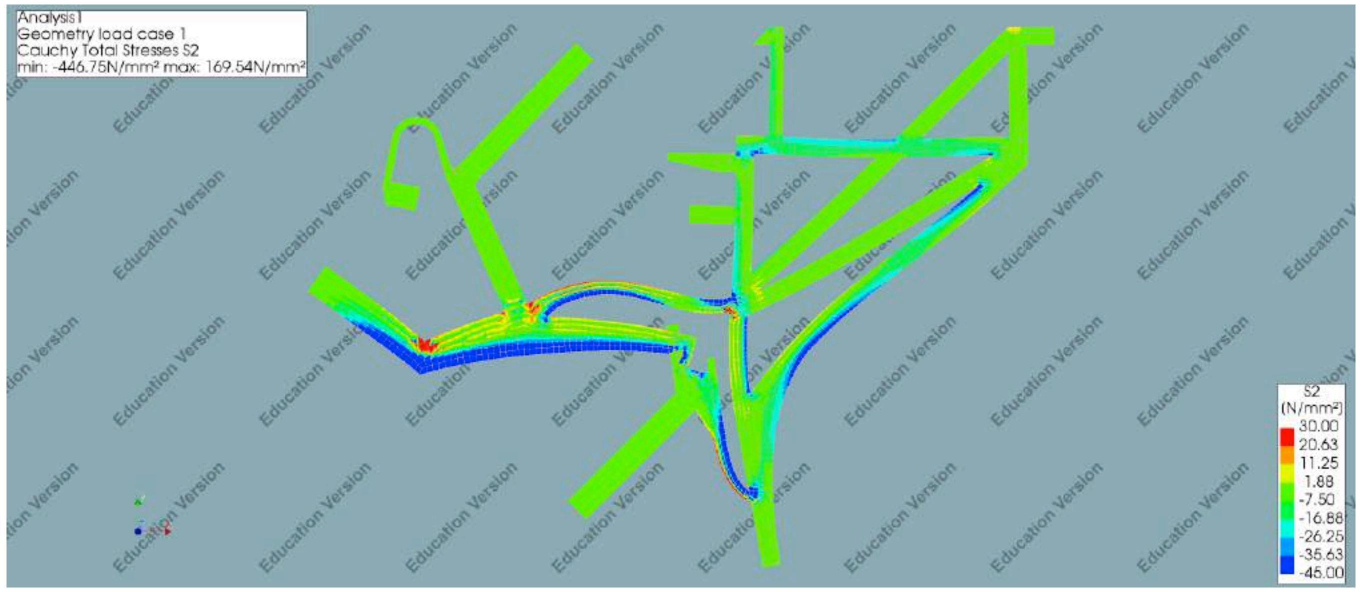


Figure 93: Compressive stresses 15mm depth

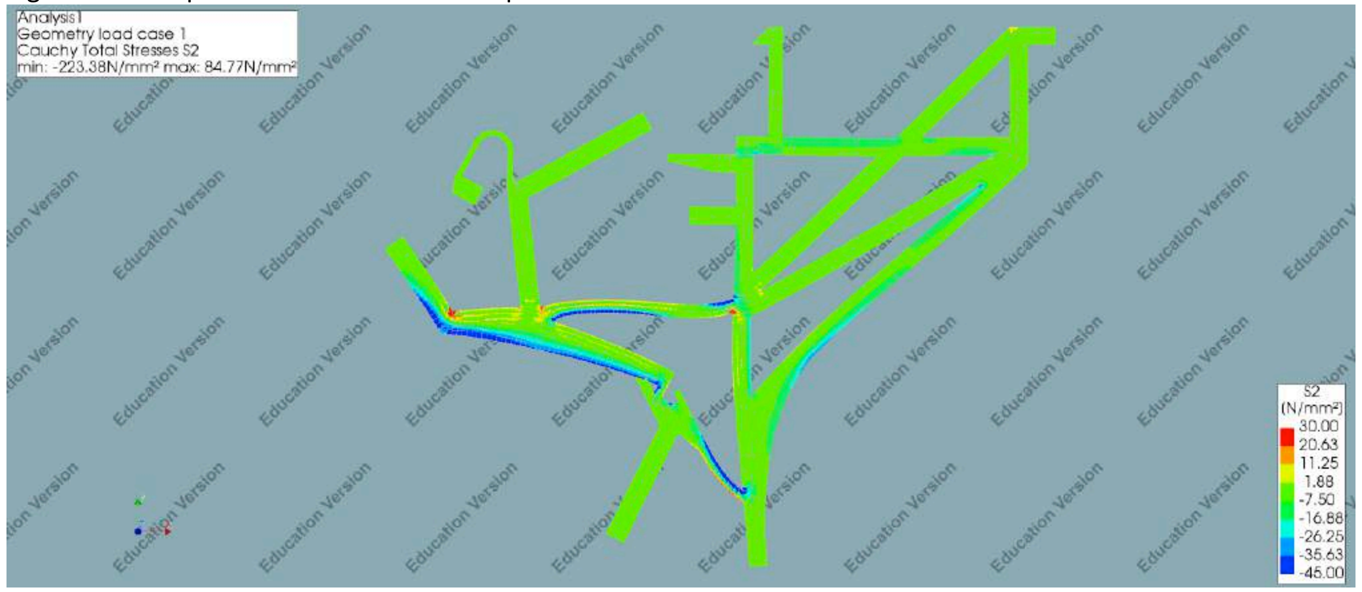


Figure 94: Compressive stresses 30mm depth

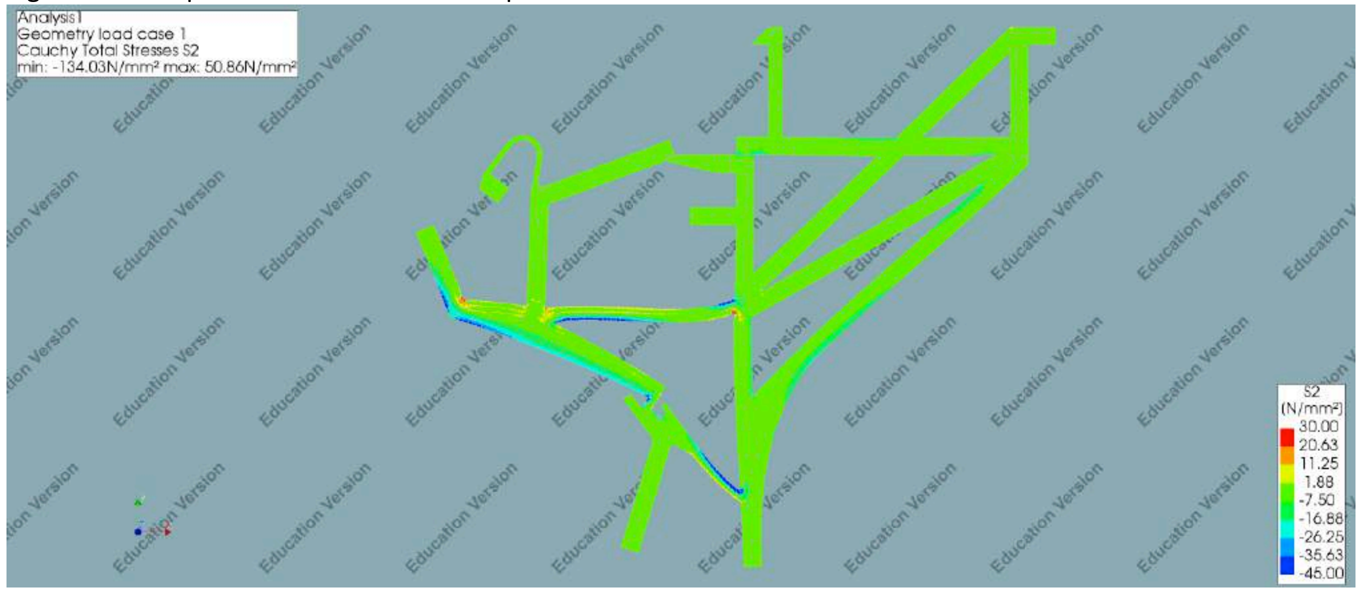


Figure 95: Compressive stresses 50mm depth

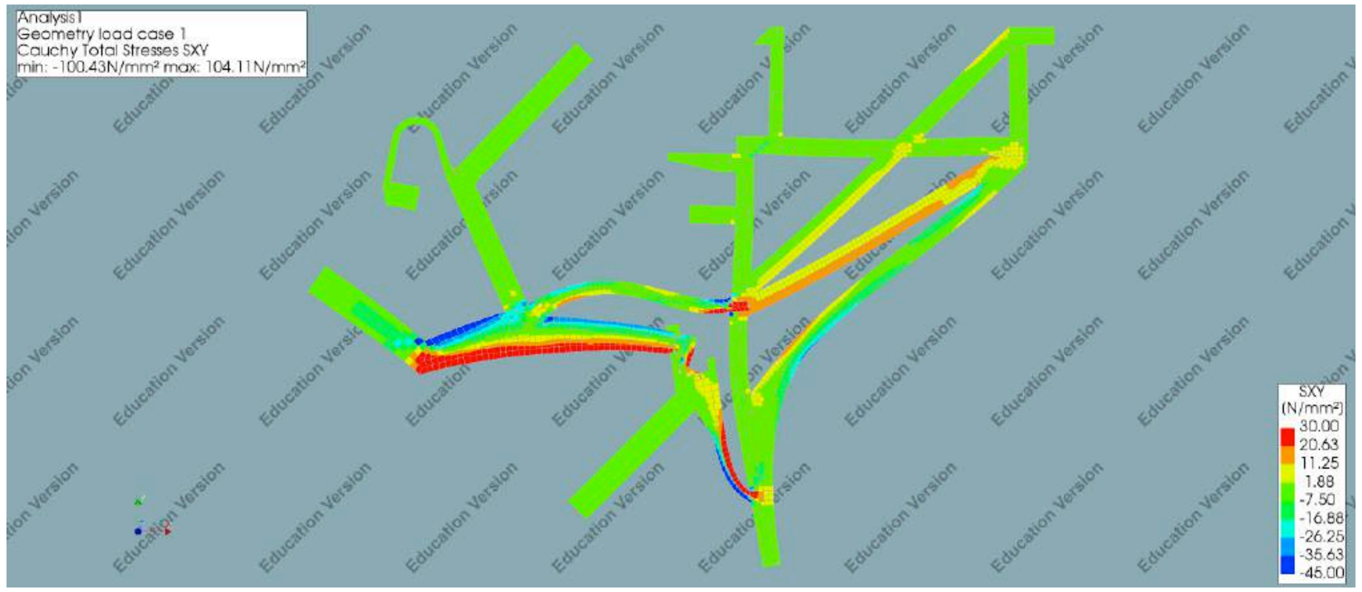


Figure 96: Shear stresses 15mm depth

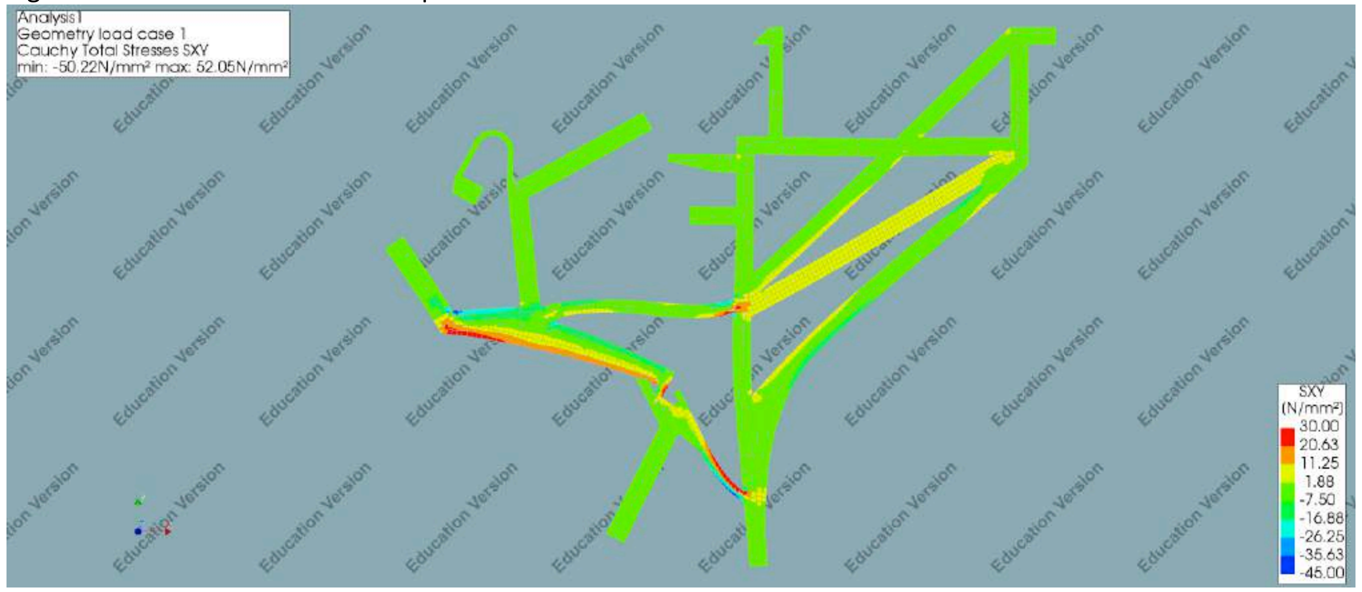


Figure 97: Shear stresses 30mm depth

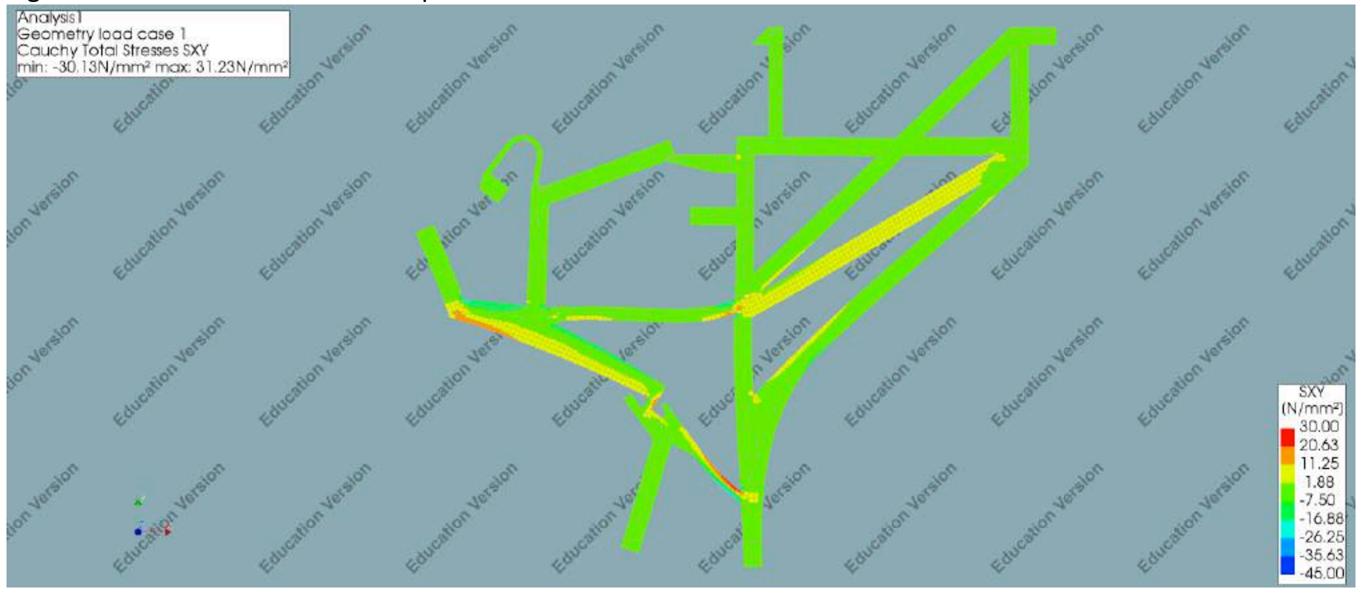


Figure 98: Shear stresses 50mm depth

Results compressive analysis

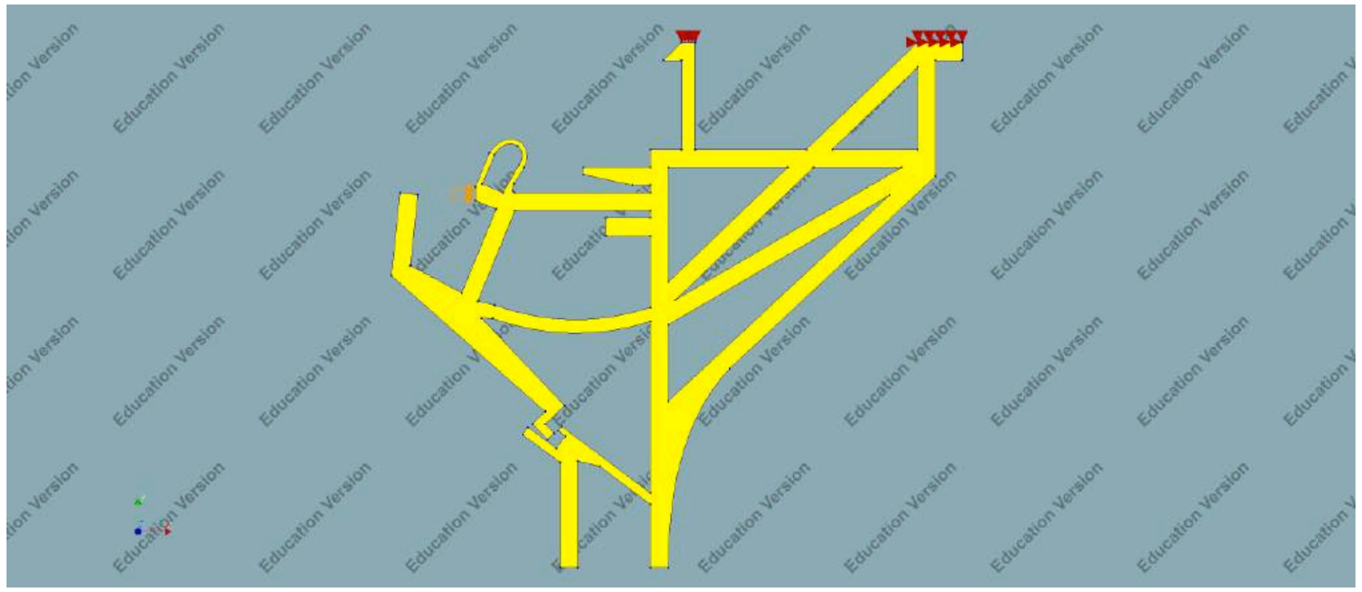


Figure 99: Geometry

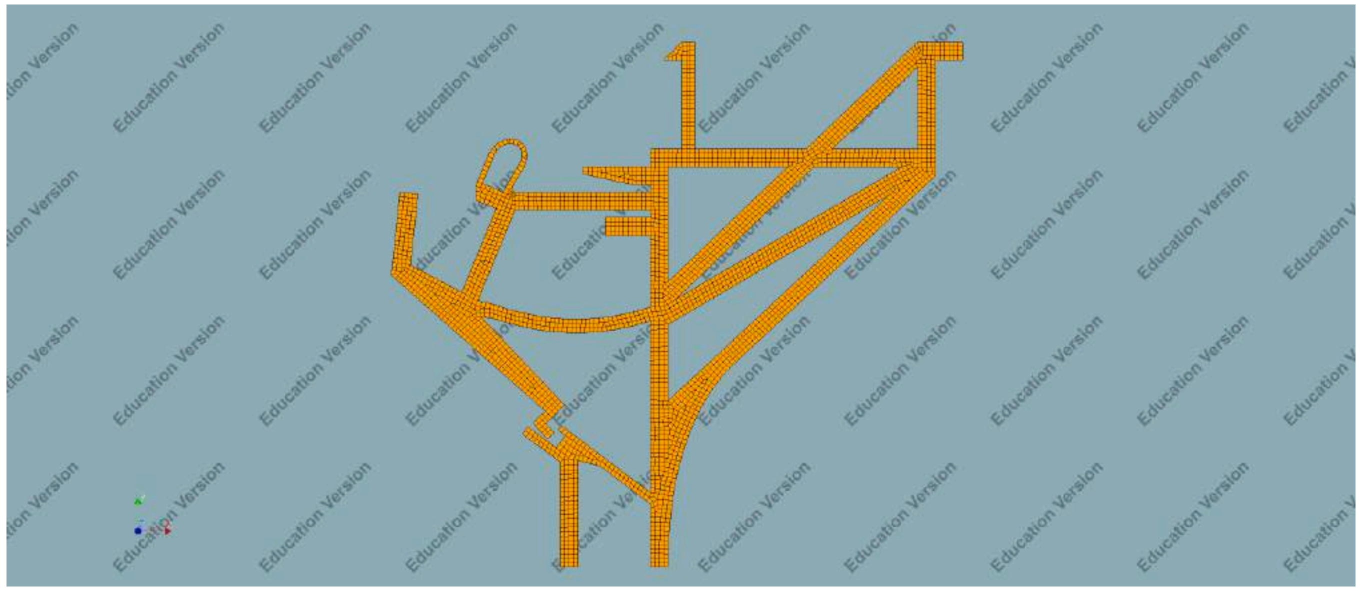


Figure 100: Mesh geometry

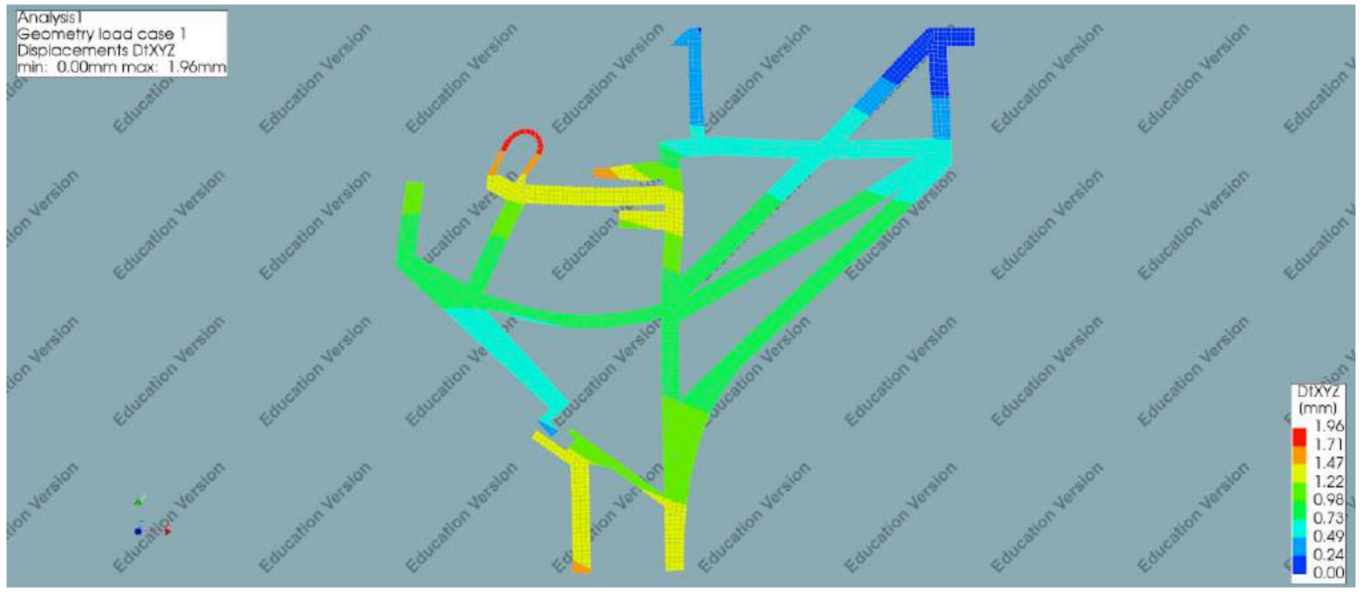


Figure 101: Displacement 15mm depth

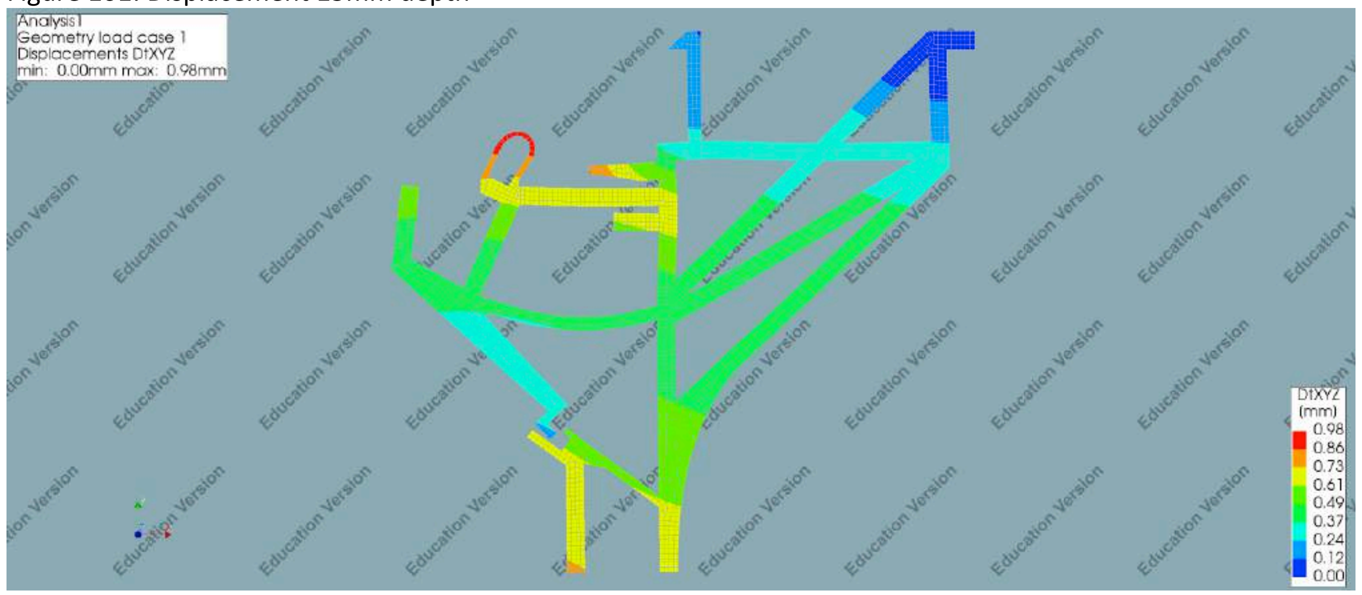


Figure 102: Displacement 30mm depth

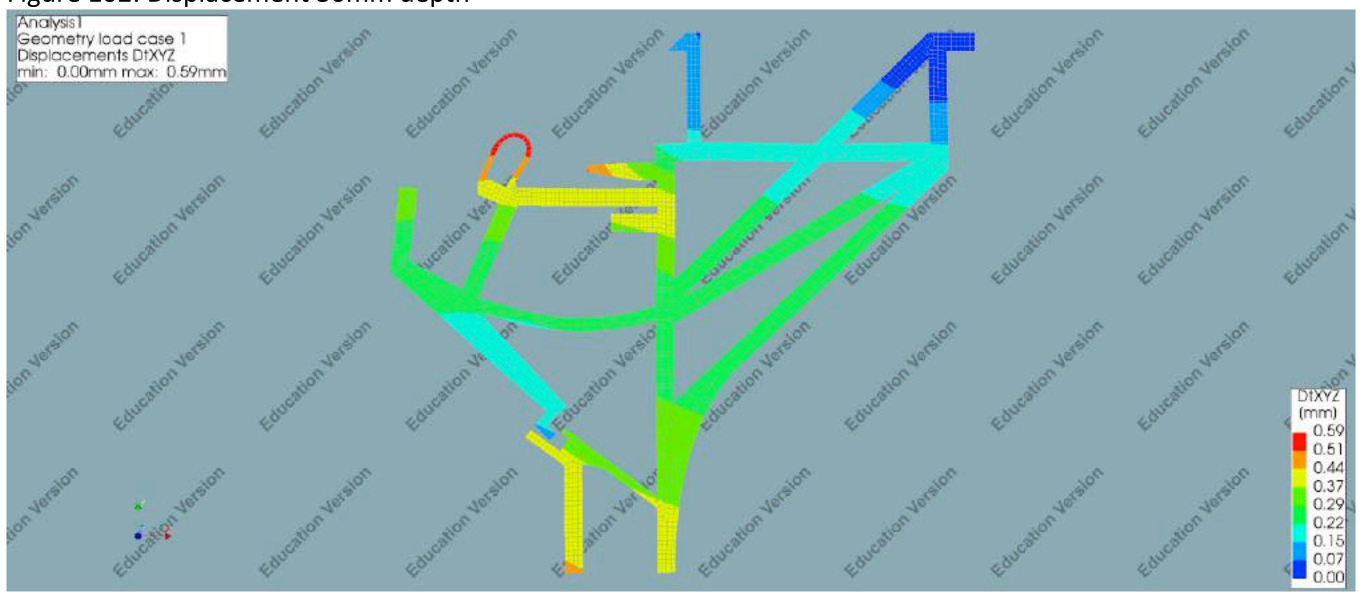


Figure 103: Displacement 50mm depth

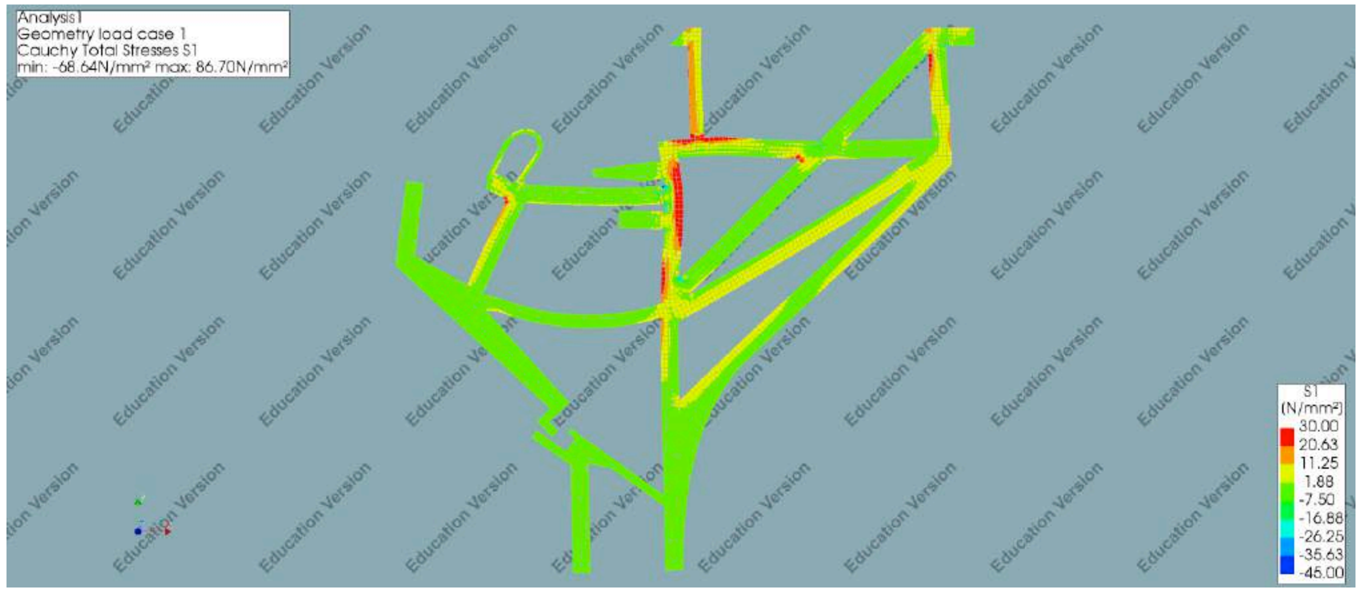


Figure 104: Tensile stresses 15mm depth

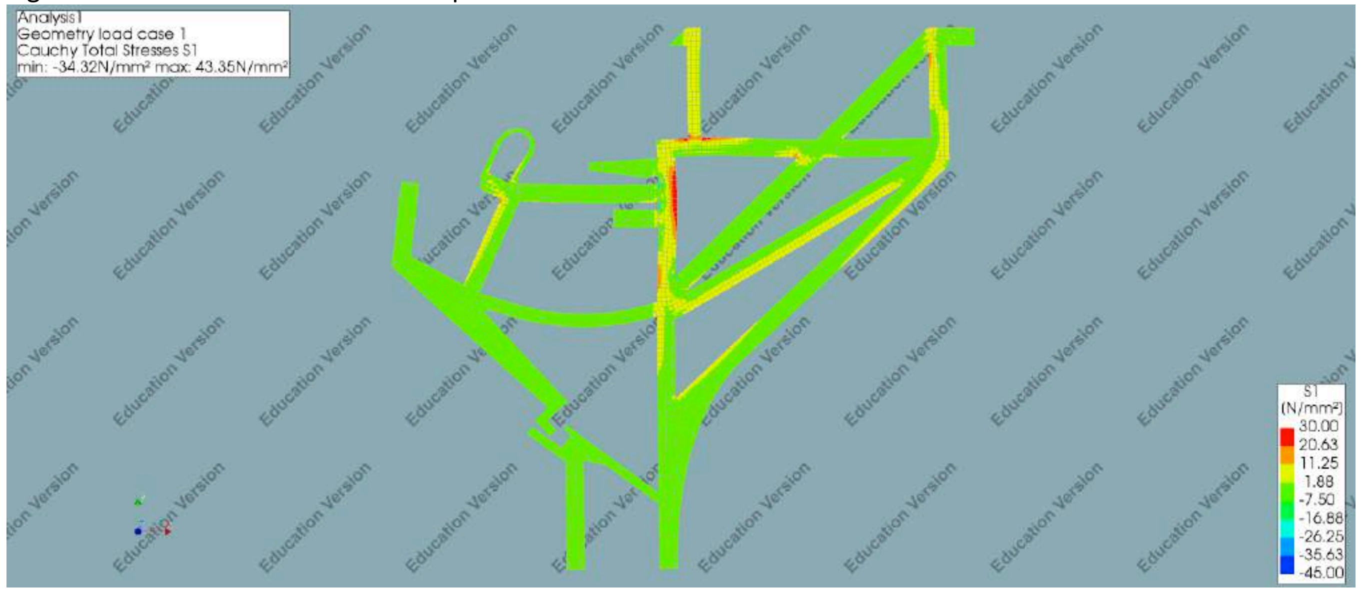


Figure 105: Tensile stresses 30mm depth

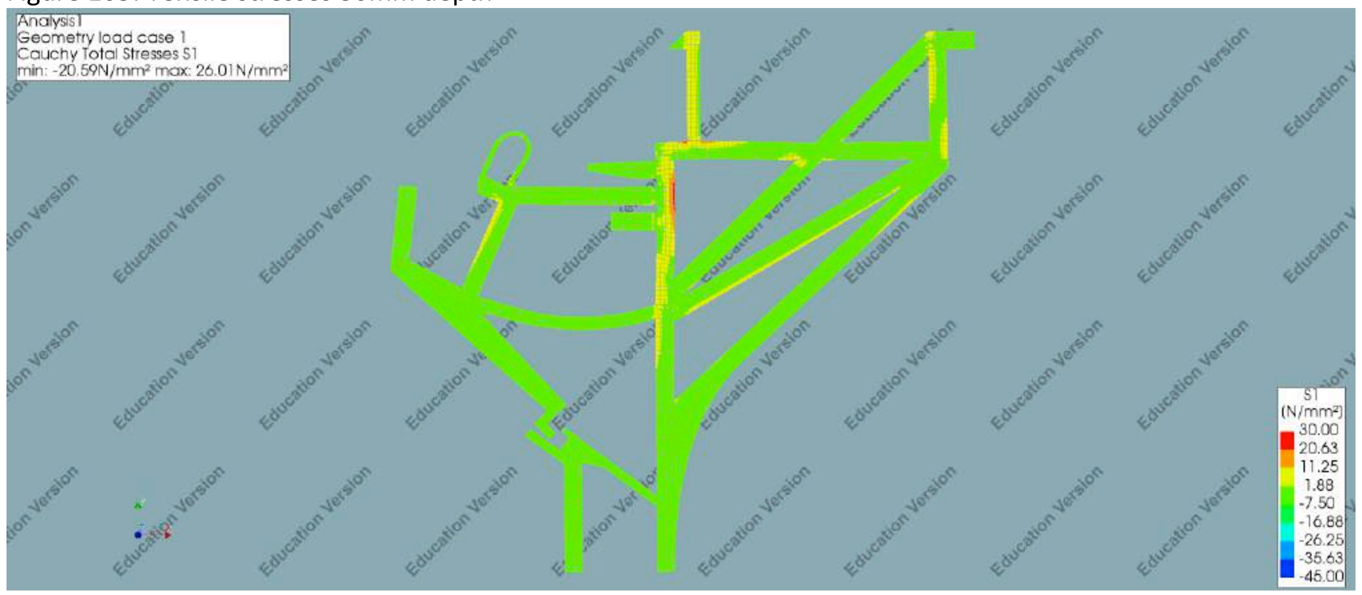


Figure 106: Tensile stresses 50mm depth

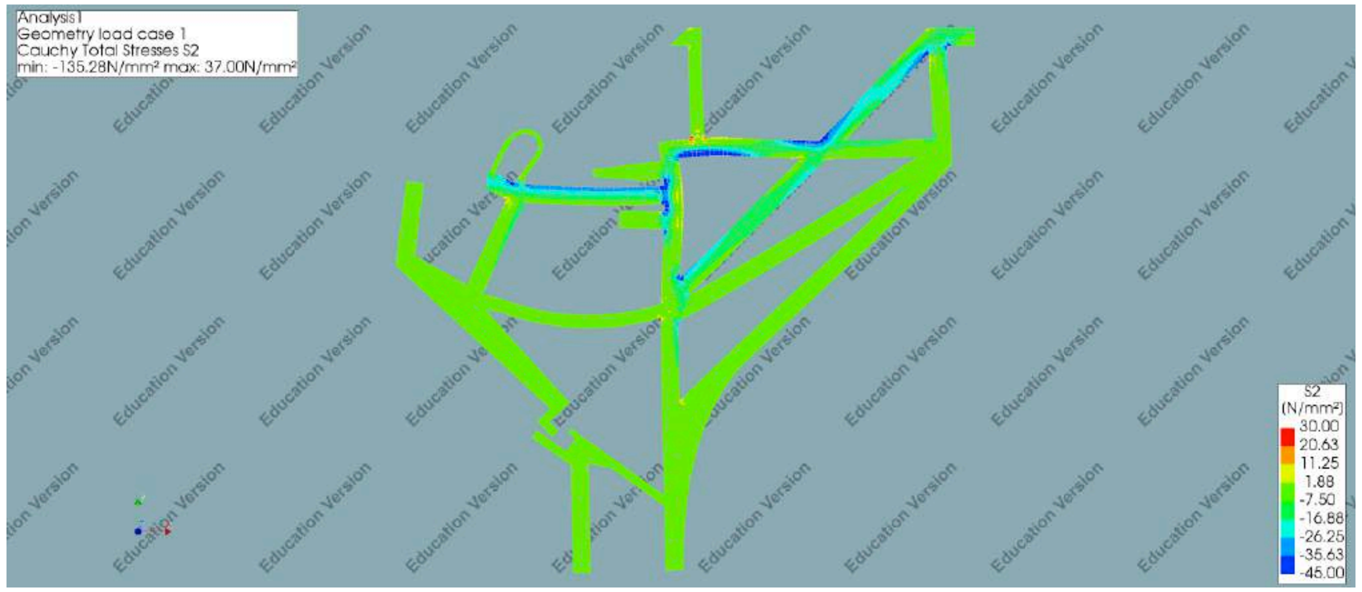


Figure 107: Compressive stresses 15mm depth

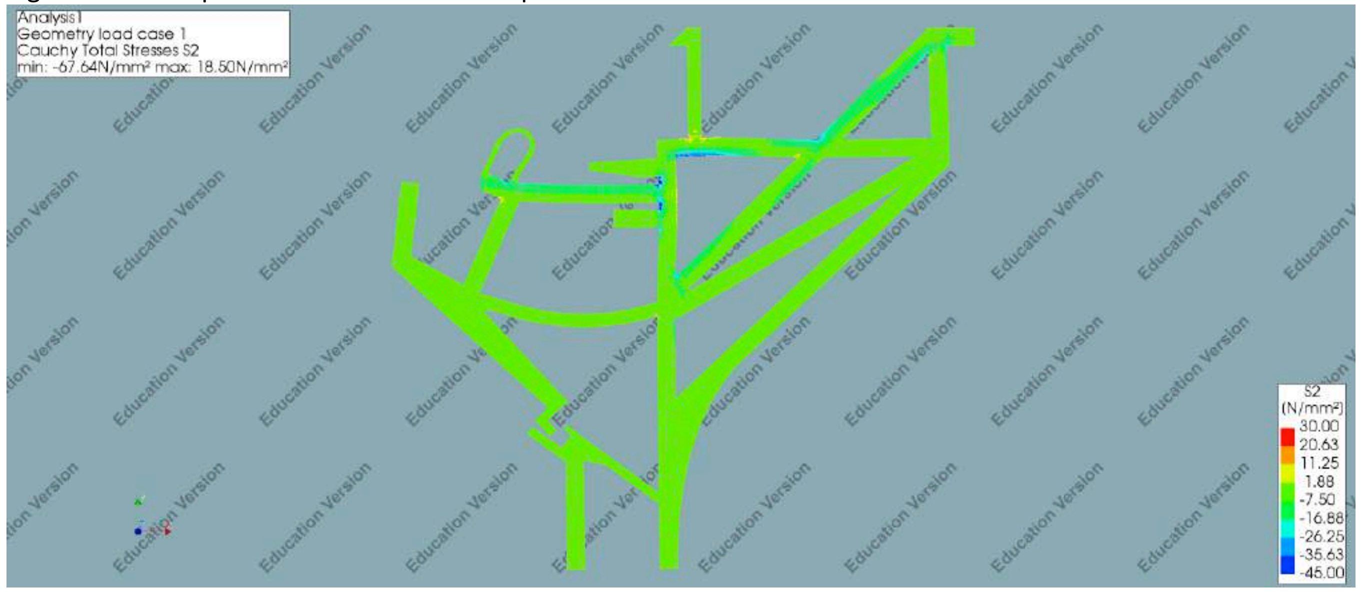


Figure 108: Compressive stresses 30mm depth

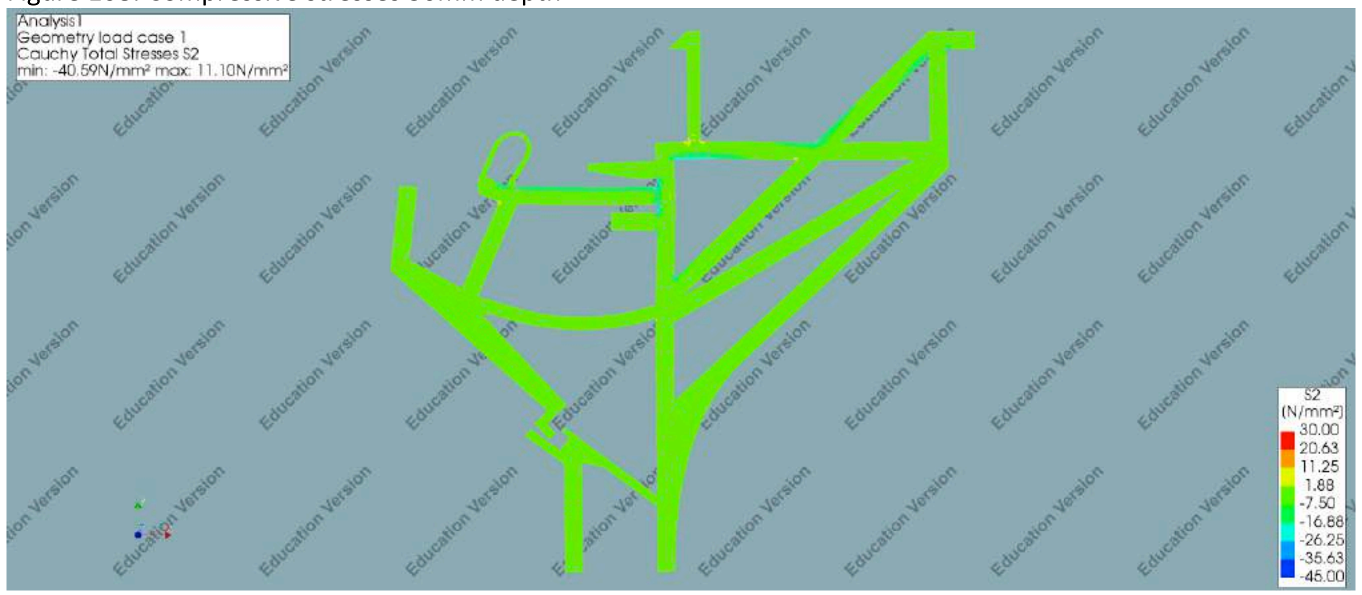


Figure 109: Compressive stresses 50mm depth

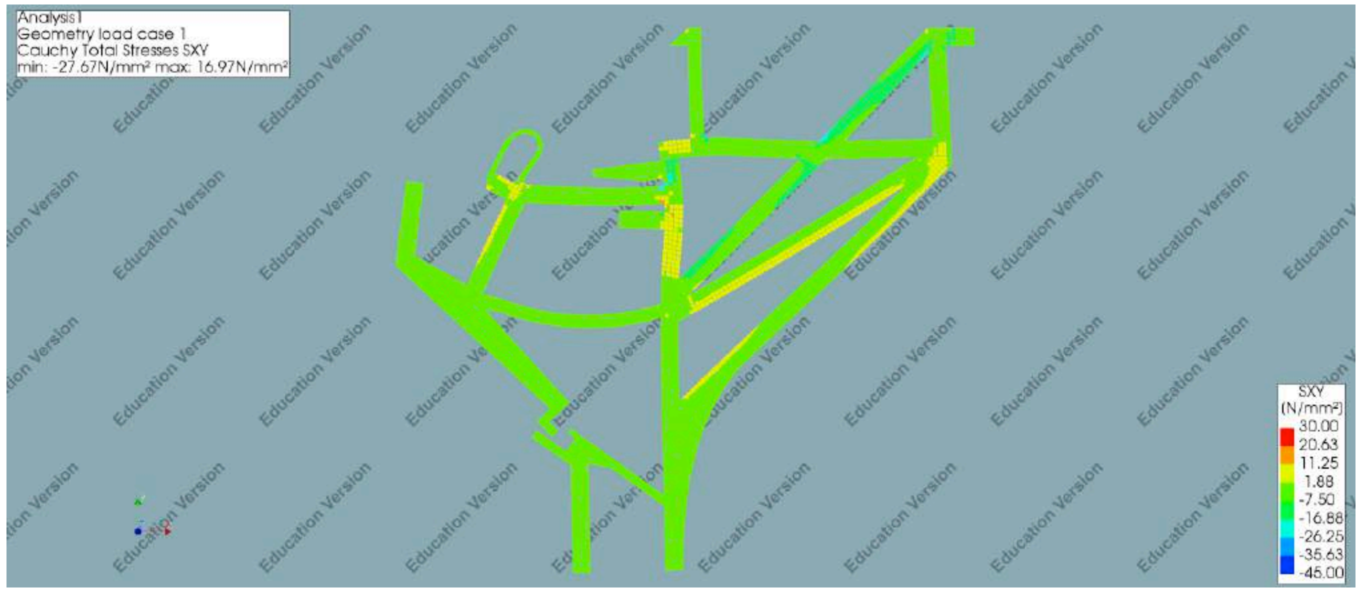


Figure 110: shear stresses 15mm depth

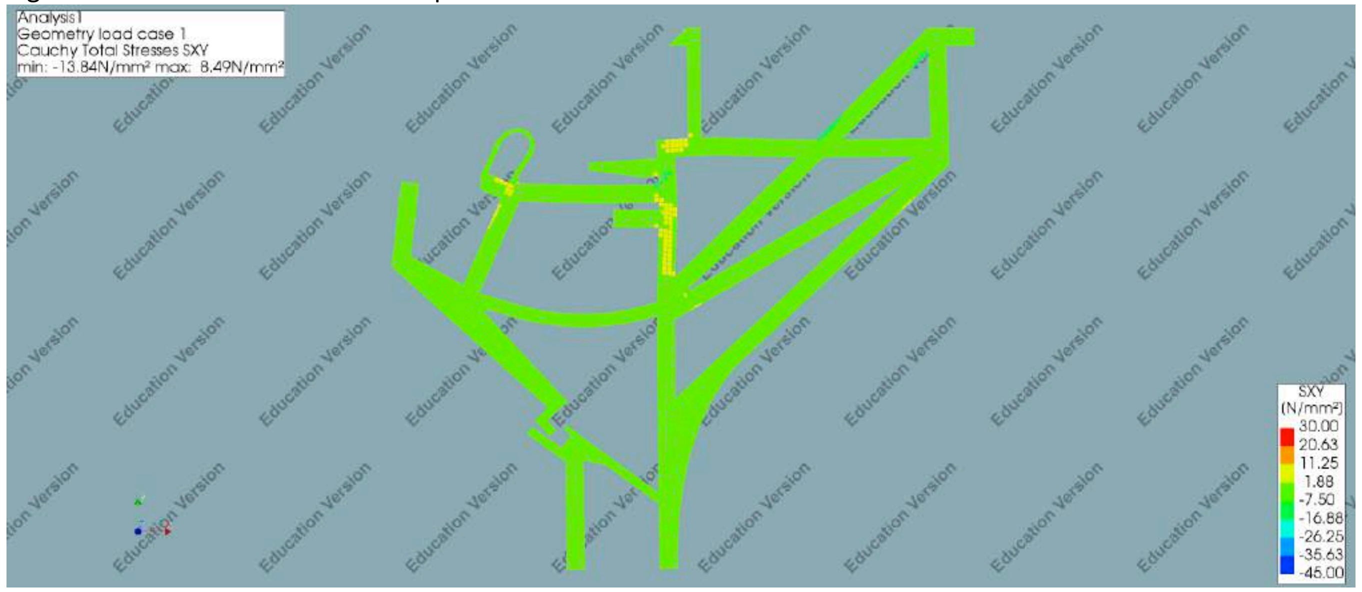


Figure 111: shear stresses 30mm depth

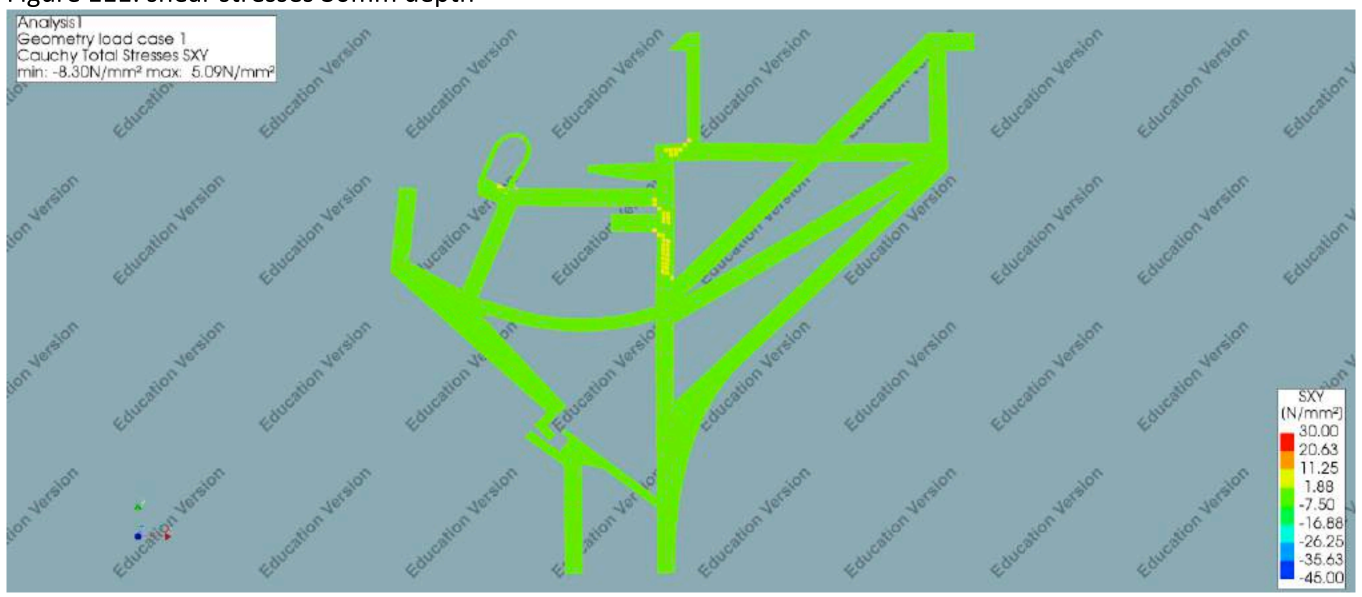


Figure 112: shear stresses 50mm depth

Analysis 5: Iteration 4

<u>Results tensile analysis</u>

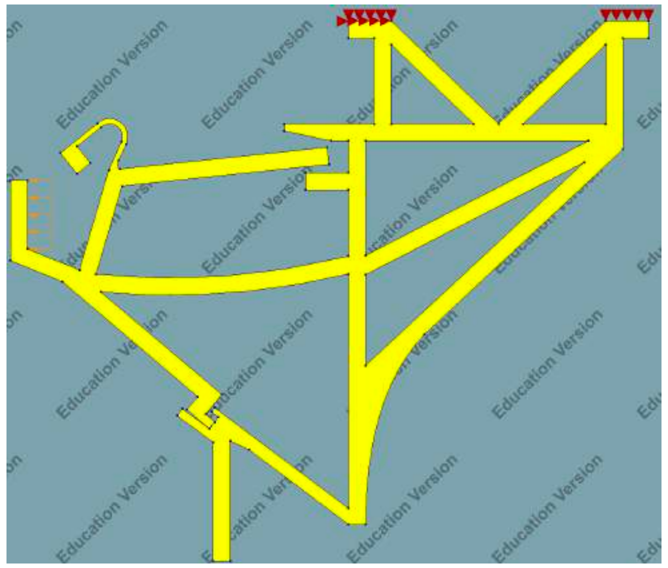


Figure 113: Geometry

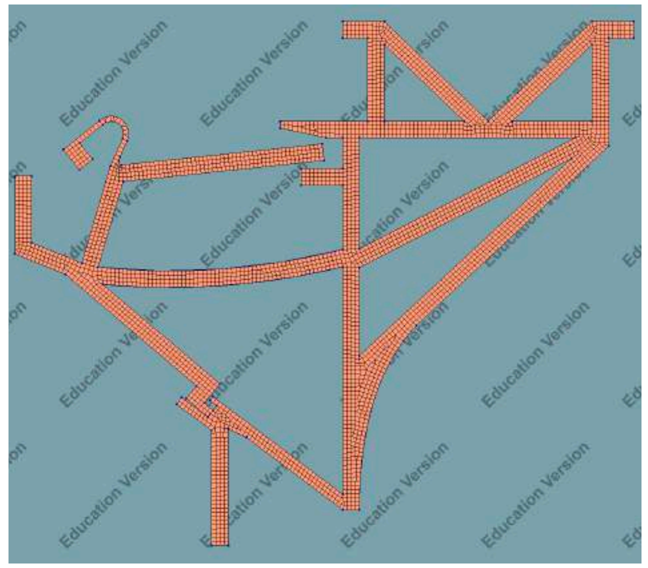


Figure 114: Mesh geometry

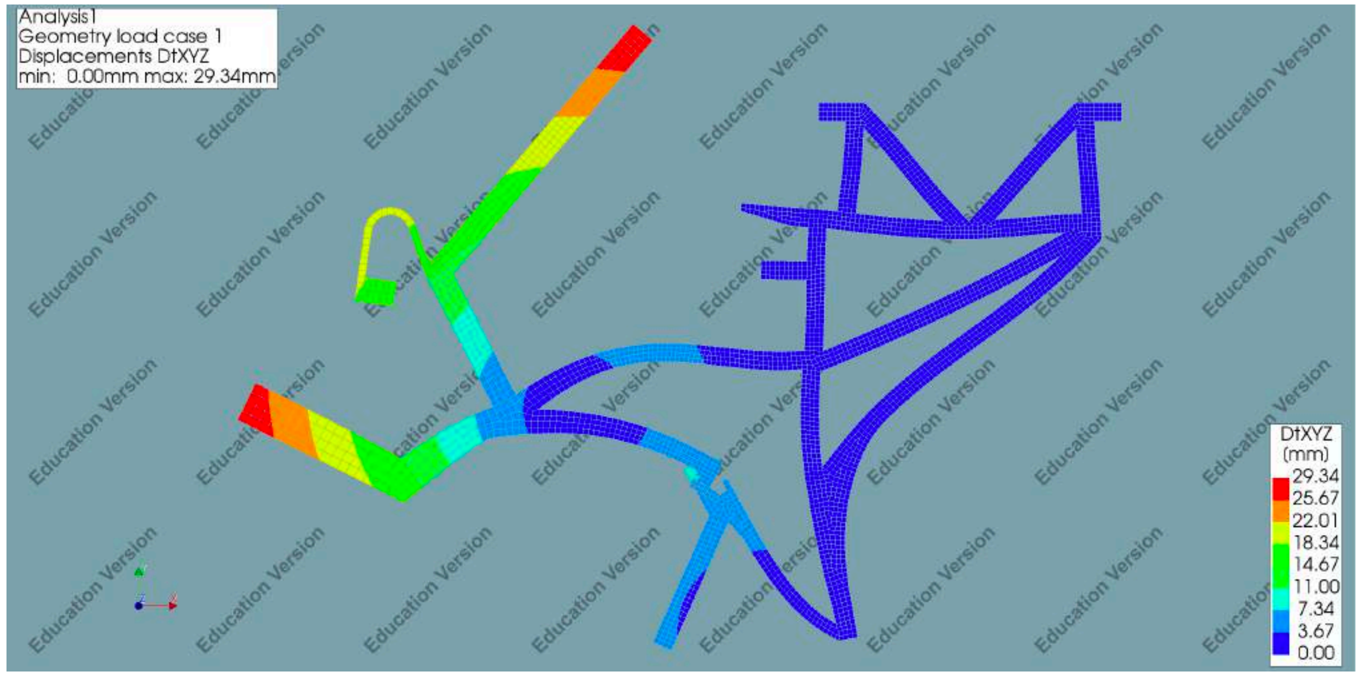


Figure 115: Displacement 15mm depth

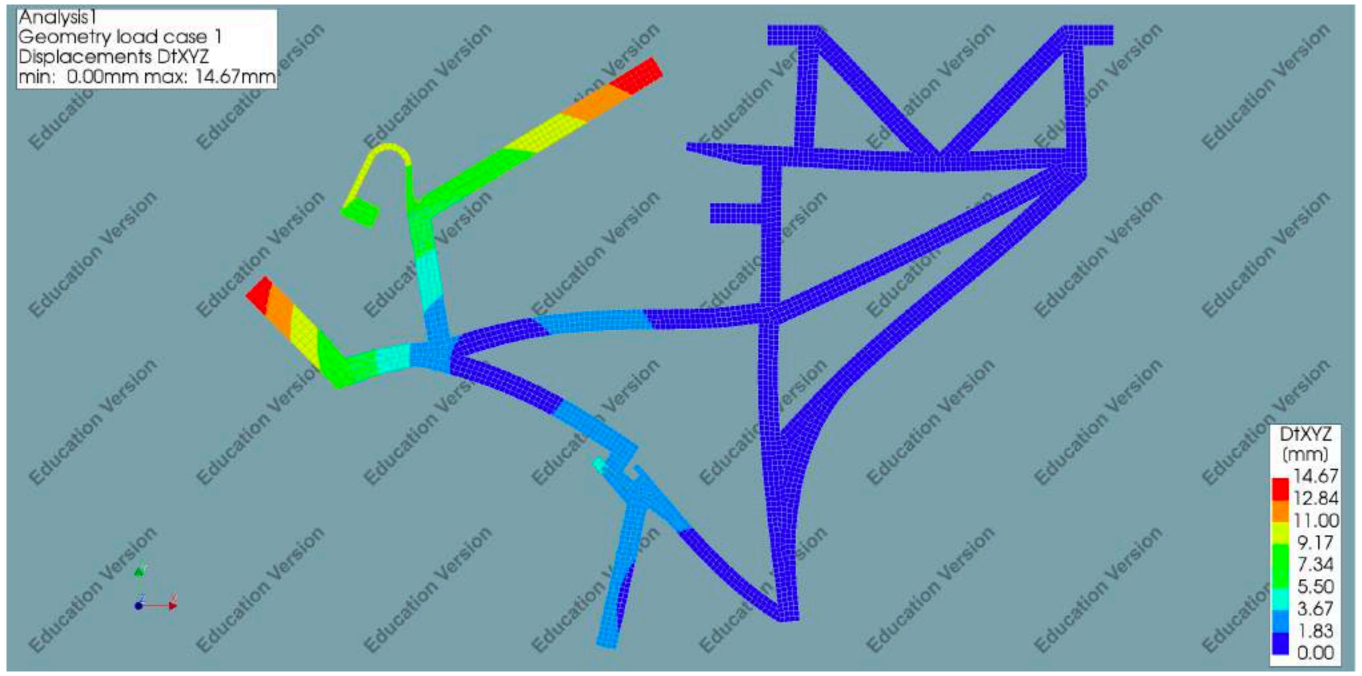


Figure 116: Displacement 30mm depth

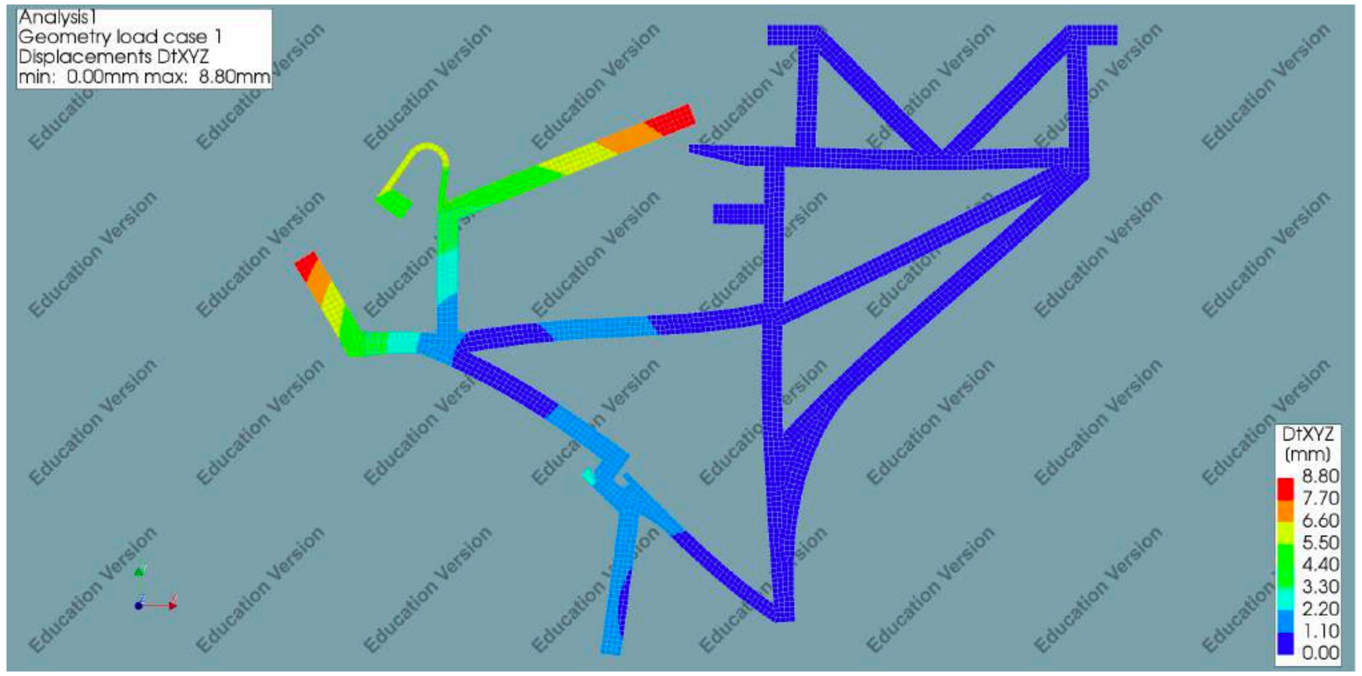


Figure 117: 50mm depth

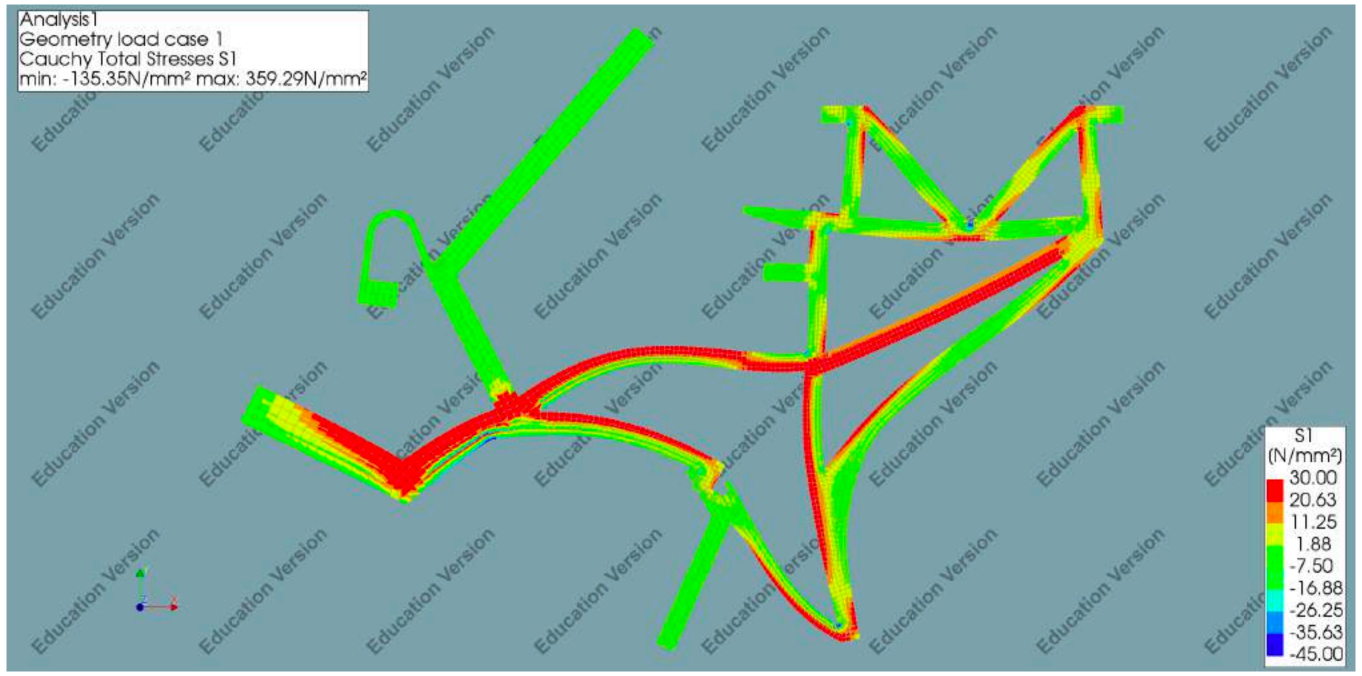


Figure 118: Tensile stresses 15mm depth

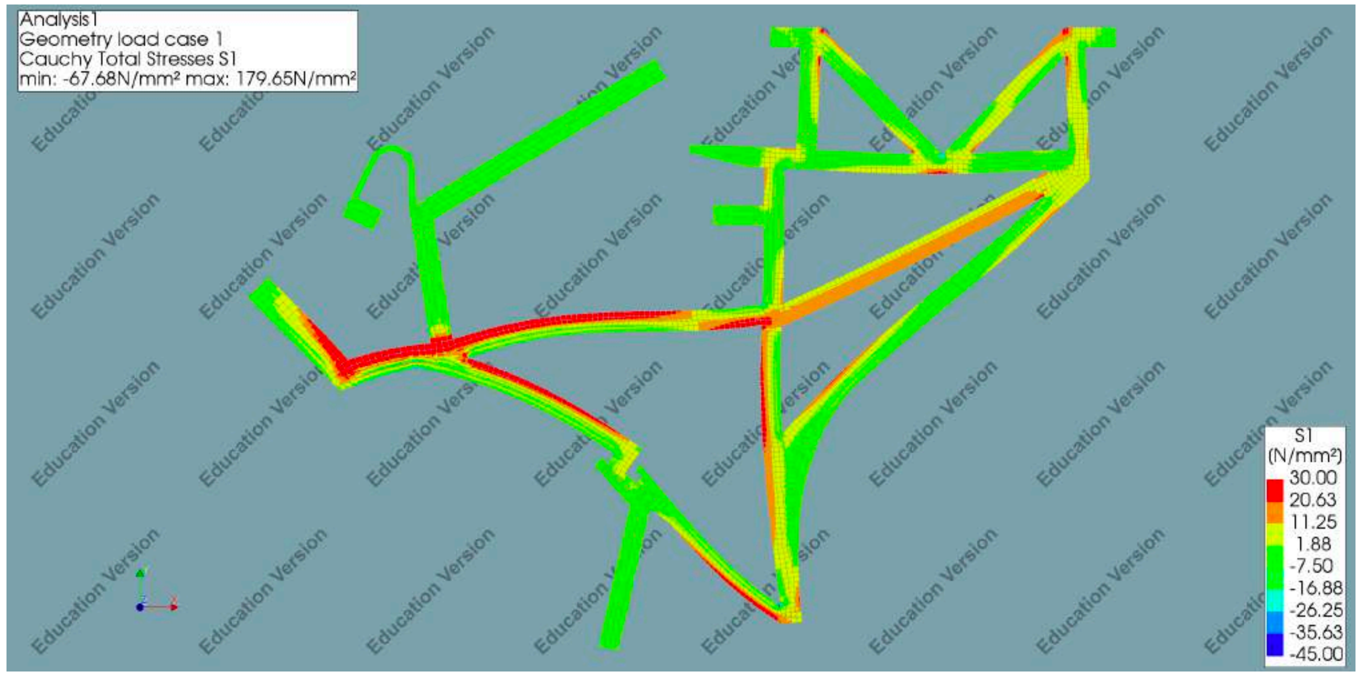


Figure 119: Tensile stresses 30mm depth

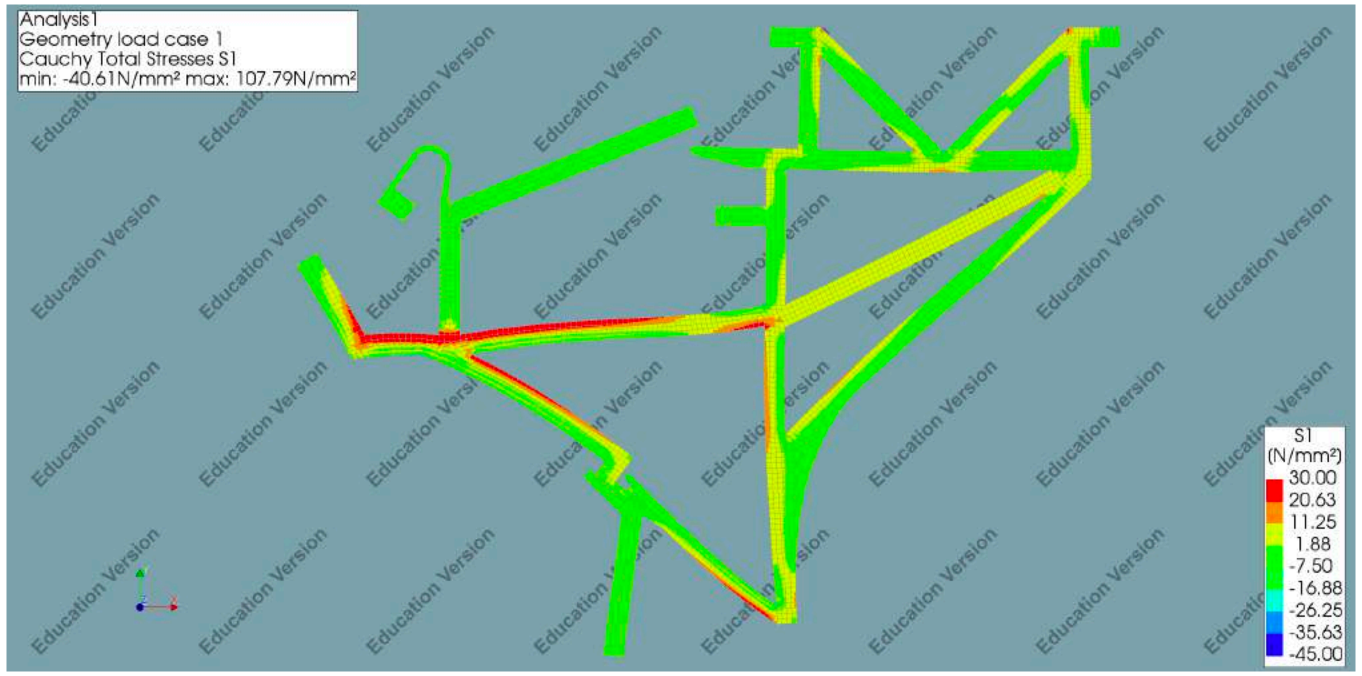


Figure 120: Tensile stresses 50mm depth

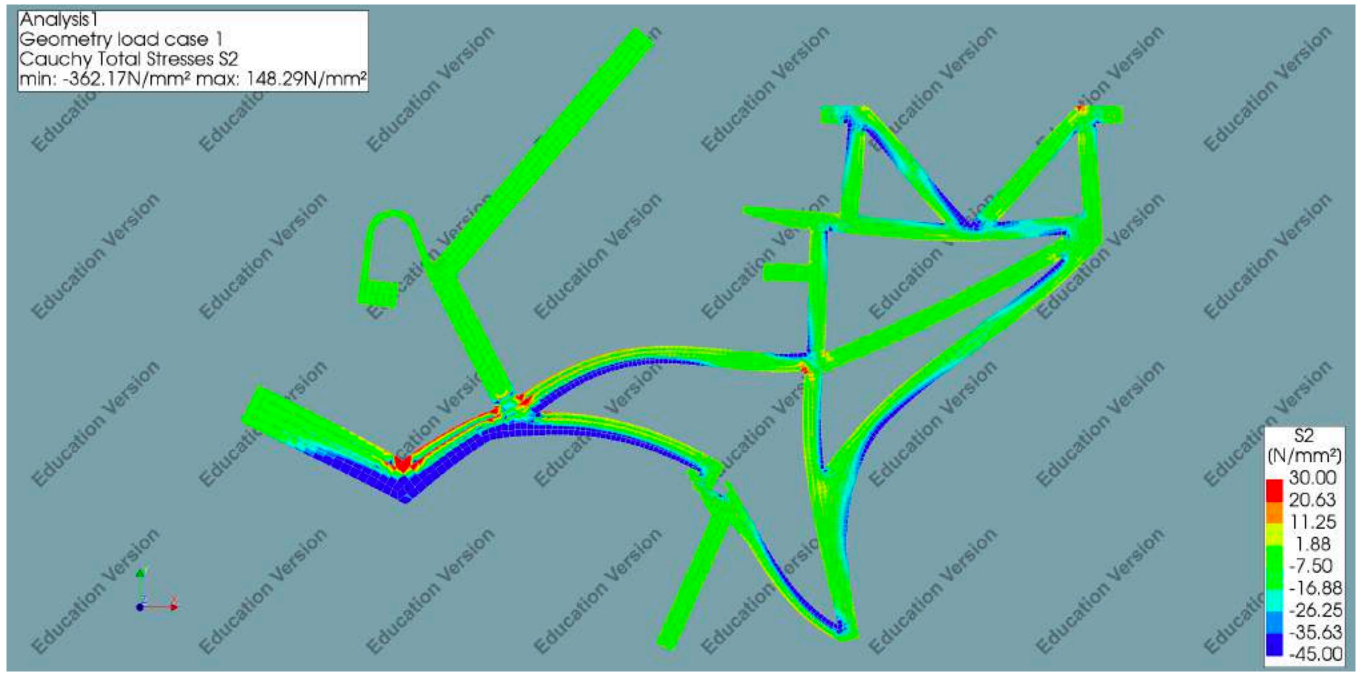


Figure 121: Compressive stresses 15mm depth

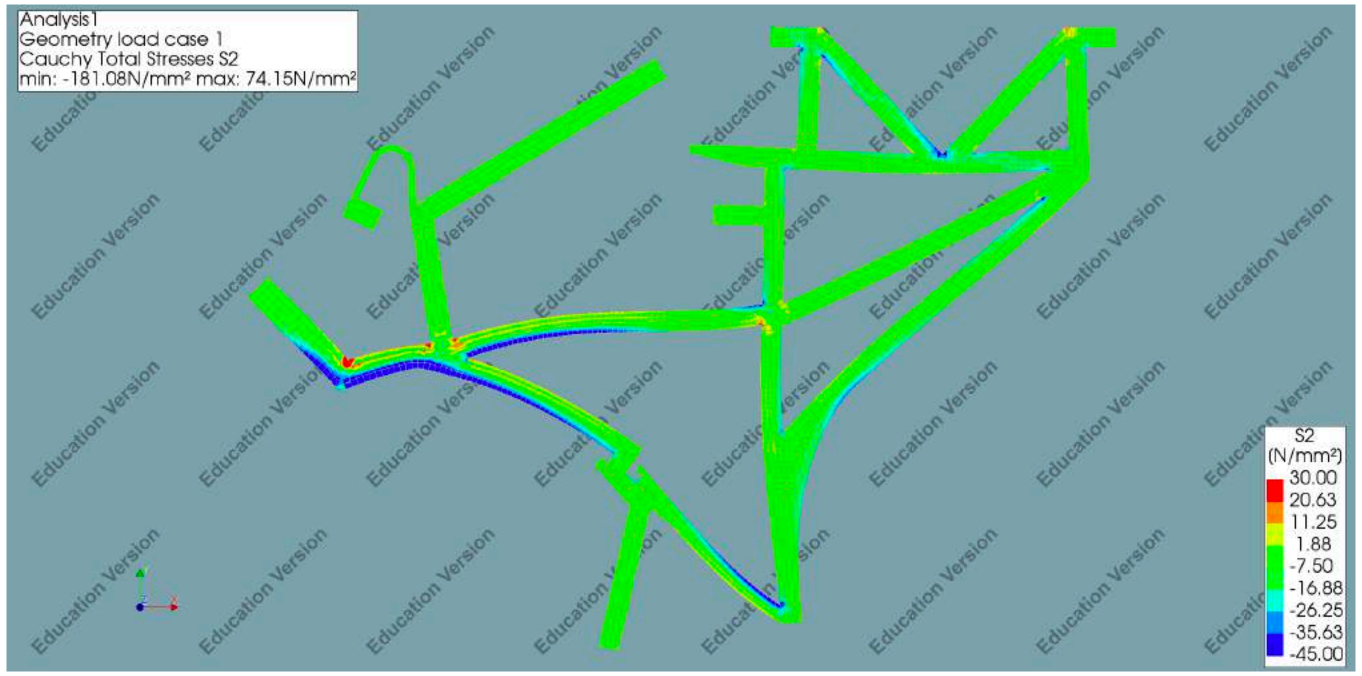


Figure 122: Compressive stresses 30mm depth

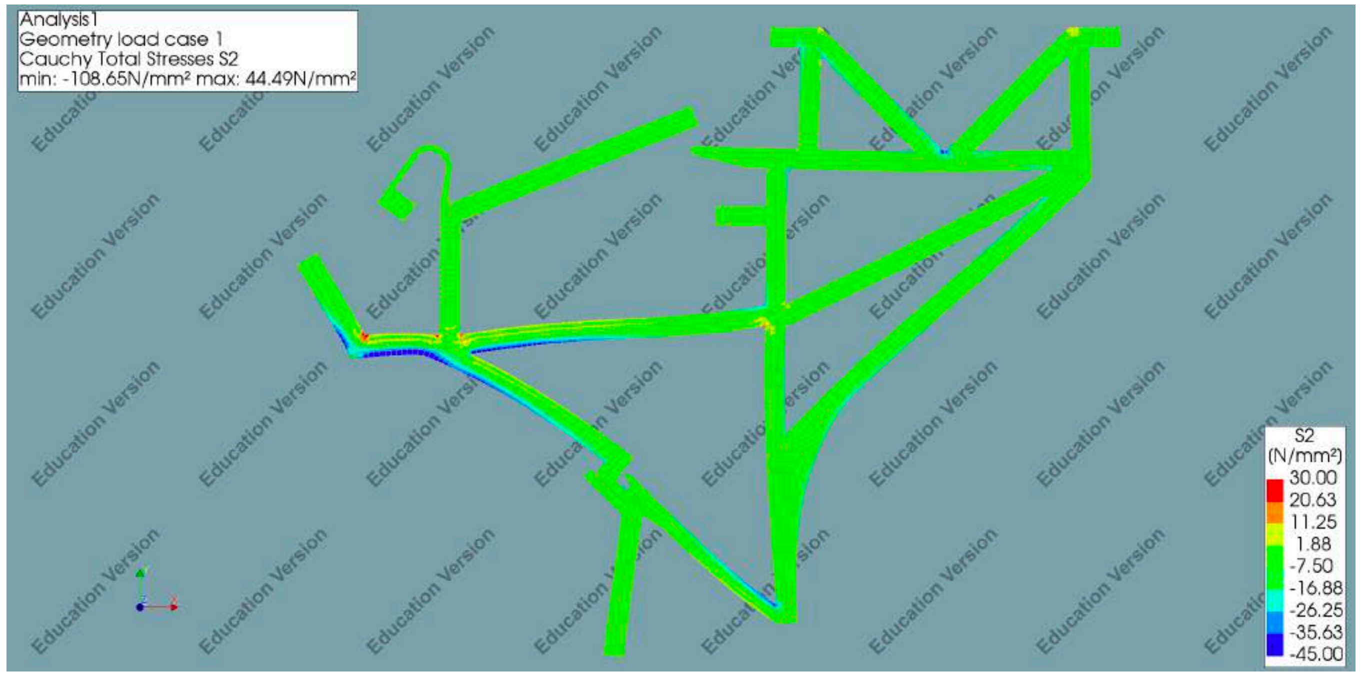


Figure 123: Compressive stresses 50mm depth

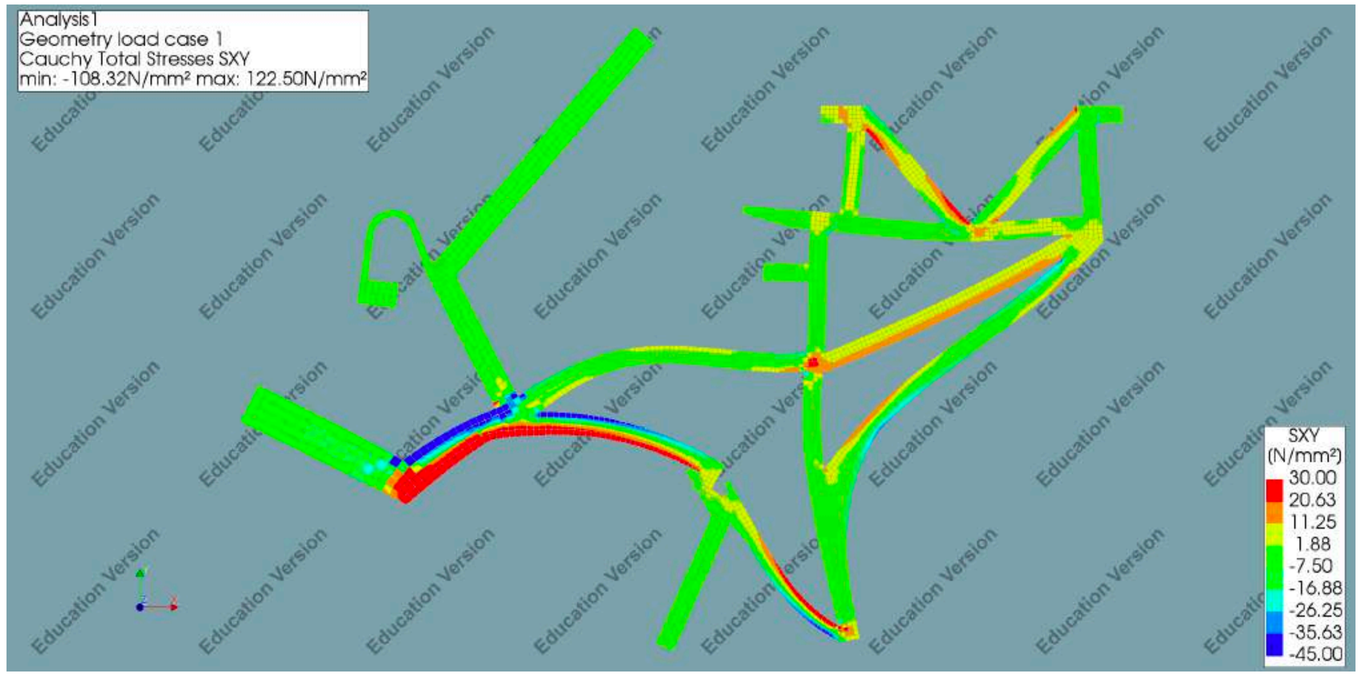


Figure 124: Shear stresses 15mm depth

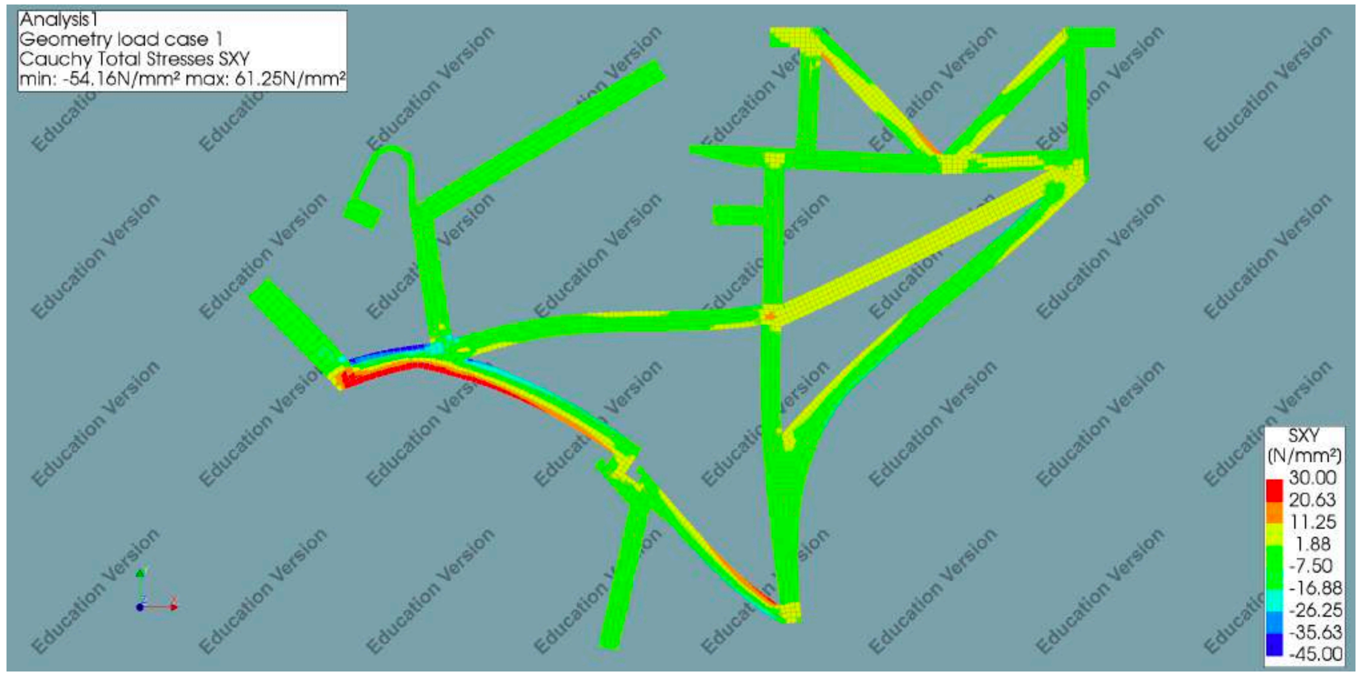


Figure 125: Shear stresses 30mm depth

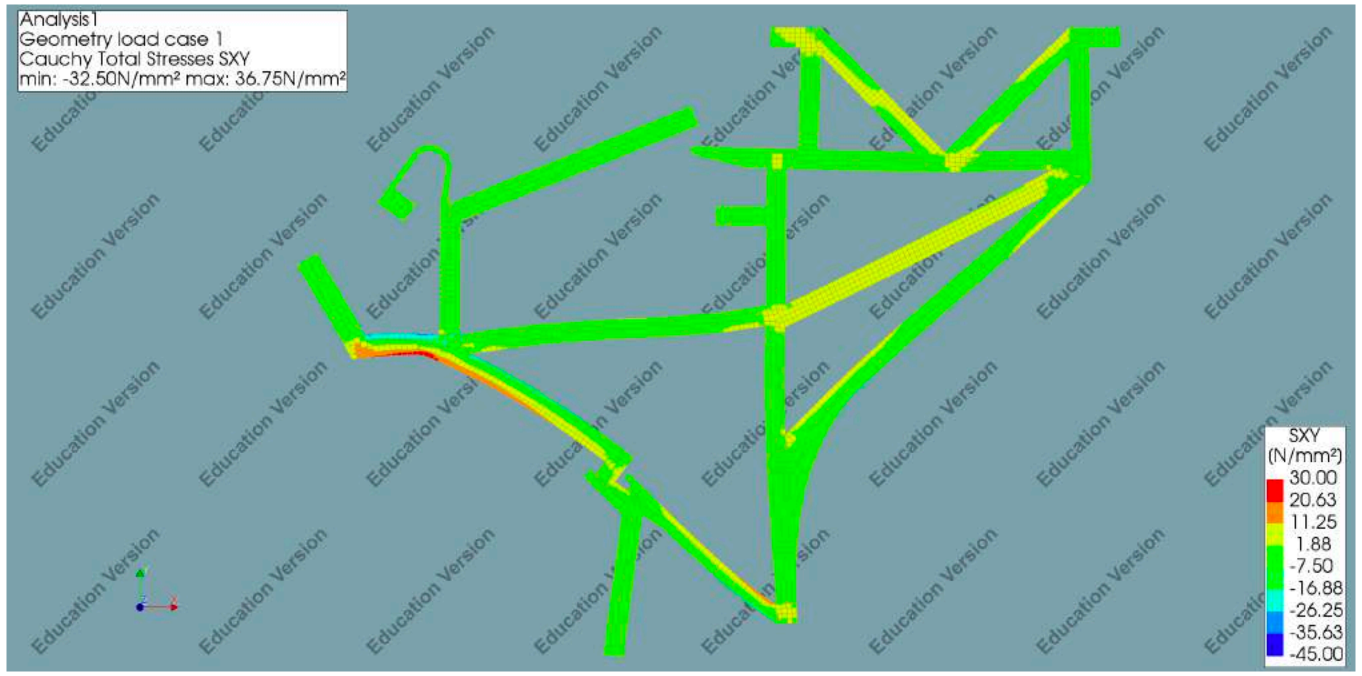


Figure 126: Shear stresses 50mm depth

Results compressive analysis

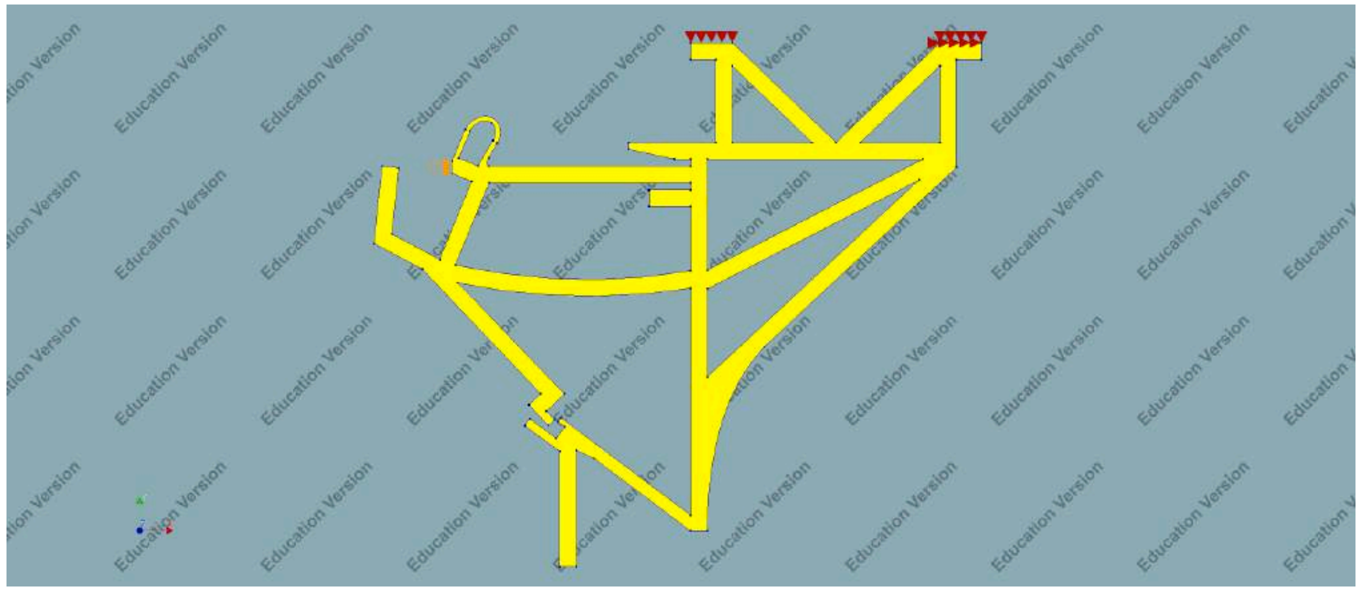


Figure 127: Geometry

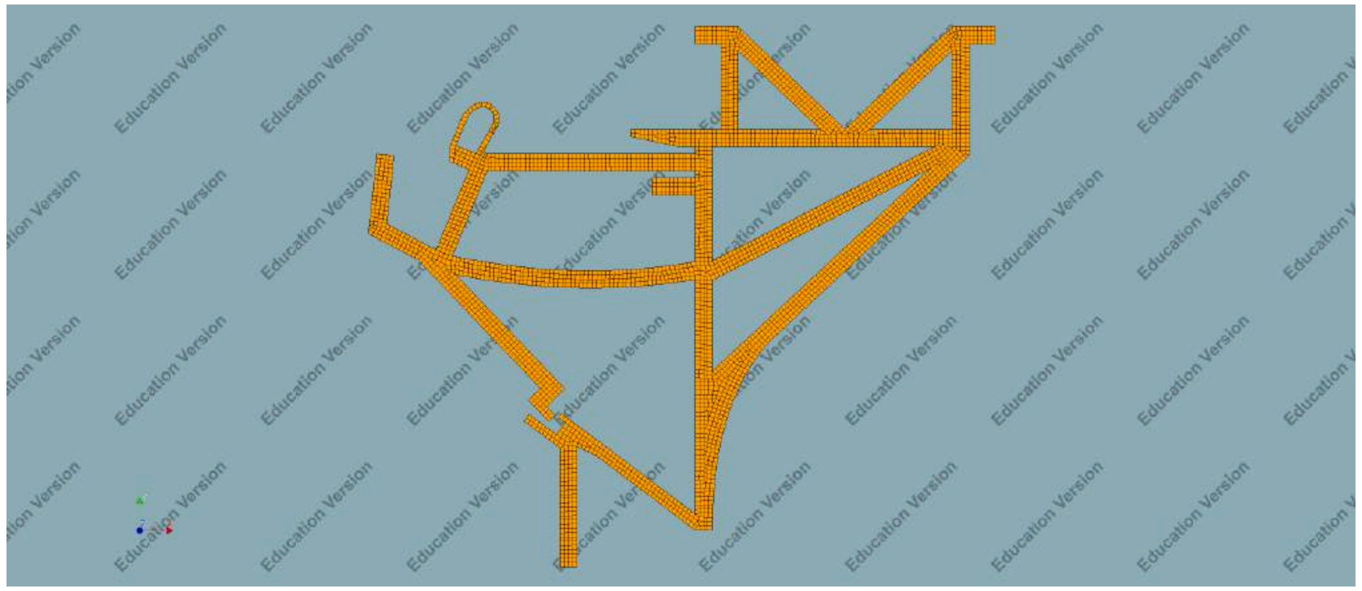


Figure 128: Mesh geometry

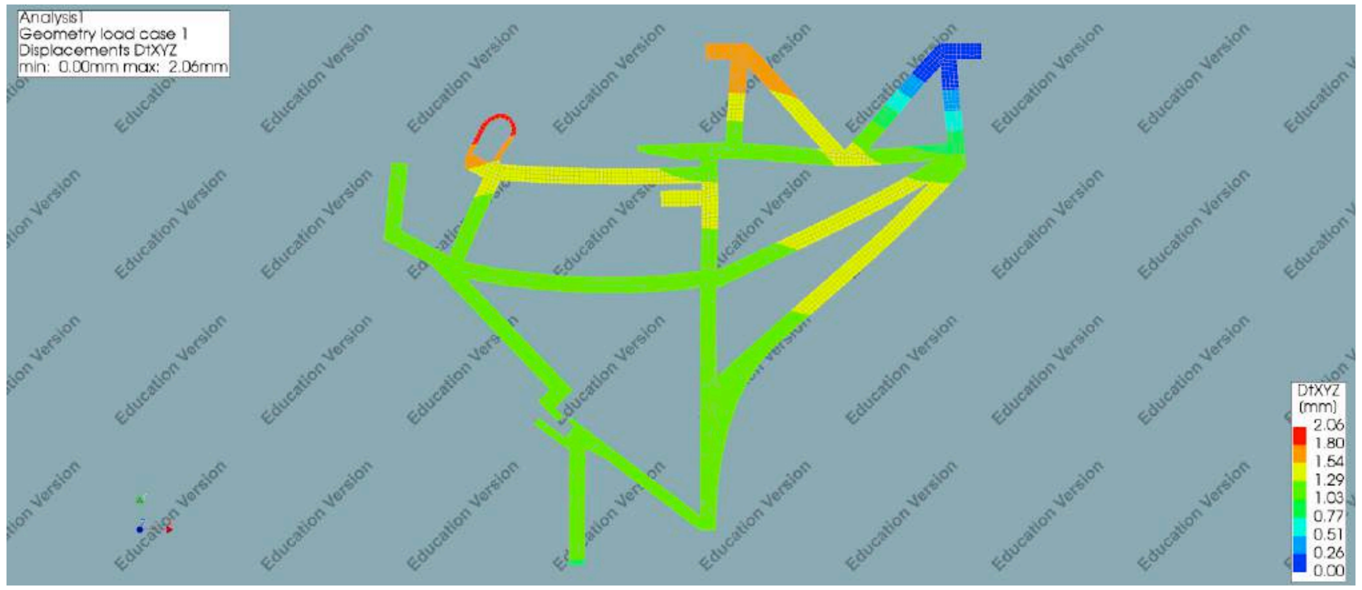


Figure 129: Displacement 15mm depth

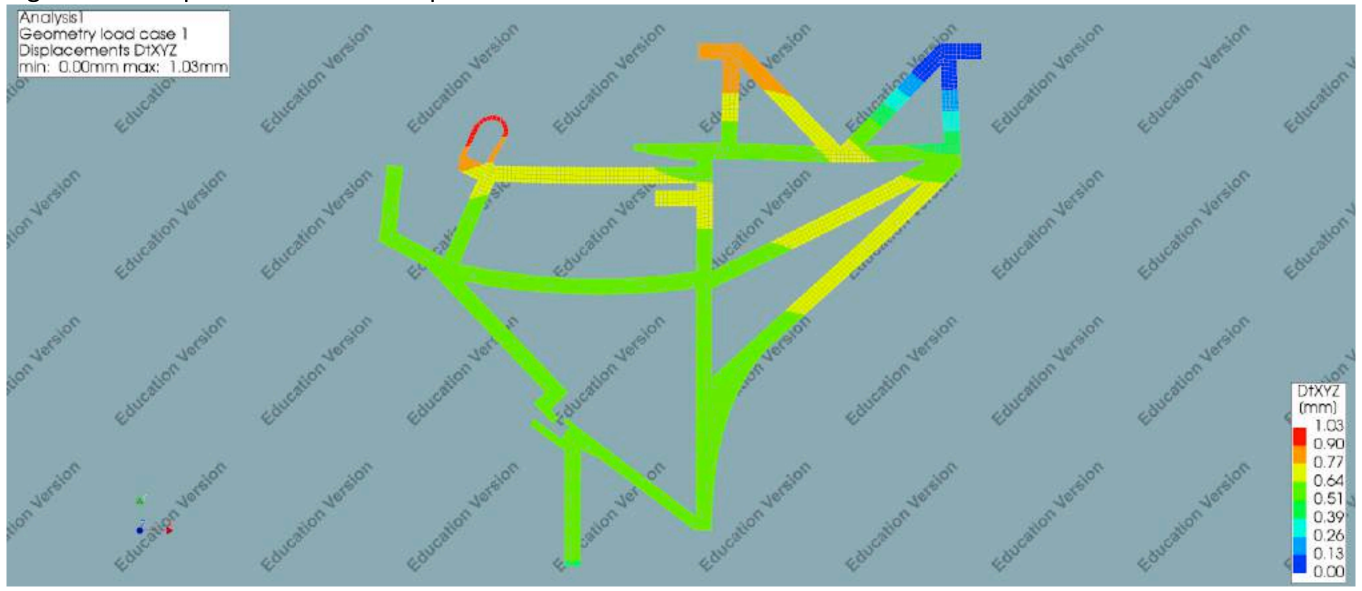


Figure 130: Displacement 30mm depth

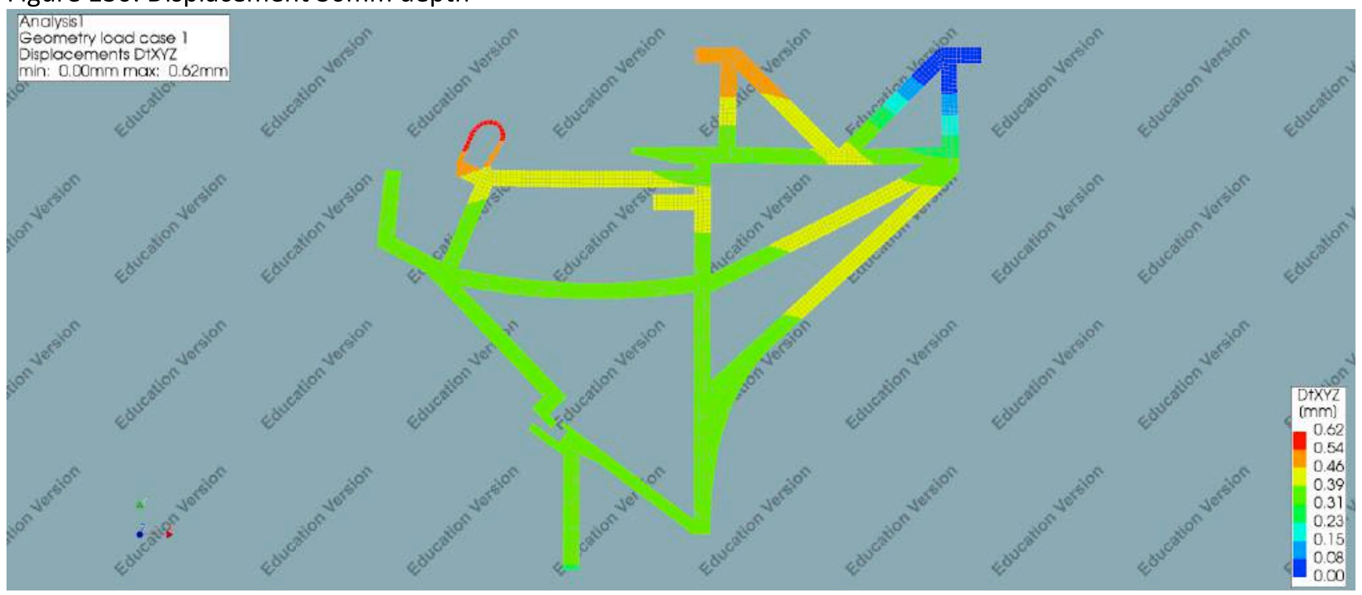


Figure 131: Displacement 50mm depth

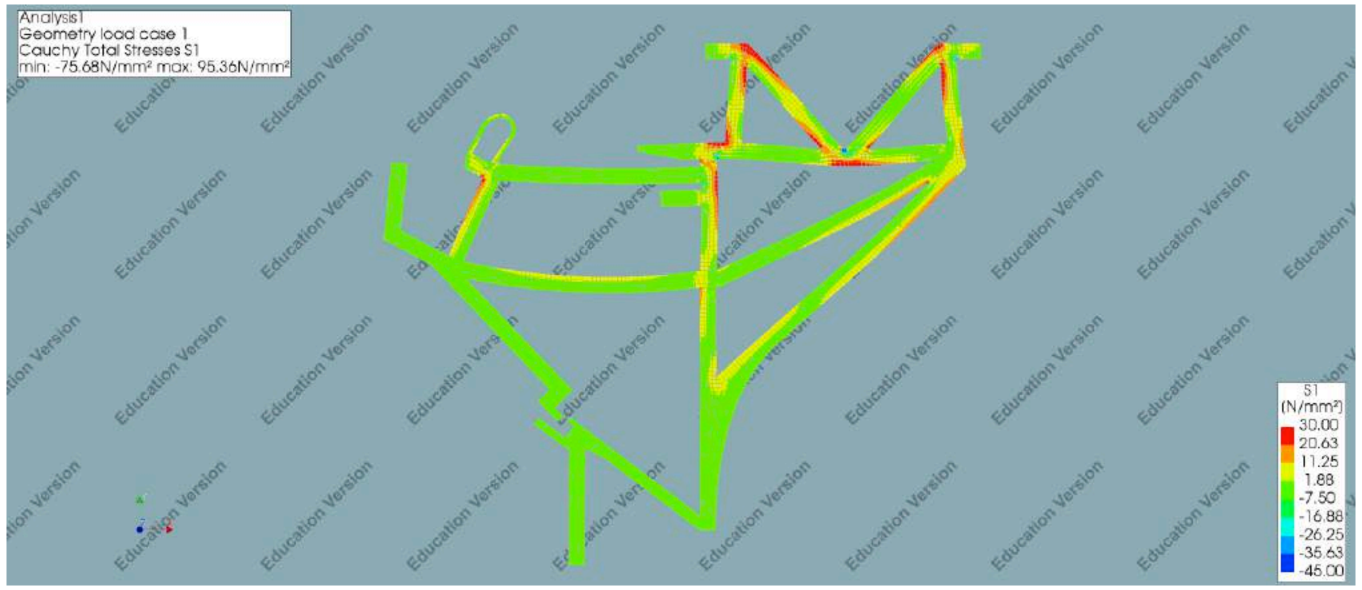


Figure 132: Tensile stresses 15mm depth

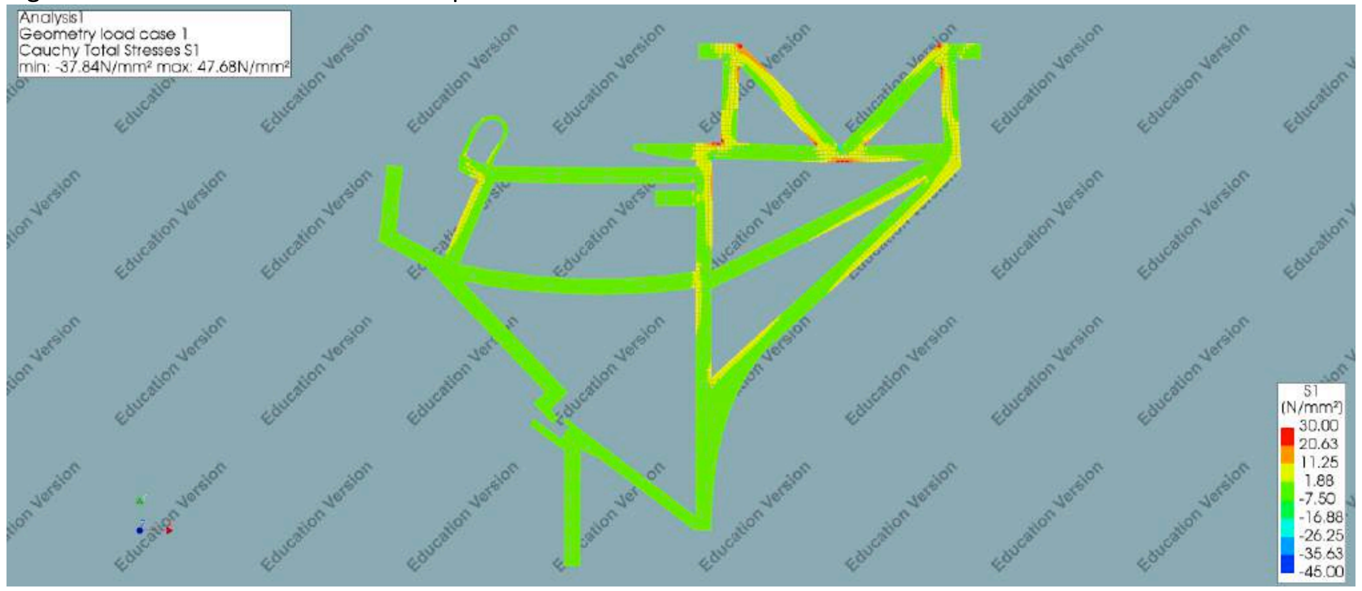


Figure 133: Tensile stresses 30mm depth

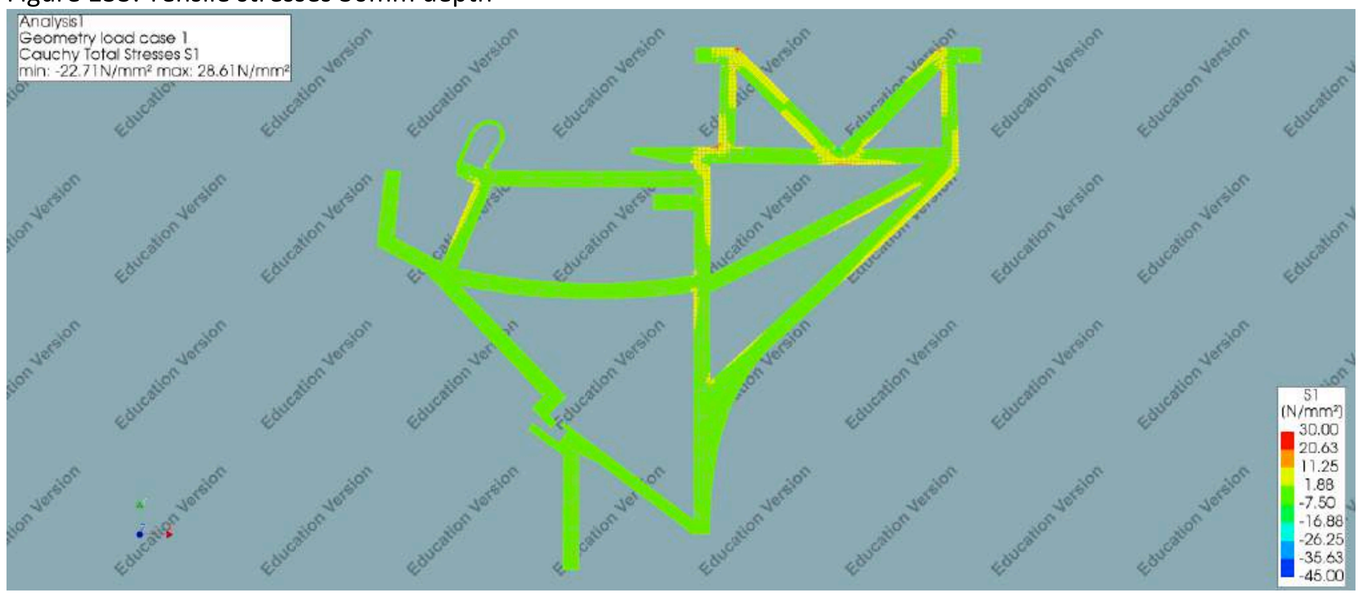


Figure 134: Tensile stresses 50mm depth

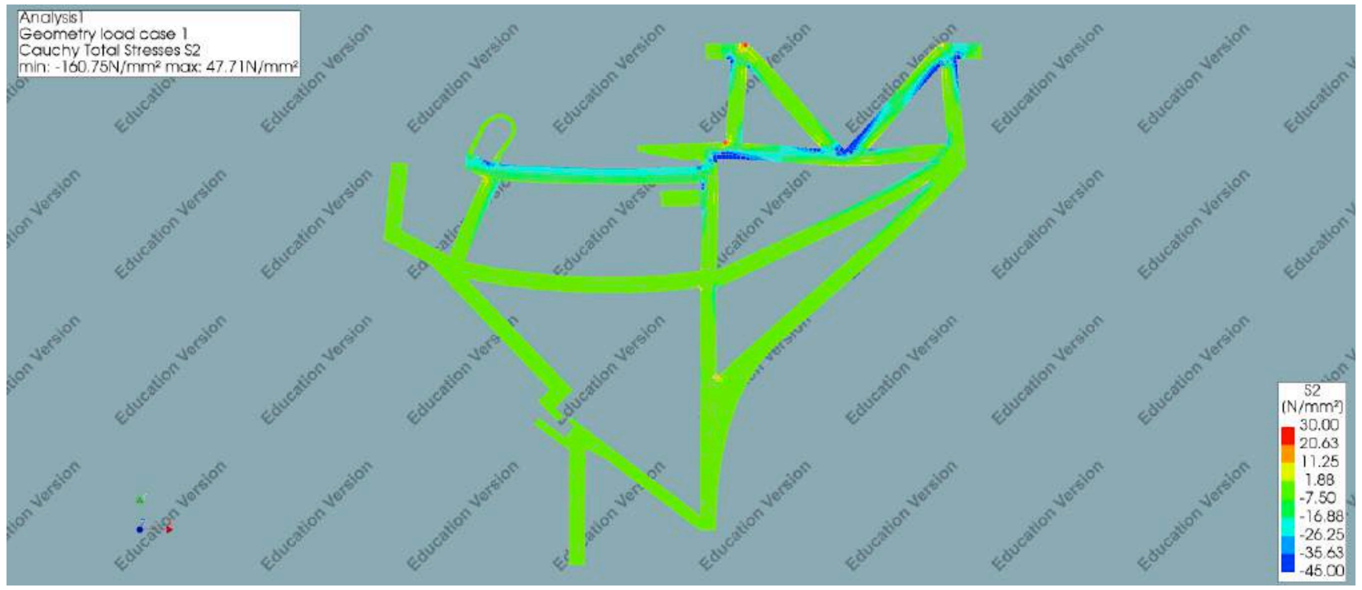


Figure 135: Compressive stresses 15mm depth

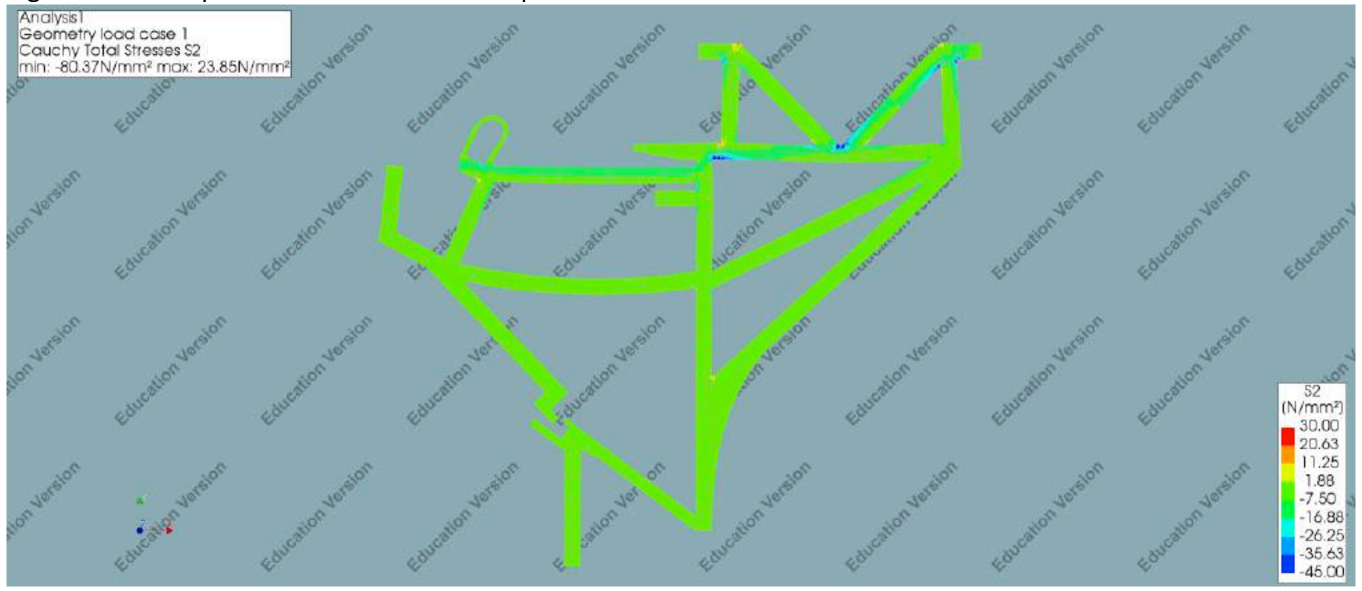


Figure 136: Compressive stresses 30mm depth

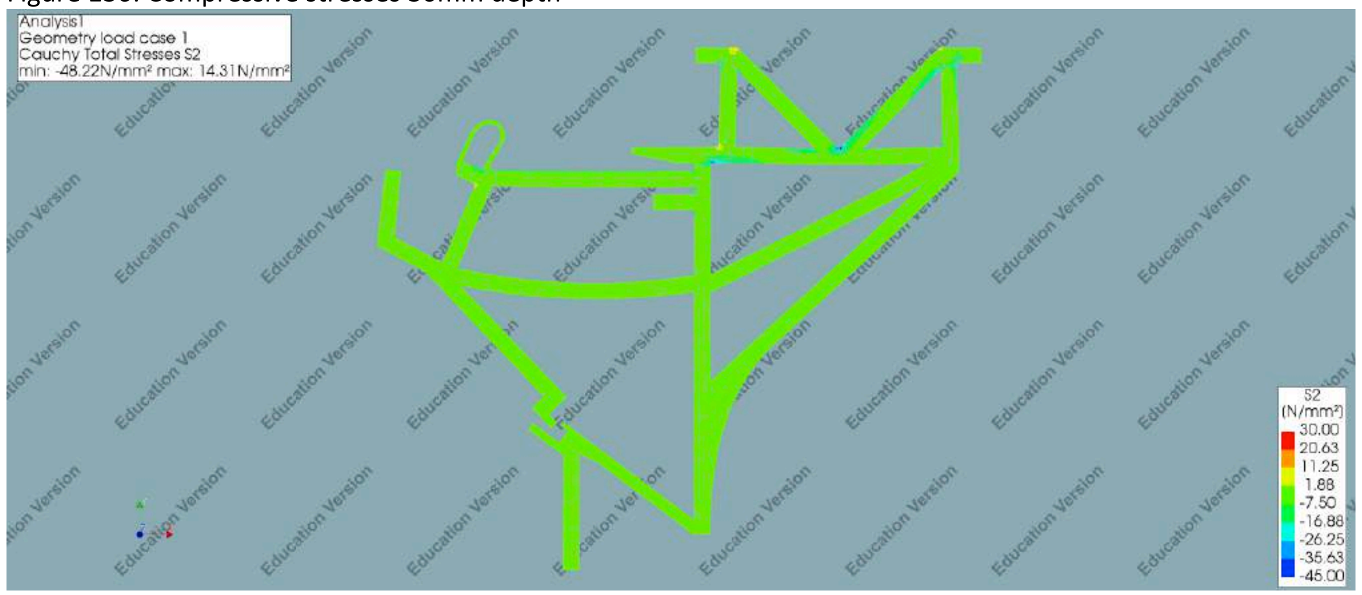


Figure 137: Compressive stresses 50mm depth

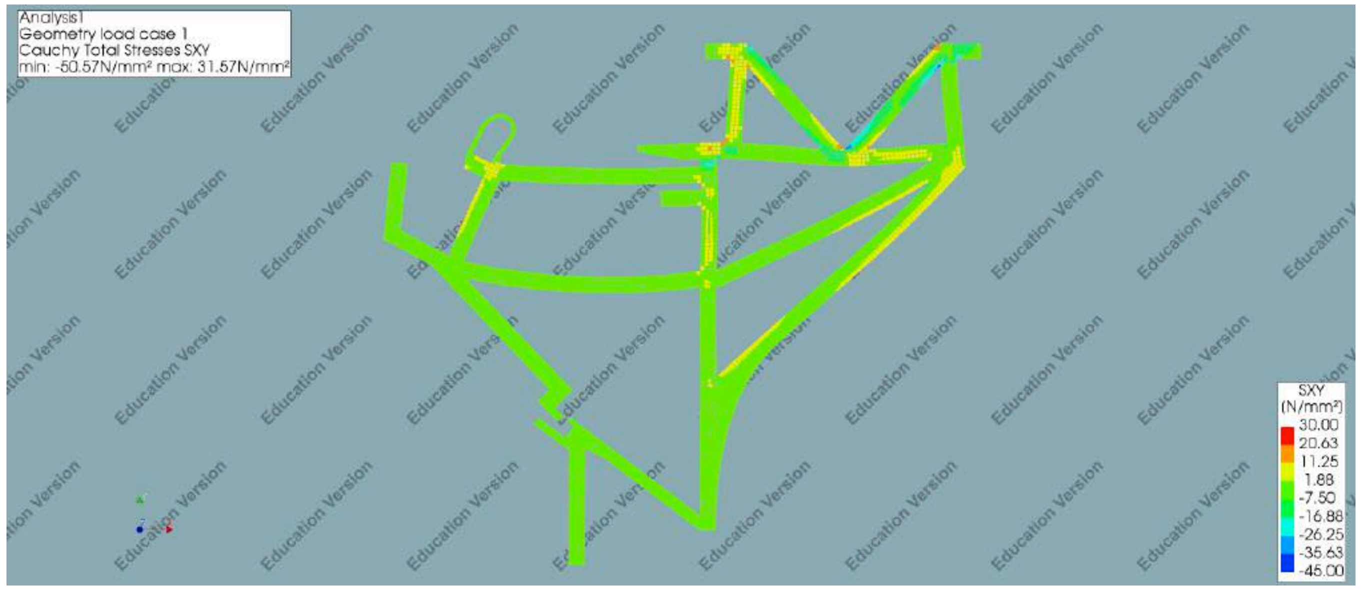


Figure 138: shear stresses 15mm depth

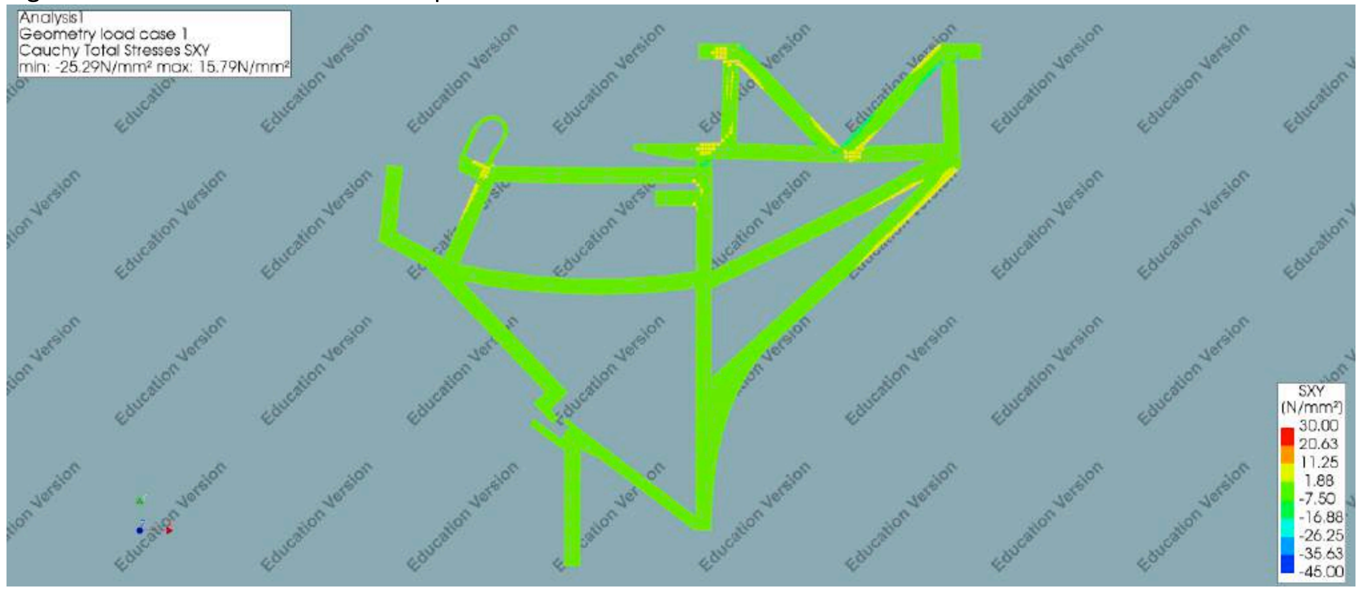


Figure 139: shear stresses 30mm depth

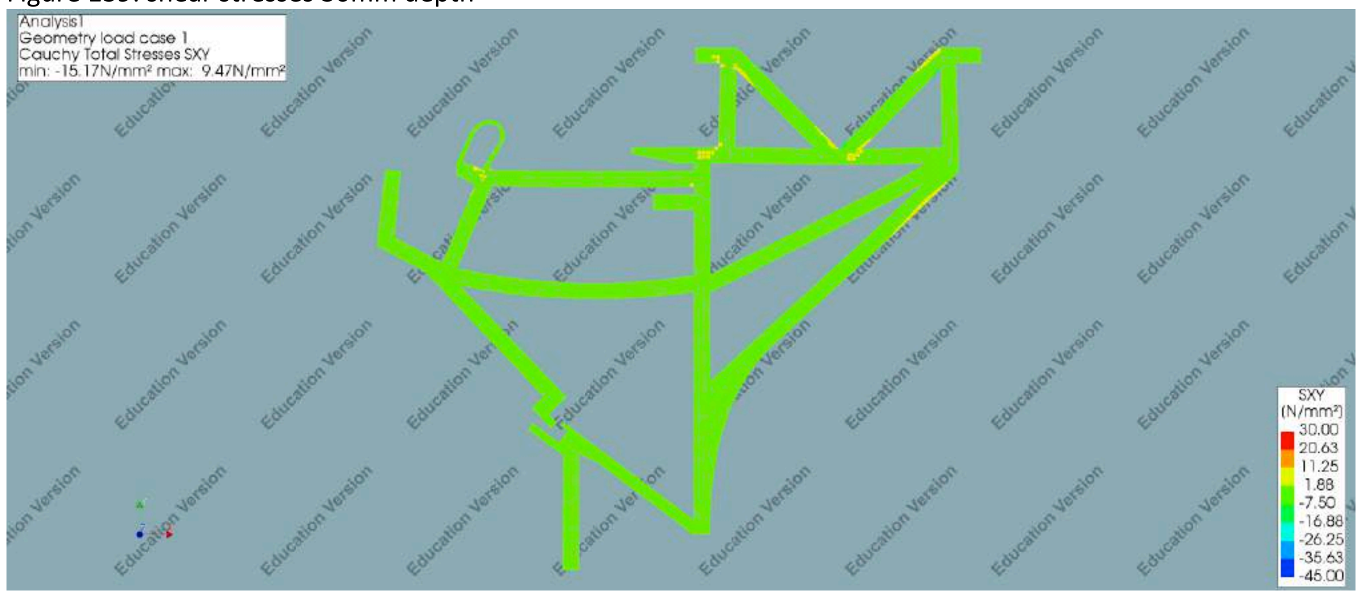


Figure 140: shear stresses 50mm depth

Analysis 6: Iteration 5

<u>Results tensile analysis</u>

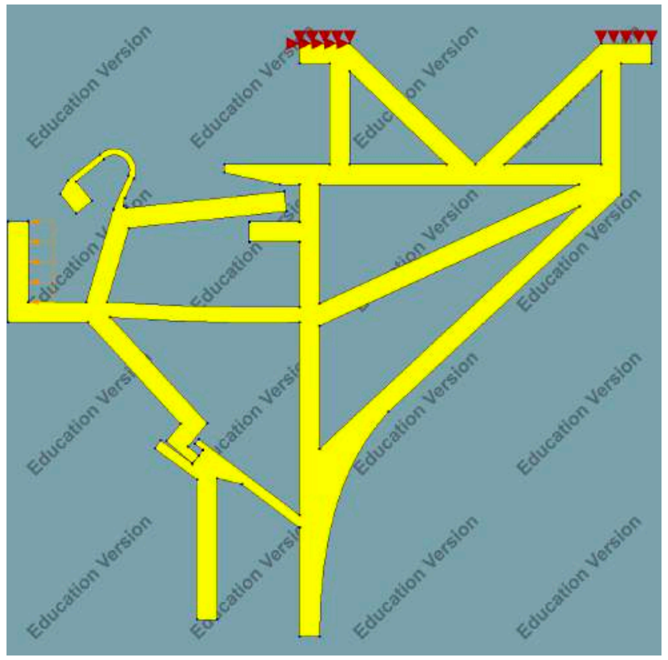


Figure 141: Geometry

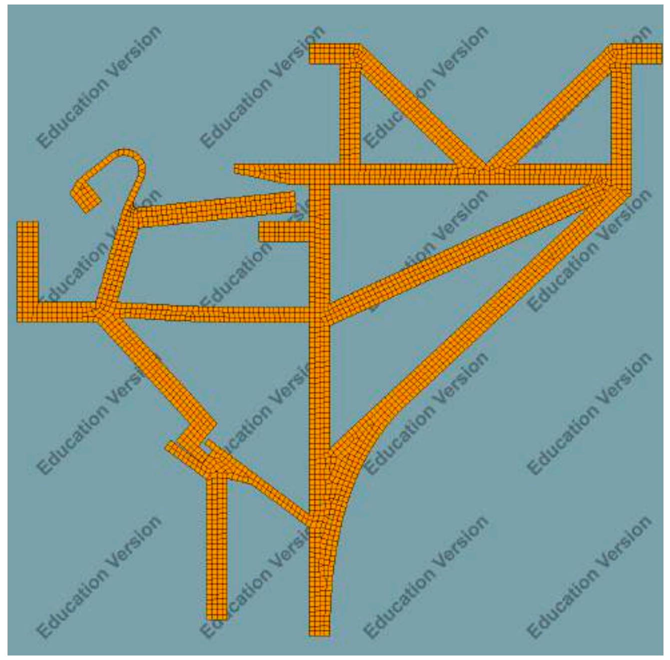


Figure 142: Mesh geometry

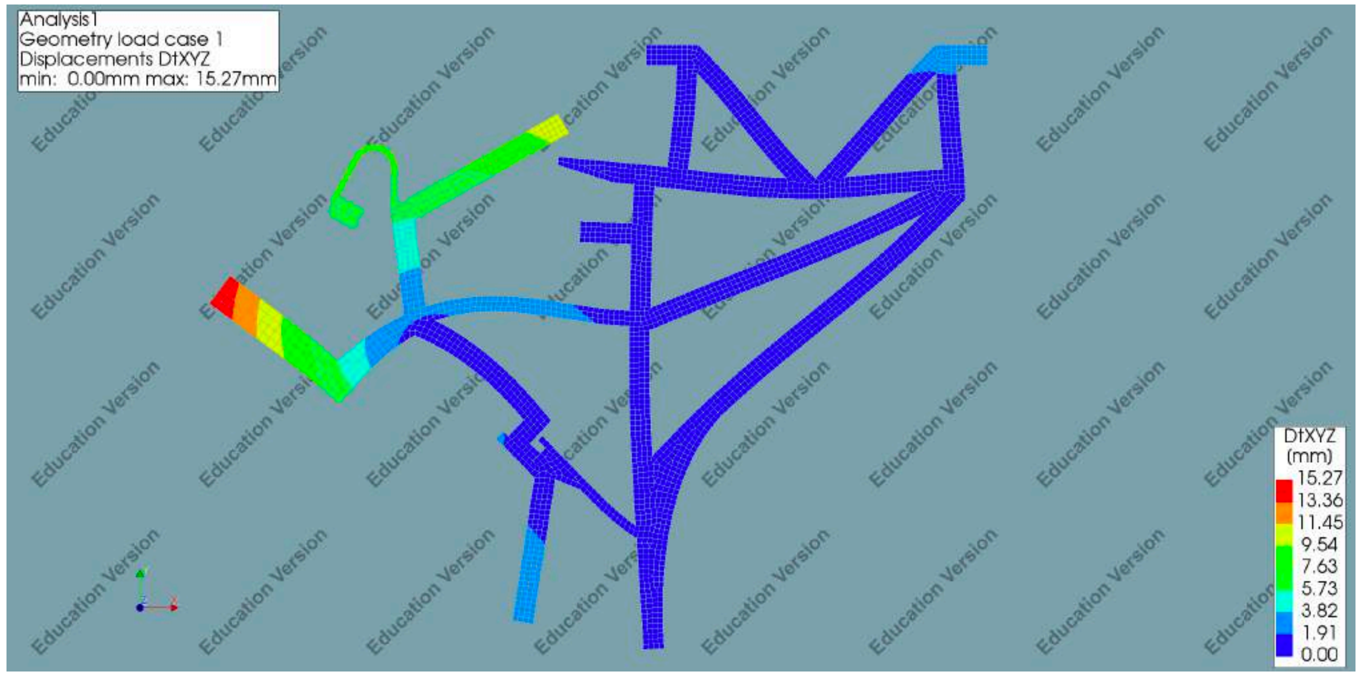


Figure 143: Displacement 15mm depth

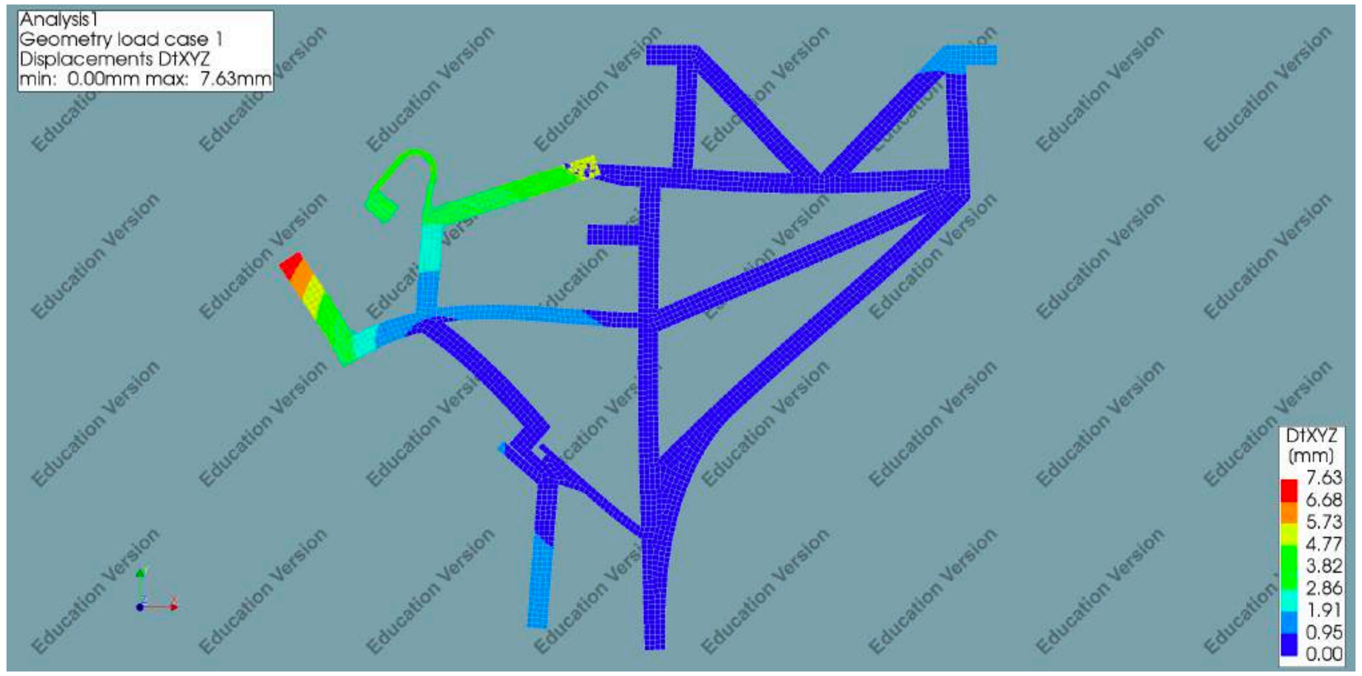


Figure 144: Displacement 30mm depth

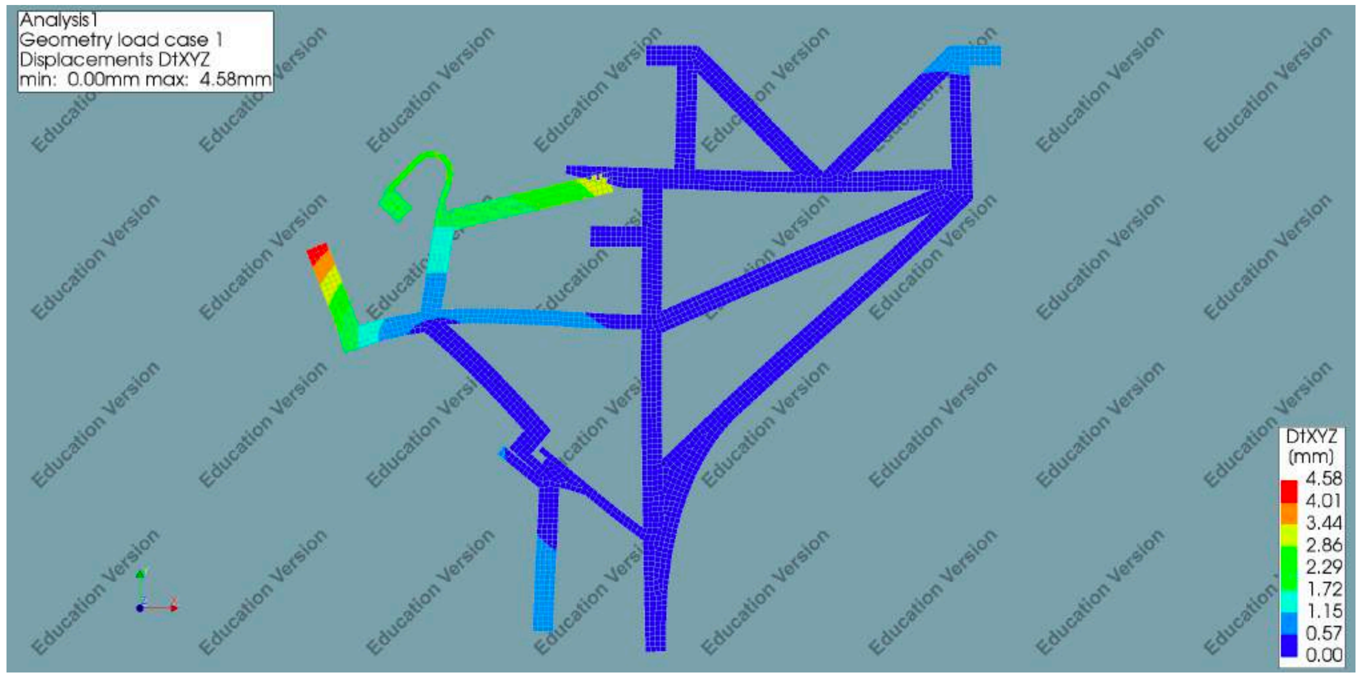


Figure 145: 50mm depth

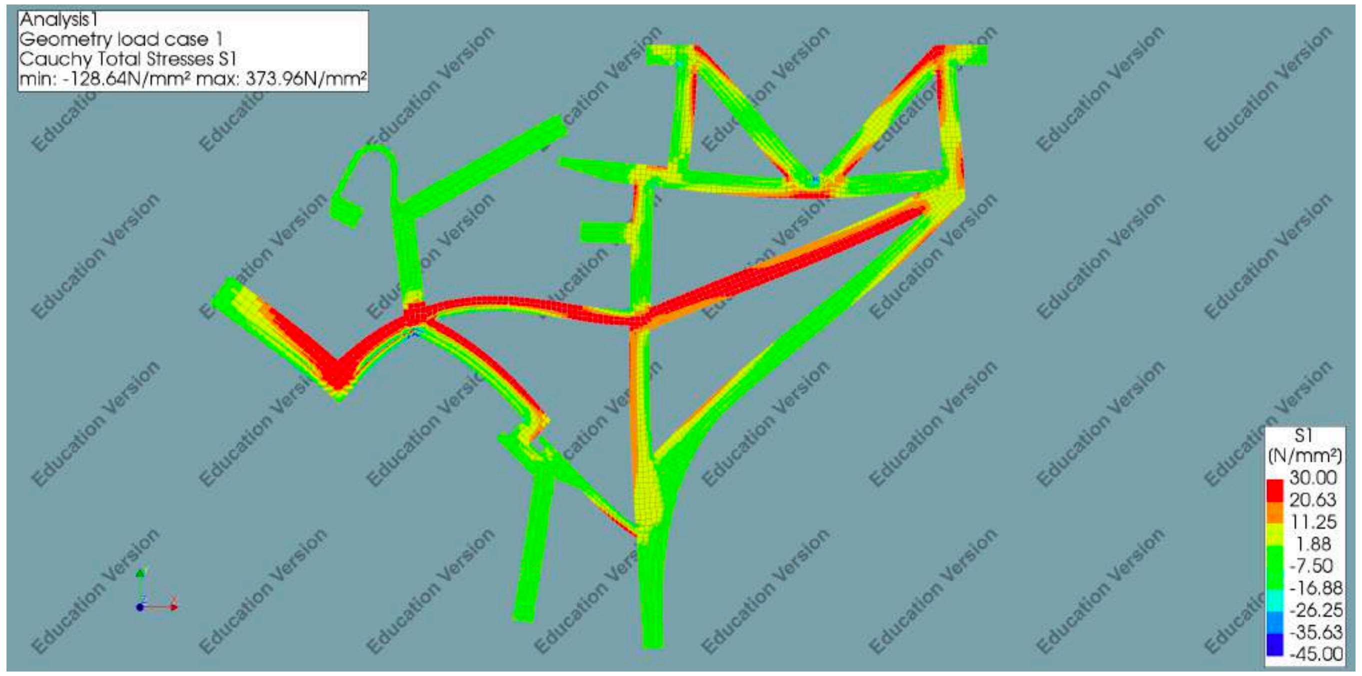


Figure 146: Tensile stresses 15mm depth

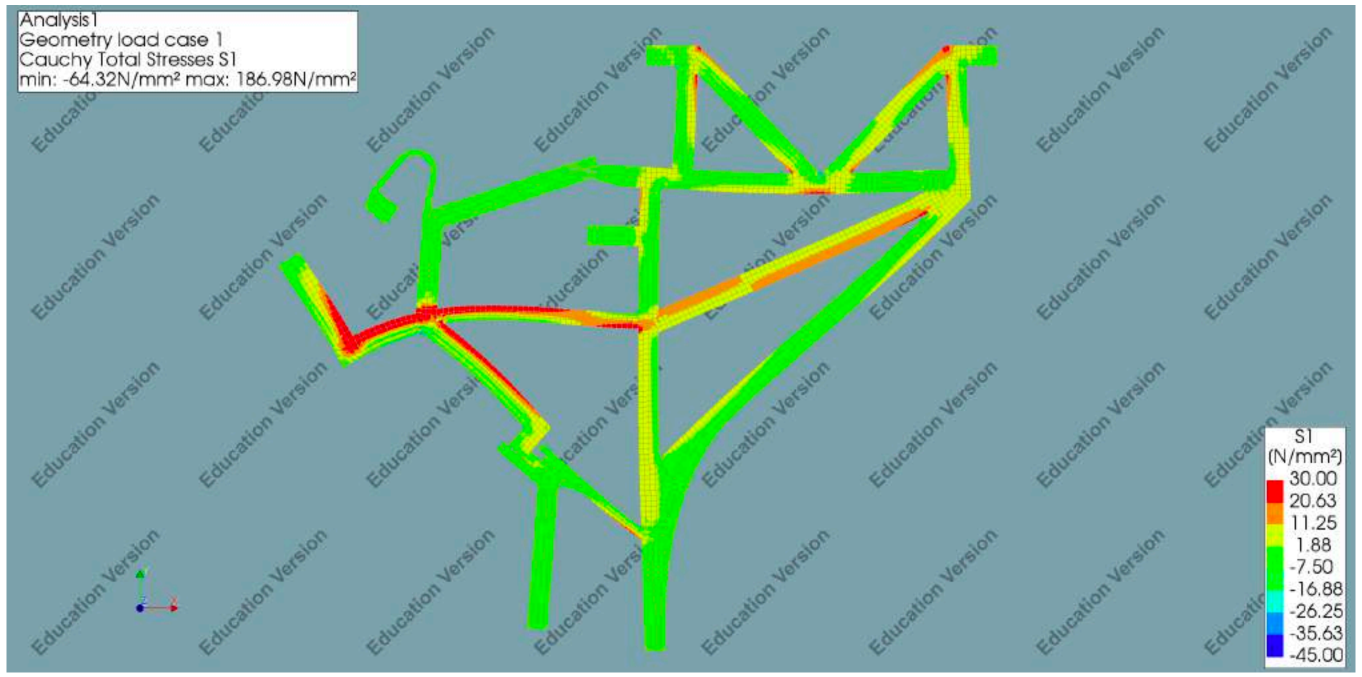


Figure 147: Tensile stresses 30mm depth

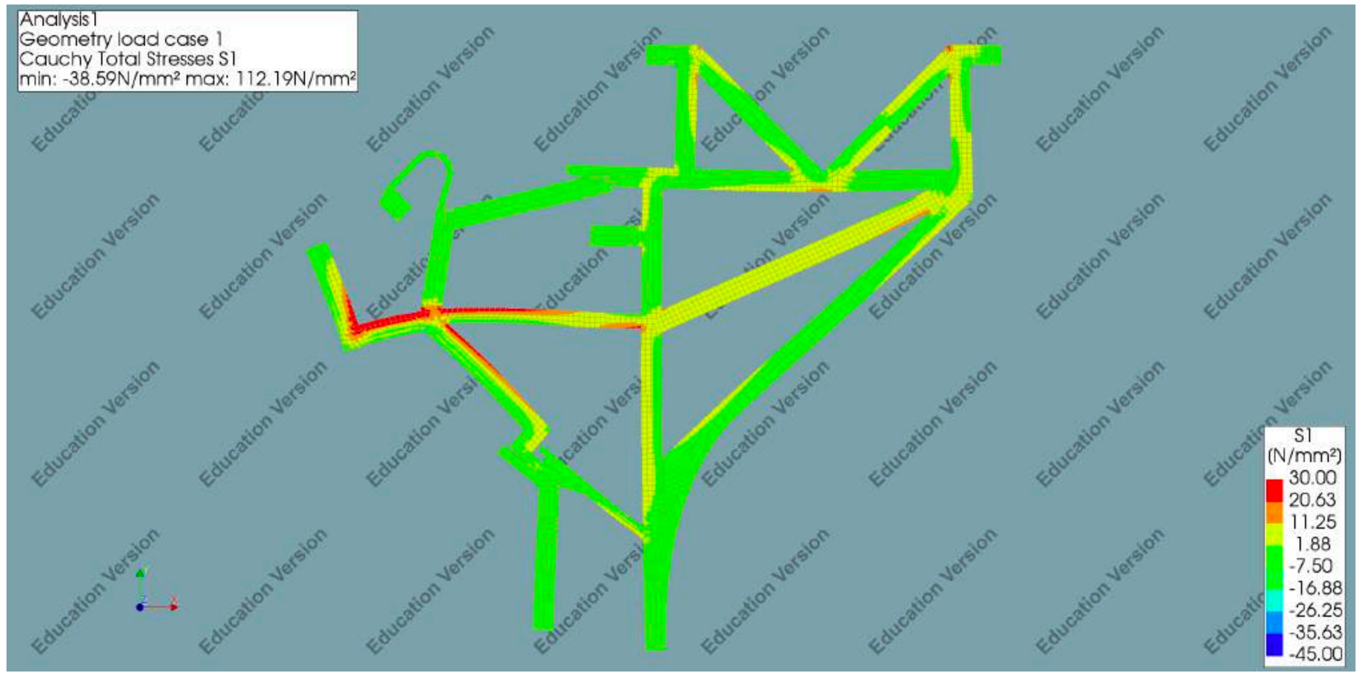


Figure 148: Tensile stresses 50mm depth

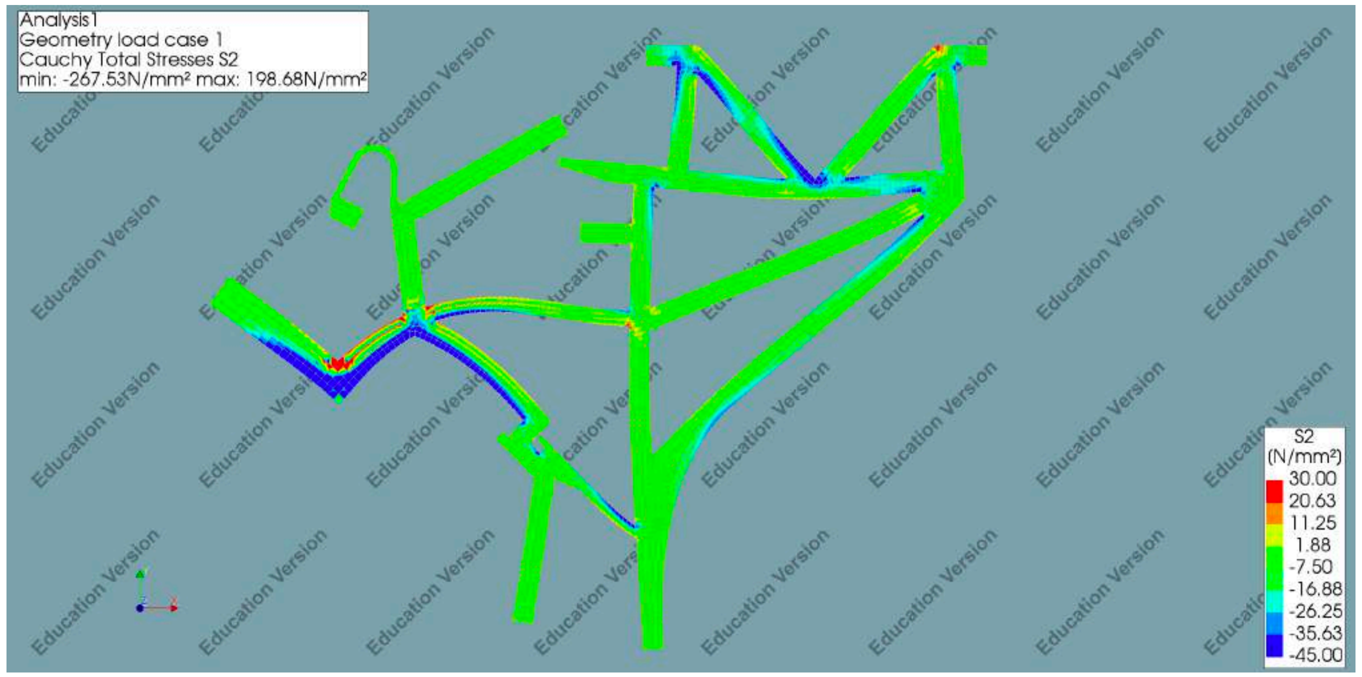


Figure 149: Compressive stresses 15mm depth

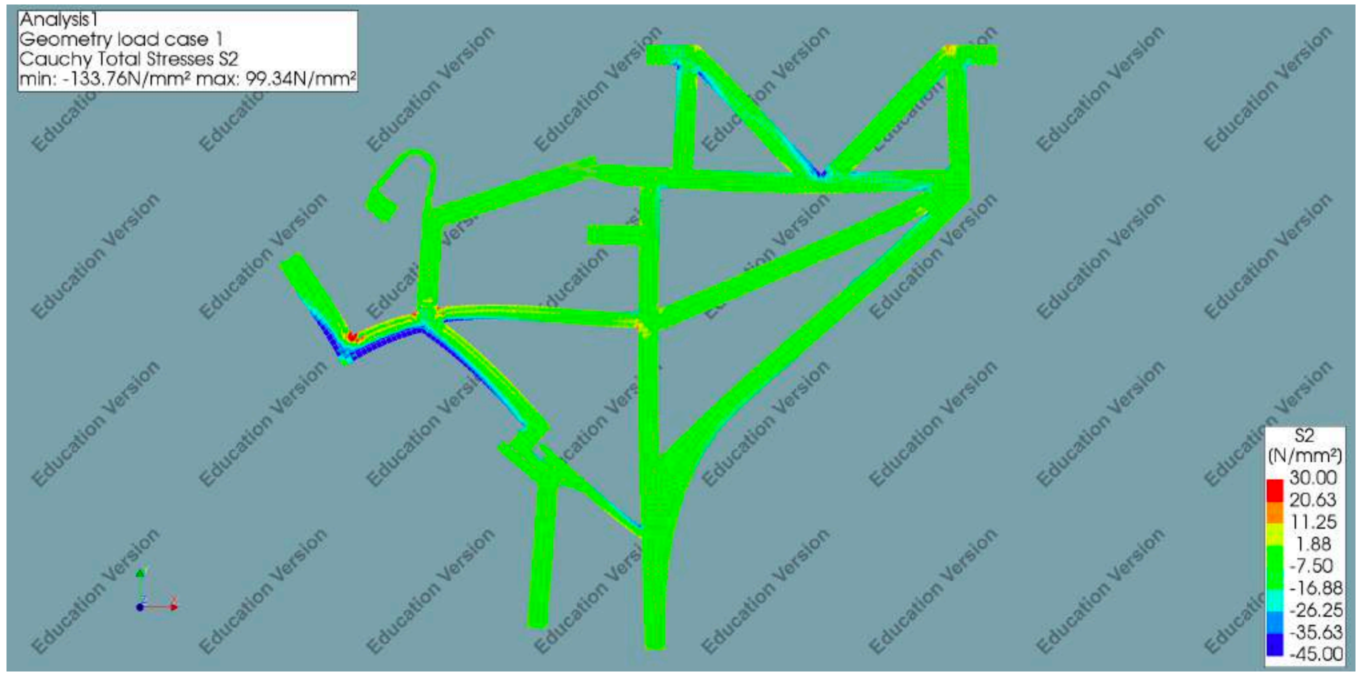


Figure 150: Compressive stresses 30mm depth

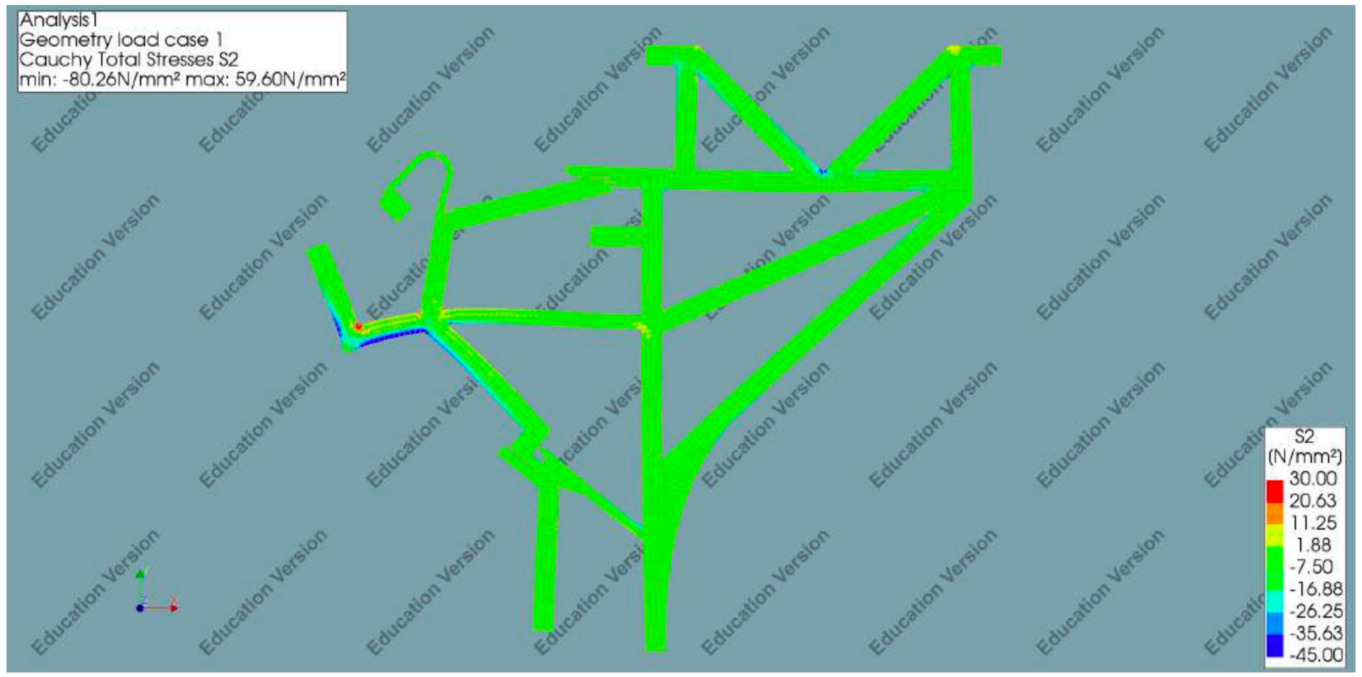


Figure 151: Compressive stresses 50mm depth

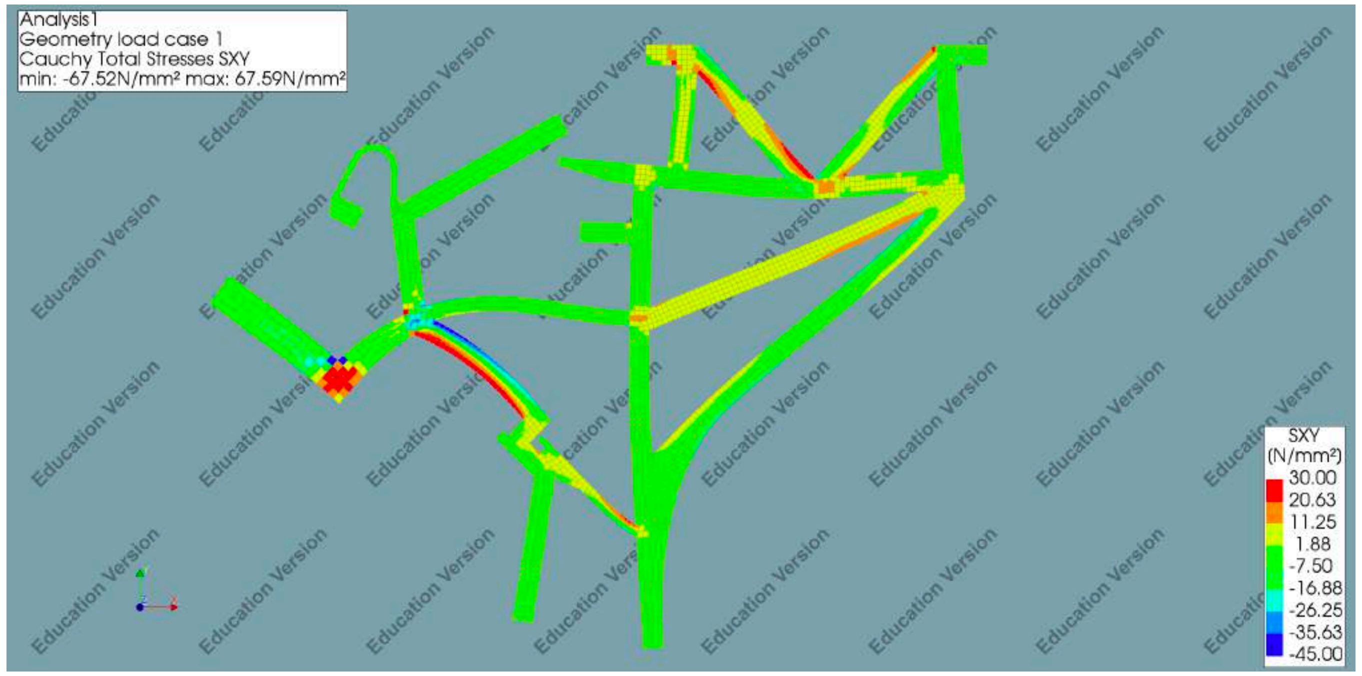


Figure 152: Shear stresses 15mm depth

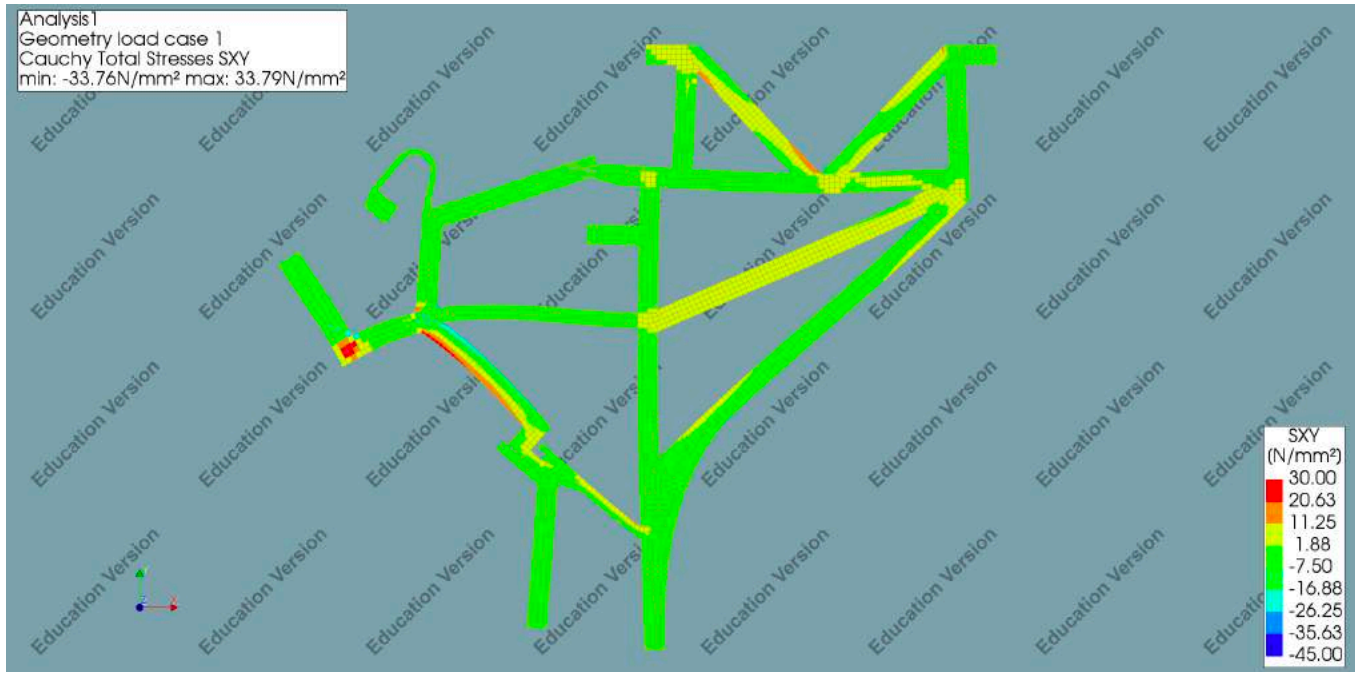


Figure 153: Shear stresses 30mm depth

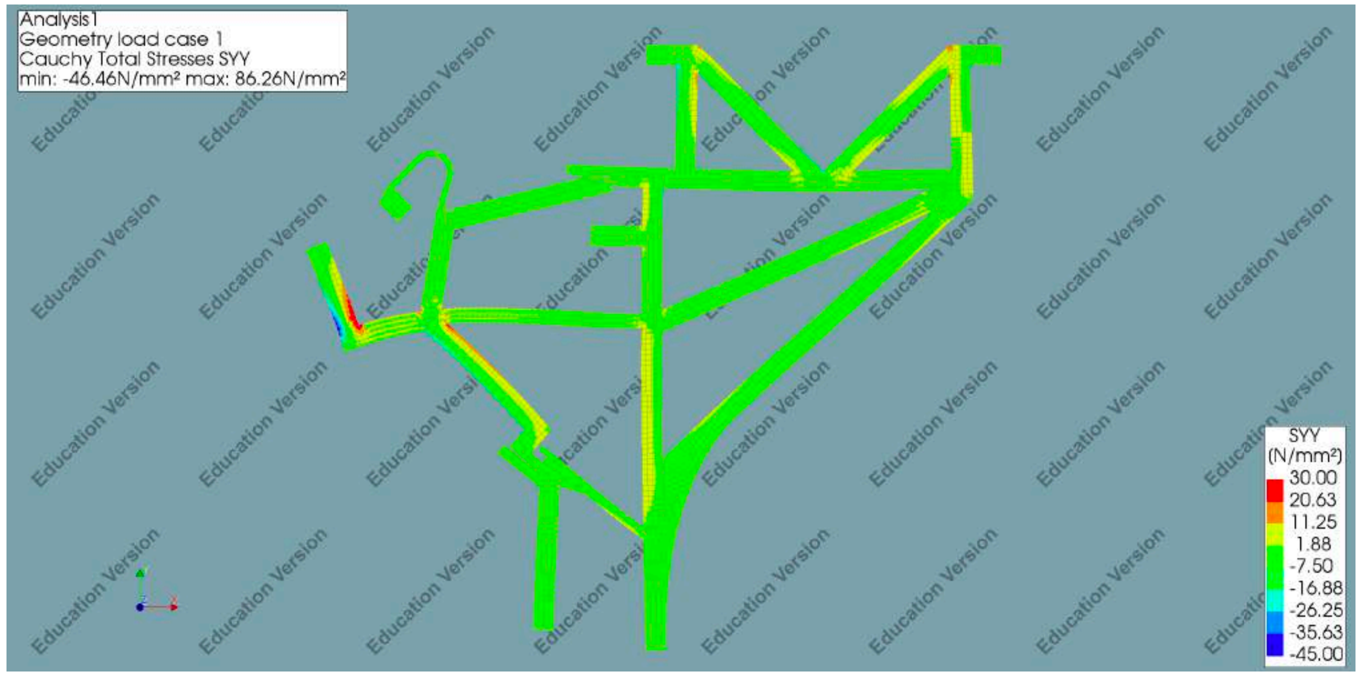


Figure 154: Shear stresses 50mm depth

<u>Results compressive analysis</u>

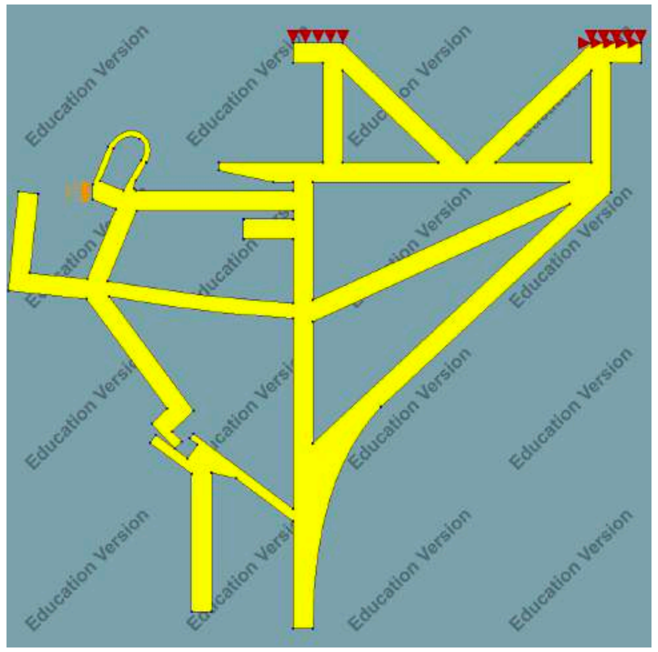


Figure 155: Geometry

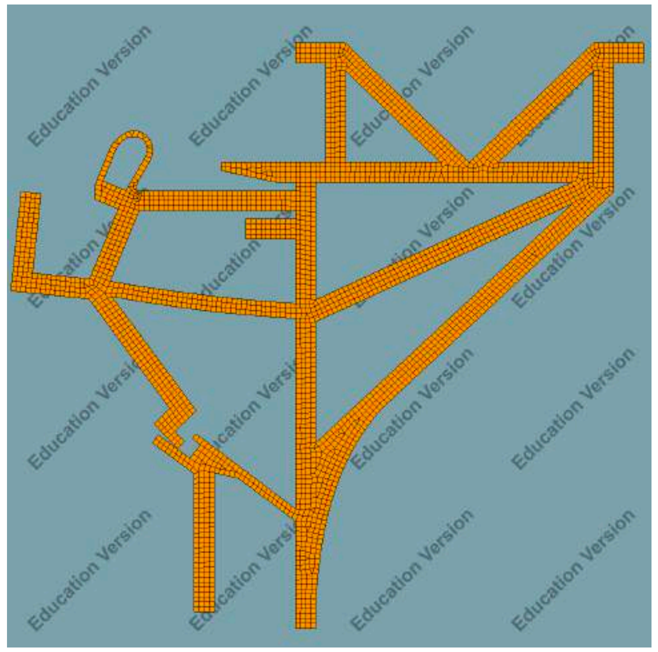


Figure 156: Mesh geometry

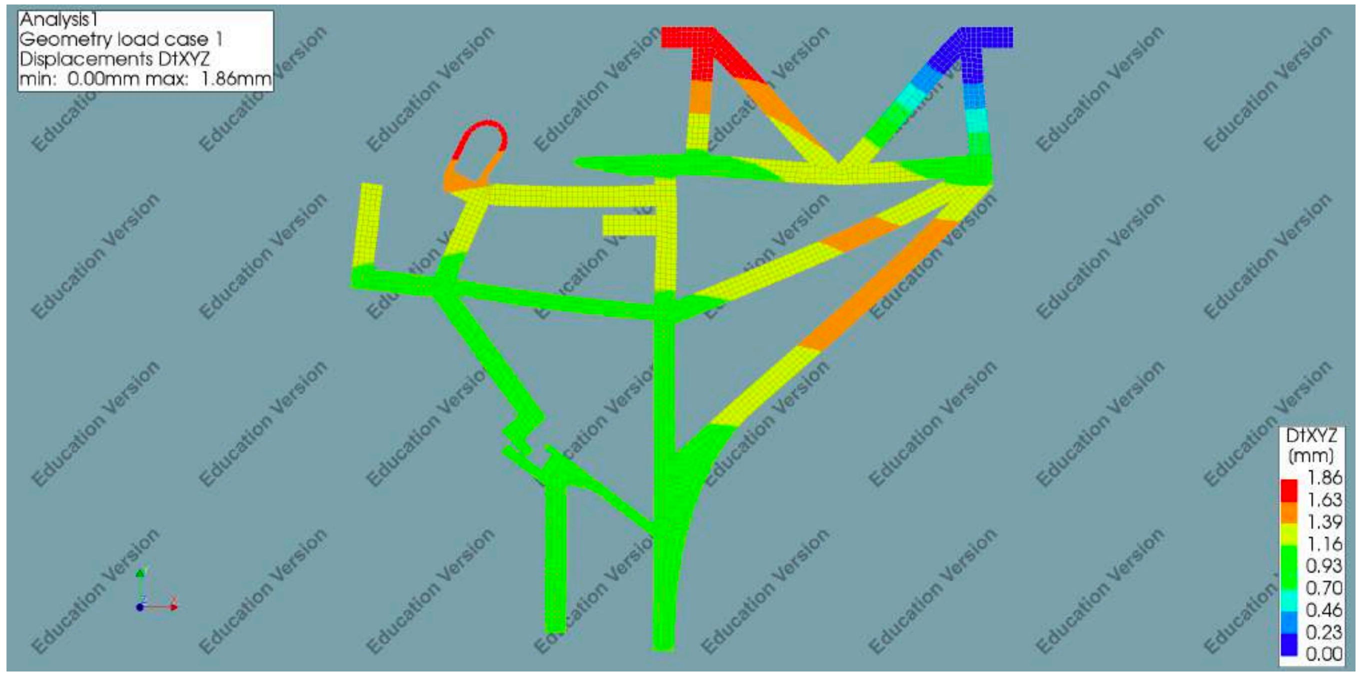


Figure 157: Displacement 15mm depth

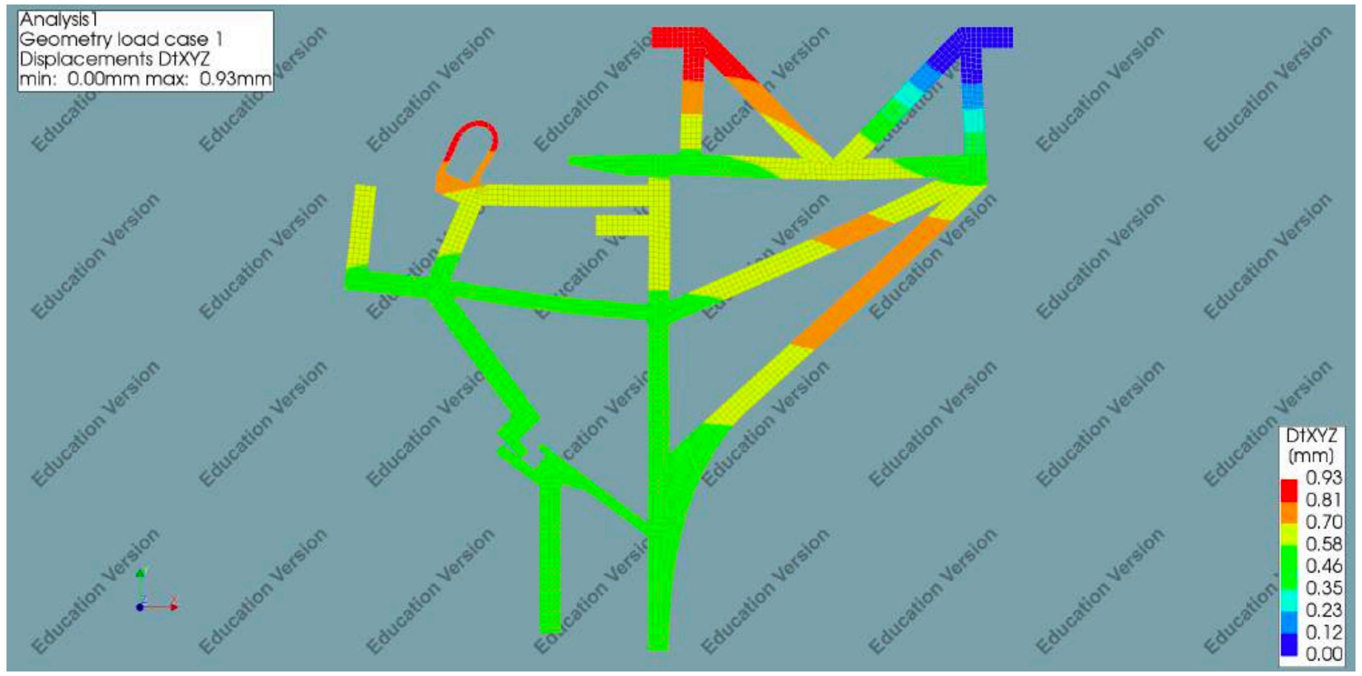


Figure 158: Displacement 30mm depth

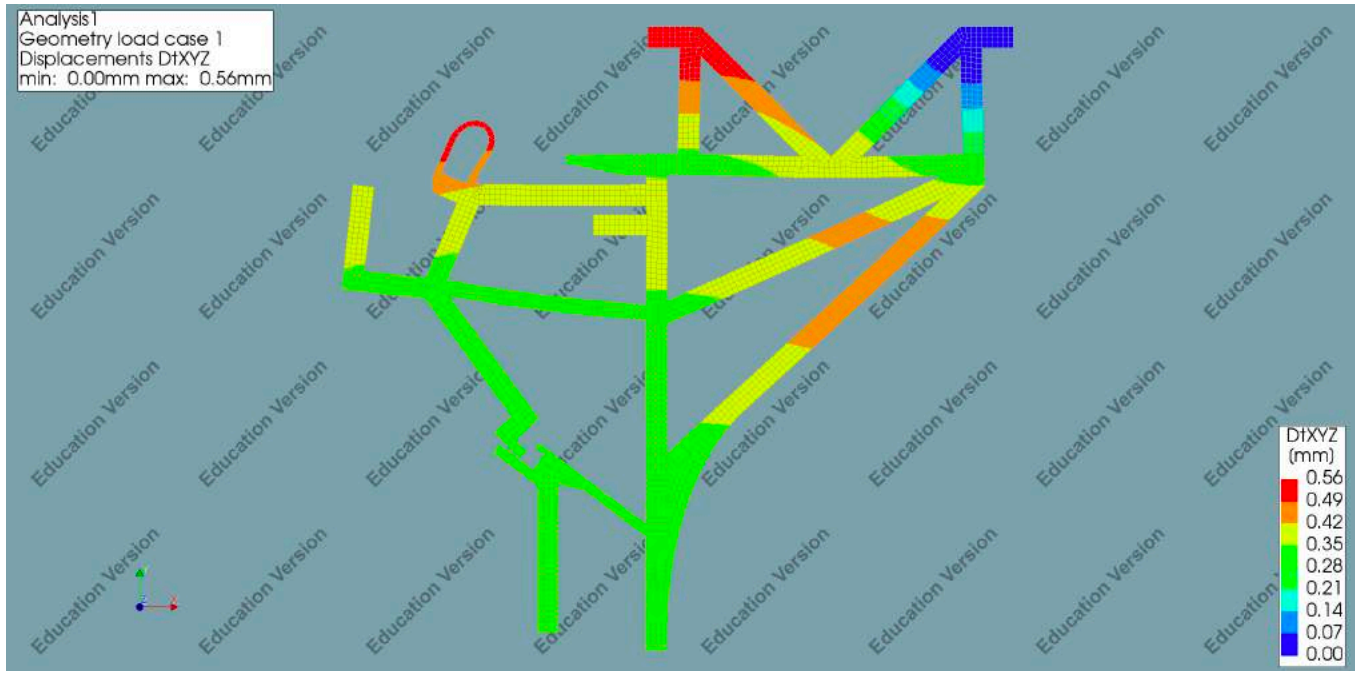


Figure 159: Displacement 50mm depth

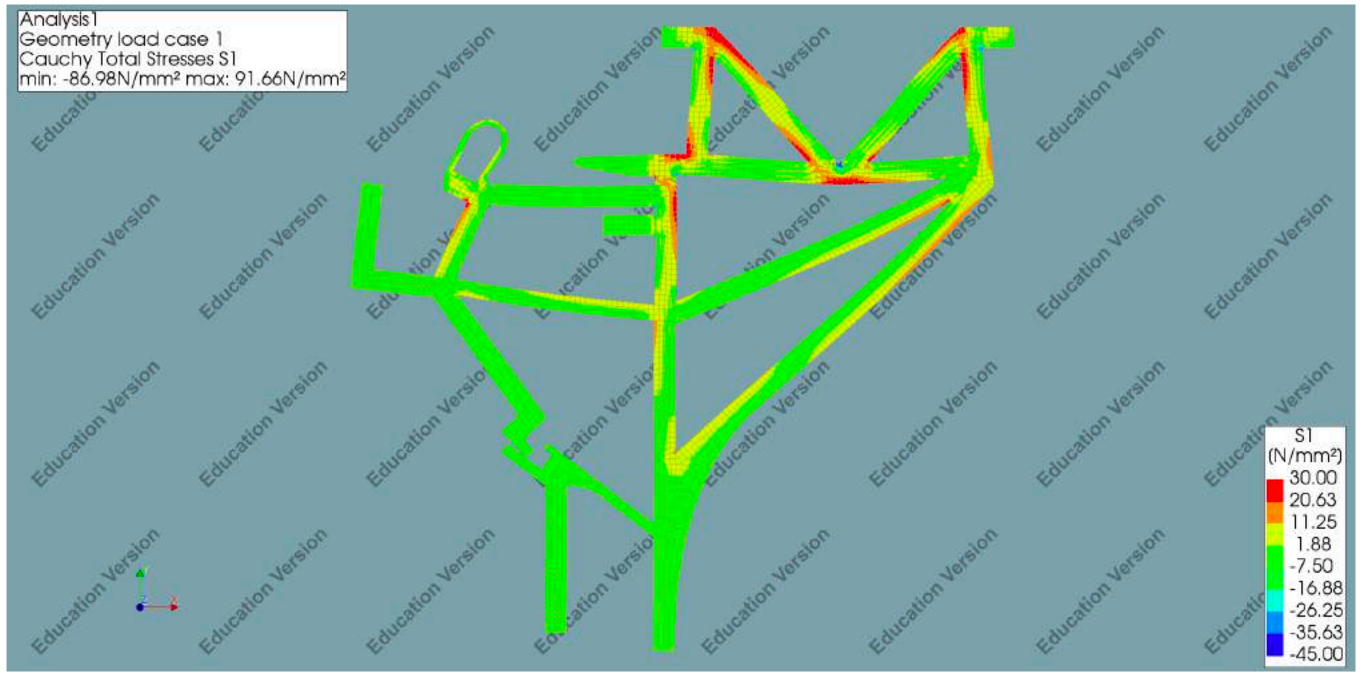


Figure 160: Tensile stresses 15mm depth

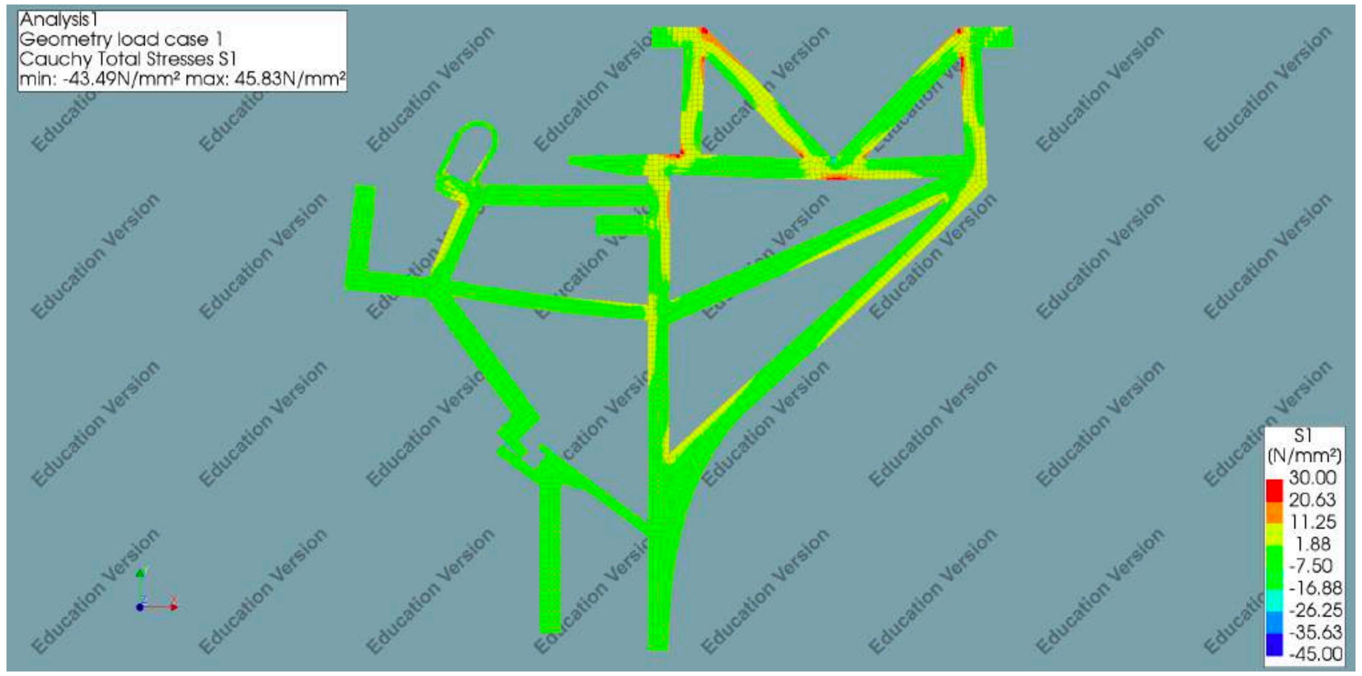


Figure 161: Tensile stresses 30mm depth

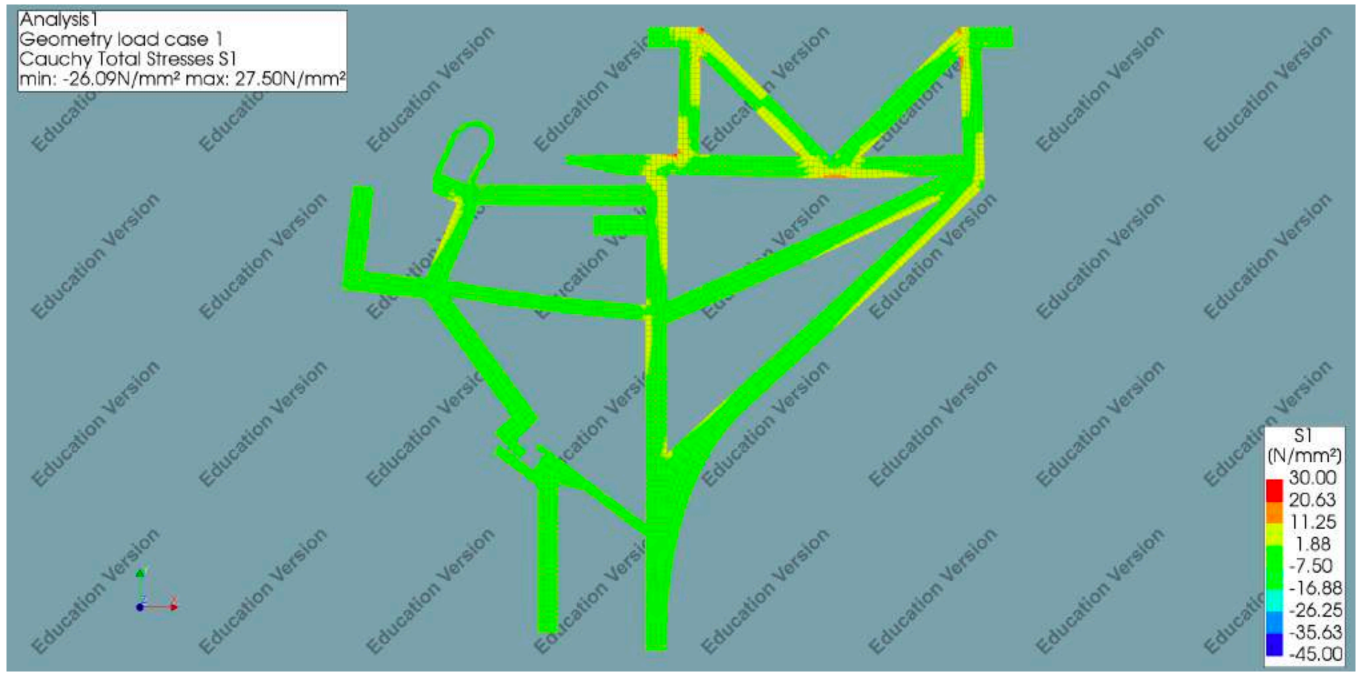


Figure 162: Tensile stresses 50mm depth

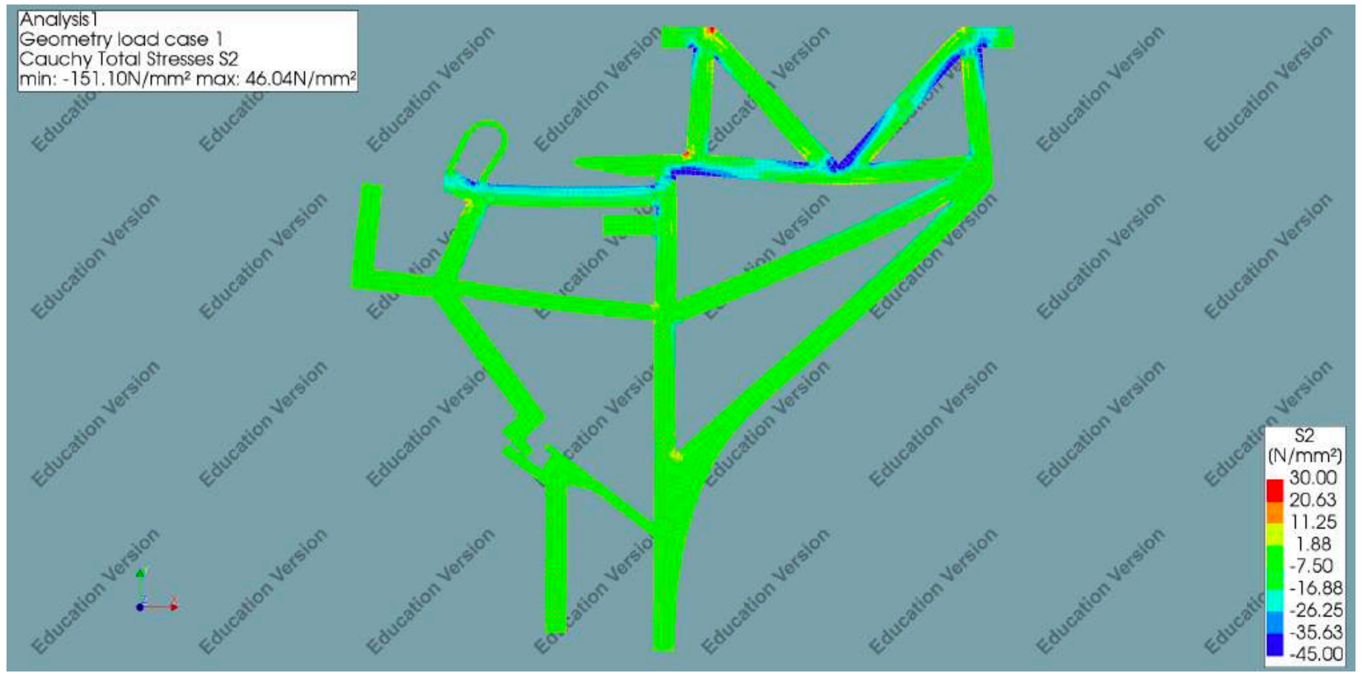


Figure 163: Compressive stresses 15mm depth

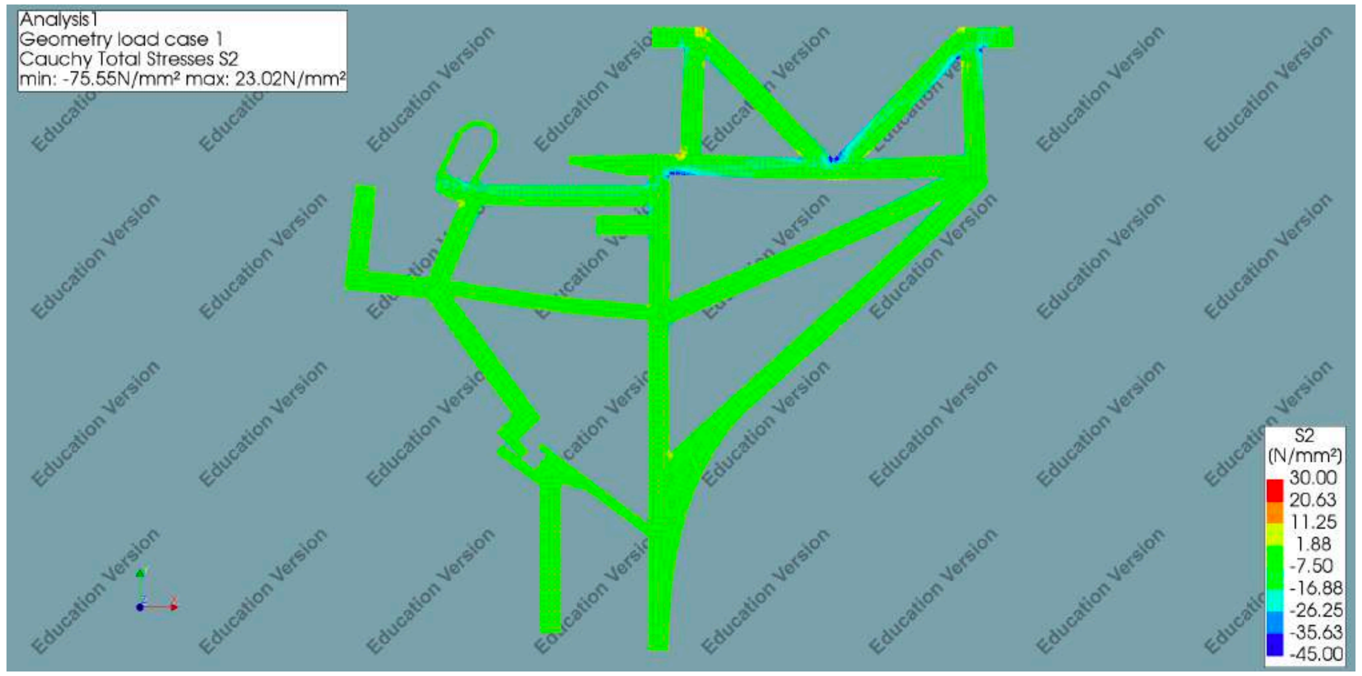


Figure 164: Compressive stresses 30mm depth

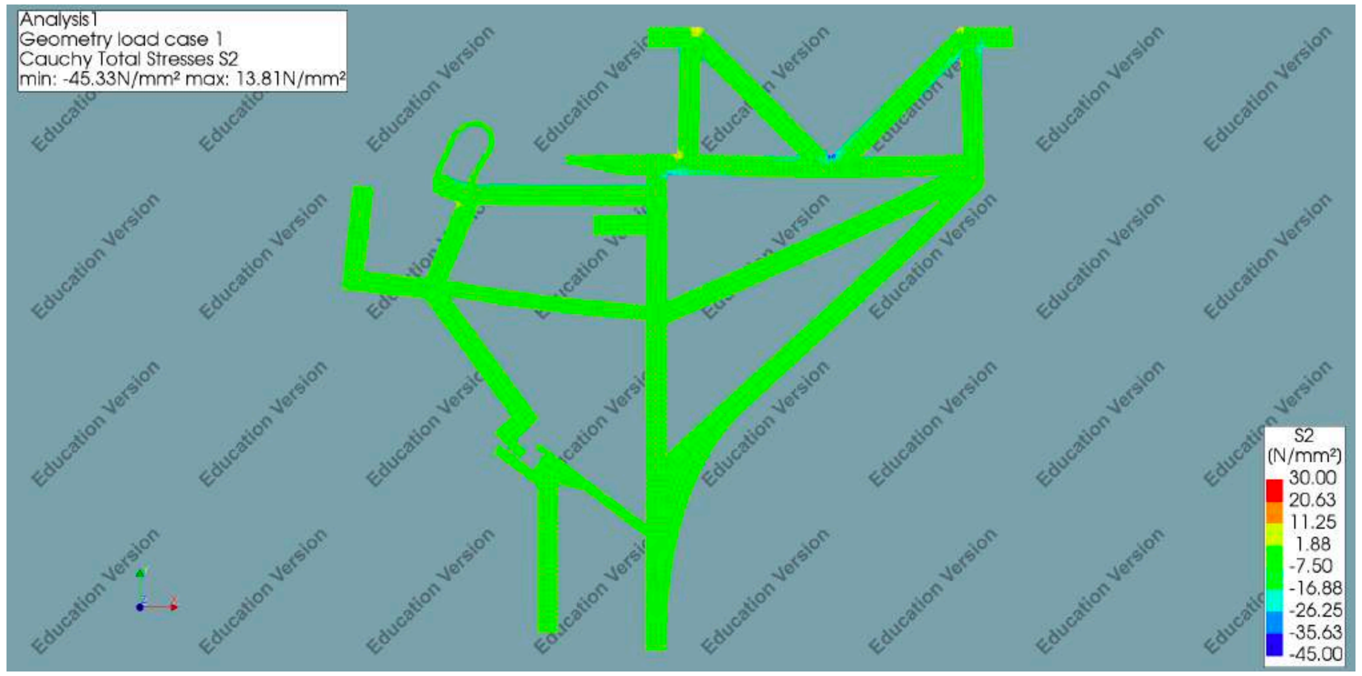


Figure 165: Compressive stresses 50mm depth

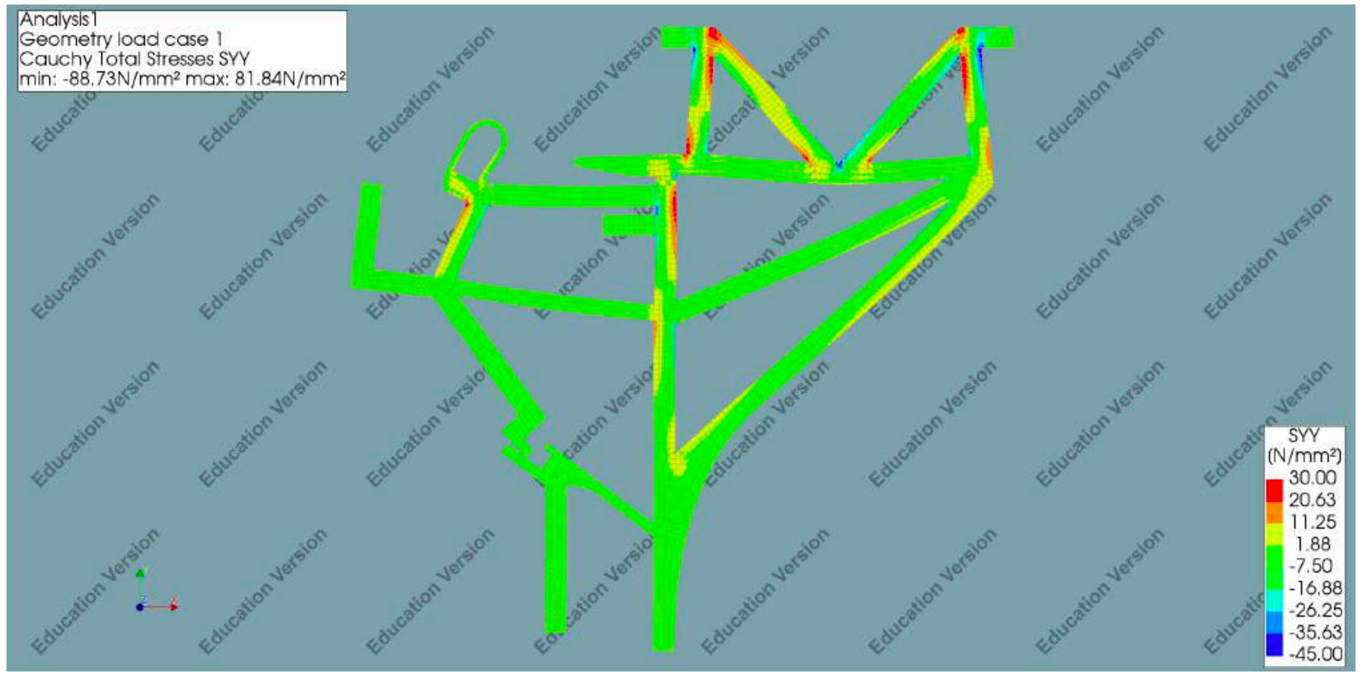


Figure 166: shear stresses 15mm depth

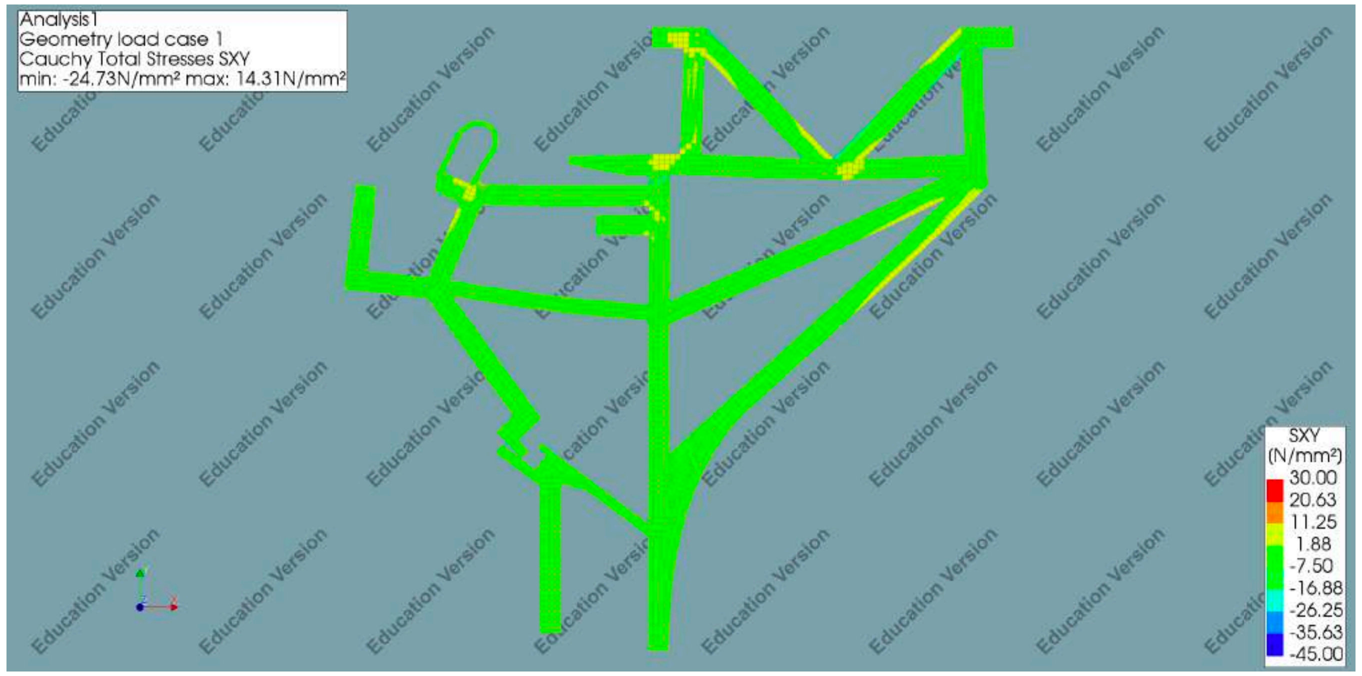


Figure 167: shear stresses 30mm depth

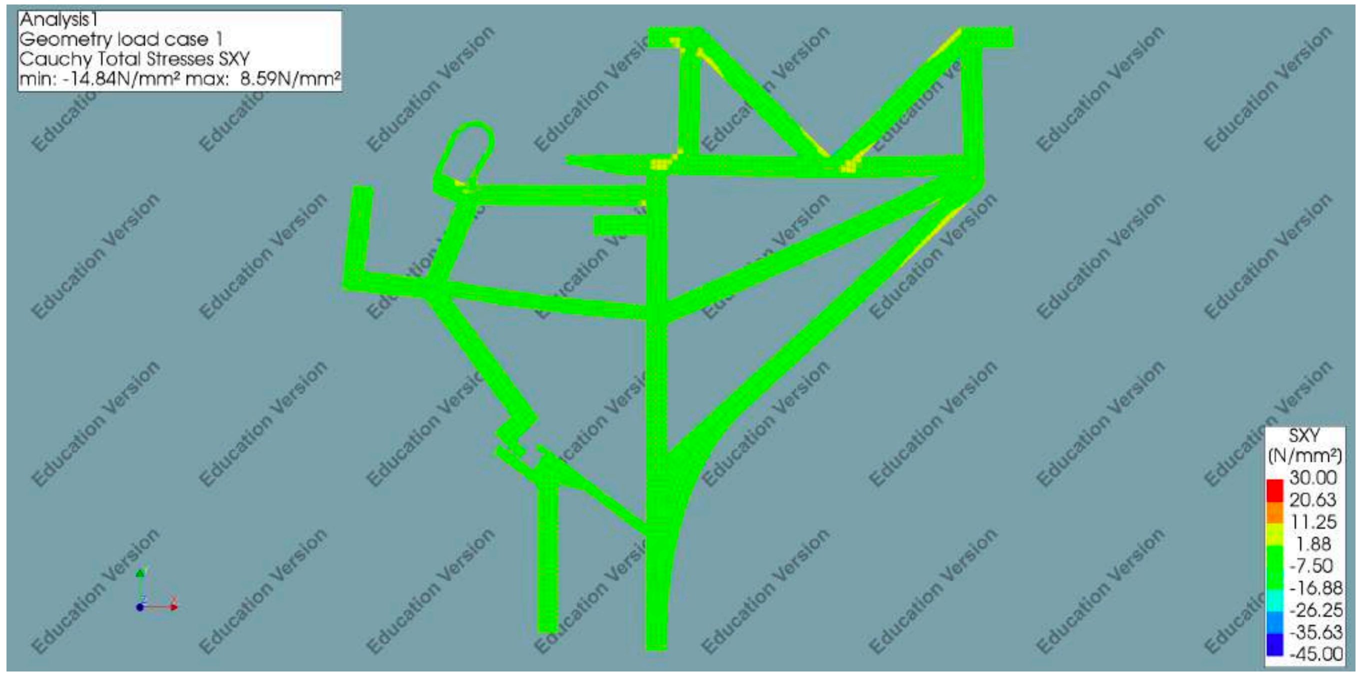


Figure 168: shear stresses 50mm depth

Analysis 7: Iteration 6

<u>Results tensile analysis</u>

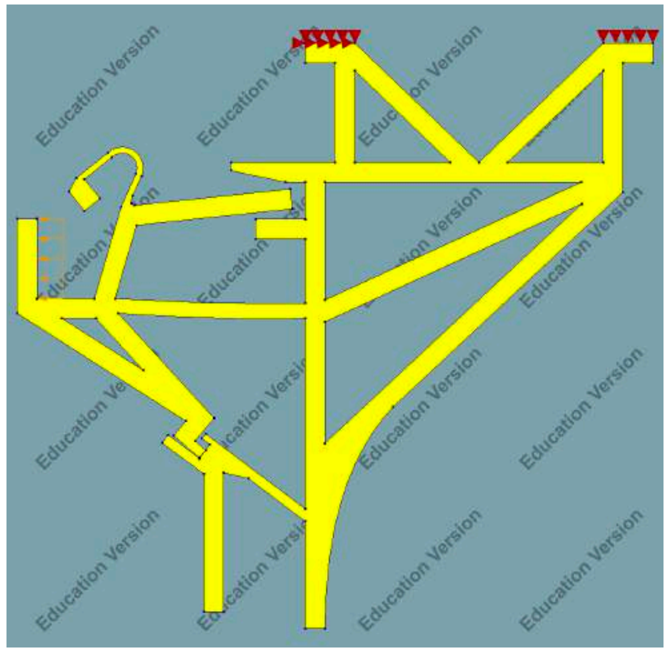


Figure 169: Geometry

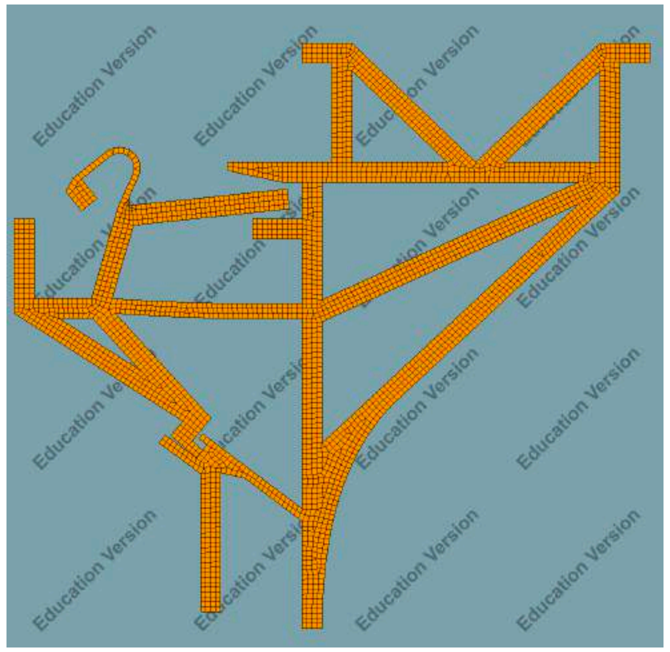


Figure 170: Mesh geometry

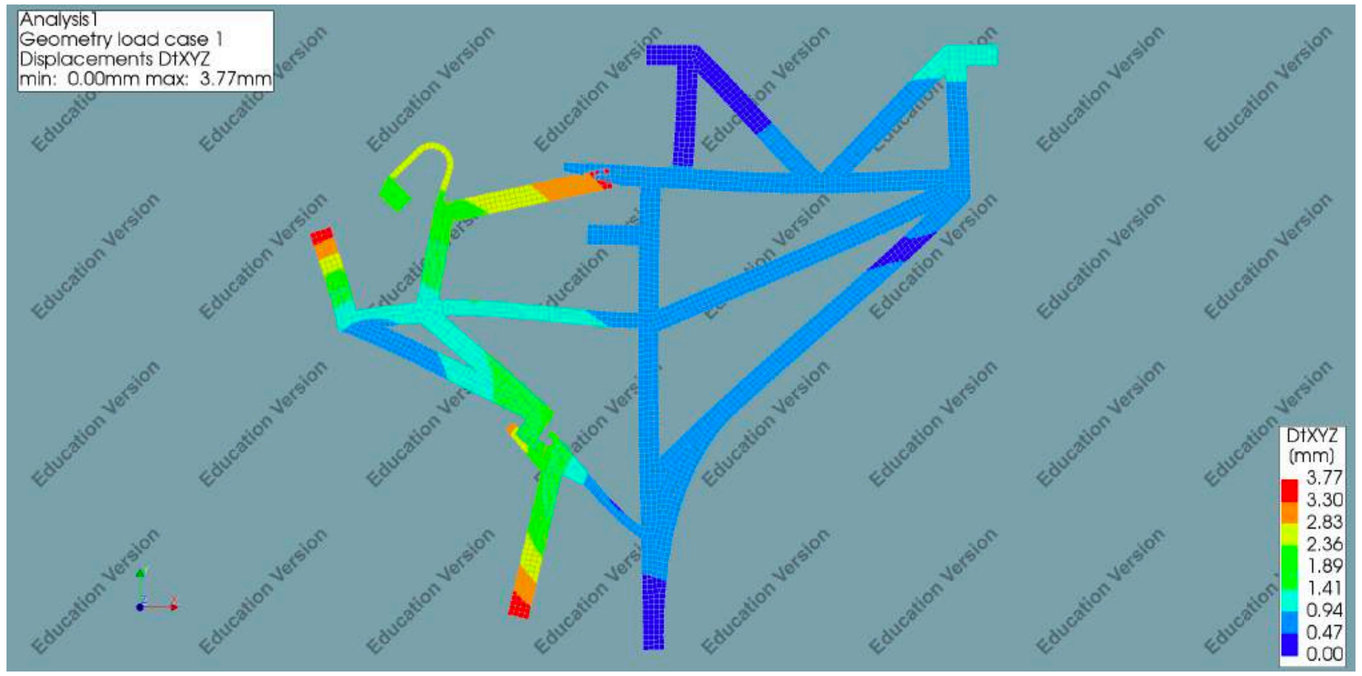


Figure 172: Displacement 30mm depth

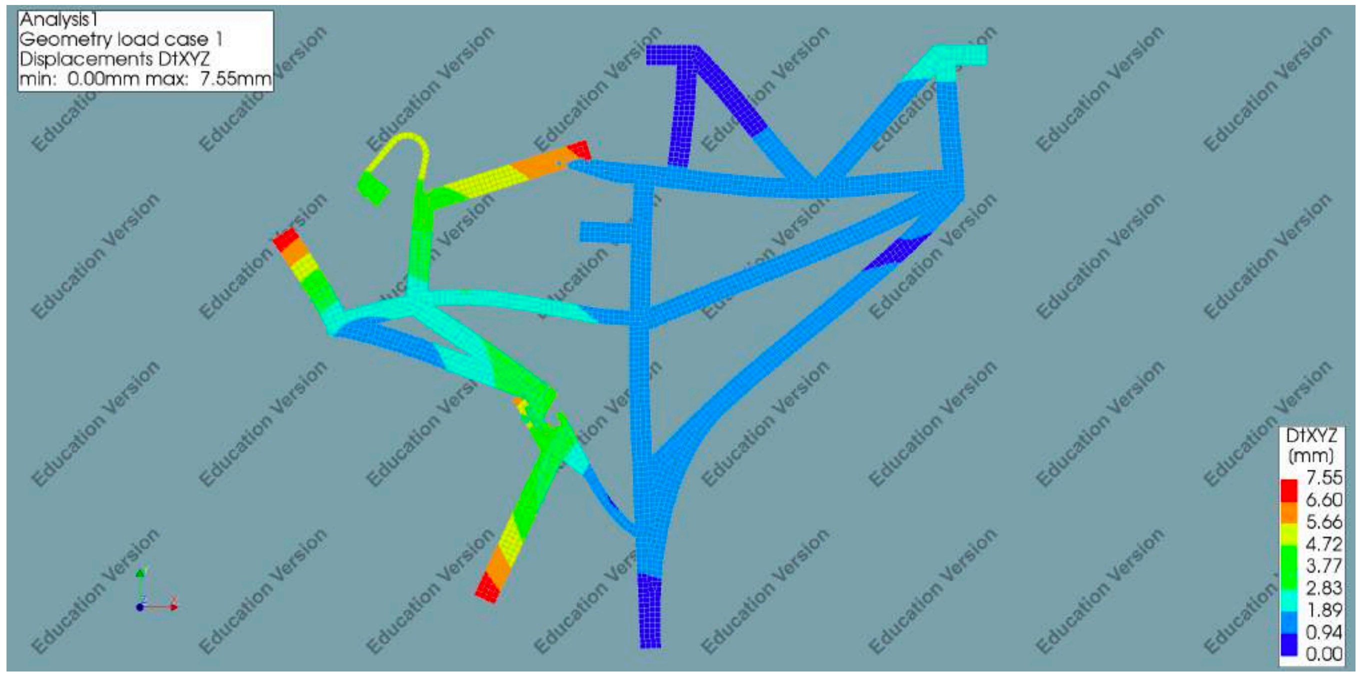


Figure 171: Displacement 15mm depth

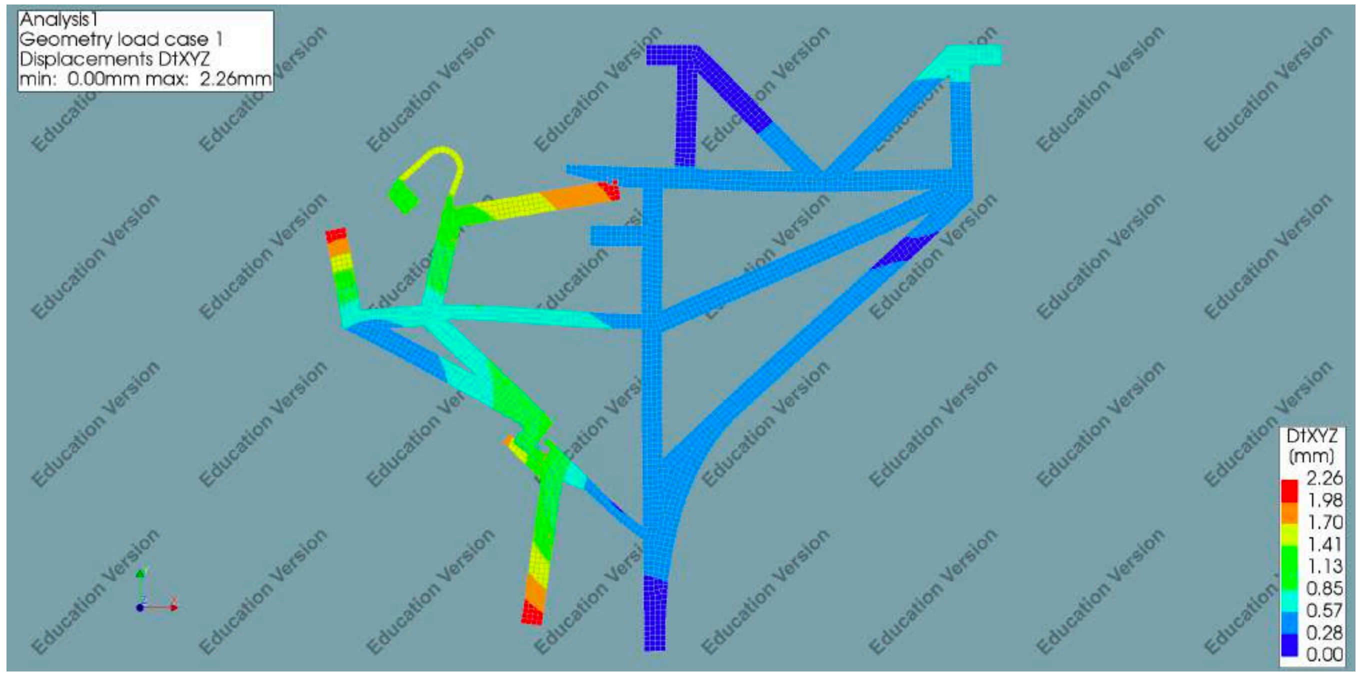


Figure 173: 50mm depth

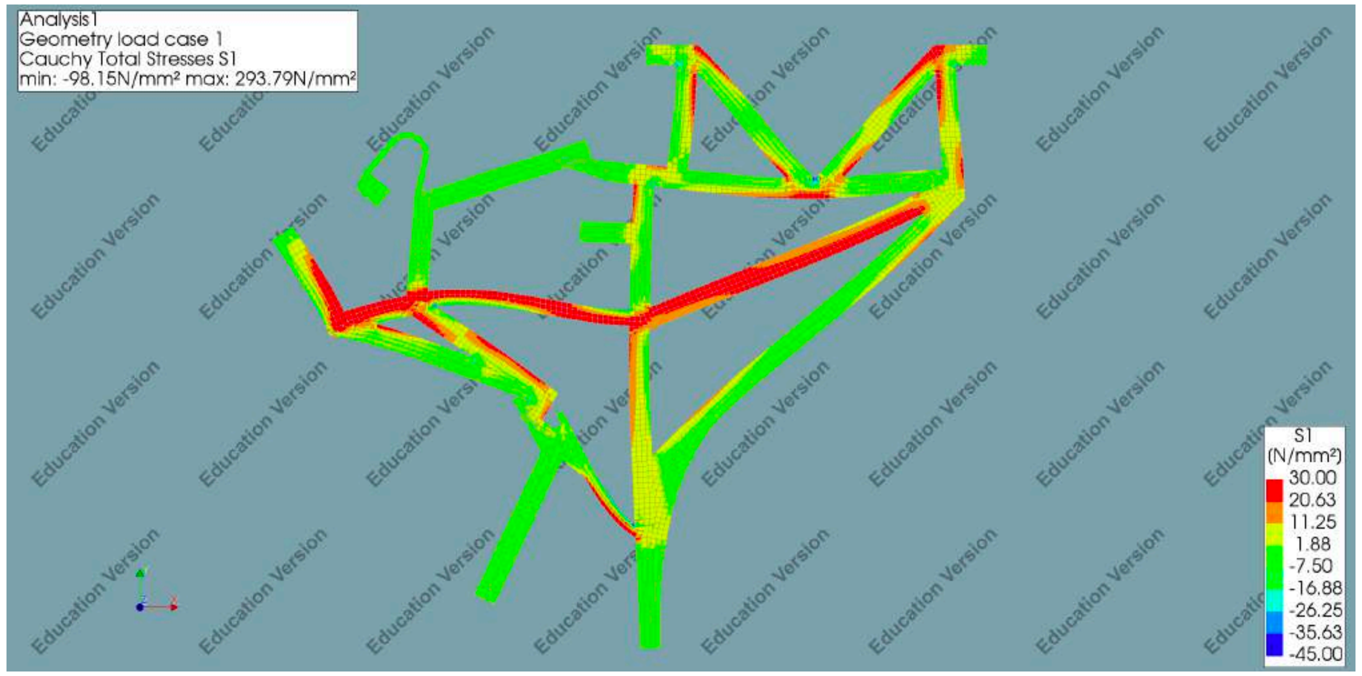


Figure 174: Tensile stresses 15mm depth

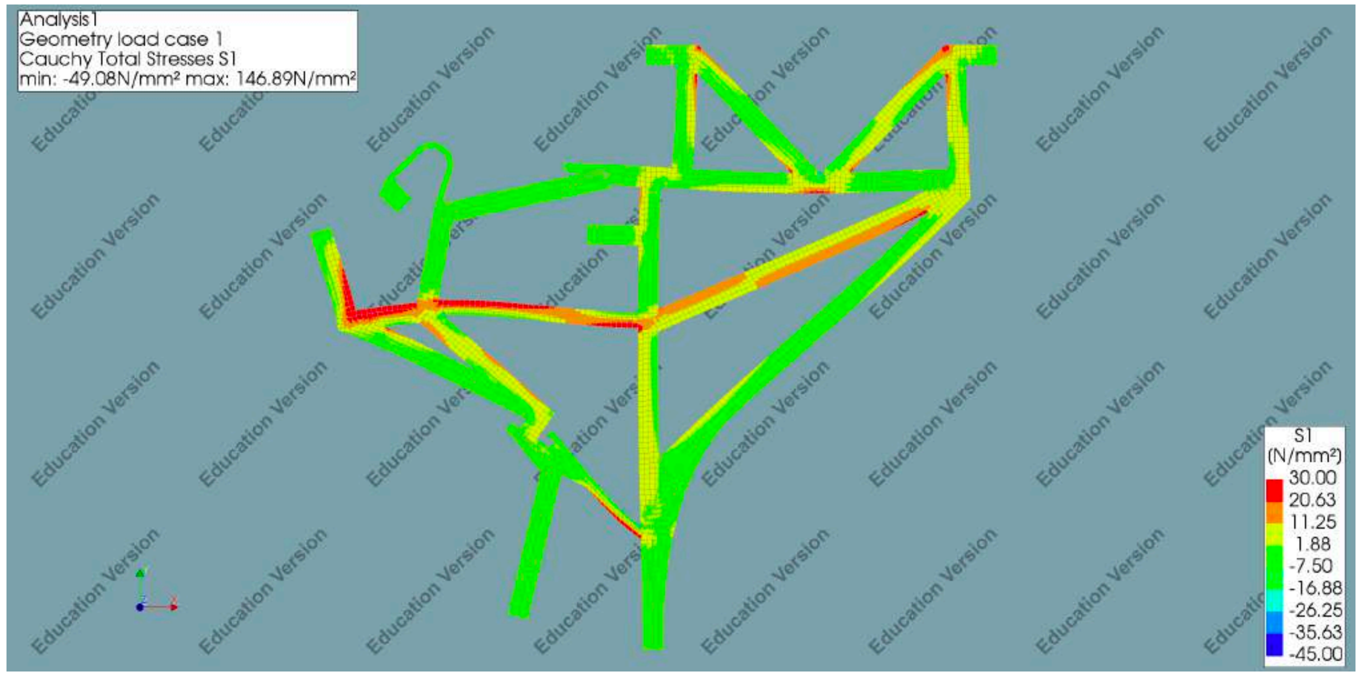


Figure 175: Tensile stresses 30mm depth

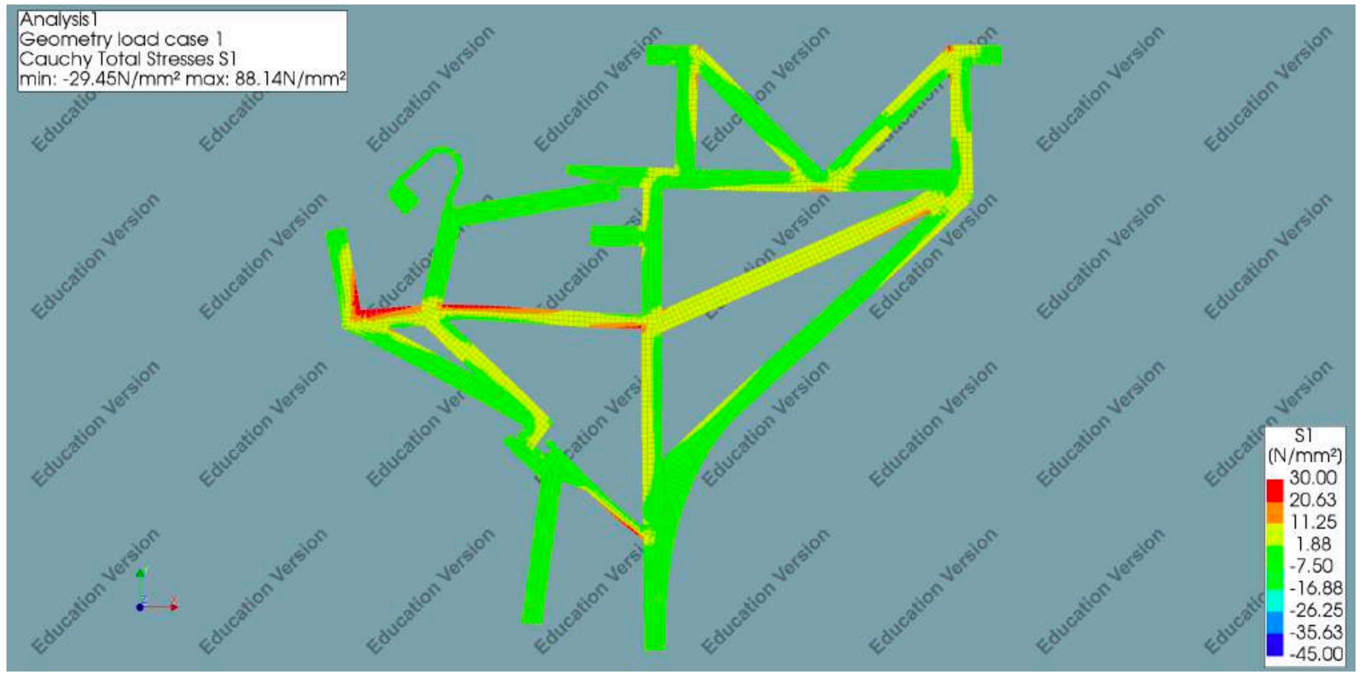


Figure 176: Tensile stresses 50mm depth

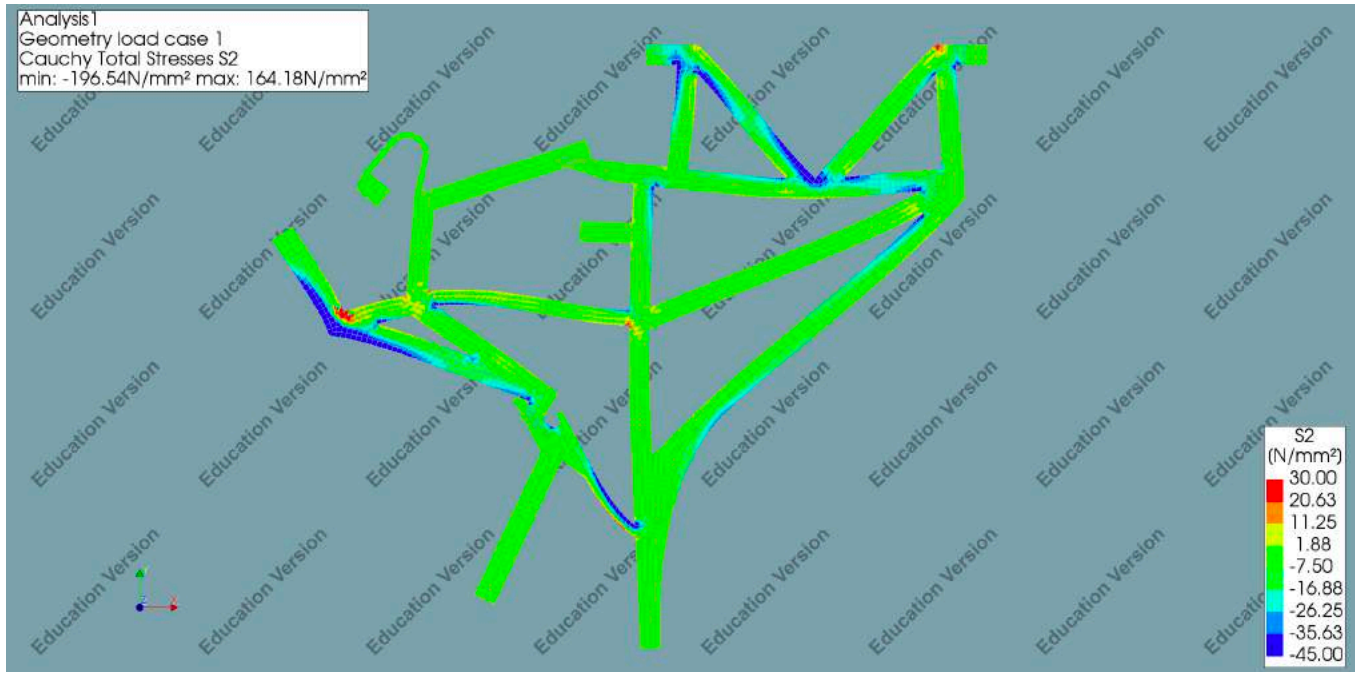


Figure 177: Compressive stresses 15mm depth

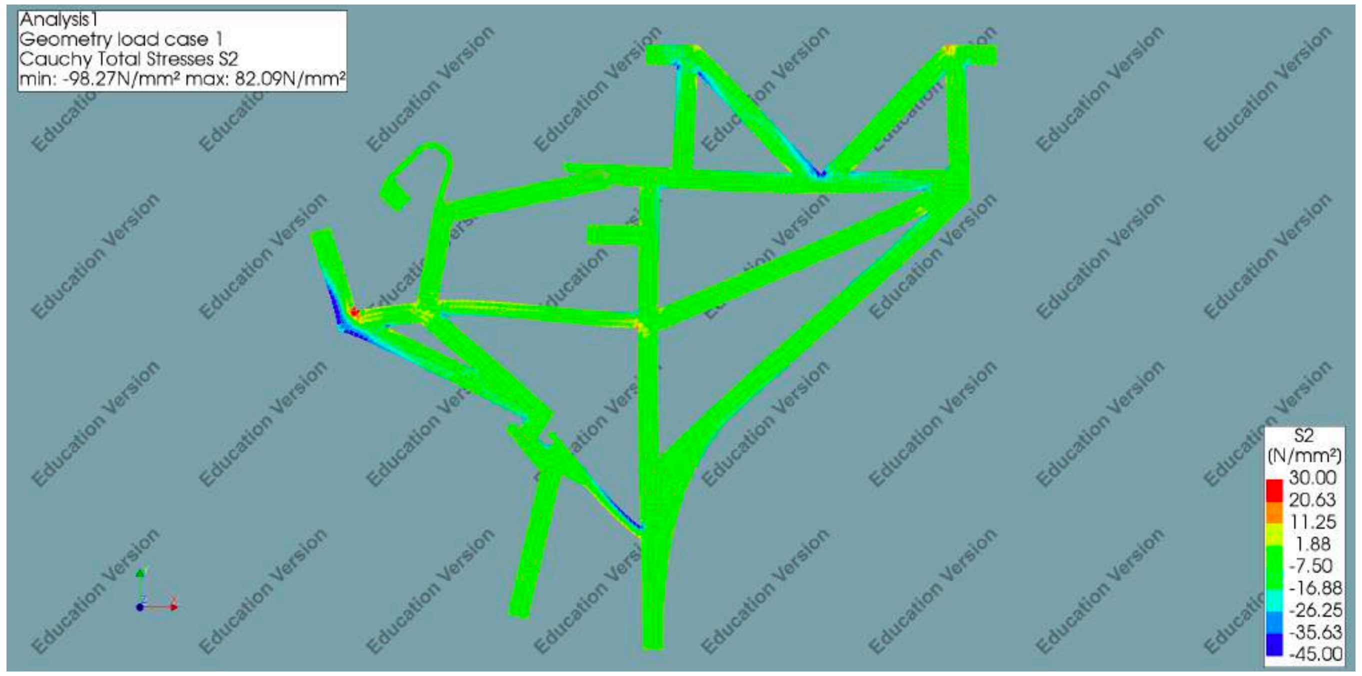


Figure 178: Compressive stresses 30mm depth

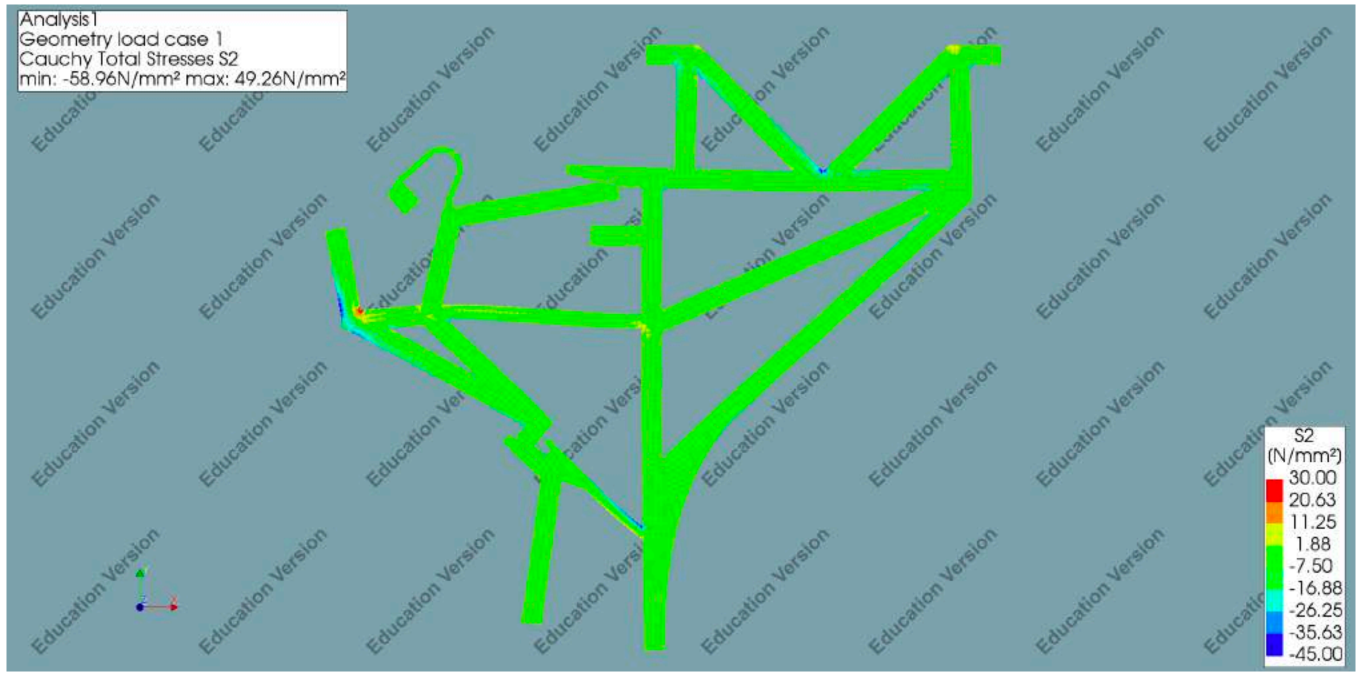


Figure 179: Compressive stresses 50mm depth

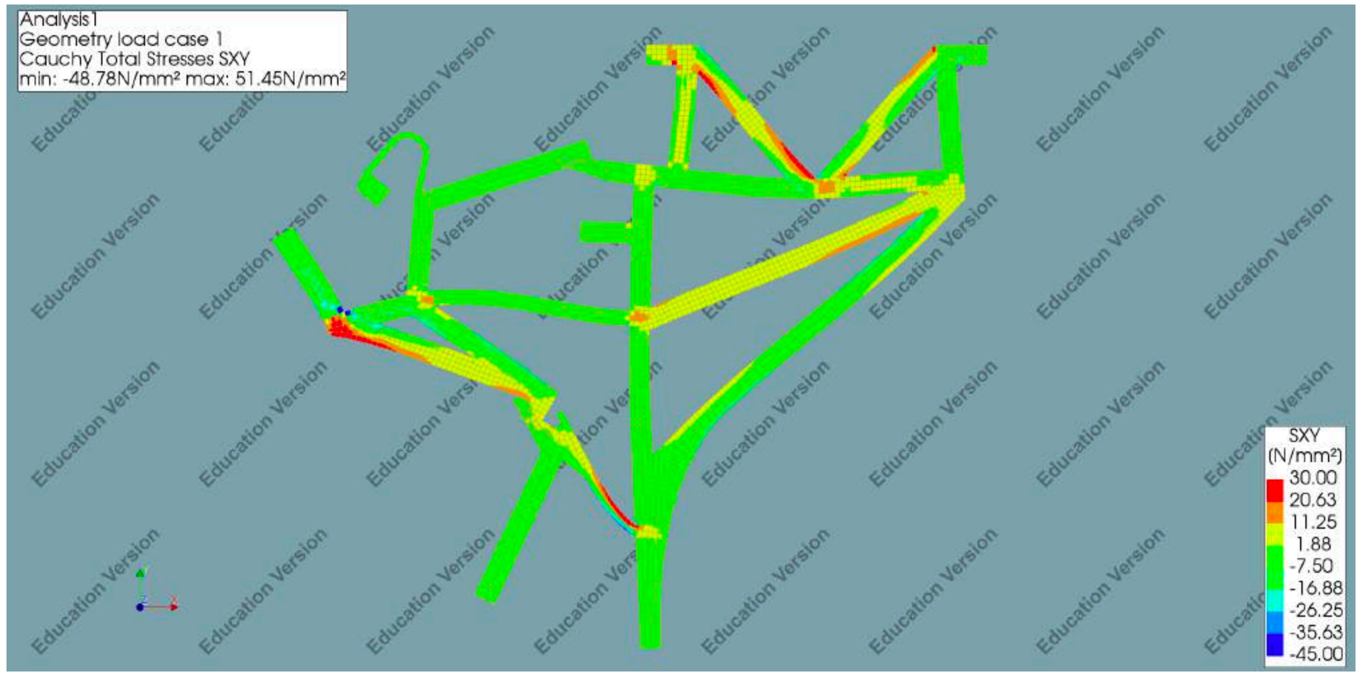


Figure 180: Shear stresses 15mm depth

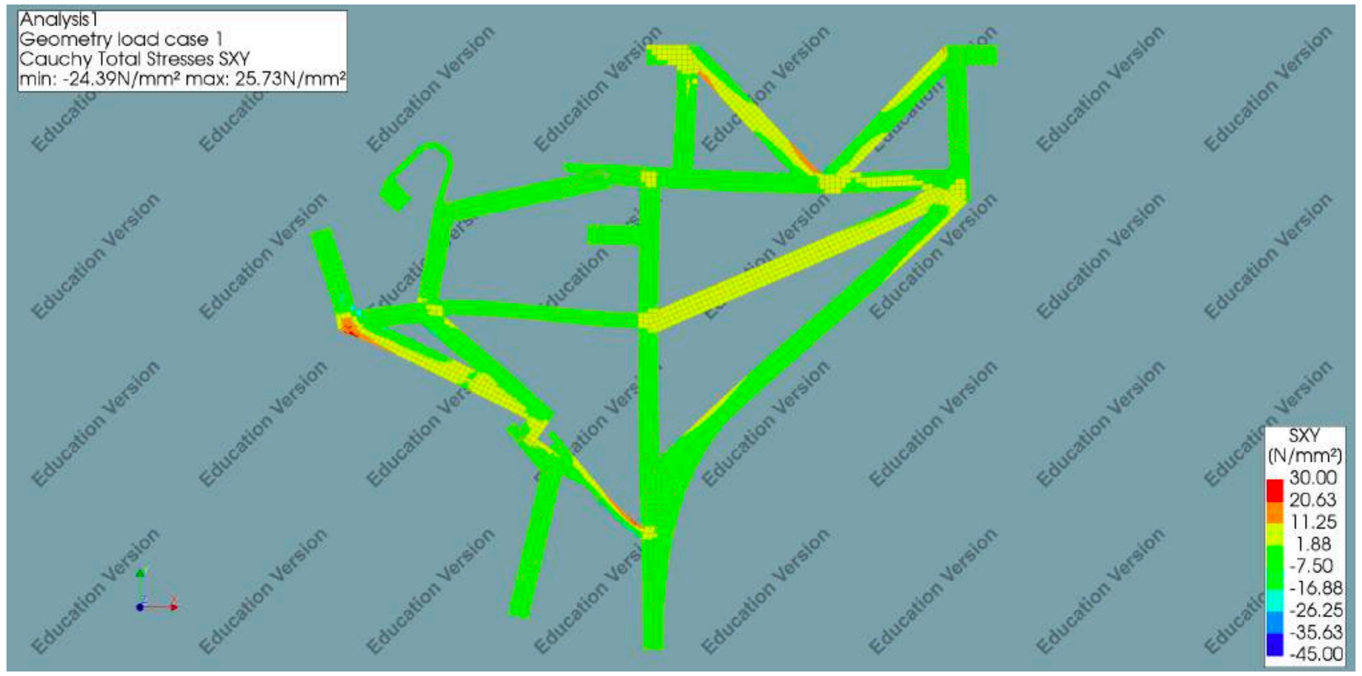


Figure 181: Shear stresses 30mm depth

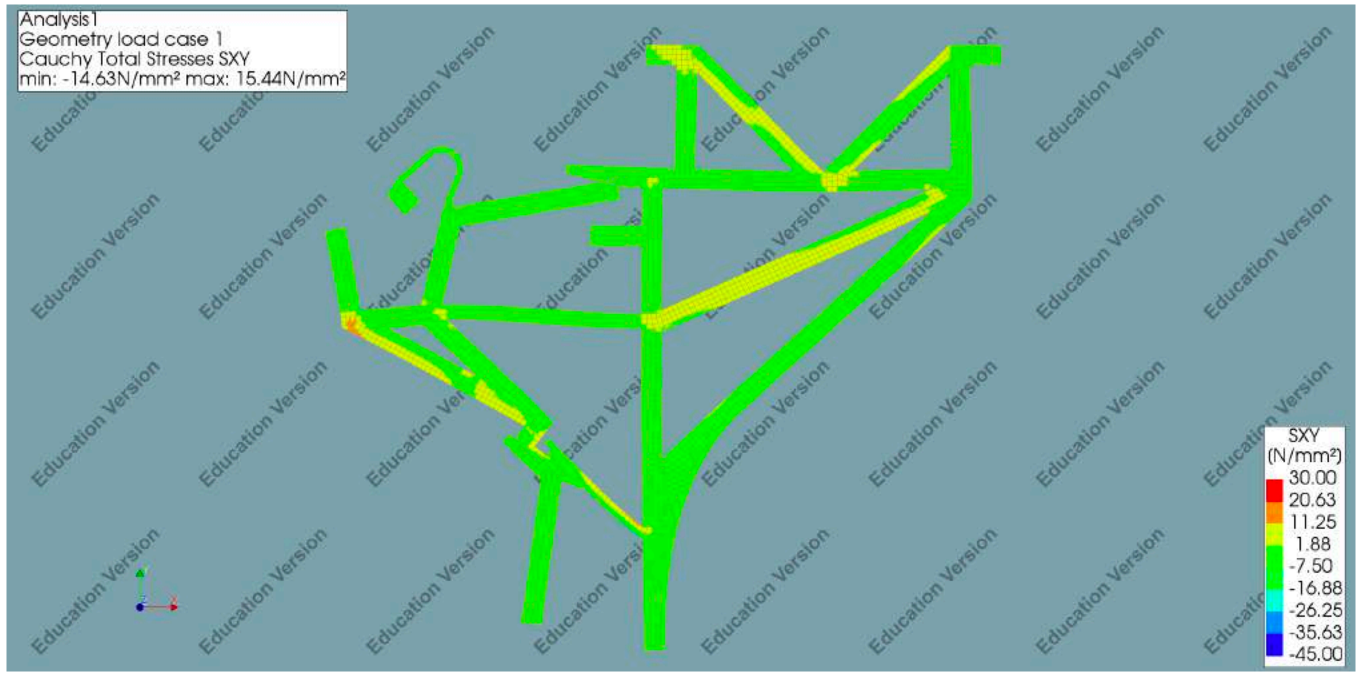
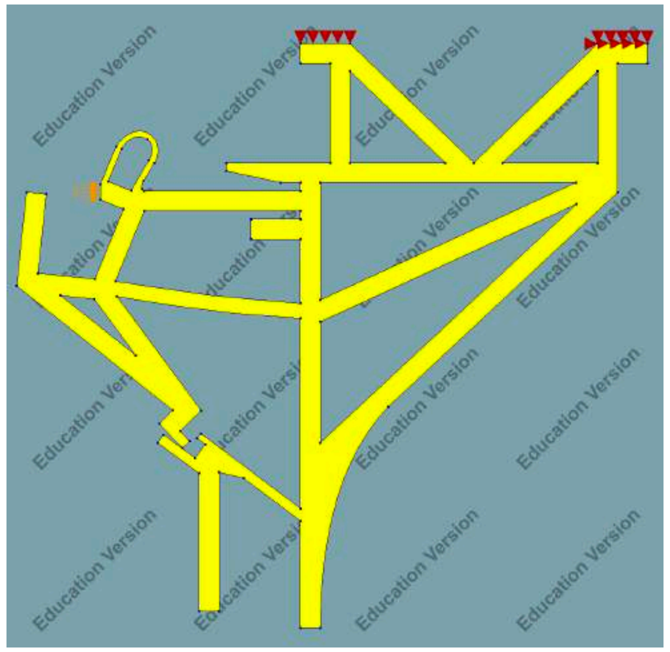


Figure 182: Shear stresses 50mm depth

Results compressive analysis



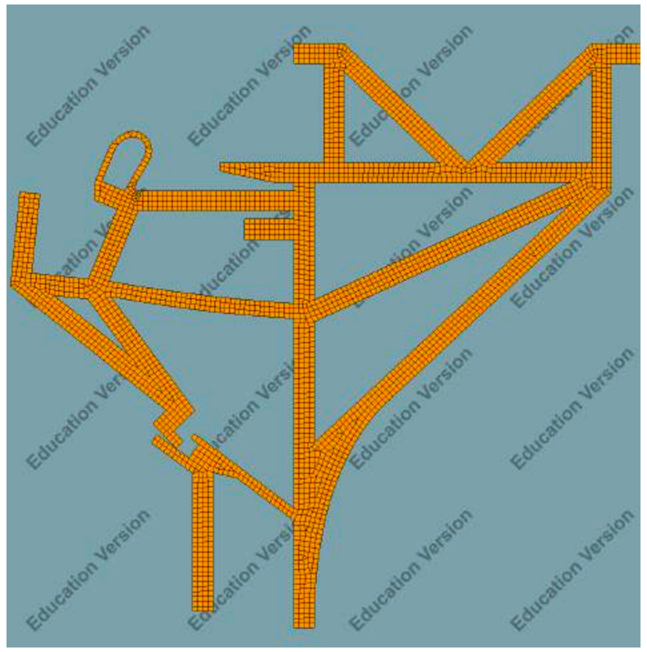


Figure 183: Geometry

Figure 184: Mesh geometry

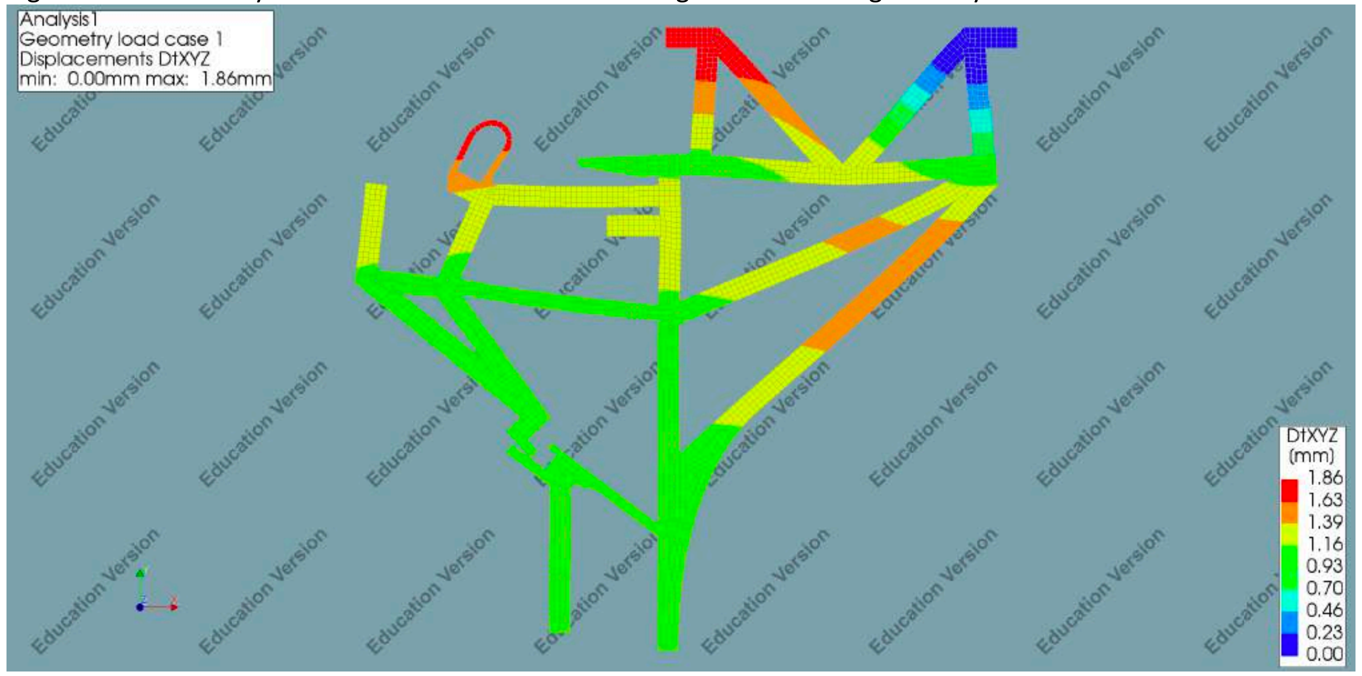


Figure 185: Displacement 15mm depth

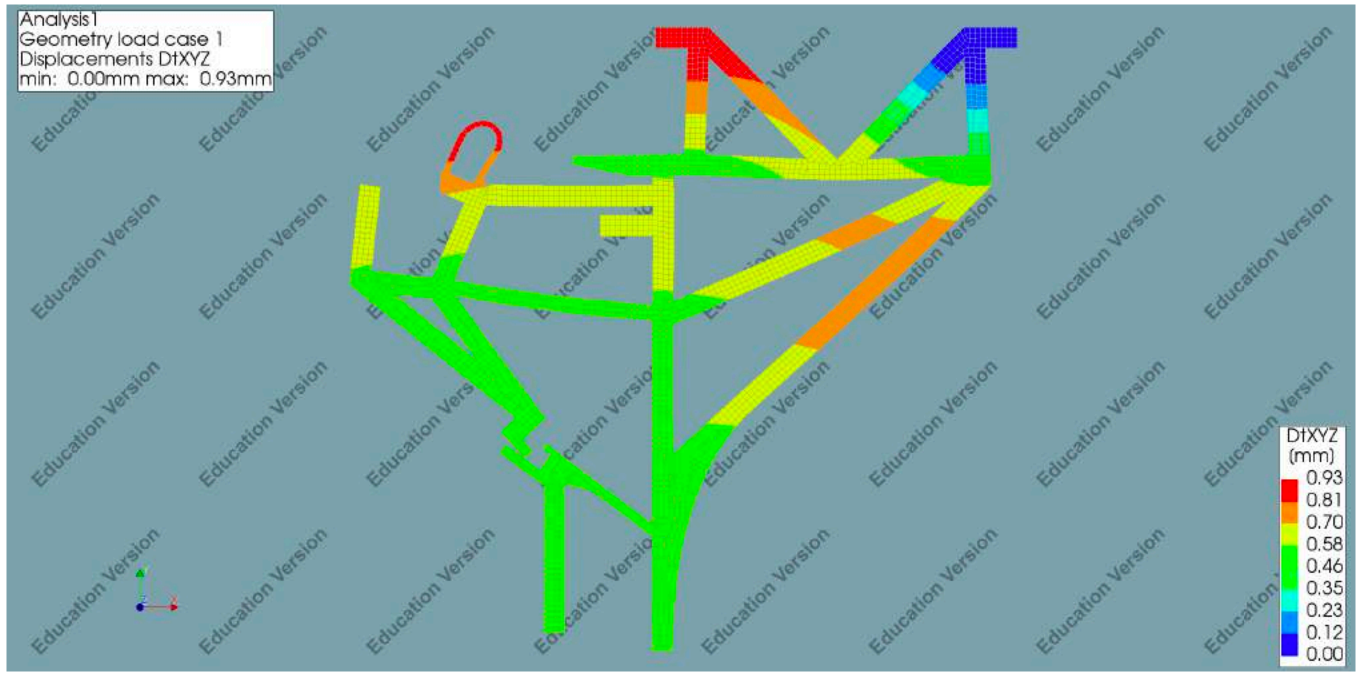


Figure 186: Displacement 30mm depth

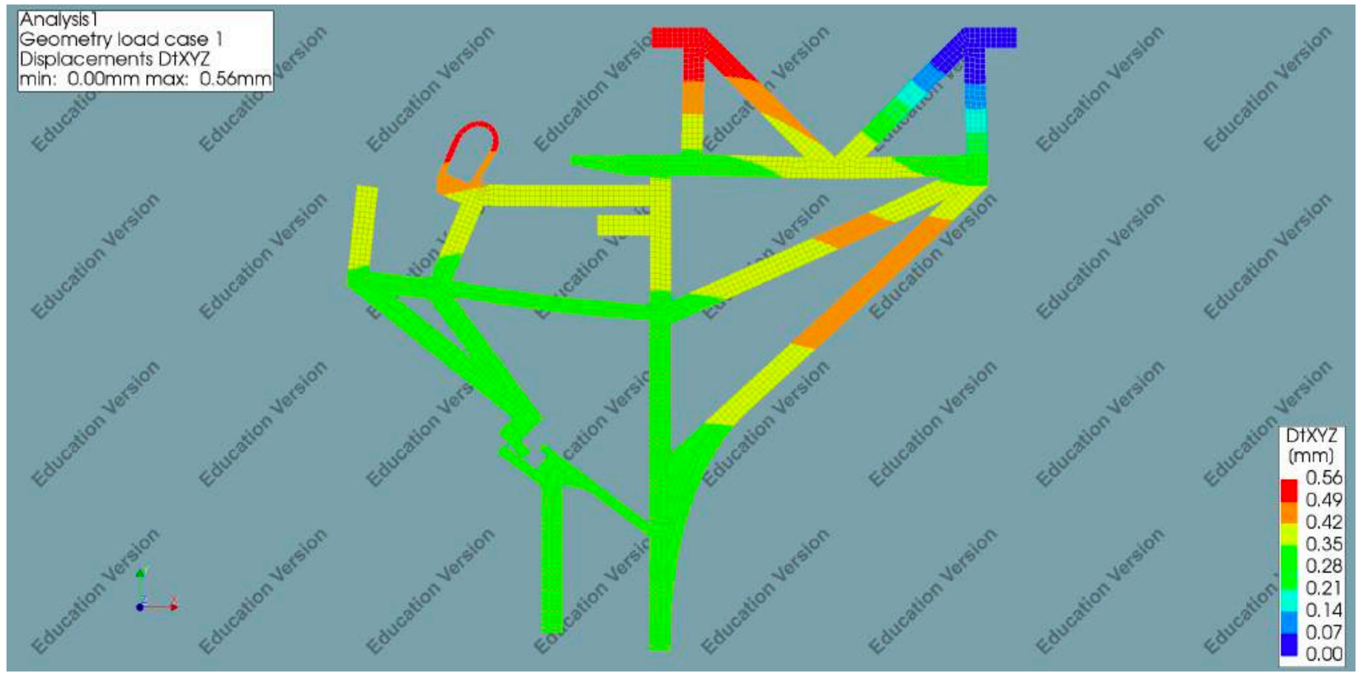


Figure 187: Displacement 50mm depth

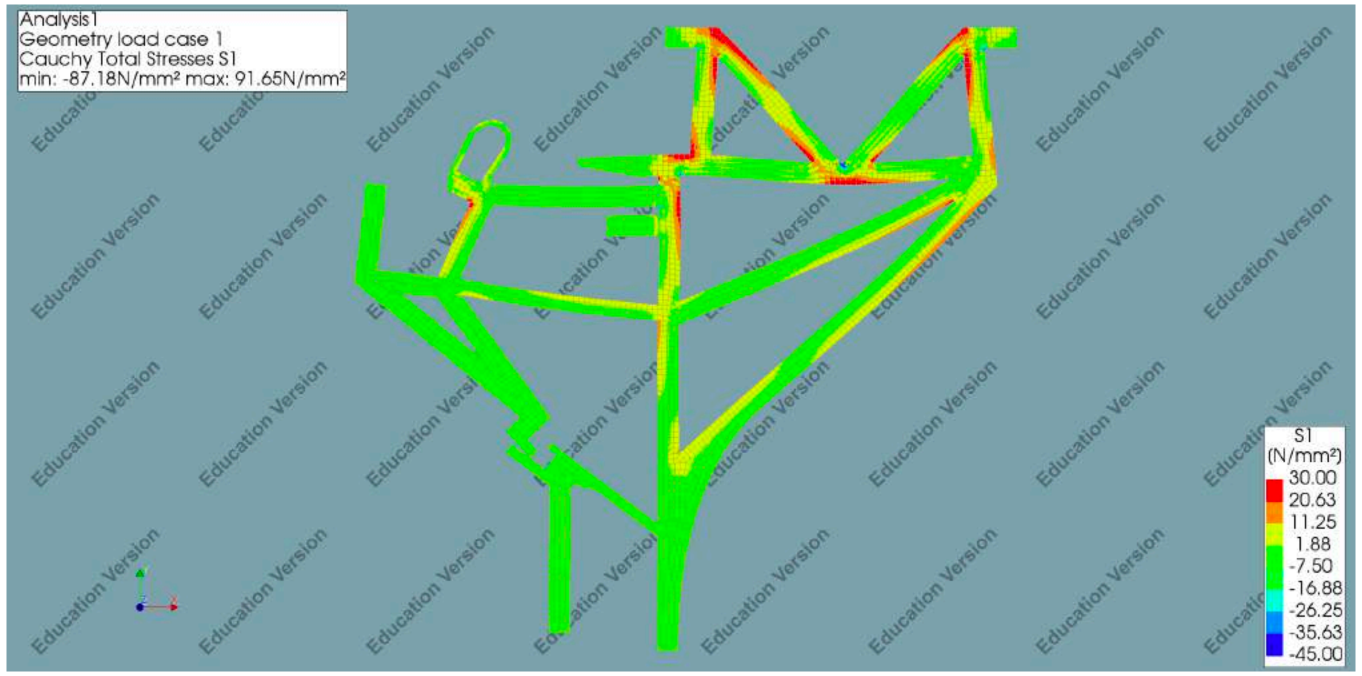


Figure 188: Tensile stresses 15mm depth

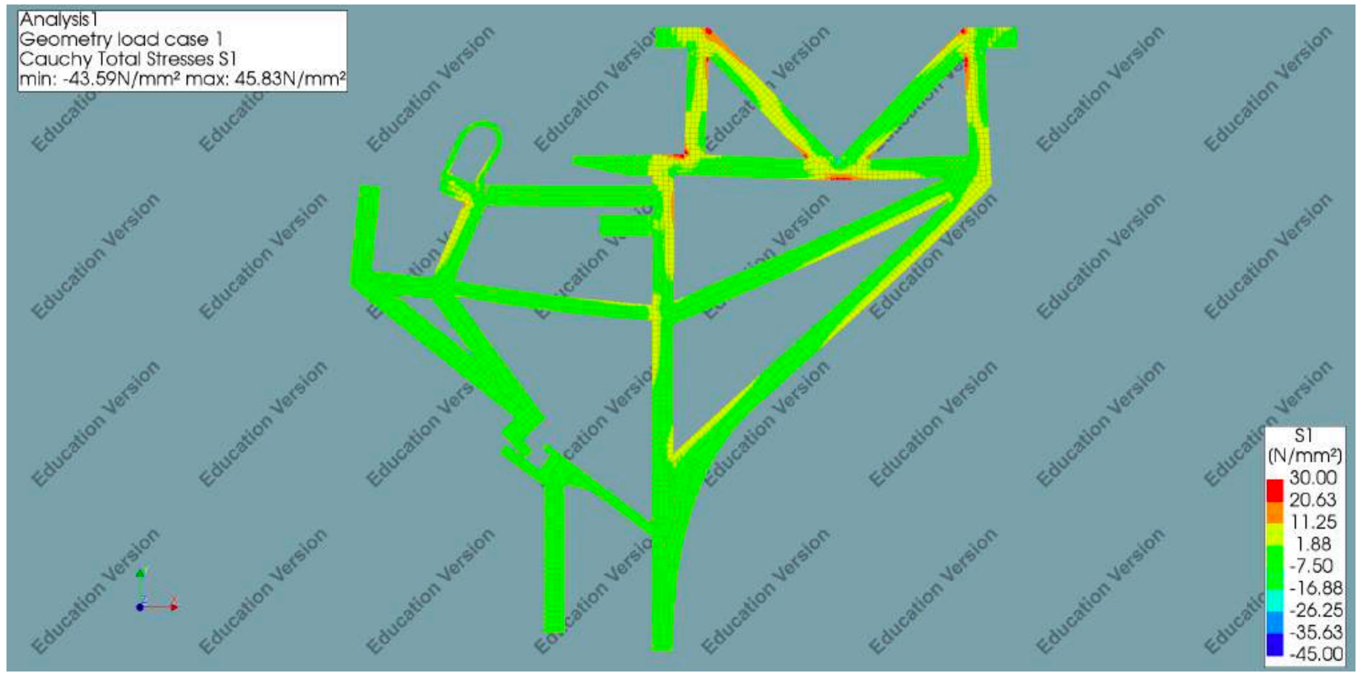


Figure 189: Tensile stresses 30mm depth

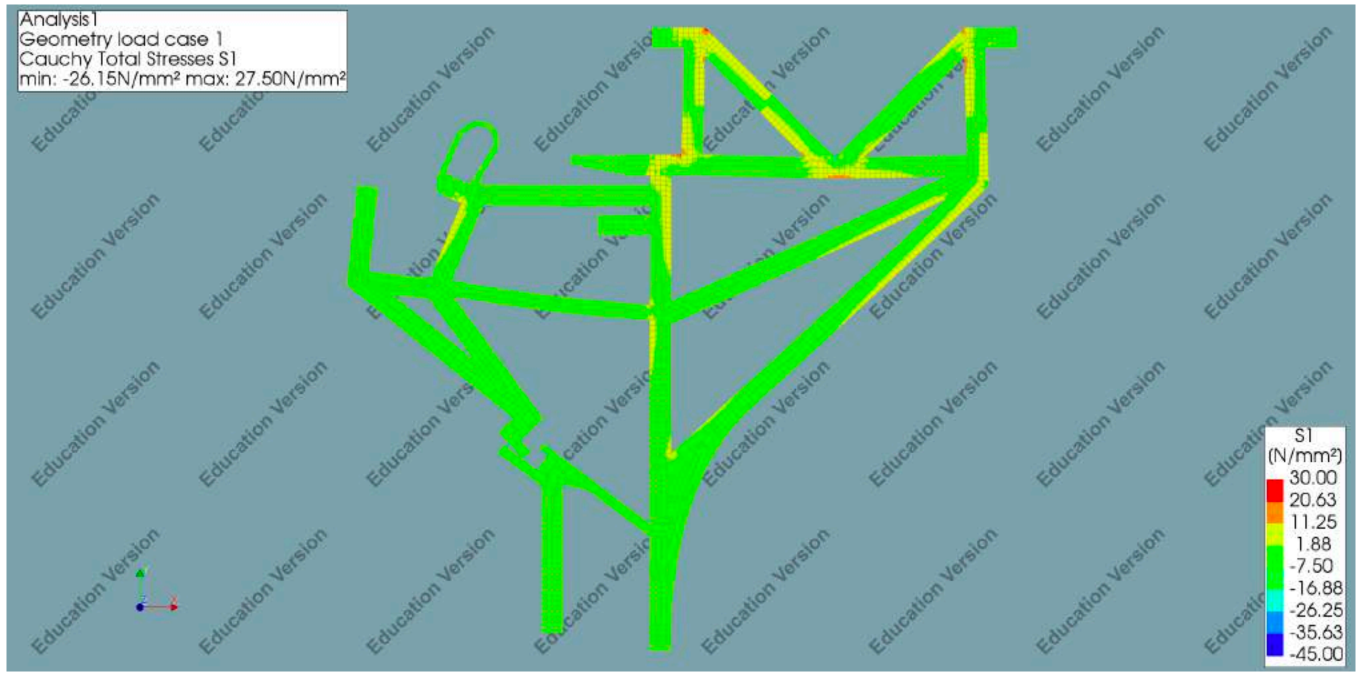


Figure 190: Tensile stresses 50mm depth

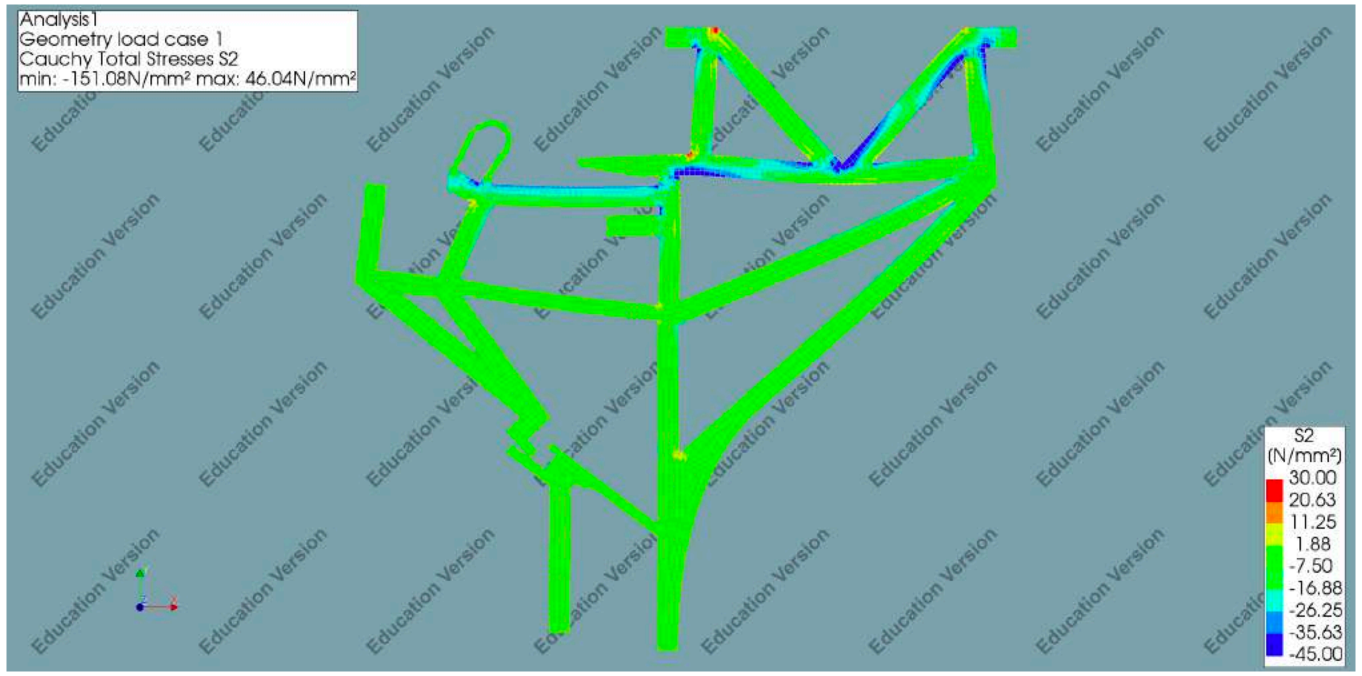


Figure 191: Compressive stresses 15mm depth

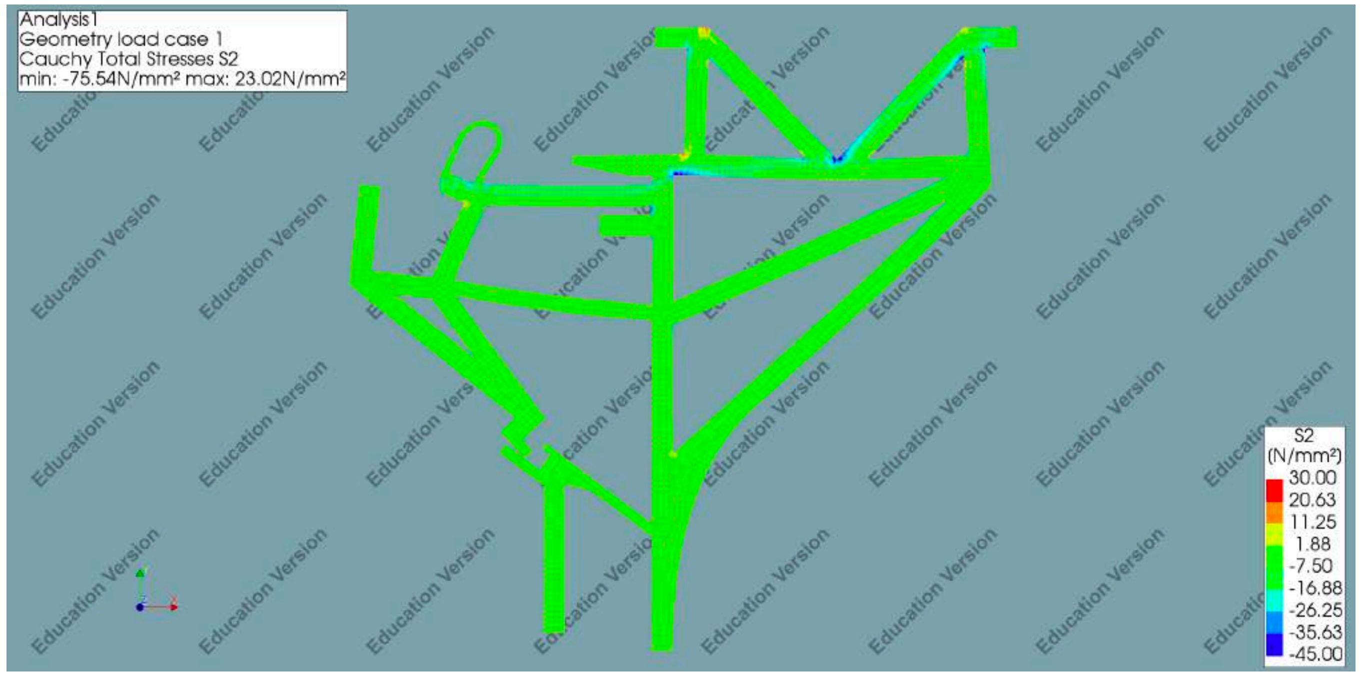


Figure 192: Compressive stresses 30mm depth

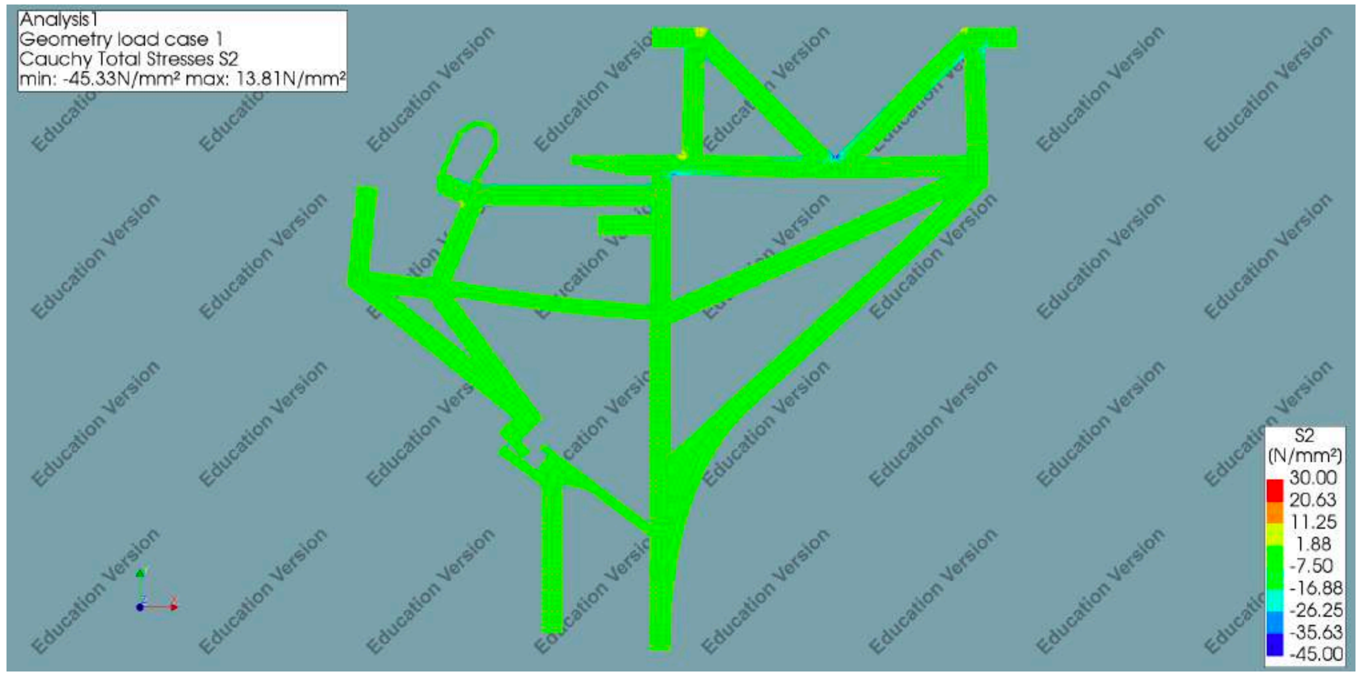


Figure 193: Compressive stresses 50mm depth

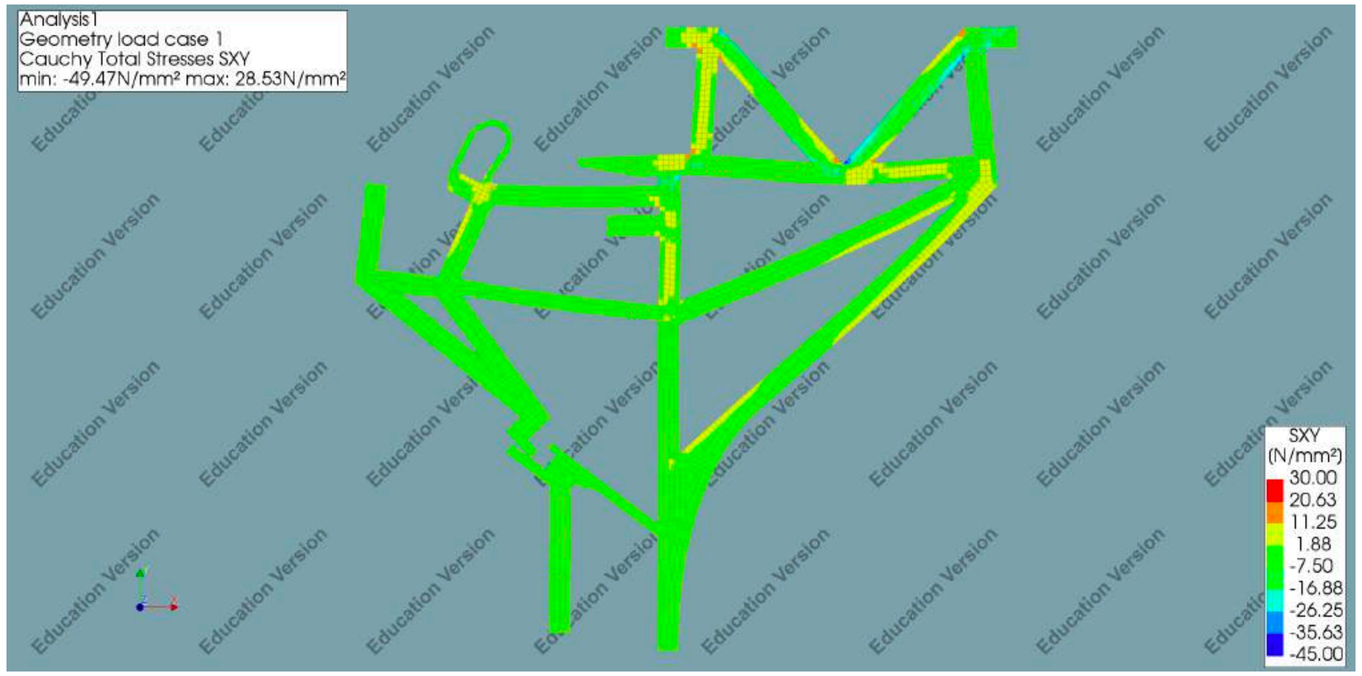


Figure 194: shear stresses 15mm depth

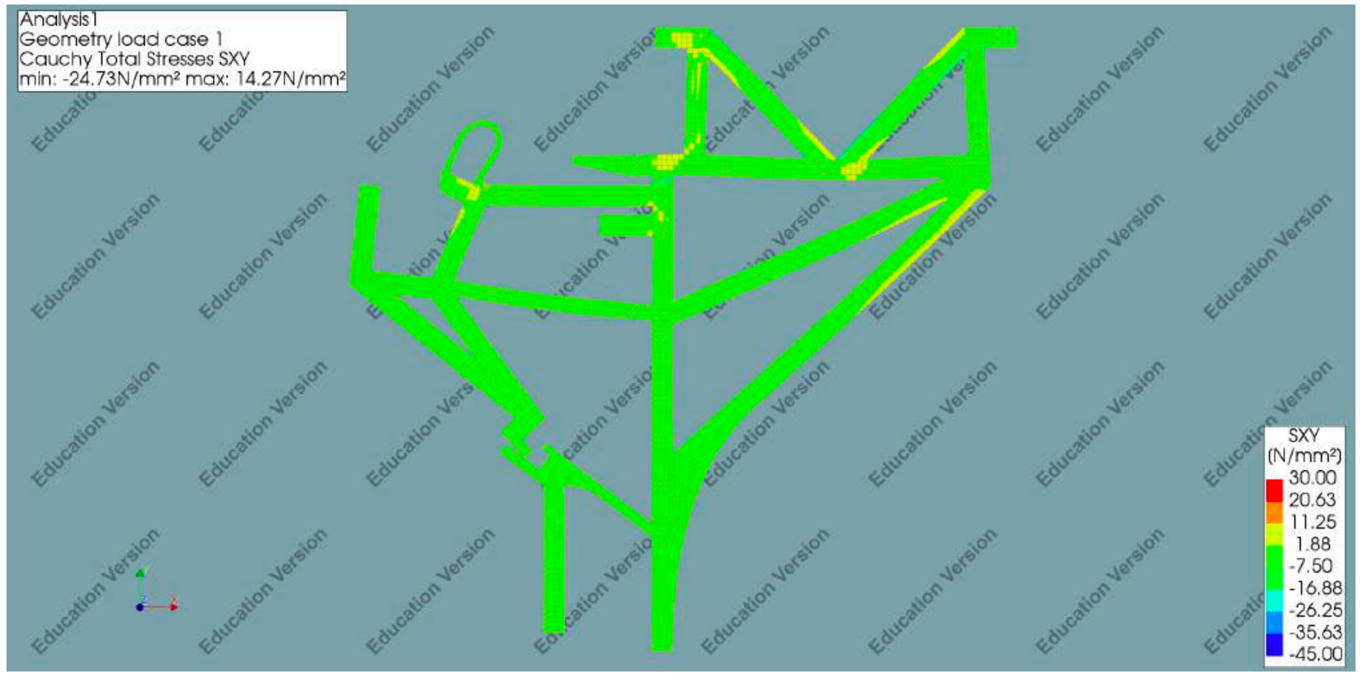


Figure 195: shear stresses 30mm depth

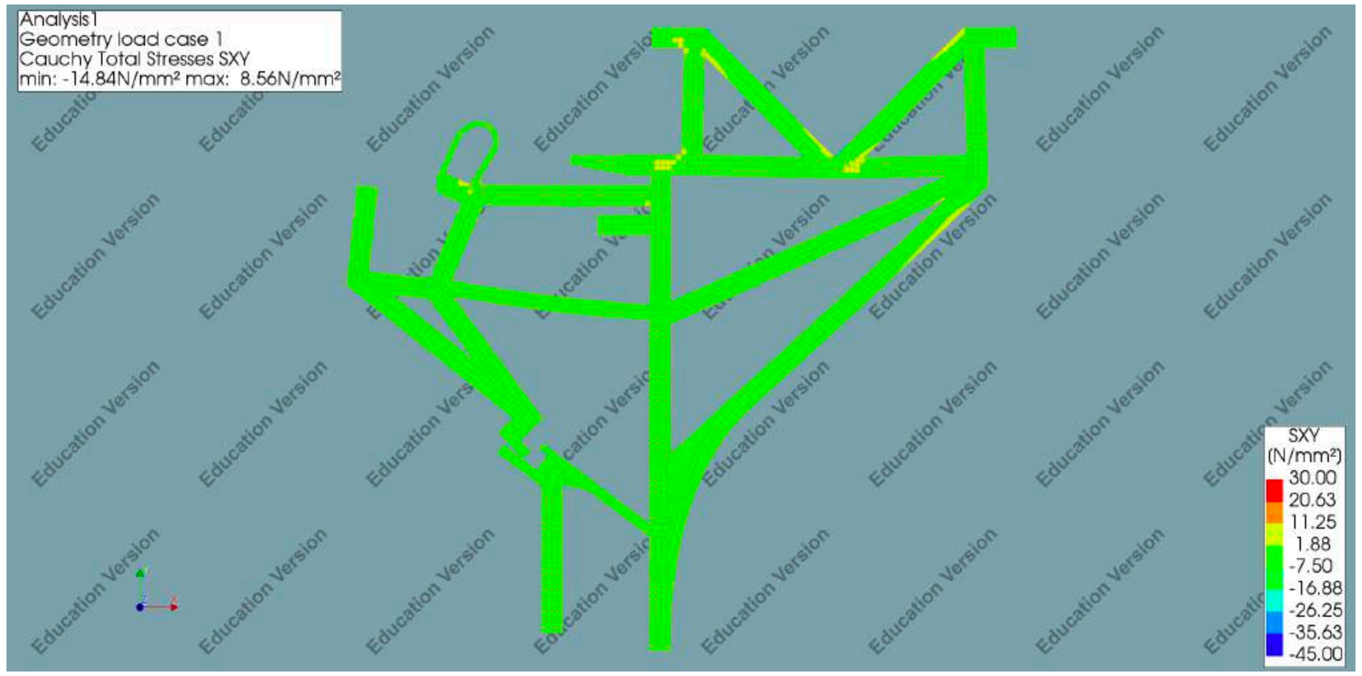


Figure 196: shear stresses 50mm depth

Analysis 8: Iteration 7

<u>Results tensile analysis</u>

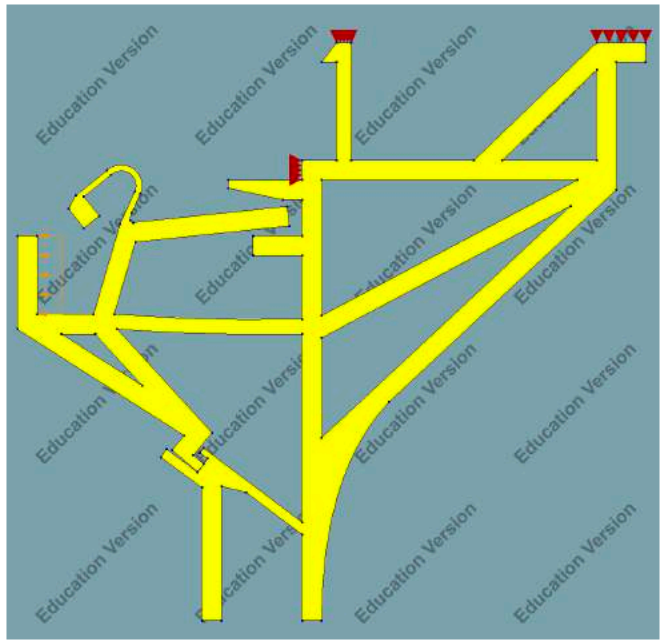


Figure 197: Geometry

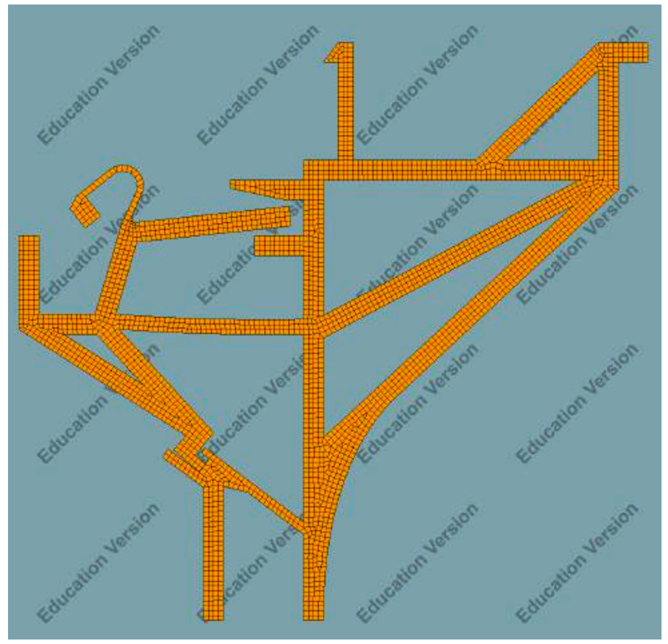


Figure 198: Mesh geometry

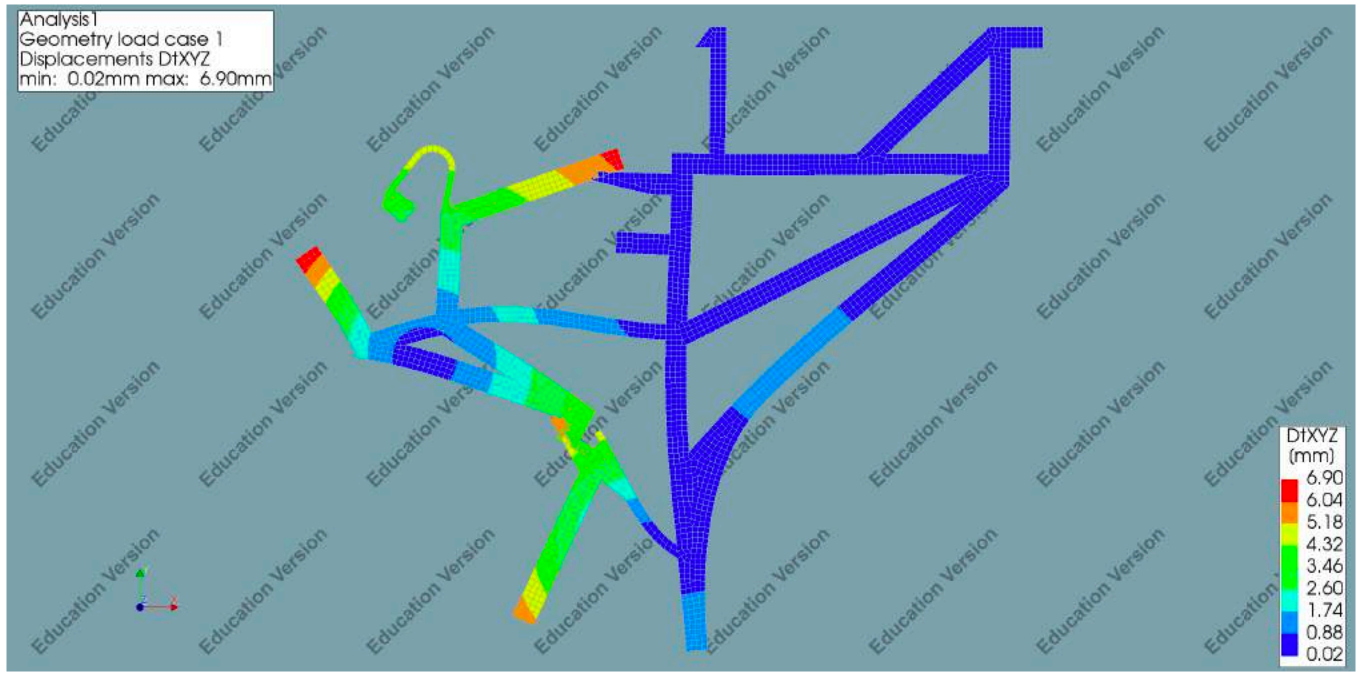


Figure 199: Displacement 15mm depth

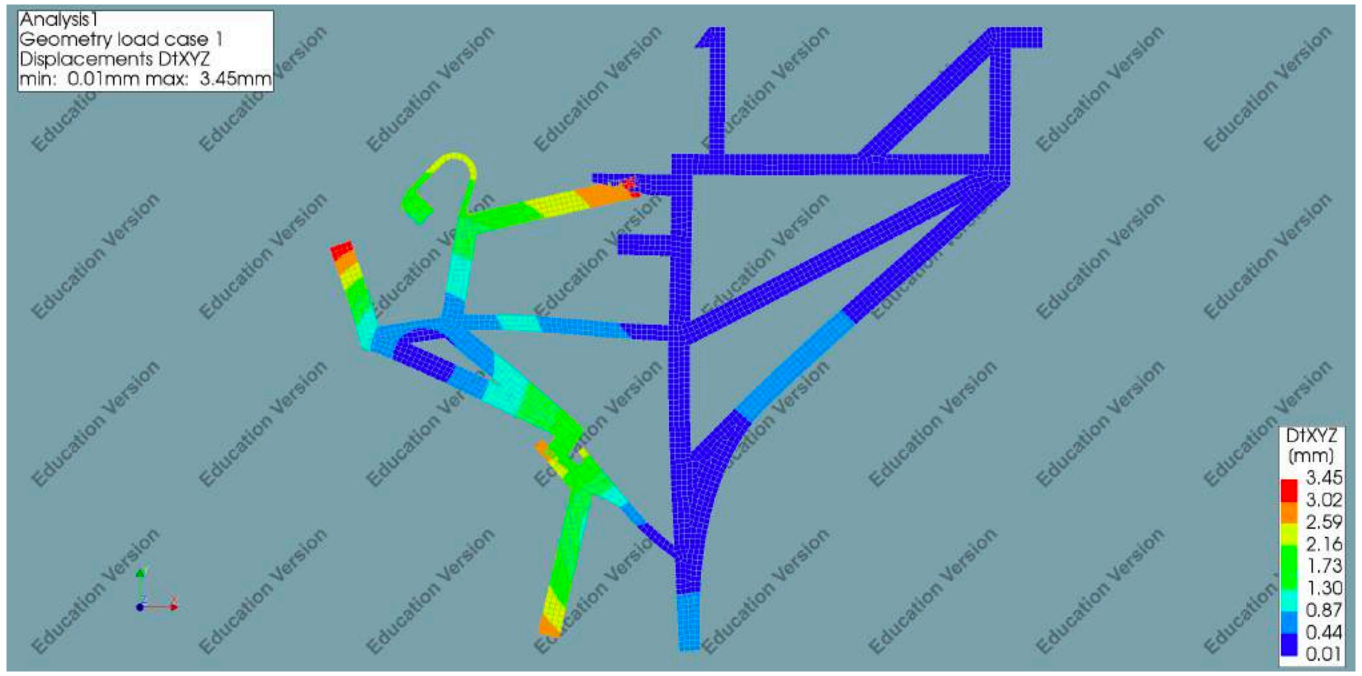


Figure 200: Displacement 30mm depth

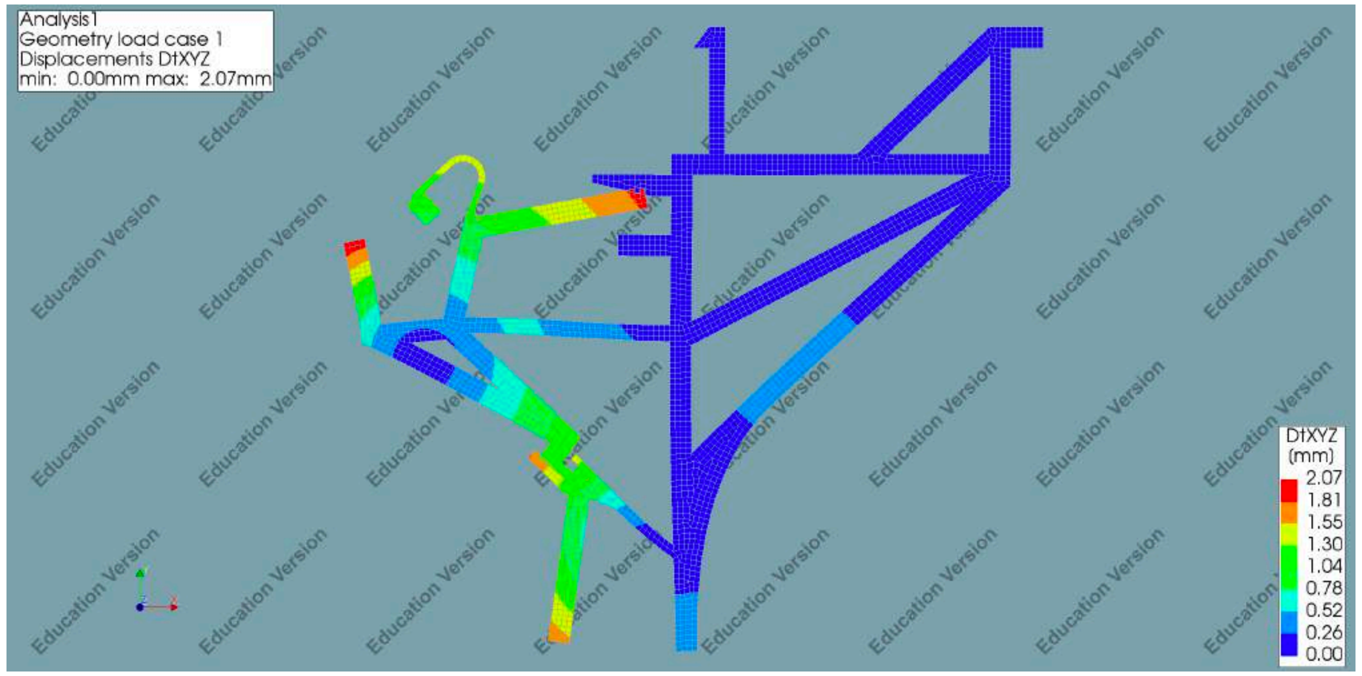


Figure 201: 50mm depth

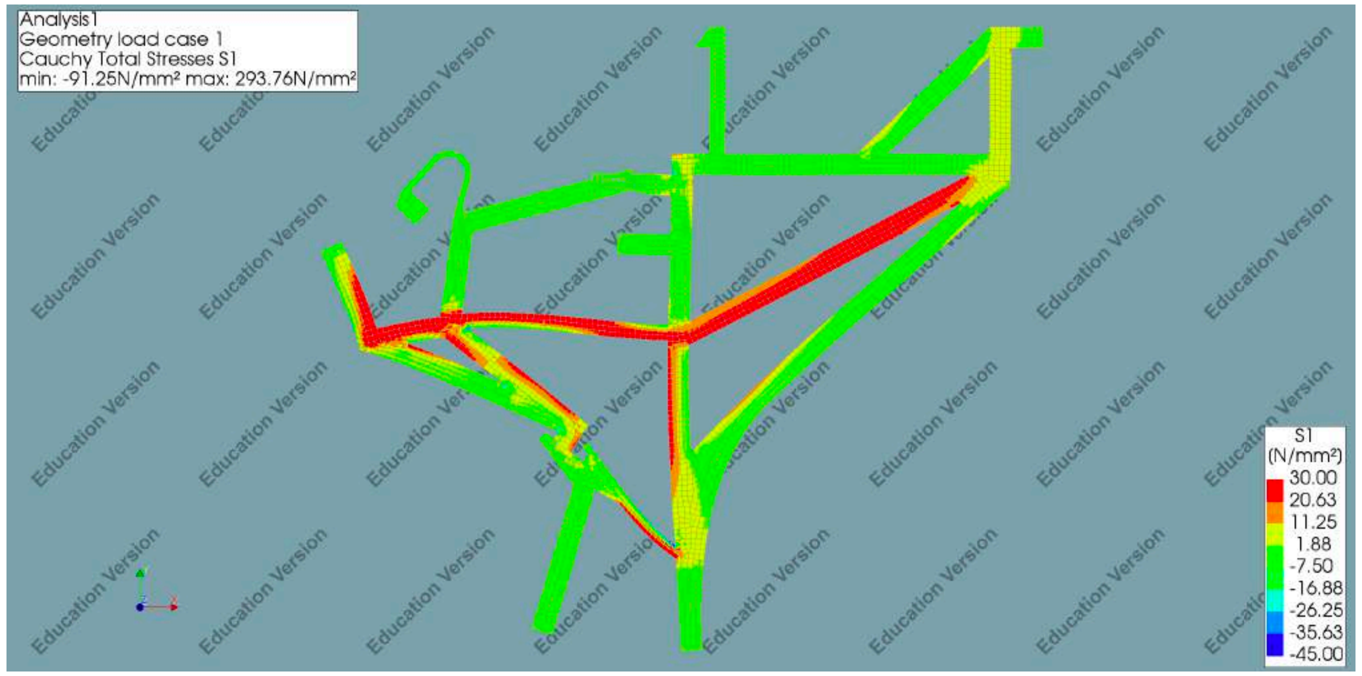


Figure 202: Tensile stresses 15mm depth

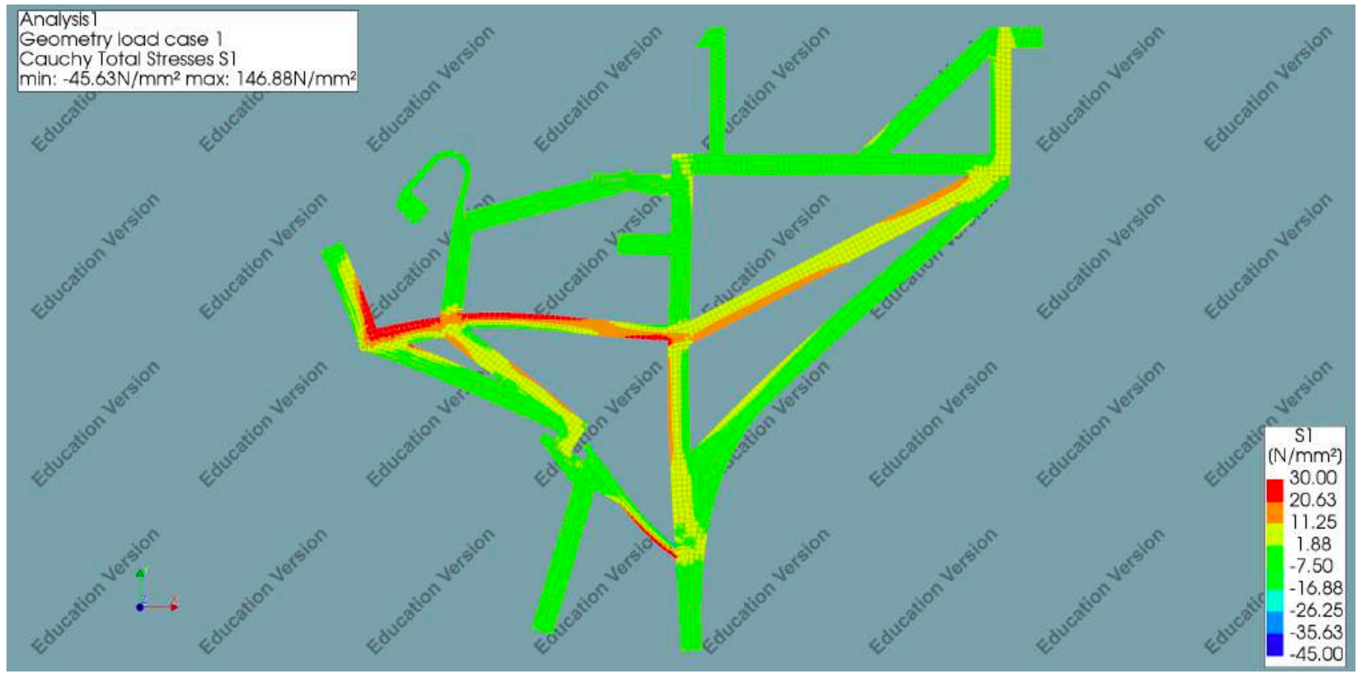


Figure 203: Tensile stresses 30mm depth

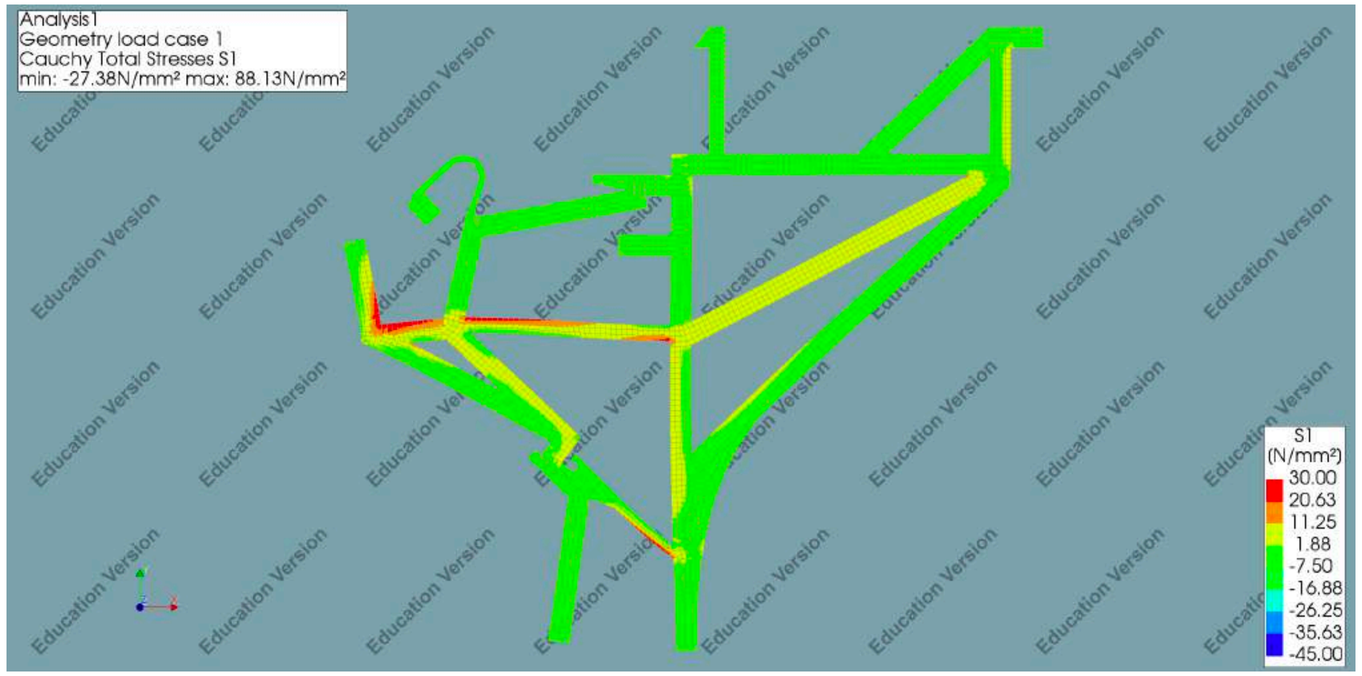


Figure 204: Tensile stresses 50mm depth

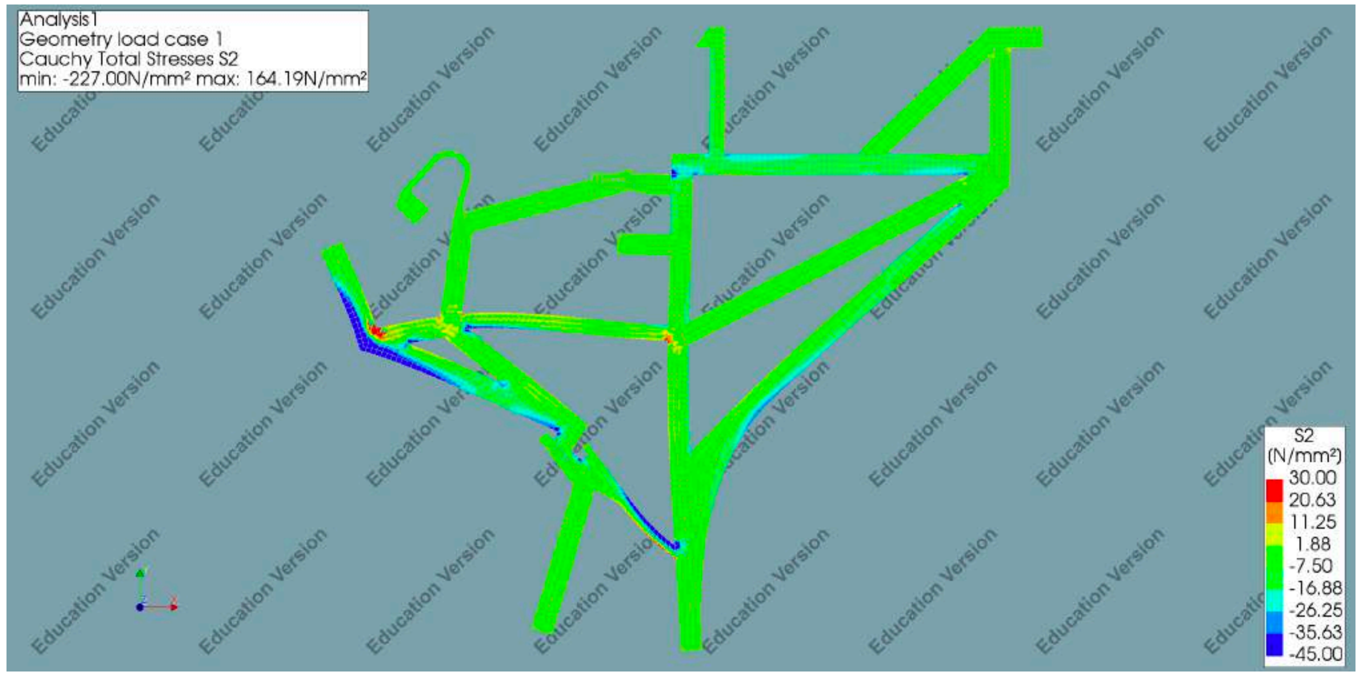


Figure 205: Compressive stresses 15mm depth

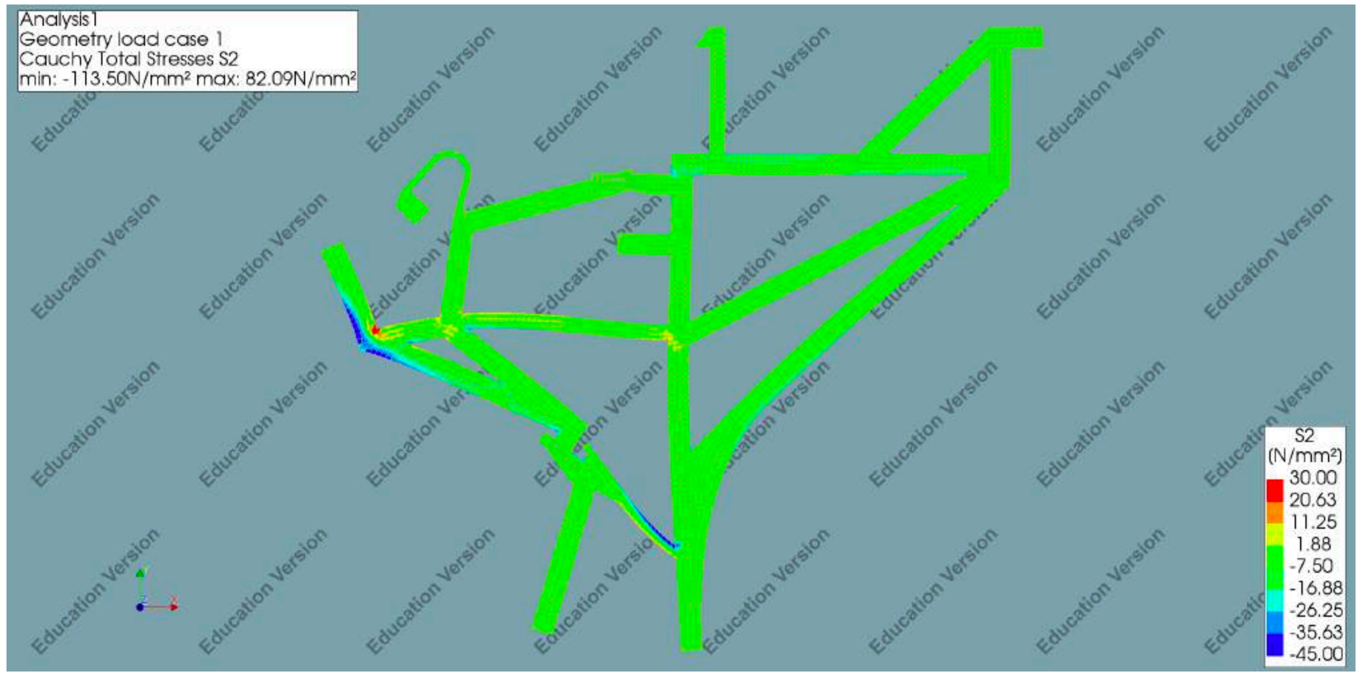


Figure 206: Compressive stresses 30mm depth

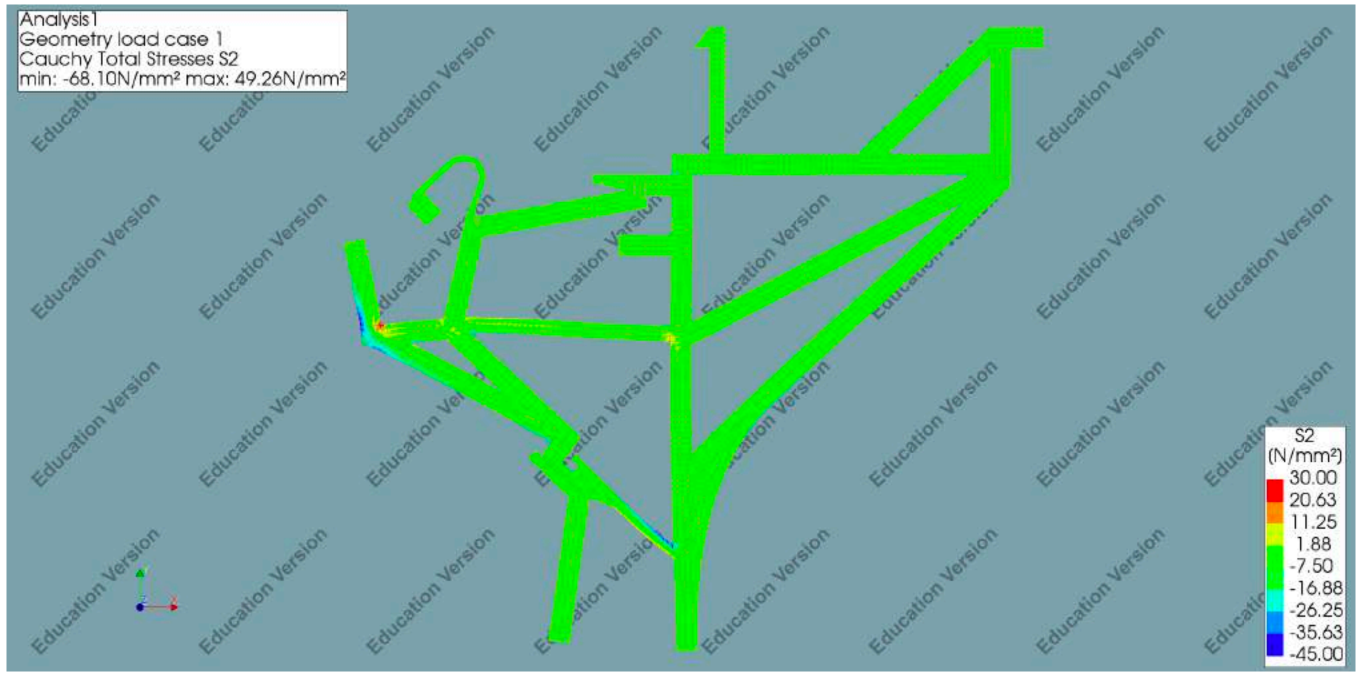


Figure 207: Compressive stresses 50mm depth

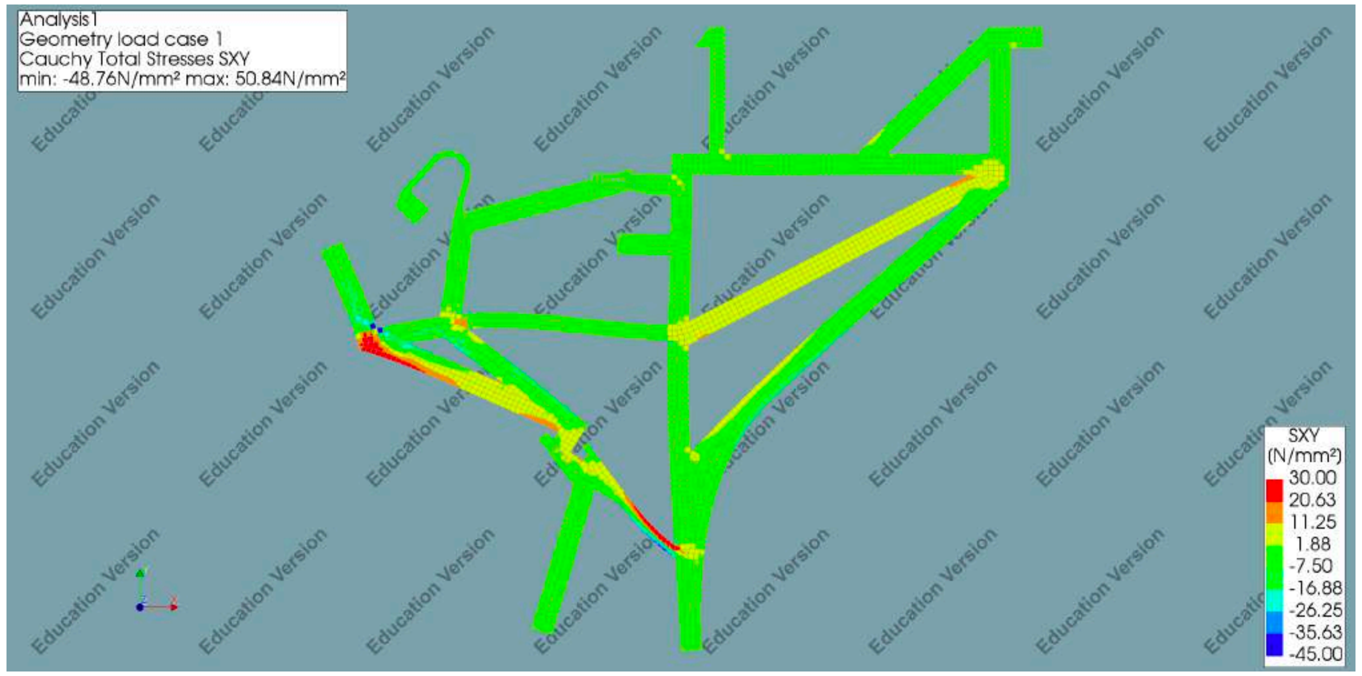


Figure 208: Shear stresses 15mm depth

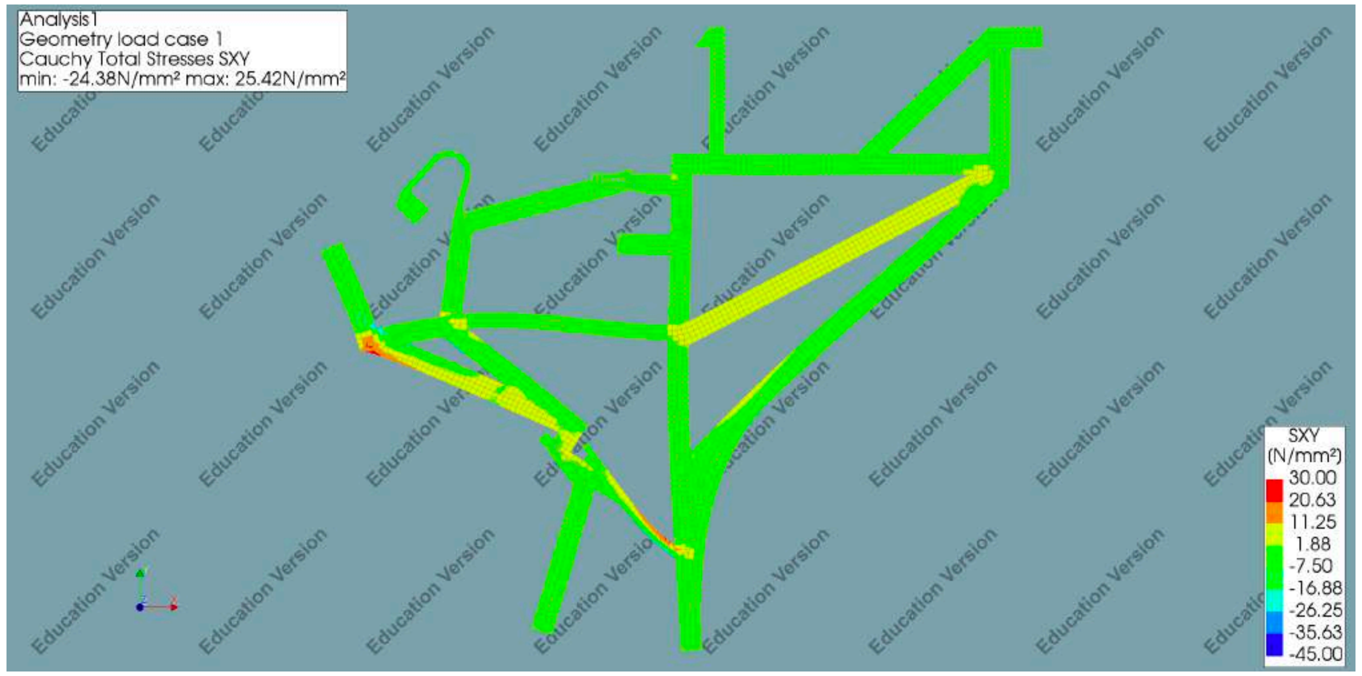


Figure 209: Shear stresses 30mm depth

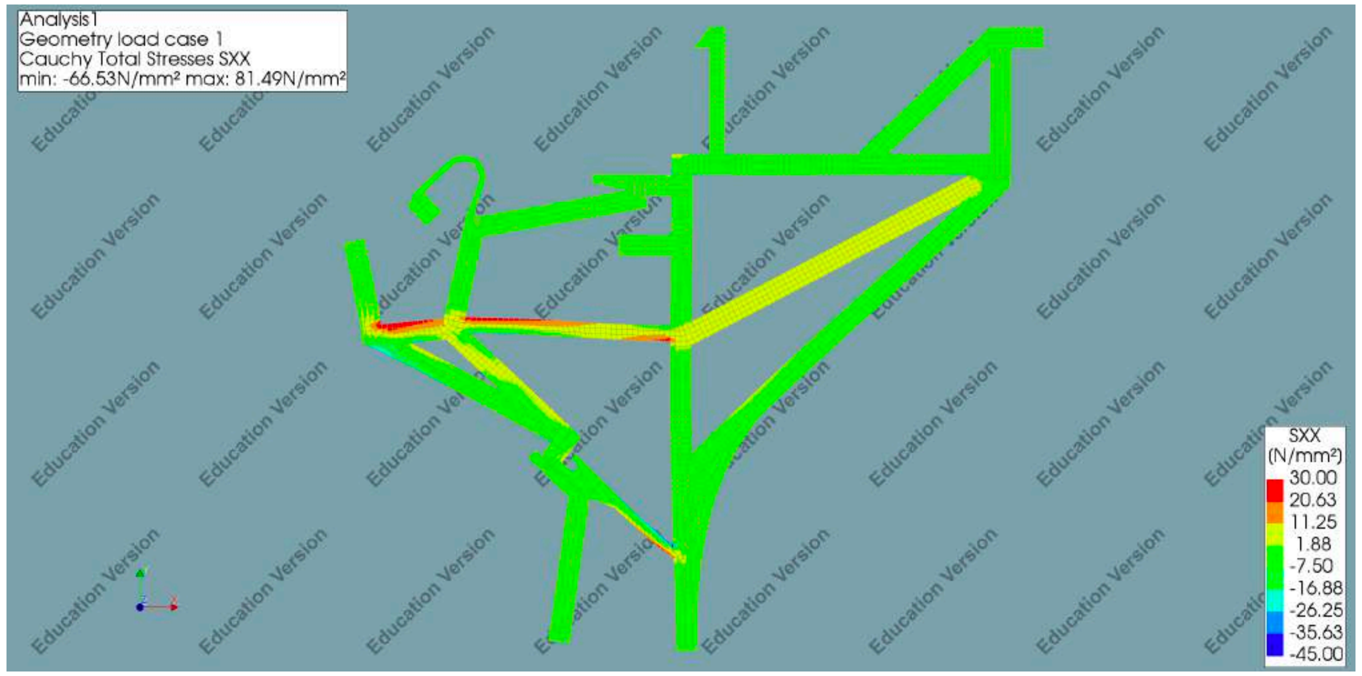


Figure 210: Shear stresses 50mm depth

<u>Results compressive analysis</u>

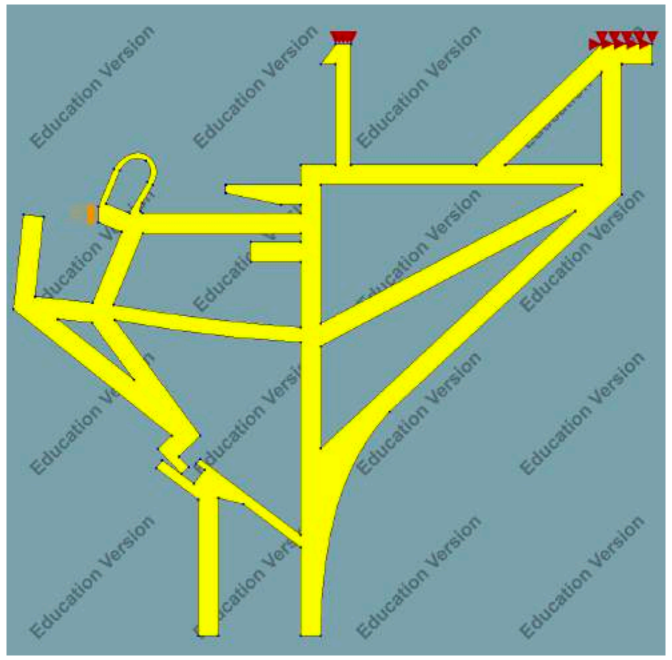


Figure 211: Geometry

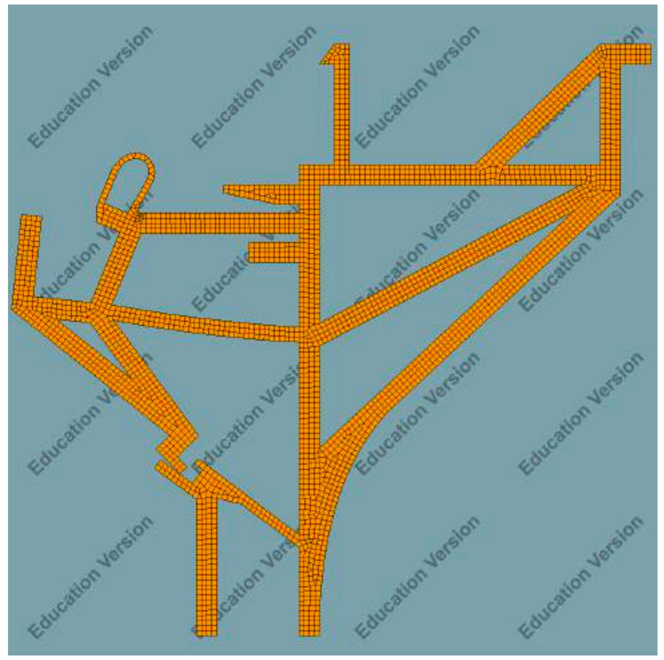


Figure 212: Mesh geometry

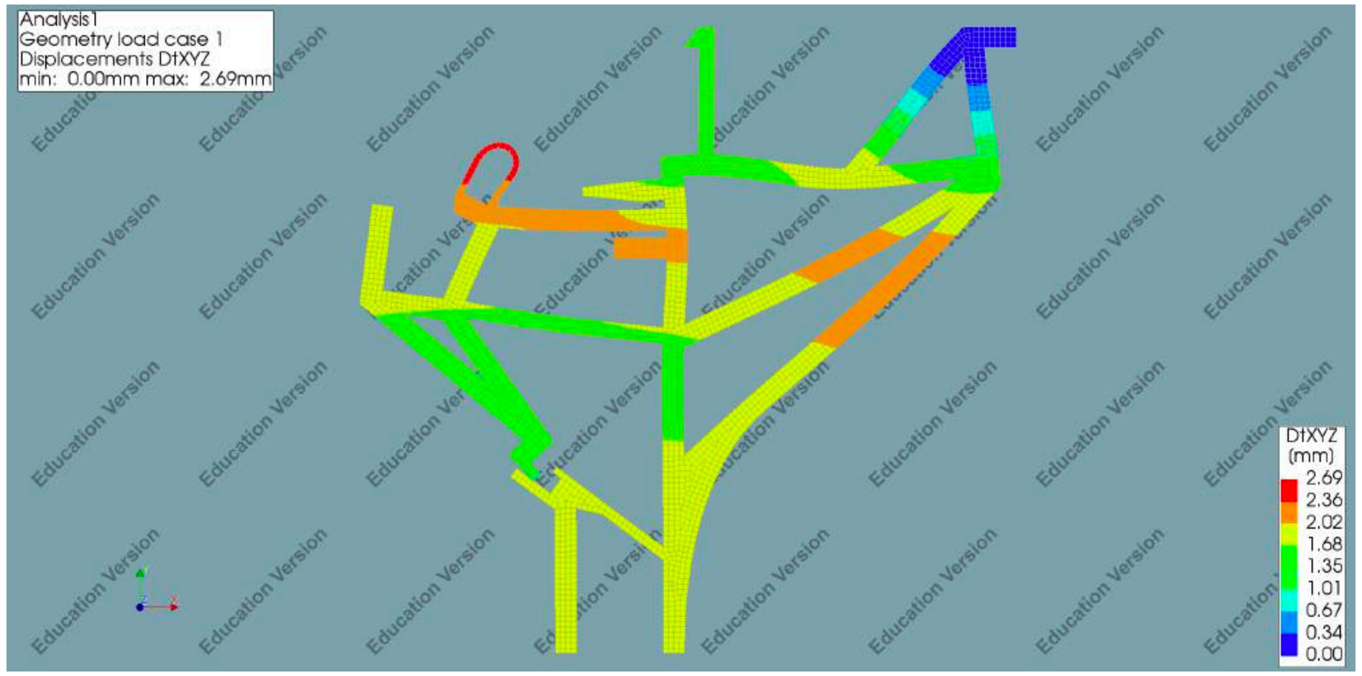


Figure 213: Displacement 15mm depth

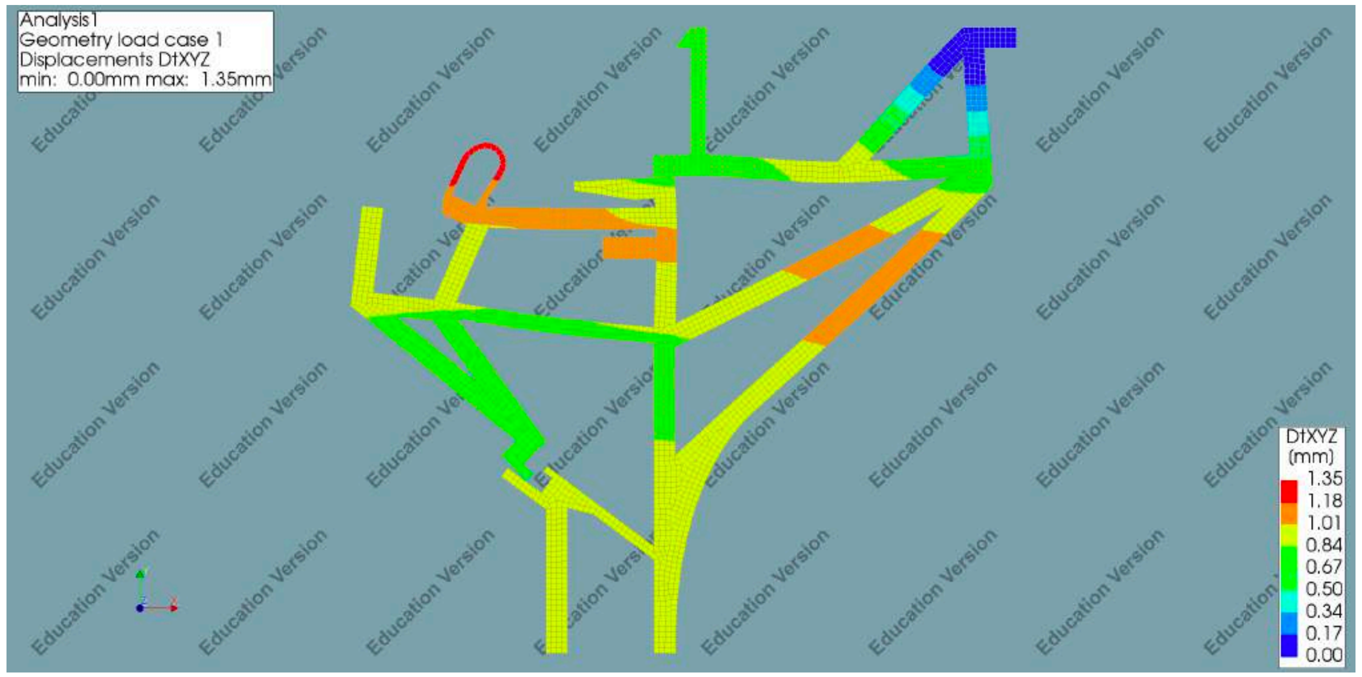


Figure 214: Displacement 30mm depth

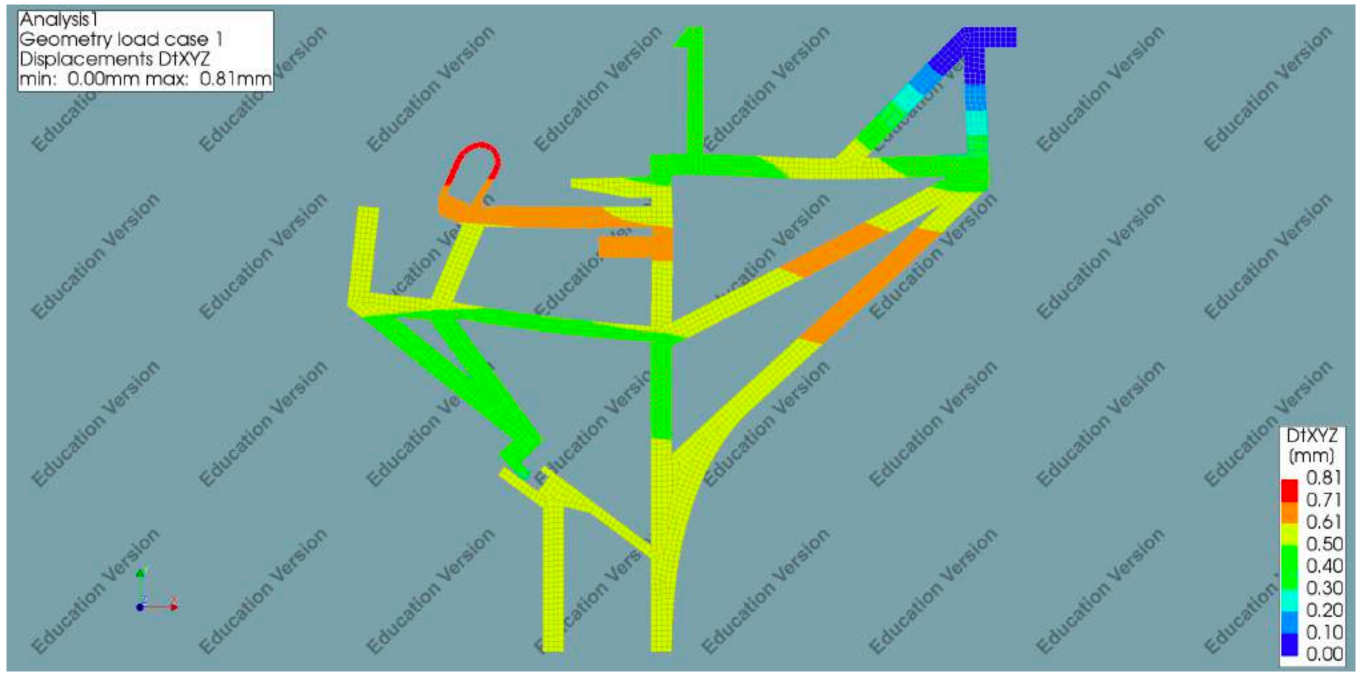


Figure 215: Displacement 50mm depth

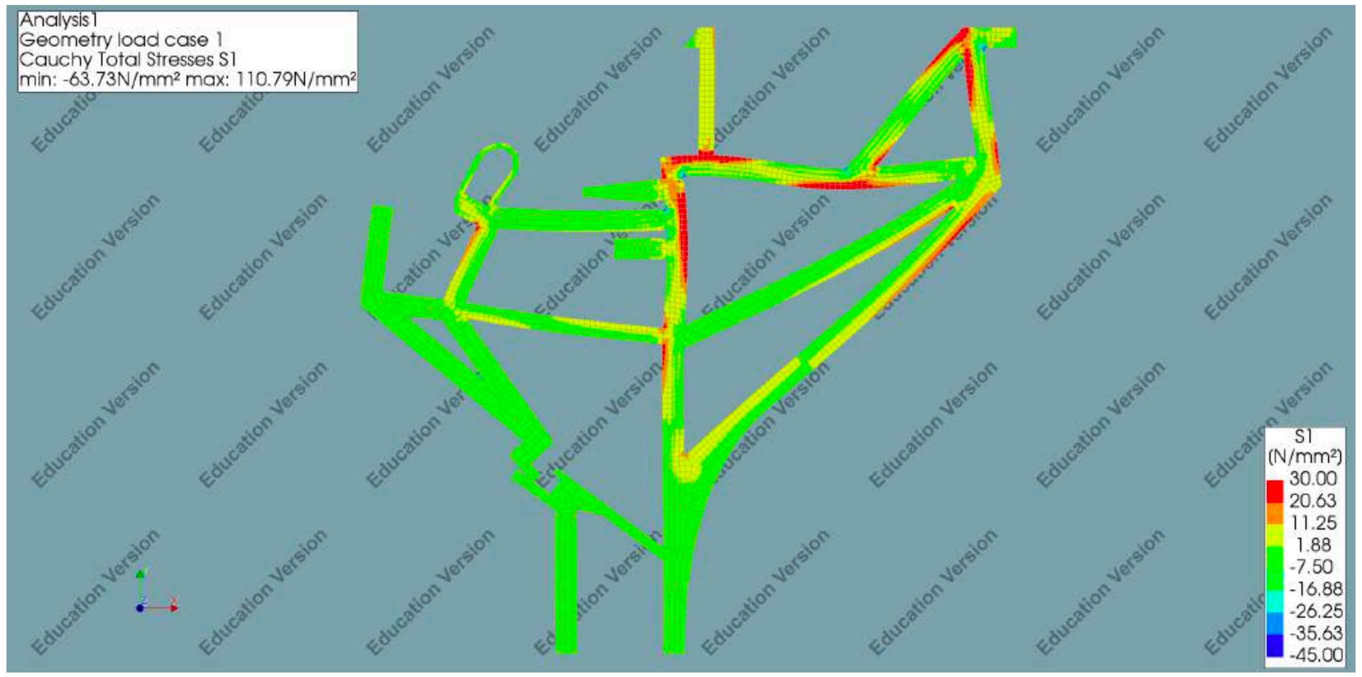


Figure 216: Tensile stresses 15mm depth

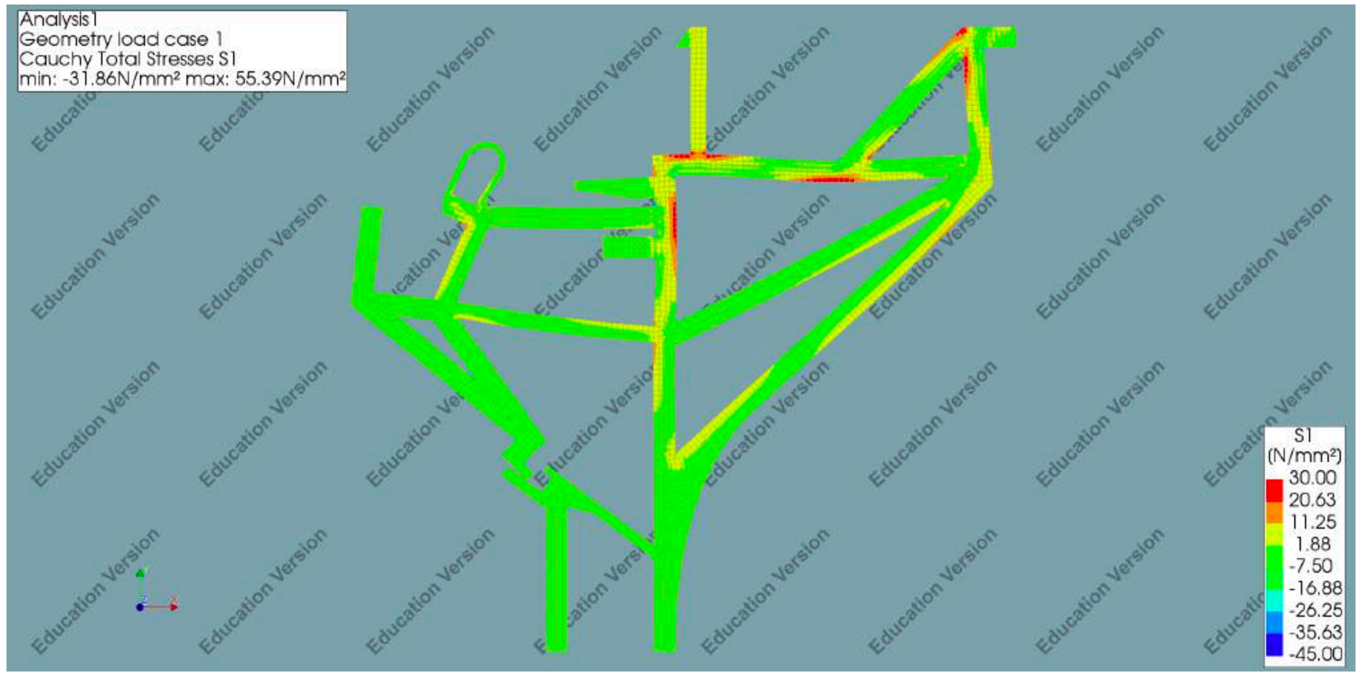


Figure 217: Tensile stresses 30mm depth

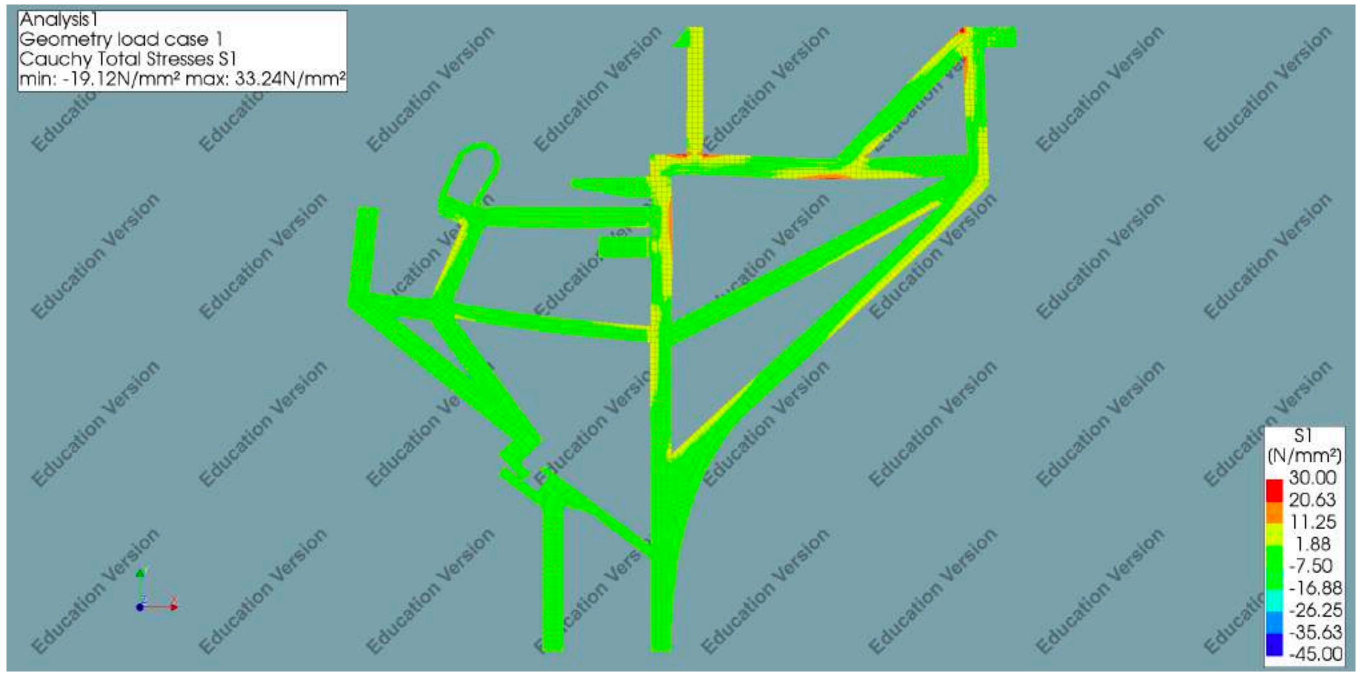


Figure 218: Tensile stresses 50mm depth

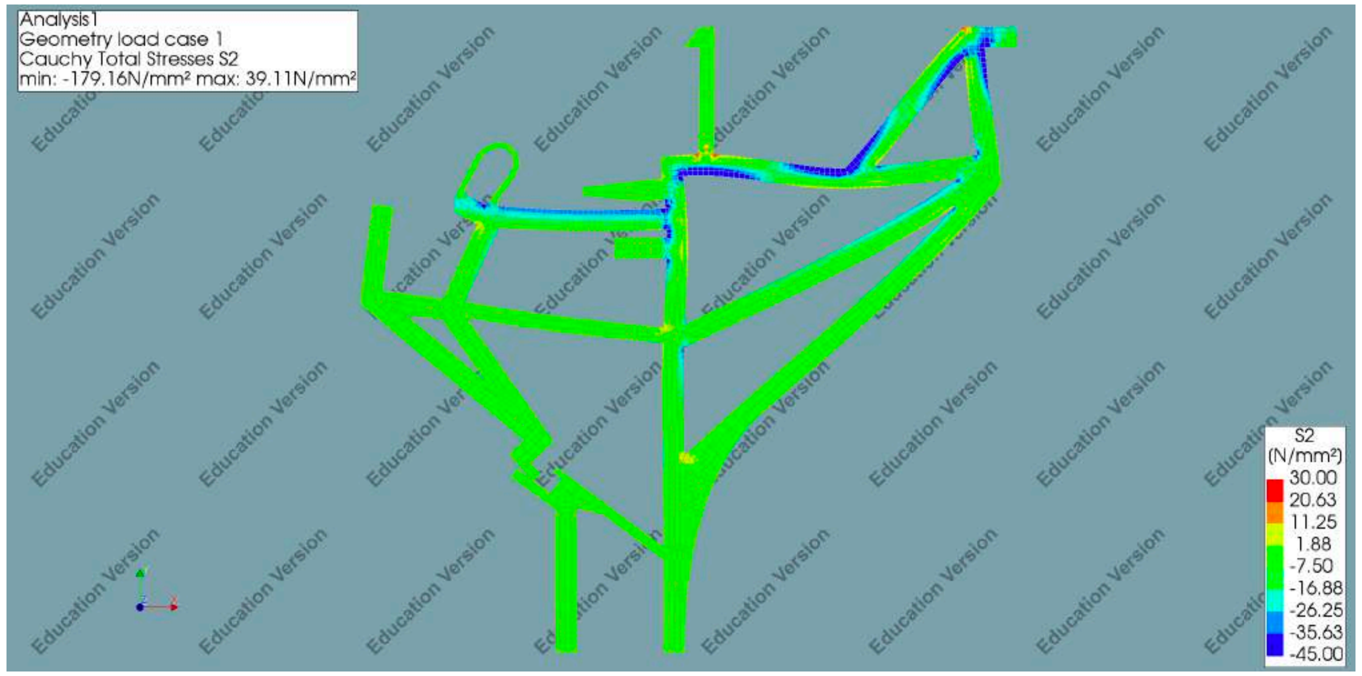


Figure 219: Compressive stresses 15mm depth

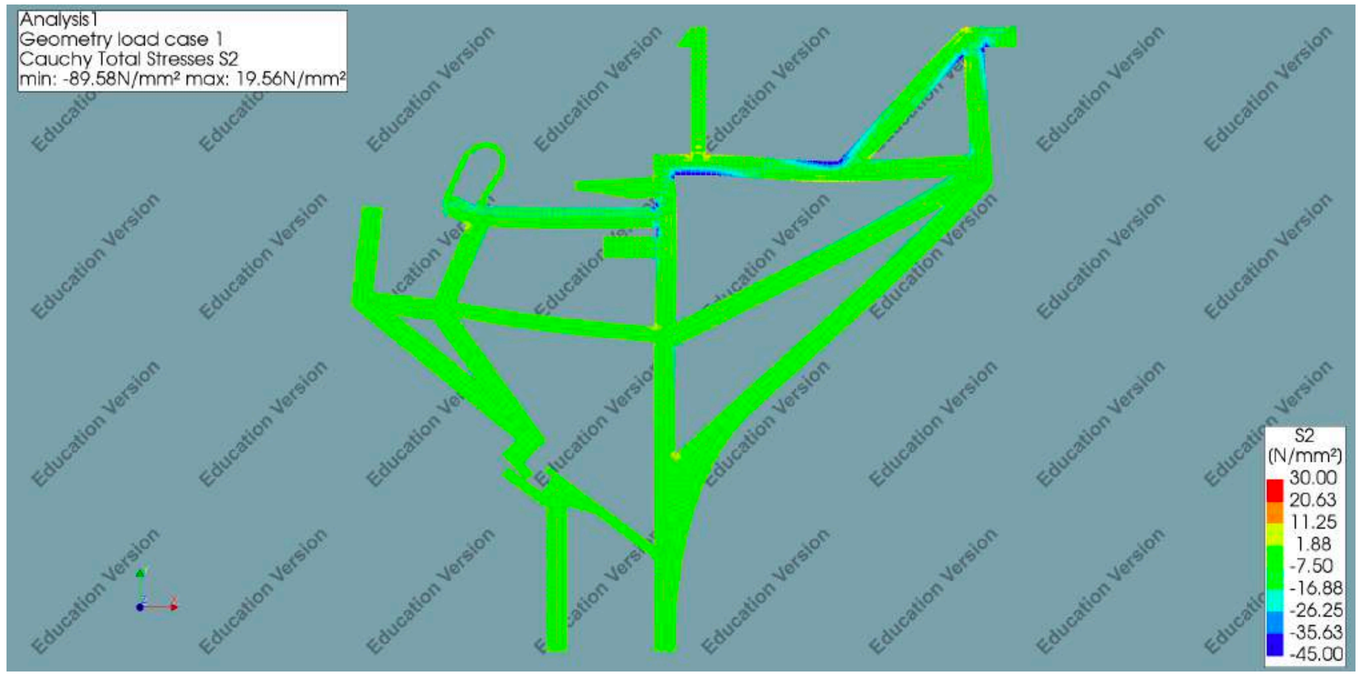


Figure 220: Compressive stresses 30mm depth

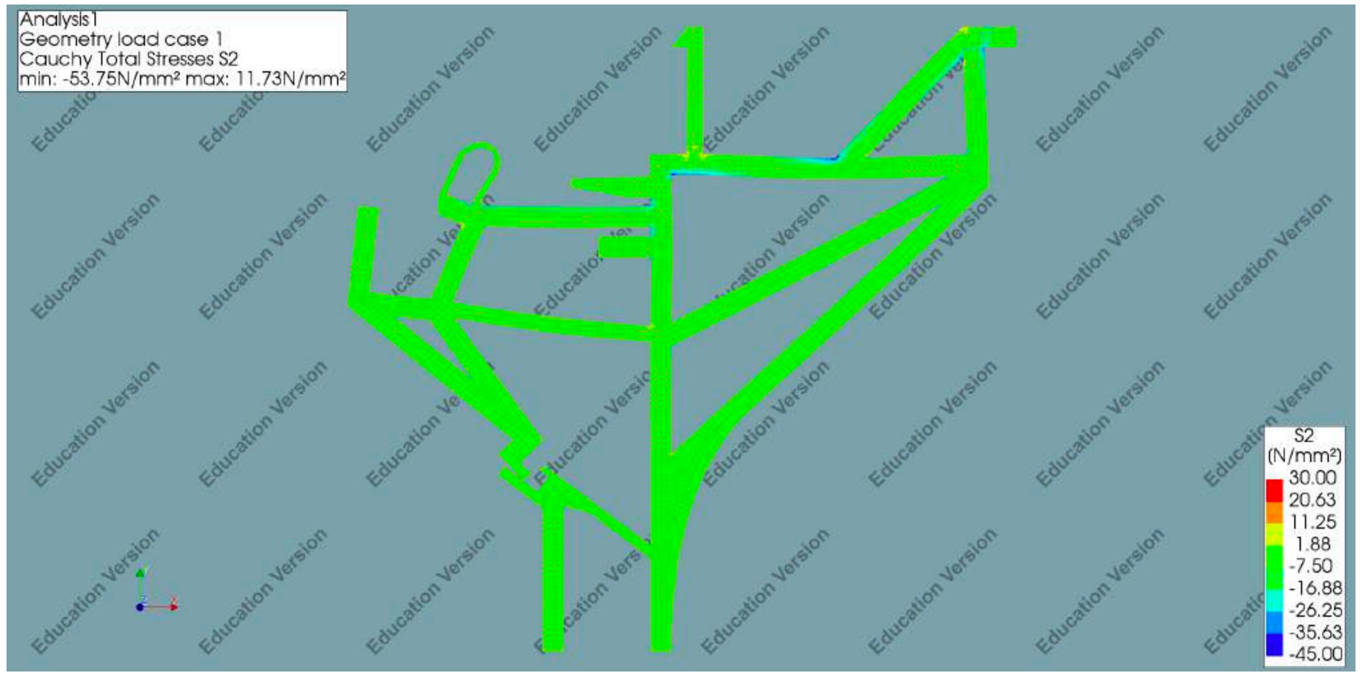


Figure 221: Compressive stresses 50mm depth

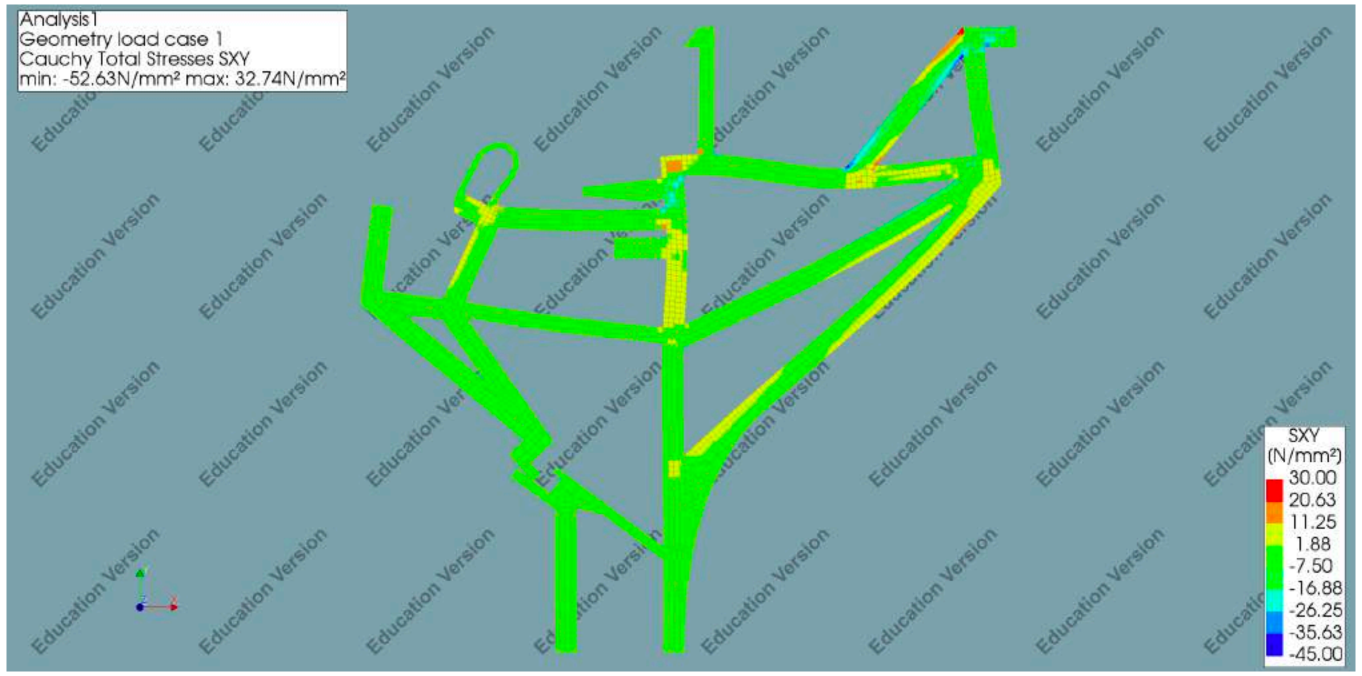


Figure 222: shear stresses 15mm depth

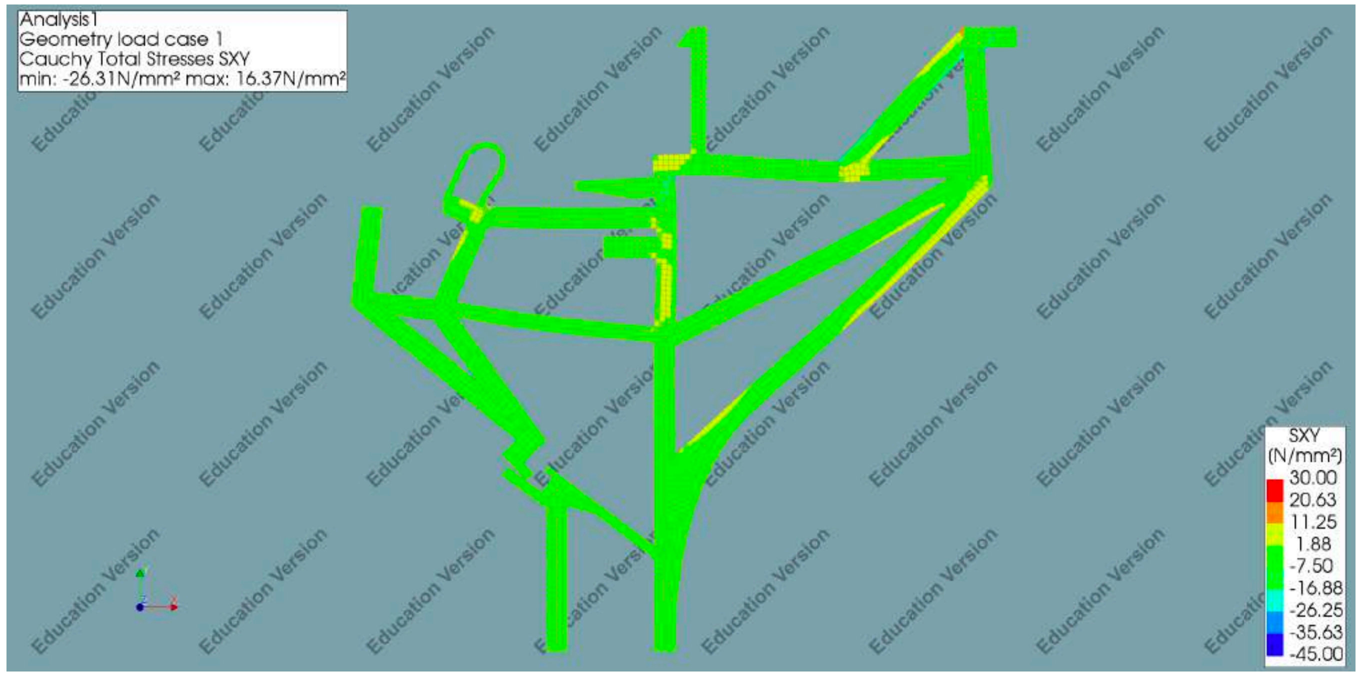


Figure 223: shear stresses 30mm depth

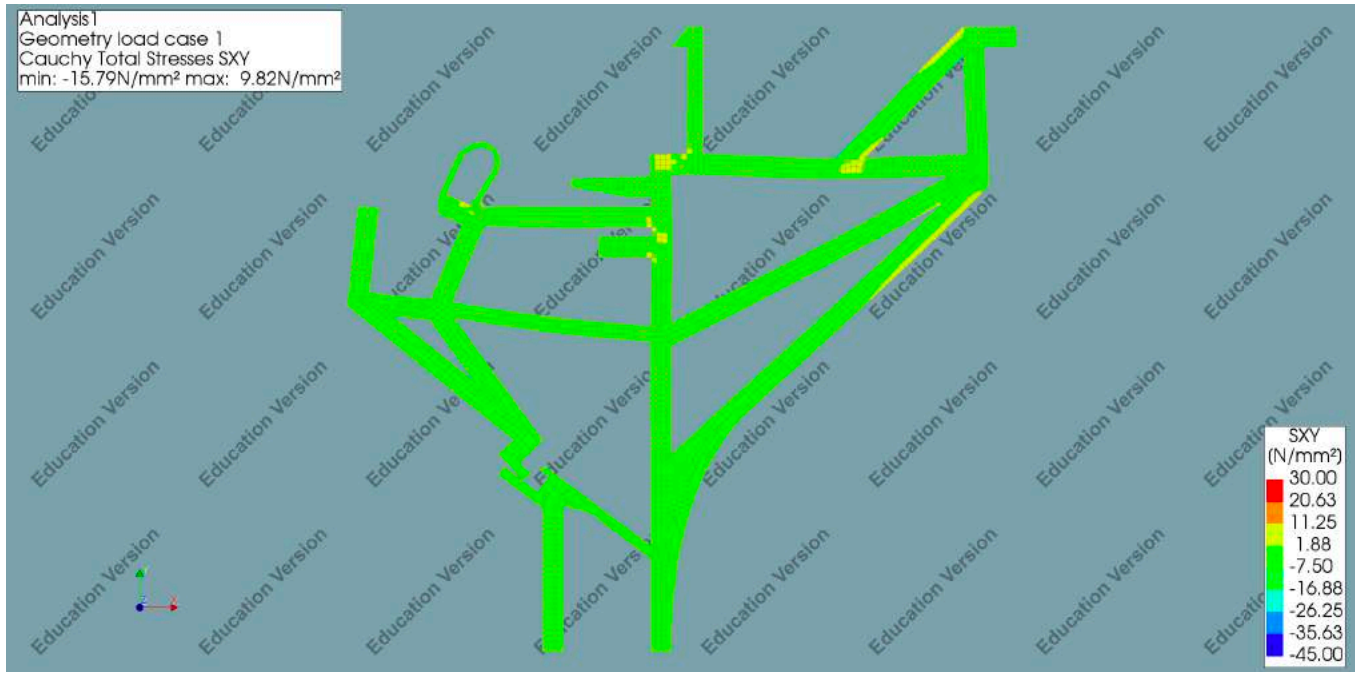


Figure 224: shear stresses 50mm depth

Analysis 9: Iteration 8

<u>Results tensile analysis</u>

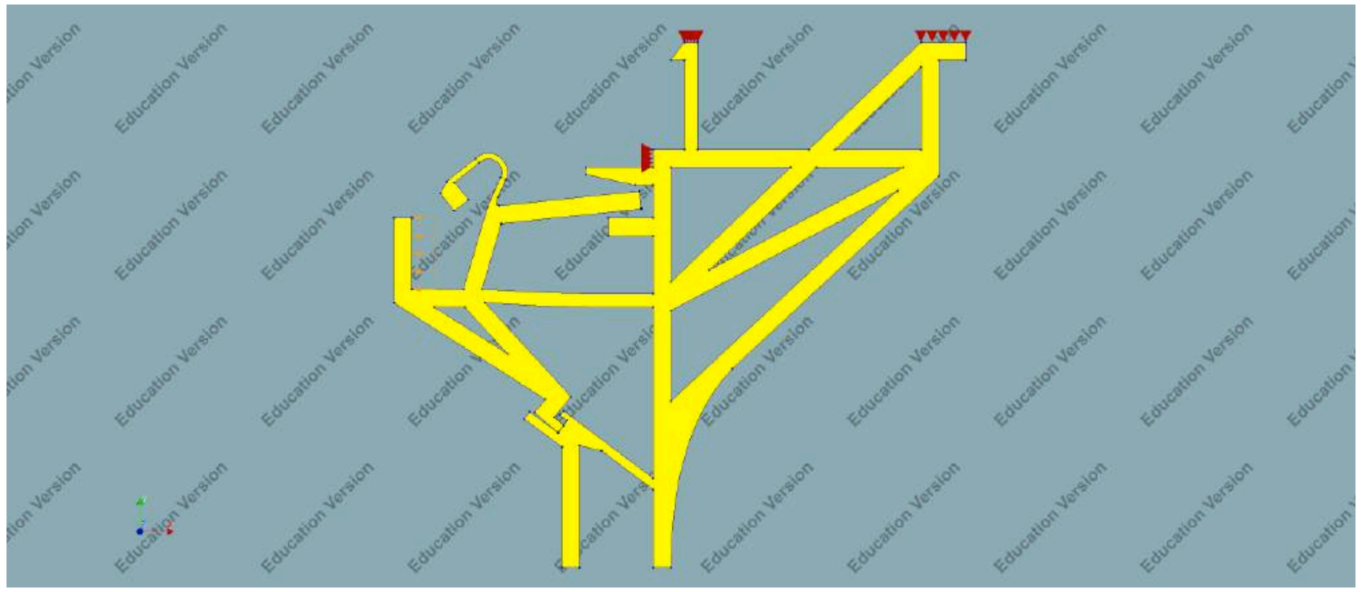


Figure 225: Geometry

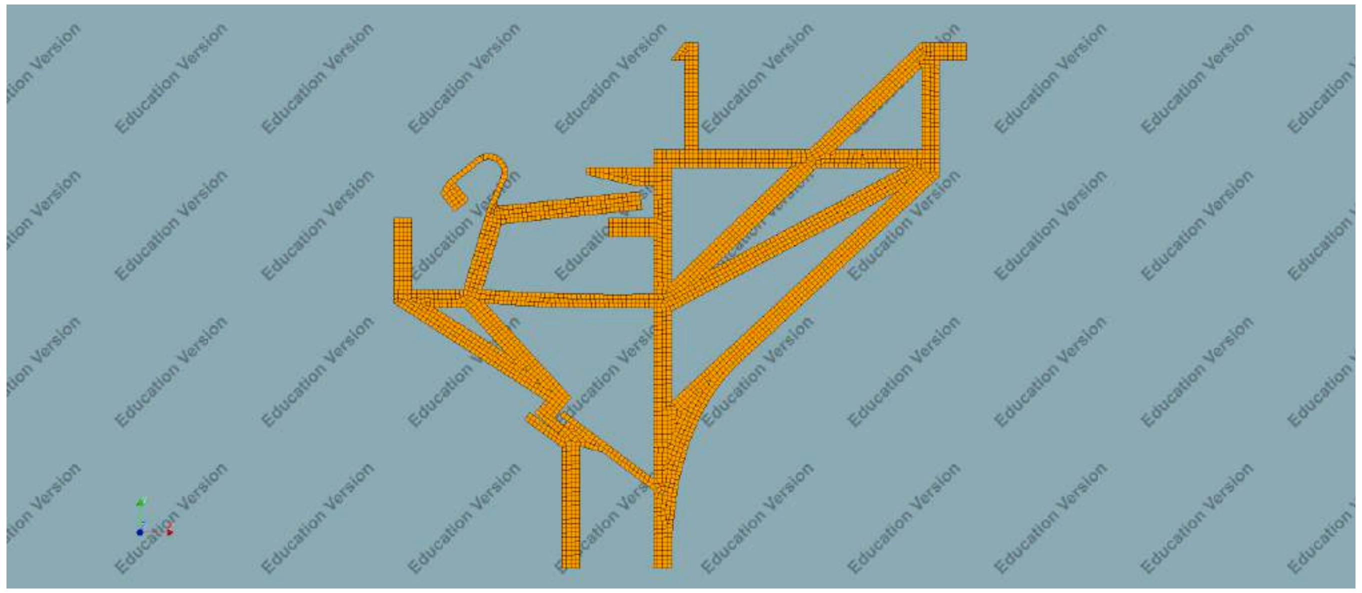


Figure 226: Mesh geometry

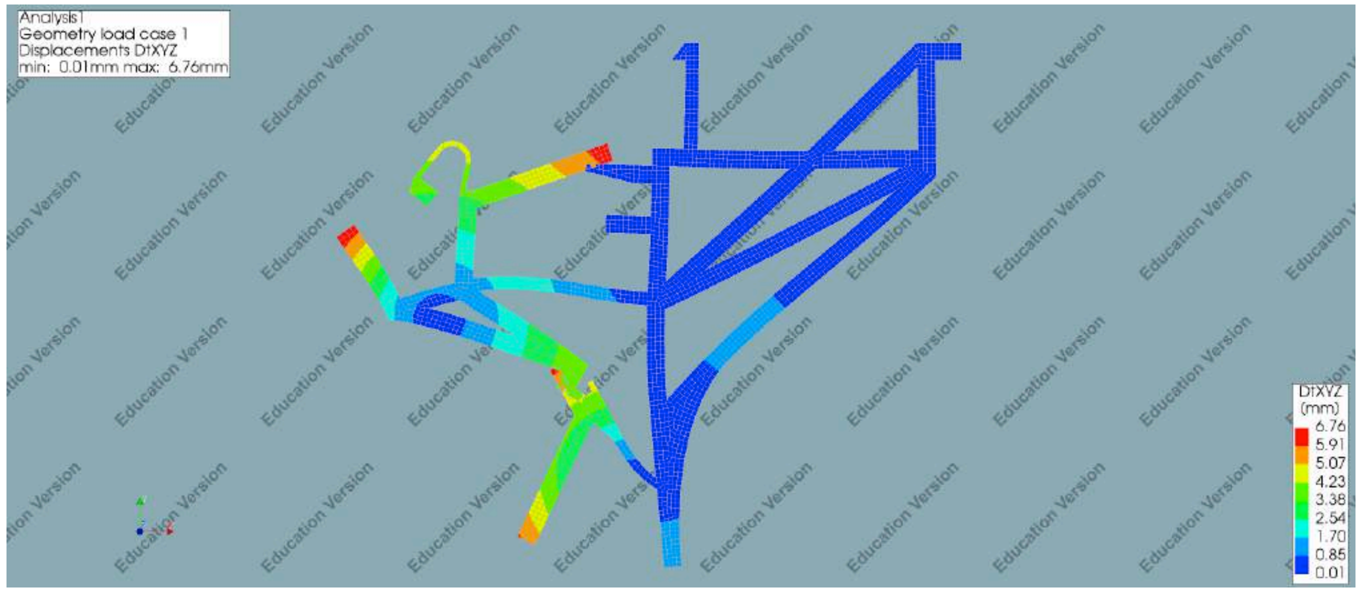


Figure 227: Displacement 15mm depth

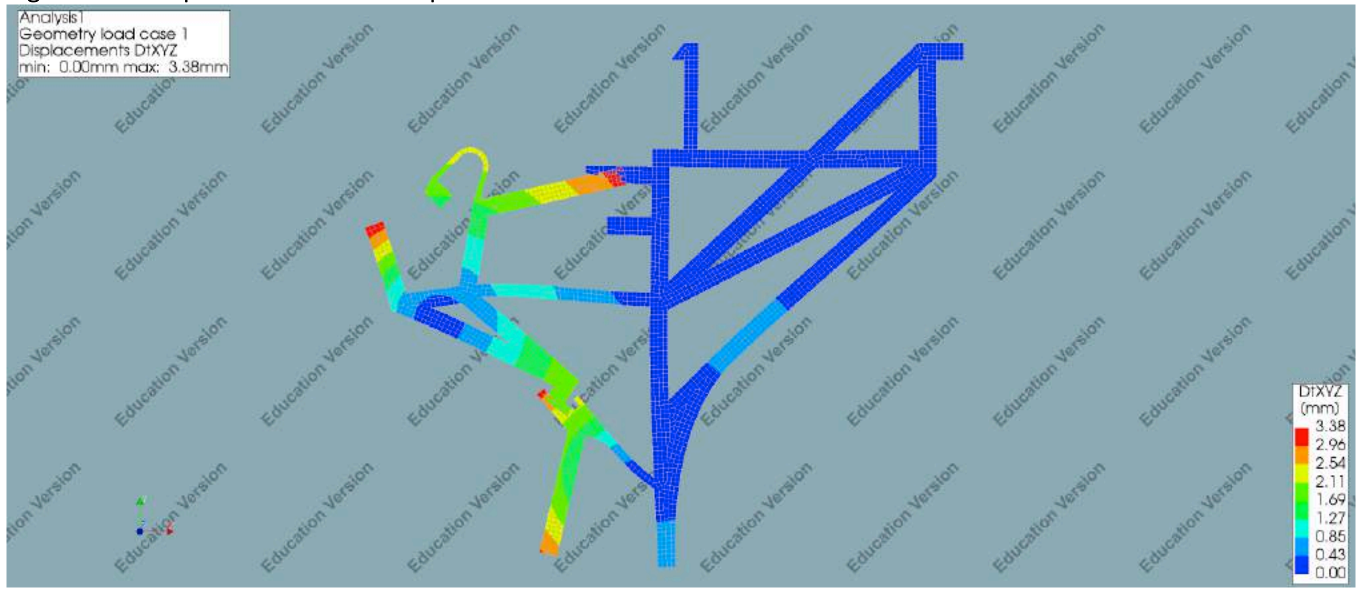


Figure 228: Displacement 30mm depth

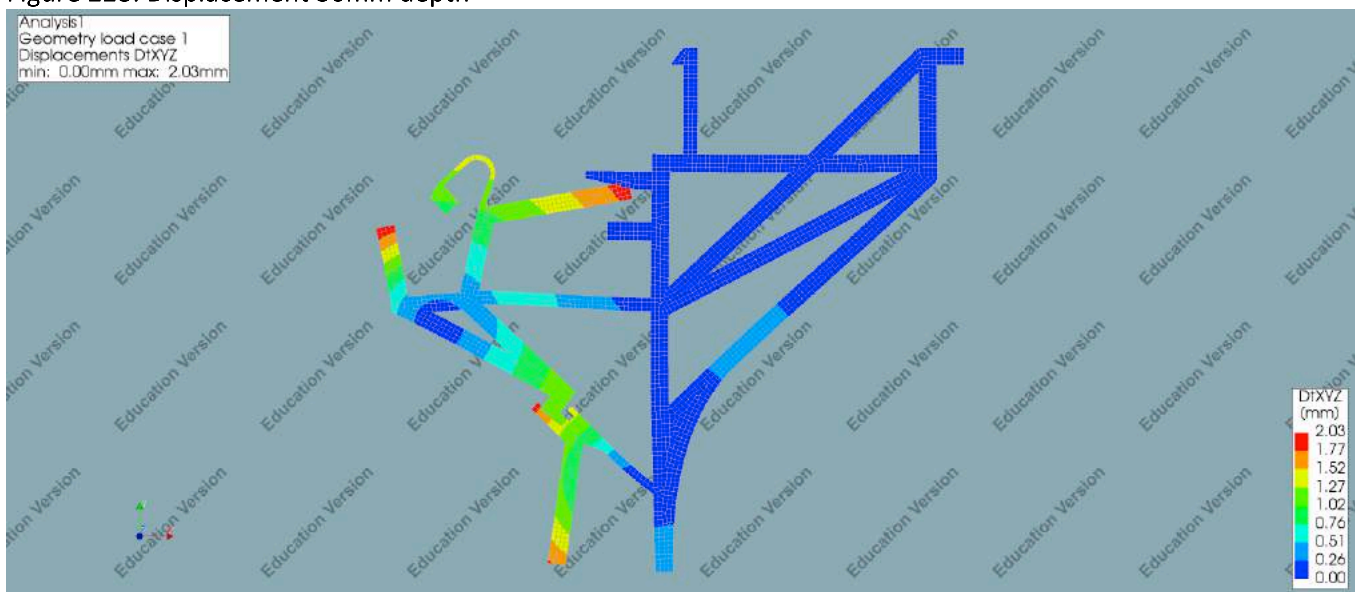


Figure 229: 50mm depth

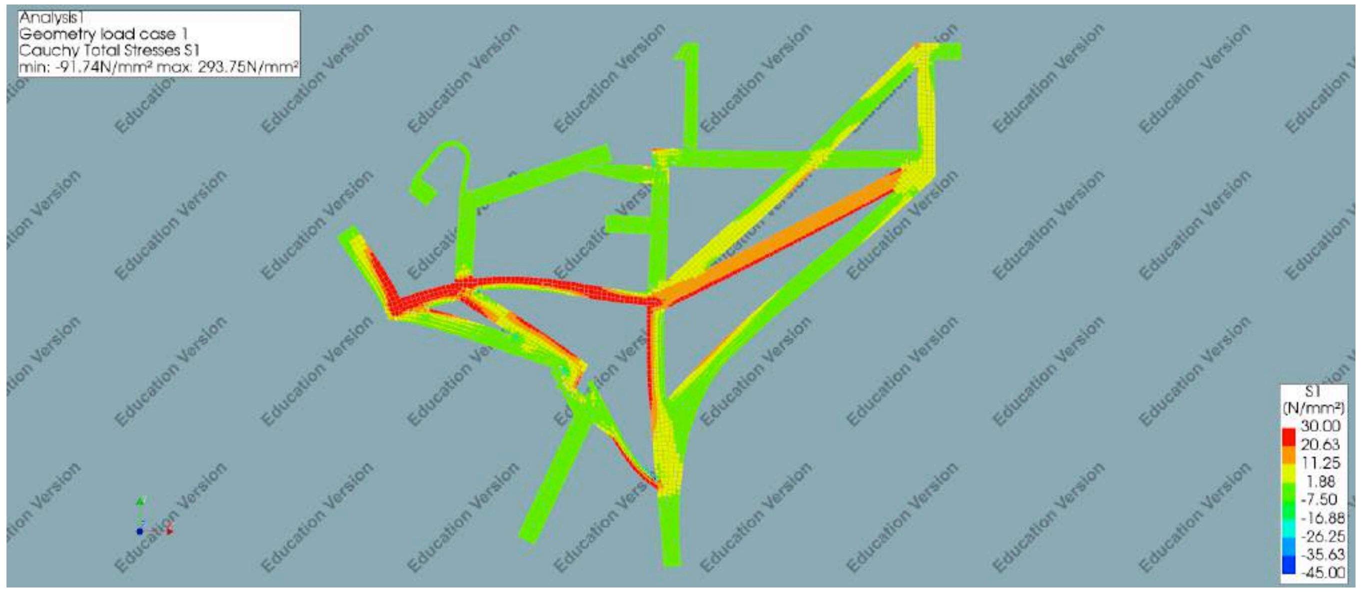


Figure 230: Tensile stresses 15mm depth

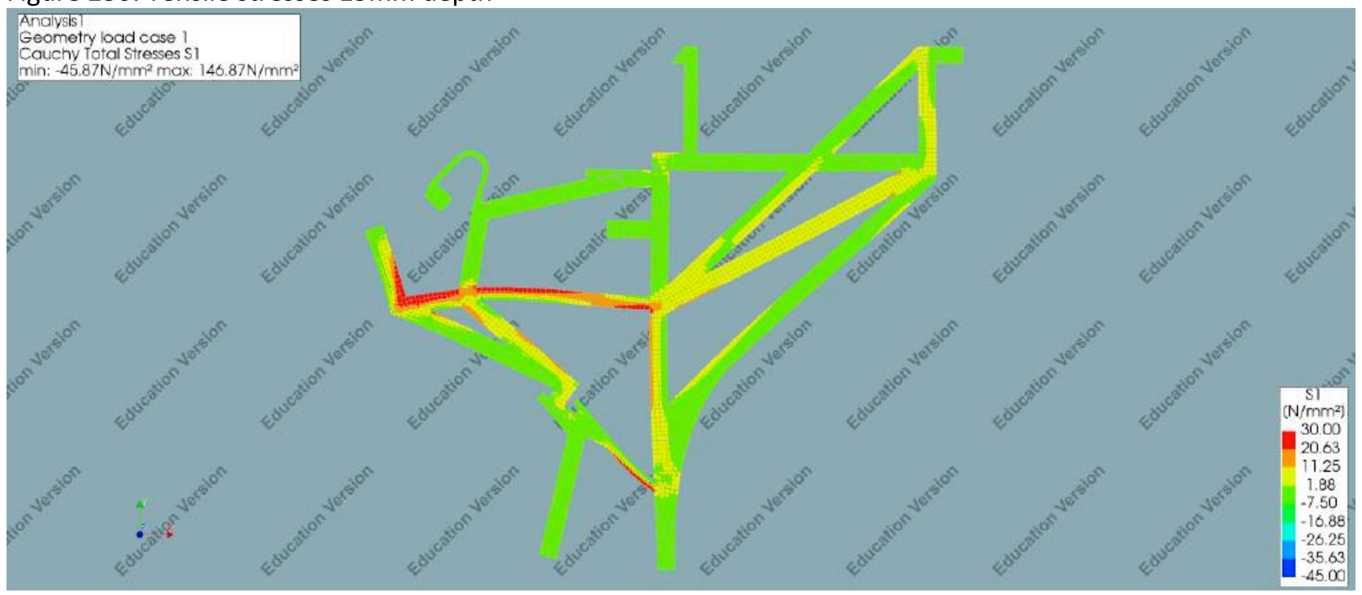


Figure 231: Tensile stresses 30mm depth

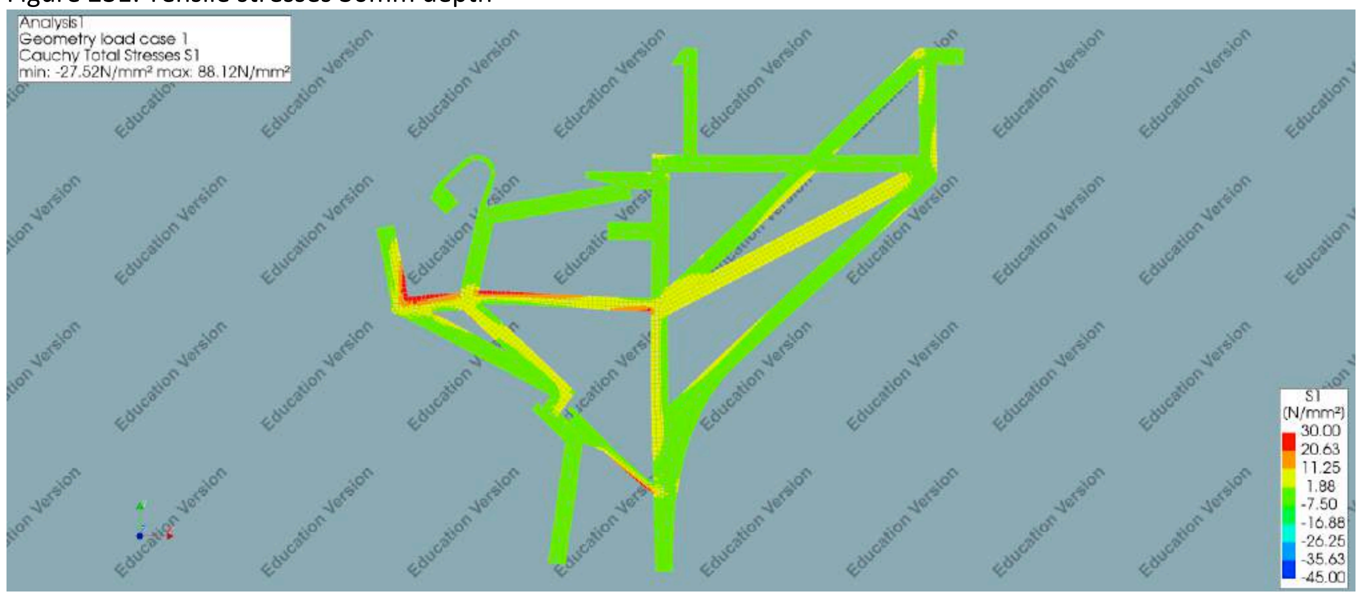


Figure 232: Tensile stresses 50mm depth

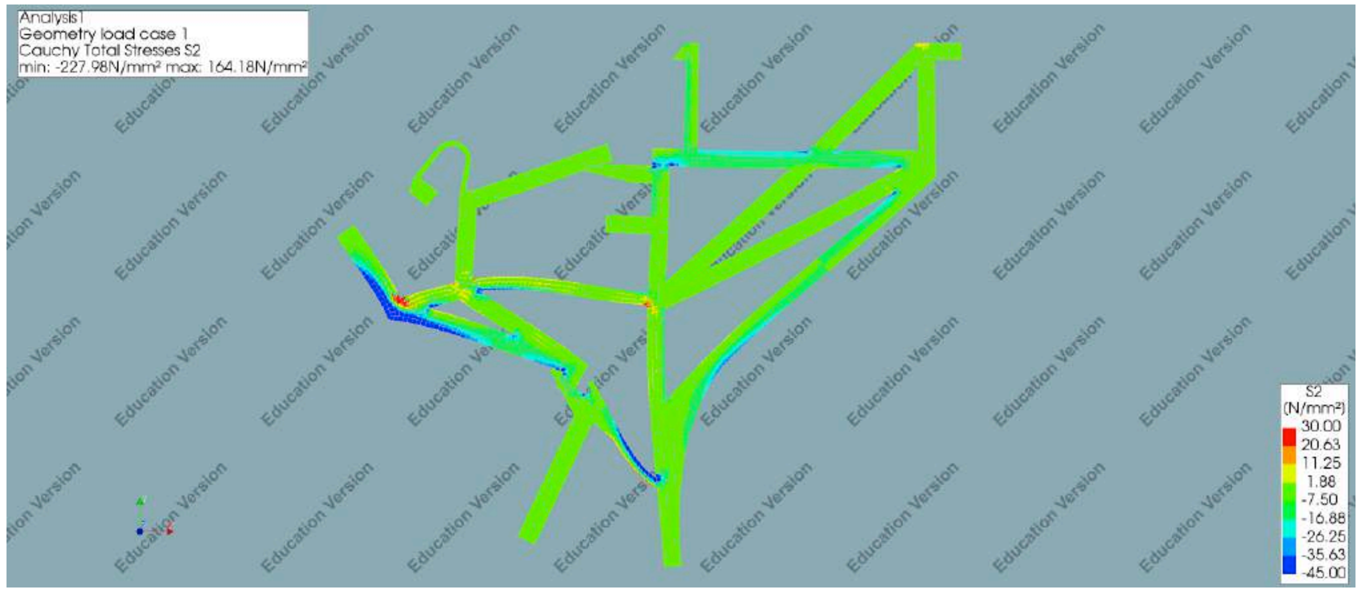


Figure 233: Compressive stresses 15mm depth

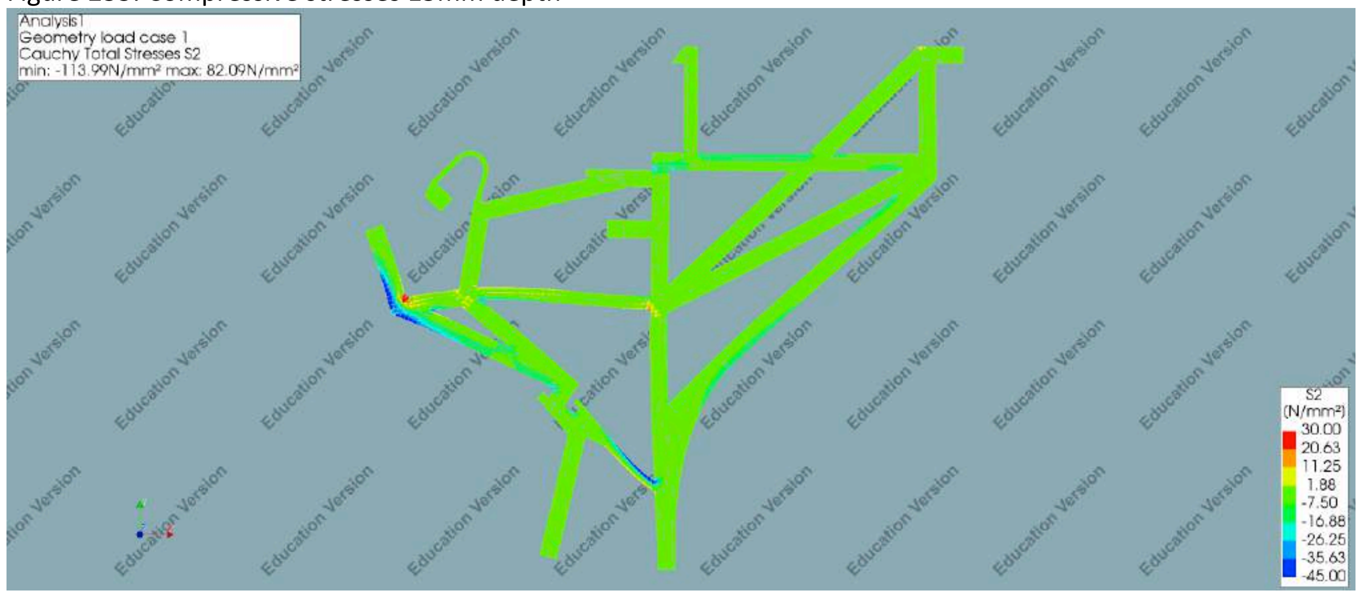


Figure 234: Compressive stresses 30mm depth

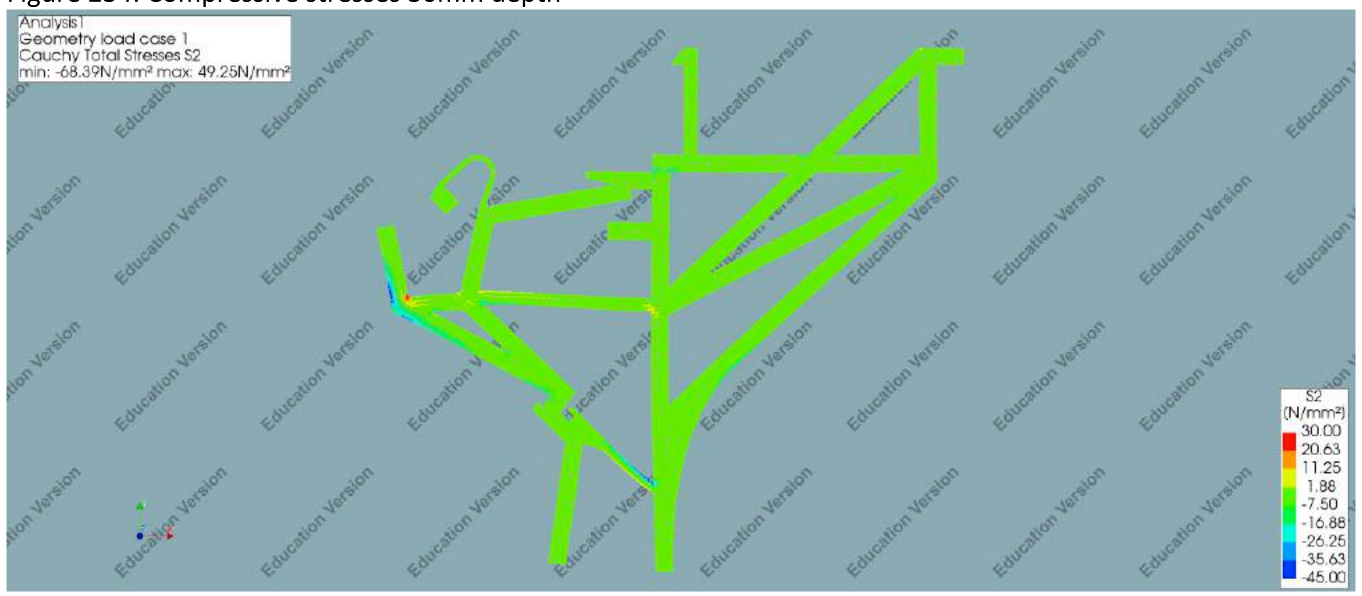


Figure 235: Compressive stresses 50mm depth

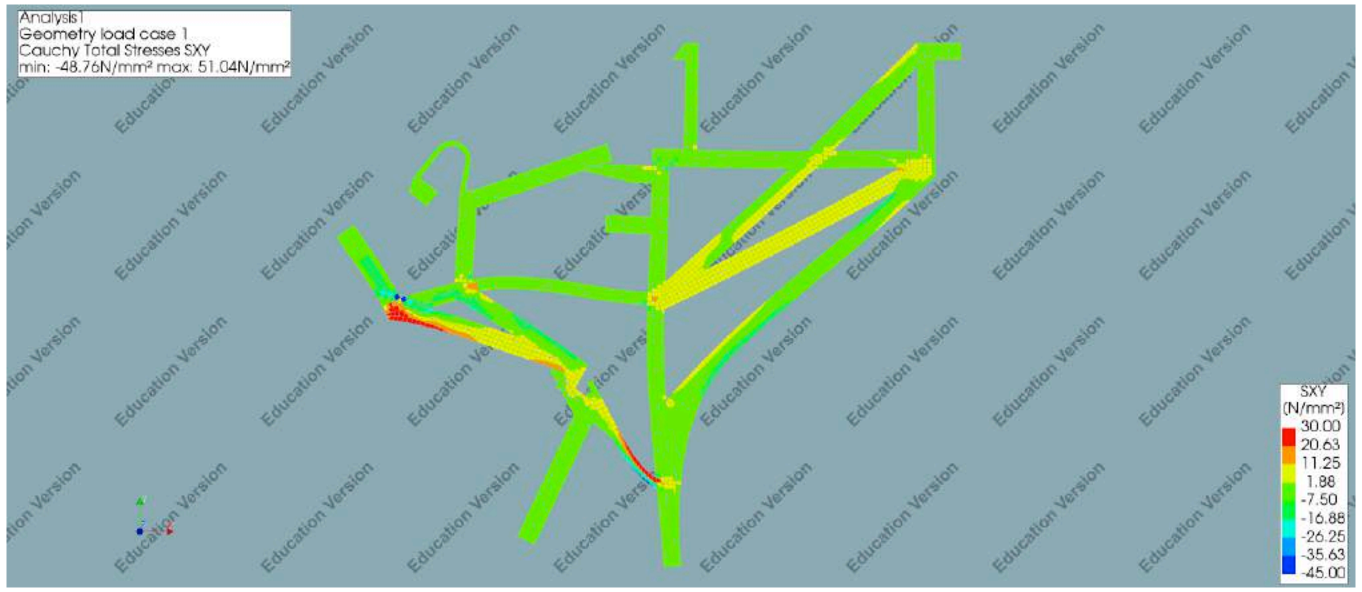


Figure 236: Shear stresses 15mm depth

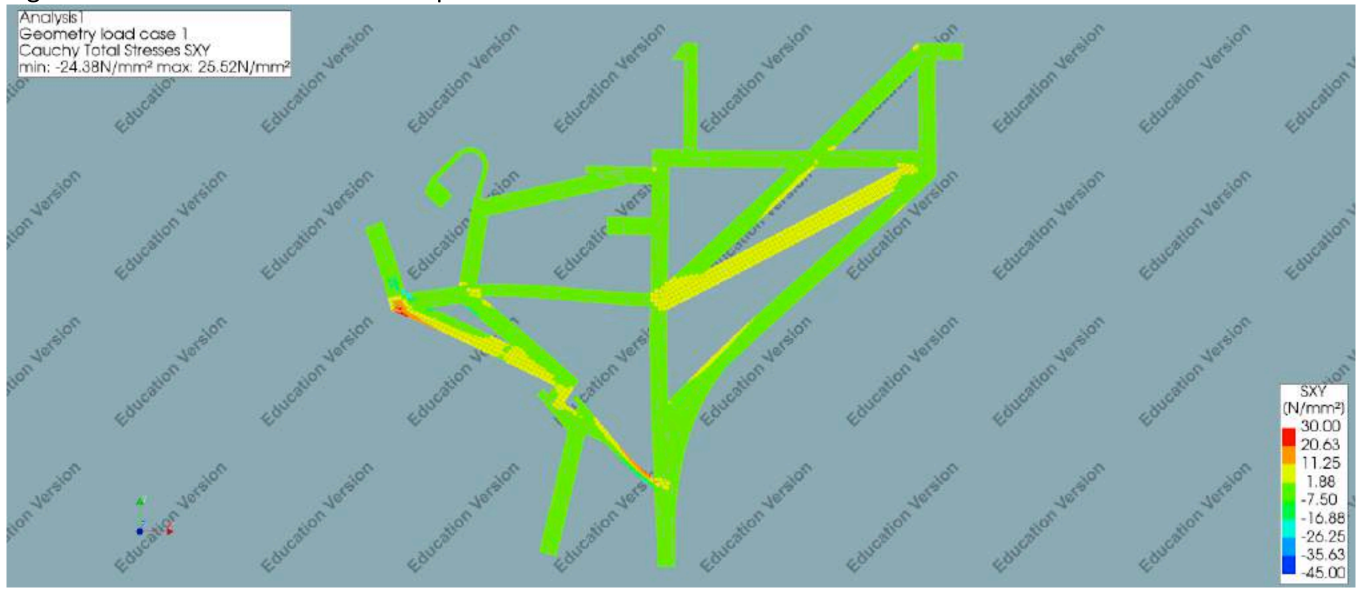


Figure 237: Shear stresses 30mm depth

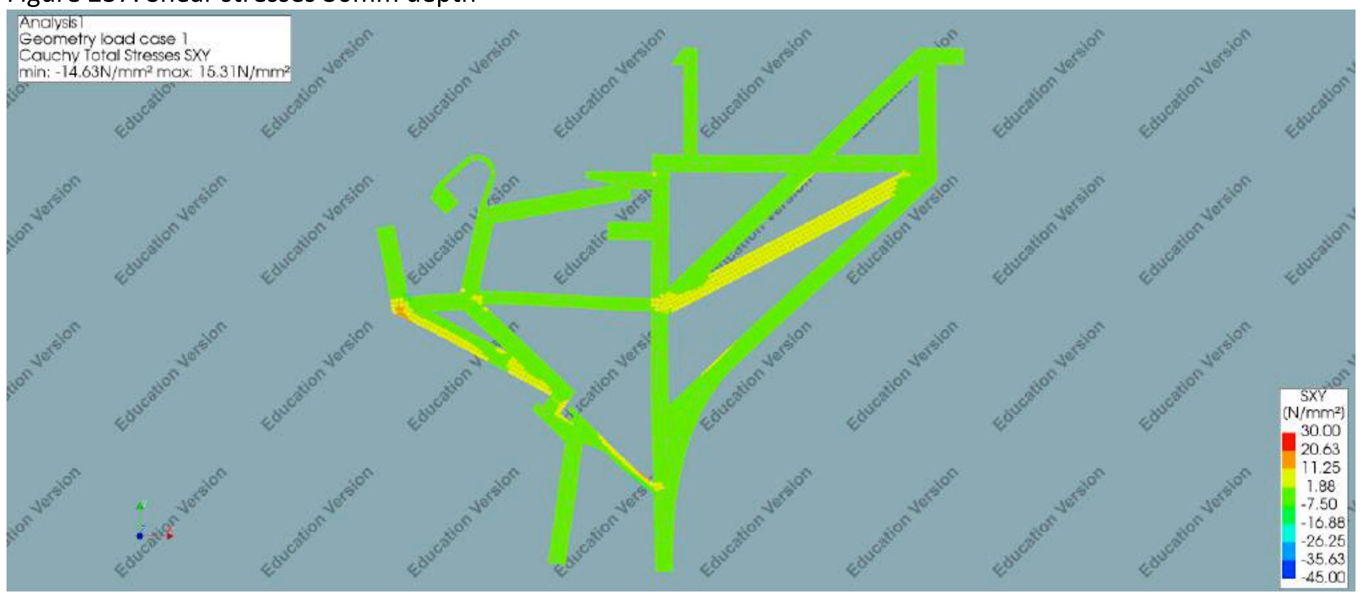


Figure 238: Shear stresses 50mm depth

<u>Results compressive analysis</u>

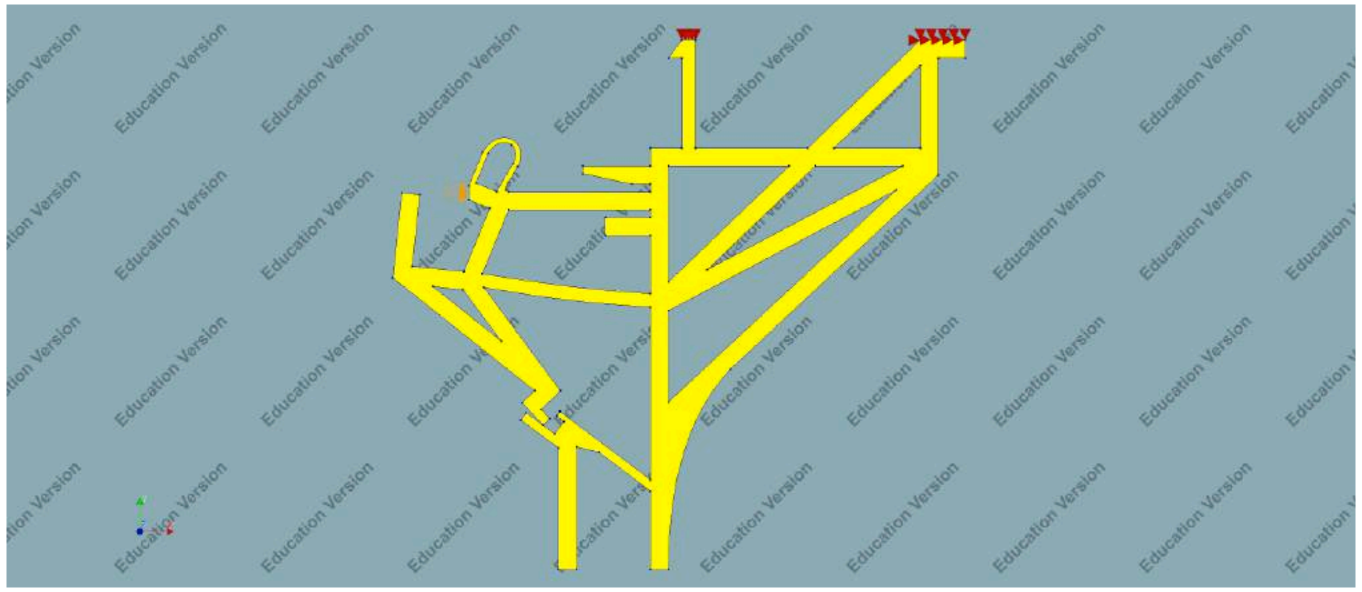


Figure 239: Geometry

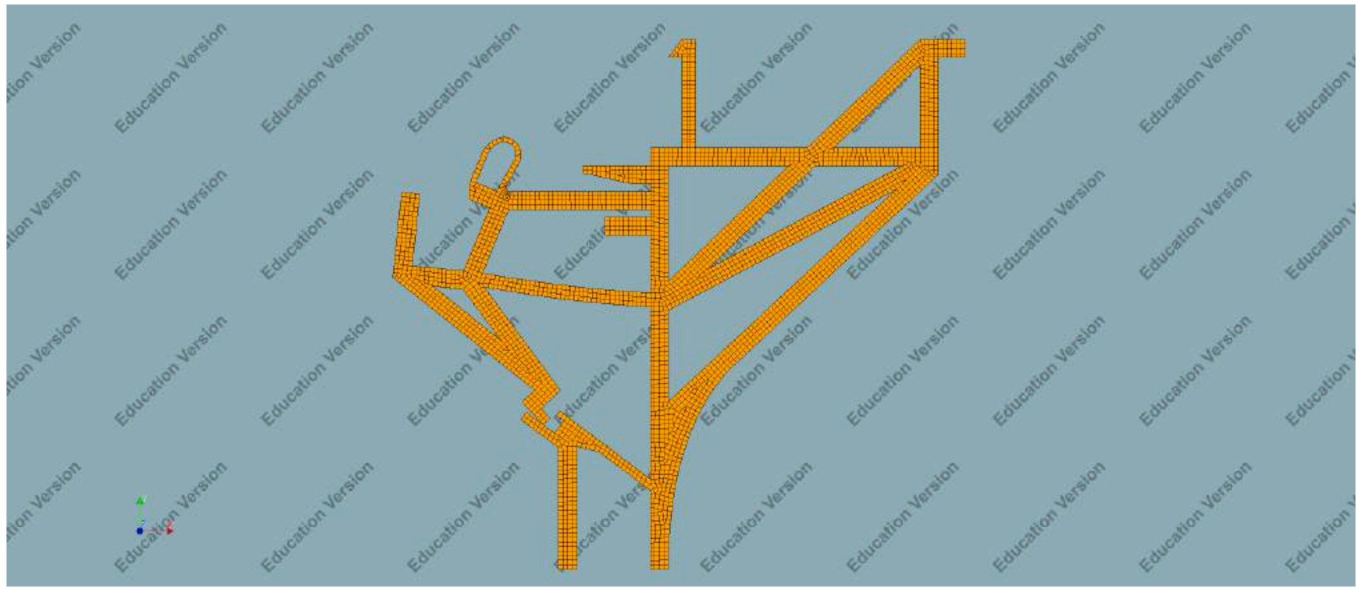


Figure 240: Mesh geometry

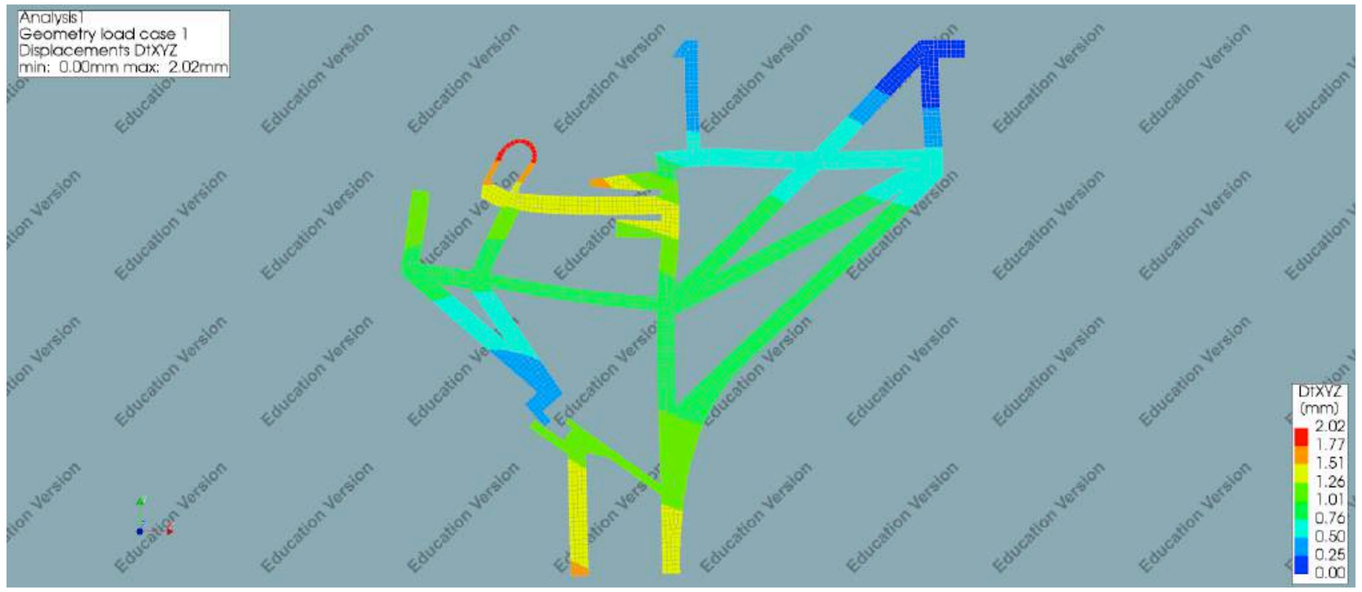


Figure 241: Displacement 15mm depth

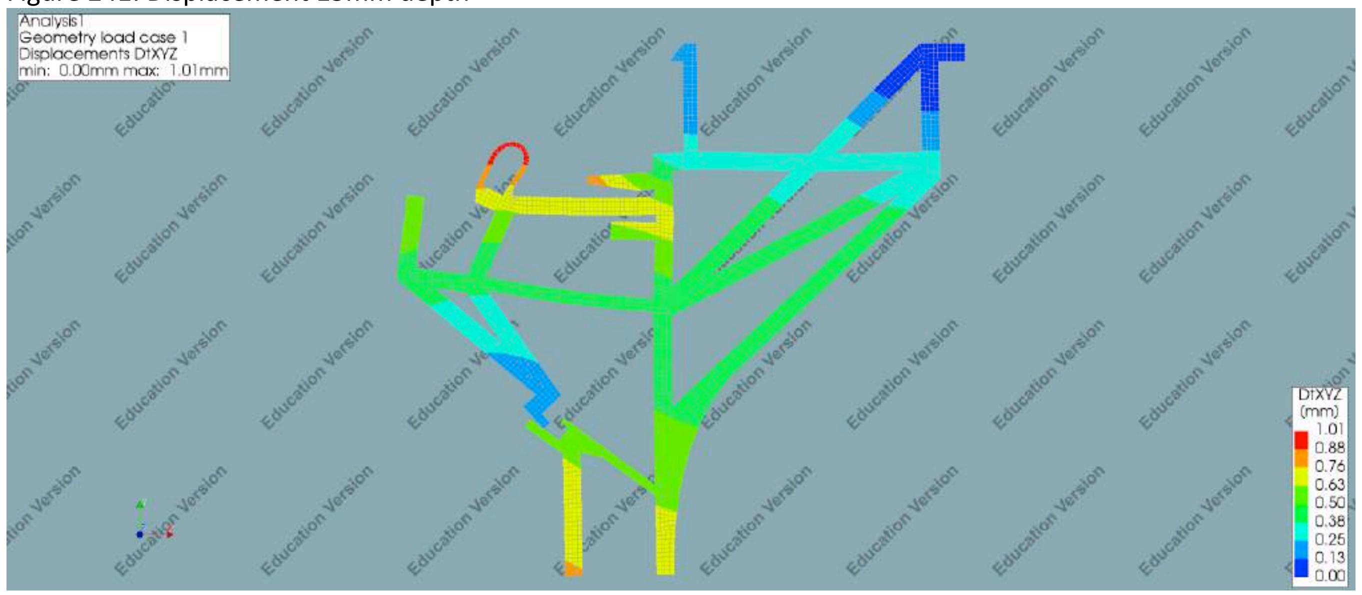


Figure 242: Displacement 30mm depth

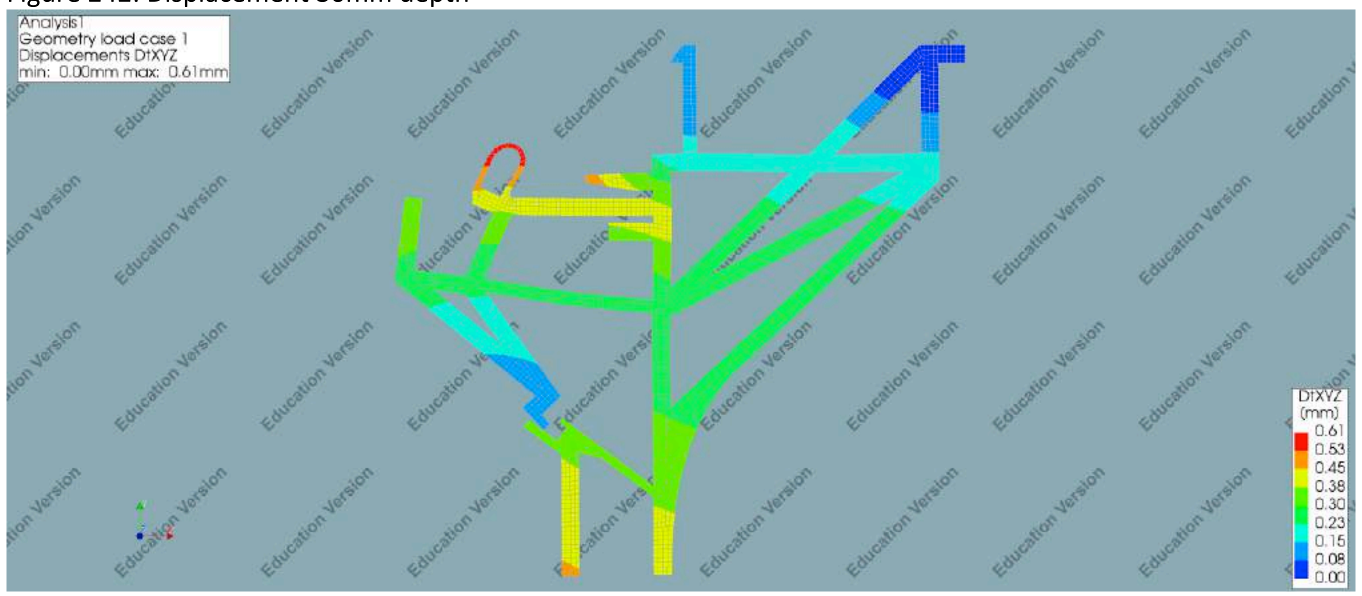


Figure 243: Displacement 50mm depth

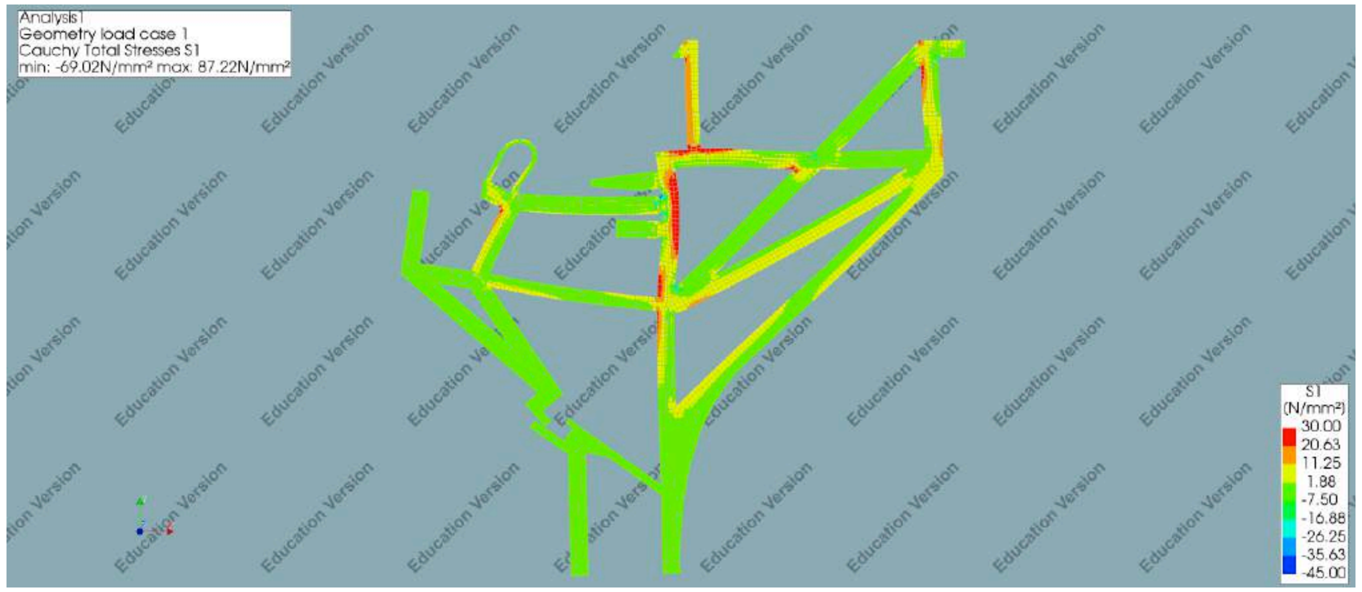


Figure 244: Tensile stresses 15mm depth

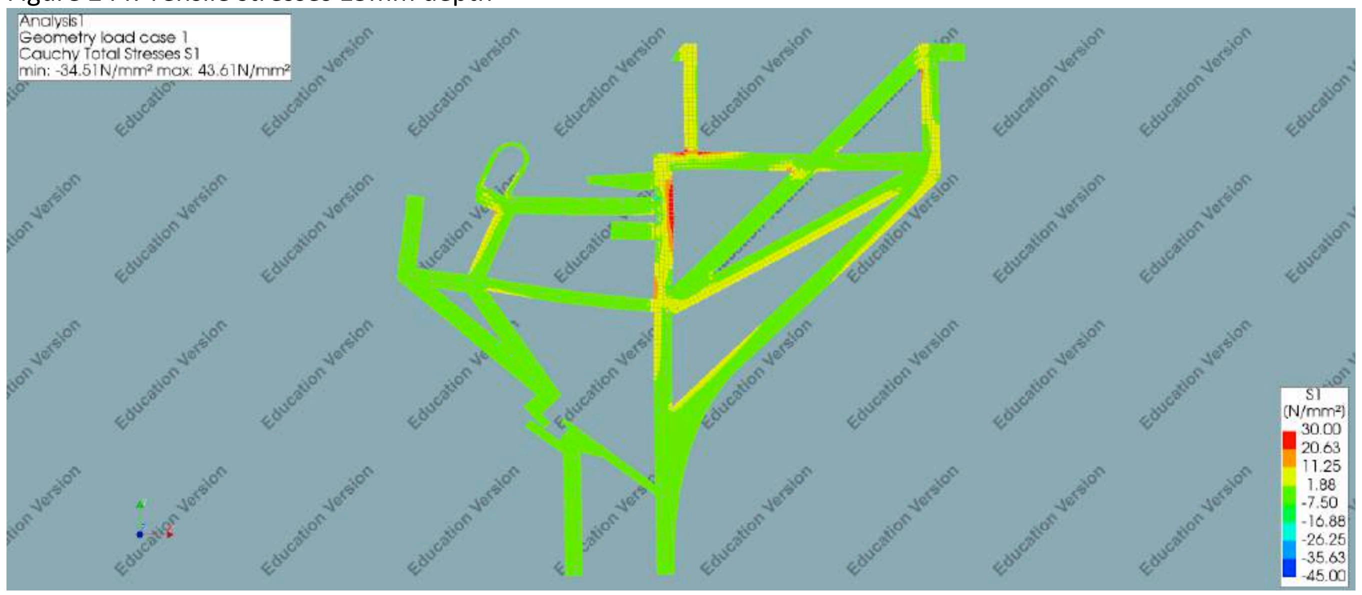


Figure 245: Tensile stresses 30mm depth

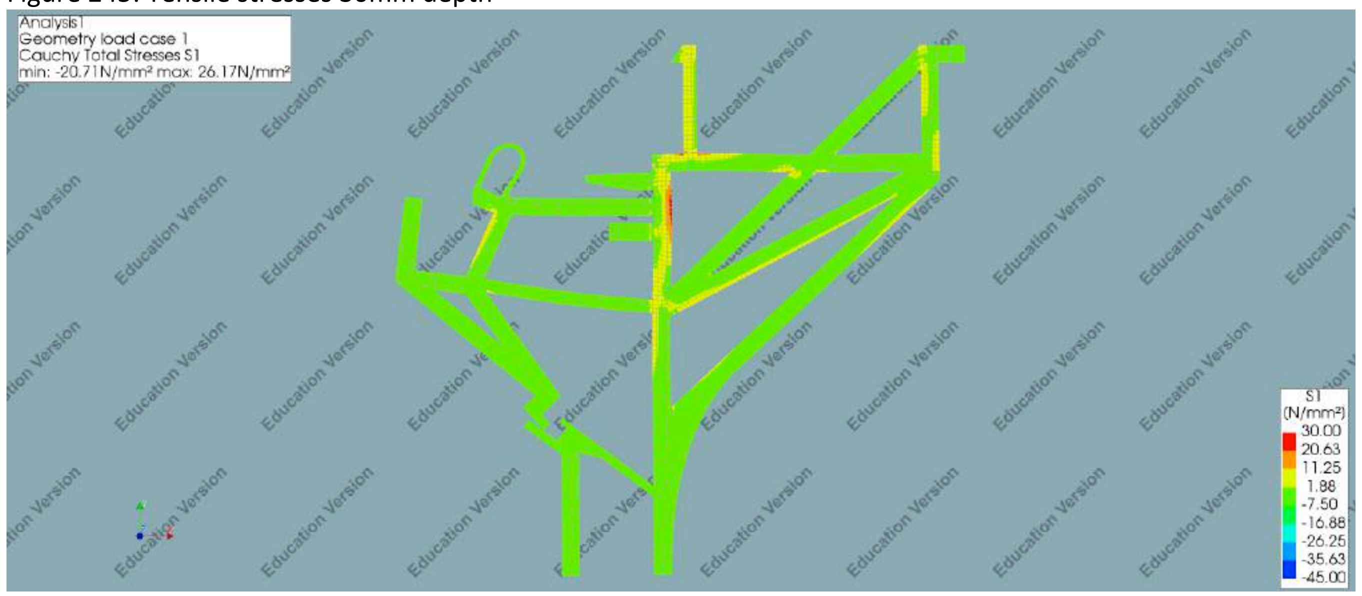


Figure 246: Tensile stresses 50mm depth

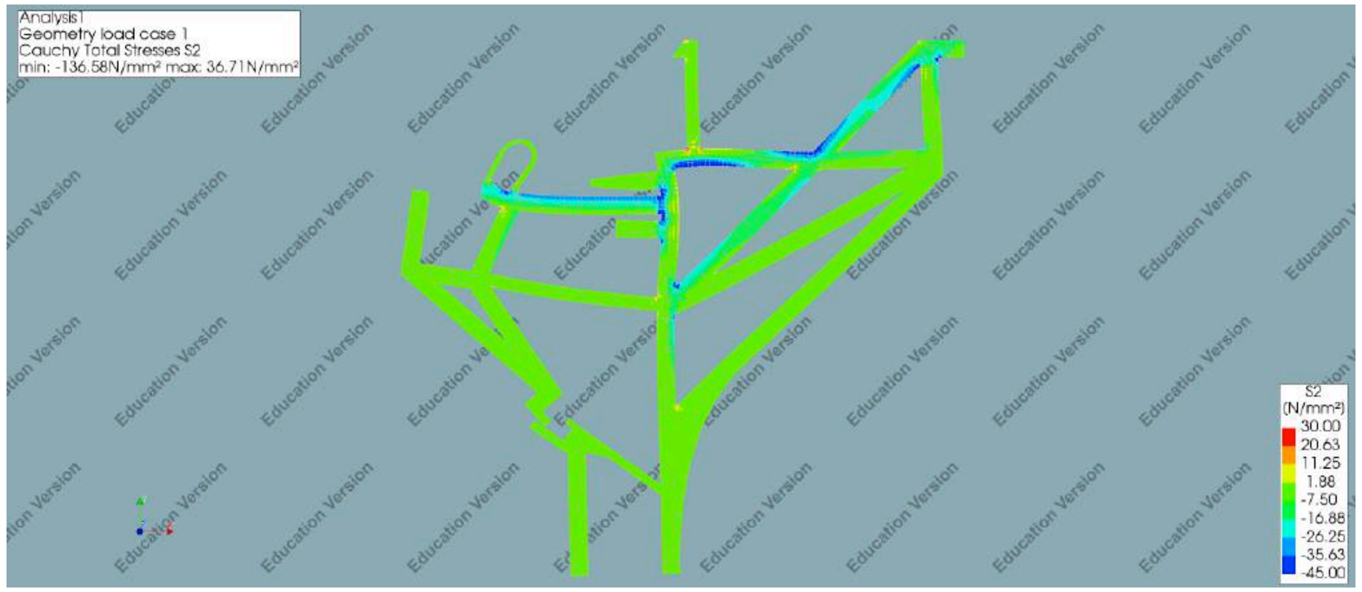


Figure 247: Compressive stresses 15mm depth

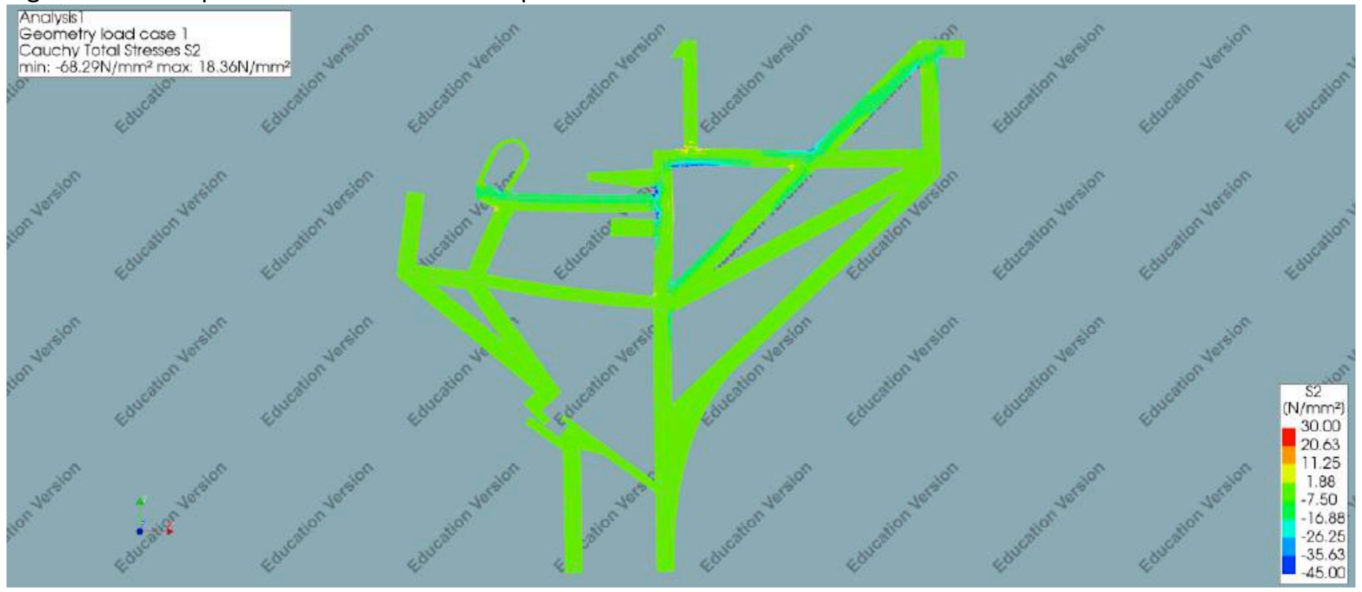


Figure 248: Compressive stresses 30mm depth

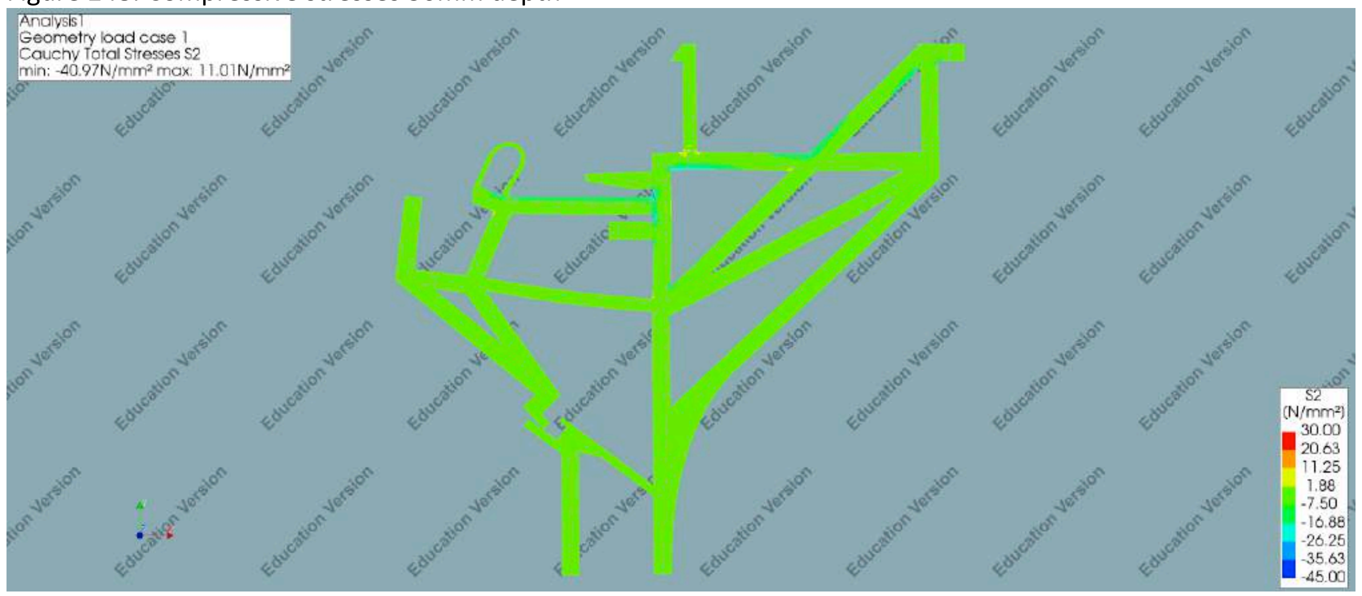


Figure 249: Compressive stresses 50mm depth

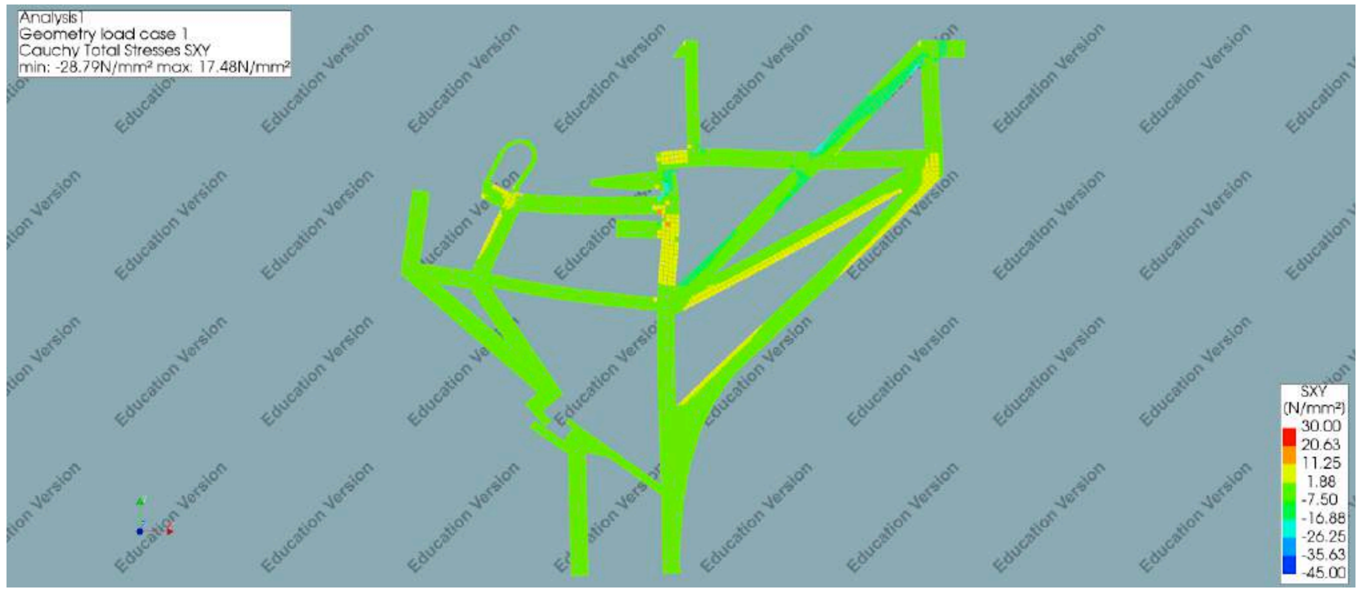


Figure 250: shear stresses 15mm depth

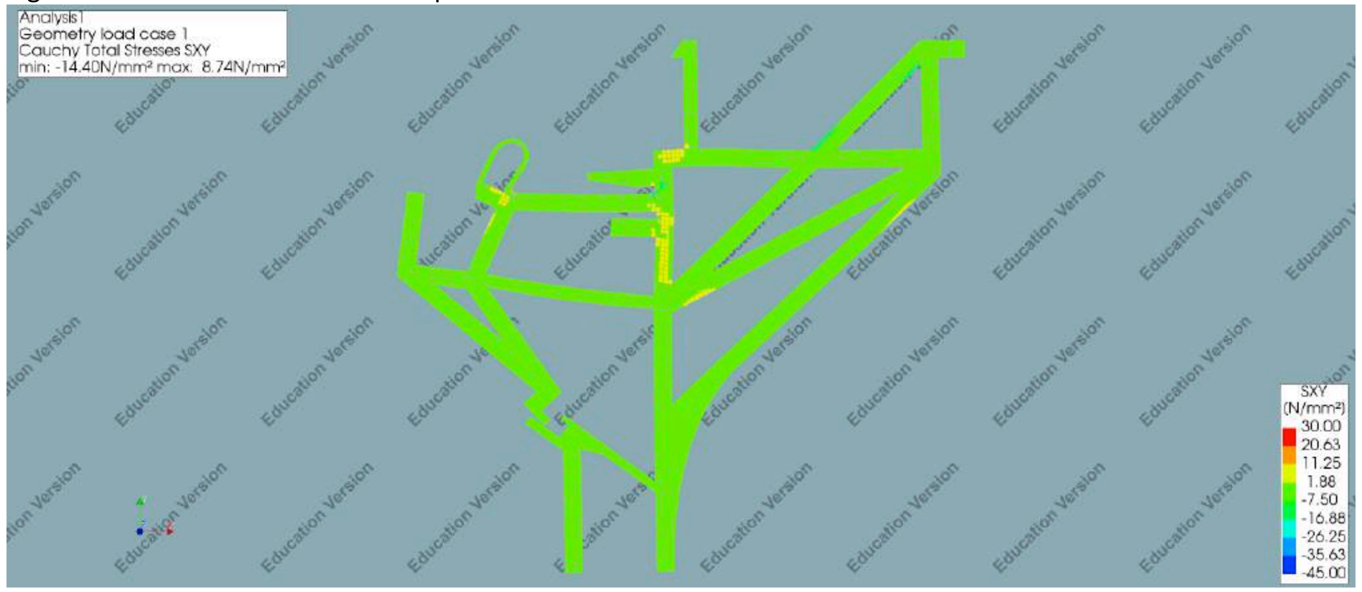


Figure 251: shear stresses 30mm depth

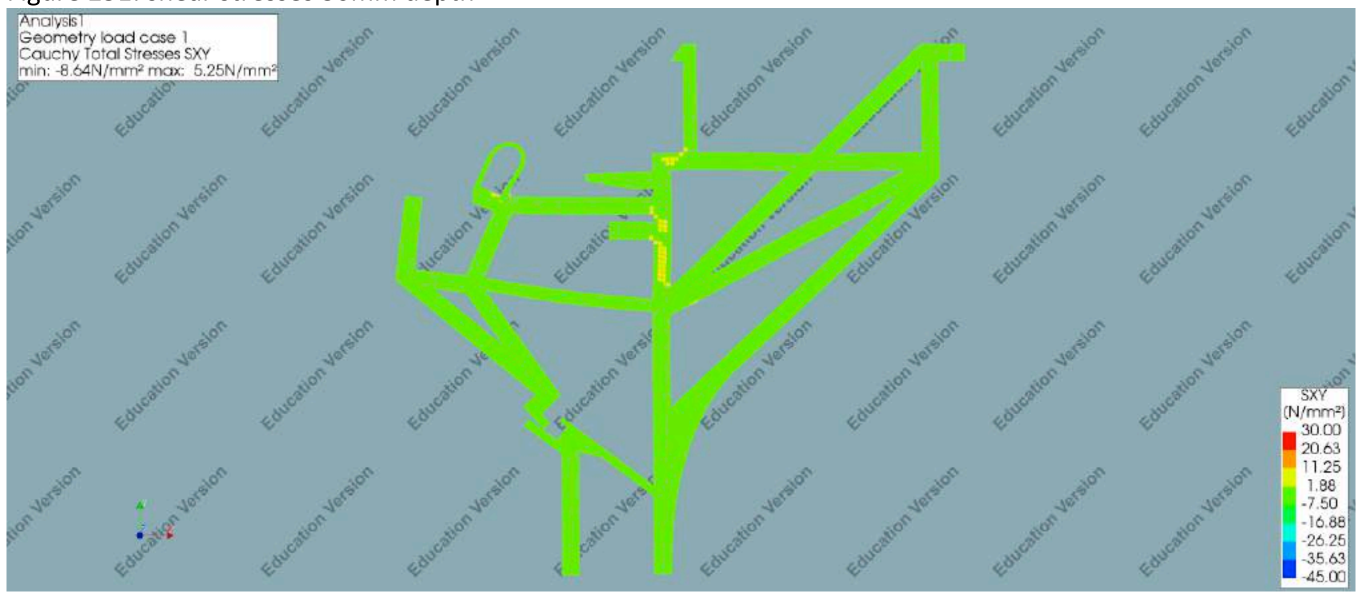


Figure 252: shear stresses 50mm depth

Analysis 10: Final design

<u>Results tensile analysis</u>

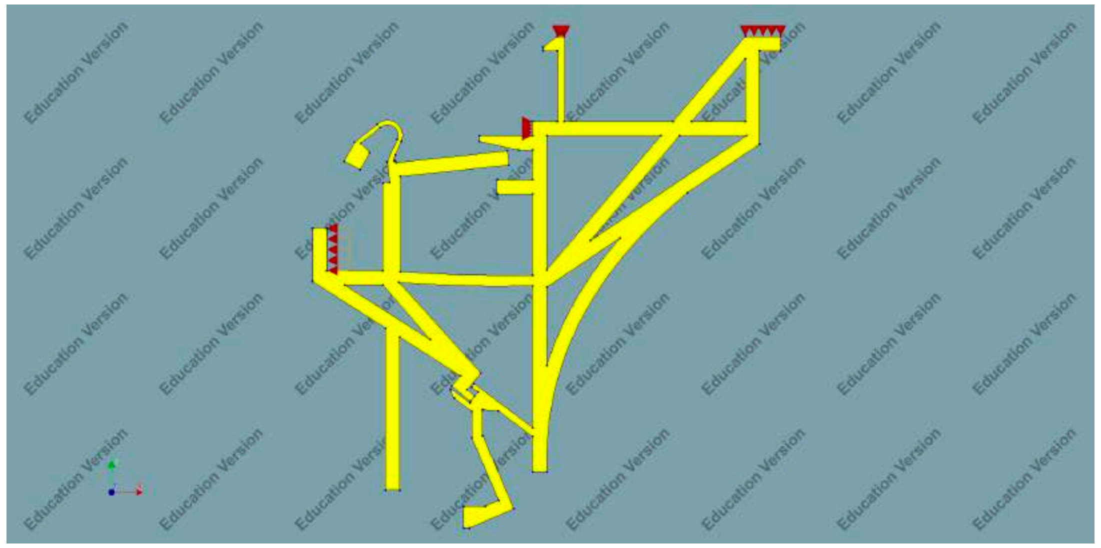


Figure 225: Geometry

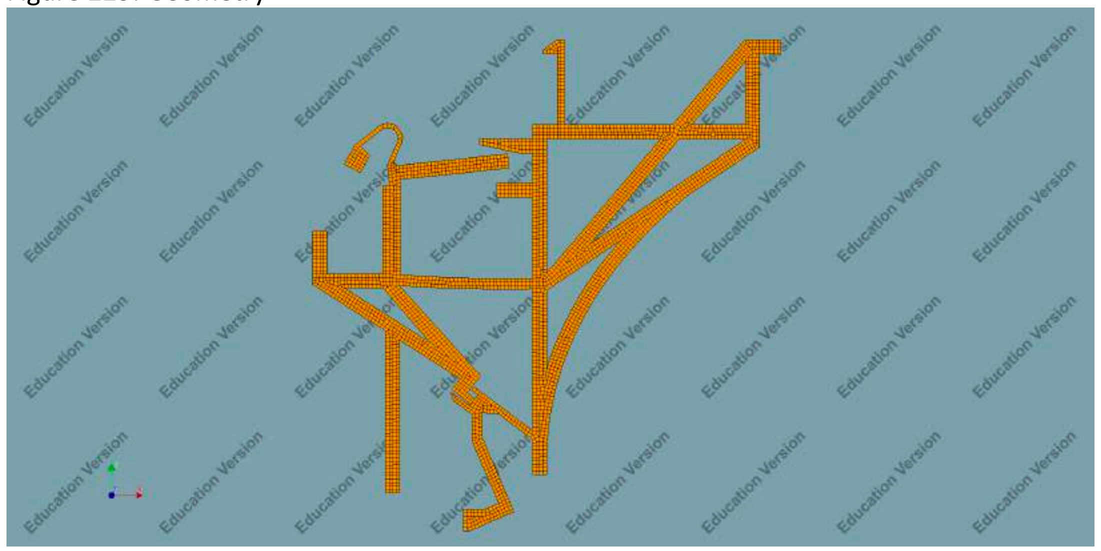


Figure 226: Mesh geometry

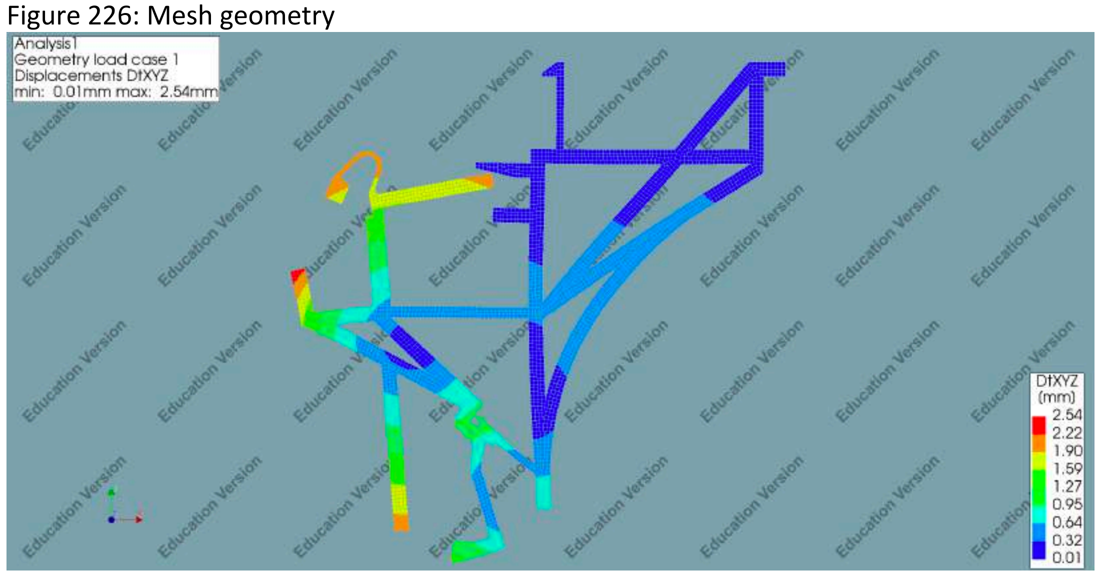


Figure 227: Displacement 30mm depth

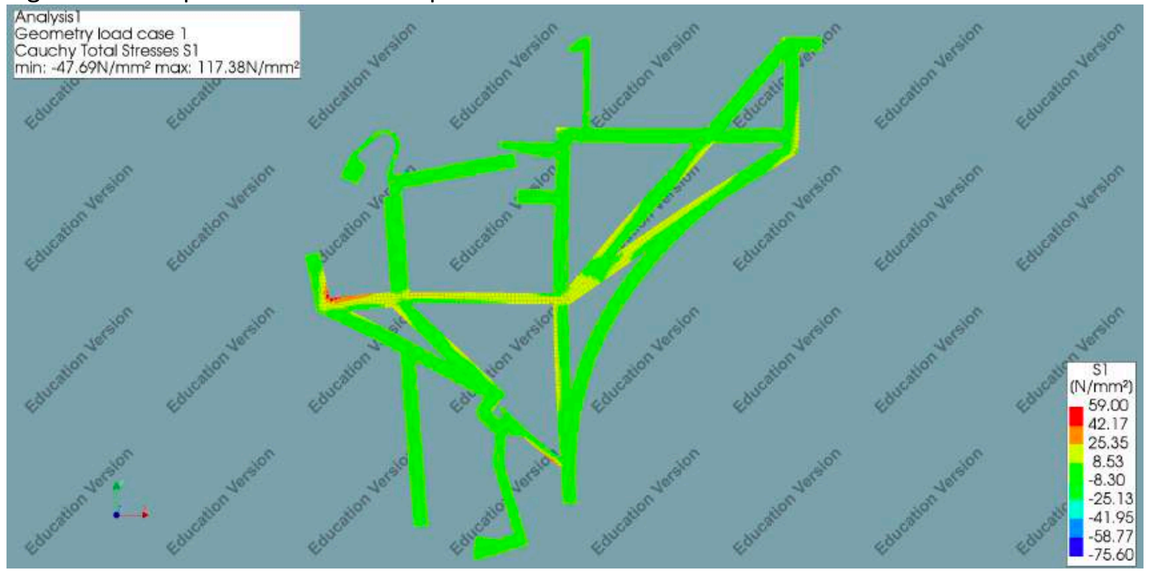


Figure 228: Tensile stresses 30mm depth

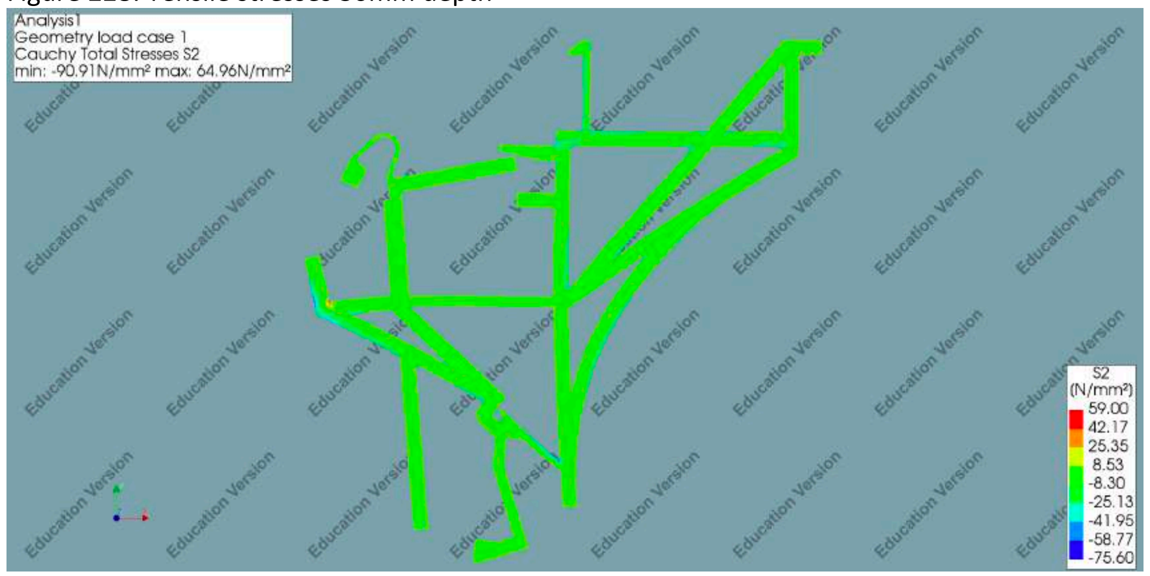


Figure 229: Compressive stresses 30mm depth

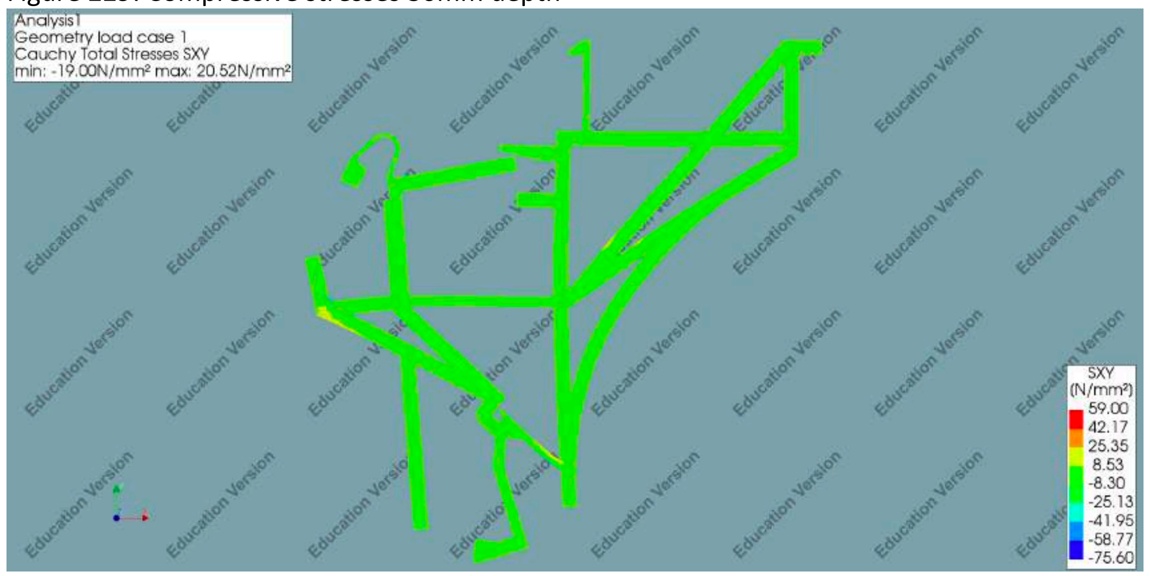


Figure 230: Shear stresses 30mm depth

Results compressive analysis

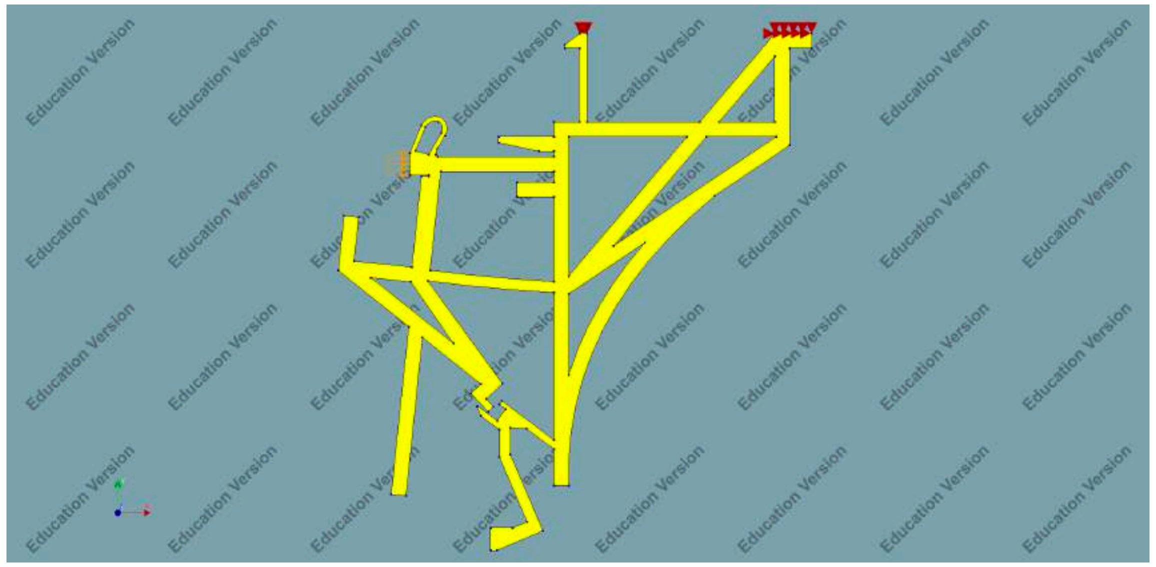


Figure 231: Geometry

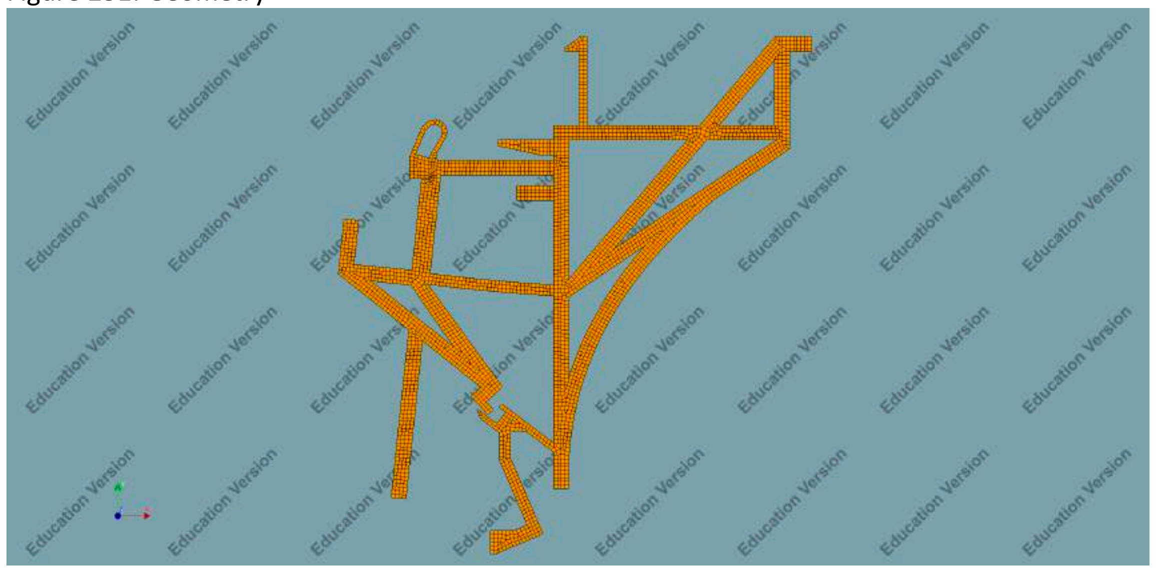


Figure 232: Mesh geometry

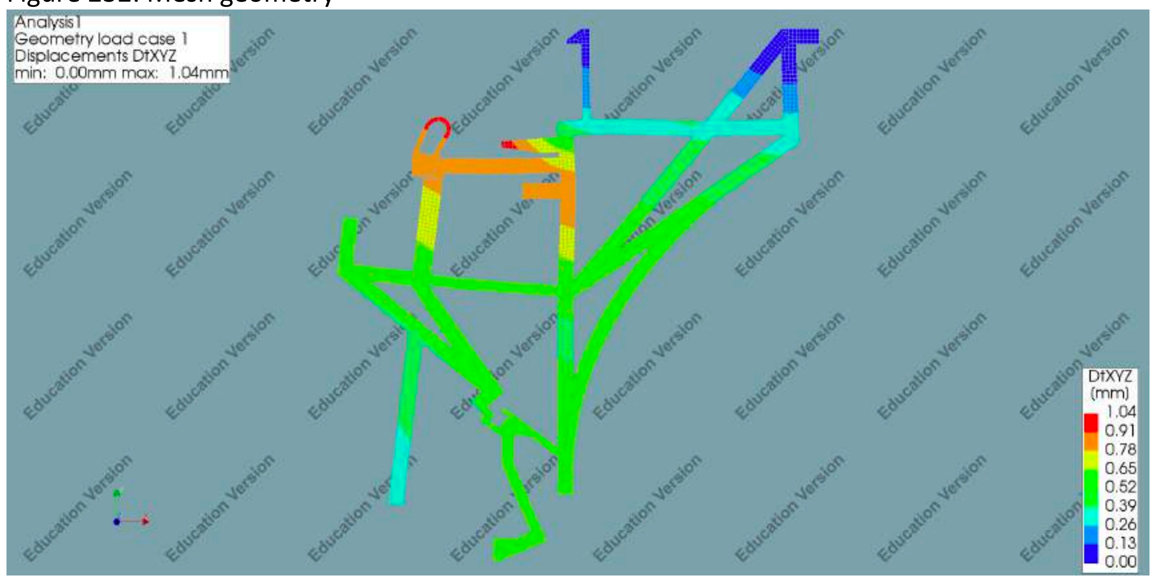


Figure 233: Displacement 30mm depth

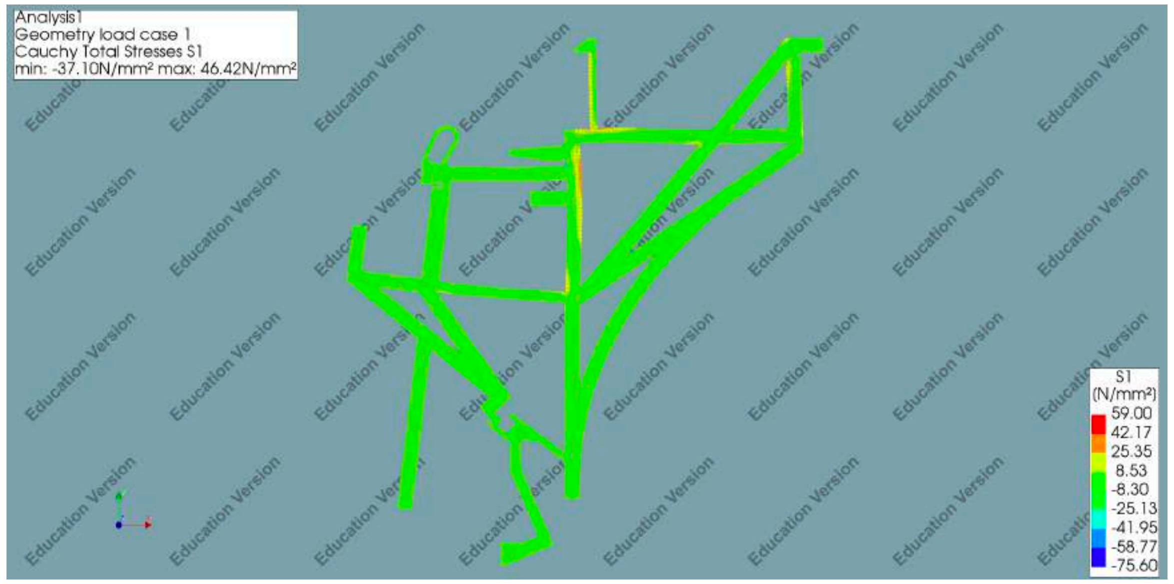


Figure 234: Tensile stresses 30mm depth

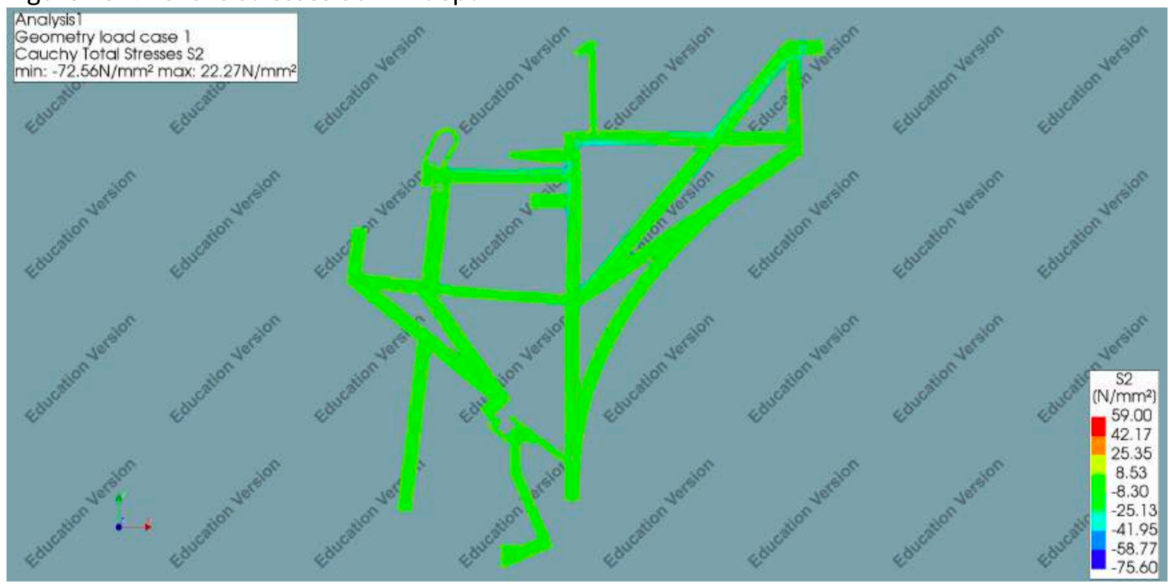


Figure 235: Compressive stresses 30mm depth

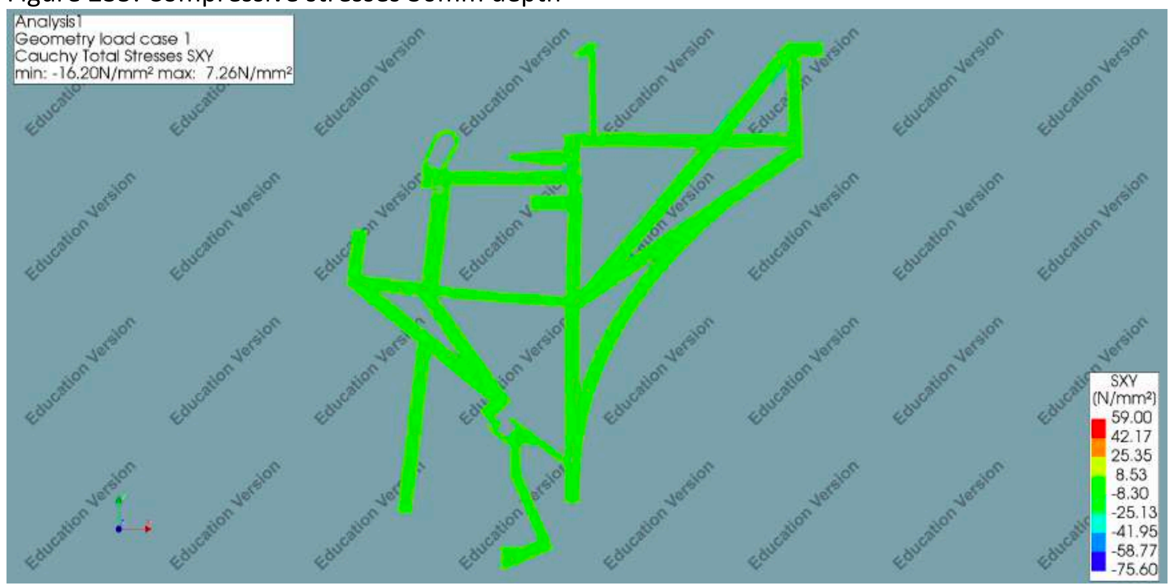
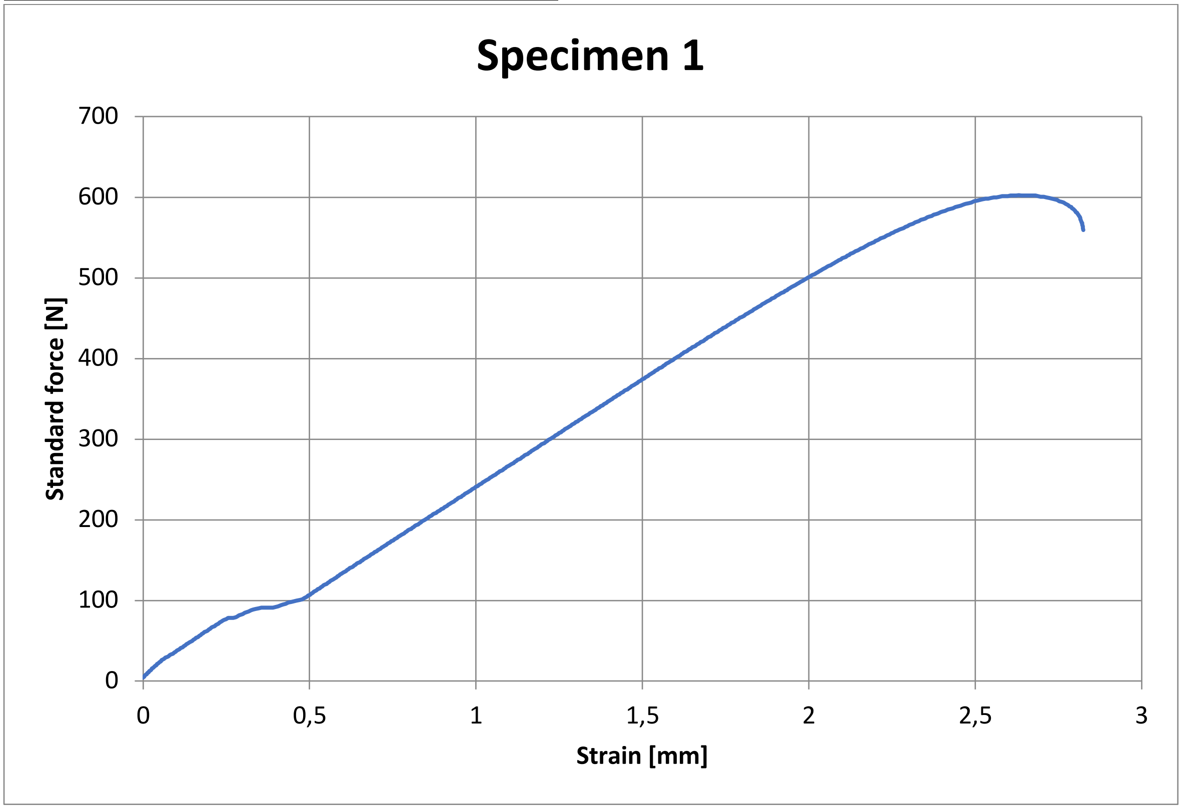
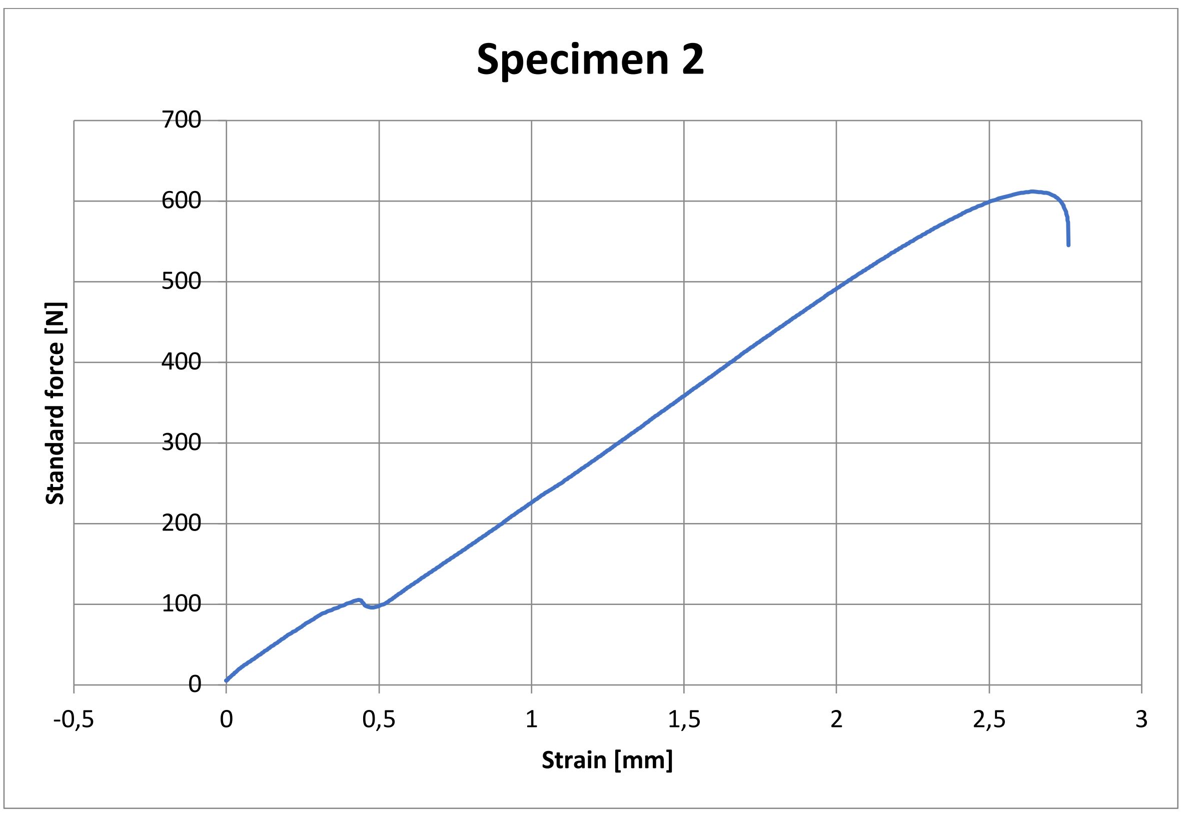


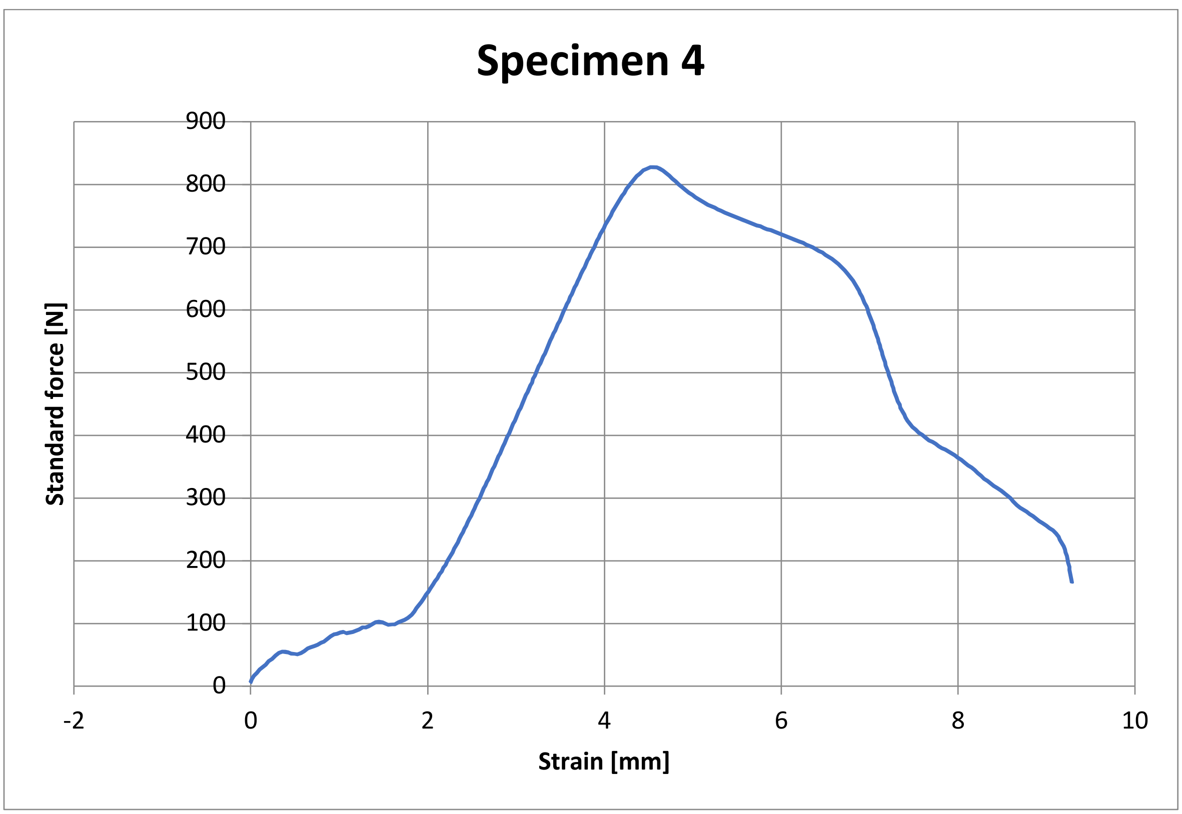
Figure 236: Shear stresses 30mm depth

Appendix VII: Graphs practical test

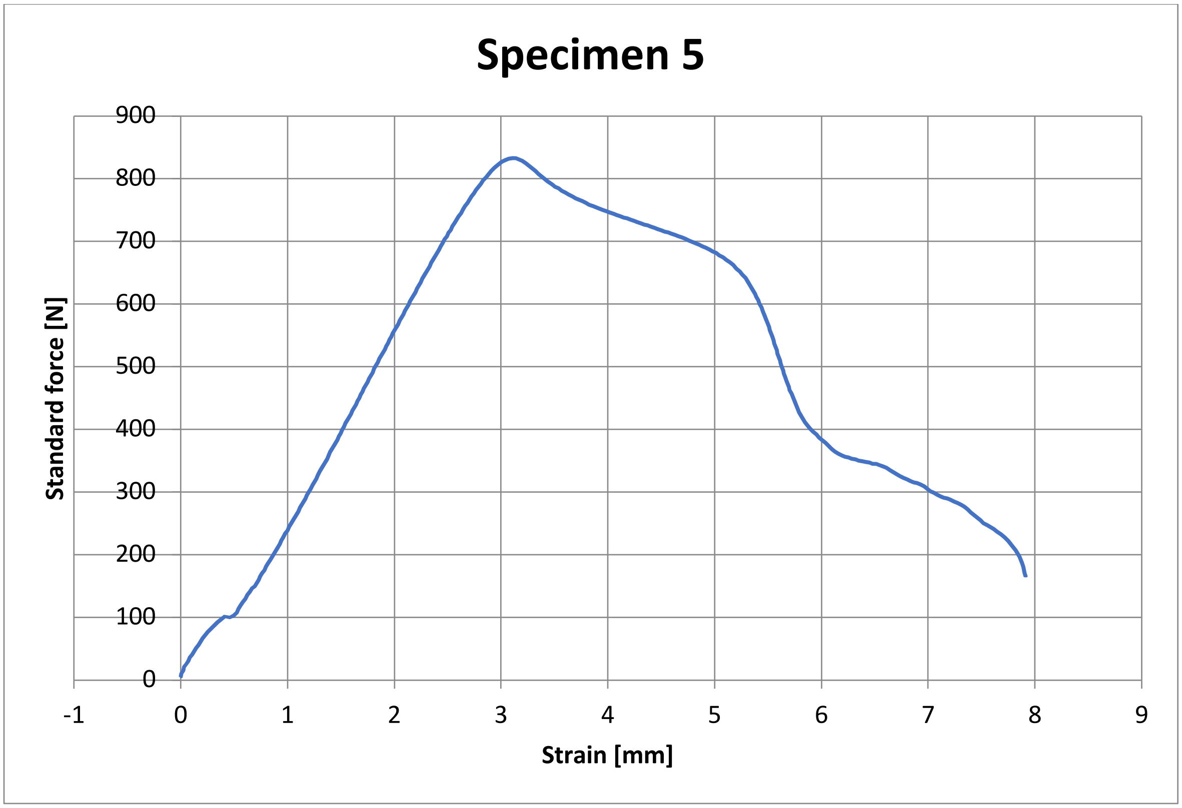


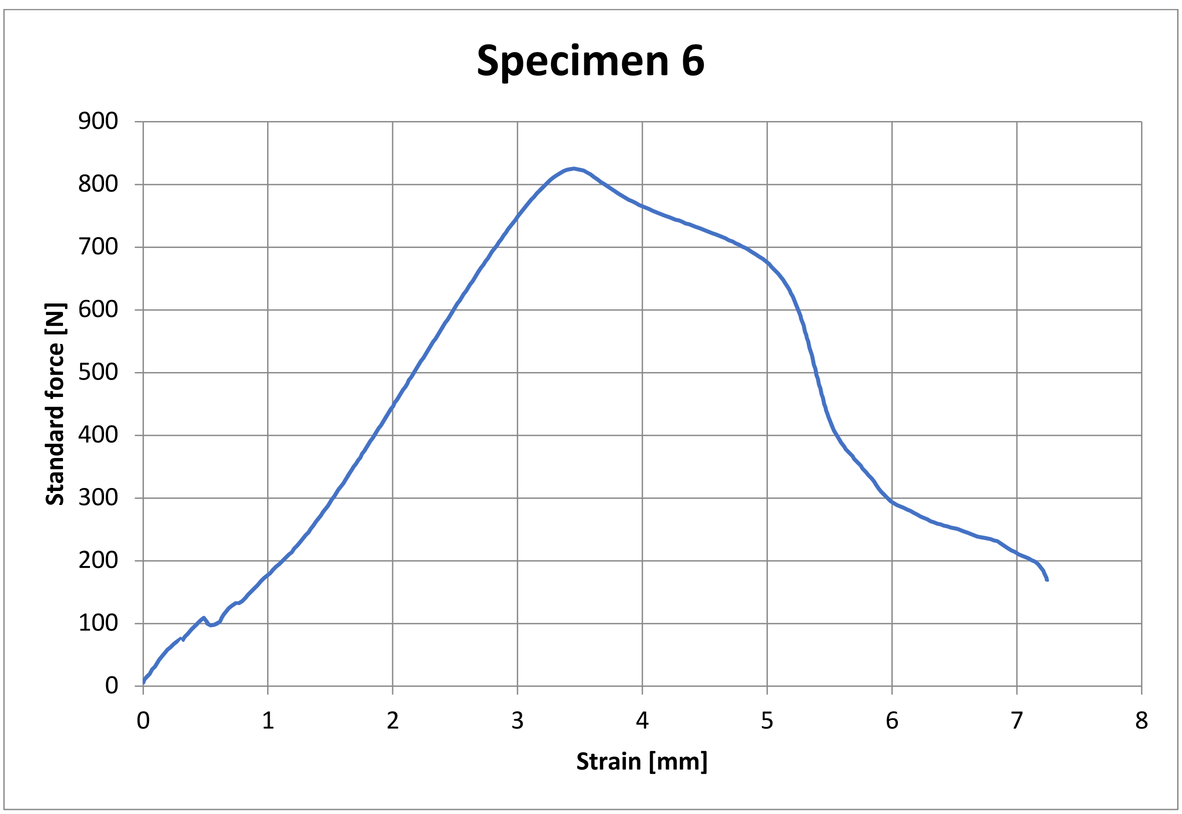


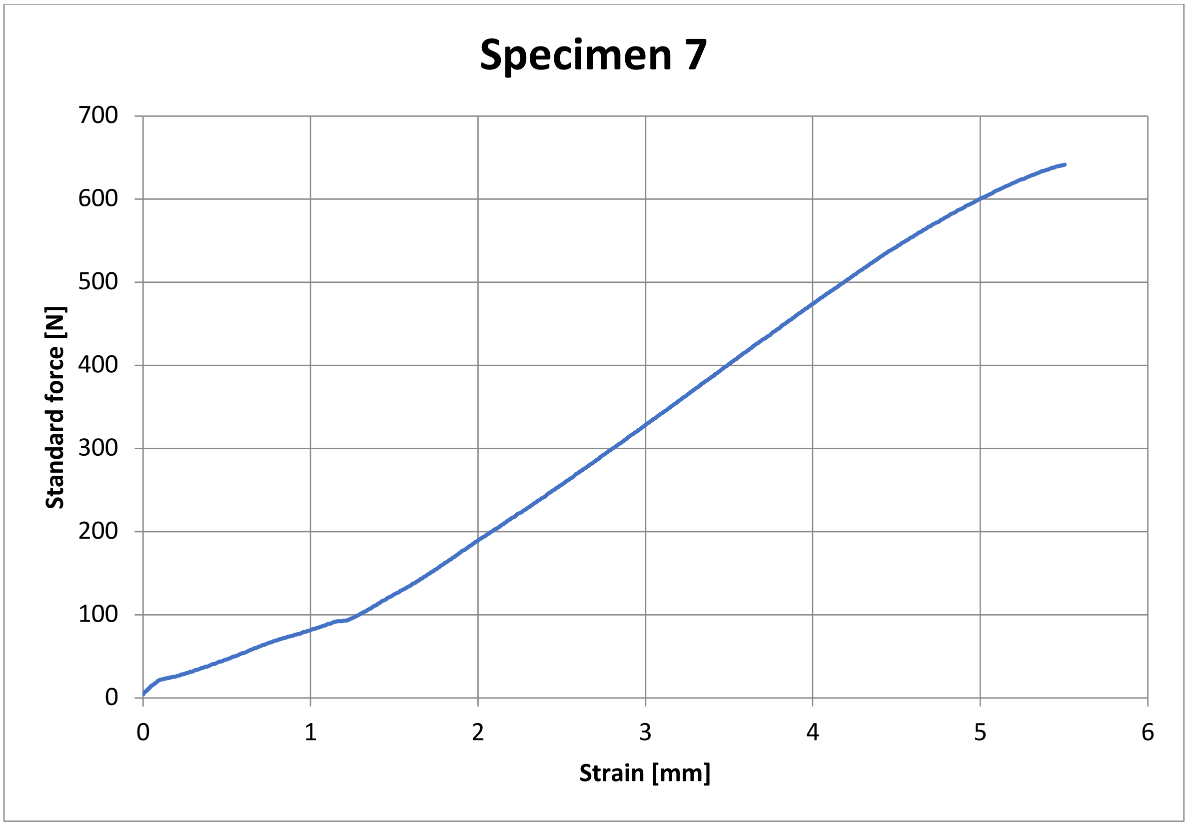
Specimen 3
Standard force [N]
600
500
400
300
200
100
0
-0,5
0
0,5
1
1,5
2
2,5
3
Strain [mm]



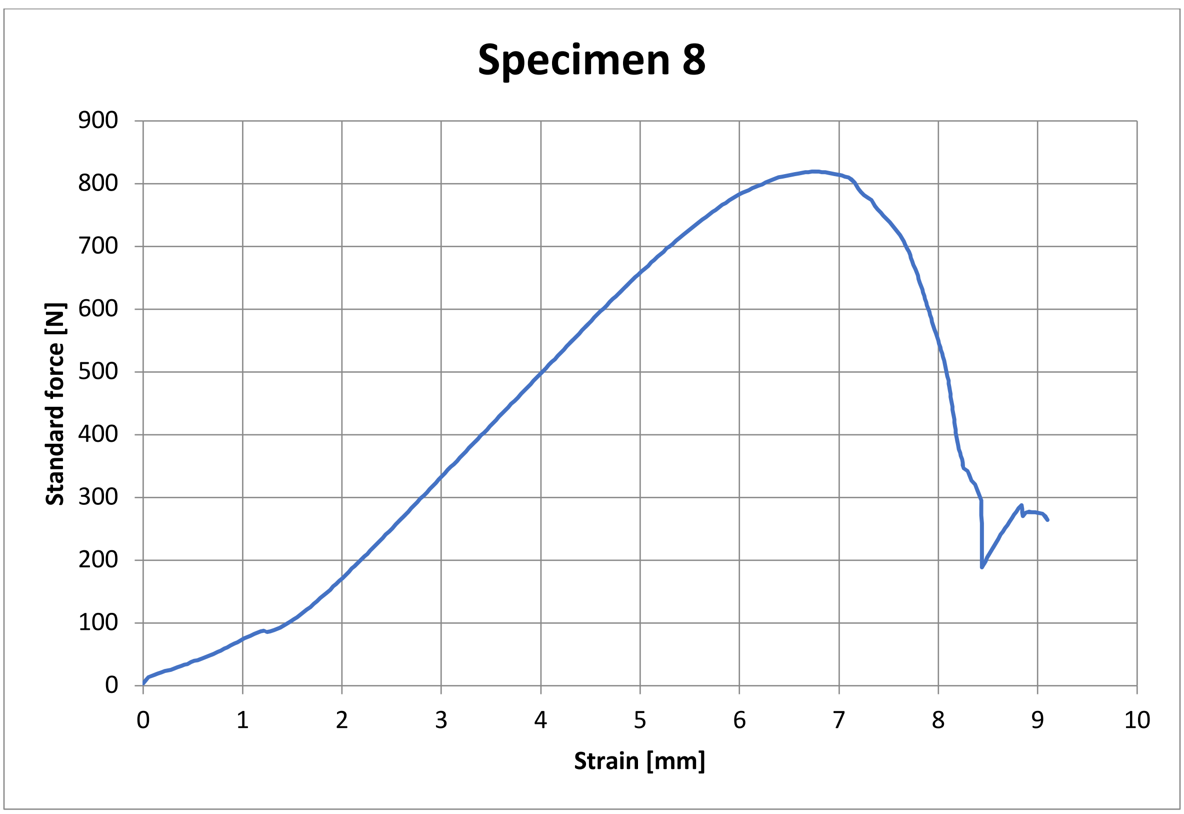
Specimen 4
Standard force [N]
900
800
700
600
500
400
300
200
100
0
-2
0
2
4
6
8
10
Strain [mm]


Specimen 5
Standard force [N]
900
800
700
600
500
400
300
200
100
0
-1
0
1
2
3
4
5
6
7
8
9
Strain [mm]

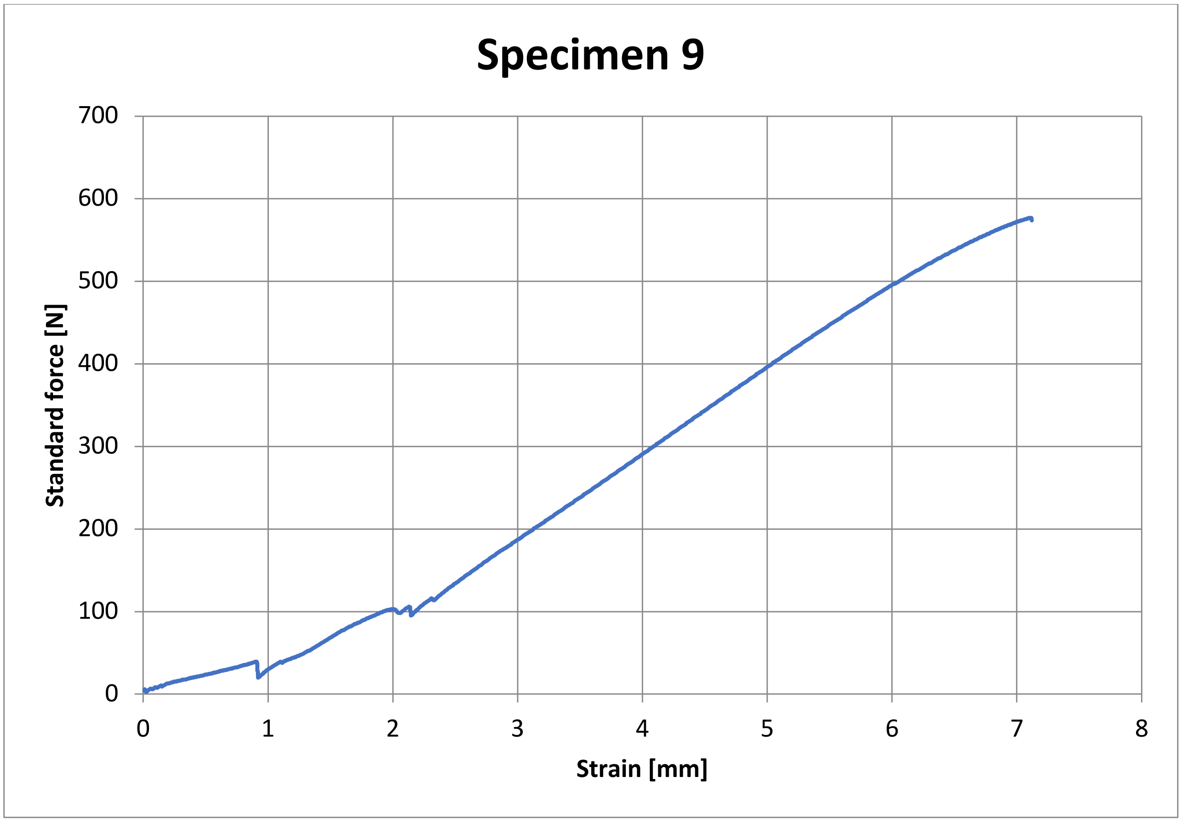

Specimen 6
Standard force [N]
900
800
700
600
500
400
300
200
100
0
0
1
2
3
4
5
6
7
8
Strain [mm]



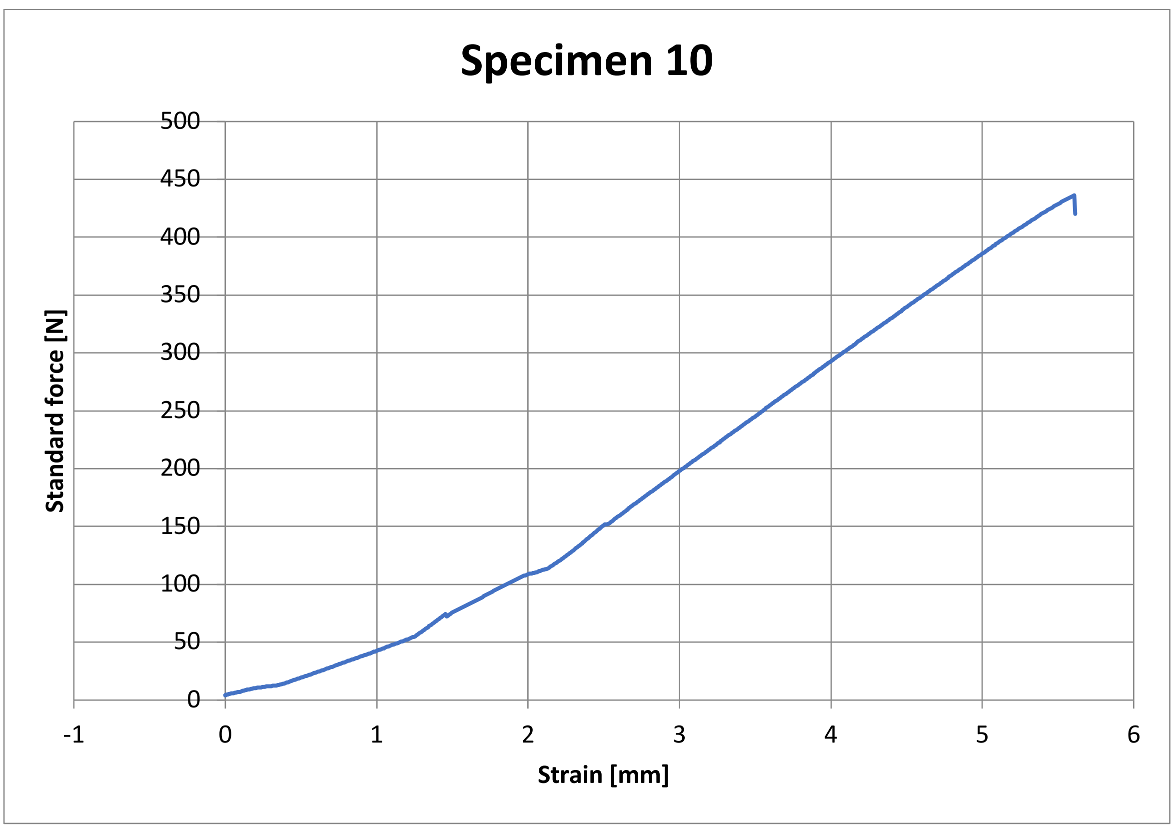
Specimen 7
700
600
500
400
300
200
100
0
0
1
2
3
4
5
6
Standard force [N]
Strain [mm]



Specimen 8
900
800
700
600
500
400
300
200
100
0
0
1
2
3
4
5
6
7
8
9
10
Standard force [N]
Strain [mm]

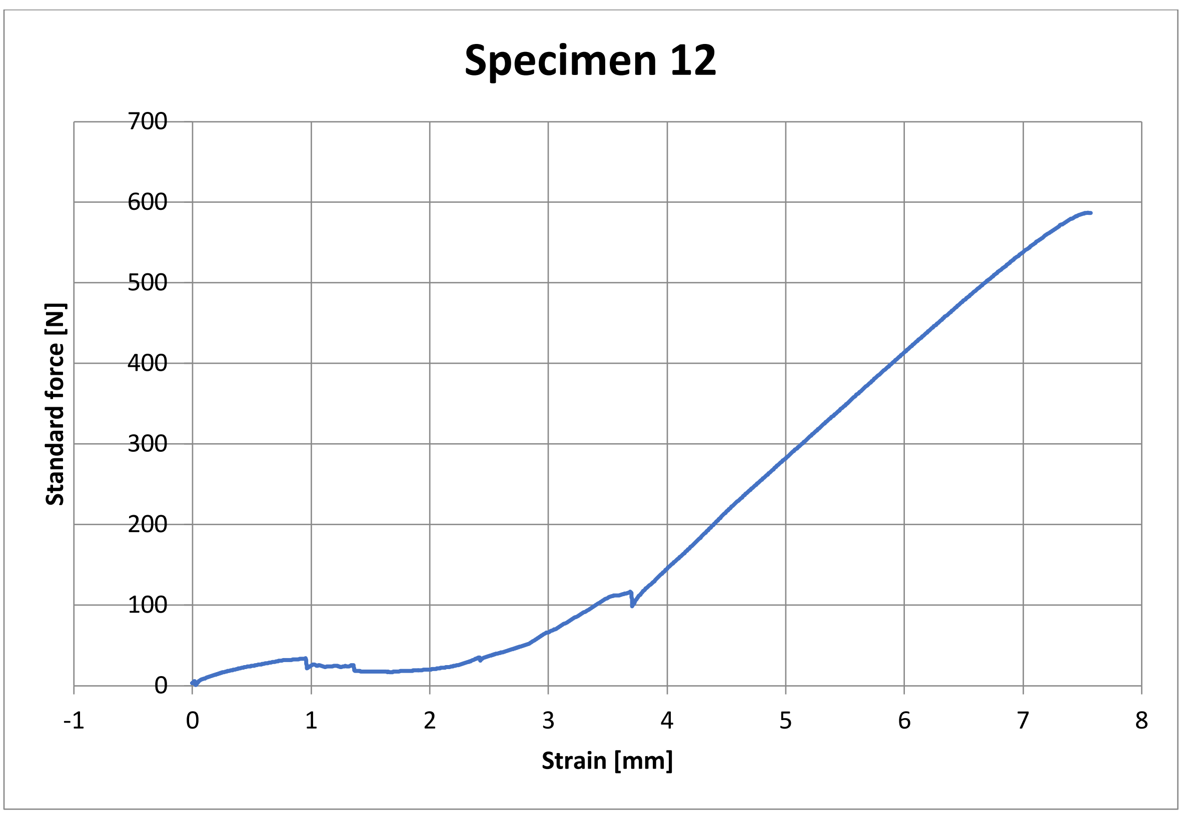


Specimen 9
Standard force [N]
700
600
500
400
300
200
100
0
0
1
2
3
4
5
6
7
8
Strain [mm]

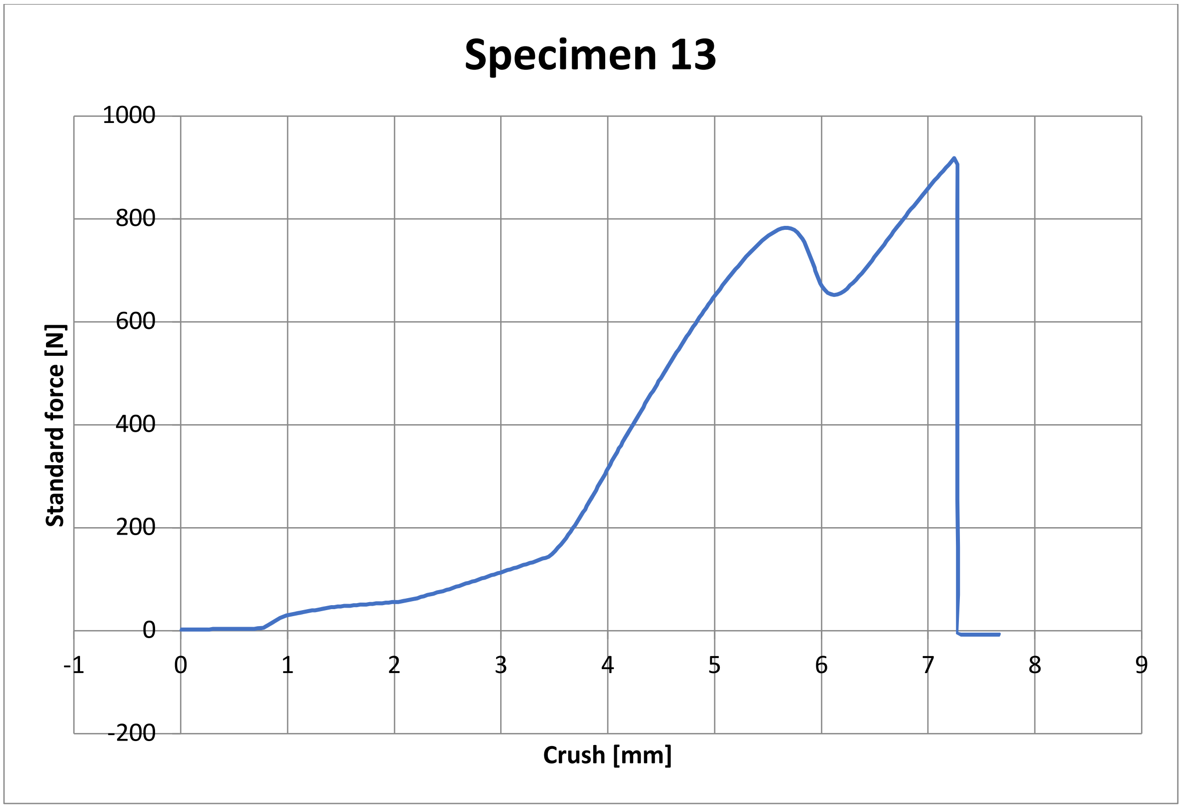


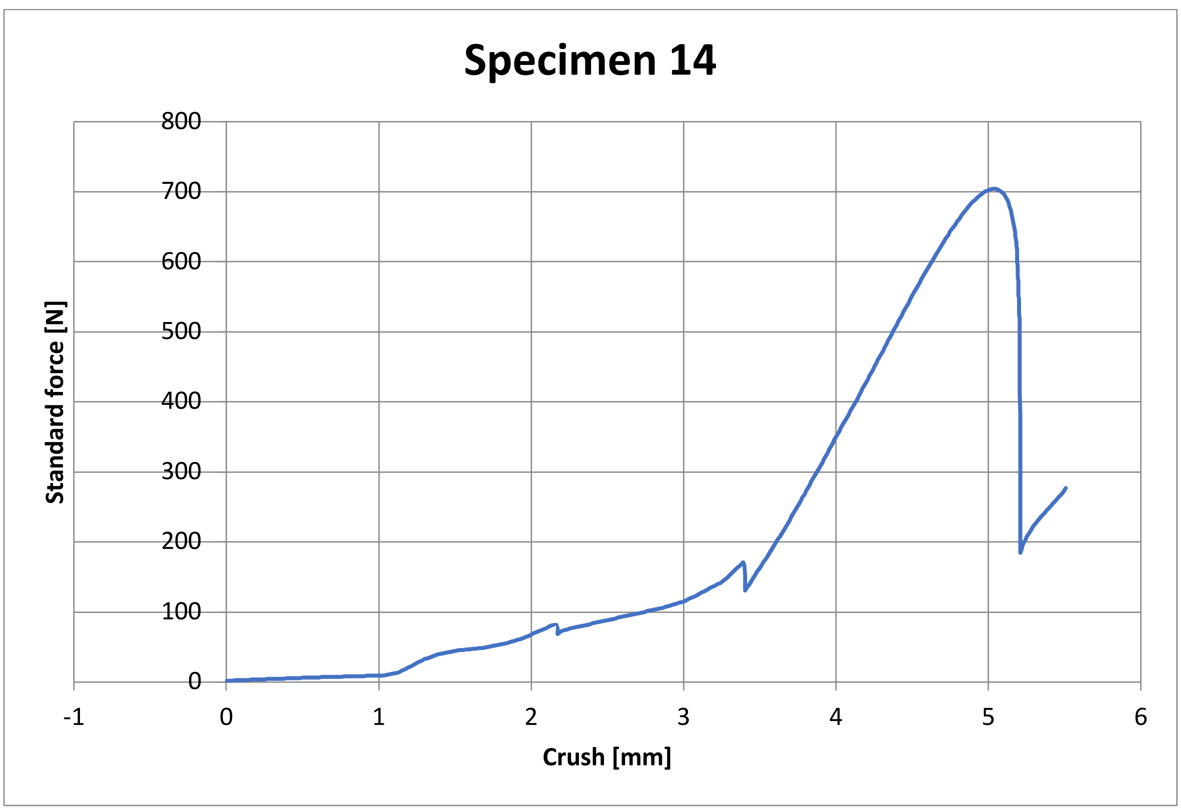
Specimen 10
Standard force [N]
500
450
400
350
300
250
200
150
100
50
0
-1
0
1
2
3
4
5
6
Strain [mm]

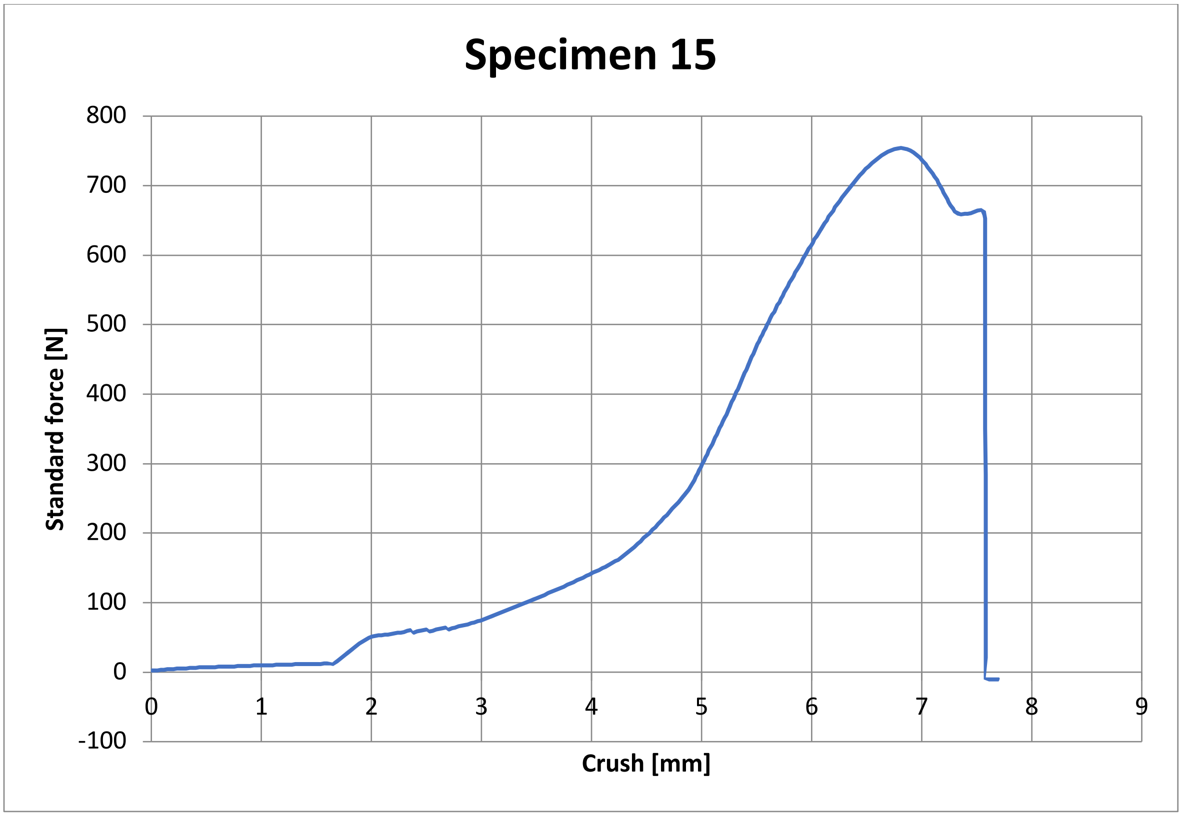
Specimen 11
Standard force [N]
350
300
250
200
150
100
50
0
0
0,5
1
1,5
2
2,5
3
3,5
4
4,5
Strain [mm]

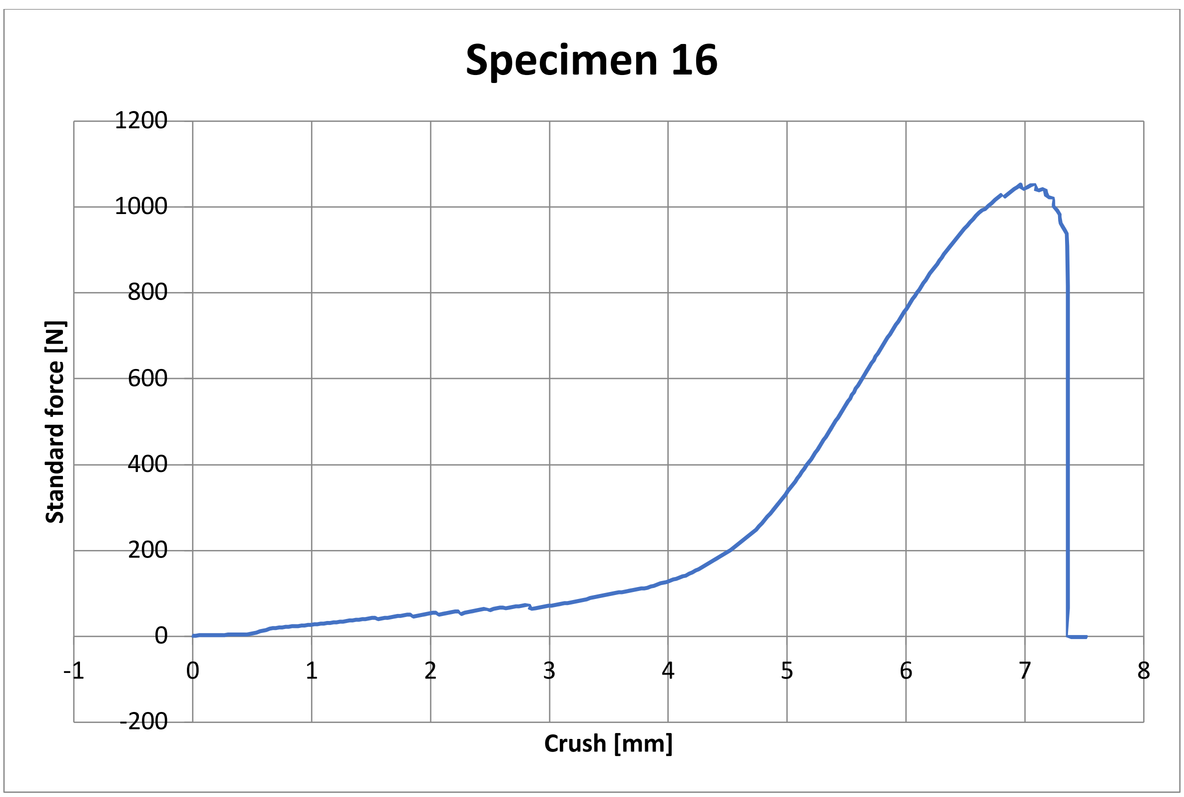


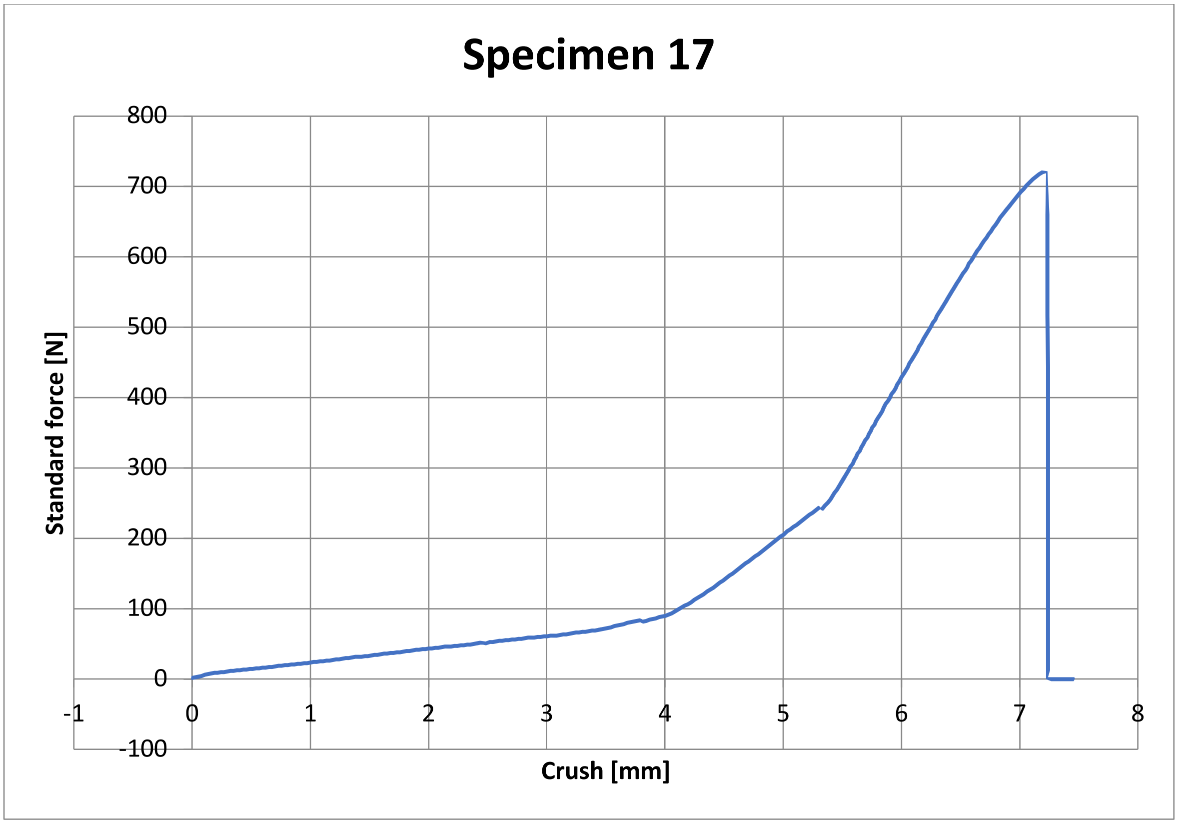
Specimen 12
Standard force [N]
700
600
500
400
300
200
100
0
-1
0
1
2
3
4
5
6
7
8
Strain [mm]


Specimen 13
Standard force [N]
1000
800
600
400
200
0
-200
-1
0
1
2
3
4
5
6
7
8
9
Crush [mm]


Specimen 14
Standard force [N]
800
700
600
500
400
300
200
100
0
-1
0
1
2
3
4
5
6
Crush [mm]


Specimen 15
Standard force [N]
800
700
600
500
400
300
200
100
0
-100
0
1
2
3
4
5
6
7
8
9
Crush [mm]


Specimen 16
Standard force [N]
1200
1000
800
600
400
200
0
-200
-1
0
1
2
3
4
5
6
7
8
Crush [mm]



Specimen 17
Standard force [N]
800
700
600
500
400
300
200
100
0
-100
-1
0
1
2
3
4
5
6
7
8
Crush [mm]