Wood-LOM

Using laminated object manufacturing to reimagine the use of wood

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Rienk Feenstra
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1. Introduction

The amount of global carbon dioxide emissions has increased by almost 50% since 1990. The effect this large growth has on the environment and climate is enormous. To be able to reach the goal of being net zero on the emissions of greenhouse gasses at 2050, we have to make radical changes to the way we live. The construction industry is responsible for approximately 15% of the emission of greenhouse gasses. The choice of material is an important factor in the total amount of pollution (Arup, 2019).

Wood is known to be one of the oldest building materials used, but is in no way a material of the past. While in the past wood was mostly used as fairly simple beams and planks, nowadays the amount of possibilities of building with wood are vast. Engineered woods like cross-laminated timber (CLT), laminated veneer lumber (LVL), and glue-laminated lumber (glulam) provide improved structural performance and are all able to cater to different requirements. Also smaller formfactor panel types like plywood and orient strand board (OSB) are a wooden alternative to other building materials. This provides architects and engineers with tools to be able to use wood in new and creative ways.

This development in engineered wood is partly motivated by its positive effect on the emissions of a building project. During its growth, a tree stores carbon dioxide in its material. If responsibly sourced, wood can be a sustainable and reliable alternative to concrete and steel in certain applications. The carbon stored in the wood will then be stored in the built environment, creating a CO_2 buffer. When more wood is used, more trees have to be planted resulting in more CO_2 storage and a larger buffer.

In construction it is already customary to exchange parts made of concrete or steel for wooden alternatives, such as columns, beams, and floor elements. Some parts, however, remain reliant on steel or concrete. Therefore it is valuable to do more research into ways to be able to use wood as an alternative material. For connective elements in construction, steel is still the material of choice. This research focuses on providing a way to use wood as an alternative to steel connective elements.

Within the construction industry there is a growing amount of development in using additive manufacturing (AM) as a construction method. With growing developments of AM in the shape of for example 3D printing, new possibilities of using AM contribute to new possibilities regarding the construction of elements. While this technique was originally developed for rapid prototyping using polymers, it is now also used for making final products with a large variety of materials like metals, ceramics, and even wood-like materials (Gibson, 2021). For 3D printing in wood however, there is still a lot of research to be done. It could even be argued, that 3D printing is not the best way to create wooden elements.

Another rapid prototyping AM method, is Laminated Object Manufacturing (LOM). This process uses the cycle of laminating a thin layer of material on the object and cutting out the contour of that layer. Repeating this process creates the desired geometry. For this method, the material has to be fed in thin layers. Wood can be processed in several ways such as beams and planks, but also in thin veneer. This thin veneer could be suited to be used in an LOM process. This thesis focuses on the possibilities, advantages, and practicalities of using LOM for creating wooden elements to be used in the built environment.

2. Research framework

Problem statement

The production of steel is an energy-intensive process and is one of the biggest producers of CO_2 emissions. The iron and steel industry amounts to 7.2% of the total CO2 emissions worldwide, which makes it the biggest CO_2 emitter of all the building processes (Ritchie et al., 2020). Therefore, reducing the need for steel in the built environment is desirable. Complex wooden structures often need steel connection elements to create a solid connection between the wooden parts. Being able to manufacture these connection elements out of wood would be an improvement for reducing the carbon footprint of a building.

While computerized numerical control (CNC) milling and 3D-printing wood have created new possibilities in building with wood, they both have drawbacks that make them unsuitable for producing complex wooden connection elements. CNC milling is an effective way to manufacture wooden elements, but in the current form, it is mostly limited to producing sheet elements. 3D printing with wood is gaining a lot of ground, but in its current form, it is not yet ready to be used as a reliable construction material.

Laminated Object Manufacturing is a way to create complex objects by laser cutting layers and laminating the layers to form a final object. This method builds up an object by cutting layers of the final model and laminating them to assemble the 3D geometry. While this method is currently only used with paper, plastic, or metal, the technique has the potential to be used with wood. Research is needed to indicate the possibilities and limits of using this technology to create complex wooden connection elements.

Goal of the research

The goal is to create a connection element made completely from wood, preferably with a wood-on-wood connection to the rest of the wooden structure. The final design will result in an example of a reliable wooden connection element that can be manufactured by LOM technology. This element needs to be able to be used in a wooden structure, replacing a conventional steel node. Also, the limited use of steel (or other materials) in the connection will be researched, to see the potential of a hybrid structure while causing a drastic reduction in the use of steel or other materials than wood in the final product.

As a final product, one or more physical models will be made to visualize what the final product could look like. This will be a 1:1 model of one of the final designs. This will be a model that also incorporates the connection to the rest of the structure. If the most relevant part of the design is inside the geometry, a cross-section model of the design should be created.

The main motivation for replacing the steel connection elements is to reduce the CO2 impact of the materials used for construction. While wood is a more sustainable material in the aspect of CO2 emissions during production, the LOM technology could prove to result in a less sustainable end product. This would not, however, render the research a failure. The benefits of being able to manufacture a mono-material wooden construction could still provide other benefits, like aesthetic quality.

Research questions

Main research question:

How can Layer Object Manufacturing (LOM) technology be used to create wooden nodes for timber structures?

Sub questions:

What are the advantages and limitations of manufacturing wooden elements using LOM?

What are the design parameters for constructing a solid wooden connection element using LOM?

What methods can be used to create reliable connections between a wood-LOM produced node and a timber structure?

Research methodology

Literature research

The literature research will function as a source of knowledge for the design. The research will focus on three main subjects.

Laminated object manufacturing

Research will be done in the field of the additive manufacturing method LOM. The knowledge gained from this research will function as the base for the design and production of the final geometry. During this research, key factors of the process will be investigated. They will be used to make decisions regarding the usability of wood as a material in this process and the manufacturing parameters.

Wood veneer and laminated wood

Wood in the shape of veneer is the most suitable form of wood to be used as a material for the wood-LOM process. Knowledge about the characteristics of various types of wood will be needed to be able to make decisions regarding the usability of the material in the wood-LOM process. The geometry created with wood-LOM is expected to have similarities with laminated wood like multiplex. Therefore, research into types of laminated wood will be done for comparison.

Material connections

Research into connecting nodes to constructions will be done to identify the possible methods of connecting a wood-LOM produced geometry to a wooden construction. The possible benefits of a wood-LOM produced construction node could be used to optimize the performance of the connection.

Research by Design

While the literature research forms a basis for the design of the element, the element that is created will also be researched. The designs will be tested on their behaviour under various stresses. This performance forms the base for design improvements, which then will be evaluated again to measure the possible improvement.

3. Laminated object manufacturing

In 1987, Michael Feygin filed a patent describing a process that would later be named laminated object manufacturing (LOM). In 1990 this process was commercialized by a company called Helisys, which is nowadays known as Cubic Technologies. (FabCentral, n.d.)

LOM is an additive manufacturing process that builds a model by adding thin layers of sheet material, often paper, polymers, or metal, and laminating it (figure 1). A sheet of material is rolled onto the model. The sheet is then pressed on the model by using a heated roller to laminate the new layer to the object, using a heat-sensitive polymer binder as an adhesive. The shape of the desired layer is then cut out of the sheet material to form the desired geometry. The sheet surface area outside of the desired shape is cut in a crosshatch pattern. During the lamination process these crosshatched areas provide support, but are also easy to remove after the process is finished (Granta EduPack, 2021; Mekonnen, 2016).

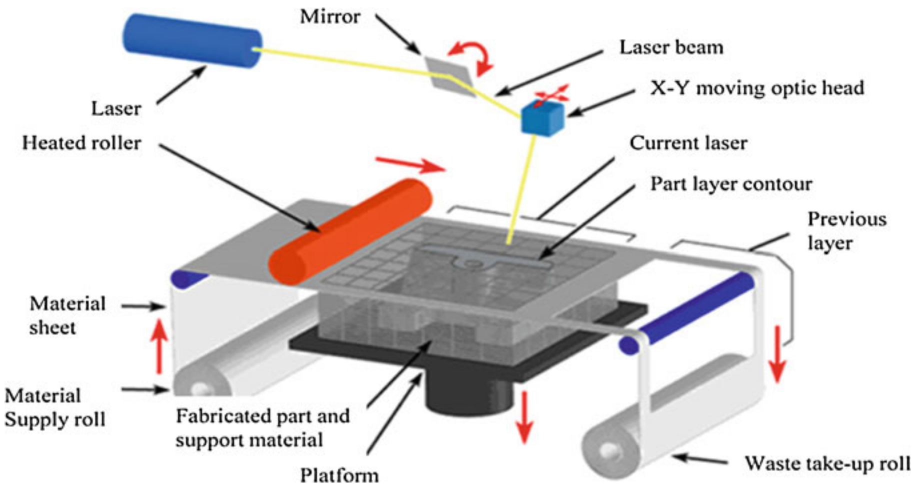


Figure 1 - Laminated object manufacturing (LOM) (Mekonnen, 2016)

This process has a lot of benefits over other additive manufacturing methods. The process is quite fast since only the outline of the model has to be traced, along with a grid to remove the remaining material around the object. Therefore this method can fabricate complex geometries with relatively low costs and production time. Furthermore, the use of a laser for cutting the material provides a lot of precision in the horizontal plane. The building envelope ranges up to 6050 x 2045 mm, with unlimited size on the Z-axis (Granta EduPack, 2021; Mekonnen, 2016).

Materials used with LOM
Various types of materials are used with LOM, but the most common types are paper, various types of plastics, and even sheet metal. The most important requirements for a material to be used with LOM are:

> It is available in sheets.
> It is possible to cut the material with a laser cutter.
> It is possible to laminate the material using a binding polymer.

Drawbacks and limitations of LOM

A drawback of this method is the fact that it produces a large amount of support material outside of the geometry which is not used in the final geometry (figure 2). Because this unused material is a mix of sheet material and adhesive, it could prove difficult to recycle this material to be used again. This drawback could be mitigated by cutting the desired shape of the layer first and then laminating it to the geometry that is already formed. This does require a way to orient the new layer onto the object in the desired position. This adds complexity to the process and adds a point of failure.

Figure 2 - Removing support material (Gibson et al., 2016)

While the level of detail of the geometry in the X and Y-plane is limited to the precision of the laser cutter, the resolution of the vertical Z-plane is limited to the layer thickness. The consequence of this fact is that there is a decision to be made about layer thickness of the geometry. A higher layer thickness results in a lower resolution in the Z-plane, but requires less layers of material to be laminated and cut. On the other hand, a smaller layer thickness results in a higher resolution in the Z-plane (figure 3). This does however, require more layers to be laminated and cut. This also causes the final geometry to have a higher amount of adhesive present. When choosing the layer thickness of the desired geometry, these factors and their effects will have to be taken into account.

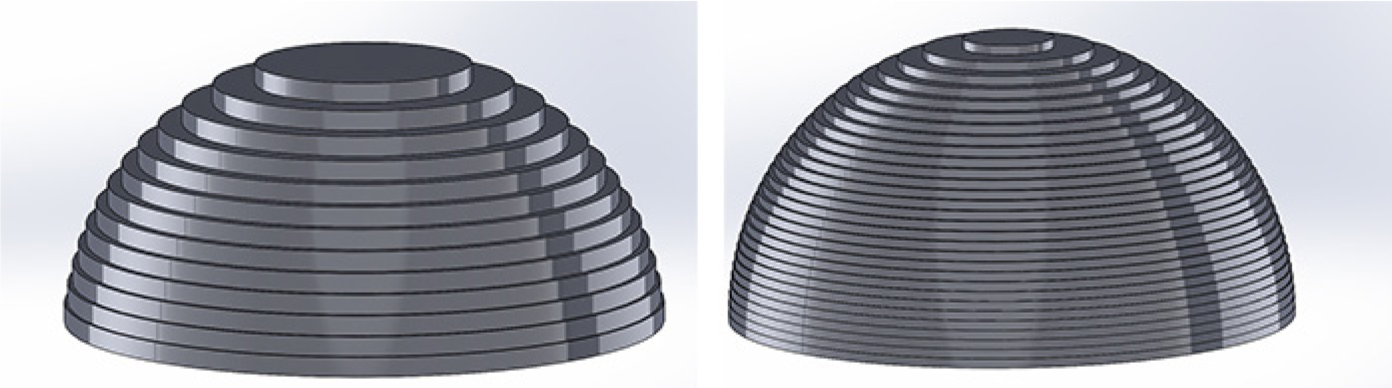


Figure 3 - The effect of layer thickness on the vertical resolution of an object (Verkstan, 2015)

Because of the use of a laser, there is also an inherent fire risk, which requires appropriate precautions (Gibson, 2021). The heat of the laser could also have undesirable effects on the material, which could warp as an effect of the large amount of heat. The heat could also affect the adhesion process, as heat sensitive adhesive polymers could cause delamination of part of the object (Mekonnen, 2016). This drawback could be mitigated by choosing a smaller layer height. A thinner layer would require less energy, and thus heat, to be able to cut the material.

4. Veneer and laminated wood

Wood is the material found in the trunk, stems, branches, and roots of trees and woody plants. The material is a natural composite made of cellulose fibres and lignin. The cellulose fibres provide tensile strength to the material, while the matrix of lignin gives the material compressive strength. The term wood is sometimes only used for the inner hardened part of the tree that is more than one year old (Henslow, 1856).

Most of the wood that is used for construction comes from the trunk of a tree. Wood can be cut in several ways, depending on the needed size, structure, or pattern. Wood could be, for example, cut in quarters or complete slices (figure 4). These are common ways to produce solid planks and beams made out of wood. A third option that can be seen in this figure, is a rotary cut. This method rotates the trunk around its longitudinal axis, while a blade cuts away material in long slices. This method is often used to produce veneer (lordfloor.com).

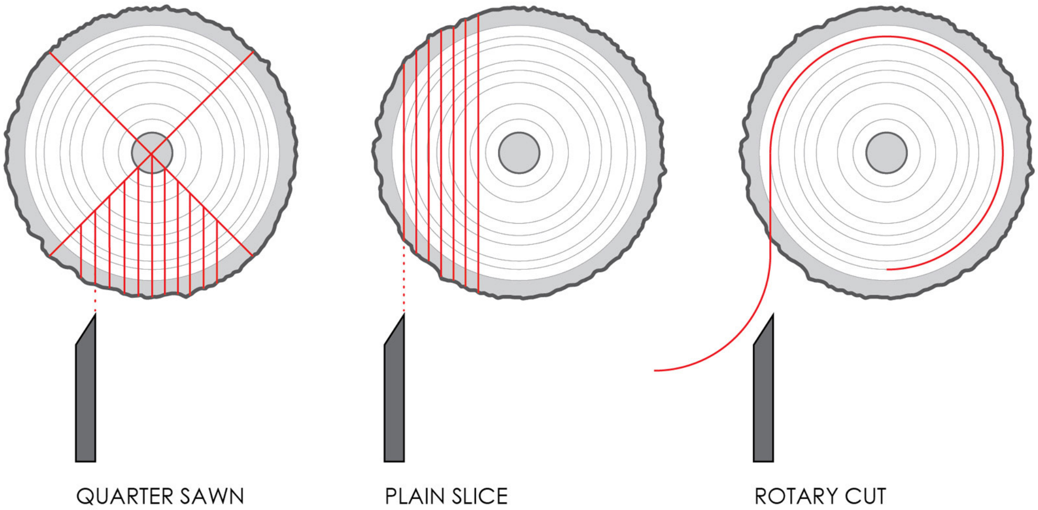


Figure 4 - Various ways of cutting wood (LORD PARQUET, n.d.)

Wood is an anisotropic material. An anisotropic material has seperate independant properties in three different directions (Ansell, 2015). These three axes (figure 5) are defined as the longitudinal, tangential and radial axis, with wood being signifficantly stronger along the longitudinal axis (Borglund Aspler et al., 2019). As the radial and tangential properties are similar when compared to the longitudinal properties, wood is often treated as an orthotropic material; a material with different properties in two perpendicular directions.

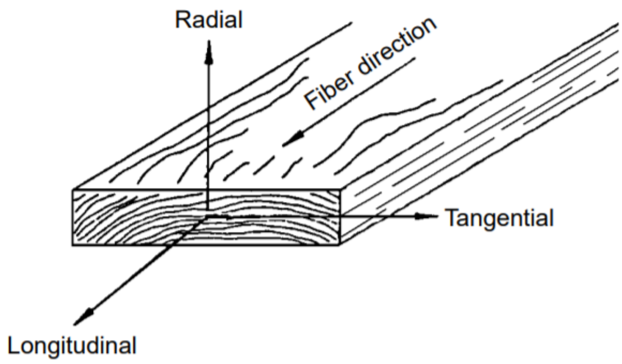


Figure 5 - The principle axes of wood (Borglund Aspler et al., 2019)

Wood veneer is defined as slices of wood which are thinner than 3mm (Ellis, 2010). However, often veneer is cut in a thickness of 0.6 - 0.8mm. Veneer can be cut in quarters and slices like planks, but as stated before, it can also be produced with a rotary cut. Which method of cutting is chosen, has an effect on the pattern that the veneer will have (figure 6).

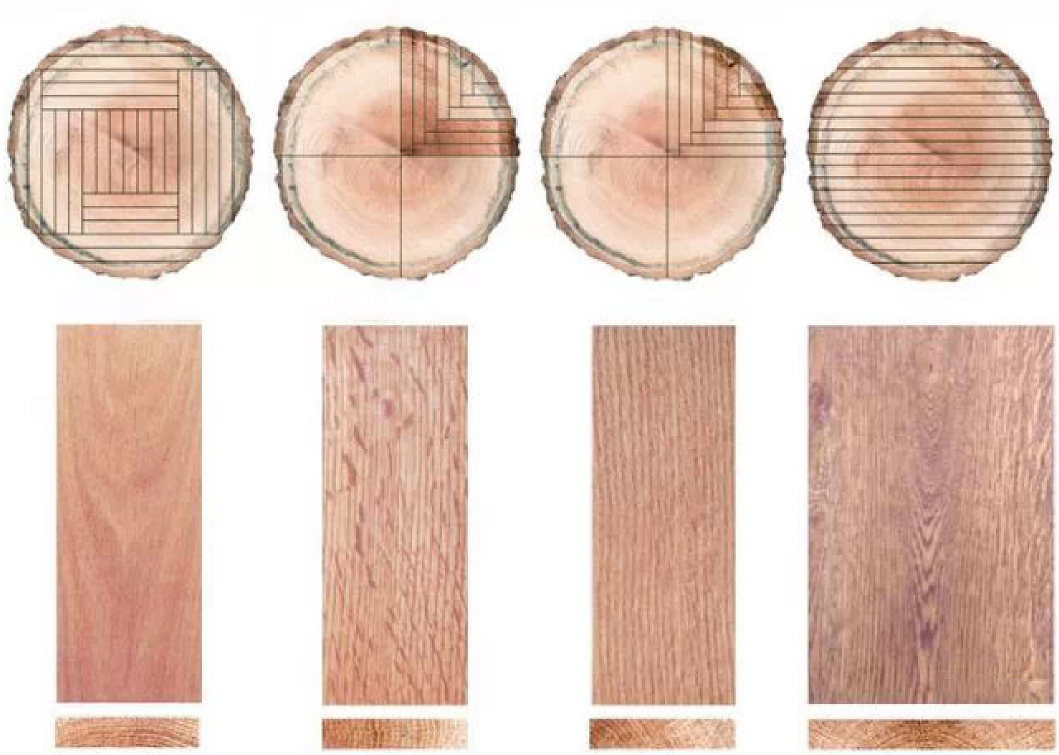


Figure 6 - Varying patterns per type of slice cut (LORD PARQUET, n.d.)

Wood veneer can be used for different purposes. Veneer from high quality wood is often used as a finishing layer on top of a core panel, for the purpose of giving it a luxurious appearance without making the entire object out of expensive wood. Wood veneer from cheaper types of wood is used to create plywood. For creating plywood, three or more layers of wood veneer are laminated with each layer placed perpendicular to the previous layer. This method causes the grain of one layer to be at a 90° angle to the ones adjacent to it. Therefore, the final panel provides strength in two directions instead of one, as is the case in solid wood. The combination of the cross-laminated layers of veneer combined with the strength of the adhesive used to laminate the layers, makes it possible to create panels that are both relatively strong and stiff compared to solid wood, while maintaining a small thickness. There is also another type of wood panel called laminated veneer lumber (LVL) which is made out of layers of veneer with a constant grain direction (figure 7). This material could be used in situations where strength along the axis is preferred.

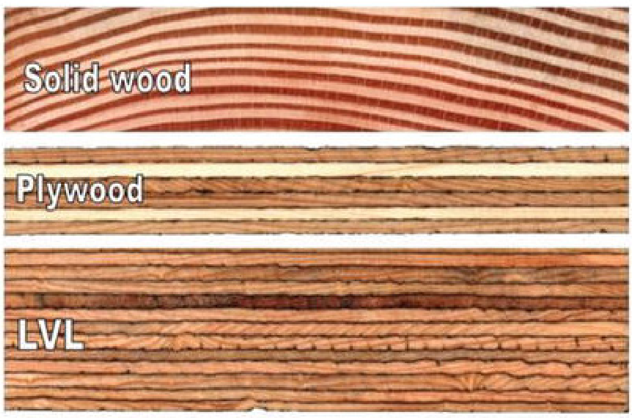


Figure 7 - Cross section of various types of wooden products (Vladimirova, 2022)

The production process of making plywood panels is almost completely automated. This makes the production process fast and therefore relatively cheap. The production process of plywood consists of several steps (figure 8) (Borglund Aspler et al., 2019). First, the logs are steamed. This makes the wood softer and therefore easier to cut. The logs are then put through a debarking process, which removes the outer layer of the log. The remaining inner wood is then cut with the rotary slicing method. The sheets produced by this cutting are then dried, scanned, and sorted. In the case of plywood, the sheets are then divided into two types of stacks. One stack will be rotated 90 degrees creating the cross-lamination principle. After applying adhesive the sheets are placed on top of each other in the alternating grain direction and laminated by pressing the material through rollers. Heating of the plywood panel will ensure the curing of the adhesive making a strong bond between the layers. After this curing process the plywood panels are cut in the desired dimensions and packed for shipping.

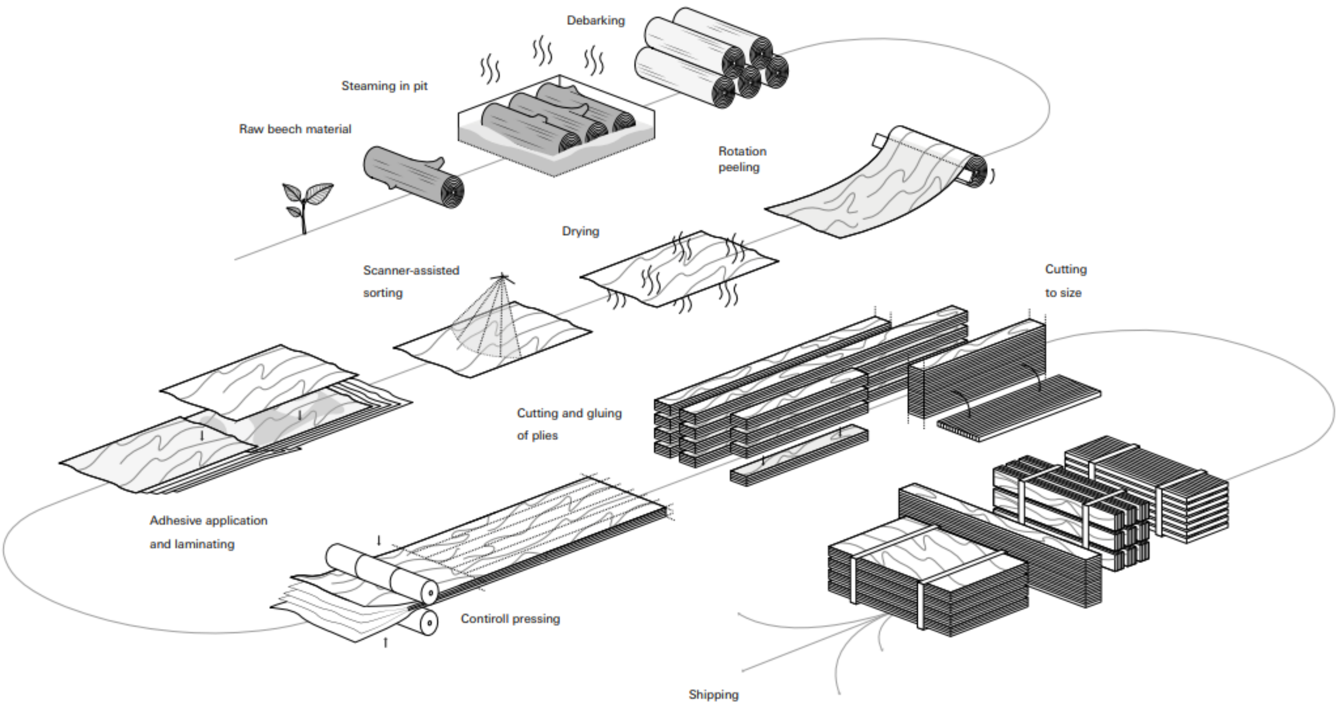


Figure 8 - Refinement process from log to engineered wood product (Borglund Aspler et al., 2019)

5. Wood-LOM

As stated before, the LOM process is mostly used with paper, polymers, and metal. However, the technique has the potential to be used with wooden sheets. In 2020, Stefan Schäfer submitted the patent 'Process and device for the additive manufacturing of a layered wood structure ' (2020). This document explains a method that could make it possible to use thin wood veneer for the LOM process. This process requires the shaving of wood and washing the material at a temperature between 40 and 90 °C. A schematic overview of the device required for this process can be seen in the figure 9.

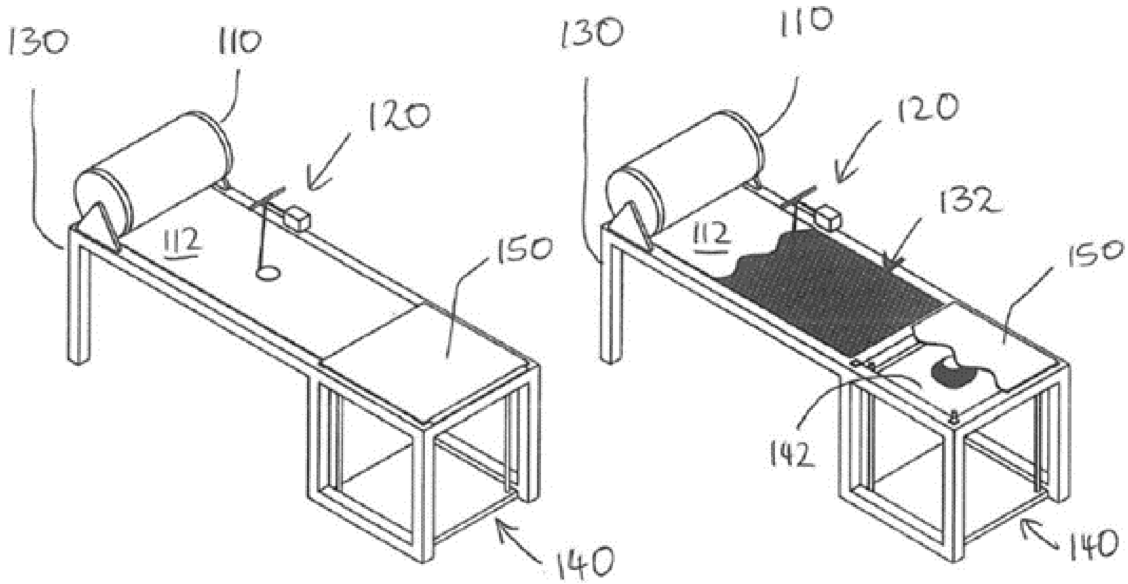


Figure 9 - Schematic overview of a device for a LOM process with wood veneer (Schäfer, 2020)

While this manufacturing method seems promising for the development of using wood with LOM technology, there are several possible improvements to make. One of the most notable improvements that can be made is changing the direction of the grain for each layer. By using thin veneer on a roll, all layers have the same grain direction providing strenght in one direction. Alternating the grain direction, as is done with cross laminated timber (CLT), could however provide a more uniformly strong object. This could be realized by rotating the object 90 ° after each added layer, or by feeding the layers alternating from two directions.

When structural rigidity is seen as more important than the resolution of the shape, thicker sheets of material could be used. Laser-cutting can be used with a wood thickness of 15 or even 20 mm. Thicker sheets would reduce the number of layers needed, reducing the total production time. Also, less adhesive would be needed to bond the sheet layers.

Furthermore, the bonding process could be expanded upon. Research could be done into the benefit of pressing the new layer on the object by creating a vacuum, with or without the use of a press. Also, different types of adhesives could be researched and tested.

6. Concept development

When using LOM it is possible to fabricate a vast range of geometries. If LOM is deemed to work with wood, research needs to be done into the suitability of different objects and geometries for wood-LOM. Additionally, it is important to evaluate the benefits of using wood-LOM compared to fabrication methods used to produce similar elements.

As stated before, it is desirable to limit the amount of steel used in constructions. A lot of building elements can already be replaced by using wooden elements, such as columns, beams, and floor elements. It is fairly easy to make connections between various elements by using steel elements as a connection.Using steel connection elements reduces the amount of engineering needed and therefore the cost of the project. Unfortunately, no alternative to steel connection elements is currently available. Replacing steel connection elements with wooden elements would largely reduce the use of steel. Therefore, steel elements were evaluated for their potential to be replaced by wooden elements.

Free-form structures
Free-form grid structures provide a way to give the architect a lot of flexibility to design exotic shapes. The availability of computer aided design (CAD) programs with powerful non-uniform rational basis spline (NURBS) functions increased the number of complex designs of free-form structures in recent years (Stephan et al., 2004). Stephan et al. (2004) defines different classifications of curvature, ranging in complexity: plane, simply curved, doubly curved synclastic, and doubly curved anticlastic (figure 10).

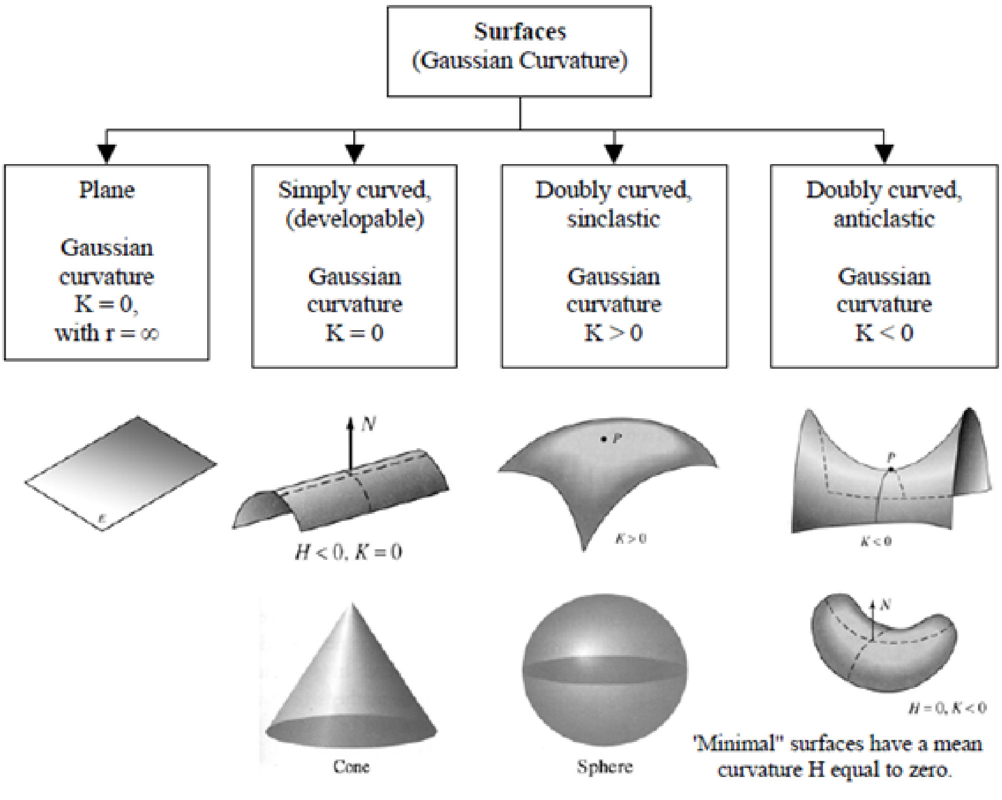


Figure 10 - Surface classification (Stephan et al., 2004)

The most complex surface, the doubly curved anticlastic surface, is the type that is most often seen in contemporary architectural designs. Most often, these complex free-form constructions are constructed with steel or other compact structural materials to be able to accommodate the high demands and complex shapes. Examples of such designs are the roofs of the New Fair in Milan (figure 11) and the Yas Hotel in Abu Dhabi (figure 12).

Figure 11 - The New Fair, Milan (Itinari, 2019)

Figure 12 - The Yas Hotel, Abu Dhabi (Basulto, 2022)

Free-form flowing structures are being increasingly constructed out of timber, with close to invisible joining methods. Examples are the Bunjil Place in Melbourne (figure 13) and the Swatch Office in Biel (figure 14). These constructions find their strength by interlocking the wood in a grid and creating large flowing shapes which strengthen the structure. These projects, however, require large amounts of wood and material and are massive in size.

Figure 13 - Bunjil Place, Melbourne (Caballero, 2022)

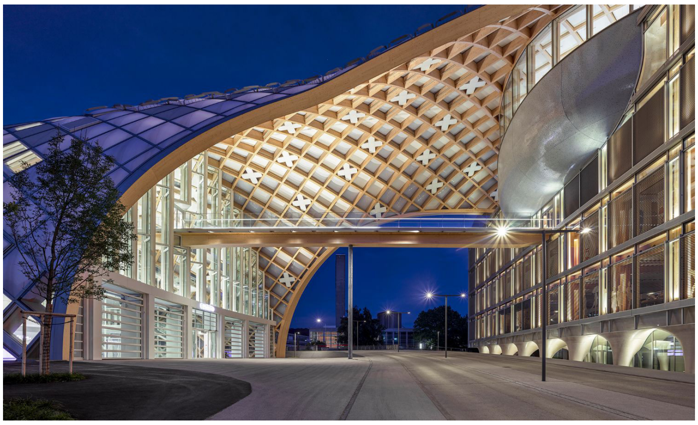


Figure 14 - Swatch Office, Biel (Blumer Lehmann, n.d.)

When a more simple free-form timber structure is desired, with straight timber beams, the complexity mostly lies in the connecting nodes. These nodes, most often made from steel, connect the wooden beams. Facades and roofing are also often attached to these nodes, making them complex and important constructive elements.

Figure 15 - Timber facade structure, The Base, Schiphol-Centrum (De Groot Vroomshoop, 2017)

An example of such a structure is the facade of The Base in Schiphol-Centrum (figures 15). In this building, a large curtain wall and glass roof are supported by a timber structure. The shape of the facade is slightly curved on one axis, making it a 'simply curved surface'. Due to this bending shape, steel nodes are used to connect the straight timber beams at an angle. The steel nodes also support the large curved curtain wall.

Figure 16 - Timber dome canopy, the Jungledome, Remouchamps (Lüning, 2006)

Another type of structure requiring steel nodes is a timber dome canopy. An example is the Jungledome in Remouchamps (figures 16). A dome-shaped canopy, which is classified as a 'double curved synclastic' surface, is bend on two axes. This makes the steel node a bit more complex, but since the curvature of the dome is constant, the different nodes in the structure could share the same shape as well.

Node types

The nodes, as discussed in the earlier examples, are examples of single-layer free-form nodes. These nodes can be divided into two general categories: splice connectors and end-face connectors (Stephan et al., 2004). Splice connectors are characterized by the fact that the node is connected to the structure by creating contact service in the longitudinal axis of the structural member and can be fixed by either using bolts to fix the spliced parts or by welding (figure 17).

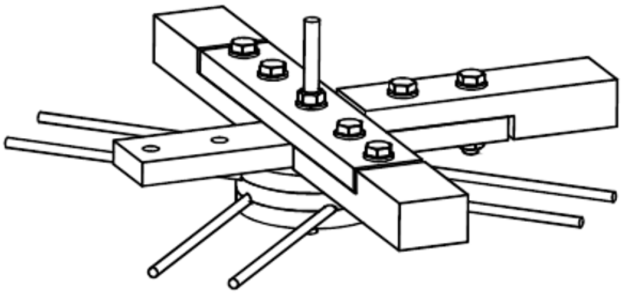
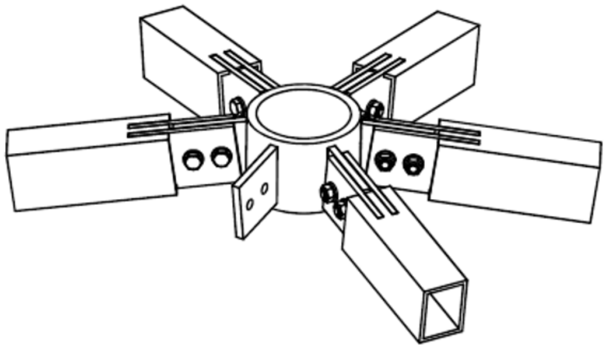



Figure 17 - Examples of splice connectors (Stephan et al., 2004)

End-face connectors are characterized by the fact that the node is connected to a structural member by creating a contact surface perpendicular to the longitudinal axis of the member (figure 18). The connection can be formed by using tension-stressed bolts or welding.

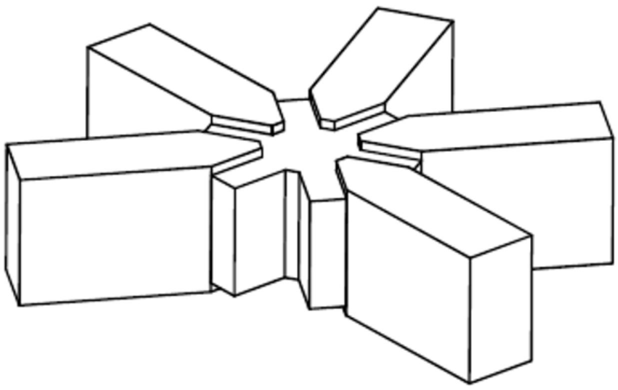
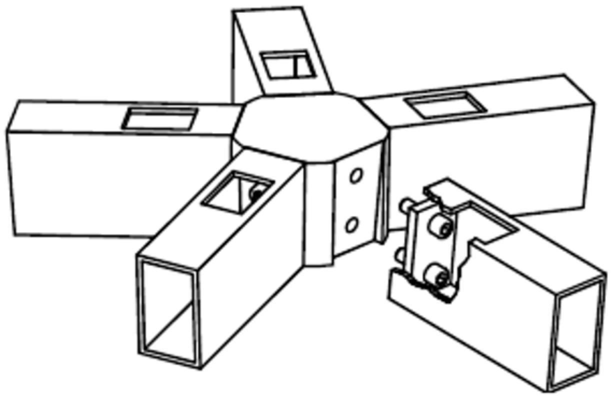



Figure 18 - Examples of end-face connectors (Stephan et al., 2004)

7. Design framework

Design philosophy
To be able to find out how a wood-LOM produced node could be valuable as a substitution of a steel node, research is needed to evaluate the benefits of a wood-LOM produced node. As stated in chapter #, it is possible to change the direction of the grain for every veneer layer of the object.. With multiplex, the grain direction is rotated by 90° for every other layer. When working with wood-LOM, however, you are laminating and cutting each layer individually. This also provides the ability to change the grain direction for each layer, providing strength in the direction that is chosen by the designer.

The performance of plywood perpendicular to the plane of a sheet of plywood is well known, while the in-plane performance remains unclear. Wang et al. conducted research into the in-plane mechanical properties of plywood (2022). The in-plane performance of plywood was tested at various angles regarding the grain direction of the outside layer of the plywood. Five types of samples were evaluated starting with a 0° difference between the load and the grain direction of the outside layer, with increments of 22.5° per sample, until the angle between the load and the grain direction of the outside layers was 90°. It was reported that when plywood is loaded in the direction of the grain of the outside layer, and thus perpendicular to the grain direction of the alternate layer, the compressive and tensile strength was at its highest. When the plywood was loaded perpendicular to the grain direction of the outside layer, and thus in the direction of the alternating layer, the second best performance was found. Plywood performed the worst in compressive and tensile strength when the load was at a 45° angle with the grain direction of the outside and the alternating layers. The results and visualisation of this research can be found in appendix I.

These findings show that it is beneficial for the mechanical performance of plywood to ensure that the grain direction of the veneer layer is along the same axis as the applied force. When producing wooden elements by LOM, the grain direction of every veneer layer can be chosen individually. Therefore, it is possible to design an object in such a way that the grain direction of the wood layers is oriented in the direction of the forces expected on an object, increasing the overall strength of the element.

Testing the design hypothesis
To be able to test the hypothesis that laminating a wood-LOM produced node with the grain direction of layers in the direction of the forces applied increased the element’s strength, an example of such a design had to be made and tested on the mechanical performance. Therefore some simplified designs of a wood-LOM node were made to test the hypothesis.

The first design was based on a simple cross connection, where two beams of a construction that were oriented in the same plane intersect. This node version however, was bearing loads from two axes. These forces were expected to travel through the object in a straight line. While the performance of such a solid object produced with wood-LOM could prove beneficial compared to a similar solid wooden node or plywood node, it seemed more important to design a version of a node that would have to redirect forces within the node itself. For this reason a Y-shaped node was designed. This node received forces along two axes and redirect these forces towards a third axes.

Testing technique

Due to a severly limited testing set-up, finite element modelling (FEM) was used to evaluate the designed node. By providing the right material data to the software and monitoring relevant performance factors, valuable results were extracted. This data was then used to improve the design, after which the new design was once again tested by FEM analysis.

The FEM software that was used is Abaqus FEA (version 6.13.1). Abaqus was chosen as the preferred software as it supports the import of 3D-elements that are made in a different software program and provides a lot of tools for monitoring performance of a material and various ways of presenting this information. Additionally, a lot of support information is available online for using this software.

As stated before, wood is an orthotropic material, which means that the mechanical performance of the material depends on the orientation of the material. While the Young's modulus, shear modulus, and Poisson's ratio for 1 direction is adequate information for Abaqus when modelling an isotropic material, engineering constants for all 3 different directions are necessary when modelling an anisotropic material such as wood. When applying these material conditions to an element within Abaqus FEA, it is needed to specify the orientation of these axis in the 3D space.

Material selection

To be able to make a choice in the material used for testing, the following criteria were used to find a suitable type of wood for creating the wood-LOM node:

> Production in Europe
One of the main goals of this research is to provide a sustainable alternative for construction nodes. When the source of the material is close to the construction site, the impact on the environment is reduced compared to a type of wood that has to be shipped from another continent. Because this research is done at the TU Delft, the research focuses on materials produced in Europe.

> Widely available and relatively affordable
The value of the end product is the highest when the material is widely available, because only then it can be used as an reliable alternative. Therefore the material should be widely available to provide a constant availability of the material at a relatively low cost.

> Available as veneer
Because the process requires the material to be used in the shape of veneer, it would be best if the material is already available as a veneer. It is virtually possible to create veneer from any type of wood, but if the material is already available as a veneer it would simplify the process.

> Easy to use
Because of the treatments the material will go through during the production process, it would be best if the material is relatively easy to use. In this case that would mean that the material is easy to cut, is strong when used in a limited thickness, and is easy to glue to another layer of the same material.

By using these criteria, four types of wood were selected for further investigation. These types of wood were:

> Birch (Betula verrucosa)
> Beech (Fagus sylvatica)
> Spruce (Picea abies)
> Oak (Quercus robur)

To be able to make a choice out of these four wood types, they were compared using information from the materials database Ansys Granta EduPack. The materials were compared in four categories:

> Young's modulus
> Compressive strength
> Tensile strength
> Shear strength

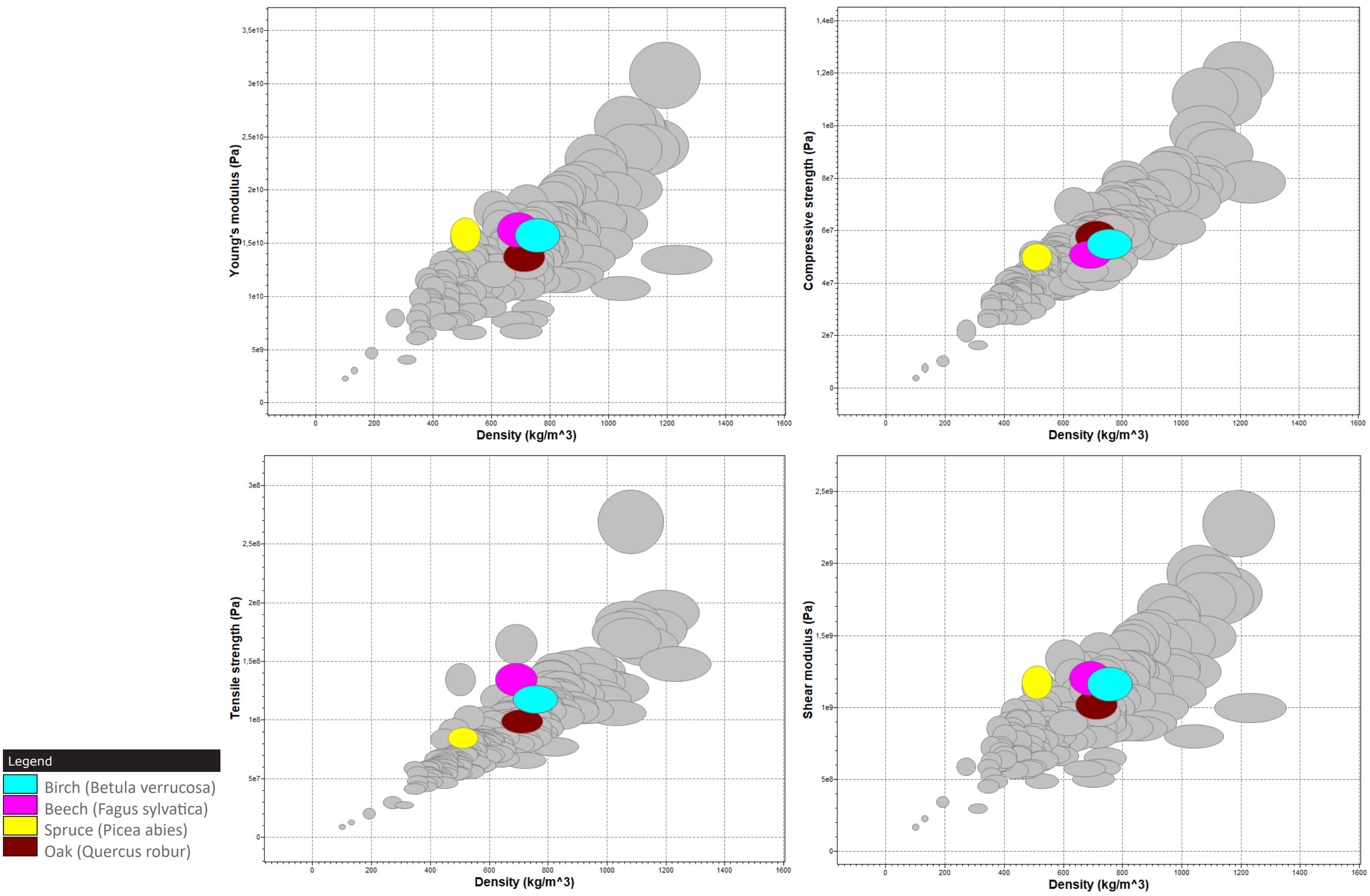


Figure 19 - A comparisson of a selection of mechenical properties of four types of wood (Ansys Granta EduPack)

The obtained material properties do not show a clear preferable wood type, as no wood type has optimal mechanical properties (figure 19). Therefore, physical research was needed. Birch, beech, and oak were investigated further, as spruce did not excel in any of the mechanical properties evaluated compared to the other three types of wood. The information gathered from Ansys Granta EduPack is based on the properties of the material in a solid shape. However, as veneer will be used for wood-LOM, the mechanical properties of the three wood types were investigated in the form of veneer.

The sheets of veneer tested (figure 20) had a thickness of 0.6 mm. Laminated samples were produced to test the veneer. Strokes of material were cut at a size of 120 x 10 mm. The strokes were laminated with a thickness of 8 plies. The adhesive used to laminate the layers of veneer was high-end Bison wood glue with classification D3 (figure 22). The lamination took place in three different ways (figure 21). The first version was made by laminating the strokes so that the grain direction of every layer was along the length of the sample (linear). The second version of the sample had all the layers laminated with the grain transversal to the length of the sample (transversal). The third version had alternating grain directions at a 90° angle, similar to plywood (multiple direction).

Figure 20 - Birch, beech and oak veneer used as base material for the sample (author)

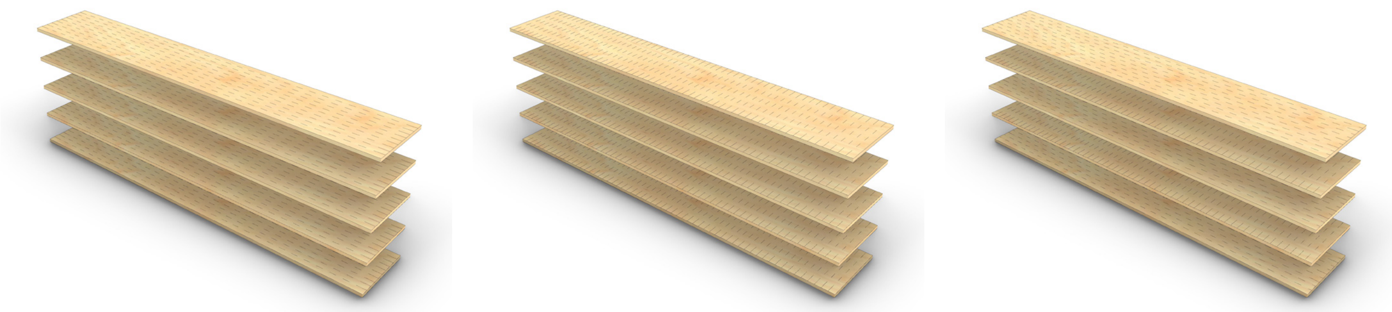


Figure 21 - Three lamination types of the samples; Linear, transversal and multiple grain directions (author)

Differences between the wood types became apparent when cutting the material by hand. While the birch and beech veneer was quite relatively soft and therefore easy to cut, the oak veneer was hard and brittle and therefore more difficult to cut. It was possible to cut the oak samples with longitudinal grain direction, but when cutting the material in the transversal direction, the material fell apart quickly (figure 23). Therefore oak veneer was seen as unfit to use in wood-LOM during this study.

Figure 22 - Bison D3 wood glue (author)

Figure 23 - Oak veneer falling apart after cutting (author)

The material samples were then tested at in a simple bending test (figure 24). The test was carried out by applying a force to the middle of the sample while the sample was supported at both ends. The load on the material was increased until the sample failed to withstand the load. All transversal grain elements provided a very low amount of bending strenght, failing at the smallest increment of load. Therefore, these results were obsolete for choosing the wood type. Images of the maximum sustained load for the linear and multiple grain directions taken just before failure of the sample, are visible in the figures 25 to 28.

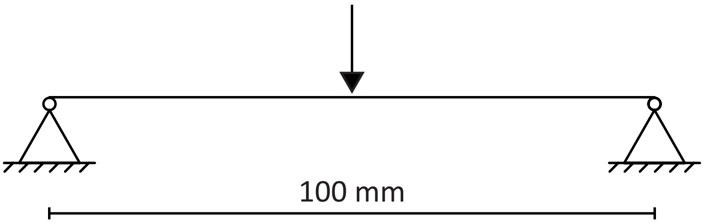


Figure 24 - Schematic of simple bending test (author)

Figure 25 - Linear birch veneer 0.6mm 8ply - Max load of 103.95 N

Figure 26 - Linear beech veneer 0.6mm 8ply - Max load of 117.68 N

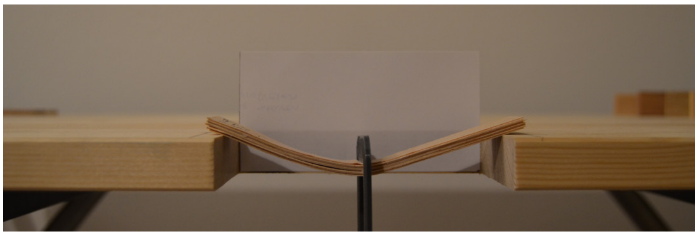


Figure 27 - Multiple direction birch veneer 0.6mm 8ply
Max load of 40.21 N

Figure 28 - Multiple direction beech veneer 0.5mm 8ply
Max load of 108.85 N

When comparing the different versions of birch and beech samples, it became clear that the beech samples were superior to the birch samples, as these samples could withstand a higher load (117.68 N compared to 103.95 N and 108.85 N compared to 40.21 N for the linear and multiple direction respectively). Therefore, beech (Fagus sylvatica) veneer was used in all further experiments.

FEM testing laminated beech wood

To be able to conduct FEM simulations on the laminated elements, it was necessary to translate the properties of the materials used to the simulation software used. As stated before, these mechanical properties had to be entered by using engineering constants. These engineering constants are determined by physically testing the material (table 1) (Gómez-Royuela et al., 2021).

Table 1 - Engineering constants of European beech (Fagus sylvatica L.) (Gómez-Royuela et al., 2021)

Elastic properties	Abaqus FAE parameters	Values
E_L (MPa)	E1	13,811
E_R (MPa)	E2	1590
E_T (MPa)	E3	832
G_{LR} (MPa)	G12	1108
G_{LT} (MPa)	G13	706
G_{RT} (MPa)	G23	349
υ_{LR}	Nu12	0.44
υ_{LT}	Nu13	0.51
υ_{RT}	Nu23	0.62

Besides the choice of wood, the adhesive had to be defined to run the FEM simulation. One of the most common adhesives used to laminate veneer when making multiplex or CLT constructions is called melamine urea formaldehyde resin, also known as MUF-resin. MUF-resin complies with the approval criteria needed for the use with timber construction elements. The cohesive parameters of MUF-resin used for simulating the bonding between two layers of beech are reported in table 2 (Tran et al., 2014).

Table 2 - Cohesive parameters for MUF-resin (Tran et al., 2014)

	Initial stiffness	Critical cohesive strengths	Maximum displacements
	K_n (N/mm²/mm)	σ_n^c (N/mm²)	δ_n^{max} (mm)
Mode I	4.5	1.6	0.005
	K_t (N/mm²/mm)	σ_t^c (N/mm²)	δ_t^{max} (mm)
Mode II	30	9.7	0.00005

The construction node

The construction node that was chosen is a simplified version Y-shaped node connecting three construction beams at a single point (figure 29 en 30). These beams have a cross-section of 60x60 mm. The exact dimensions for the Y-node can be found in appendix II.

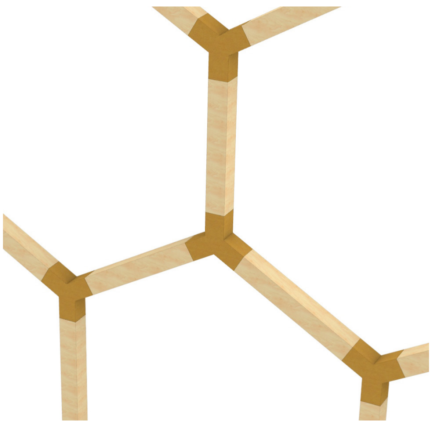


Figure 29 - A simplified visualisation of the node in a construction

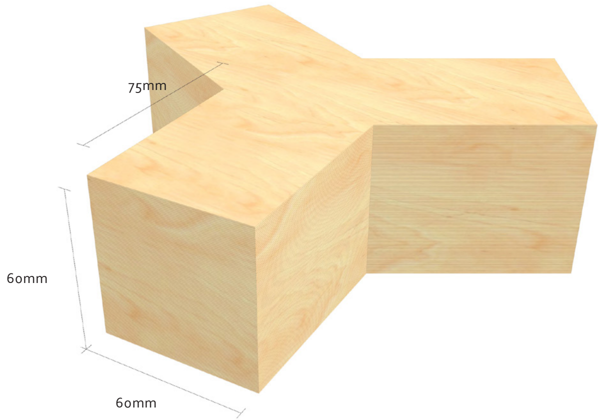


Figure 30 - A visualisation of the simplified node design

Simplification of simulation models

The simulation of a model within a FEM program requires a large amount of computing power. For this reason, the models were kept as thin as possible while still having a relevant amount of layers. The complete size nodes will be a combination of a repetition of a certain layer structure. Therefore, a single part of such a combination of layers can give a valuable representation of the performance of an entire object. At the chosen dimensions of a complete node, buckling is not expected to be a problem. For this reason, buckling will not be part of the simulation at a lower amount of layers, despite this being a possible factor at such a low amount of layers.

Either three or seven layers were used for all iterations of the designed node as required to produce different layer combinations. When comparing design iterations, the number of layers is kept consistent.

Load cases

Three different types of load cases were used to simulate the performance of the wood-LOM node (figure 31). In each load case the bottom side of the node was fixed, to restrain it from any movement. The loads were then applied to both top sides of the Y-node. Simulation 1 was carried out by applying a compressive force to both sides. Simulation 2 was carried out by applying a tensile force to both sides. Simulation 3 was a combination of a compressive force on one side and a tensile force on the other side.

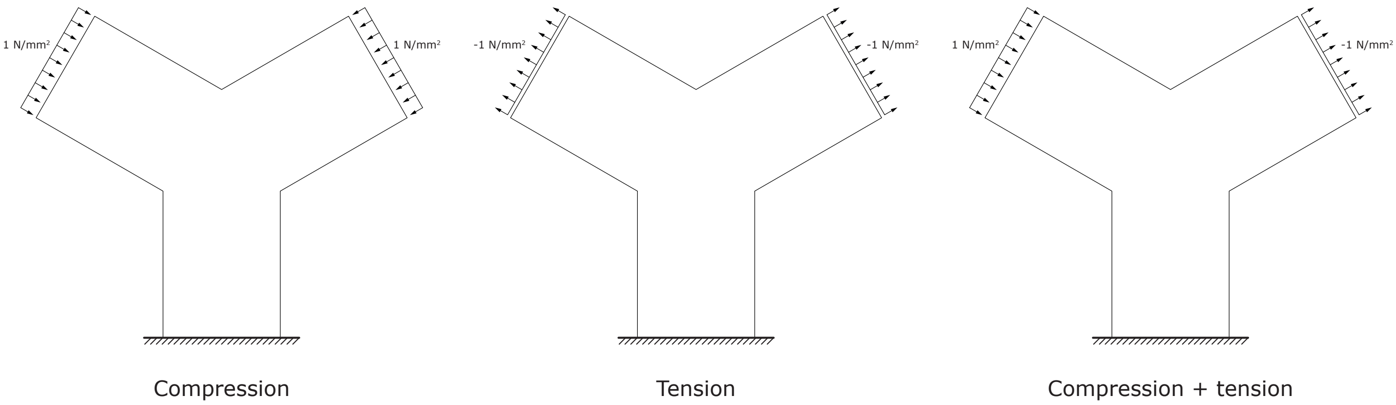


Figure 31 - A schematic view of the three types of load cases

Monitoring the results
To be able to monitor the performance of the Y-node and to be able to make decisions regarding the improvements of the design, a choice had to be made about the specific output to monitor in the results of the simulation. Failure of the material is expected to occur at the point where the stress of the material is at its highest. Therefore it was chosen to monitor the amount of stress in the material and the location of the stress within the geometry.

The location of the highest stresses is mapped by making a cross-section through the layer where the highest stress occurs, and showing the stress that occurs by using a colour map of the element. In almost all cases, the layer where the most stress occurs is the middle layer. The results will always show the colour map of the middle layer of the element unless stated otherwise.

It is important to note that the specific amount of stress is not seen as important in this case, only the difference in the amount of stress between the two versions of the design. For this reason, the load was also arbitrarily chosen to be a constant pressure of 1 MPa (1 N/mm^2).

Comparing design variations
When comparing different iterations of designs, it is important to keep as many parameters constant as possible. Therefore the material, type of adhesive, the number of plies, and amount of pressure will always stay the same between two instances. The only variable between the two versions will be the shape of the element and the way the layers of the element are oriented.

8. Design development

10 design versions were tested in a total of 37 simulation. In this chapter, only the results that are regarded relevant for the research and the development of new designs are discussed. The results of all the simulations performed, grouped per design version and load case, can be found in appendix III. Here you can find three images per simulation. One is a colour map of the amount of stress, while the other two show the location and direction of respectively compressive and tensile stresses. While all performed simulations result in a colour map with unique minimum and maximum values for stress, the range of the stress values for figures in this chapter was made consistent to be able to properly compare different node designs.

To be able to compare the improvements made with using a wood-LOM produced node against conventional types of laminated wood, two base versions of the design were made to simulate a node made out of LVL (the same grain direction for each layer) and plywood (alternating grain directions with a 90 ° angle between layers). The LVL configuration is named v0.0 and the plywood version is named v0.1.

To be able to evaluate the effect of individually controlling the grain direction per layer in connective nodes, three version series (figure 32) were designed and investigated.

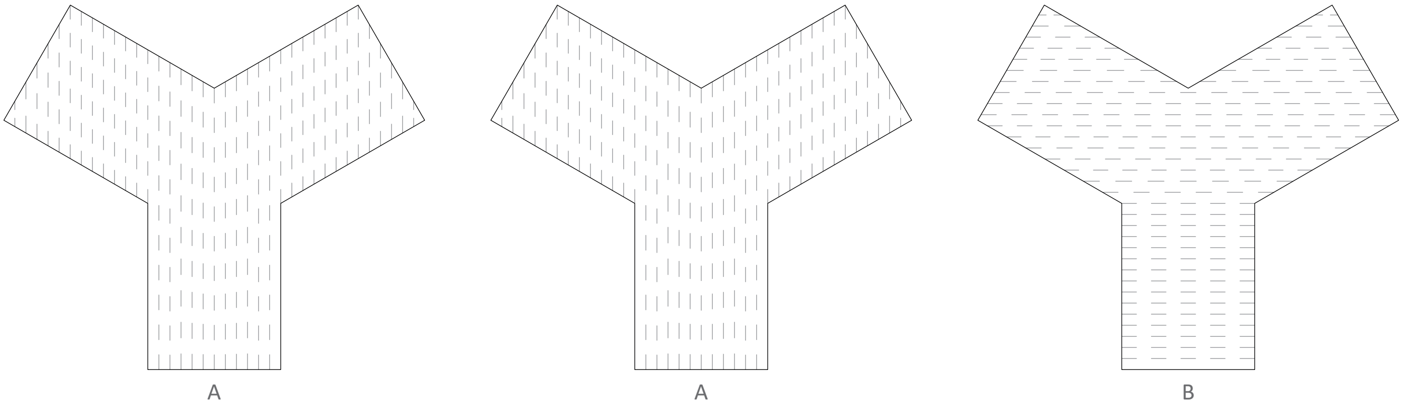
Version 1 series
The v1 series are based on building the node out of layers that each cover the entire area of the node. While each layer of the object consists of one part, the grain direction is different for every layer compared to the layer previous and after.

Version 2 series
The v2 series is based on the hypothesis that it could be beneficial for the node to divide certain layers into individual elements, with the grain direction of each element chosen individually. To be able to keep these individual elements together, the segmented layers will always be enclosed by two layers that cover the entire section of the node.

Version 3 series
The v3 series is based on the same notion as the v2 series, but in the v3 series adding an additional constructive element to the geometry is explored; a steel element was used during this study. However, within this design any material stronger than wood could be used to strengthen the geometry.

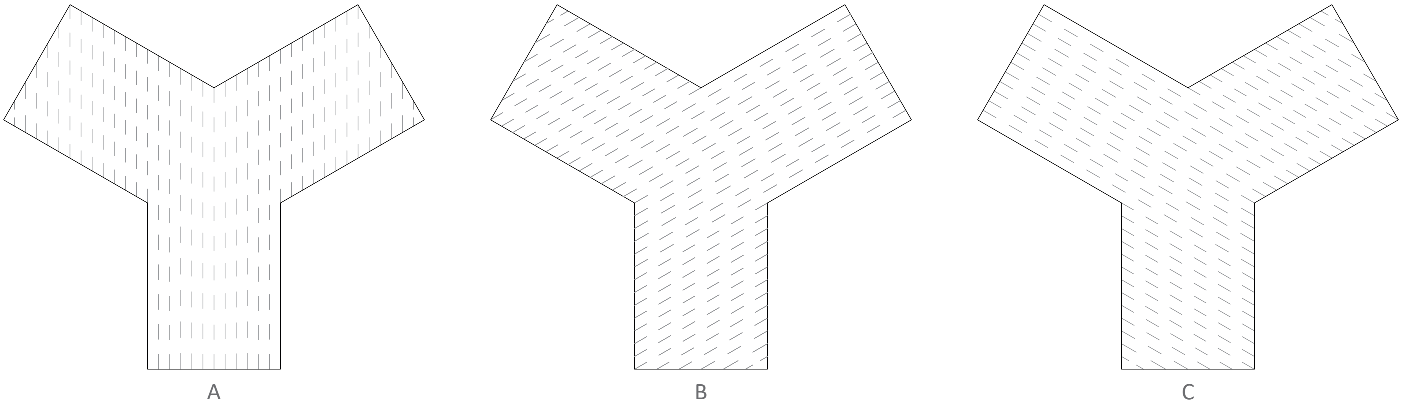
v0 layer structure

v0.0 A-A-A v0.1 A-B-A



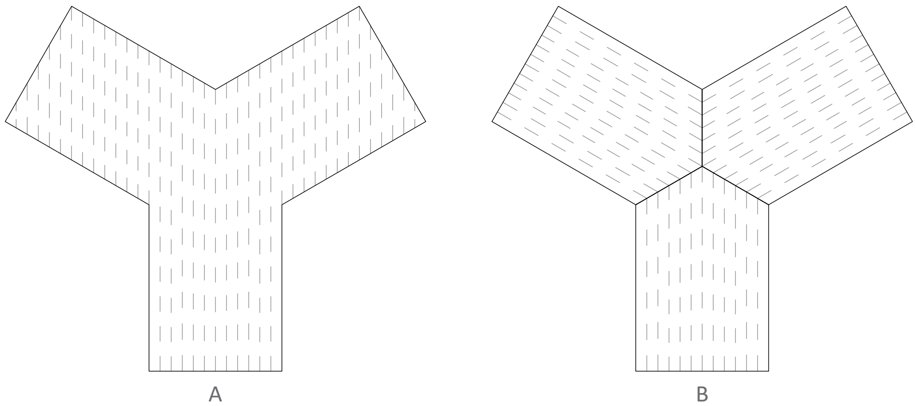
v1 layer structure

A-B-C-A-C-B-A



v2 layer structure

A-B-A



v3 layer structure

A-B-A

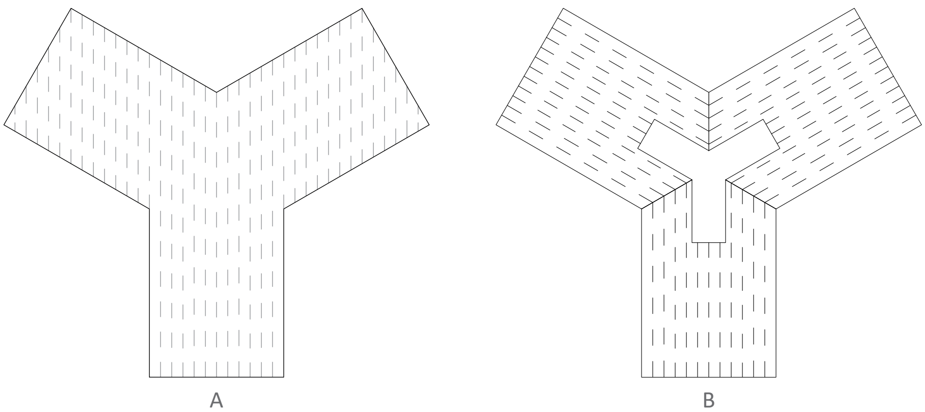


Figure 32 - A schematic view of the variations in layer structure per design version (author)

v0.0 and v0.1 - compressive force

In figure 35 and 36, two planar sections can be seen of the node versions v0.0 and v0.1 in a compressive load case for the seven layer version. Due to the fact that the results for compression and tension are almost identical in amount of stress and stress distribution, only the compression state is discussed here.

The maximum stress in v0.0 is 3.27 MPa and 6.59 MPa in v0.1. For v0.1 this maximum stress occurs in the lower corners of the geometry, while for v0.1 the maximum stress occurs in the top corner. On first impression this would suggest that v0.0 performs better in the sense that is has the lowest maximum stress to endure. However, if we look at a perspective view of the results, it can be seen that the maximum stress in v0.1 occurs only in three of the seven layers (figure 34). In v0.0 however, the stress seems constant throughout the layers (figure 33). While the layers that have the horizontal grain direction in v0.1 endure a higher amount of maximum stress, these layers are fixed between two layers that endure a relatively low amount of stress. Therefore there is a chance that the layers with the lower amount of stress would strengthen the higher stressed layers. Based on these results it is not yet possible to conclude which version is better equiped to handle tension and compression. Physical testing of these two concepts could provide an answer to the exact behaviour of these two node versions.

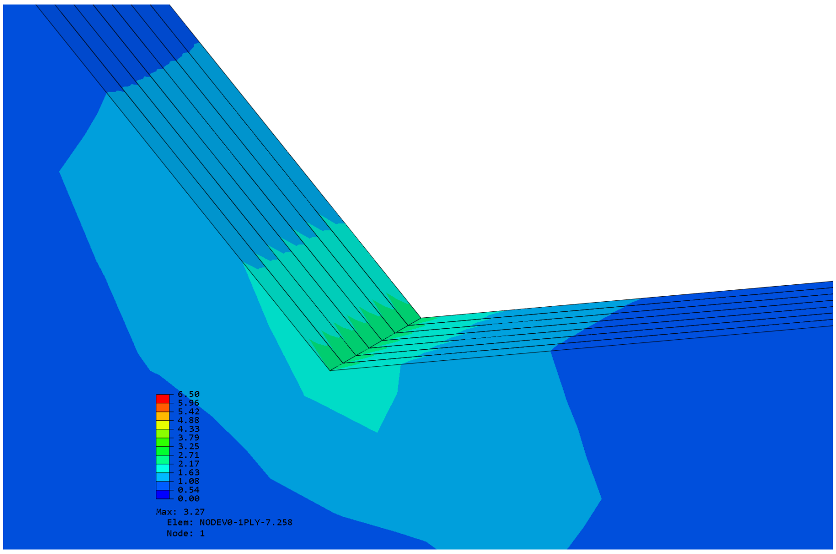


Figure 33 - Perspective view of the compression test on v0.0

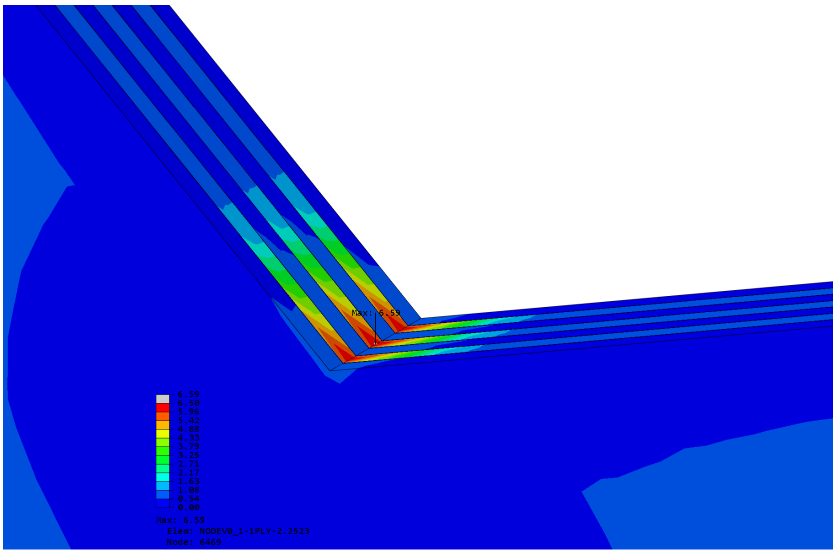


Figure 34 - Perspective view of the compression test on v0.1

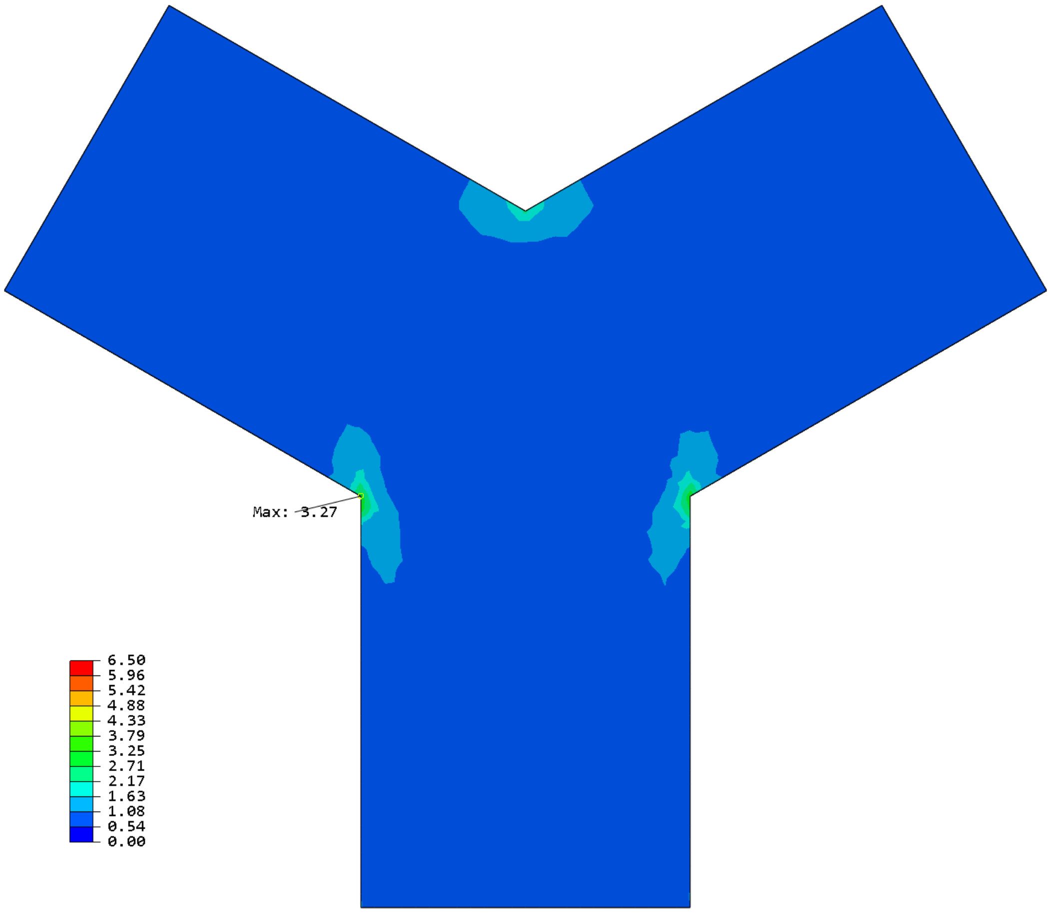


Figure 35 - Planar section of the compression test on v0.0

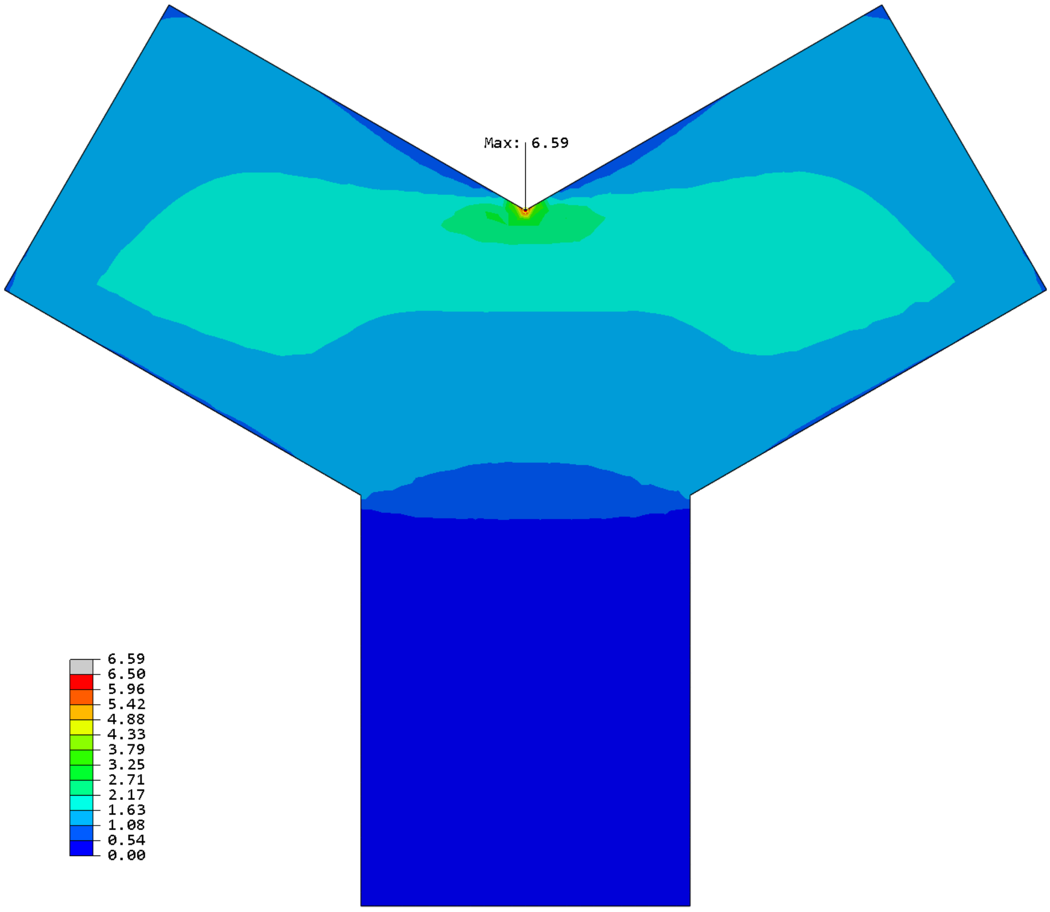


Figure 36 - Planar section of the compression test on v0.1

v0.1 and v1.1 - compressive force

In figure 39 and 40, two planar sections can be seen of the node versions v0.0 and v0.1 in a compressive load case for the seven layer version. Just like the previous case, the results for compression and tension are almost identical in amount of stress and stress distribution. Therefore only the compression state is discussed here. The section from node v0.1 is taken from the fourth layer in the middle while the section from v1.1 is taken from the third layer.

In v1.1 each layer is oriented in the direction of one of the connections with the rest of the structure. This is done by alternating the directions in a way that the geometry is balanced regarding the directions of the layers. The third layer from v1.1 is oriented in a NW direction. It is clearly visible that the area of the geometry in the arm closest to the load with the same direction as the grain shows the largest amount of stress (figure 40). This is expected, because the grain direction results in more strength in that direction, and thus more stress. It is also visible that this stress is relatively evenly distributed across this arm of the node when compared to the same arm in v0.1. This distribution of stress is likely the reason that the maximum amount of stress in v1.1 (4.49 MPa) is lower compared to v0.1 (6.59 MPa). In the perspective view (figure 37 and 38) of this simulation it is also visible that the maximum amount of stress is distributed across a larger area and in alternating direction, as a result of the alternating grain directions.

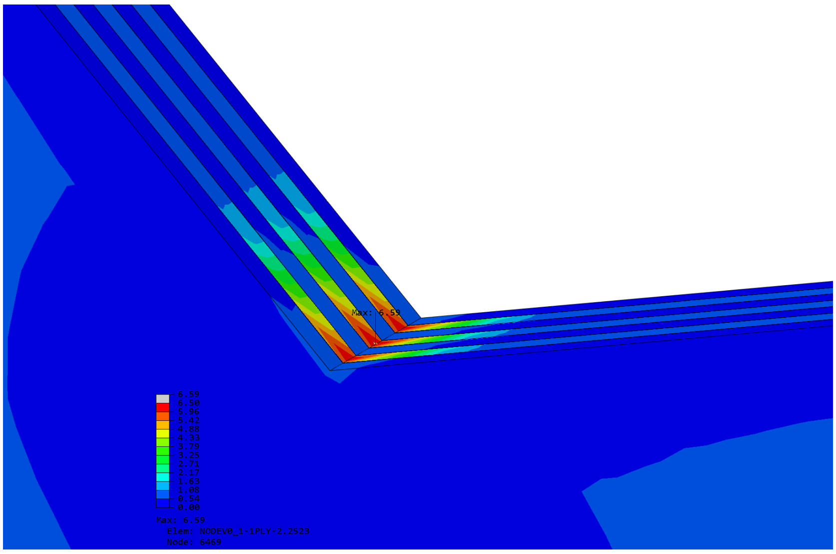


Figure 37 - Perspective view of the compression test on v0.1

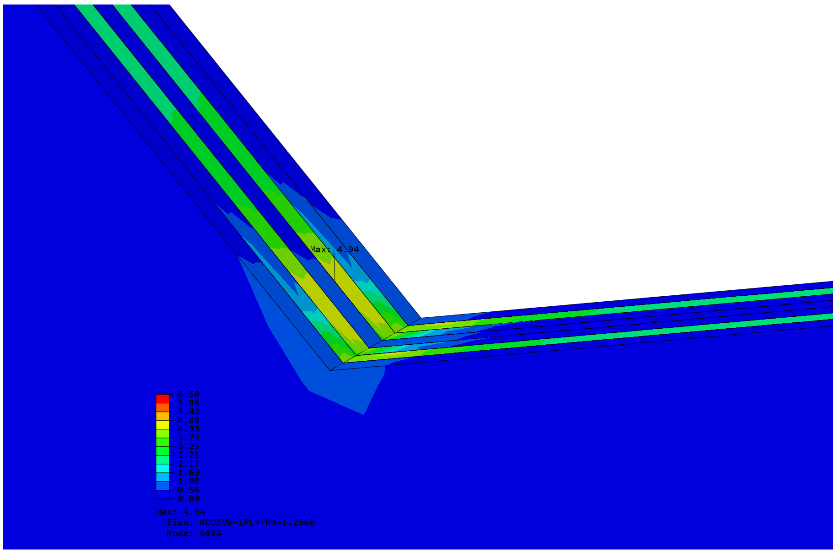


Figure 38 - Perspective view of the compression test on v1.1

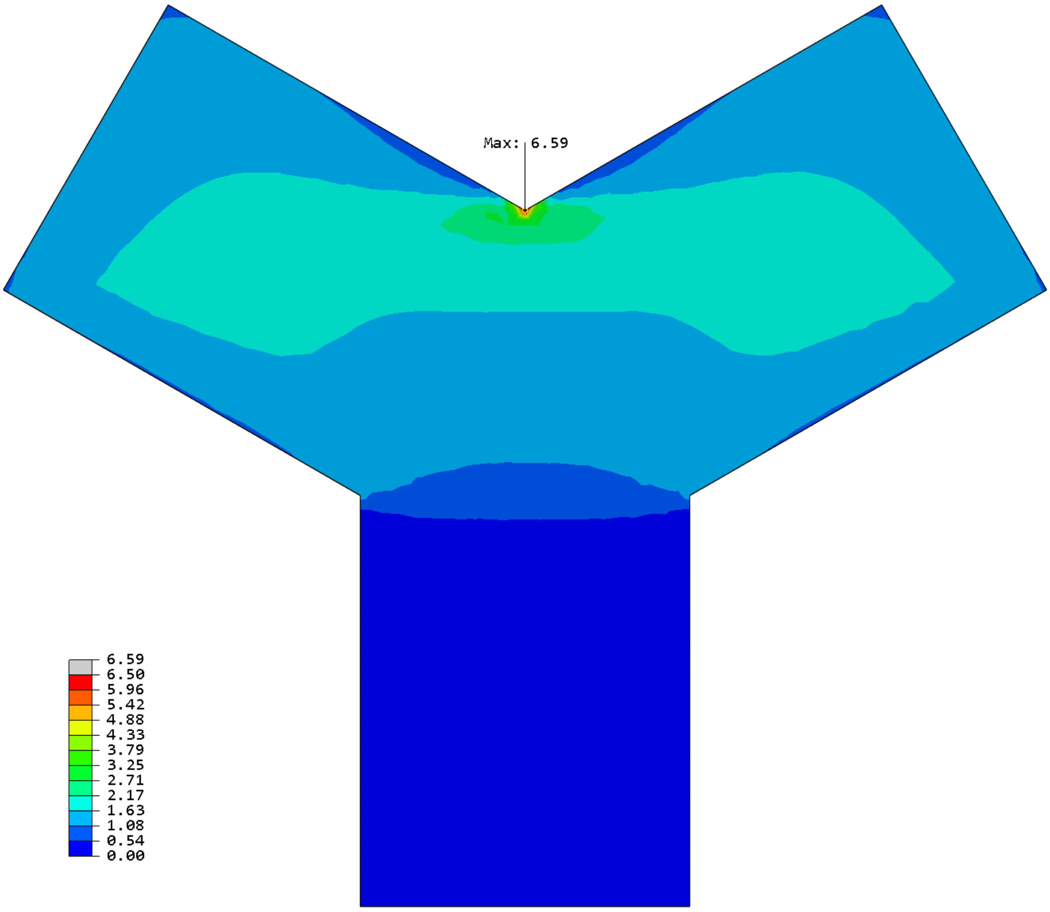


Figure 39 - Planar section of the compression test on v0.1

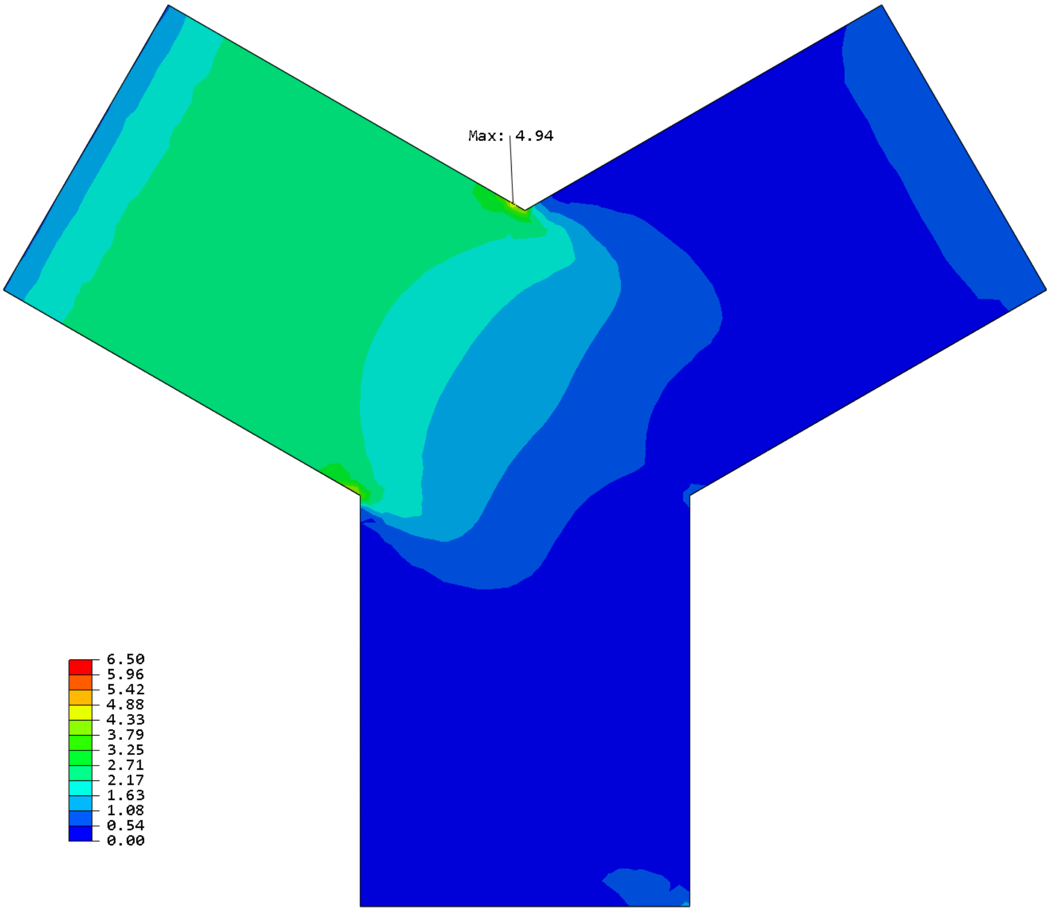


Figure 40 - Planar section of the compression test on v1.1

v1.1 and v1.2 - compressive force

In figure 43 and 44, two planar sections can be seen of the node versions v0.0 and v0.1 in a compressive load case for the seven-layer version. Just like in the previous case, the results for compression and tension are almost identical in the amount of stress and stress distribution. Therefore only the compression state is discussed here. Both sections are taken from the third layer.

While the previous case made it clear that alternating the grain direction per layer showed an improvement in the maximum stress, the location of the maximum stress was still concentrated in the top corner of the node. Because this sharp corner creates a stress concentration, the design was changed to include rounded corners in v1.2. The results show that this results in a significant improvement regarding the maximum amount of stress in the material. Not only is the maximum amount of stress in v1.2 (3.75 MPa) significantly lower compared to the maximum amount of stress in v1.1 (4.94 MPa), but it is also visible in the perspective view that the stress is more evenly distributed across the layers (figure 41 and 42).

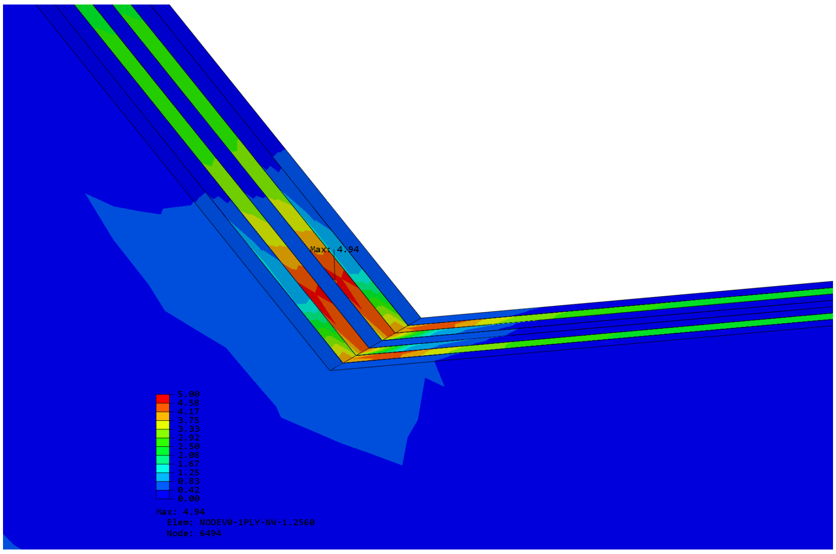


Figure 41 - Perspective view of the compression test on v1.1

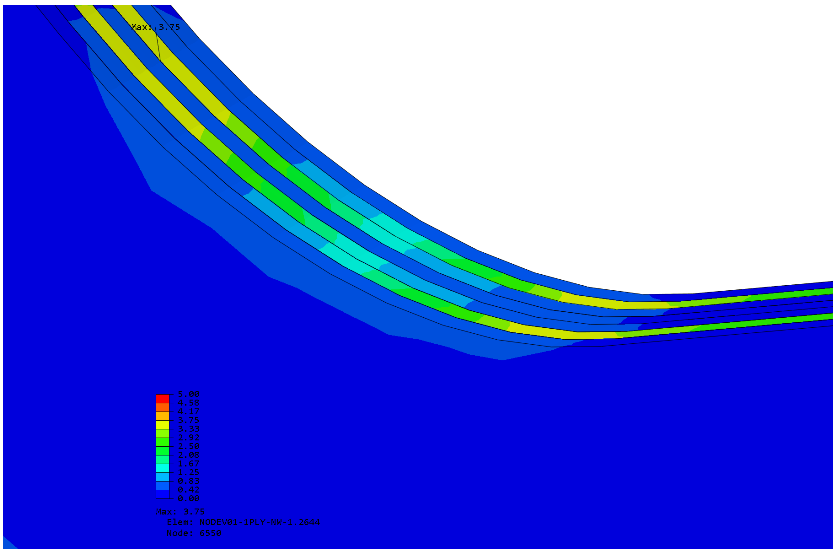


Figure 42 - Perspective view of the compression test on v1.2

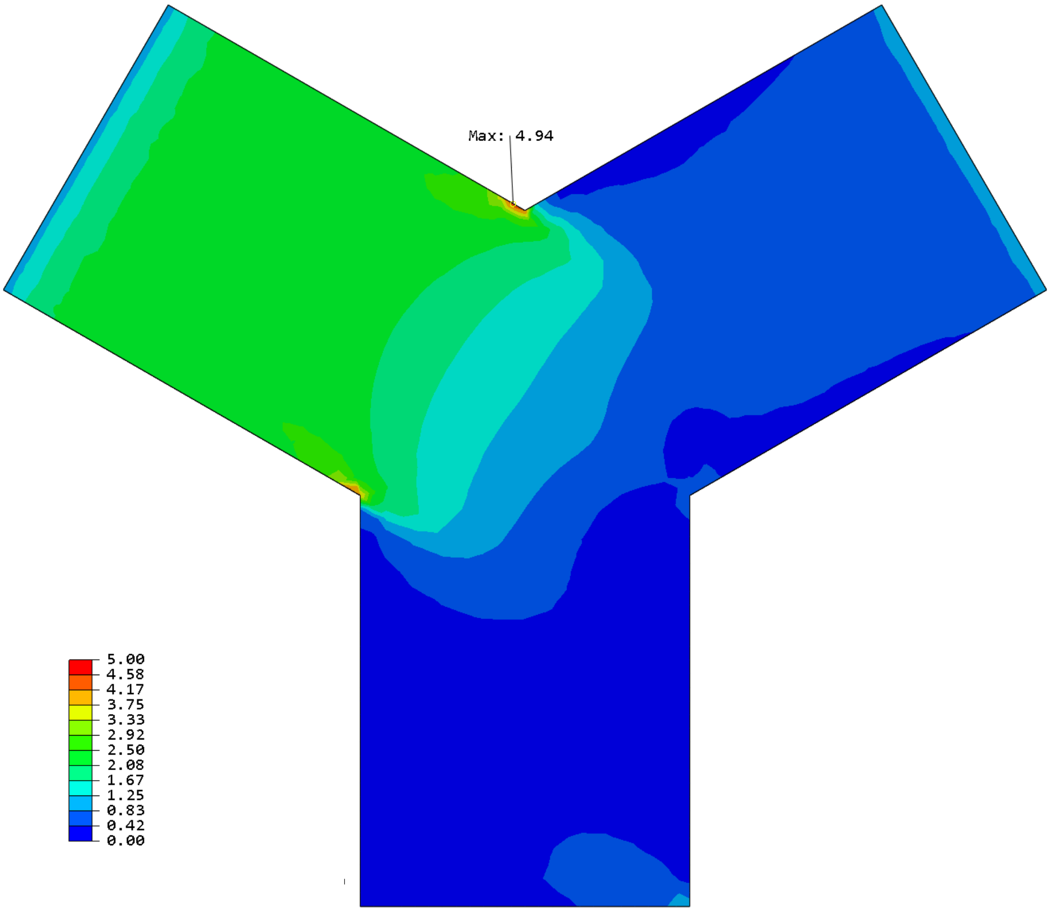


Figure 43 - Planar section of the compression test on v1.1

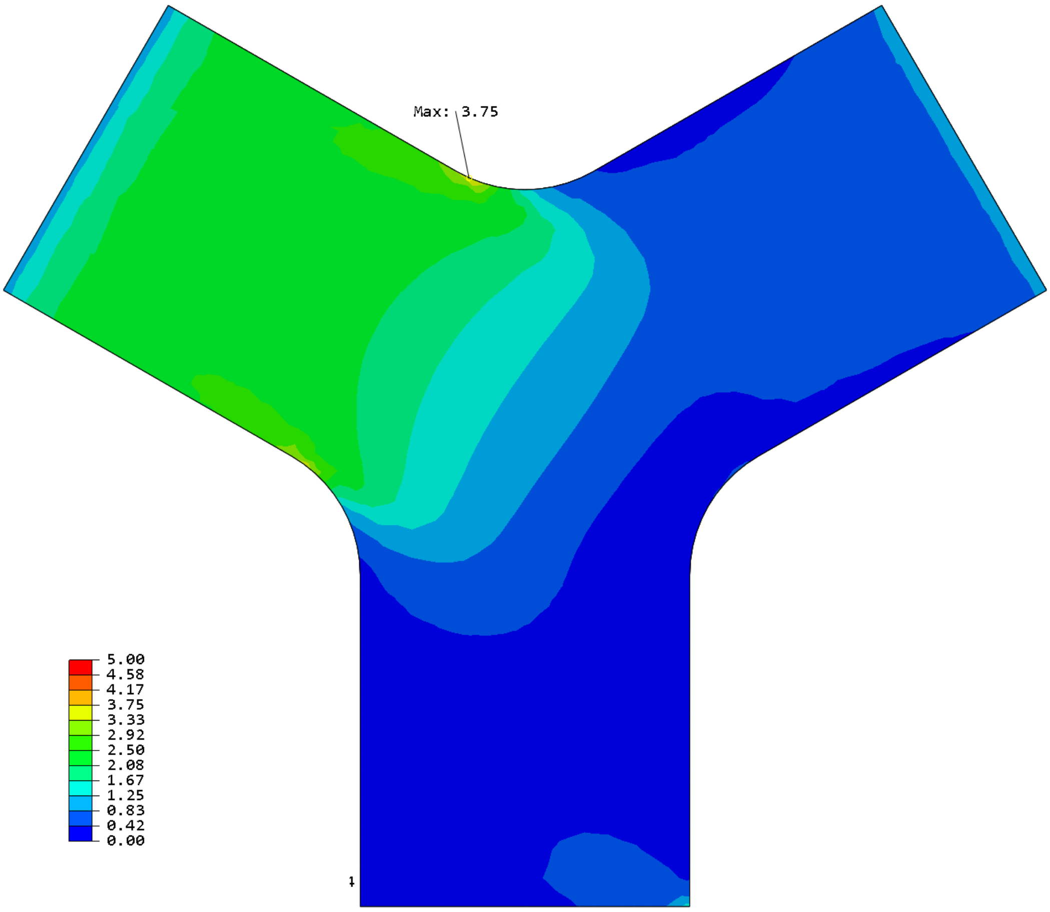


Figure 44 - Planar section of the compression test on v1.2

v1.2 and v2.2 - compressive force

In figure 47 and 48, two planar sections can be seen of the node versions v1.2 and v2.2 in a compressive load case for the seven-layer version. Just like in the previous case, the results for compression and tension are almost identical in the amount of stress and stress distribution. Therefore only the compression state is discussed here. The section from node v1.2 is taken from the third layer while the section from v2.2 is taken from the fourth layer in the middle.

In v2.2 the principle of the segmented layer is introduced, while the improvement of the rounded corners is inherited from v1.2. It is visible that in v2.2 the stress in the two arms of the node is more evenly distributed across the section compared to v1.2. The amount of stress also seems to be balanced between two sides in v2.2, while the amount of stress on one side of v1.2 is higher depending on which layer you look at.

This stress distribution in v2.2 is likely the cause for the lower amount of stress (2.62 MPa) compared to the maximum amount of stress in v2.1 (3.75 MPa).

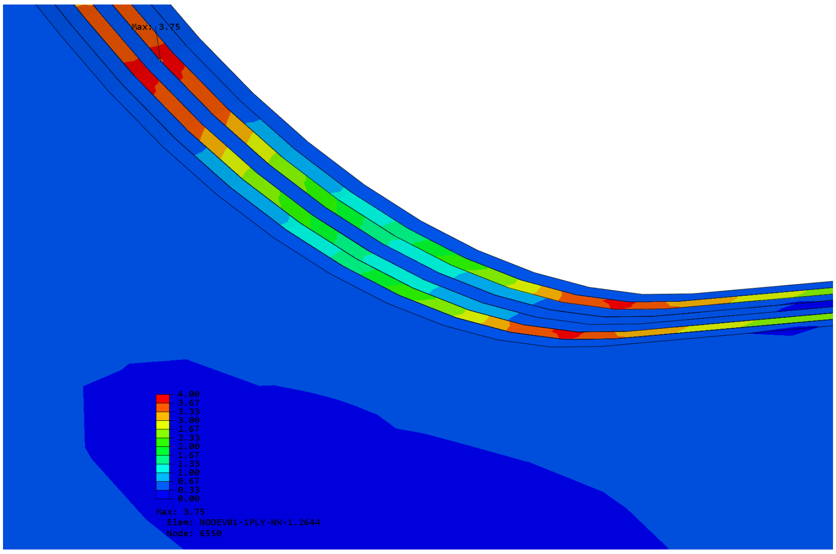


Figure 45 - Perspective view of the compression test on v1.2

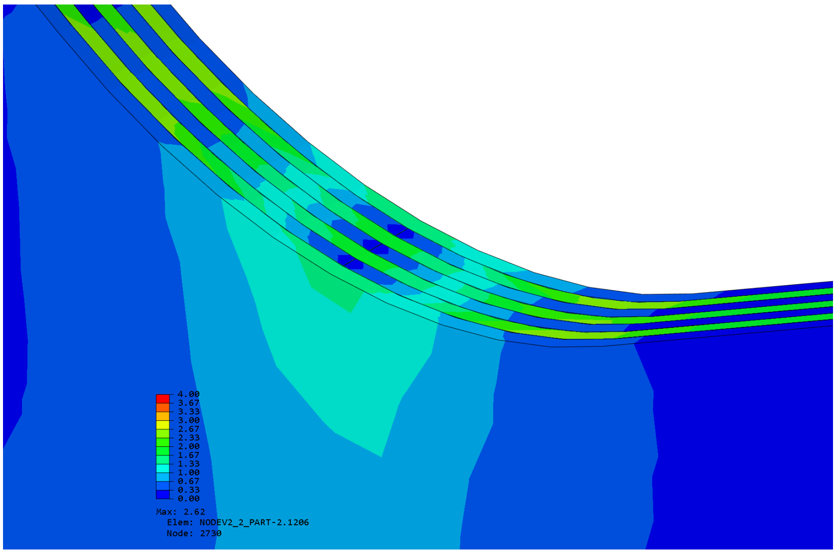


Figure 46 - Perspective view of the compression test on v2.2

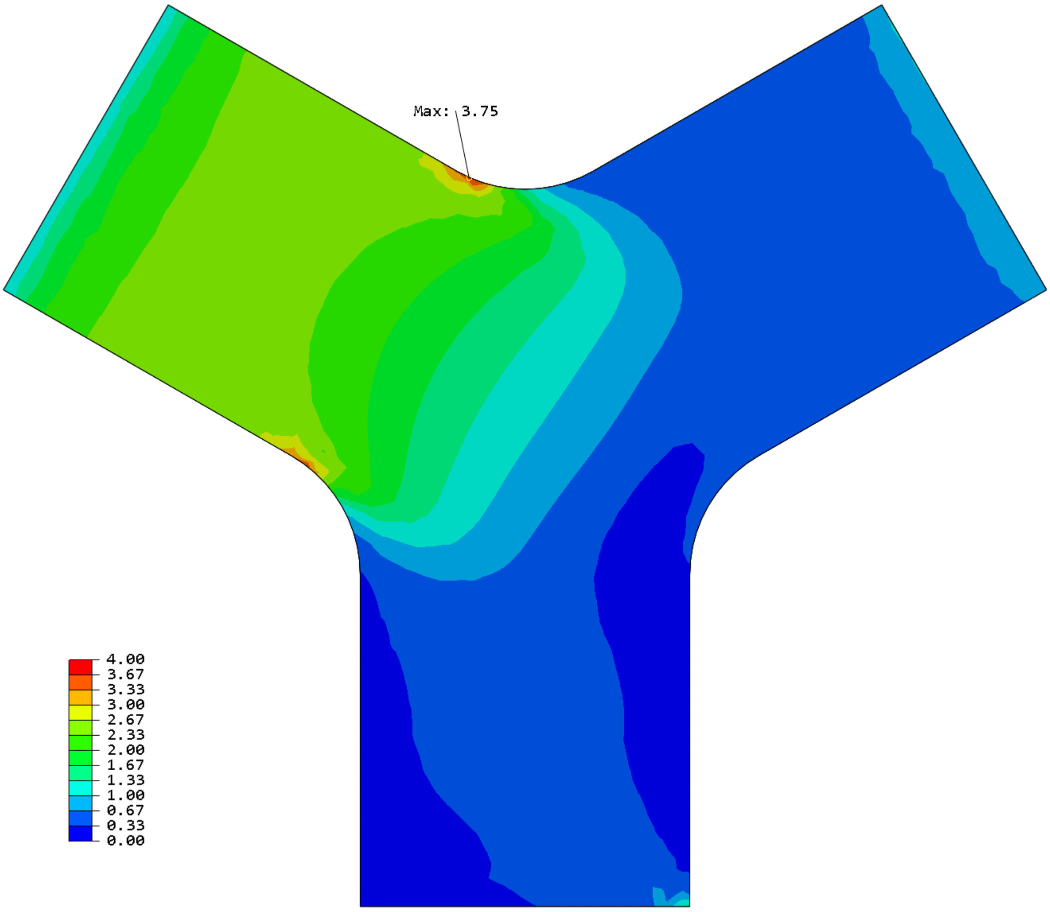


Figure 47 - Planar section of the compression test on v1.2

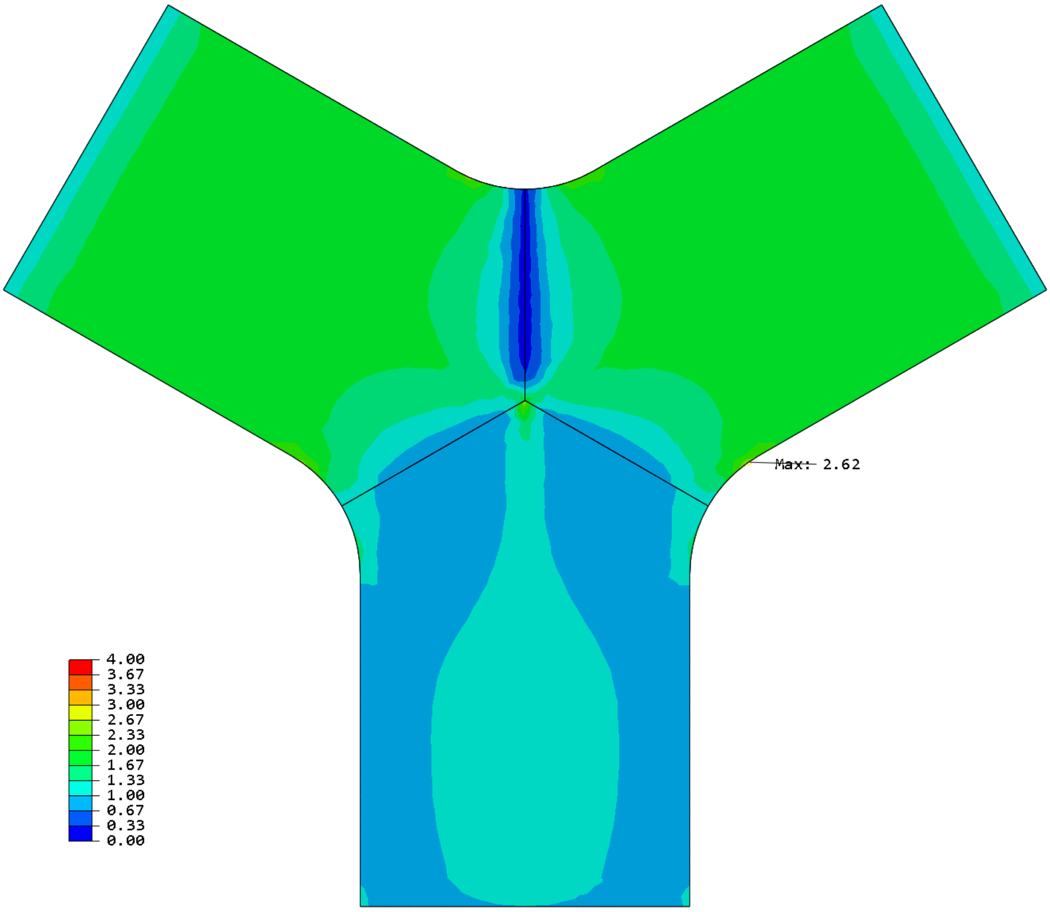


Figure 48 - Planar section of the compression test on v2.2

v2.2 and v2.3 - compressive force

In figure 49 and 50, two planar sections can be seen of the node versions v2.2 and v2.3 in a compressive load case for the three-layer version. Because the results for the tensile stress differ from the compressive stress, the results from the tensile test are discussed in the next comparison. The sections are both taken from the second layer in the middle of the object.

While the three-layer version of the v2.2 node is identical to the seven-layer version of the v2.2 node, apart from the layer count, the three-layer version does show another location of the maximum stress. In this case, the maximum amount of stress can be found in the centre of the section, where the three segments meet at one point. This change in the location of maximum stress could suggest that there is a significant difference in simulating the same design with a different amount of layers. Because the simulations are already performed on a small section of the entire geometry, this effect is not further investigated. It is, however, important to note this effect regarding extrapolating the performance of a certain design to a complete version of the node.

The effect of the concentration of the maximum stress is mitigated in v2.3 by rounding the corners of the segments at the location where they meet. This causes the location of the maximum stress in v2.3 to be at the side of the node arm, which is slightly lower (3.22 MPa) compared to the maximum stress in v2.2 (3.34 MPa).

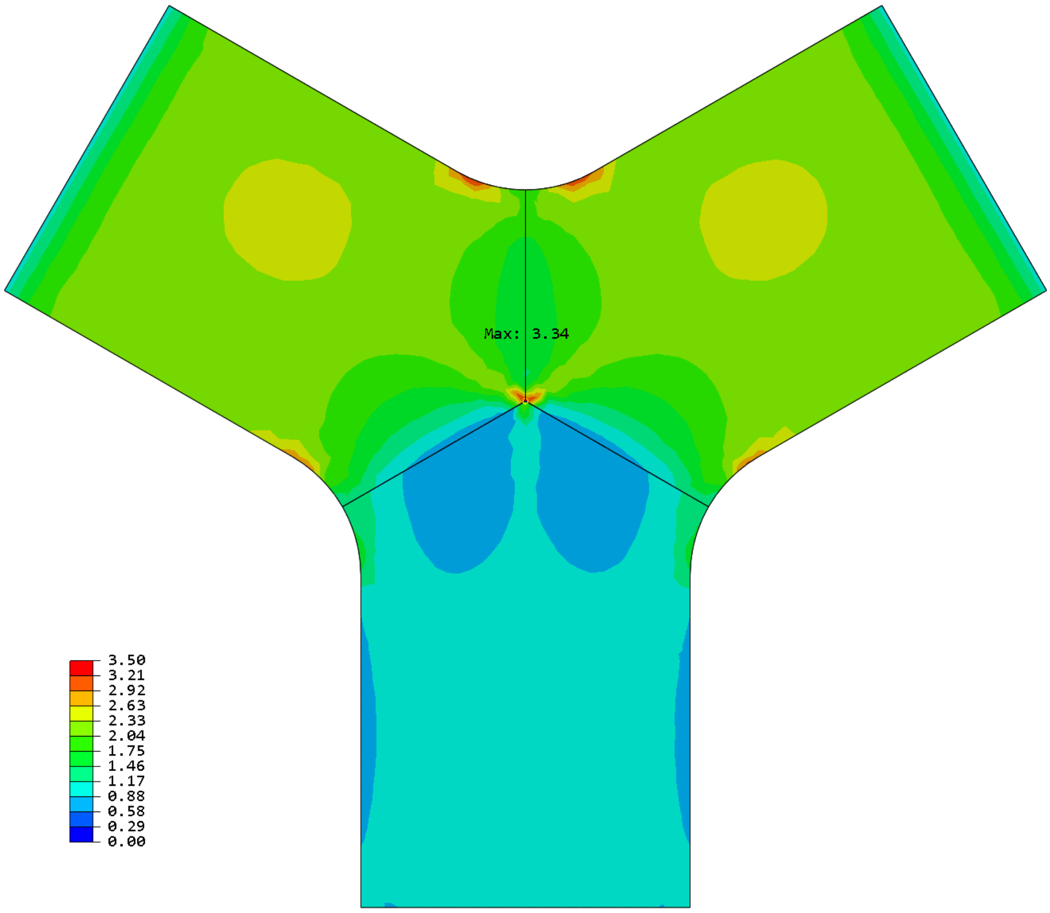


Figure 49 - Planar section of the compression test on v2.2

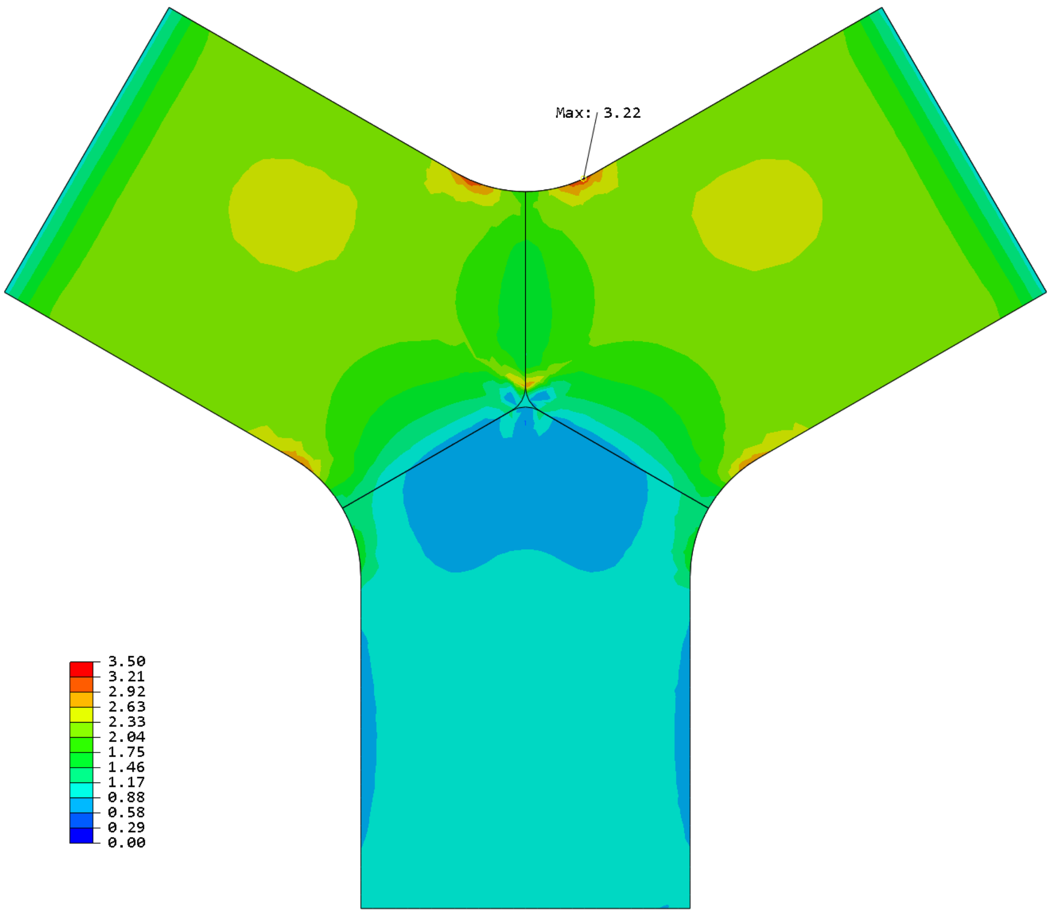


Figure 50 - Planar section of the compression test on v2.3

v2.2 and v2.3 - tensile force

In figure 51 and 52, two planar sections can be seen of the node versions v2.2 and v2.3 in a tensile load case for the three-layer version. The sections are both taken from the second layer in the middle of the object.

V2.2 and v2.3 show a very similar stress distribution across the section, where the maximum stress is again found at the side of the arm of the node. The reason for the slight reduction in maximum stress in v2.3 (2.86 MPa) compared to v2.2 (2.91 MPa) is not entirely clear. Because this is a 0.05 MPa difference, this could be explained by the use of a slightly different mesh due to the different segment shapes of v2.3. It is not expected that the change made in v2.3 improves the tensile performance of v2.3.

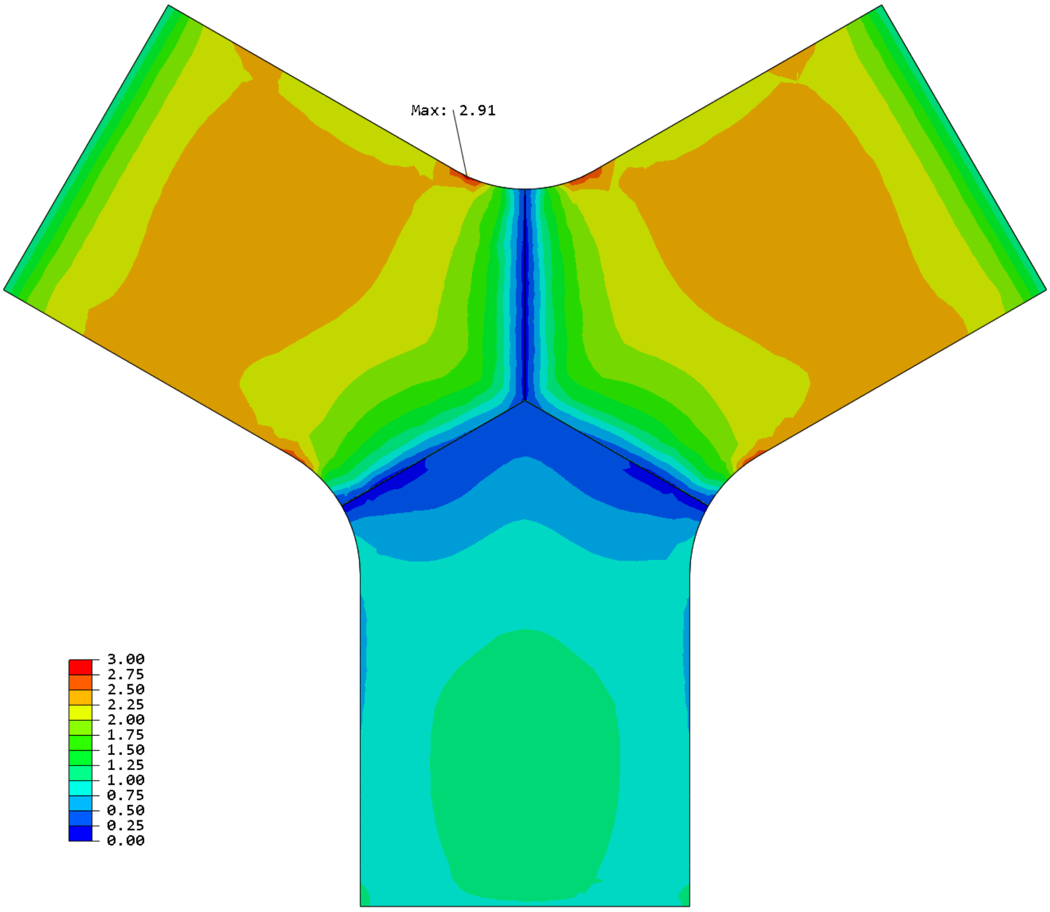


Figure 51 - Planar section of the tension test on v2.2

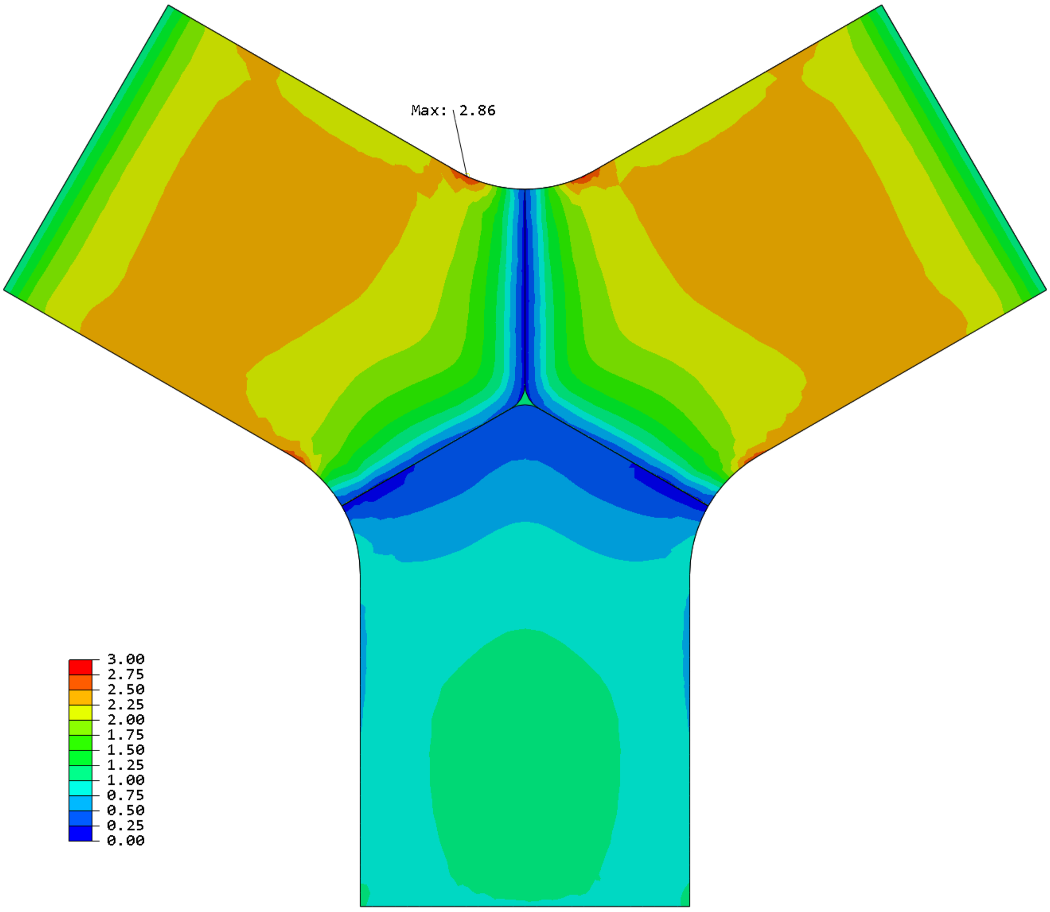


Figure 52 - Planar section of the tension test on v2.3

v3.1 and v3.2 - compressive force

As stated before, the version 3 series introduces a second type of material to the construction. The goal of this addition is to explore the effects of elements with different properties and different shapes, and the improvements this has on the performance of the element.

The introduction of another material could seem contradictory to the original goal of the research, which was building a node which was completely made out of wood. It would, however, be valuable to know what the potential of such an addition could be. In this case, steel is used. While the goal was to replace a steel node, a wooden node reinforced with steel would still provide a significant reduction in the amount of steel used.

The first idea of reinforcement was made in the same shape as the node itself but in a much smaller size. This had the potential to concentrate the forces in the middle of the node, to relieve the wooden part of the node of a significant portion of its stress. This version of the design, however, did not provide the potential to support the wood in the case of a tensile force. The second version of the reinforcement added an extended shape perpendicular to the arms of the node, forming a T-shape. This had the potential to provide both compressive and tensile support to the structure. This type of reinforcement became the base of node v3.1.

For the material of the reinforcement, low-carbon steel was used. Steel is an isotropic material and therefore only the Young’s modulus and Poisson’s ratio had to be entered into Abaqus. These properties were taken from Granta EduPack.

Mechanical properties of low-carbon steel:

Young’s modulus:	210000 MPa
Poisson’s ratio:	0.285

In figure 53 and 54, two planar sections can be seen of the node versions v3.1 and v3.2 in a compressive load case on the three layer version. The sections are all taken from the second layer in the middle of the object. In this comparison the maximum stress in the wood was deemed to be the most significant. Therefore, the steel elements were taken out of the results, showing only the stress present in the wooden part of the structure.

The simulation of v3.1 in the compressive load case was performed successful, but the simulation of the tensile load case of v3.1 gave problems during simulating; the underlying problems causing the simulation failure are not yet found. It is, however, possible to reason the cause of this problem. The compression case of v3.1 shows a relatively large amount of stress in the wood on a very small area. It could be the case that the amount of stress induced by the tensile force on v3.1 is even larger, and possibly also in a small area. This could very likely be the cause of the problems in the simulation.

To try and mitigate the problems, the material of the reinforcements was changed from steel to beech. While this did cause the tensile simulation to be successful, the difference in the results between the two types materials in the compressive simulation was deemed to be too large to be comparable. Therefore an improved design of the reinforcement was made.

Based on the fact that the largest amount of stress in the material was located at a sharp corner of the reinforcement, there was an attempt made to make these corners less sharp in v3.2. This design, however, was also not able to perform the tensile simulation. For that reason, another design without sharp corners was made in v3.3.

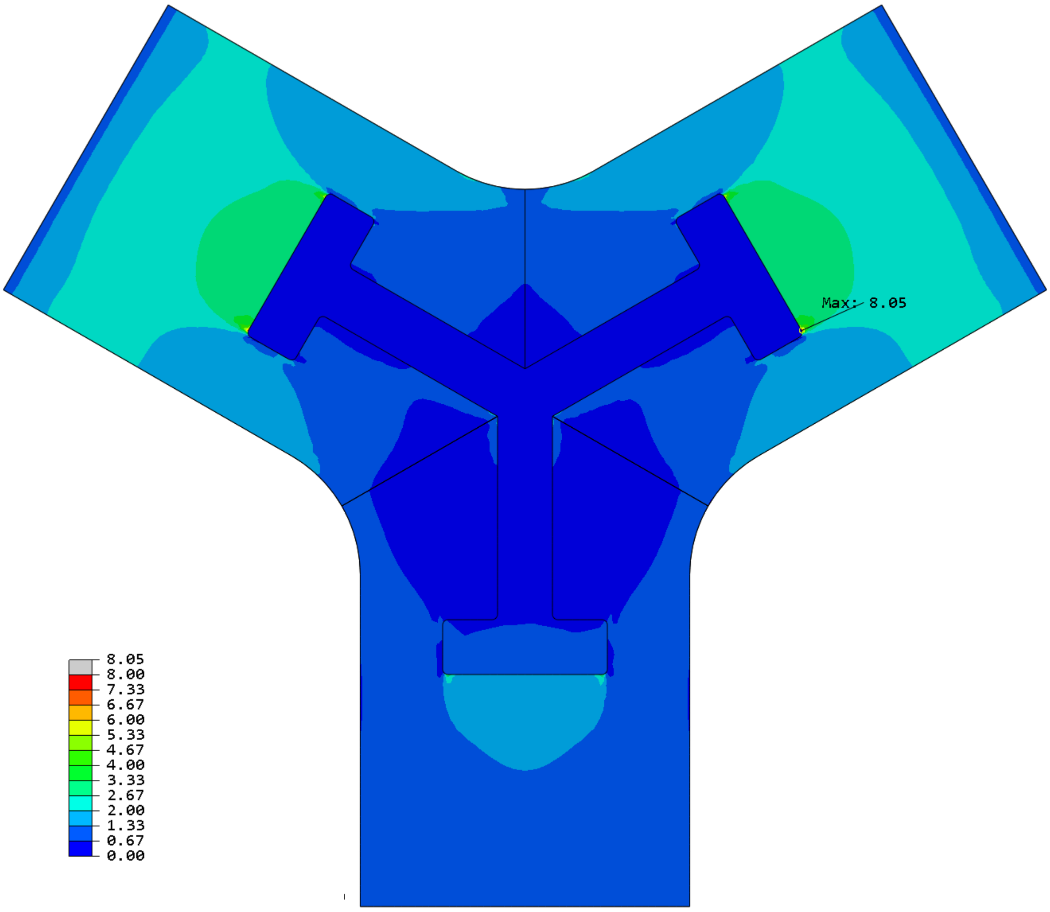


Figure 53 - Planar section of the compression test on v3.1

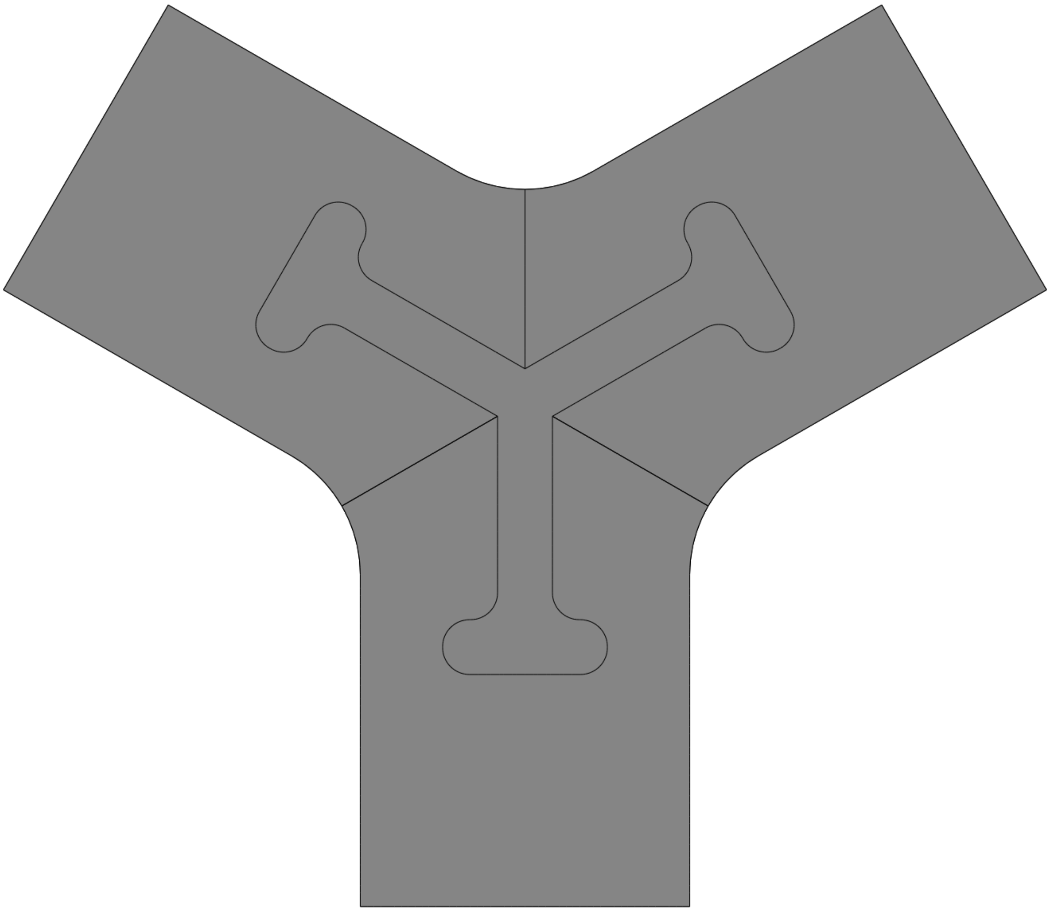


Figure 54 - Planar section of the failed compression test on v3.2

v2.3 and v3.3 - compressive force

In figure 55 and 56, two planar sections can be seen of the node versions v2.3 and v3.3 in a compressive load case for the three-layer version. The sections are all taken from the second layer in the middle of the object. In this comparison, the maximum stress in the wood was deemed to be the most significant. Therefore, the steel elements were taken out of the results, showing only the stress present in the wooden part of the structure.

The reinforcement in v3.3 is made out of a single loop of material without sharp corners. This design caused no problems when performing both compressive and tensile simulations. The highest amount of stress in v3.3 (5.89 MPa) is found at the centre of the segment where the segment connects with the steel element. This is significantly higher compared to v2.3 (3.22 MPa). This does not, however, have to be an immediate problem. The location of the highest stress in the centre of v3.3 is a spot that is enclosed by other materials. It is expected that this enclosed part is less likely to fail than when the maximum amount of stress is found at the edge of the geometry. Physical testing would be needed to determine if this is the case.

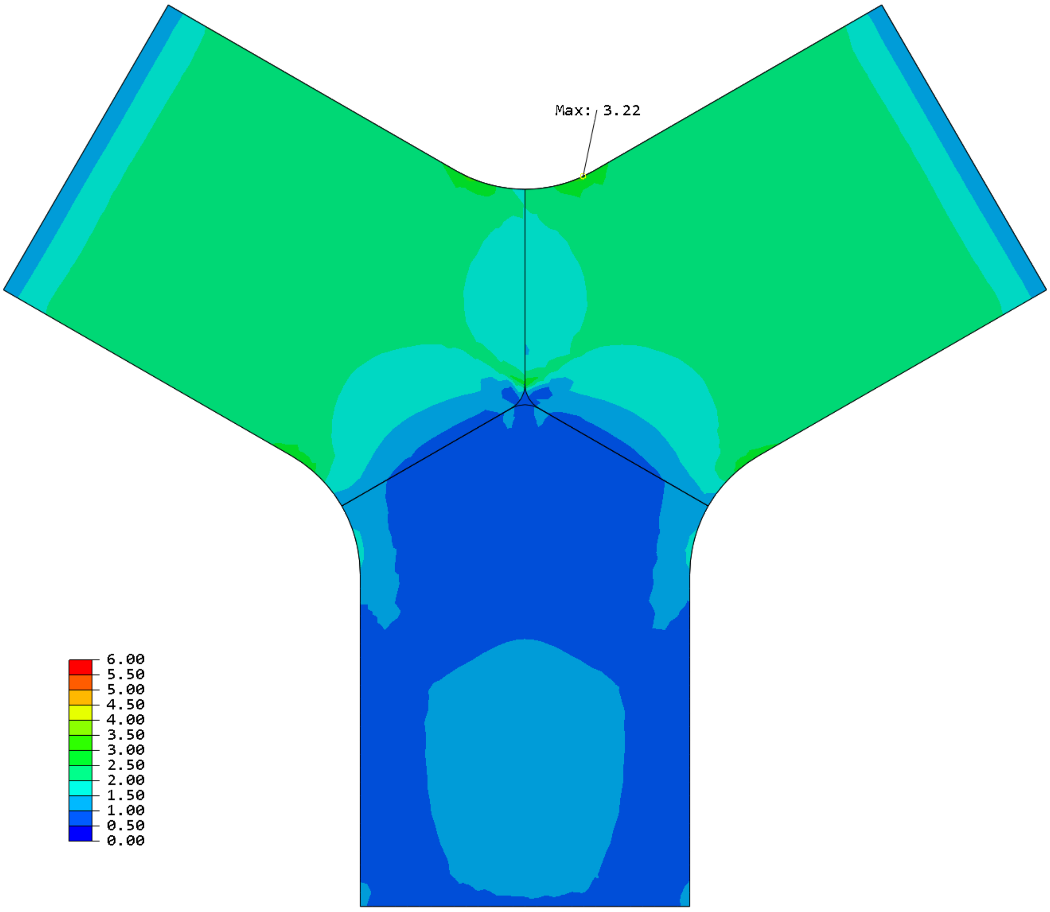


Figure 55 - Planar section of the compression test on v2.3

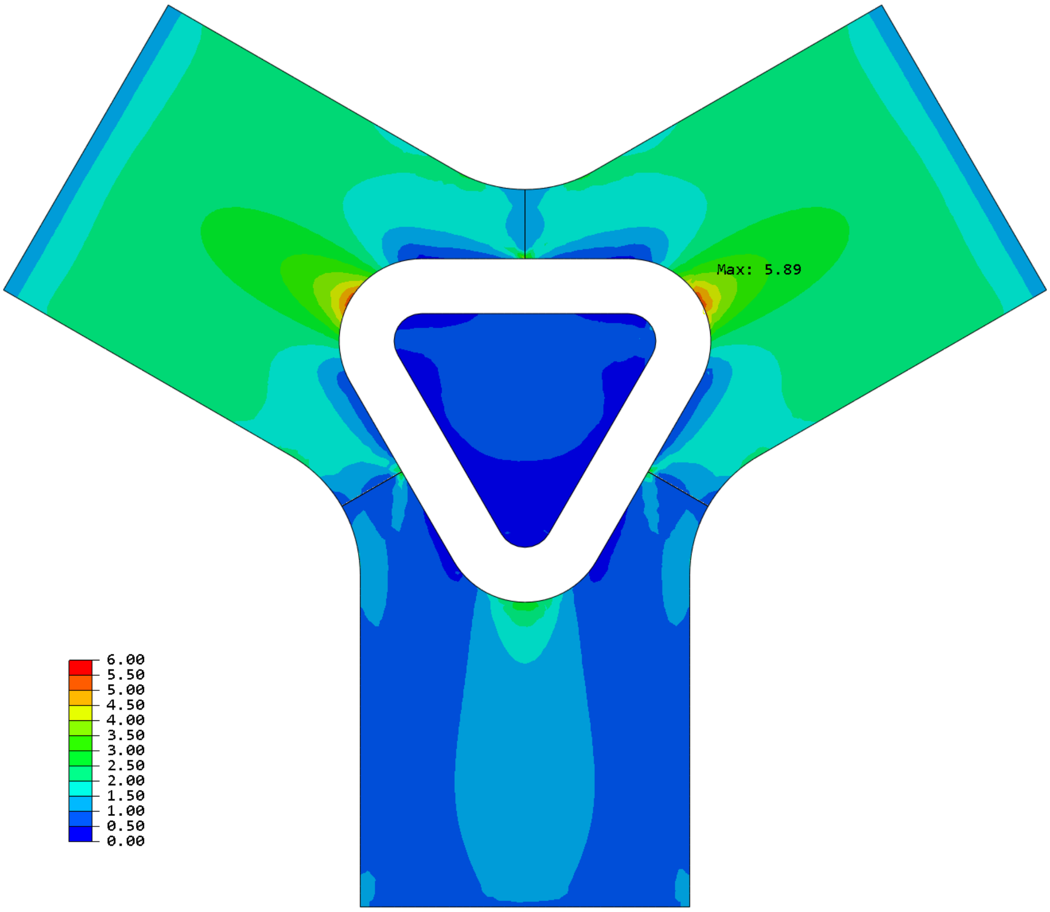


Figure 56 - Planar section of the compression test on v3.3

v2.3 and v3.3 - tensile force

In figure 57 and 58, two planar sections can be seen of the node versions v2.3 and v3.3 in a tensile load case for the three-layer version. The sections are all taken from the second layer in the middle of the object. In this comparison, the maximum stress in the wood was deemed to be the most significant. Therefore, the steel elements were taken out of the results, showing only the stress present in the wooden part of the structure.

While the tensile simulation shows a lower amount of maximum stress in v3.3 (2.81 MPa) compared to v2.3 (2.86 MPa), the 0.05 MPa difference is not deemed significant enough to be considered an improvement. In general, however, the wood shows a slight reduction in stress present in v3.3. This is expected to be caused by the steel element taking up part of the tensile stress.

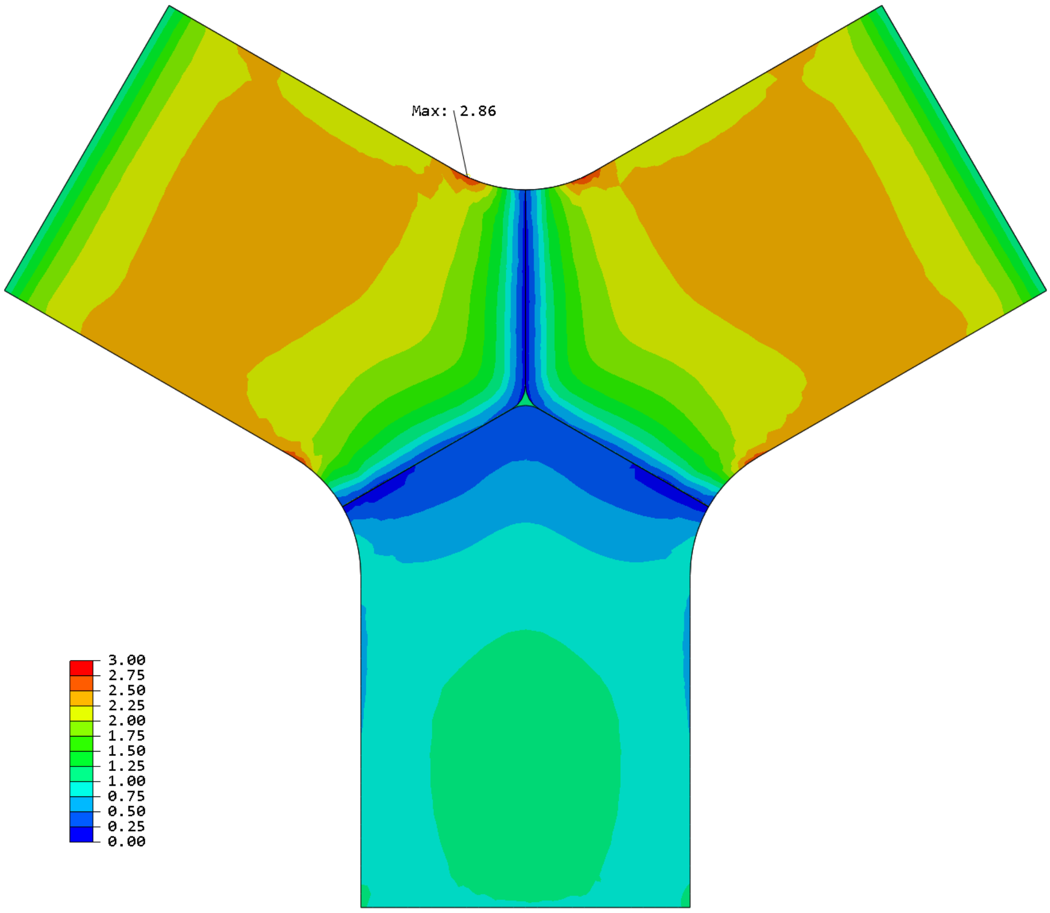


Figure 57 - Planar section of the tension test on v2.3

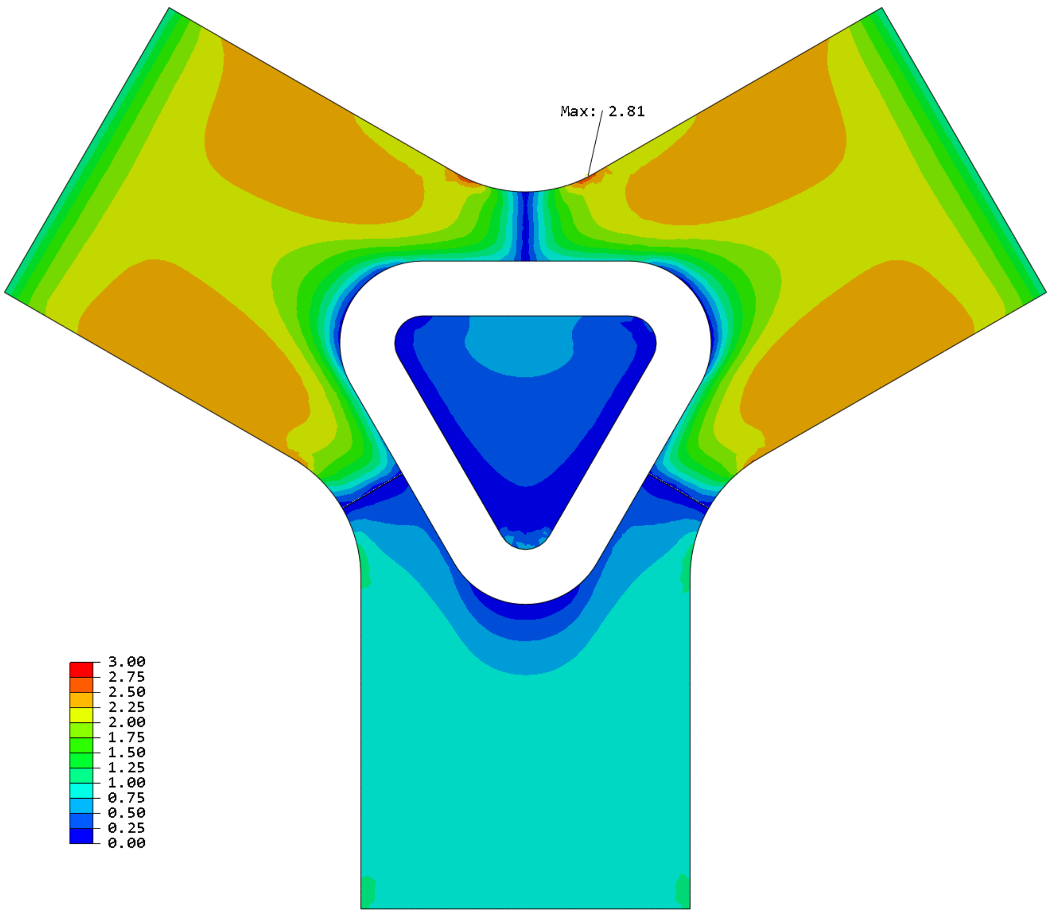


Figure 58 - Planar section of the tension test on v3.3

9. Final design

As a result of the simulation, v2.3 and v3.3 can be seen as the most developed and best performing design variations. However, based solely on the amount of maximum stress in the node, it could be argued that v0.0 (3.25 MPa) (figure 59) performs very similarly to v2.3 (3.22 MPa) (figure 60). This begs the question of whether it is worth all the extra effort to make the segmented node designs.

The maximum amount of stress, however, is one of many properties of a design version. Between v0.0 and v2.3 there is a significant difference noticeable in stress distribution within the material. V2.3 shows a more evenly spread load across the plane with a gradual decrease in stress in the direction of the bottom of the node. V0.0, however, shows a more chaotic stress distribution pattern with hot spots of stress around the plane of the material. The gradual type of stress distribution of v2.3 may be also beneficial when the design is exposed to other types of loads; further research into different load cases should be performed.

As stated earlier, v3.3 shows a larger amount of stress within the material compared to v2.3 (figure 61). While it was already stated that this did not seem to be an immediate problem, using this design variation also has the potential to provide benefits. While bending and buckling was not part of this research as of now, the addition of reinforcement in the node could provide more strength and stiffness to the node. In turn, this could mean that the node could suffice with a smaller thickness, thus a lower amount of layers, material, and production time.

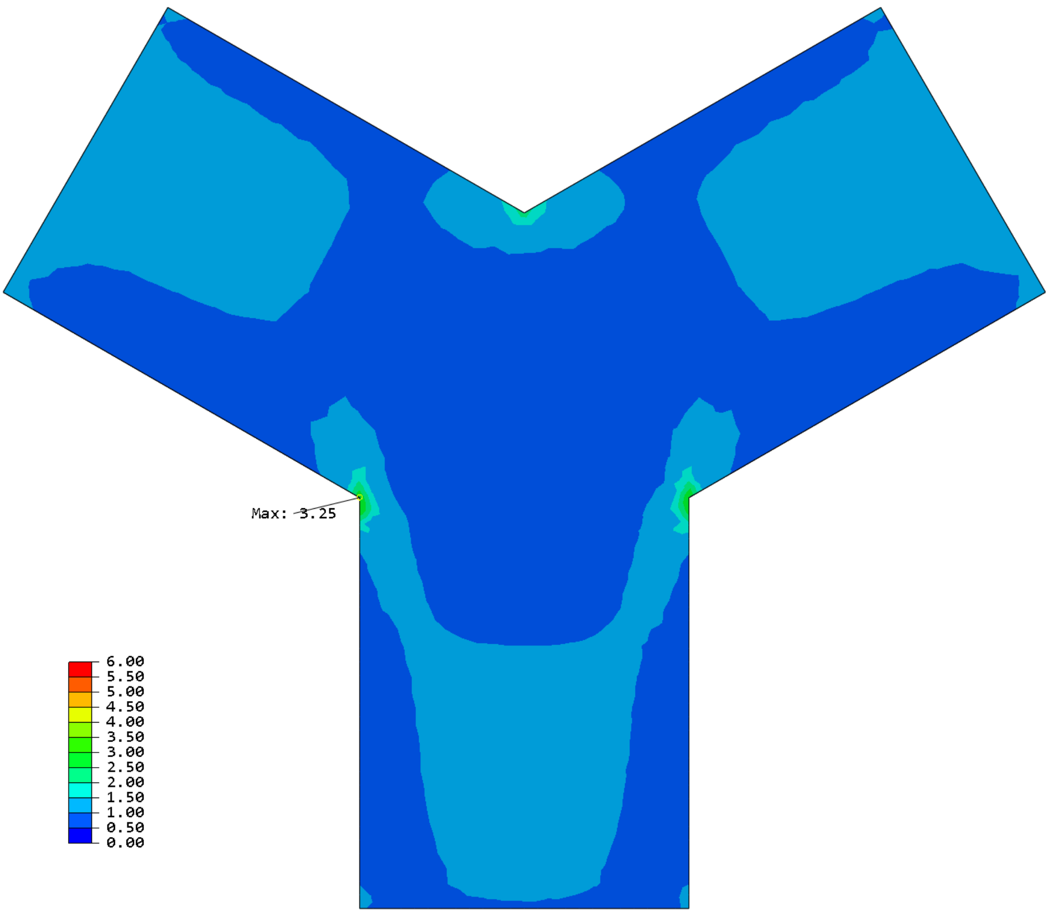


Figure 59 - lanar section of the compression test on v0.0

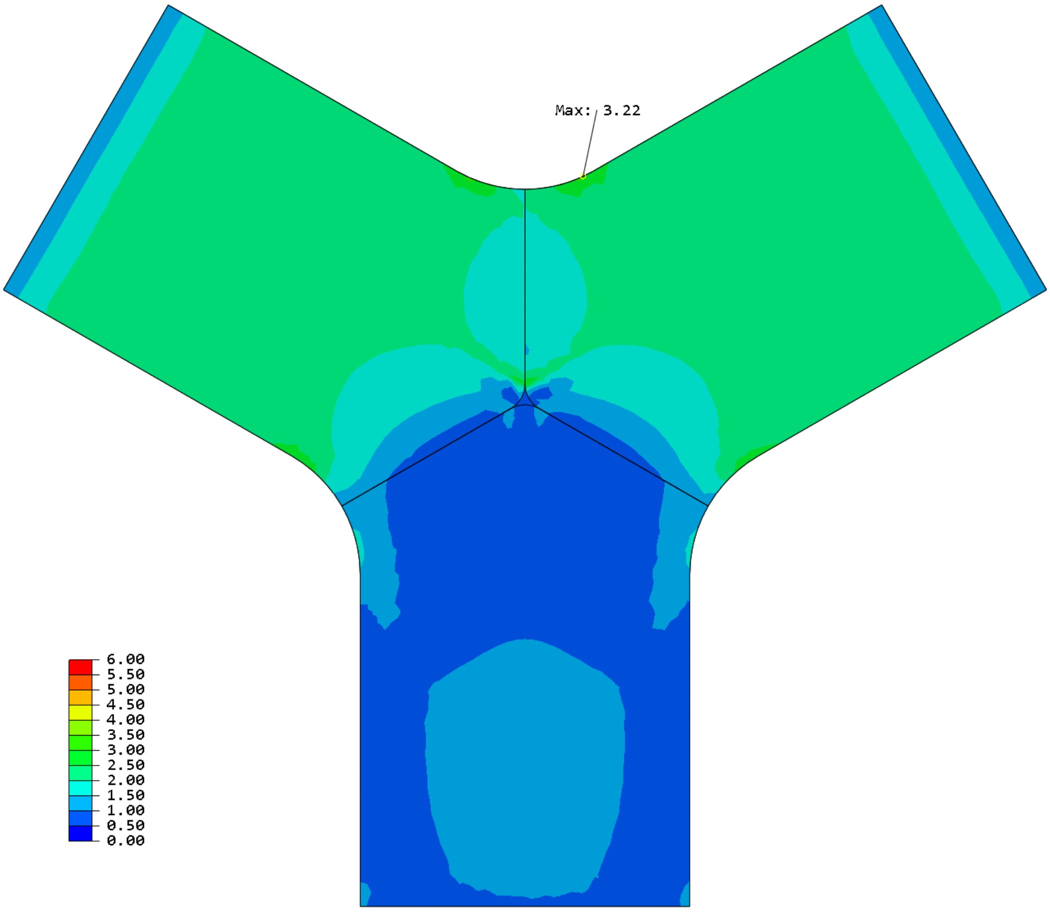


Figure 60 - Planar section of the compression test on v2.3

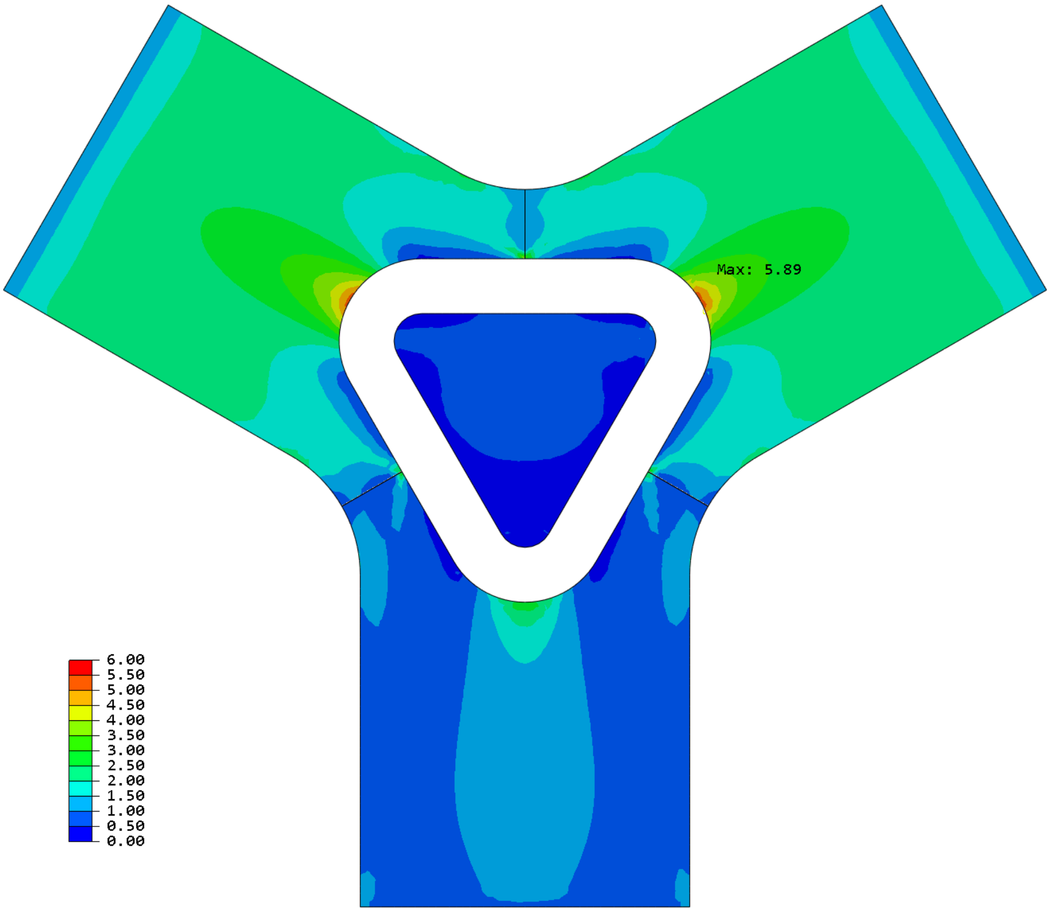


Figure 61 - Planar section of the compression test on v3.3

Production of a wood-LOM node
Now that a few examples of what a wood-LOM node could look like have been explored, it is necessary to think about the way in which these wooden will be produced. The use of wood-LOM produced nodes would have a high value if it is not only structurally beneficial, but also fast and reliable to produce. While the normal LOM procedure is known to be fast, reliable and precise, the wood-LOM process could create new difficulties.

One of the difficulties when using wood-LOM top produce, is the alignment of the various elements that have their own orientation. When using the regular LOM process, the sheet is rolled in one constant direction and all the layers have the same orientation. When you would use the design process as explained in the version 1 series of this research, each layer has one direction. If the direction changes, it would be sufficient to rotate the object in such a way that it receives the next layer in the right orientation. If you want to have multiple segments with various orientations in one layer, this method will not work. For the construction of these kinds of elements, a more complex solution is needed.

As stated before, the LOM process often laminates a new layer onto the object, and cuts it after the lamination is done. A possible solution to this problem with several segments in one layer, is cutting the desired shape out of the material first and then moving the segments onto the object to laminate it (figure 62). This does, however, require a reliable way to pick up the segment, a way to align the segment with the object at the desired location, and laminate the segments to the object. For this to work, the object needs to have a certain minimum size to be able to be handled automatically. Another option is to align and laminate the segments manually, but this would slow down the process and would increase the labour needed to process an element.

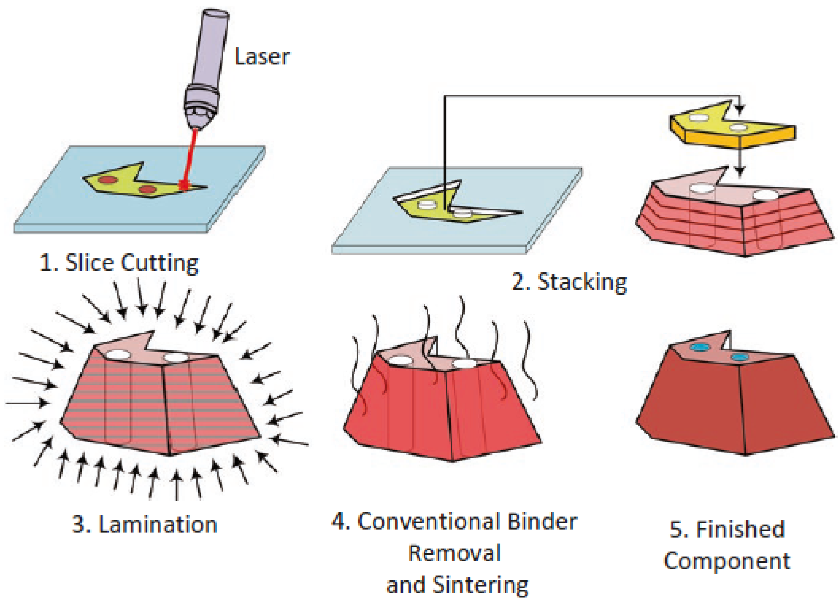


Figure 62 - Alternative assembly method for the LOM process (Gibson, 2021)

Another possible difficulty could be the reaction of wood to the application of an adhesive. During the production of the laminated specimen for material testing earlier in this research, it was discovered that when a layer of adhesive was applied to one surface of the wood veneer, the material tended to bend due to the expansion of the material on the side of the applied adhesive (figure 63). This effect could prove less of a problem when the object is fixed on the bottom, or when another type of adhesive is used compared to the adhesive used during the production of the tested samples. Further research is needed to be able to determine the effects and solutions for these challenges.

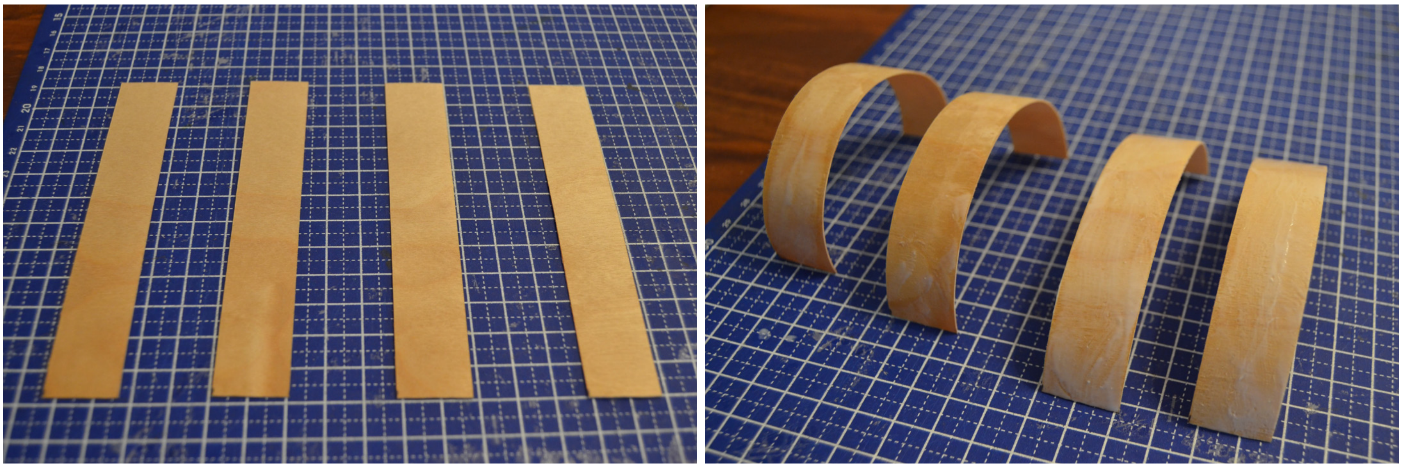


Figure 63 - Veneer layers reacting to application of adhesive (author)

Connecting a node to a structure
Another important factor that has to be addressed, is the method of connecting the construction node to the rest of the wooden construction. Research has been done into various ways of connecting wooden elements.

With wood being one of the oldest building materials known to man, the joining of wooden elements is also an age-old technology. All over the world, different wood joining techniques were developed. The characteristics of these joints were influenced by for example local climate and social factors (Zwerger, 1997).

While there are some basic wood-on-wood principles to define, the variations on these basic principle are almost endless. For example, two pieces of wood could be 'butt-jointed' (figure 64). To create more contact surface, a 'halved-and-lapped' joint (figure 65) could be formed. By varying the shape of this overlap, a large variety of joints (figure 66) could be formed with varying properties and manufacturing difficulty.

Figure 64 - Butt-jointed pieces of wood (Zwerger, 1997)

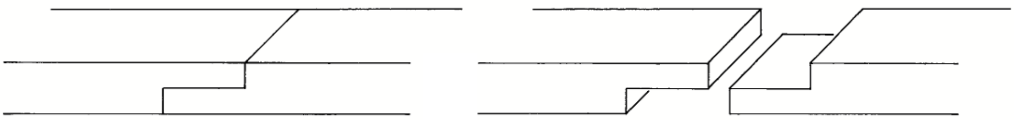


Figure 65 - Halved-and-lapped joint (Zwerger, 1997)

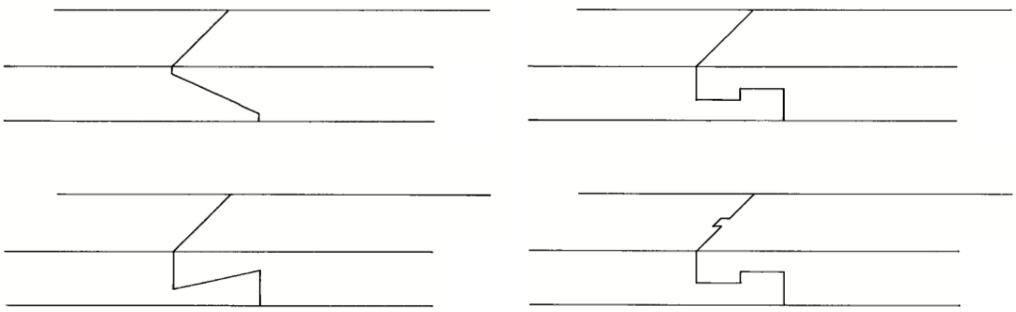


Figure 66 - Variations on a halved-and-lapped joint (Zwerger, 1997)

Another important example of a wood joining principle is the use of a dovetail connection. This connection was used when the two pieces of timber were subjected to tension as well as compression (Zwerger, 1997). By cutting a triangular-like shape out of one side, and the negative of that shape out of the other, the two pieces of timber could be hooked into each other (figure 67).

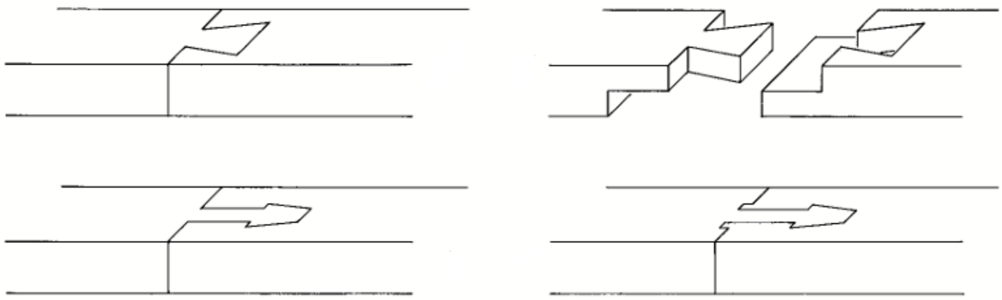


Figure 67 - Variations of the dovetail connection (Zwerger, 1997)

Another commonly used joint for timber elements is the finger joint (figure 68). For this joint, long grooves are cut into the end faces of both elements. Along with glue, these elements are pressed together. Due to a large amount of contact surface, a strong bond can be created.

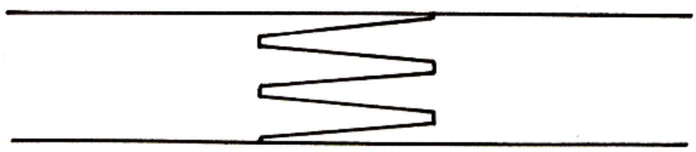


Figure 68 - Example of a finger joint (Martin, 1977)

While these connections are relatively complex and have a limited amount of tensile strength, they do provide good examples of the possibilities wood provides for joining wooden elements.

Bolting connections

Steel connectors can be added to wooden joints. The simplest form of connecting wooden elements with the use of bolts is adding them to the earlier mentioned lapped joints (figure 69). This strengthens the connection by taking on the shear forces in the connection.

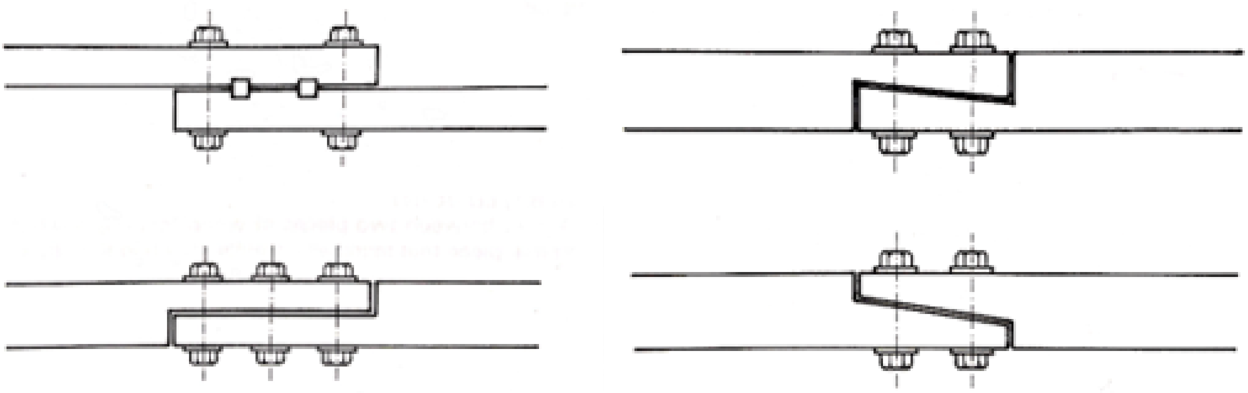


Figure 69 - Bolted lapped joints (Martin, 1977)

External connectors

The use of external connectors could provide an easier way to connect two timber elements (figure 70). Most often steel profiles of varying thickness and shapes are used for this type of connection, fitted to the timber elements by screws. This provides a solid connection without a complex cut pattern.

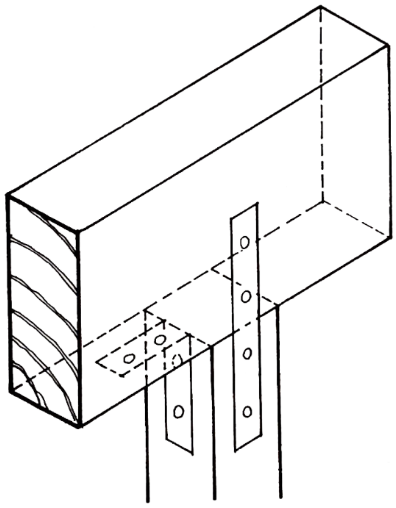


Figure 70 - Example of an external connector (Martin, 1977)

Wooden peg connection

Kromoser et al. (2021) studied the connection of a plywood node to a wooden structure by wooden pegs. As a result, a load bearing structure was made which was completely constructed out of wood (figure 71). These findings can provide valuable insights for developing a method of connecting wood-LOM nodes to structural elements.

Figure 71 - (Kromoser et al., 2021)

In this research a wooden construction was made to serve as a support for a canopy. By using a parametric computer model, a construction was made that was optimised for this specific load case. The construction is made from straight wooden beams connected with plywood CNC cut nodes. Wooden pegs were used to connect the plywood nodes with the construction beams, making a complete wood-on-wood connection throughout the construction. In this experiment different materials were tried and tested. As a result of these test, the final design used beech plywood for the nodes, beech wood for the pegs and spruce for the beams.

Connections in wood-LOM produced nodes

When the results of the research into the use of pegs would be used to connect a wood-LOM produced node to a construction, there are new possibilities to improve the performance of such a connection by using the characteristics of a wood-LOM produced node. The research of Kromoser et al. (2021) also did experiments to find the effects of changing the angle between the grain direction of the outside layer of the plywood (the main load-bearing direction) compared to the direction of the applied force. Their conclusions were in line with statements made earlier in this research, stating that aligning the grain direction of the outside layer of the plywood in the same direction as the force applied is beneficial for structural performance.

Kromoser et al. (2021) designed a connection using wooden pegs (figure 72). The assumptions made earlier in this research, concerning the benefit of aligning as much of the grain directions in the material in the direction of the applied force, could also be applied to the concept of this type of connection.

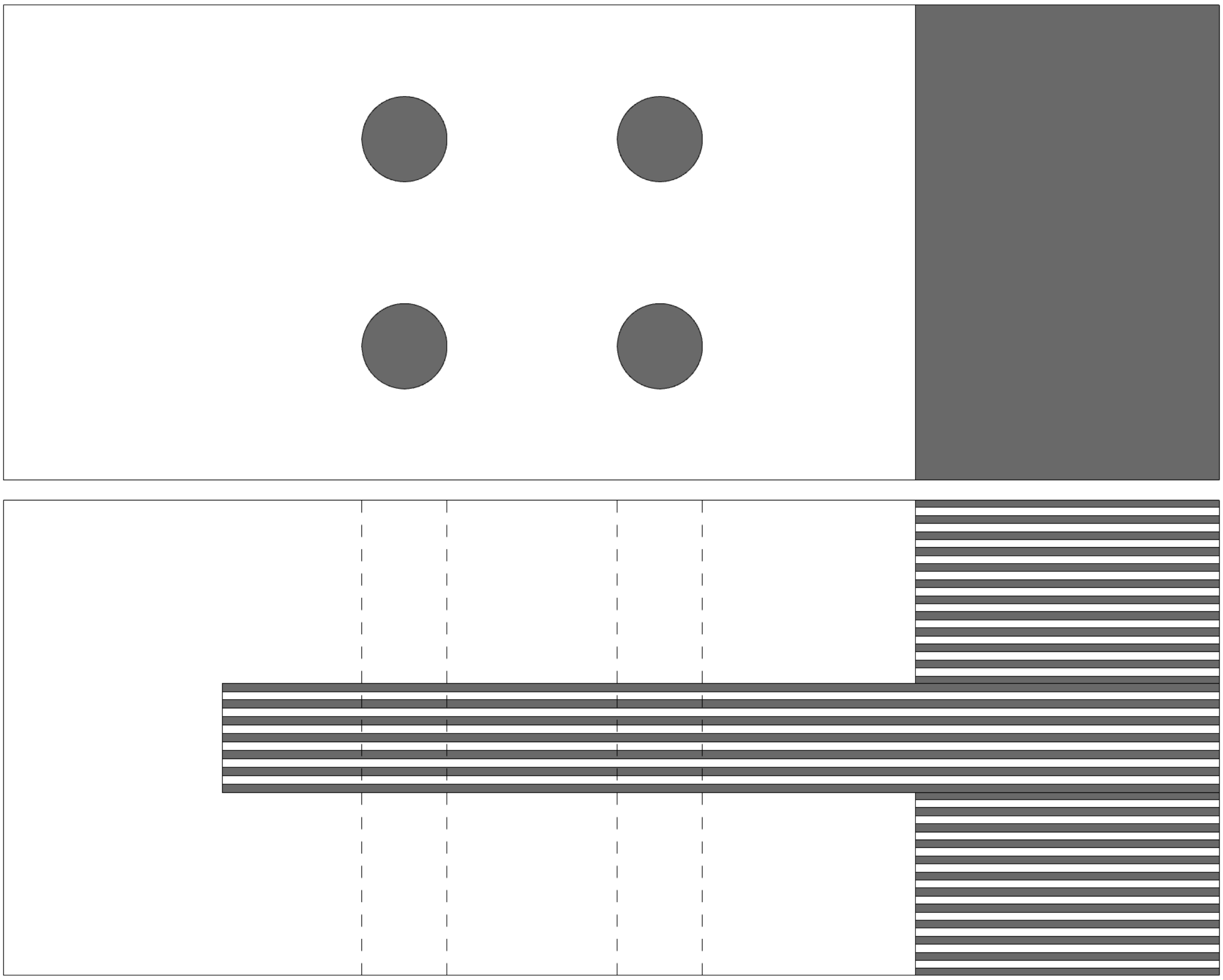


Figure 72 - Schematic visualisation of the wooden peg connection designed by Kromoser et al. (2021). Grey represents a layer with the wood grain in the same direction as the applied load.(author)

Several improvements can be made to this design using the possibilities that wood-LOM provides. In the first place, a larger amount of plywood from the node could be inserted into the beam element. In this situation the layers inserted can be made smaller, approaching a structure that has similarities with a finger joint (figure 68). The grain direction of the veneer layers of the plywood that is inserted into the beam could also be made stronger by aligning more veneer layers in the main direction of the applied force.

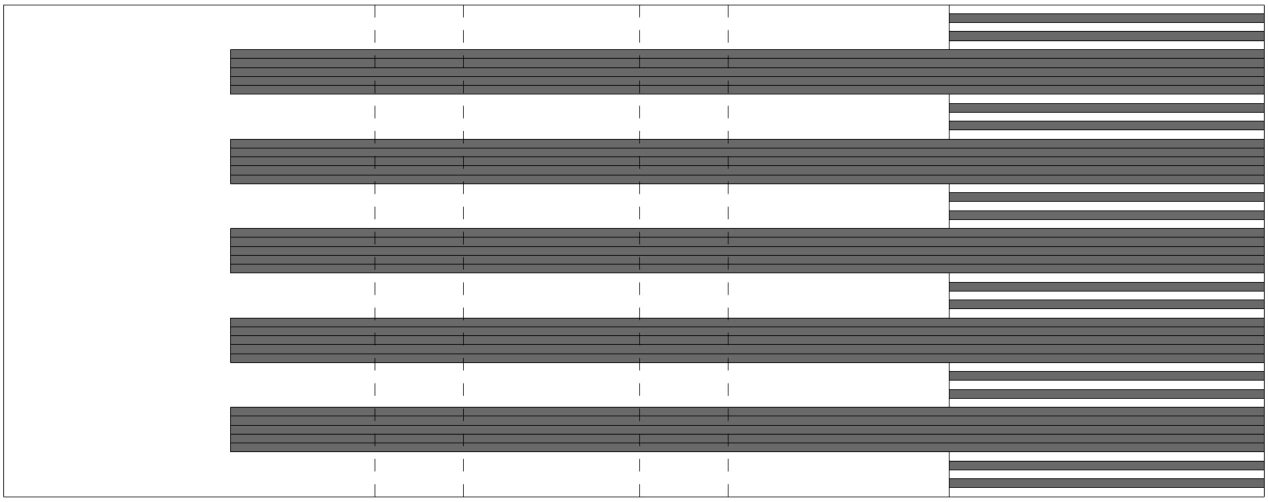


Figure 73 - Design variation of the wooden peg connection. Grey represents a layer with the wood grain in the same direction as the applied load. (author)

While this type of structure has the potential to be beneficial to the strength of the connection, there are also potential drawbacks. One drawback is that a larger amount of inserted parts also requires a larger amount of slots to be cut at the end of the beam, creating thinner 'fingers' at the end of the beam. This would slightly complicate the process of cutting the slots. The thinner 'fingers' could also have unwanted effects on the performance of the material. The process of sliding the layers into the slots could also prove more difficult because more layers of material have to be aligned when combining them.

This type of structure also has effects on the structure of the nodes. By altering the layer structure of the material, the layer structure of the node will also change. While this would not necessarily have to be a disadvantage, it is something that has to be taken into account when using this technique.

To be able to make a valuable assessment of the performance benefit of this type of connection structure compared to the other example, extensive testing of various design iterations will have to be conducted.

Angled nodes

So far in this study only nodes were designed that were used for forces working in one plane. This is, however, not the only type of node that would be used in practice. Construction nodes often need to connect construction elements under a certain angle (figure 15). It would be valuable to design a version of the node which has an angle incorporated into the design. This angle will possibly have a significant effect on the design choices that have to be made for the design. These design choices and the effects these have will have to be investigated in a test case.

To be able to create the angled version of the node design, the original design will have to be altered slightly. In addition, a method to transform the newly designed node into layers that can be cut out of veneer layers will have to be developed. Various options of organising the layering structure for an angled design have to be studied to decide on the most suitable option.

As an example case, a rectangular shape was used. The shape was bent at an 20° angle, creating an inner corner of 160° (figure 74).

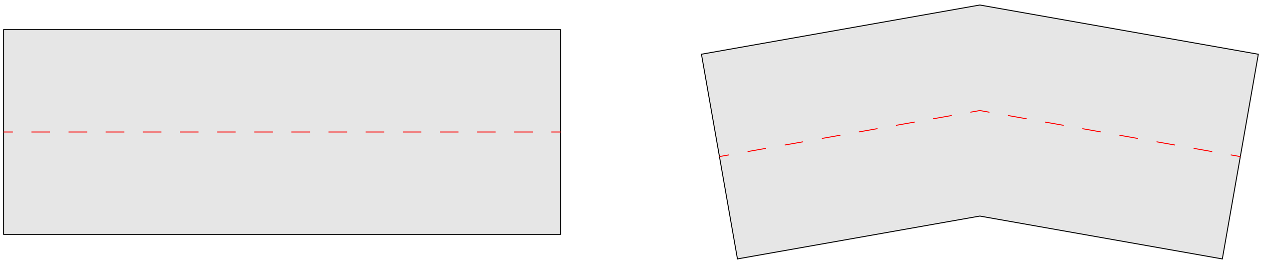


Figure 74 - Straight and bended version of example section (author)

The layer organisation of the straight version used straight horizontal layers (figure 75). However, the layer organisation of the bent version left various possibilities. Three distribution types and their characteristics are discussed. The first organisational option was a bent layer organisation (figure 76). Continuous veneer layers were used with a bend in the middle. While in theory this would be an option, this type of structure could prove difficult to make with wood-LOM. The lamination process and laser cutting are done in a horizontal plane. To be able to laminate an element with such angles, a completely new type of lamination and cutting will have to be used making the process far more complex. Therefore, at this stage, this version seemed too complicated for this design case.

The second organisational option laminated two sides separately and joined them together. This could be created with wood-LOM, but it has the drawback of having a seam in the middle of the node. This aspect of the design version lowered the potential strength of this type of node.

Figure 75 - Straight layer organisation (author)

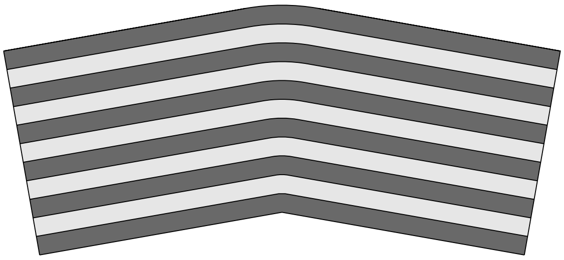


Figure 76 -Alternative layer organisation type 1 (author)

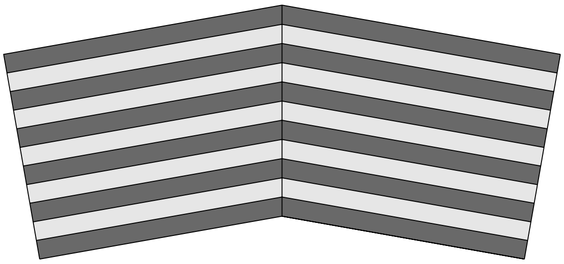


Figure 77 - Alternative layer organisation type 2 (author)

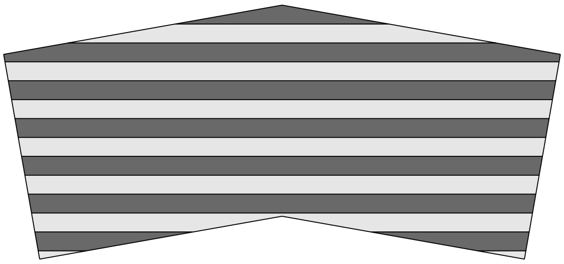


Figure 78 - Alternative layer organisation type 3 (author)

The third investigated option (figure 78) was a type of layer organisation that used the same layer orientation as the original shape (figure 75). The benefit of using this layer organisation is that there were still a large number of continuous layers throughout the object, improving the strength compared to the other two options. This type, however, provides the difficulty that the straight edges of the layers are not in line with the angled parts of the geometry. Fortunately, this is a fixable problem.

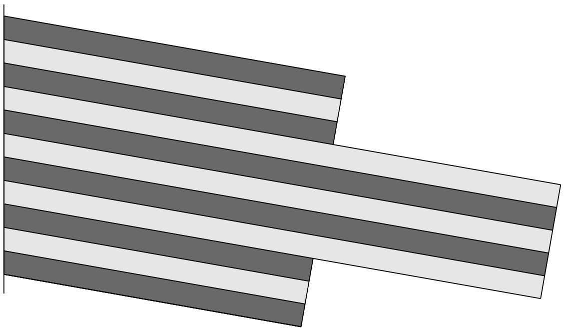


Figure 79 - Angled layer organisation segment (author)

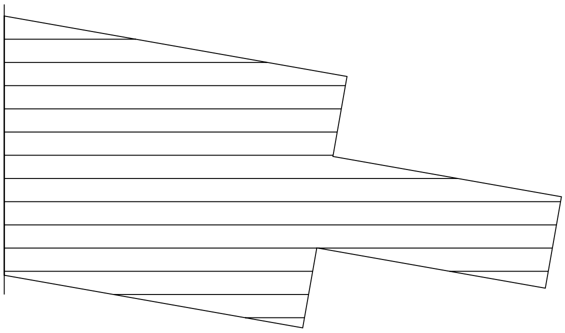


Figure 80 - Horizontal layer organisation segement (author)

The difficulty in choosing the horizontal layer distribution is visualised by a segment of the connective part of the node. Using the angled layer organisation, the layers can easily follow the shape of the connective part (figure 79). When horizontal layering was used (figure 80), a decision had to be made about the best way to closely follow the designed geometry.

When the horizontal lines were used as the contour of each layer of the element, an angular structure was produced (figure 81). The vertical resolution of this version of the node was limited by the layer thickness of the material. Therefore the produced shape became an approximation of the desired final geometry. This characteristic was seen as undesirable.

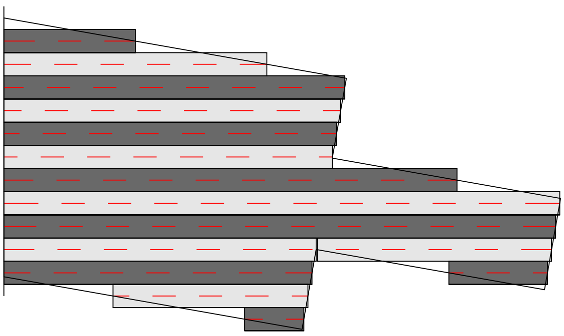


Figure 81 - Example of horizontally layered stucture (author)

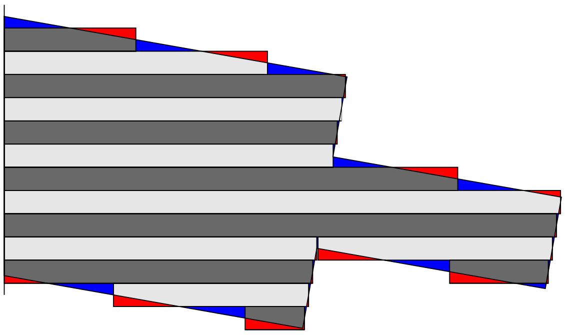


Figure 82 - Comparison between desired shape and the produced layer structure. Red represents excess material, blue represents lacking material (author)

A way of solving this problem would be to layer the element in such a way, that solely excess material was created after laminating the layers (figure 83 and 84). In that case, the excess material could be removed afterwards by, for example, a CNC mill, creating a smooth final shape (figure 85).

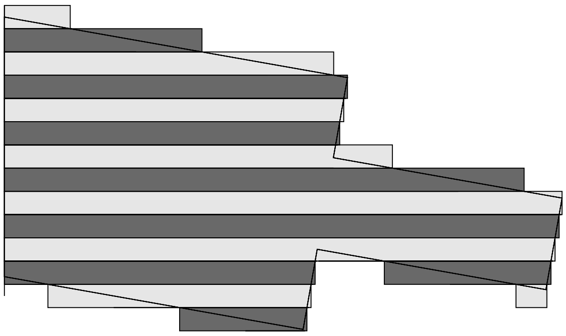


Figure 83 - Example of horizontally layered stucture (author)

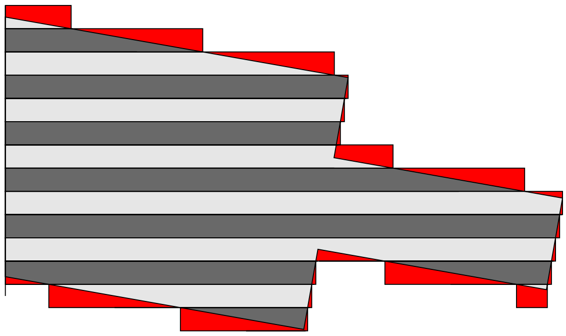


Figure 84 - Comparisson between desired shape and the produced layer structure. Red represents excess material (author)

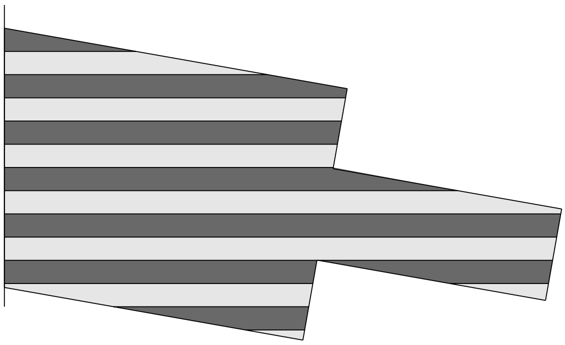


Figure 85 - Finalised stucture (author)

Translating an angled shape into layers

To be able to translate a complex 3D geometry to independent layers, a couple of steps were needed. The 3D geometry was first created in Rhinoceros 3D. Then Grasshopper was used to translate the 3D geometry to 2D layers, which could be laser cut. The various steps taken to conduct this translation will be explained further.

First, we start with the base 3D geometry from earlier in the research (figure 86). The arms of the geometry are then each bent 10° downward, creating an angled shape (figure 87).

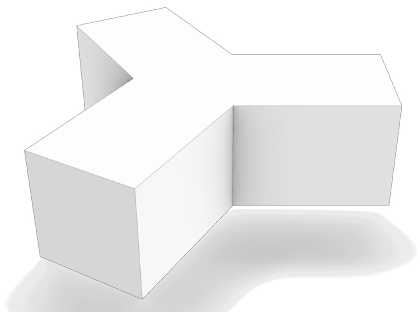


Figure 86 - Base geometry (author)

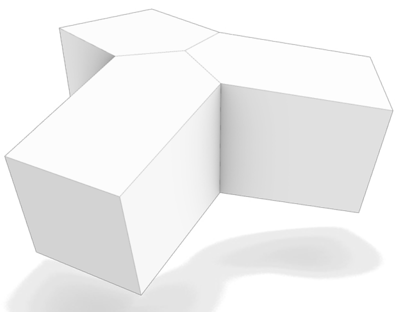


Figure 87 - Angled geometry (author)

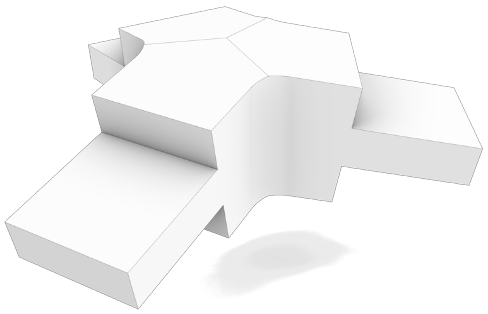


Figure 88 - Angled geometry with connective part (author)

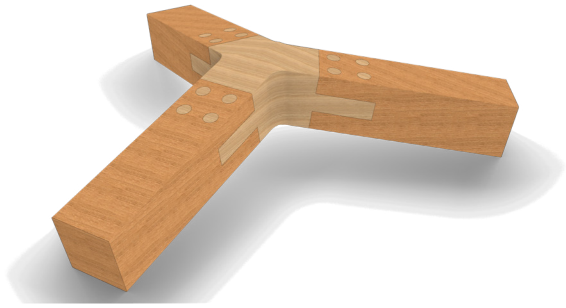


Figure 89 - Impression of final construction (author)

The corners were rounded and the elements that connect to the wooden beams were added (figure 88). Wooden pegs and beams were added to the model to create an impression of the final assembled product (figure 89). Note that the simplified version of the connection using one 'finger' was used as to clearly visualize the final connective model.

Using a Grasshopper model (appendix IV) the geometry was transformed into an object constructed of individual layers (figure 90). The Grasshopper model was parametric, which created the possibility to alter the desired layer height.

The base geometry was loaded into the Grasshopper model as a source geometry. The contour element then divided the geometry in layers based on a layer height and fixed base point. In this case, the heighest point of the model was chosen as the base point. However, the power of parametric tools like Grasshopper lies in the possibility to change parameters and immediately being able to see the changes. In the Grasshopper model, the final 3D-layered structure was also directly visualised as a geometry with the desired layer thickness, providing a tool to see the effect of design choices. For the final iteration of the design, a layer thickness of 0.6 mm was chosen and the final 3D geometry was exported from Grasshopper (figure 90).

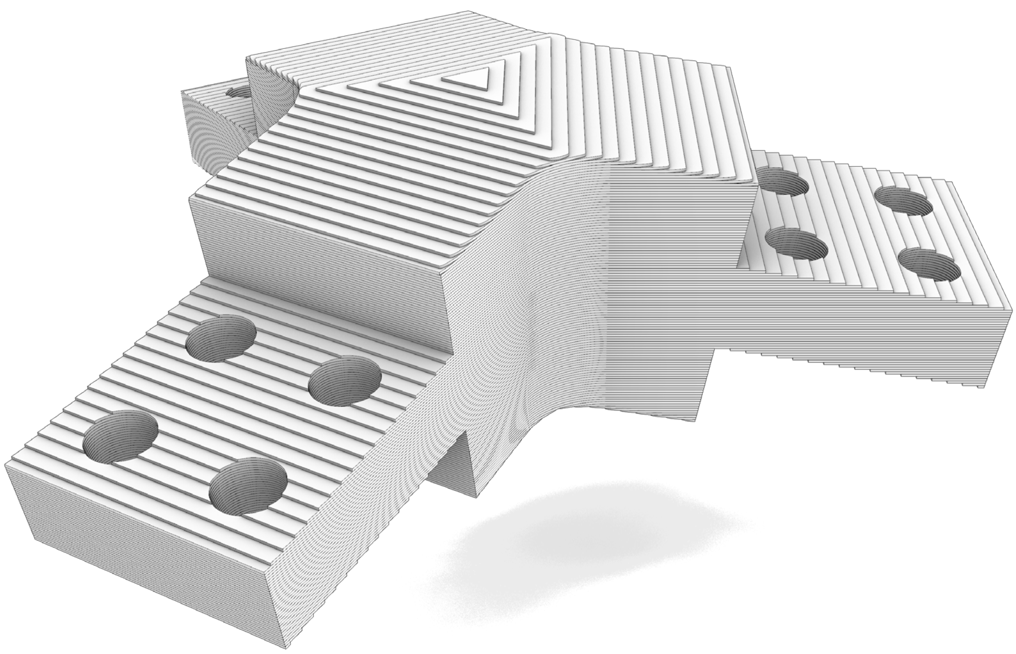


Figure 90 - Visualitation of geometry divided in layers of 0.6 mm (author)

10. Conclusion

What are the advantages and limitations of manufacturing wooden elements using LOM?

Several advantages of using LOM to create wooden elements were found during this research. The most significant advantage of using LOM for creating wooden elements is the possibility to dictate the grain direction of each layer of material. This gives the designer of the object more freedom in using the strengths of wood to its full potential. Another advantage of using wood-LOM to create a wooden element is the fact that the principle of using layers to create an object creates the possibility to optimise the process of cutting out the layers. If the nesting of the sections that are being cut out of a sheet of material is done in a well-organised manner, the amount of waste material can be reduced.

Manufacturing a wooden element by using wood-LOM also has several possible limitations. If an object is made by using several orientations of a material in the same layer, the conventional LOM process of laminating each layer before cutting will not work. The sections will first have to be cut and then transferred to the object where it is necessary to align the section with the part of the geometry that is already created. Another disadvantage of this production method at this point is the lack of information available about this technique and the performance of the elements created with this technique. A lot of research and testing will need to be performed to find suitable ways to be able to utilize the advantages of this manufacturing technique.

What are the design parameters for constructing a solid wooden connection element using LOM?

Due to the limits of this research, the main parameters focused on were object geometry, the grain direction per layer, and the division of layers into several elements. Rounded corners were shown to decrease the maximum stress in the entire node. Laminating layers with the grain direction in line with the applied loads, showed a more optimal distribution of stress in the object compared to conventional material structures, with a reduction in stress along the edge of the node. Segmenting layers so the grain direction in both arms of the Y-formed node is along the line of the applied force, further decreased the maximum stress in the node. Additionally, the stress in the node was found to be more evenly distributed, suggesting a smaller change of element failure.

While the tested variations show some effect of grain direction, geometry, and the division of layers into several elements, many more variations can be explored. Additionally, numerous different parameters should be investigated, such as layer thickness, layer repetition, and the used adhesive, leaving a lot of room for innovations and improvements.

A hybrid node, using a steel element to reinforce the object, was designed and tested; the localisation of stress was found to be more focused on the center of the object, in contrast to along the edges in non-reinforced designs. If completely wooden nodes are not deemed suitable in the future, more research should be done to properly investigate the use of hybrid elements to still reduce the use of steel.

Another design parameter could be found in utilizing the benefits of a wood-LOM manufactured structure in connection to another part of a structure. In the current state, this research is not yet able to provide valuable insight into that design parameter.

What methods can be used to create reliable connections between a wood-LOM produced node and a timber structure?

In this study, several conventional methods of connecting a wooden element to a timber structure have been discussed. Based on literature findings it was concluded that using wooden pegs would suffice to create a reliable connection in a wooden construction. This study aimed to reduce the use of steel in construction. Using wooden pegs instead of steel bolts would further reduce the use of steel. This method was therefore applied to a wood-LOM produced node. Aligning the grain direction of the layers connected with pegs to the direction of the applied force and increasing the number of layers of the node connected to the pegs are suggested to improve the connection method.

How can Layer Object Manufacturing (LOM) technology be used to create wooden nodes for timber structures?

This study explored several design methods based on the principles of LOM and combining these principles with the specific properties of wood. By exploiting the freedom that this manufacturing method provides, new structures were created that aimed to maximize the structural performance of the constructed element. Insights were gathered regarding the effects of the improvements made to the objects.

LOM technology can be used to create objects with an individual layer structure specifically designed for the function of that element. LOM also provides the possibility to create a new type of hybrid structure to strengthen the wooden elements created with LOM. While the technique still has to be developed further, it shows potential to be used to replace steel node designs.

11. Recommendations

Due to the experimental and explorational nature of the research, there is still a lot of room for new research into the subject of wood-LOM. The number of recommendations that are listed in this chapter is in no way a conclusive list. Only the recommendations that are deemed relevant as a result of this research are listed.

The most important recommendation would be to investigate the method of connecting a wood-LOM produced node to the construction. The specific layer structure of a wood-LOM produced node could have the potential to strengthen the connection to the solid wood of the connection. When connecting the structure to the layers with the grain direction along the longitudinal axis, the structure and the node would be connected at the strongest parts of the node; using LOM to manufacture the node would make it possible to create this complicated geometry with ease. However, it is also important to consider the ease of installation when designing these more complicated connection methods.

This research was mostly focused on the benefits of a wood-LOM produced node. The practicalities of the manufacturing process were explored, but more research is needed to be able to develop a method to create wood-LOM objects of a consistent level of quality. This process would be most valuable if the manufacturing process is automated as much as possible.

Regarding the complexity of the designs made in this research, the node design was based on a two-dimensional construction with forces within a single plane. It would be valuable, however, to conduct research into the possibilities of creating a wood-LOM produced node for a three-dimensional structure with forces in more than one plane. This will add a layer of complexity to the design, but this will also create an opportunity for wood-LOM node properties to excel compared to other wooden structures.

With the most relevant benefit of a wood-LOM produced node being the enhanced structural performance of the node, it could be beneficial to try and automate the optimalisation of the design of a wood-LOM produced node. Computer aided optimisations are already found in other types of constructions and have the potential to be used with wood-LOM produced nodes. To be able to realize this, computer simulations will have to be fed with information from physical testing, to be able to make accurate estimations and design suggestions.

In one of the design variations of this research, steel was used to reinforce the wooden element. This was, however, only an example of a combination of materials. The wood-LOM process provides room for a number of materials to be combined with wood to reinforce the element. Using another reinforcing material could possibly improve the sustainability and recyclability of the element, while still improving the mechanical performance of the connective node.

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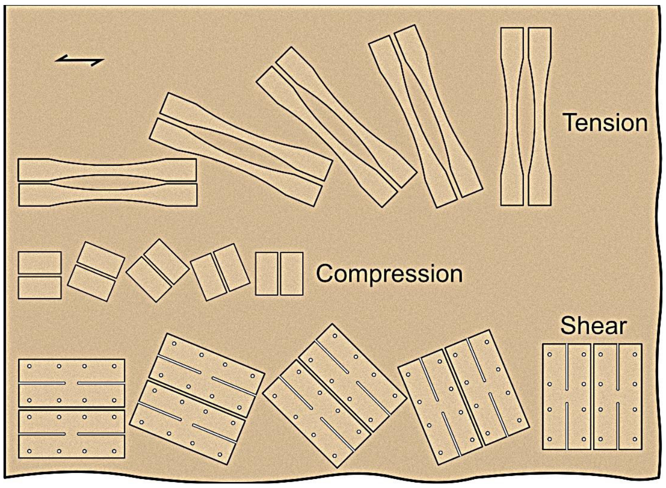
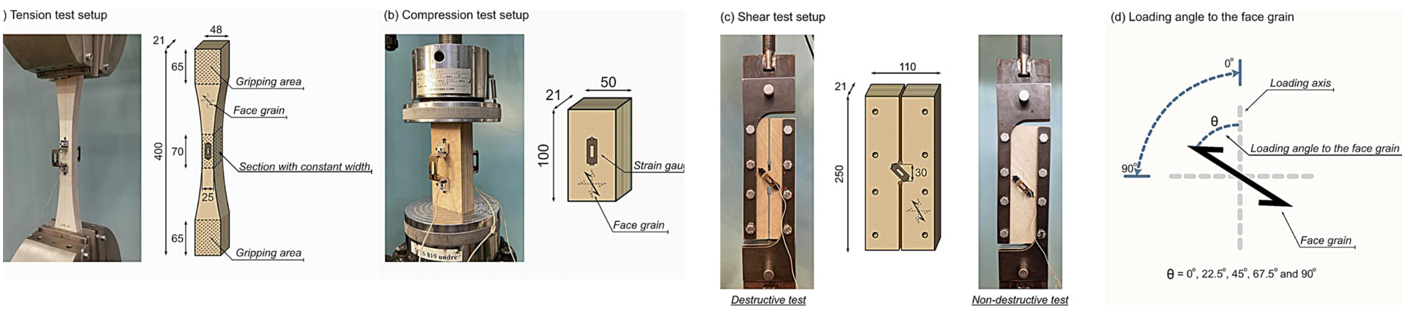
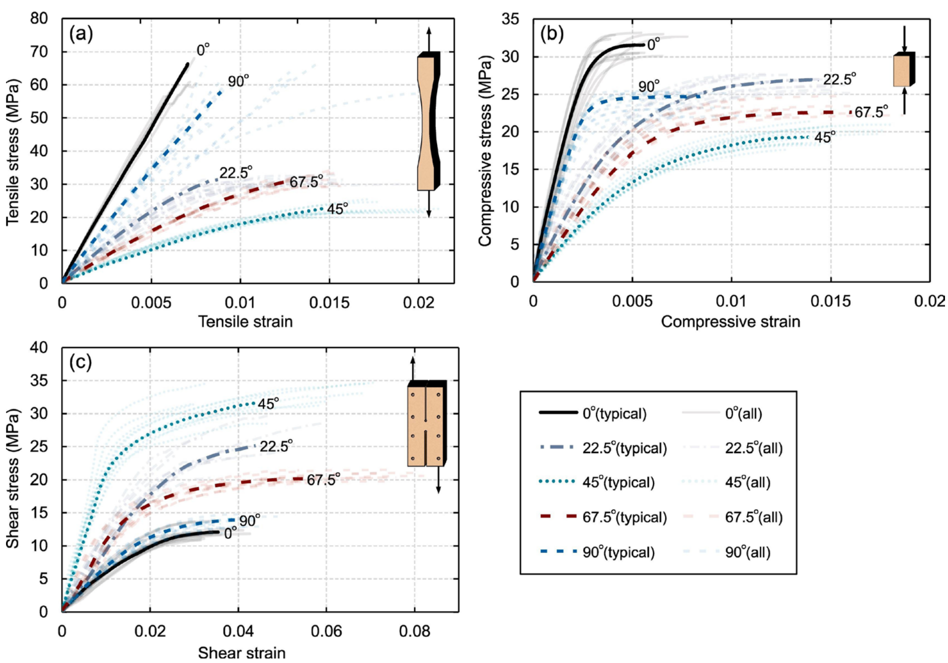
Appendix I

Supporting literature results

(Wang et al., 2022)

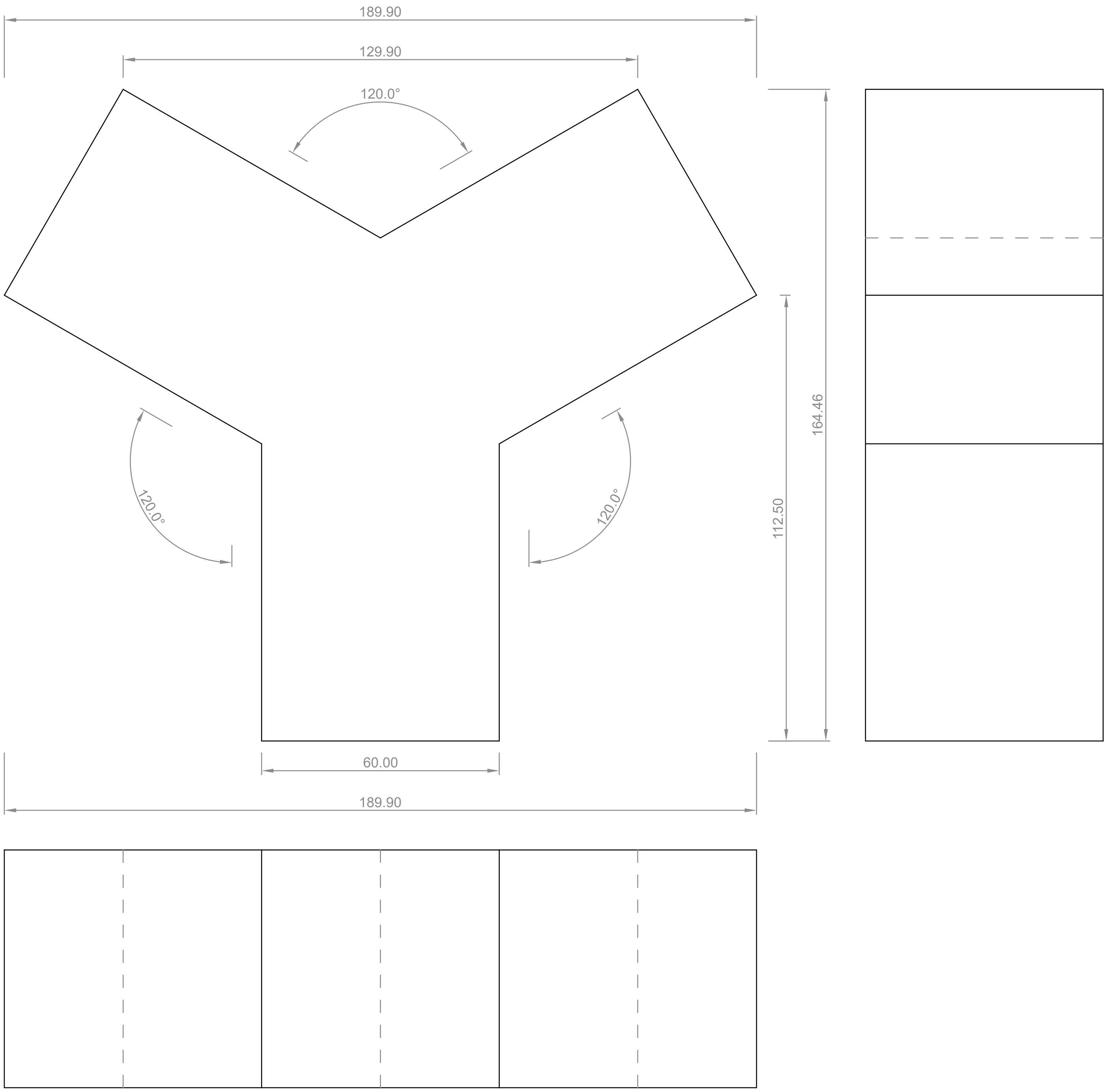






Appendix II

Node dimensions [mm]



Appendix III

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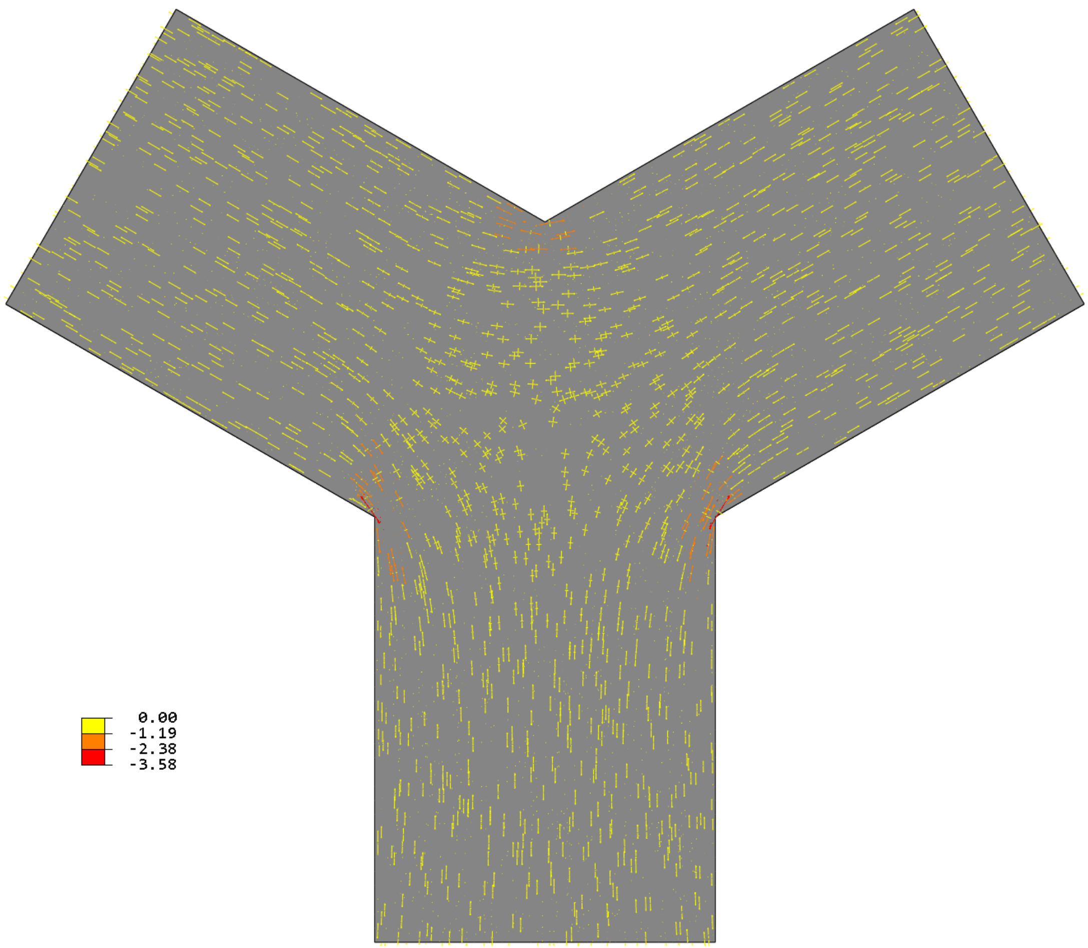

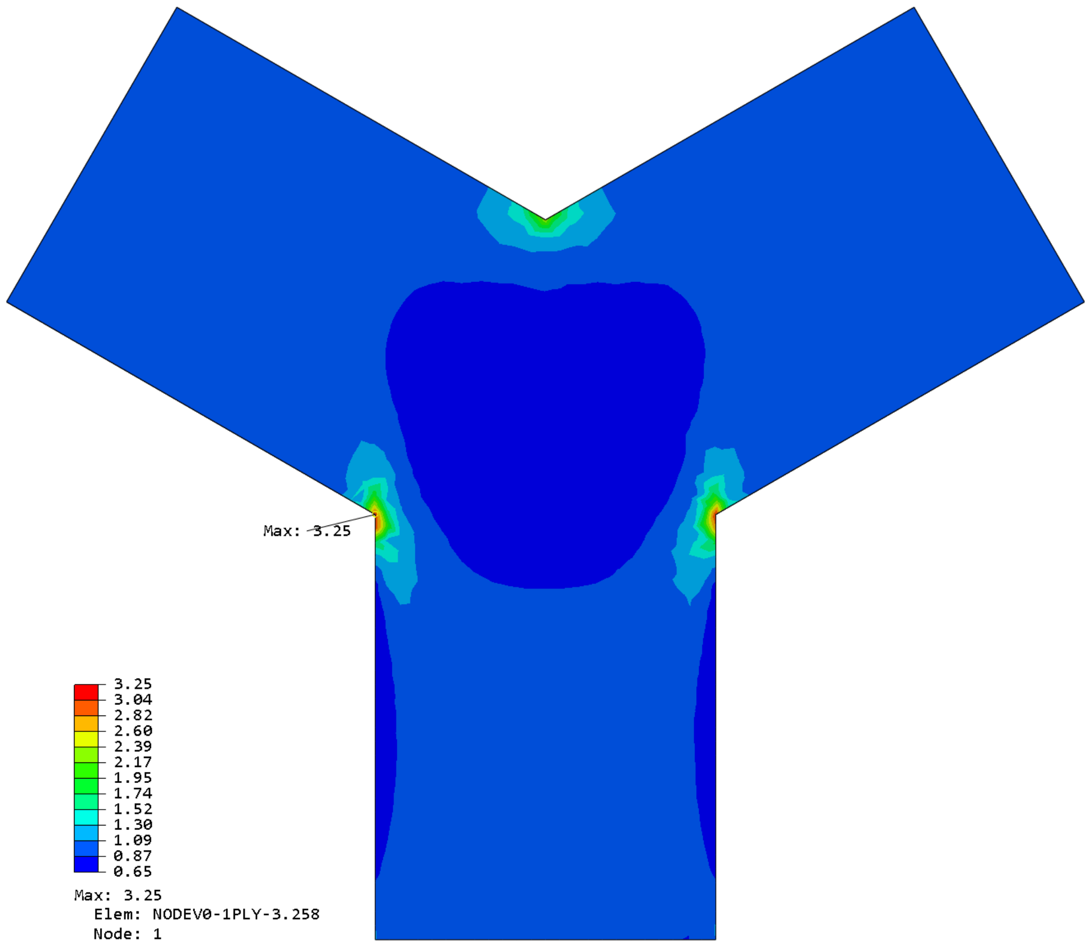
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2.17
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1.09
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0.65
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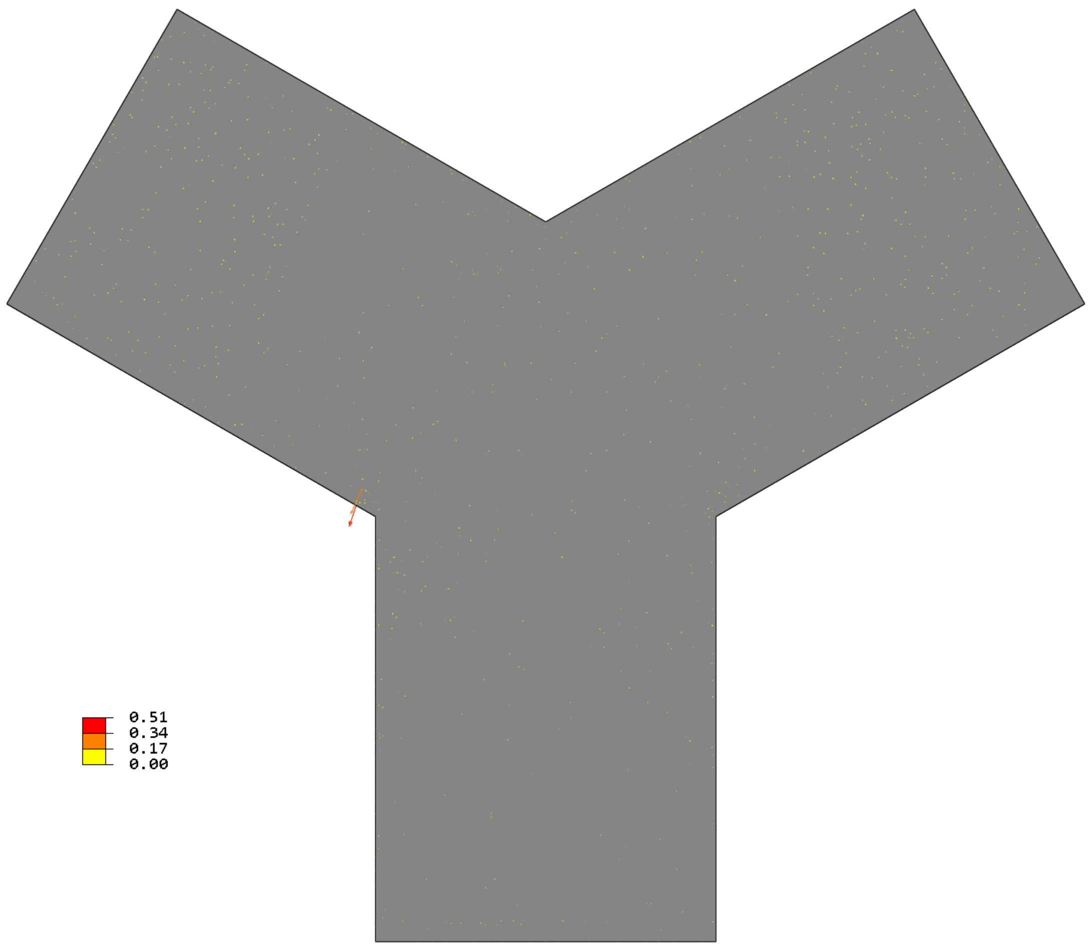
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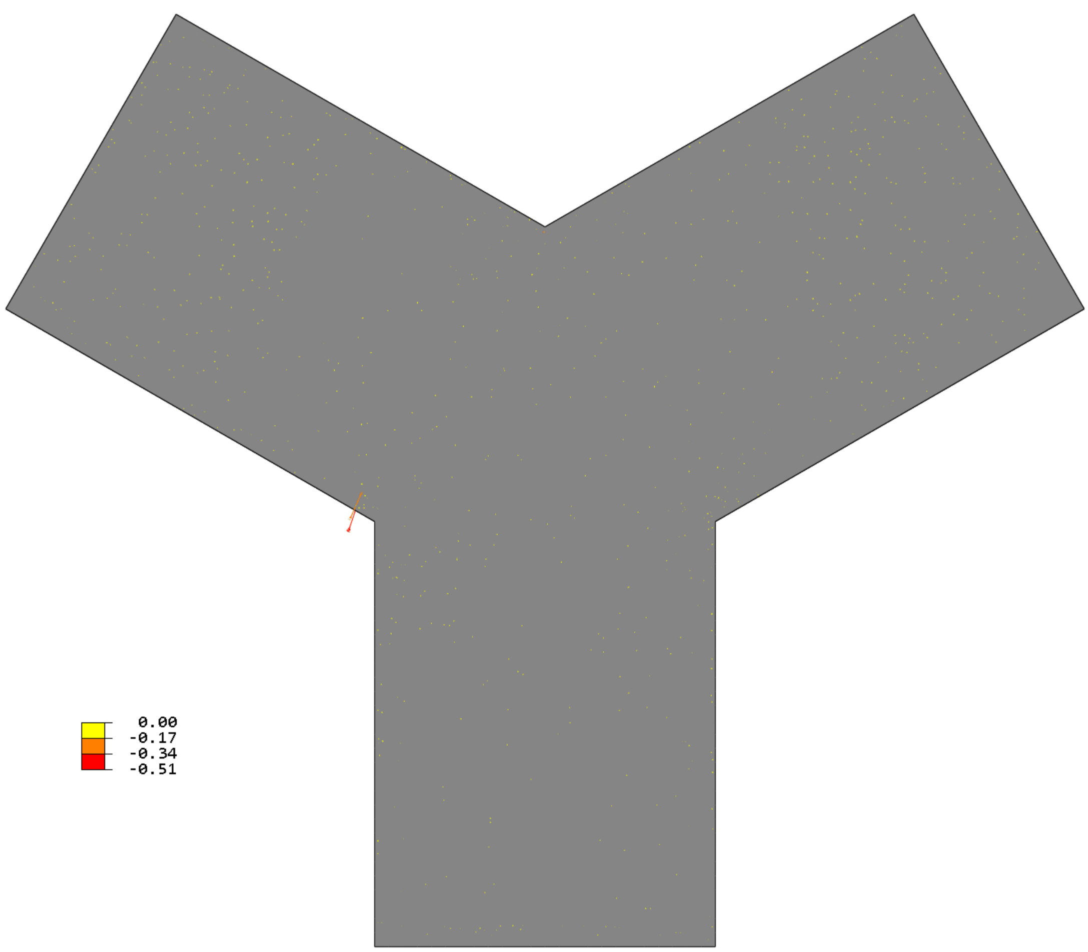

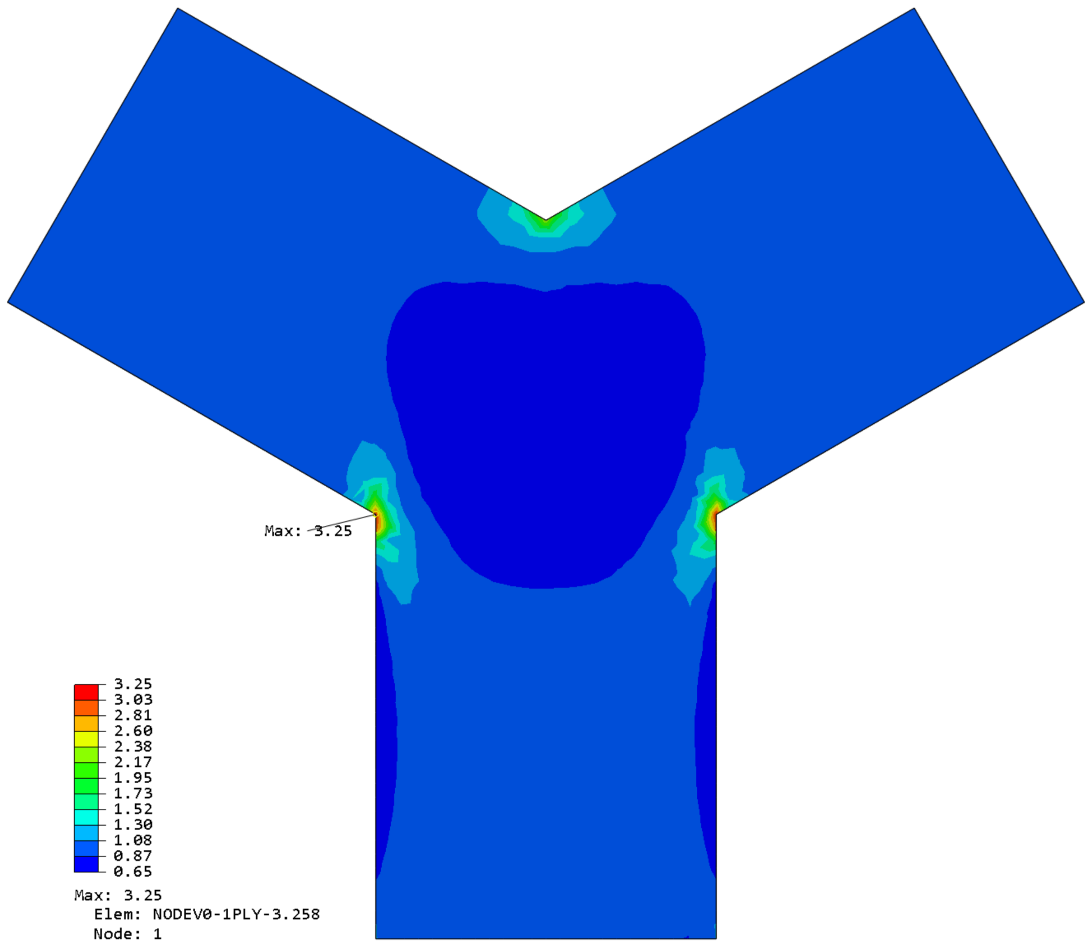
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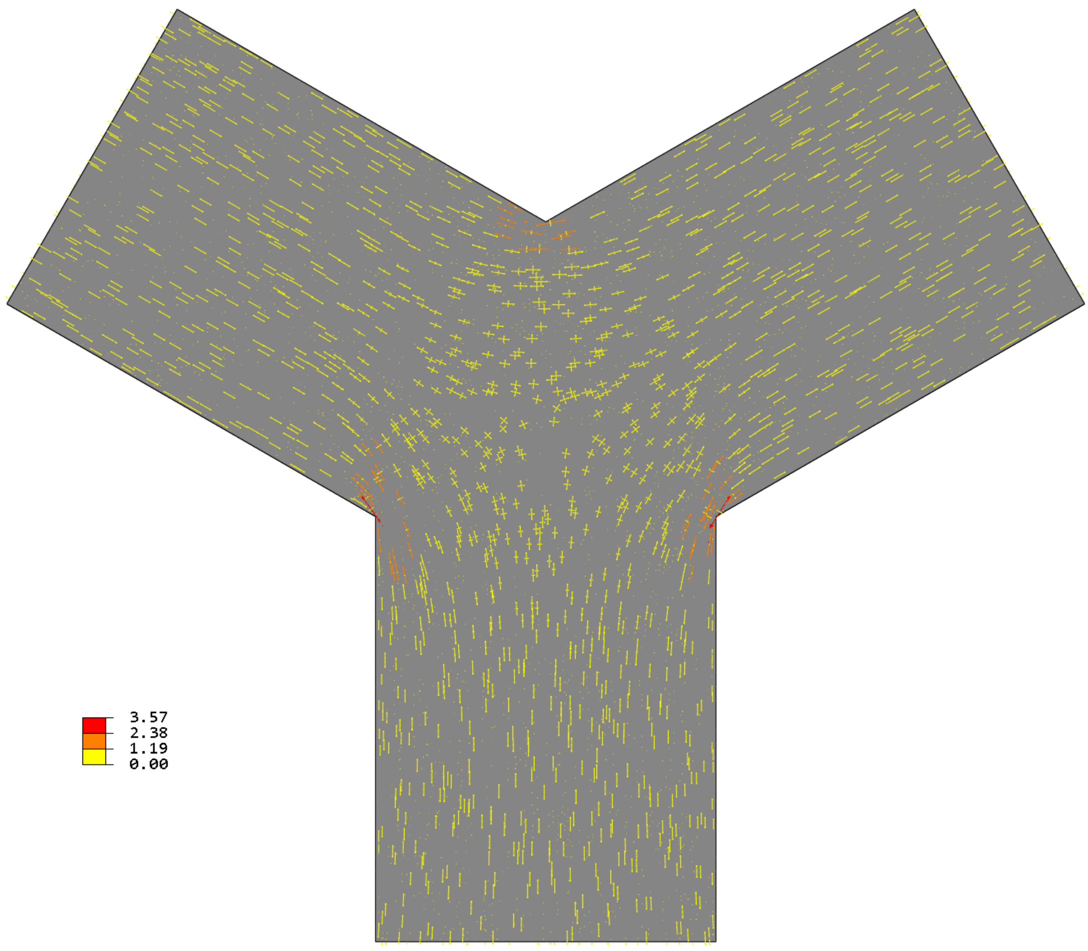
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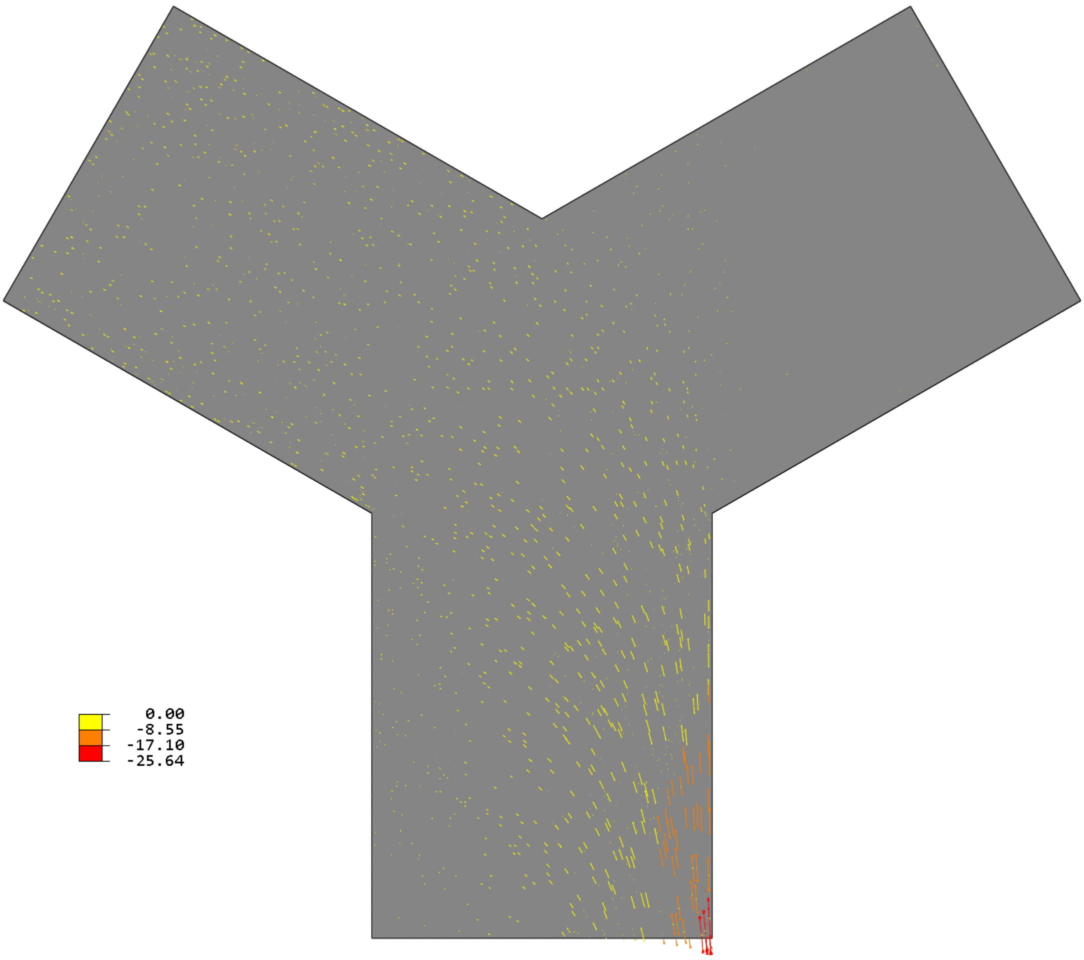

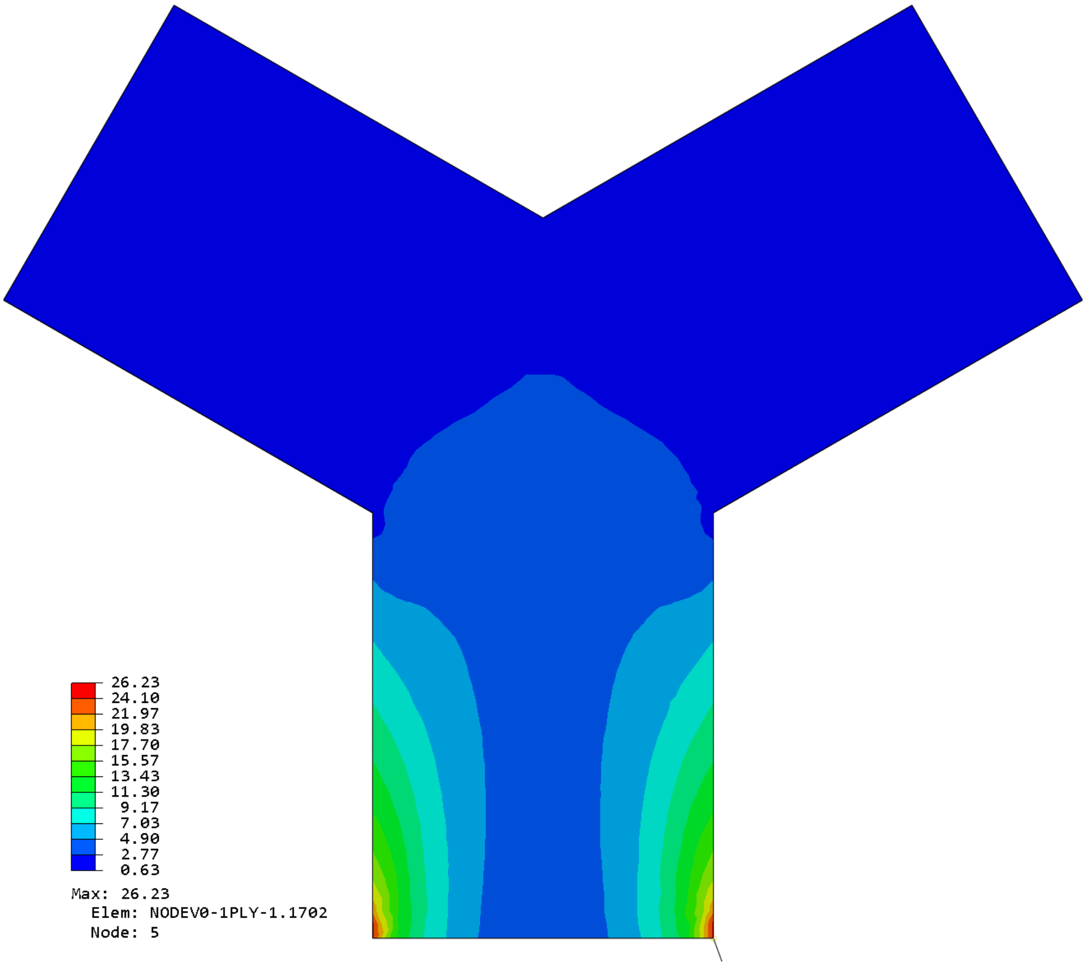
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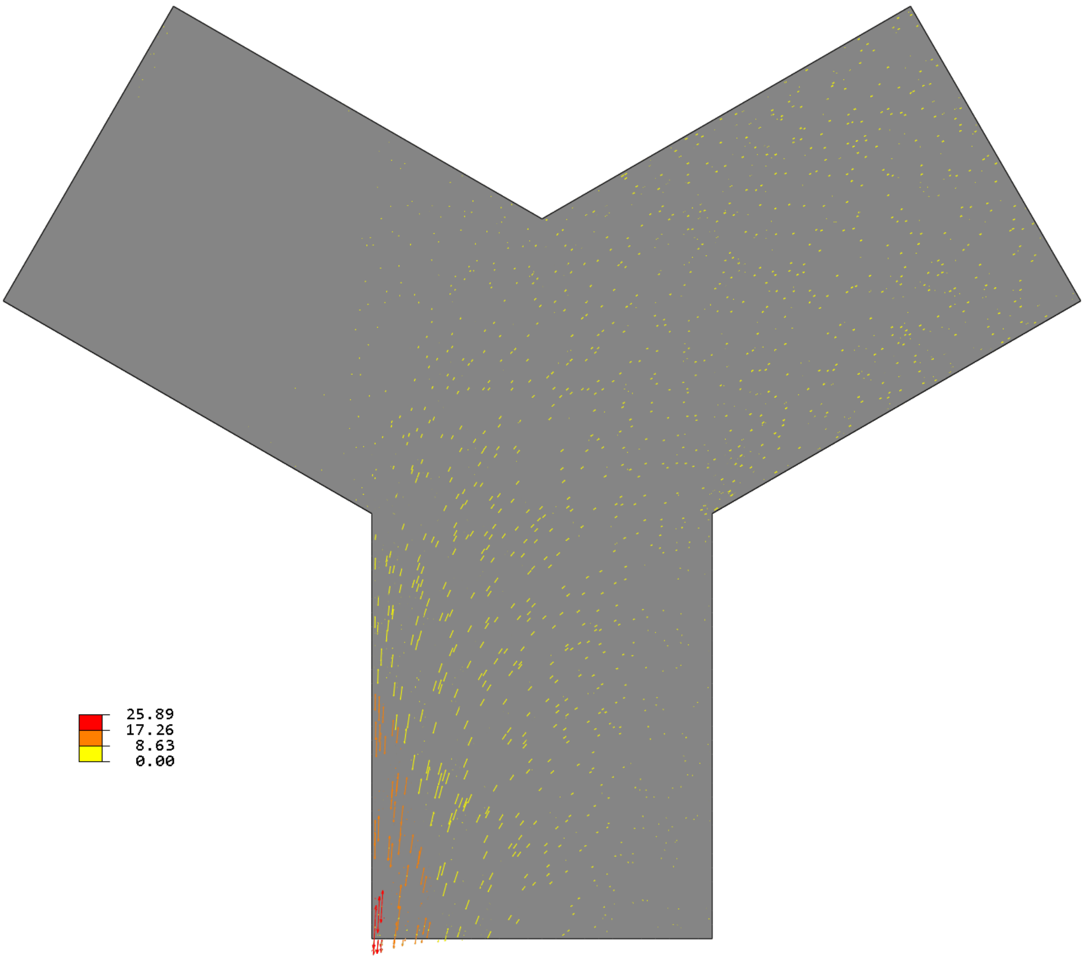
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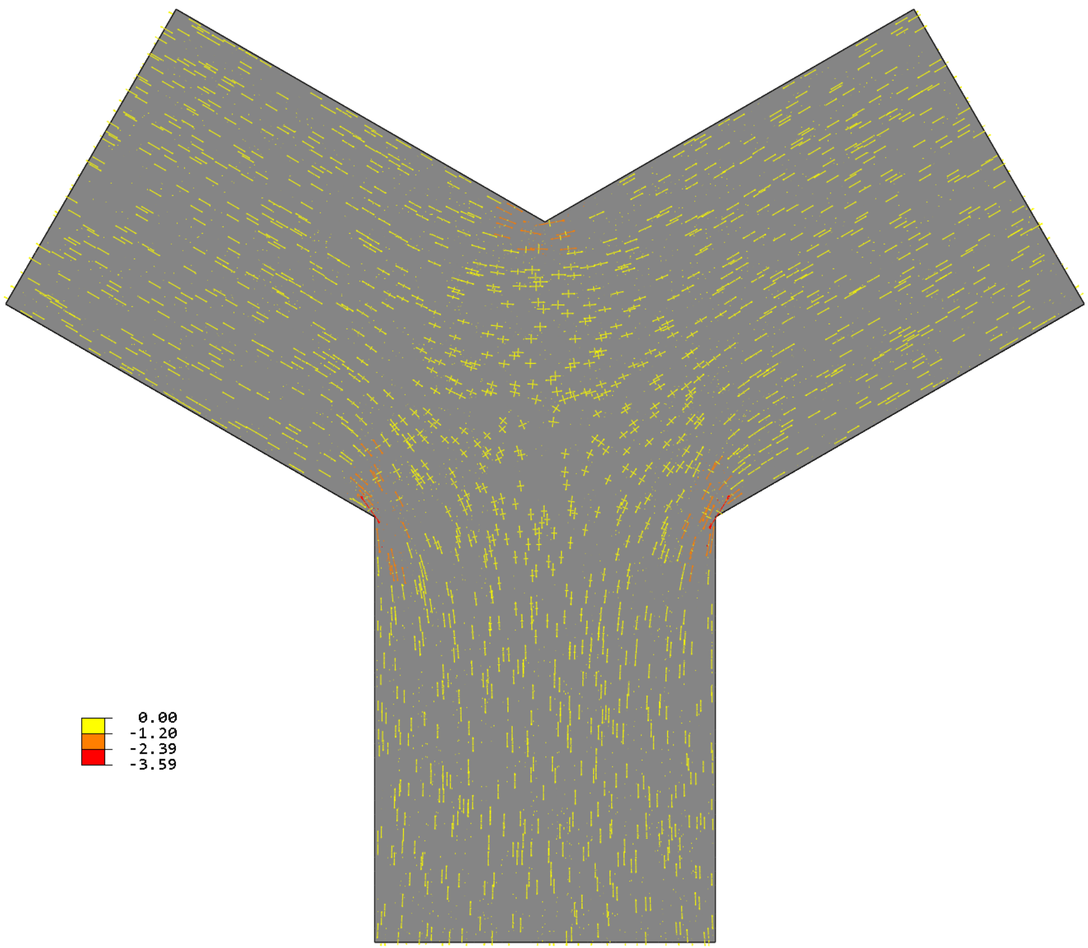

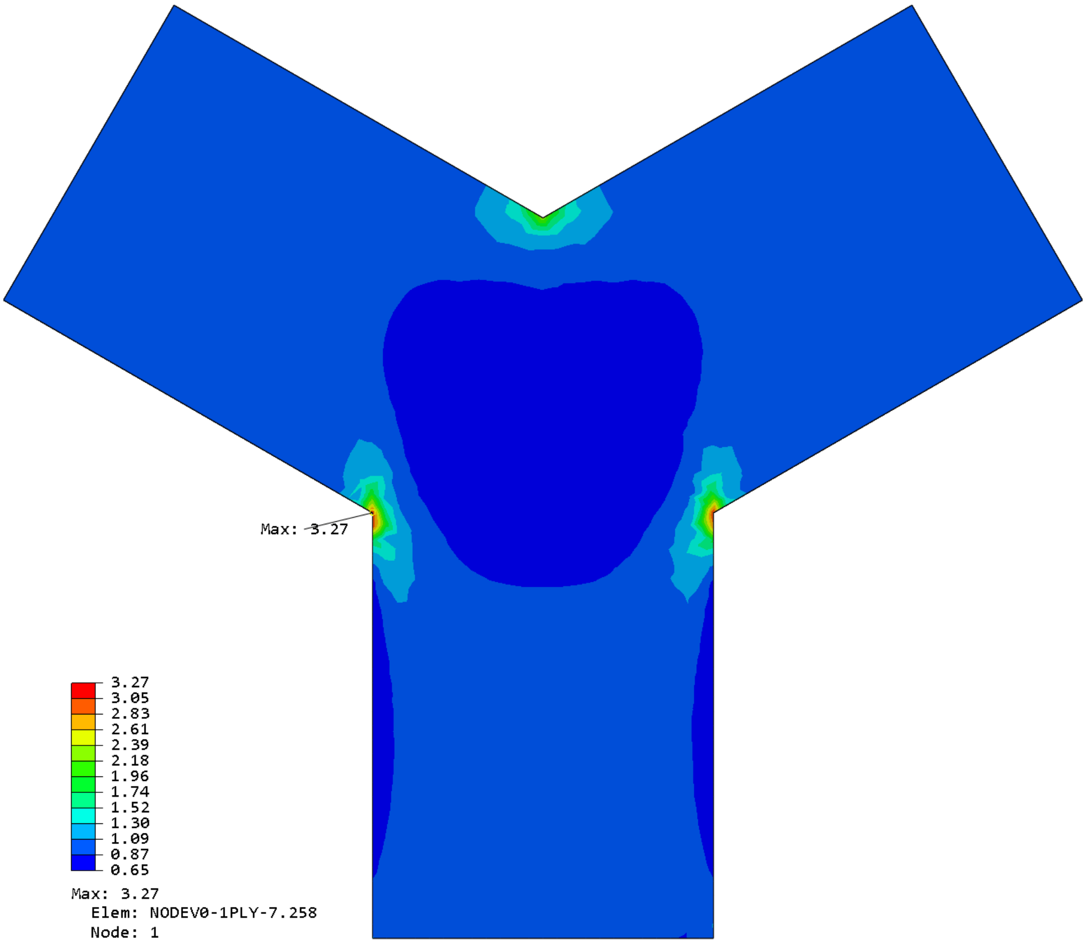
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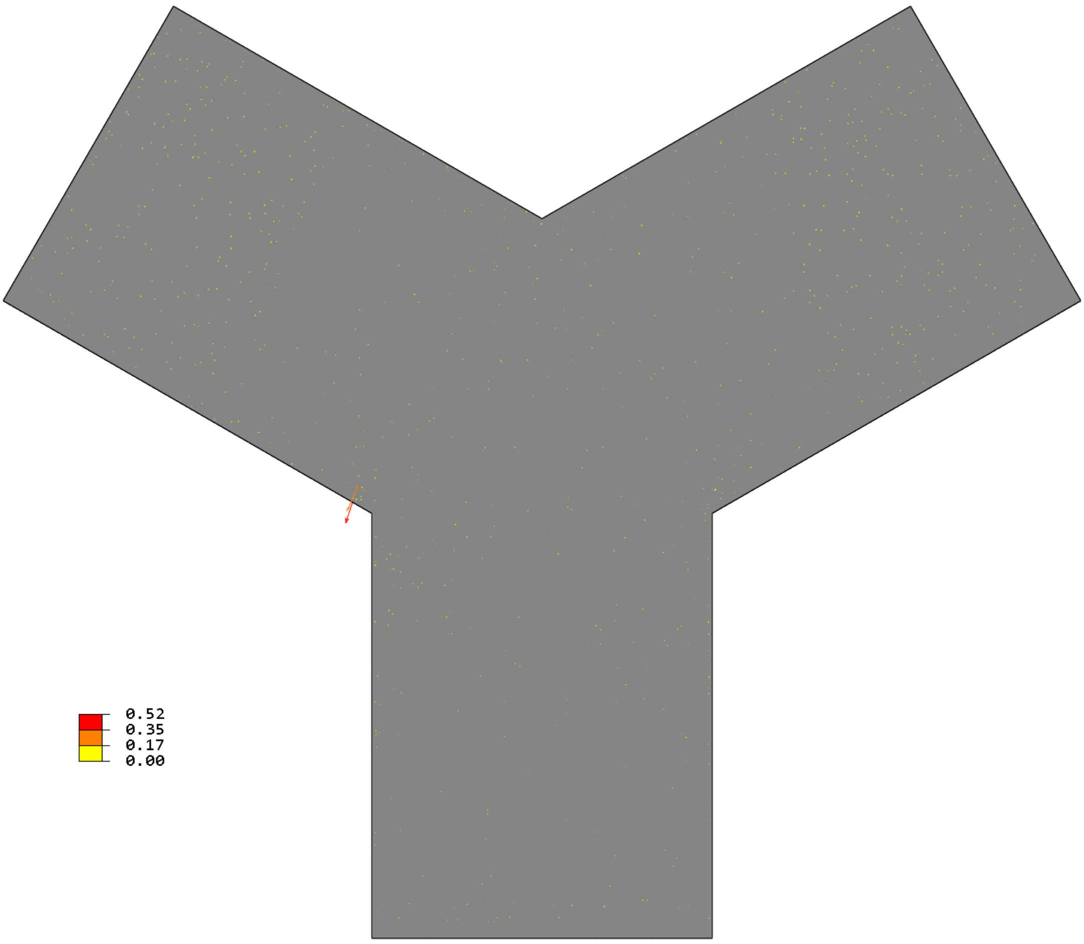
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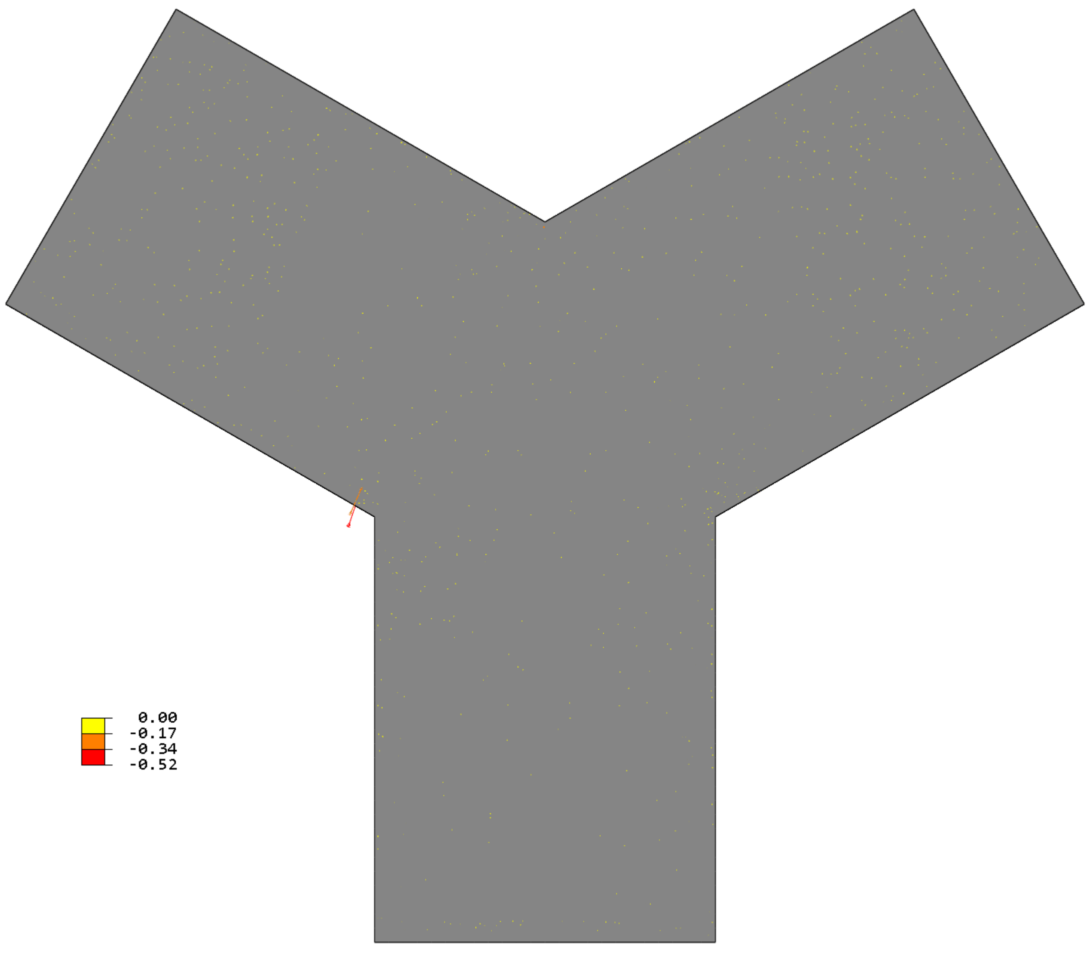

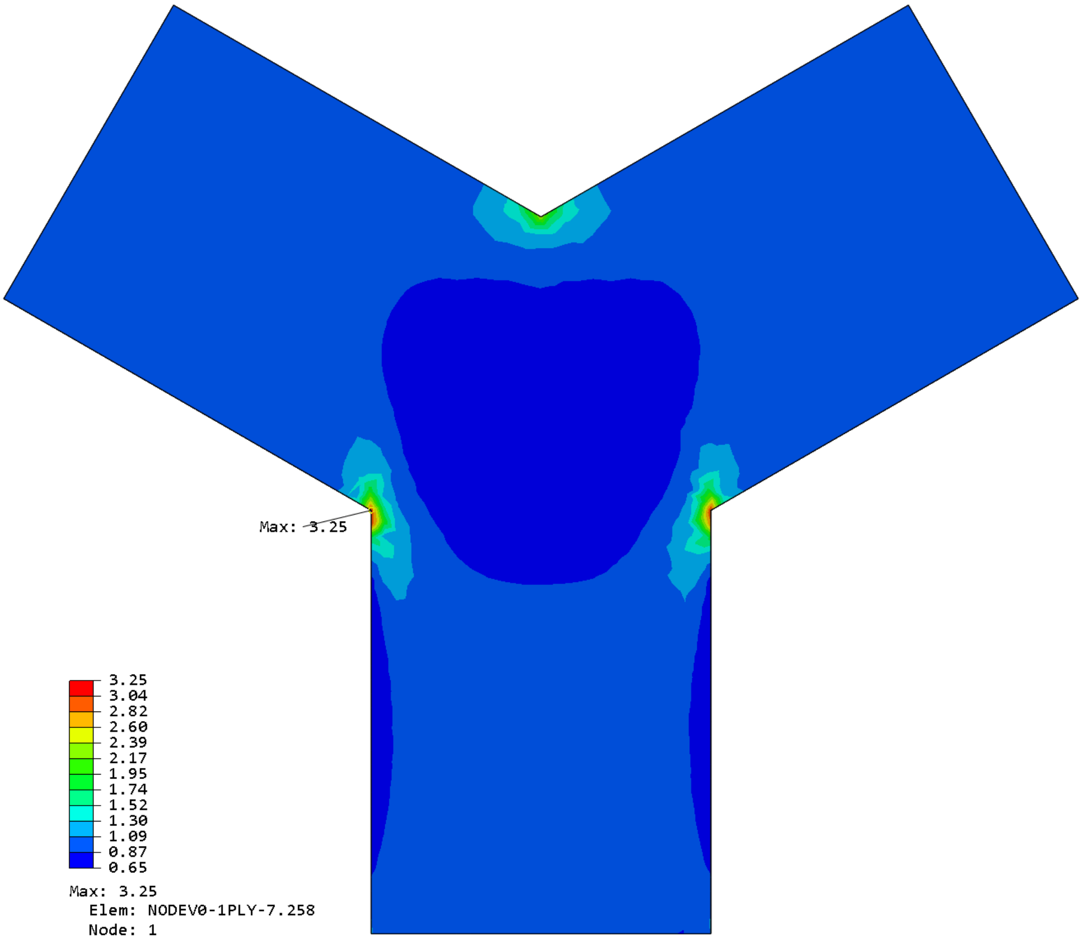
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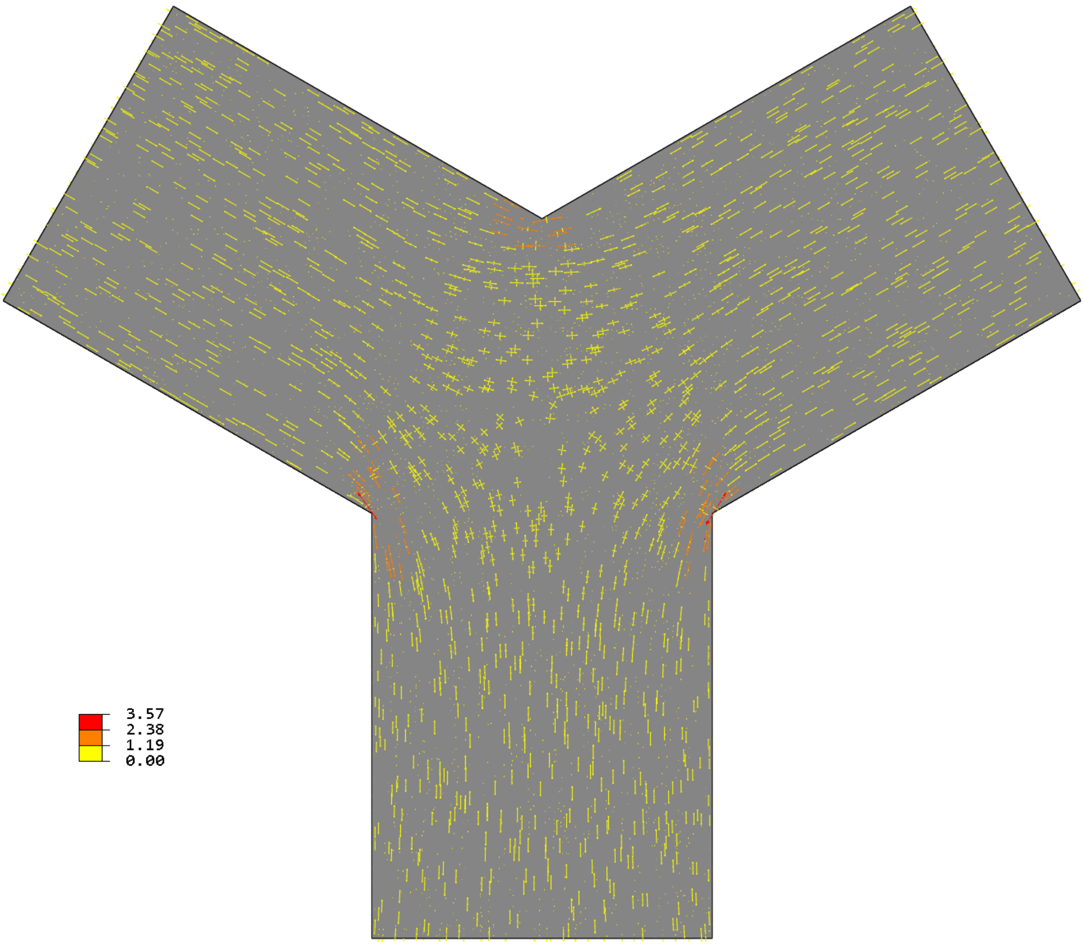
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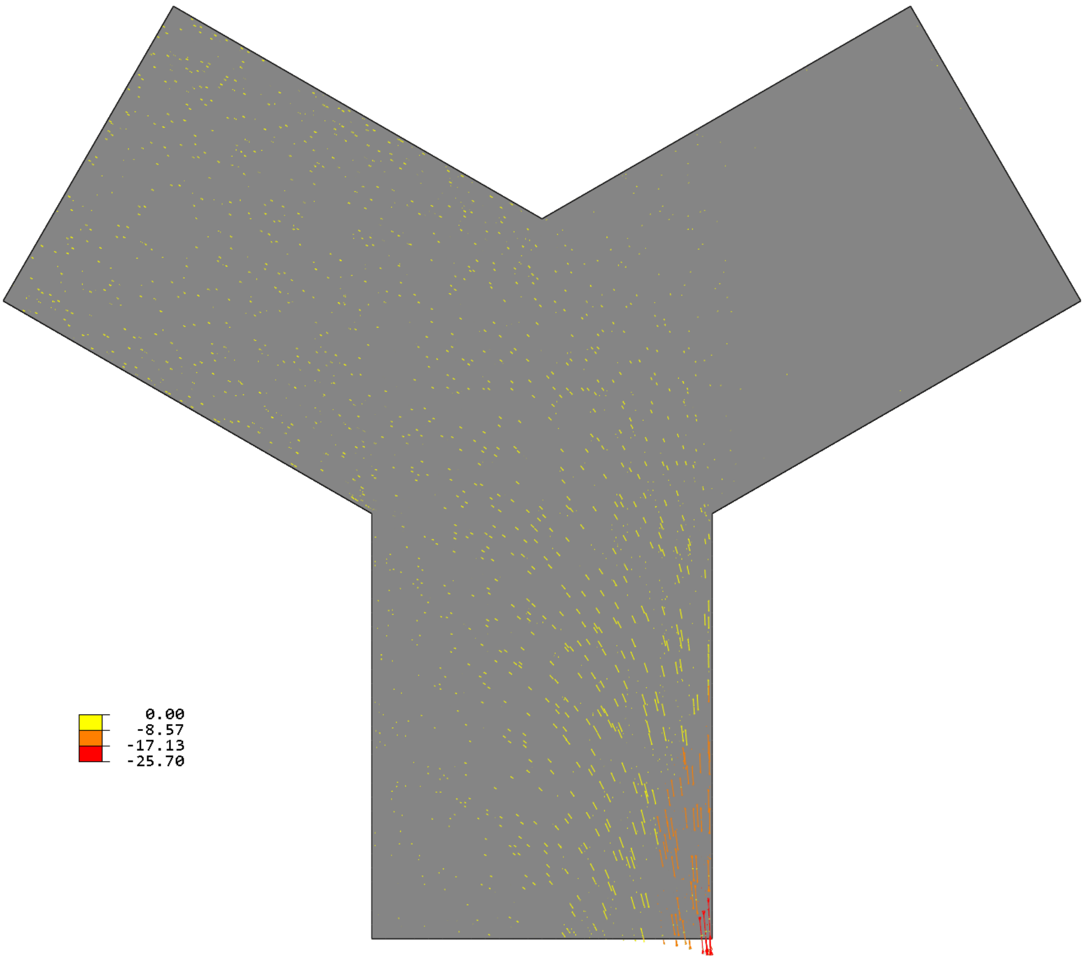

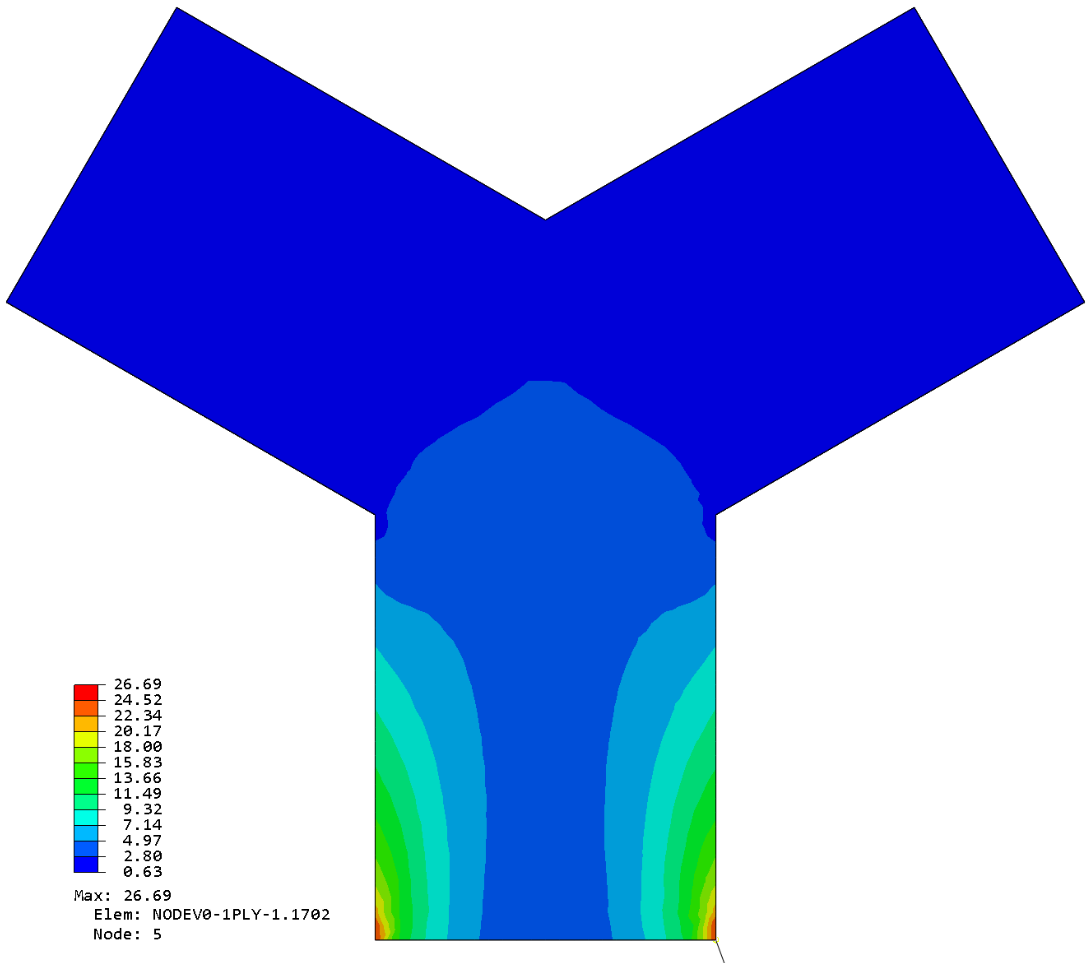
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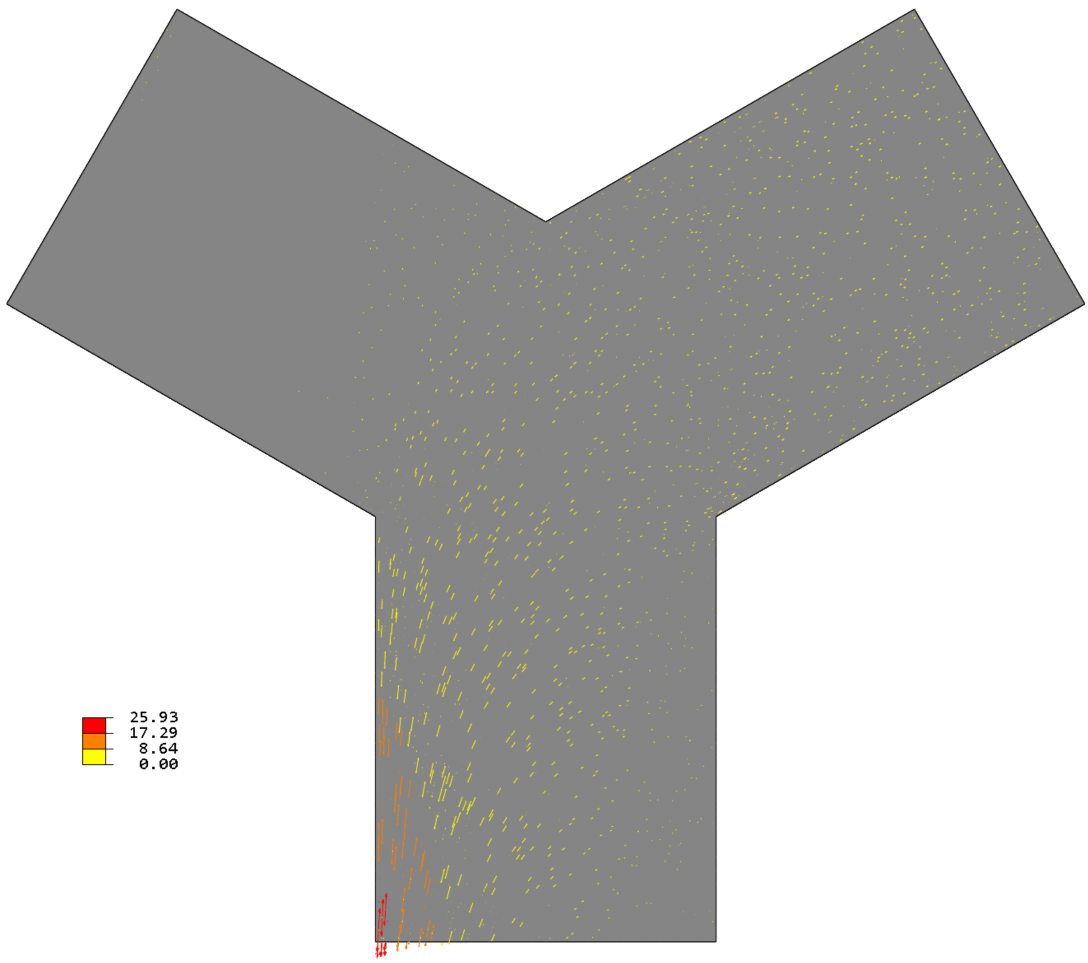
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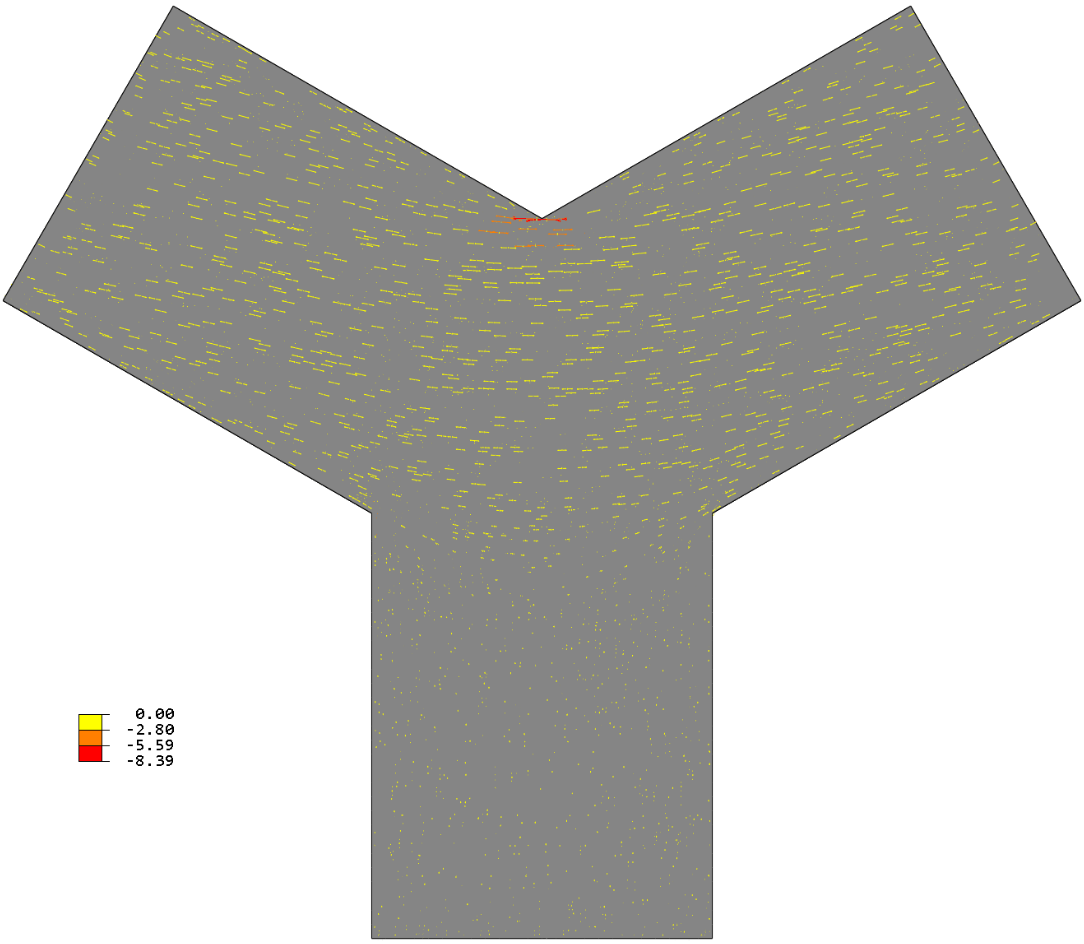

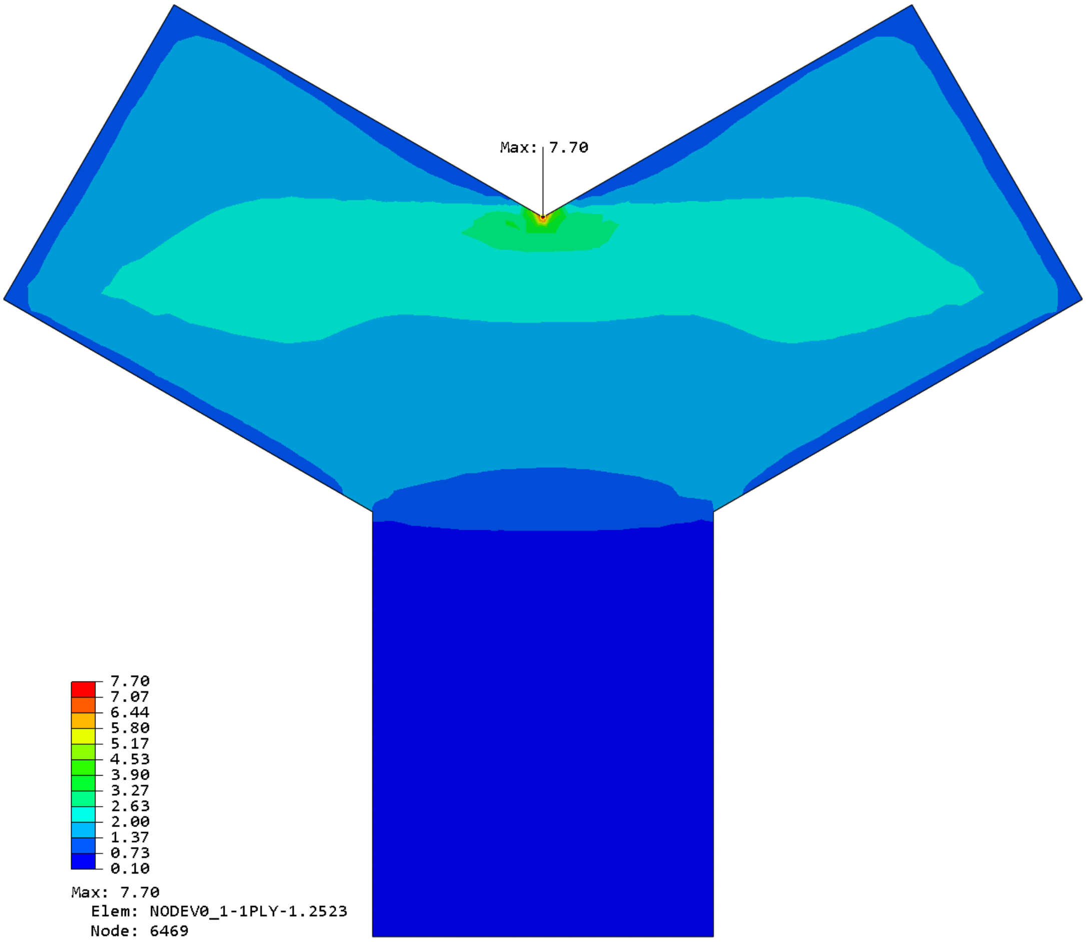
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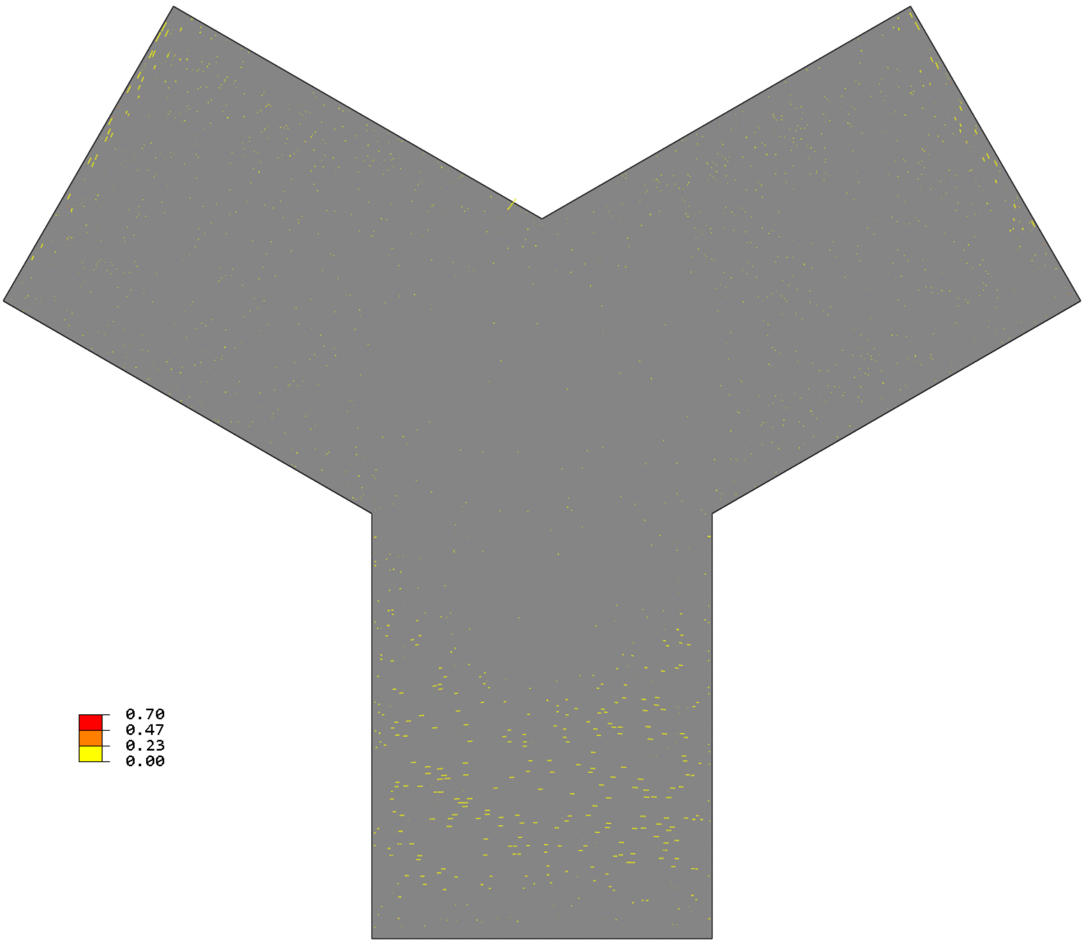
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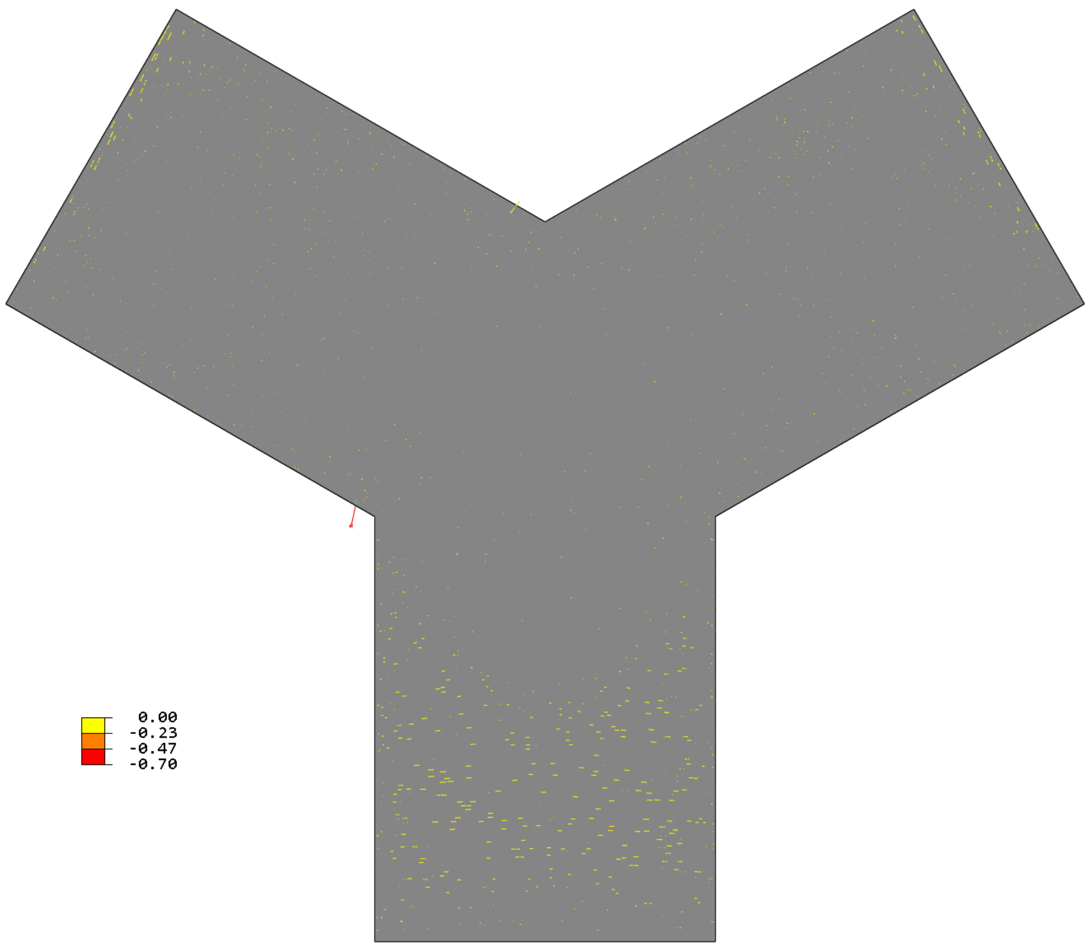
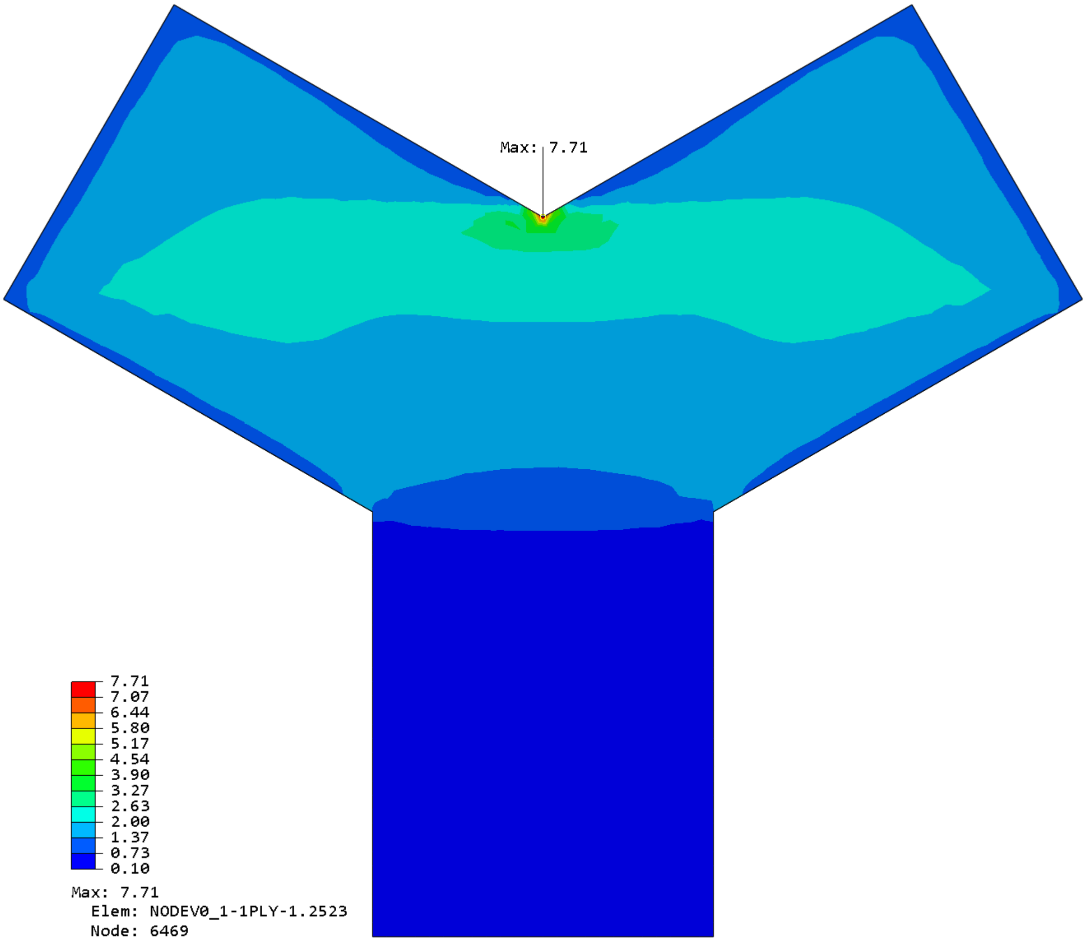
v0.1 3ply Tensile load

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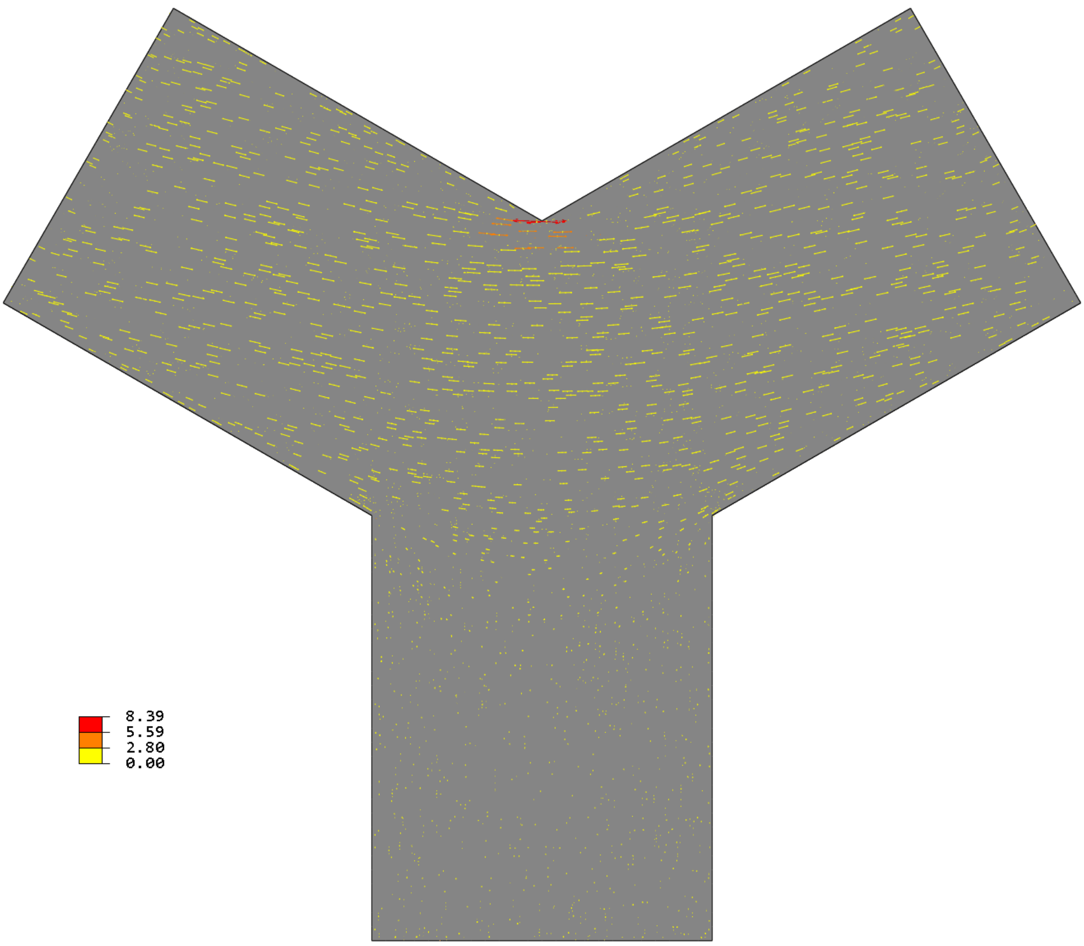
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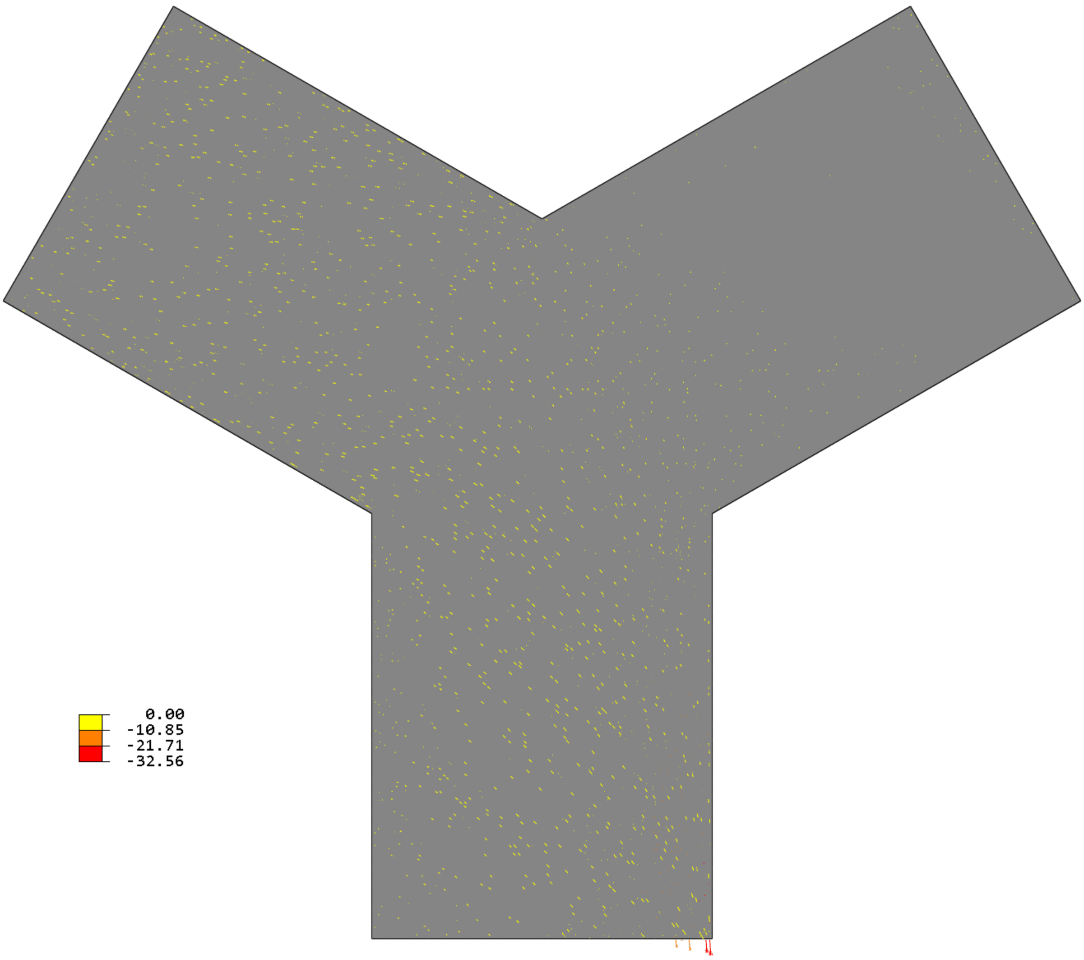
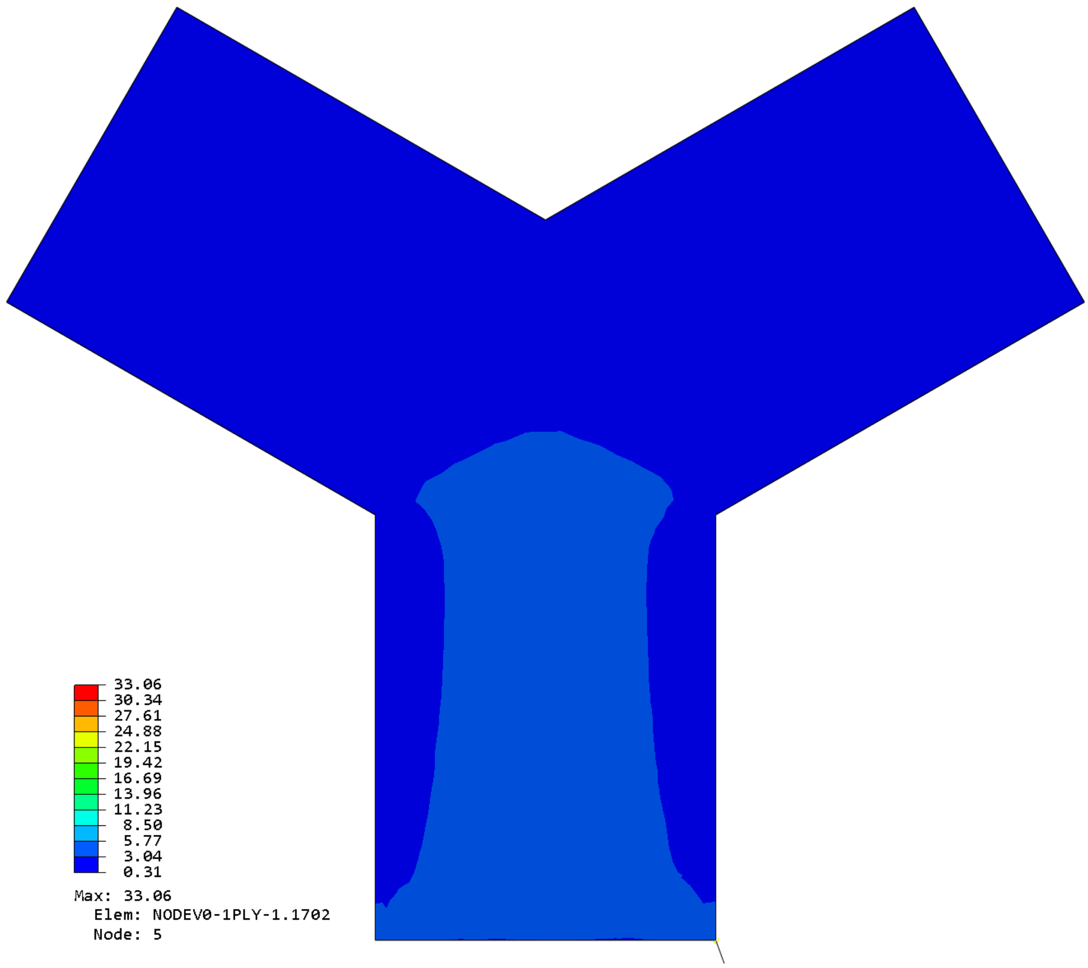
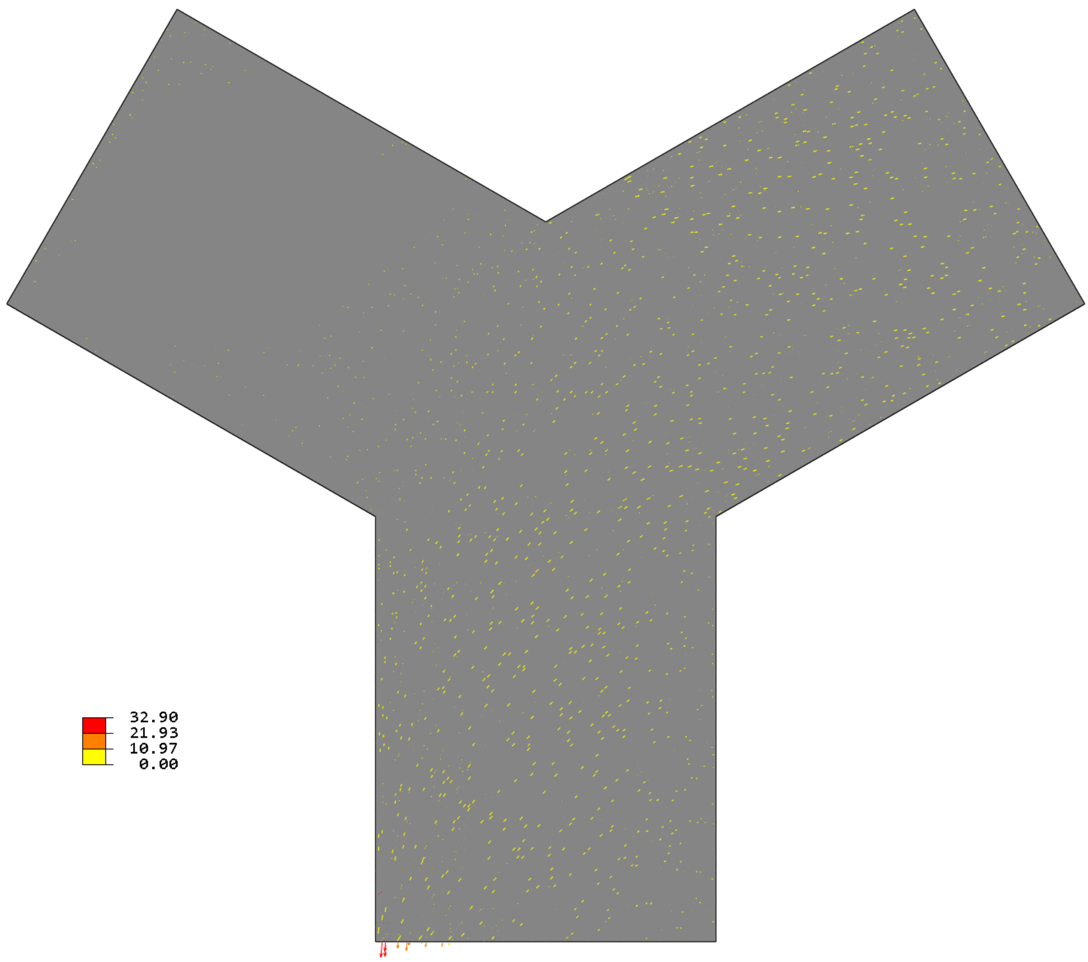
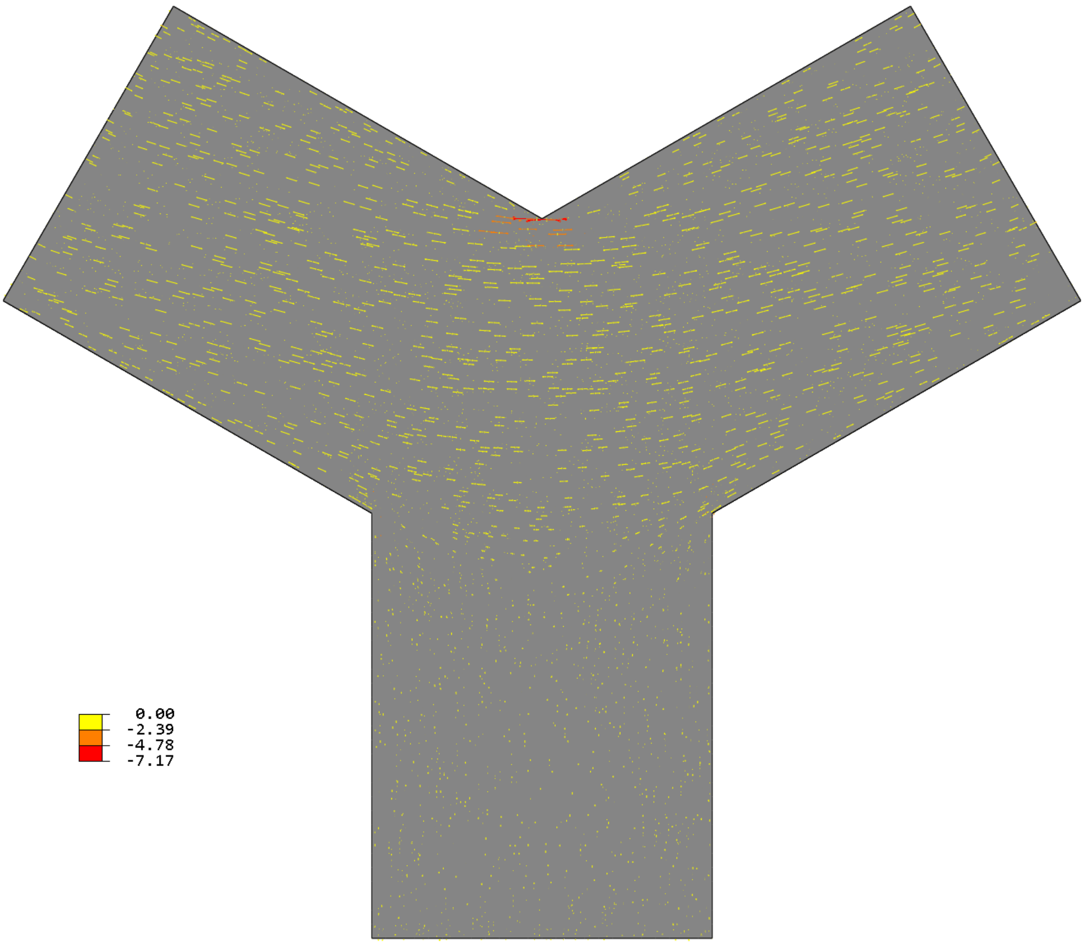
v0.1 3ply Compressive + tensile load

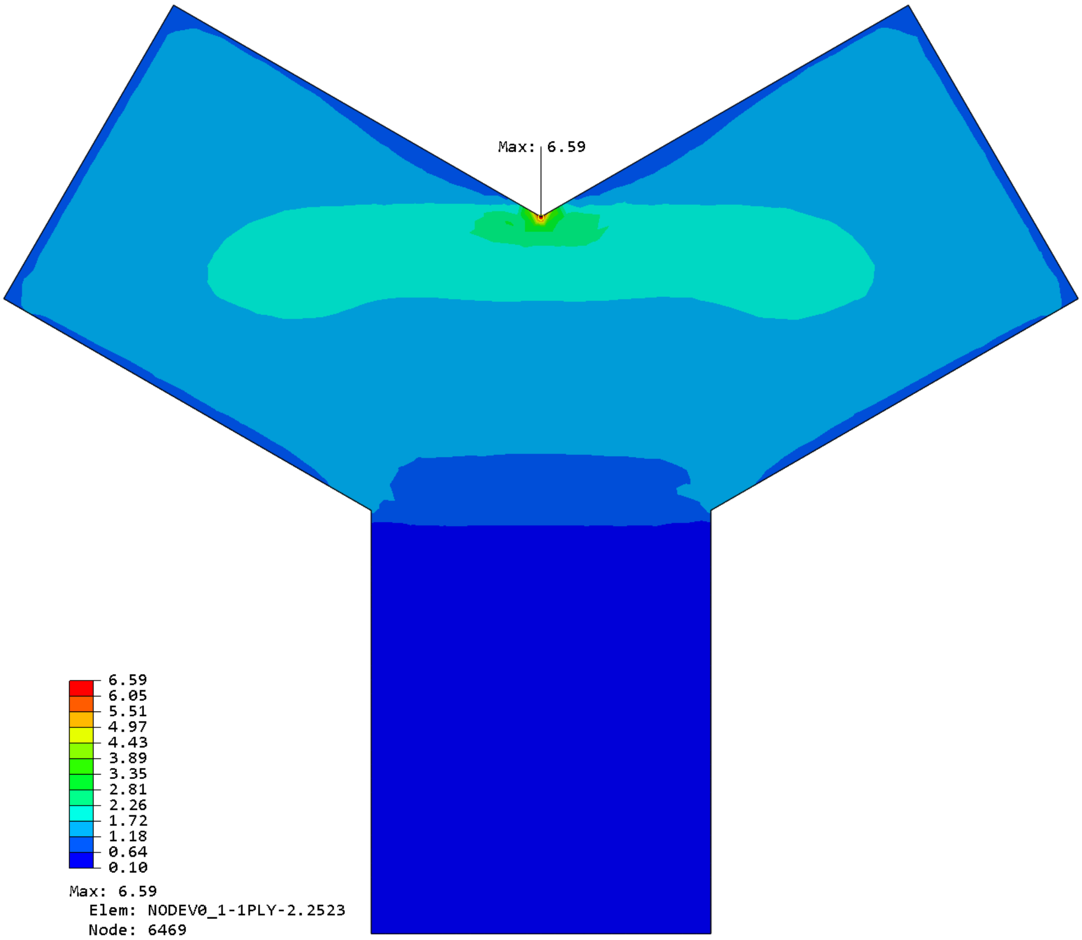


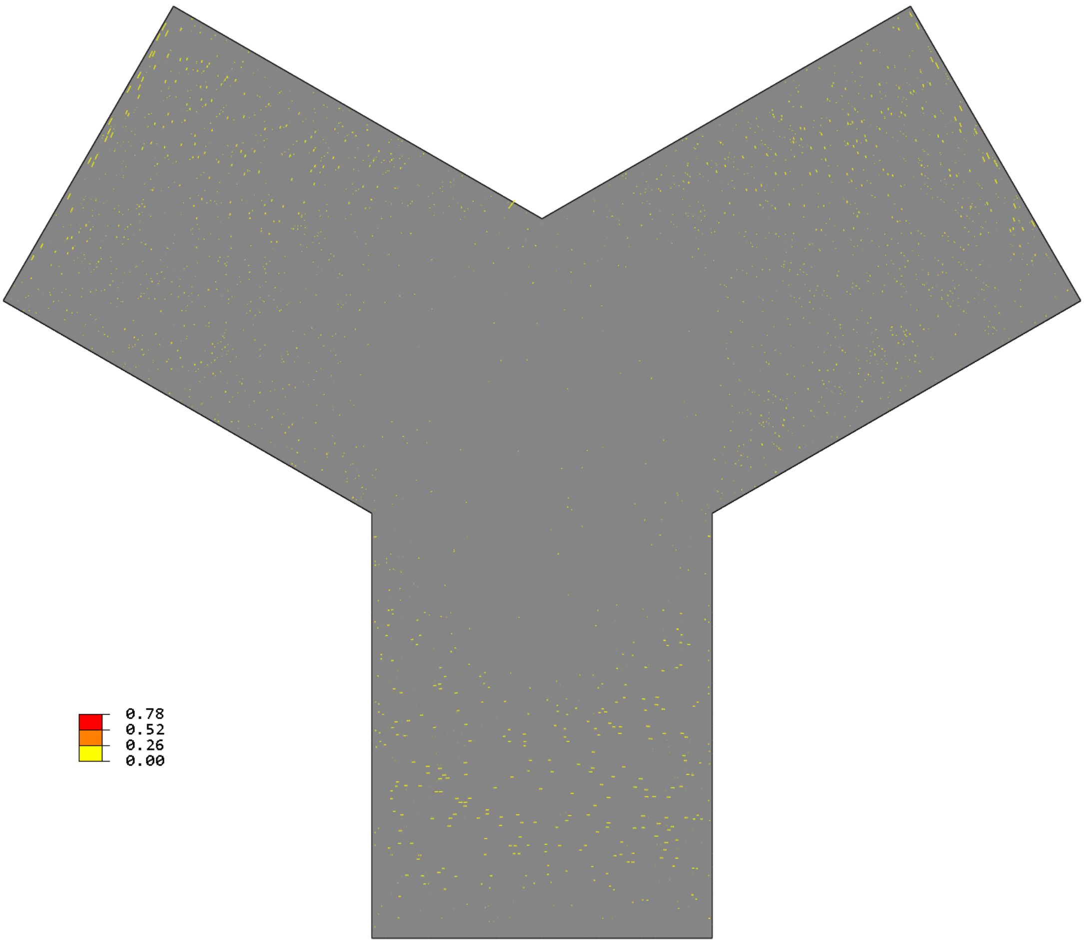

33.06
30.34
27.61
24.88
22.15
19.42
16.69
13.96
11.23
8.50
5.77
3.04
0.31
Max: 33.06
Elem: NODEV0-1PLY-1.1702
Node: 5


32.90
21.93
10.97
0.00

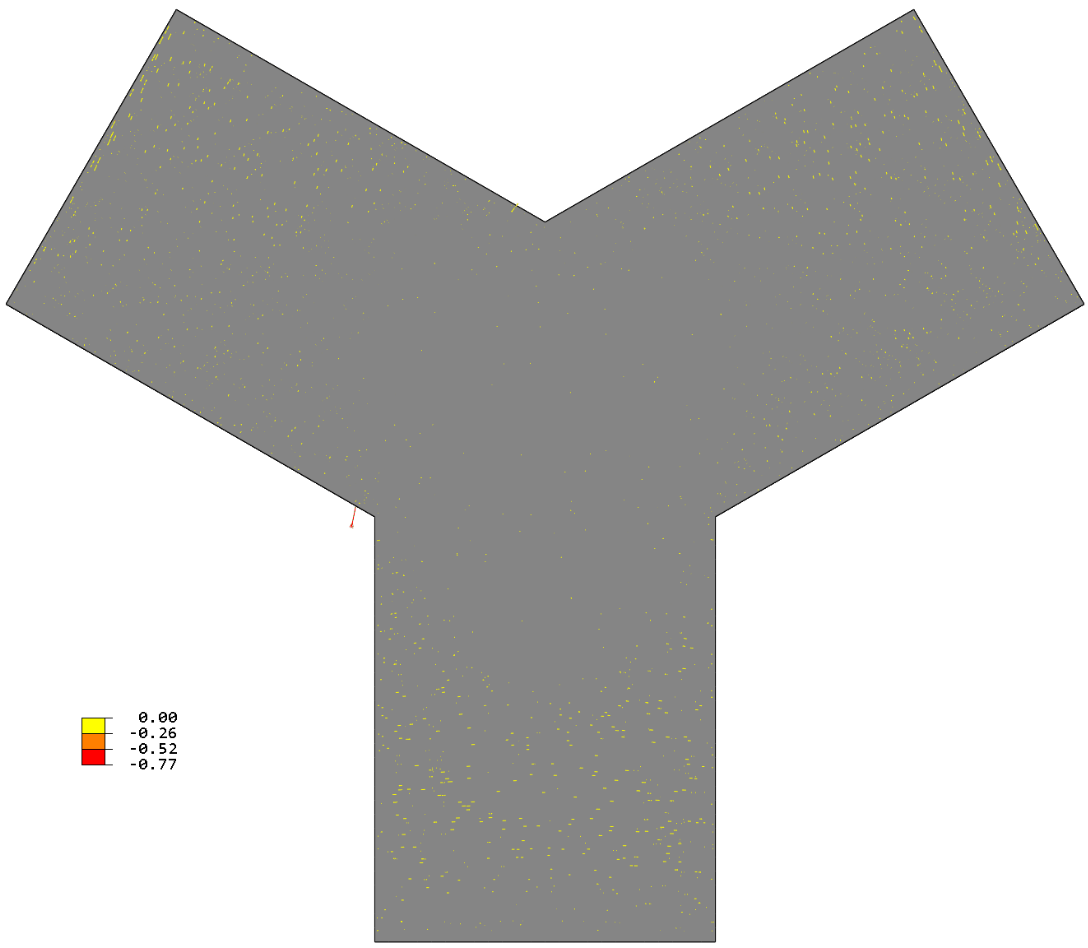
v0.1 7ply Compressive load

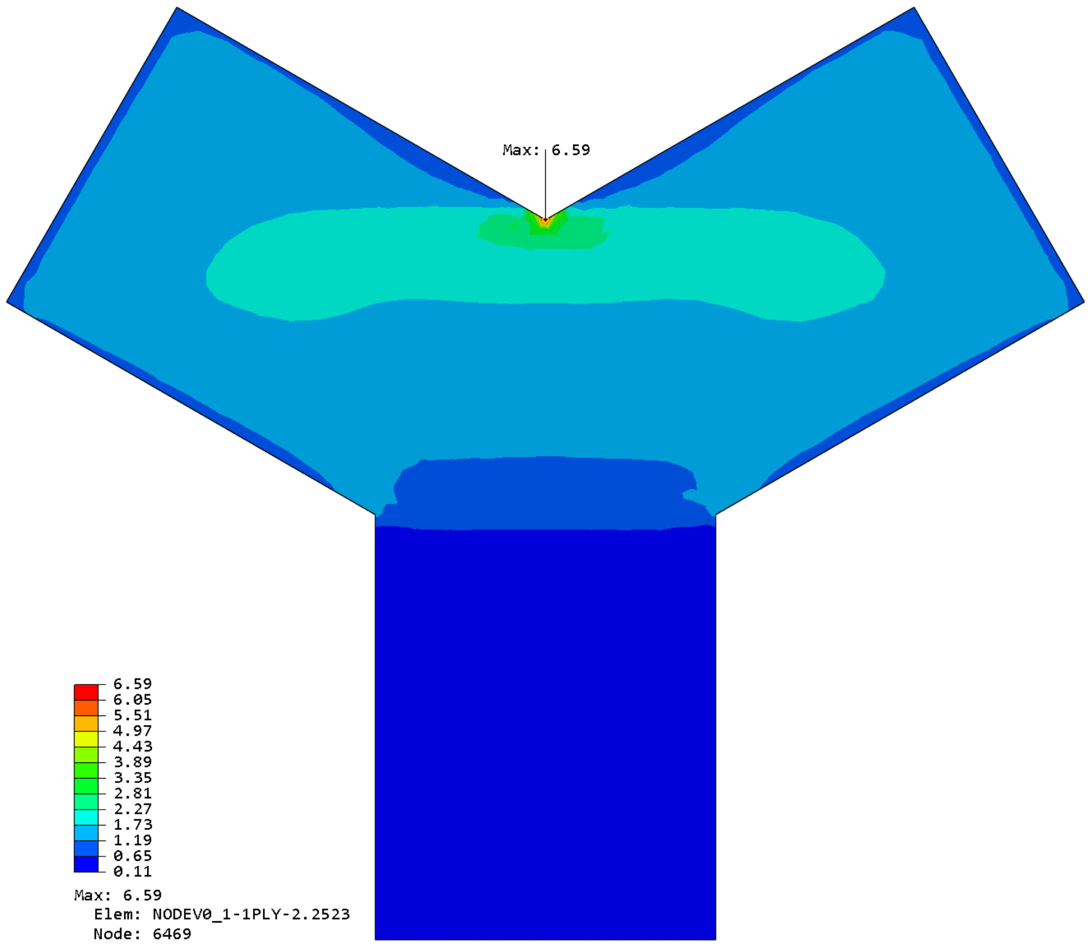


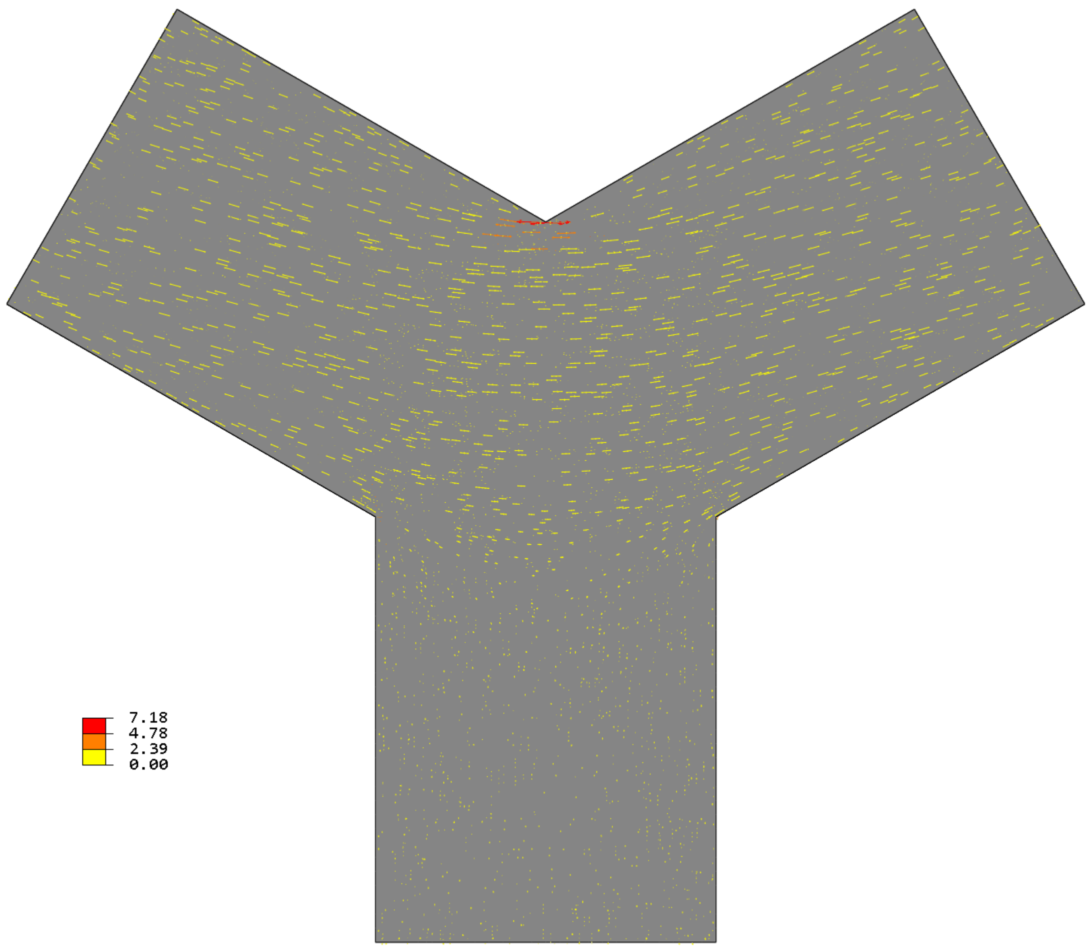

Max: 6.59
6.59
6.05
5.51
4.97
4.43
3.89
3.35
2.81
2.26
1.72
1.18
0.64
0.10
Max: 6.59
Elem: NODEV0_1-1PLY-2.2523
Node: 6469


0.78
0.52
0.26
0.00

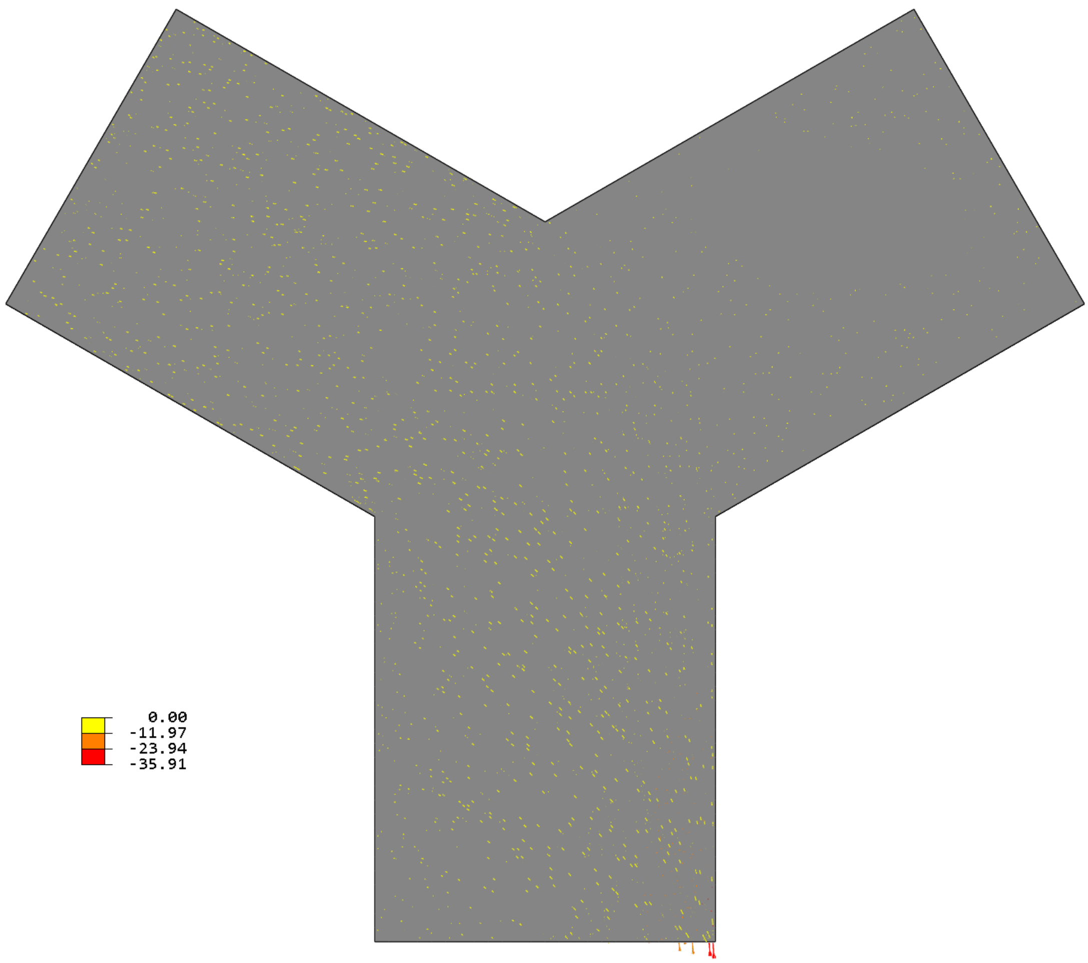
v0.1 7ply Tensile load

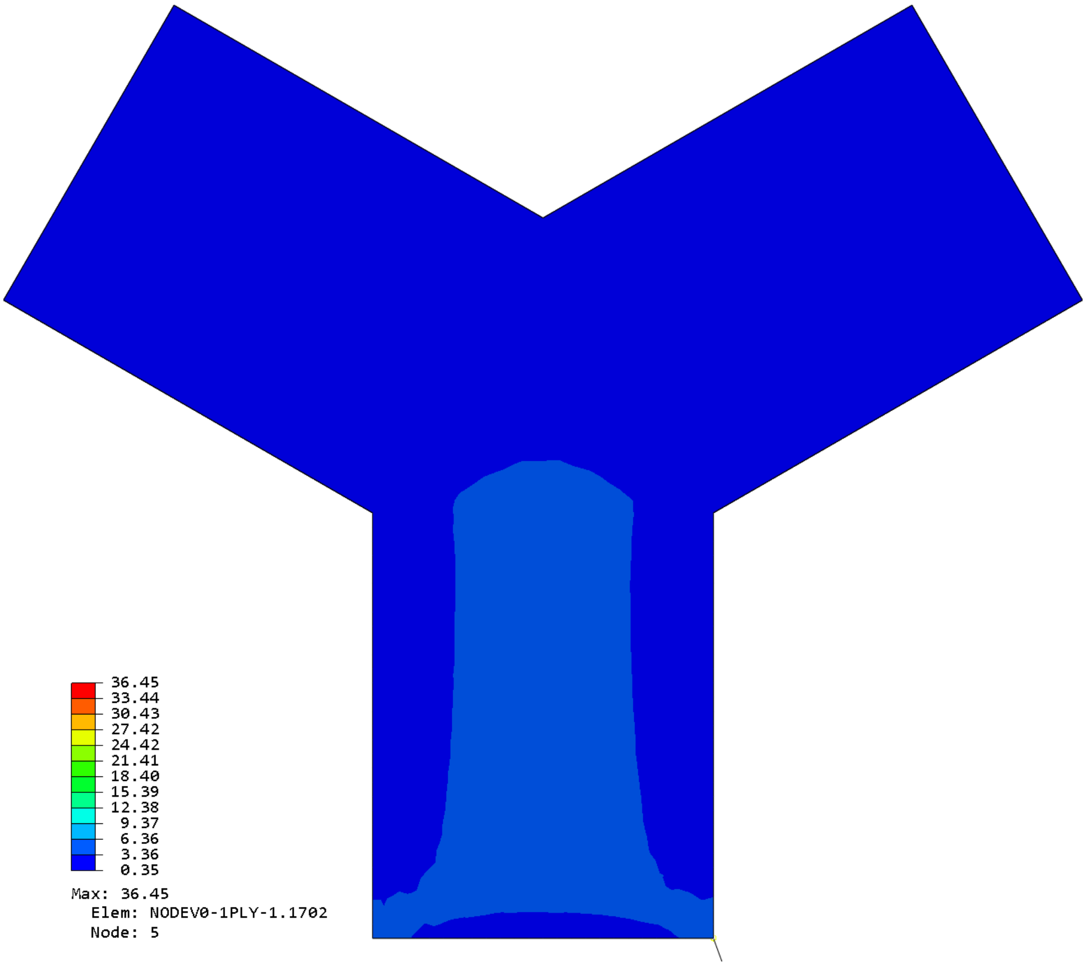


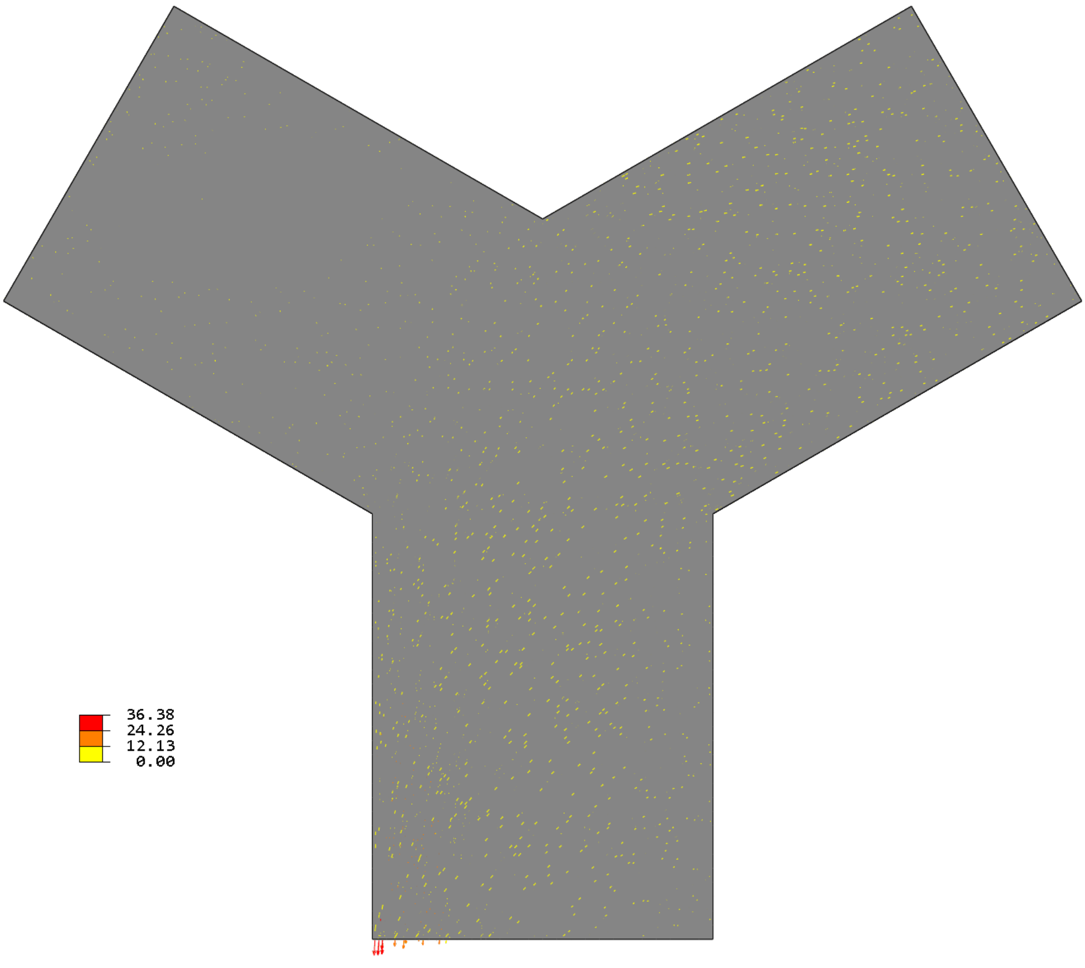

Max: 6.59
6.59
6.05
5.51
4.97
4.43
3.89
3.35
2.81
2.27
1.73
1.19
0.65
0.11
Max: 6.59
Elem: NODEV0_1-1PLY-2.2523
Node: 6469


7.18
4.78
2.39
0.00

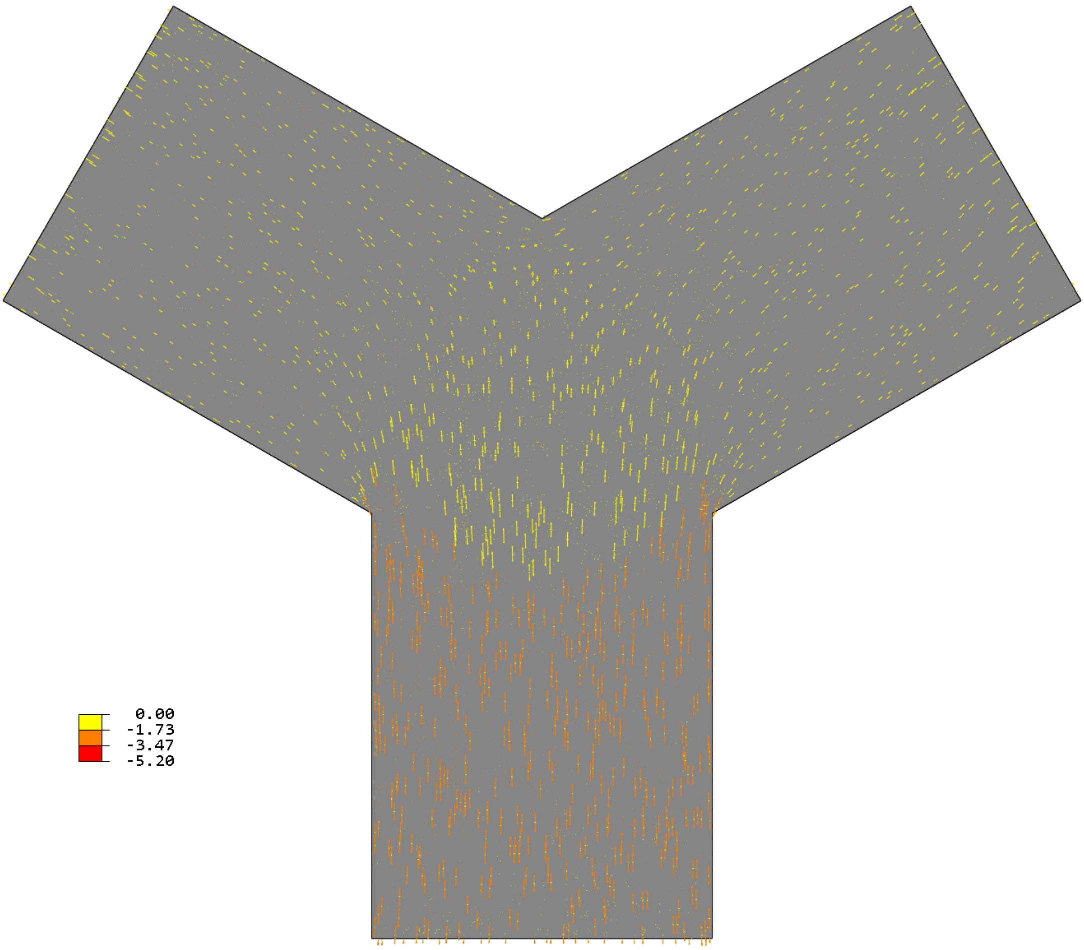
v0.1 7ply Compressive + tensile load

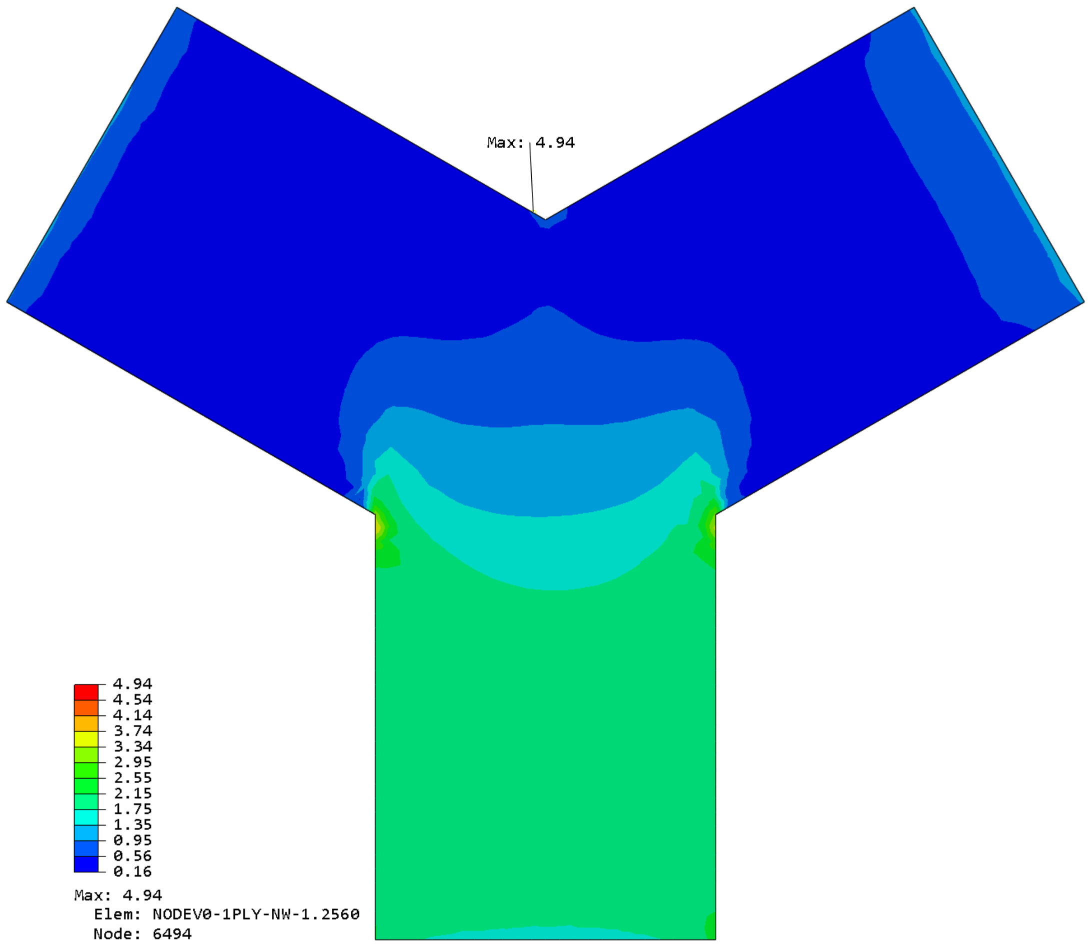



36.45
33.44
30.43
27.42
24.42
21.41
18.40
15.39
12.38
9.37
6.36
3.36
0.35
Max: 36.45
Elem: NODEV0-1PLY-1.1702
Node: 5

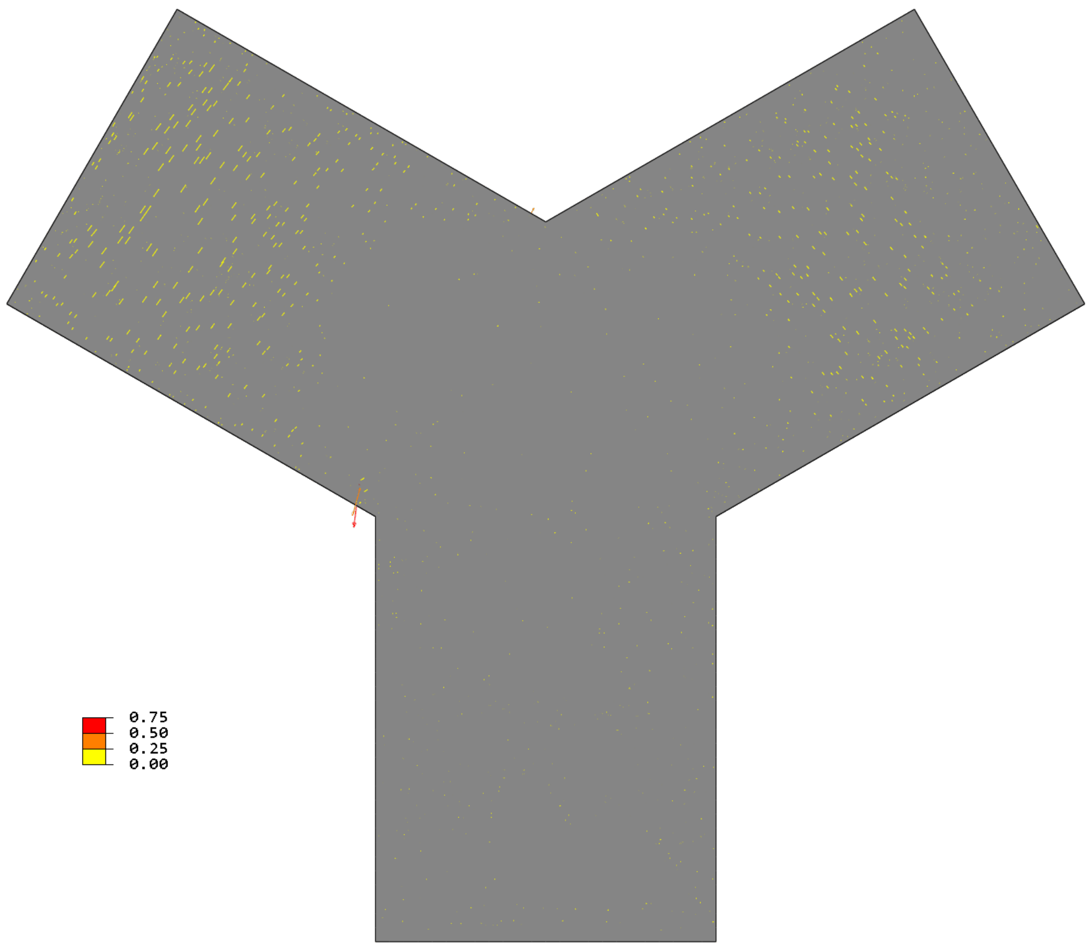

36.38
24.26
12.13
0.00

v1.1 7ply Compressive load



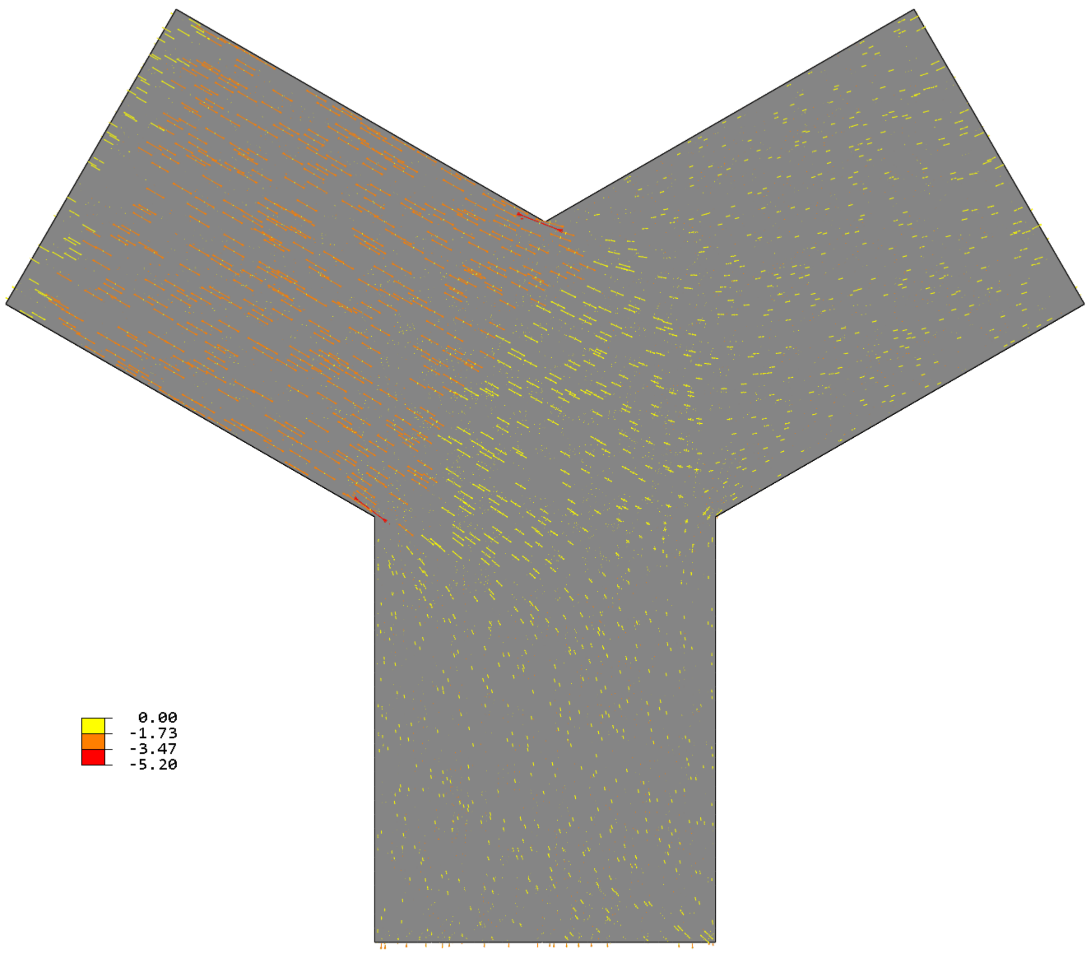


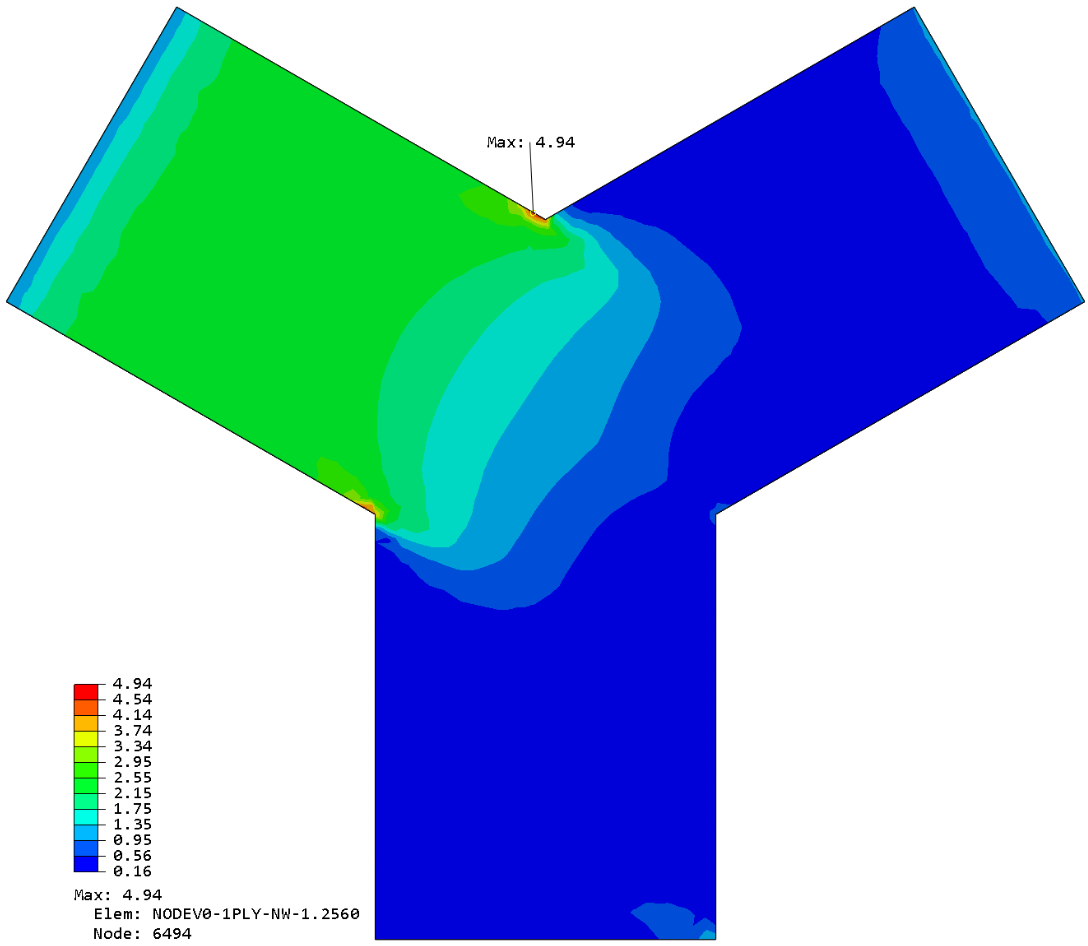
Max: 4.94
4.94
4.54
4.14
3.74
3.34
2.95
2.55
2.15
1.75
1.35
0.95
0.56
0.16
Max: 4.94
Elem: NODEV0-1PLY-NW-1.2560
Node: 6494

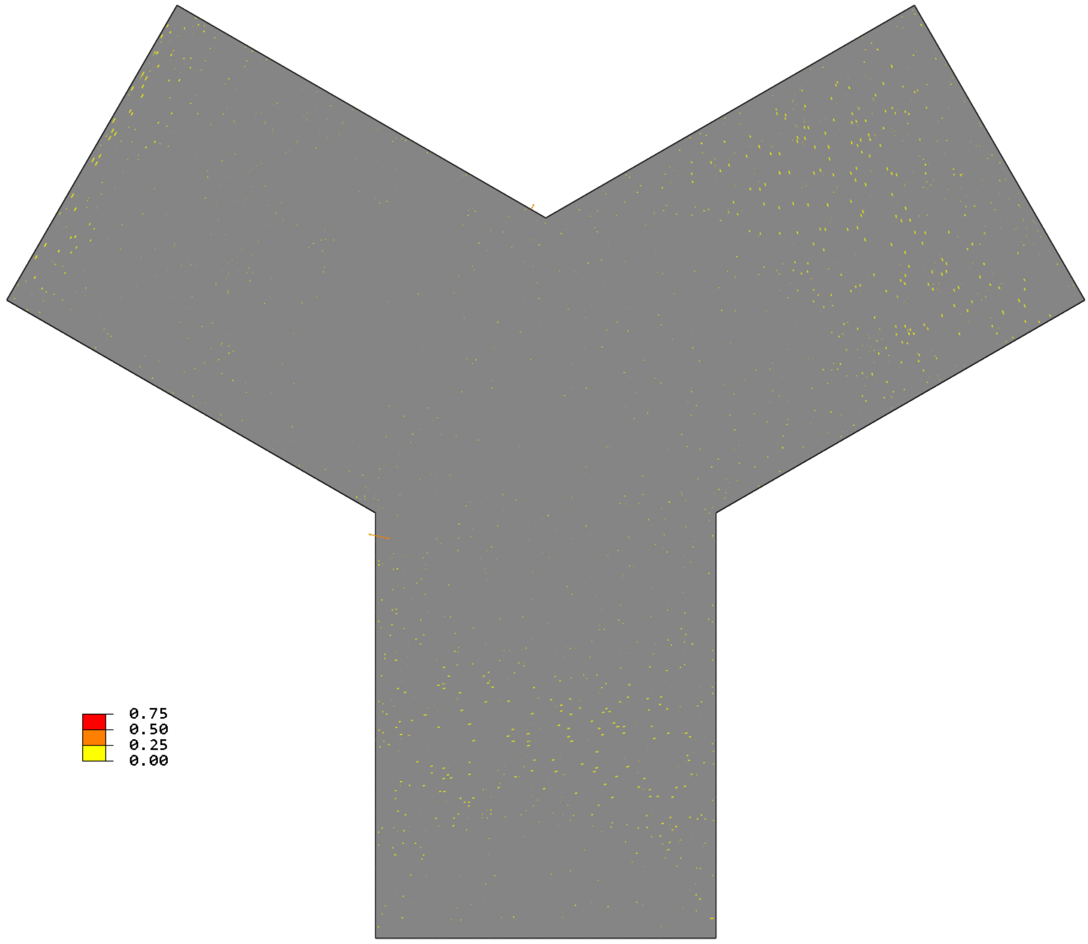


0.75
0.50
0.25
0.00

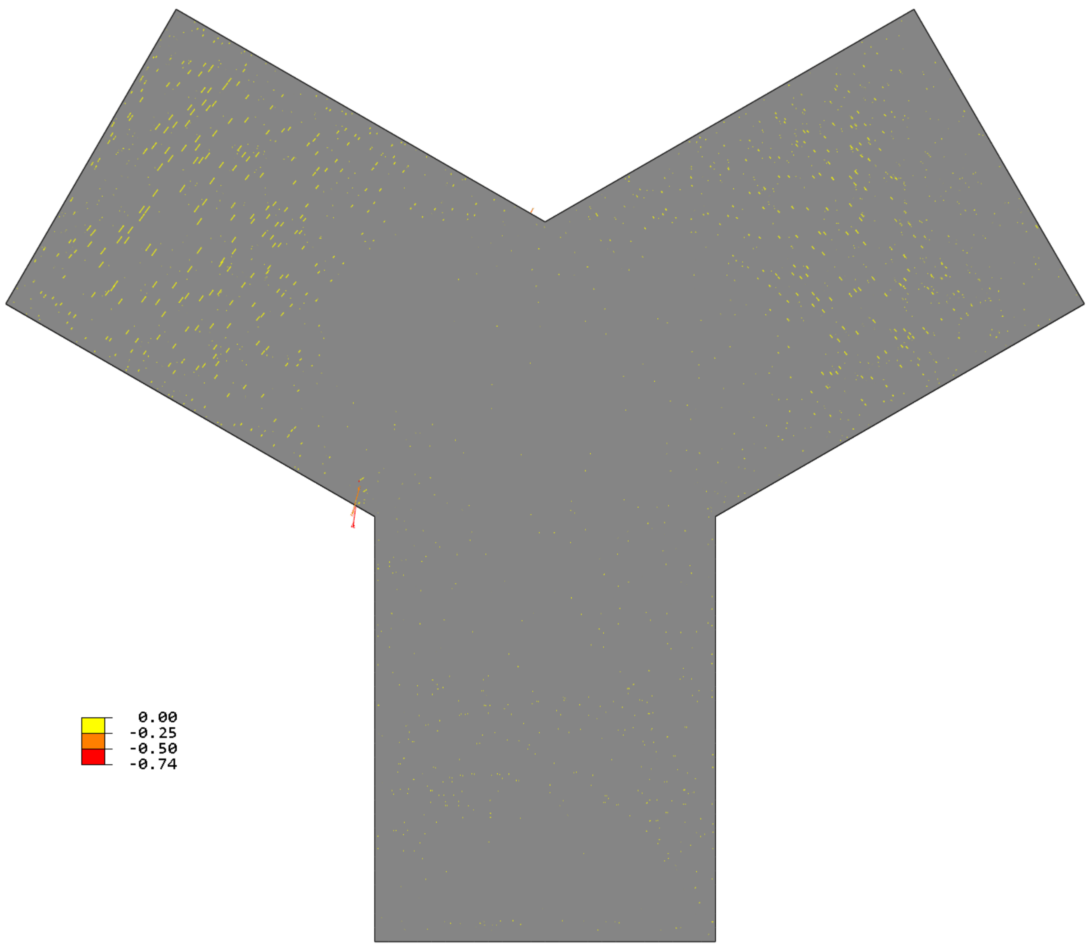
v1.1 7ply Compressive load (Alt section - ply 3)

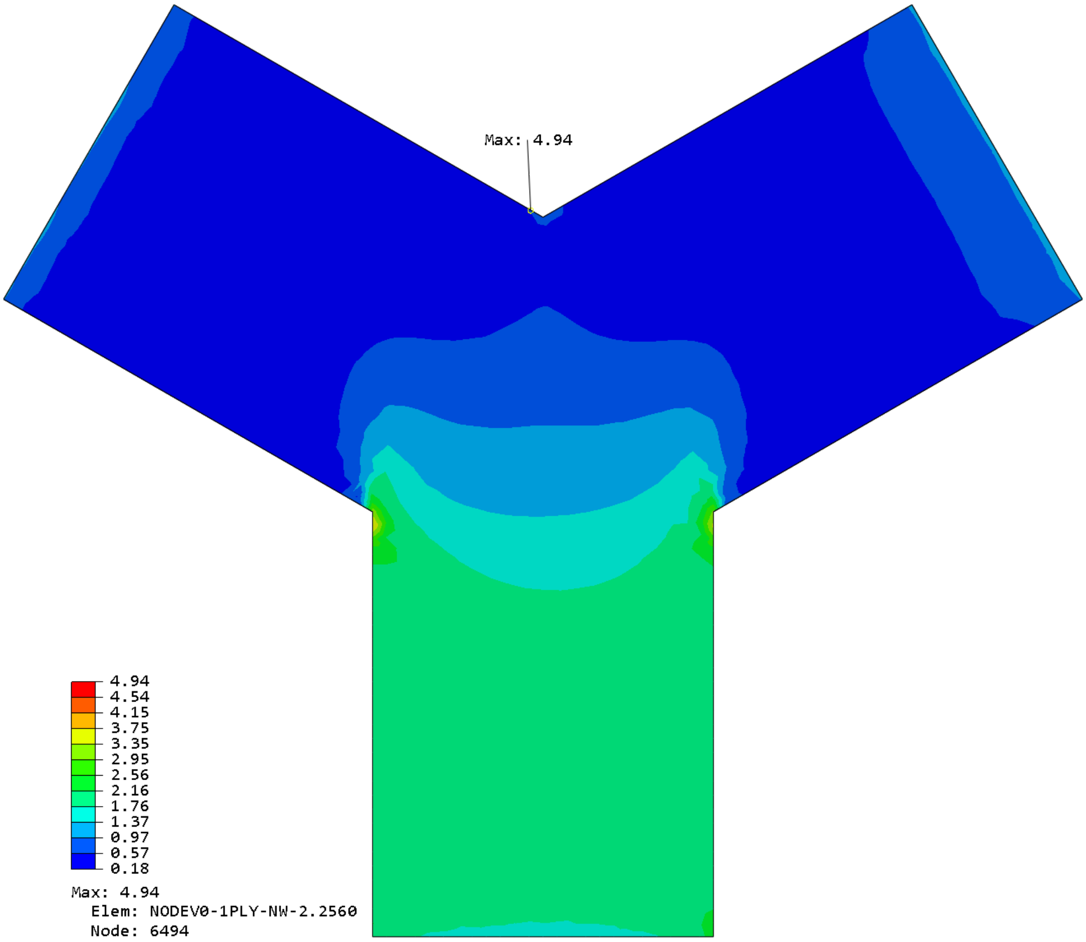


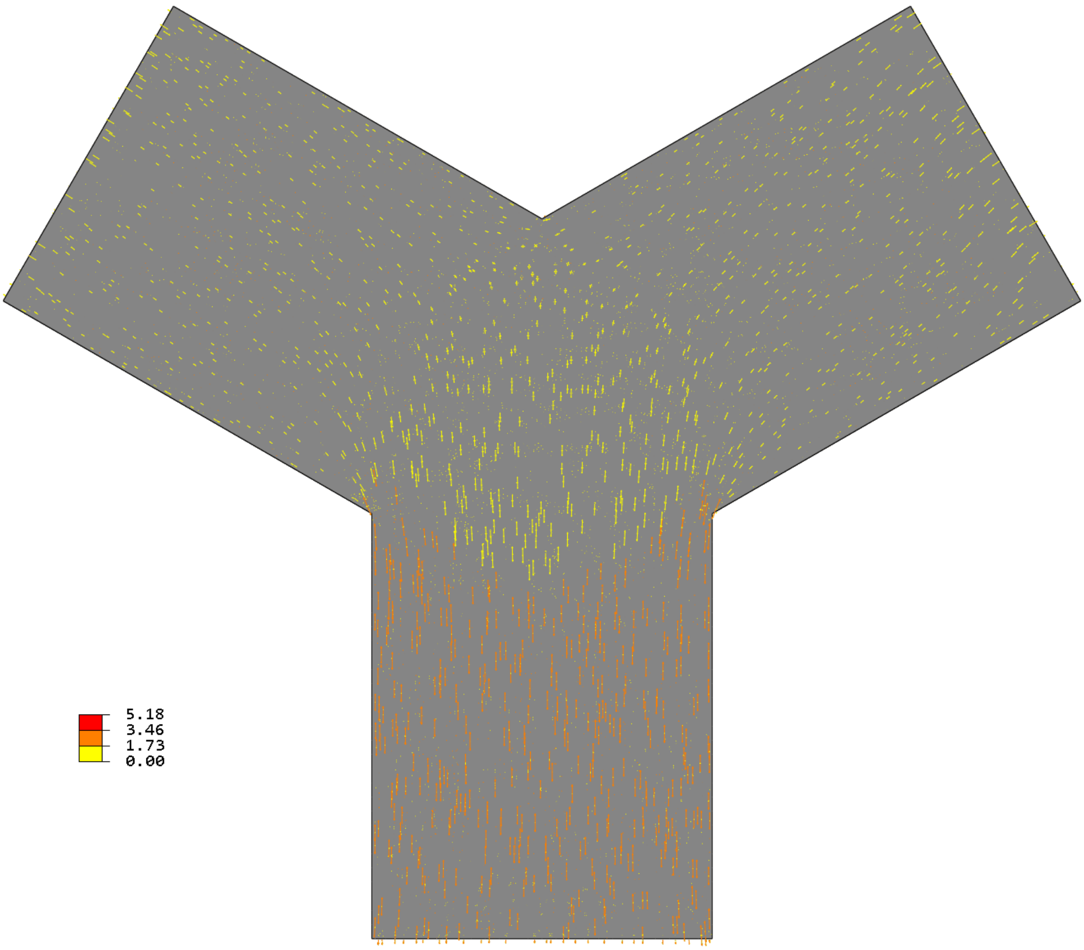

Max: 4.94
4.94
4.54
4.14
3.74
3.34
2.95
2.55
2.15
1.75
1.35
0.95
0.56
0.16
Max: 4.94
Elem: NODEV0-1PLY-NW-1.2560
Node: 6494


0.75
0.50
0.25
0.00

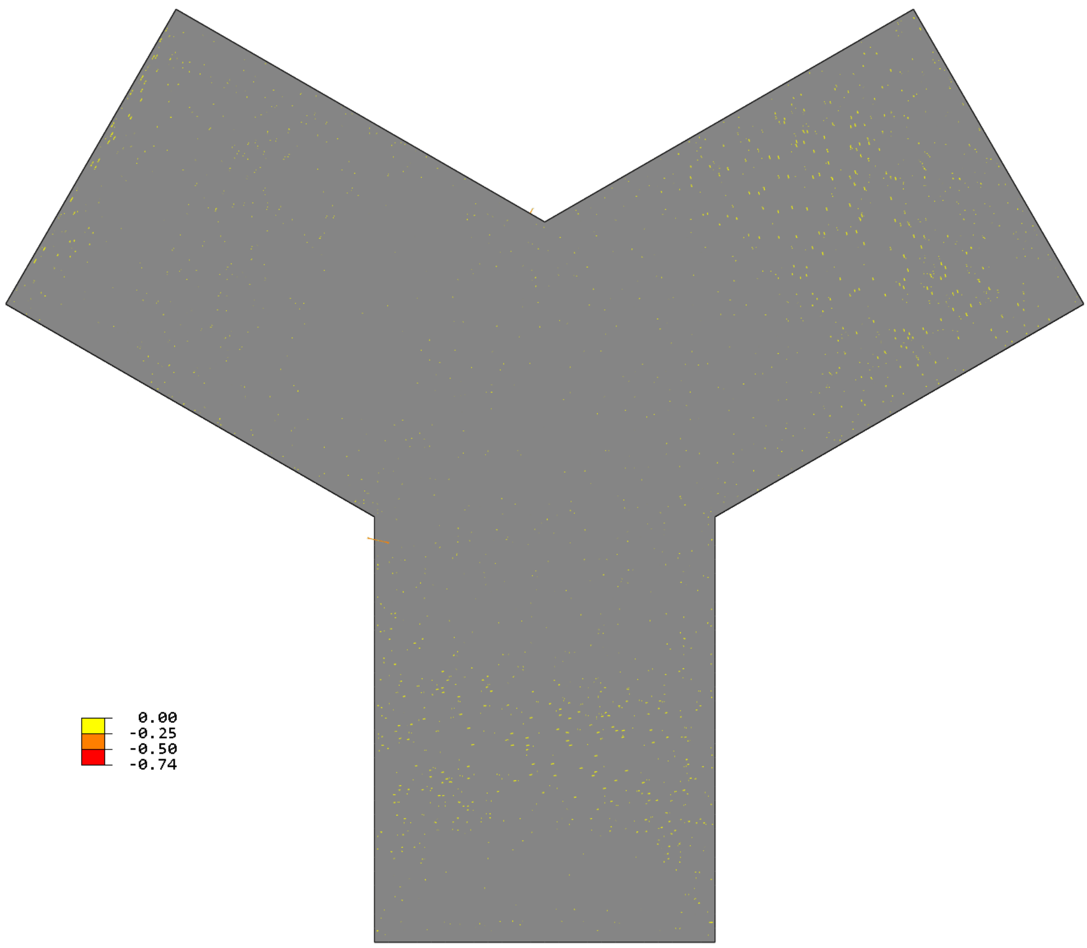
v1.1 7ply Tensile load

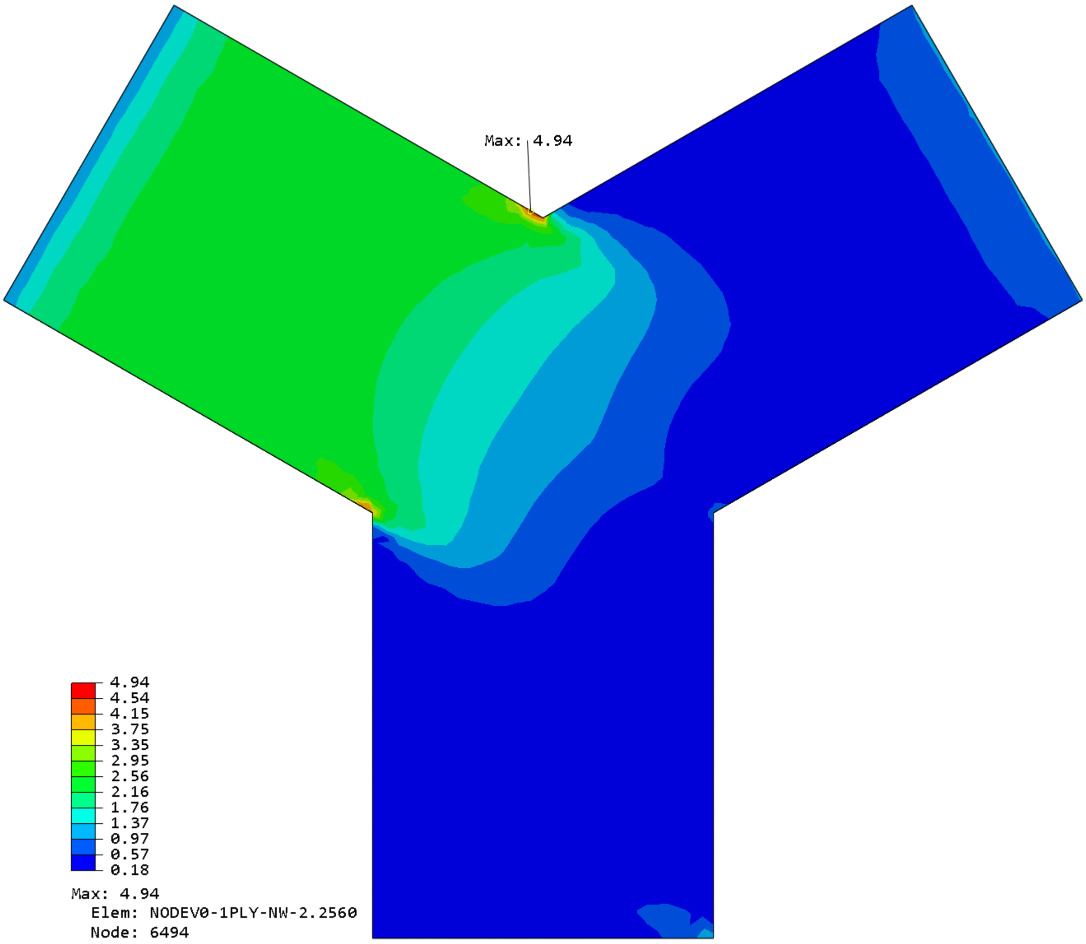


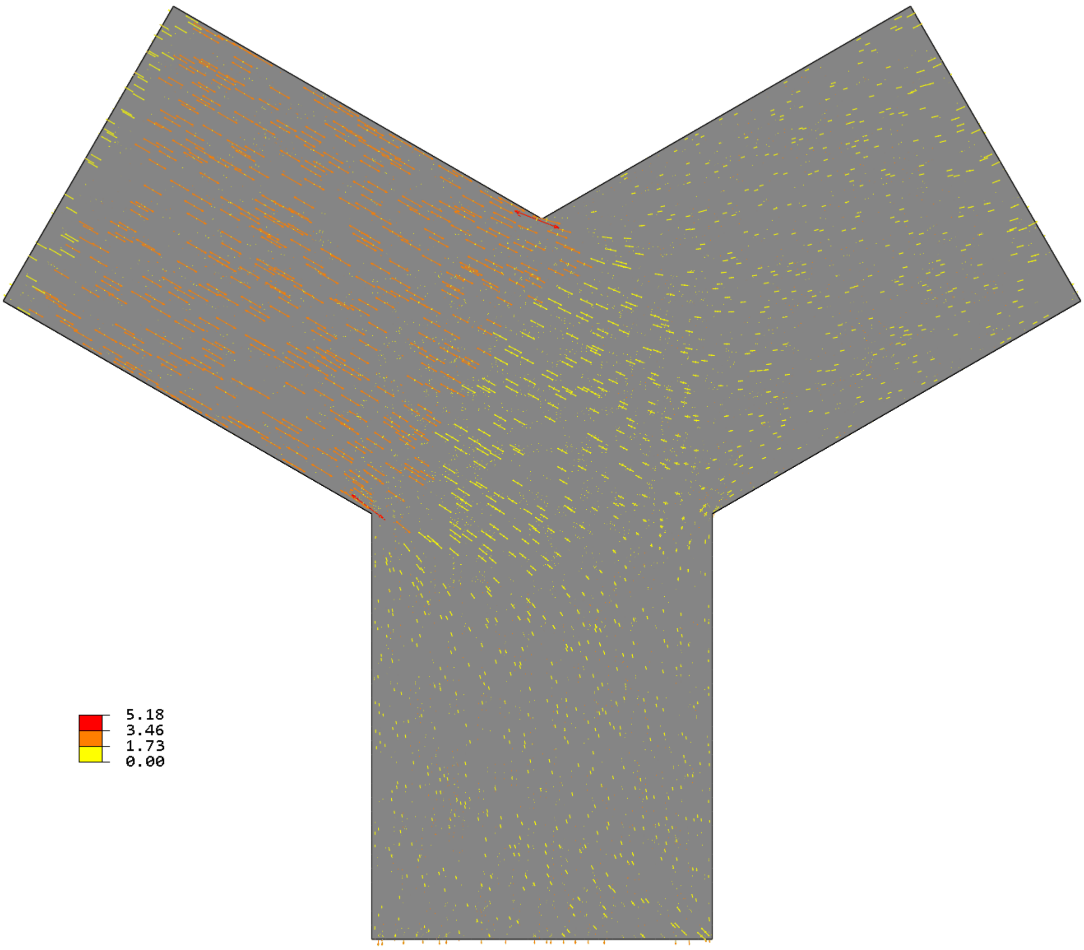

Max: 4.94
4.94
4.54
4.15
3.75
3.35
2.95
2.56
2.16
1.76
1.37
0.97
0.57
0.18
Max: 4.94
Elem: NODEV0-1PLY-NW-2.2560
Node: 6494


5.18
3.46
1.73
0.00

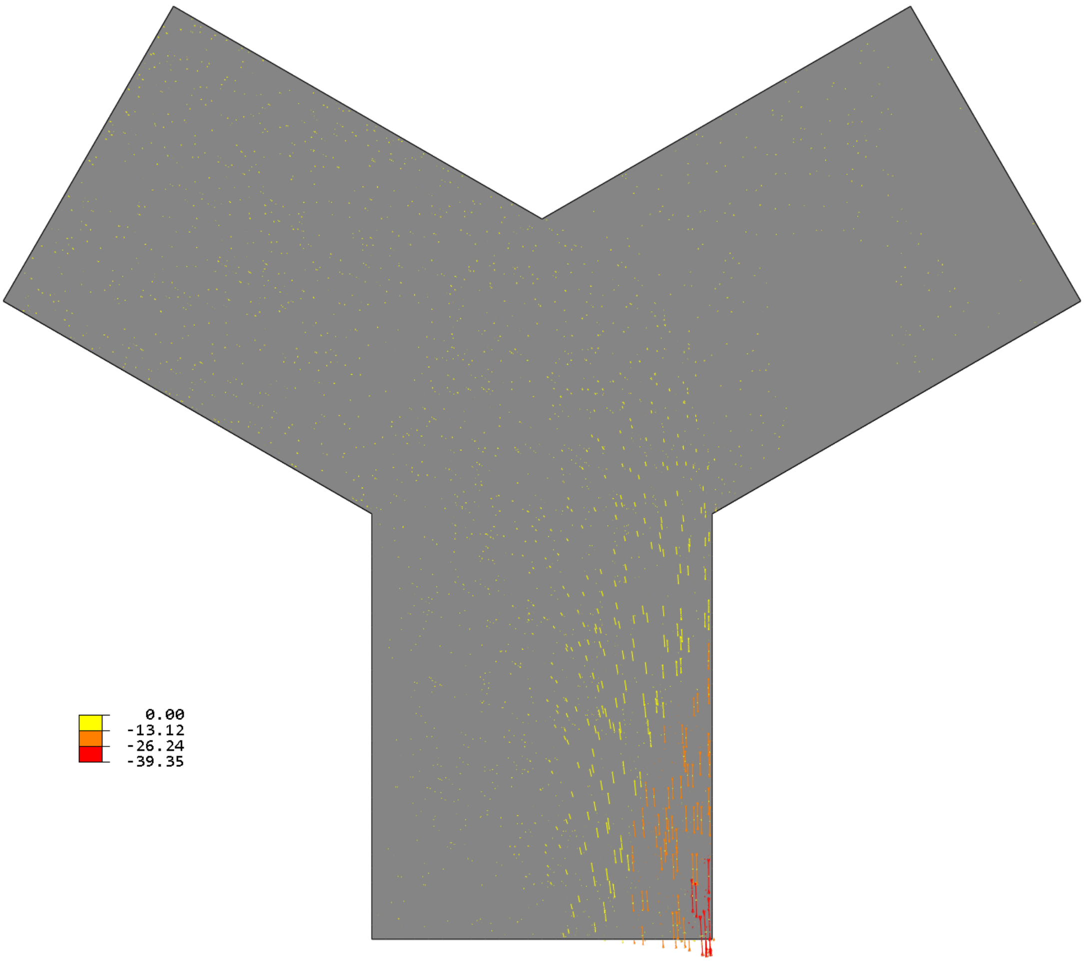
v1.1 7ply Tensile load (Alt section - ply 3)

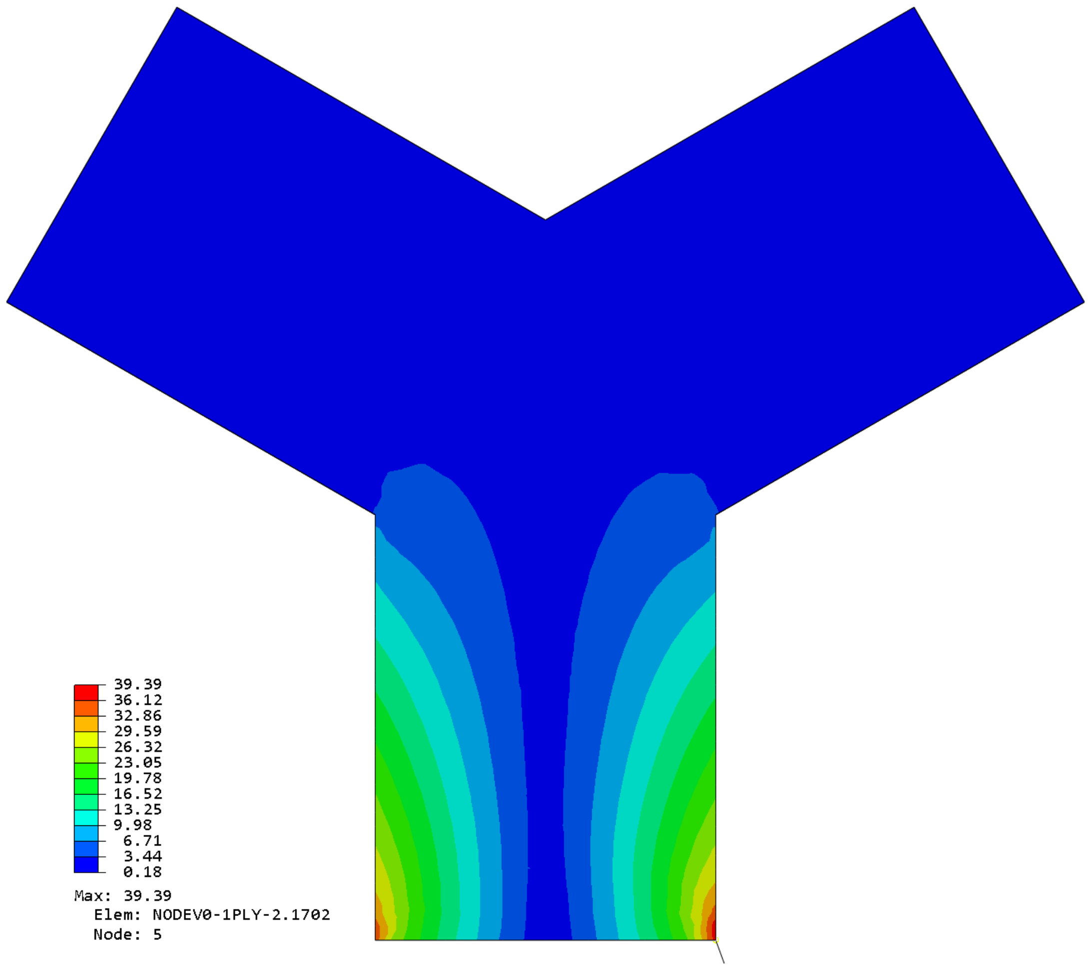


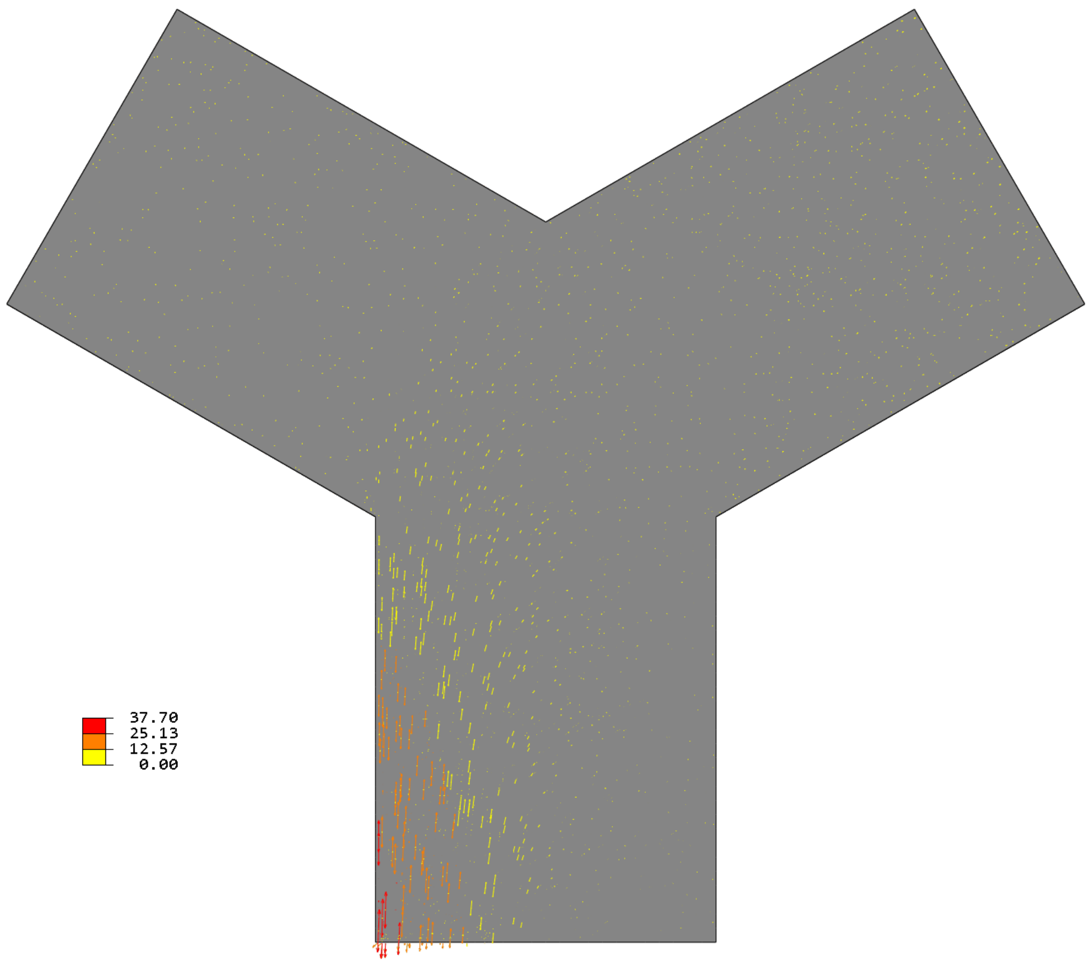

Max: 4.94
4.94
4.54
4.15
3.75
3.35
2.95
2.56
2.16
1.76
1.37
0.97
0.57
0.18
Max: 4.94
Elem: NODEV0-1PLY-NW-2.2560
Node: 6494


5.18
3.46
1.73
0.00

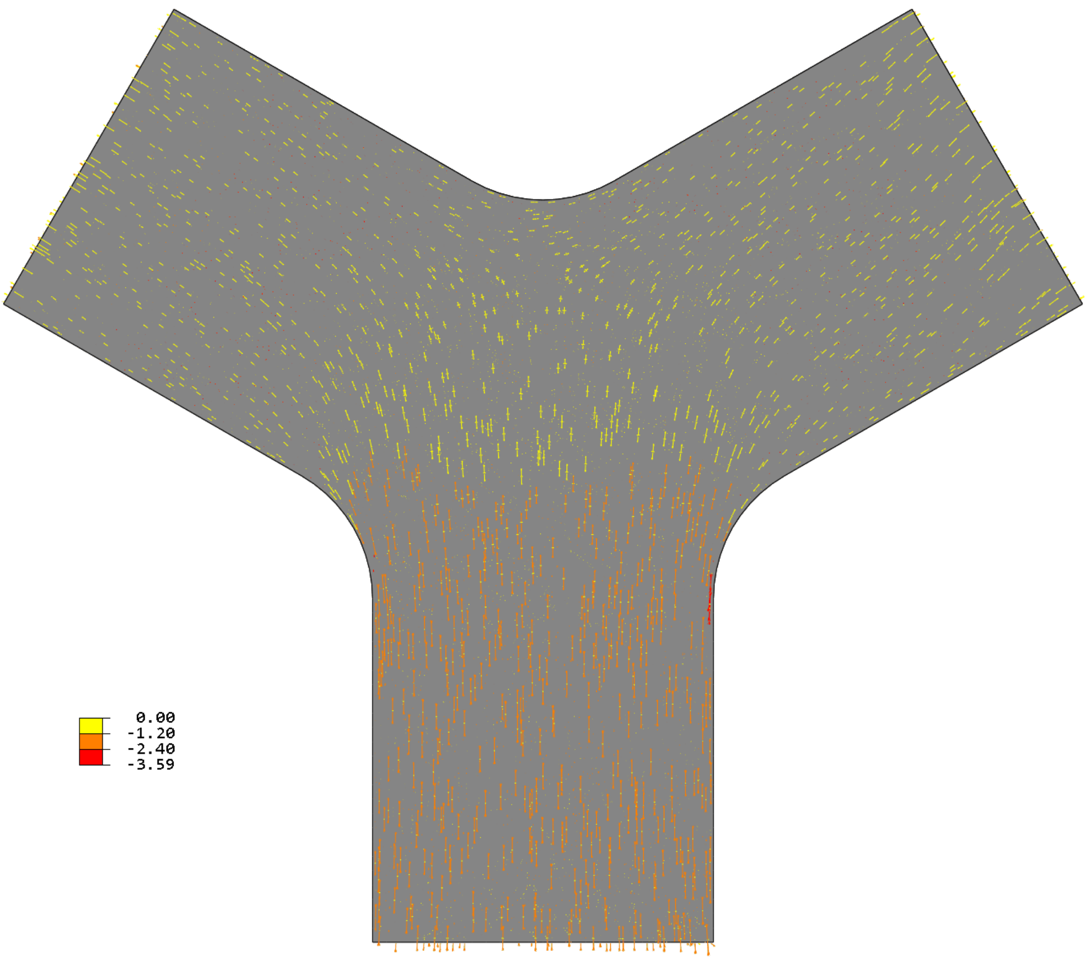
v1.1 7ply Compressive + tensile load

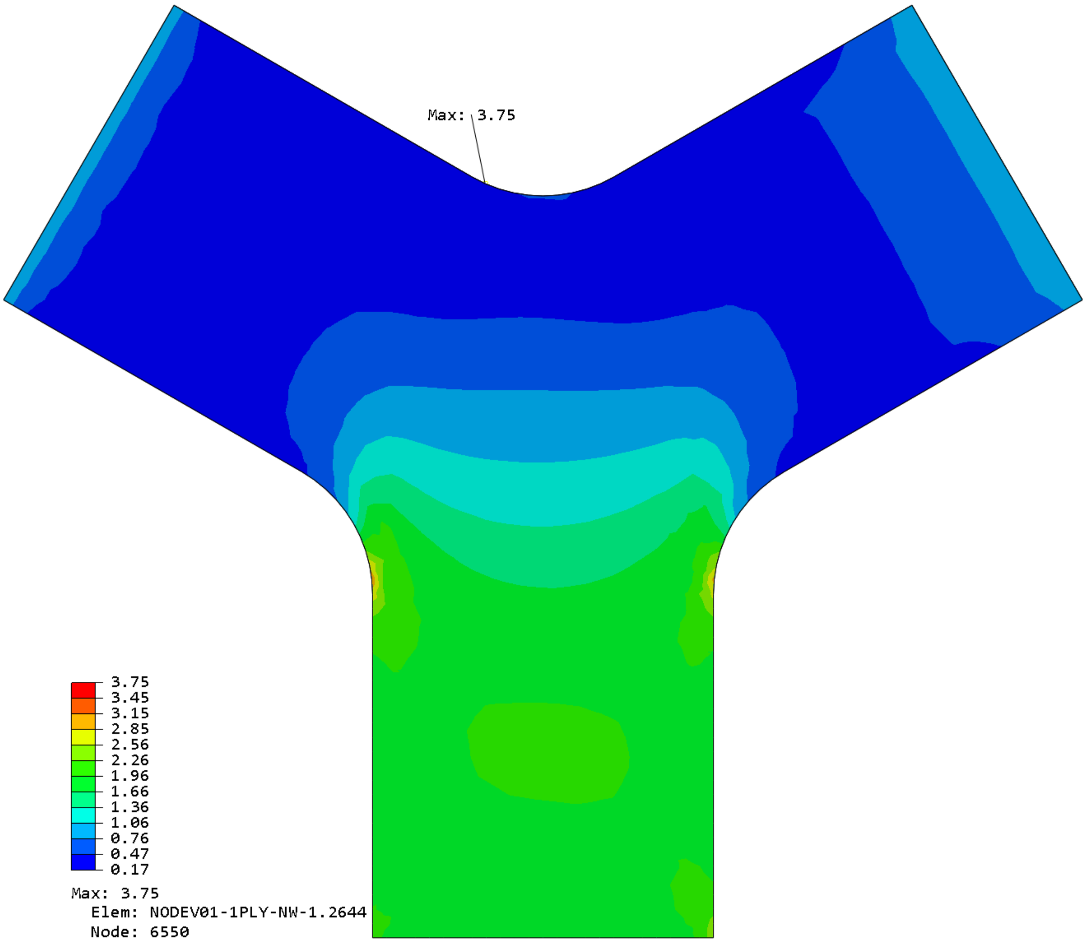


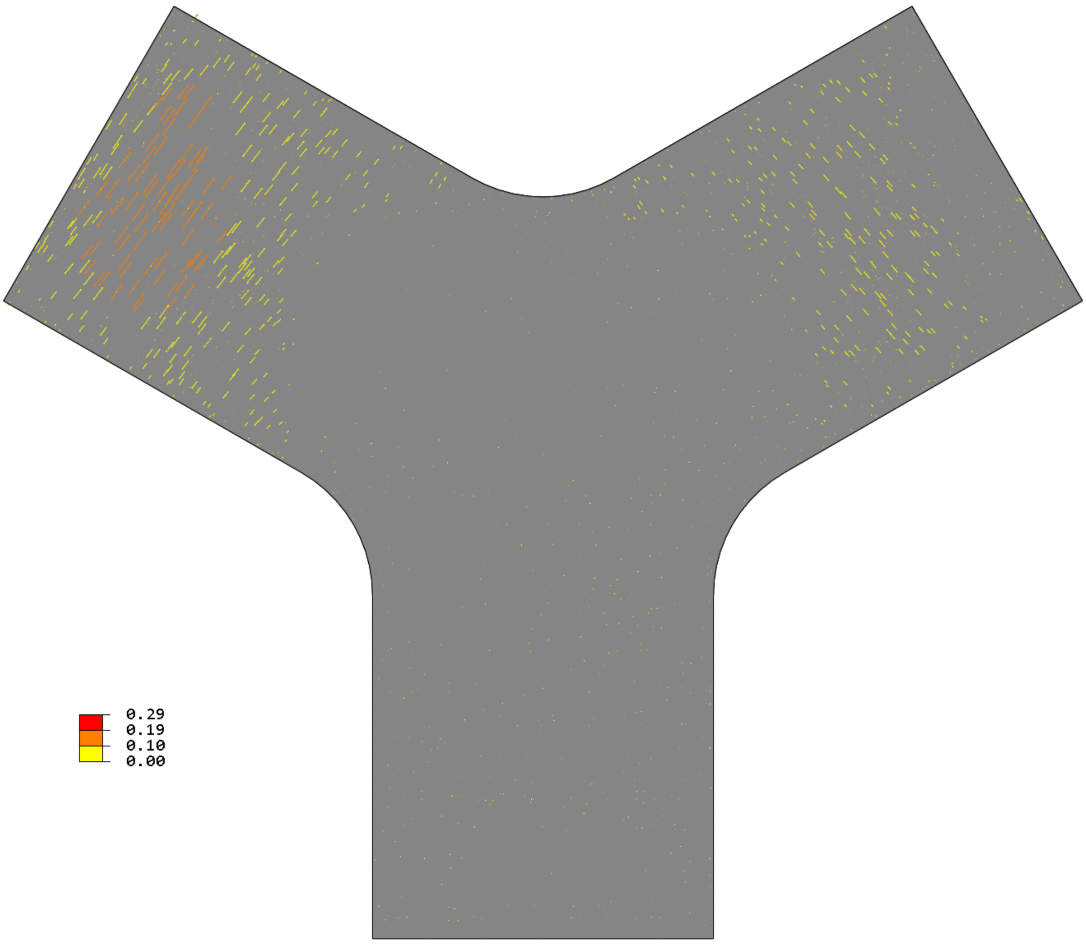

39.39
36.12
32.86
29.59
26.32
23.05
19.78
16.52
13.25
9.98
6.71
3.44
0.18
Max: 39.39
Elem: NODEV0-1PLY-2.1702
Node: 5


37.70
25.13
12.57
0.00

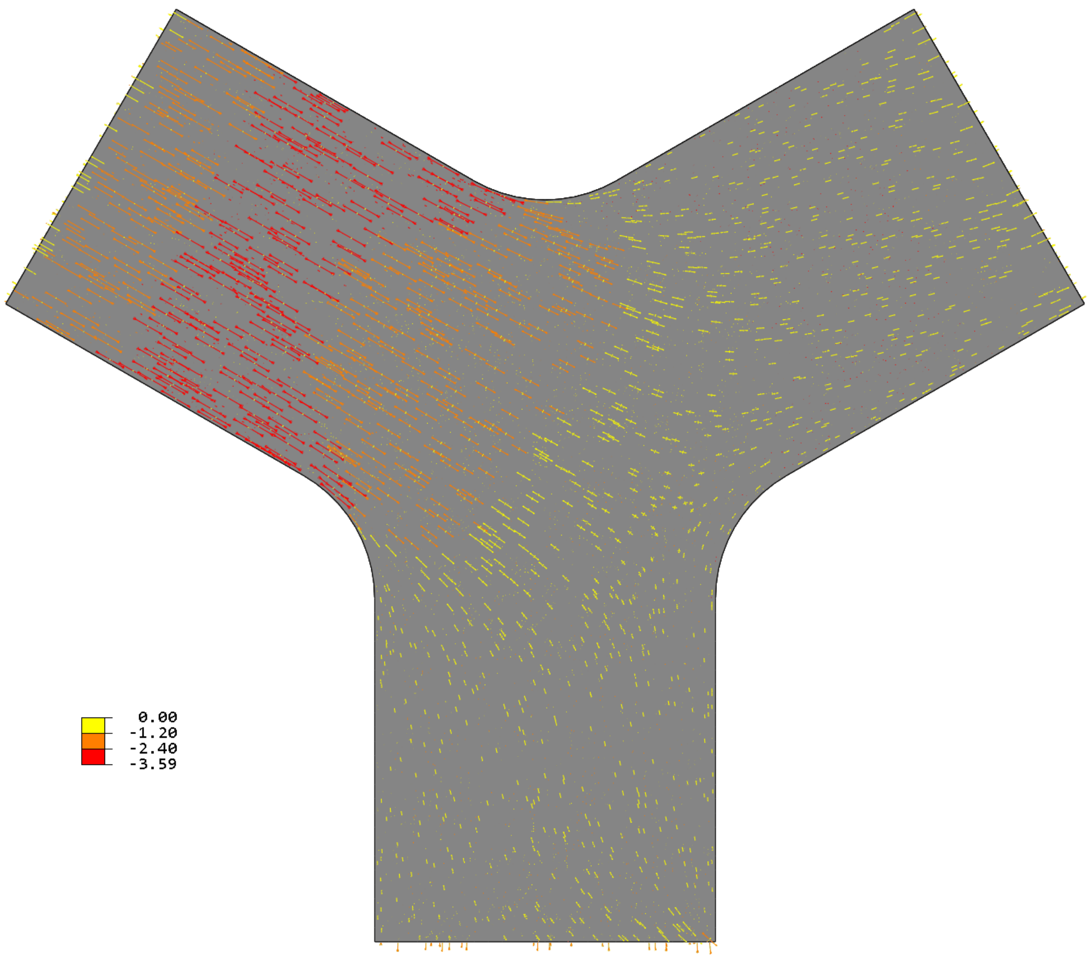
v1.2 7ply Compressive load

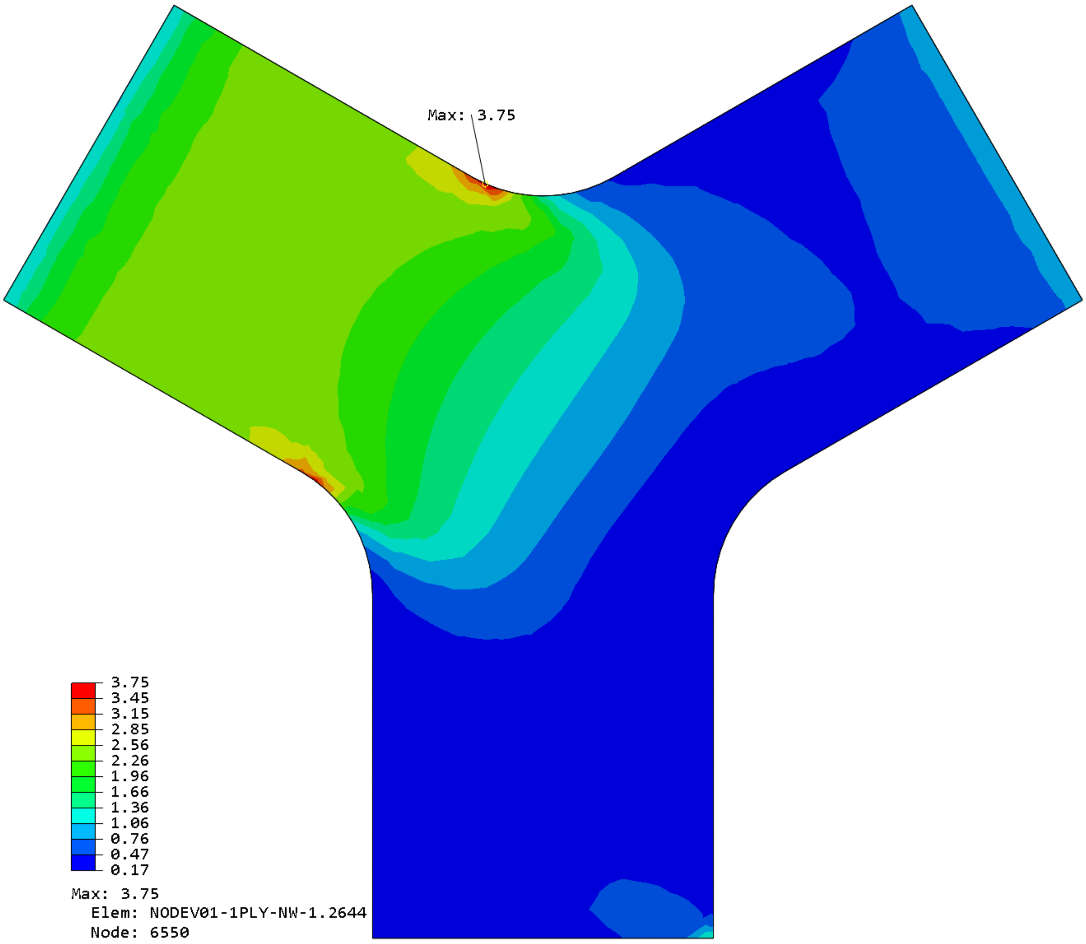


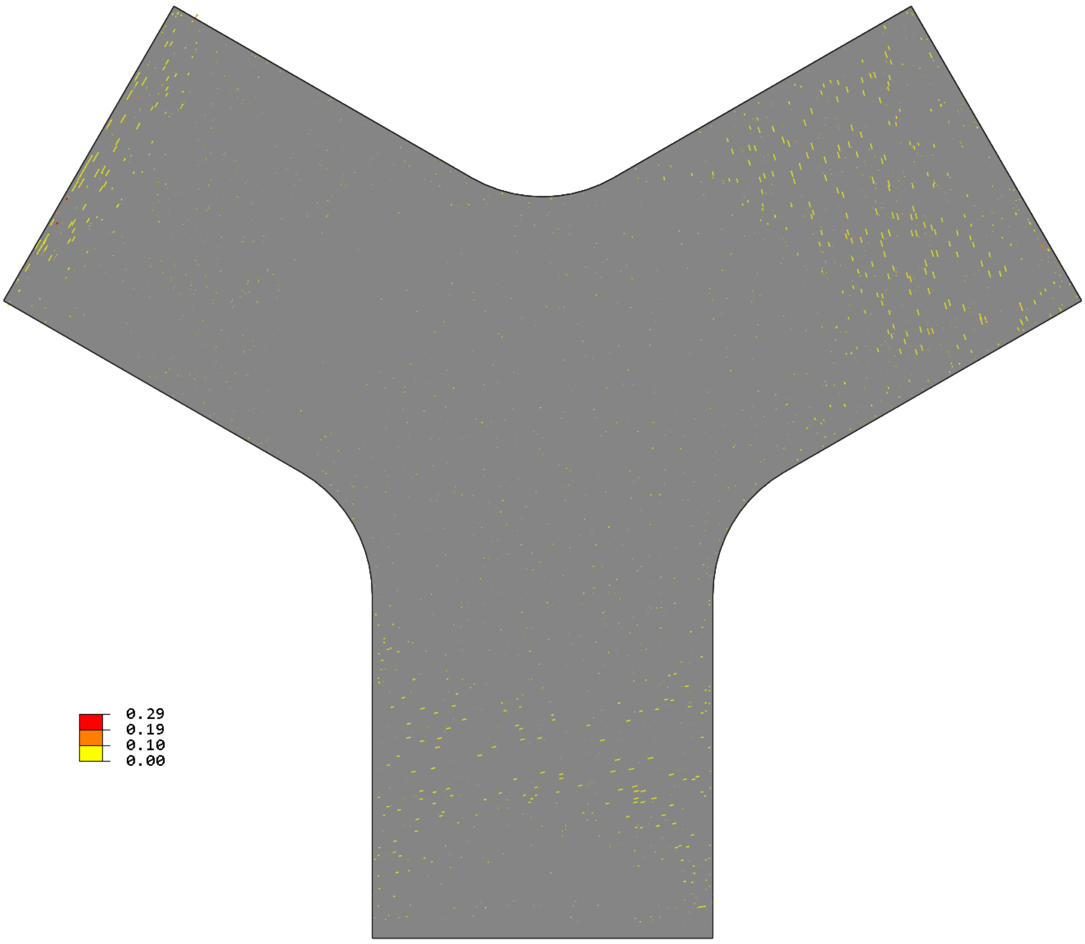

Max: 3.75
3.75
3.45
3.15
2.85
2.56
2.26
1.96
1.66
1.36
1.06
0.76
0.47
0.17
Max: 3.75
Elem: NODEV01-1PLY-NW-1.2644
Node: 6550


0.29
0.19
0.10
0.00

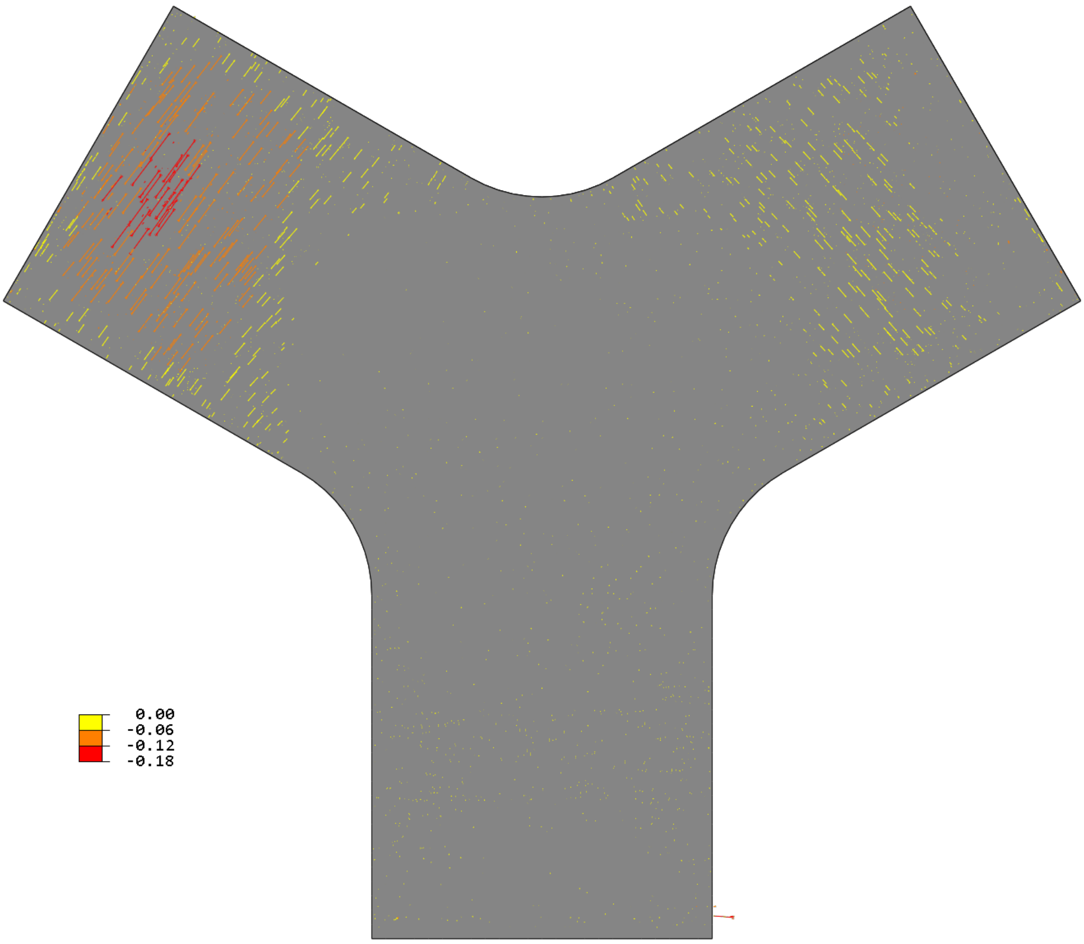
v1.2 7ply Compressive load (Alt section - ply 3)

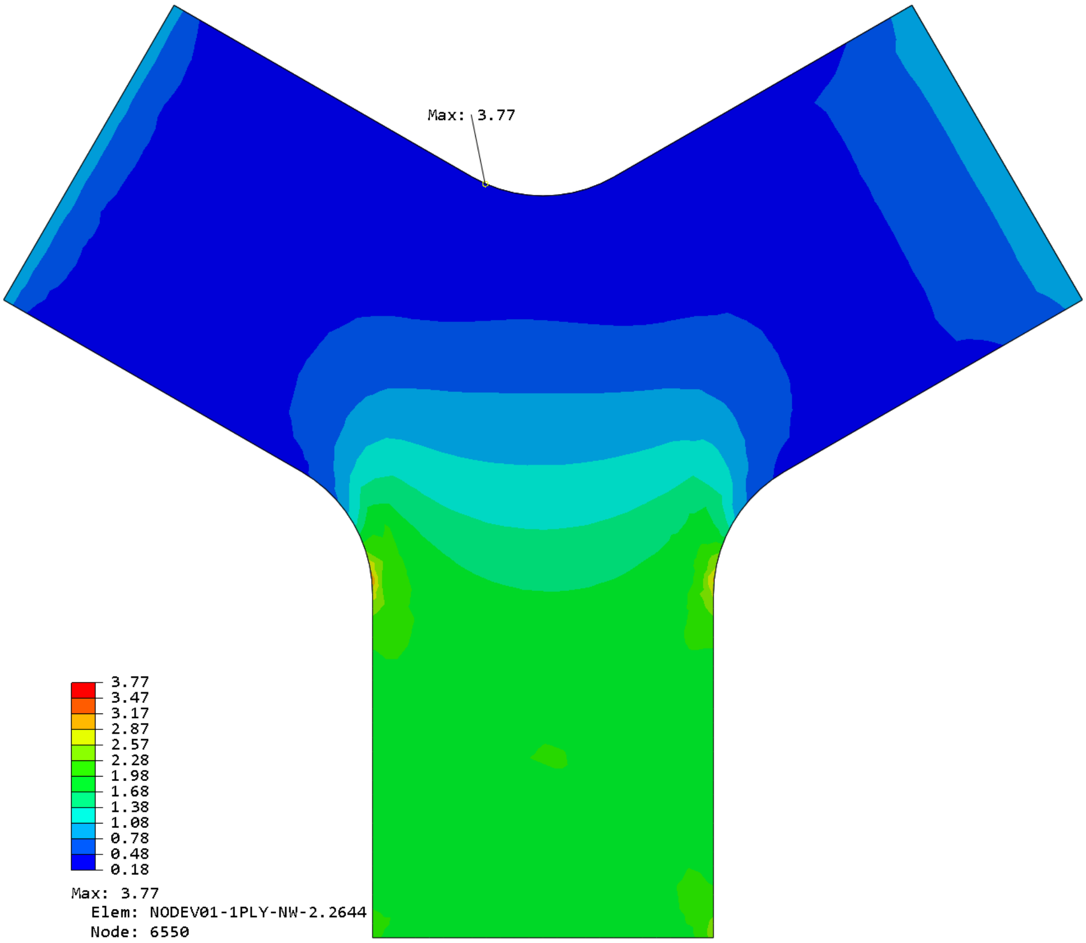


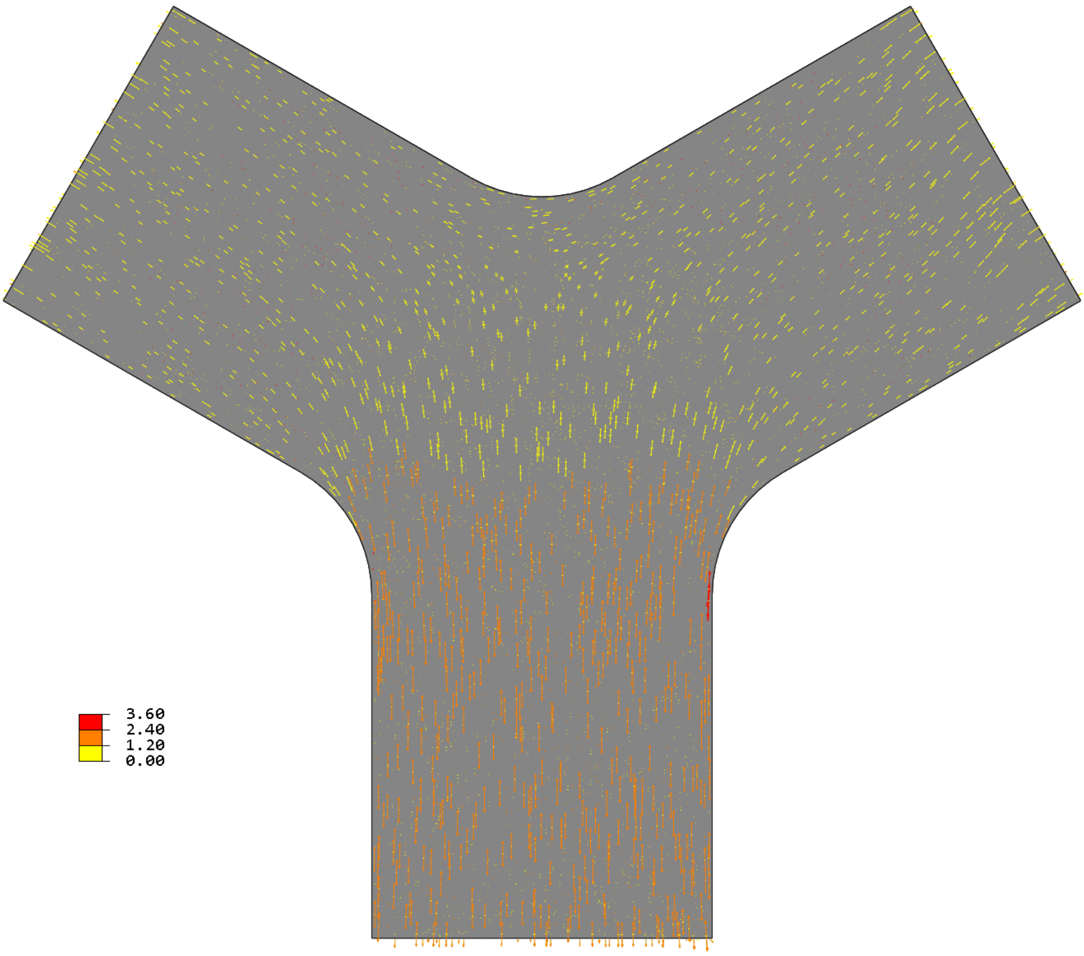

Max: 3.75
3.75
3.45
3.15
2.85
2.56
2.26
1.96
1.66
1.36
1.06
0.76
0.47
0.17
Max: 3.75
Elem: NODEV01-1PLY-NW-1.2644
Node: 6550


0.29
0.19
0.10
0.00

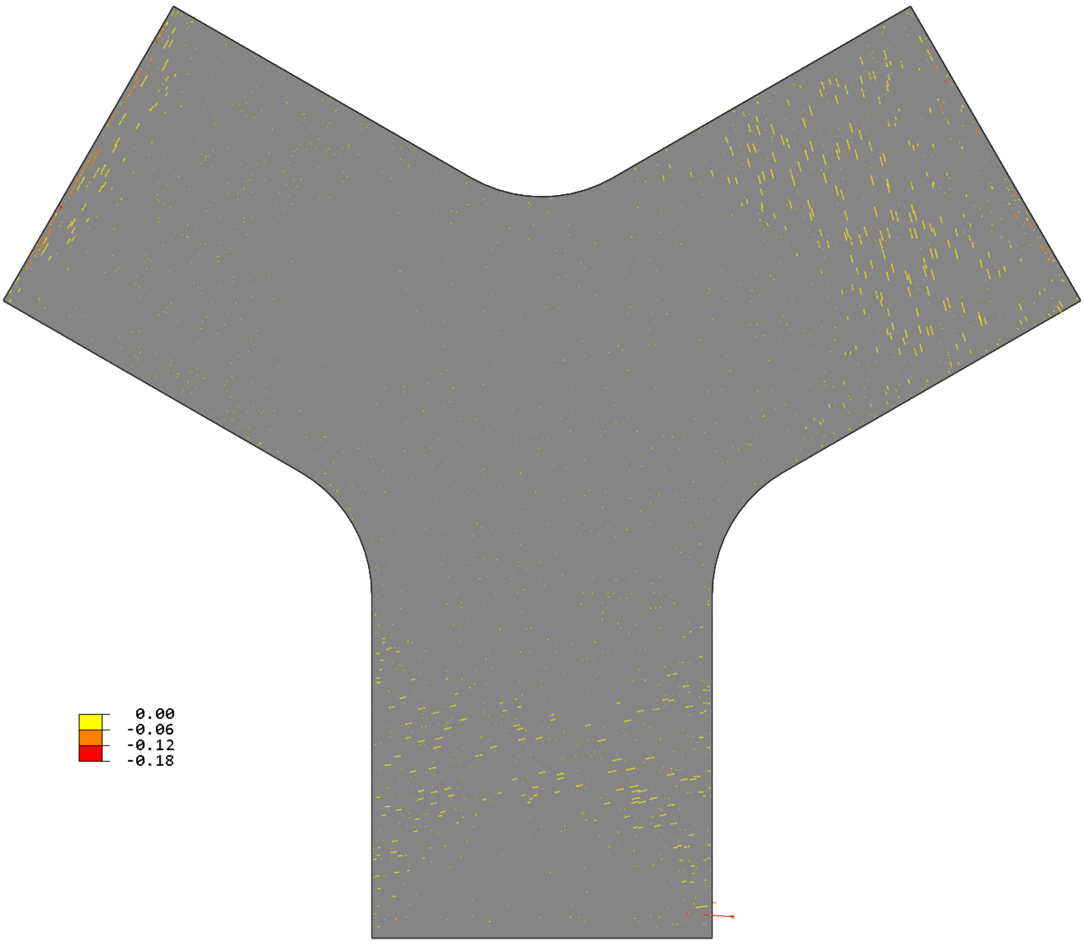
v1.2 7ply Tensile load

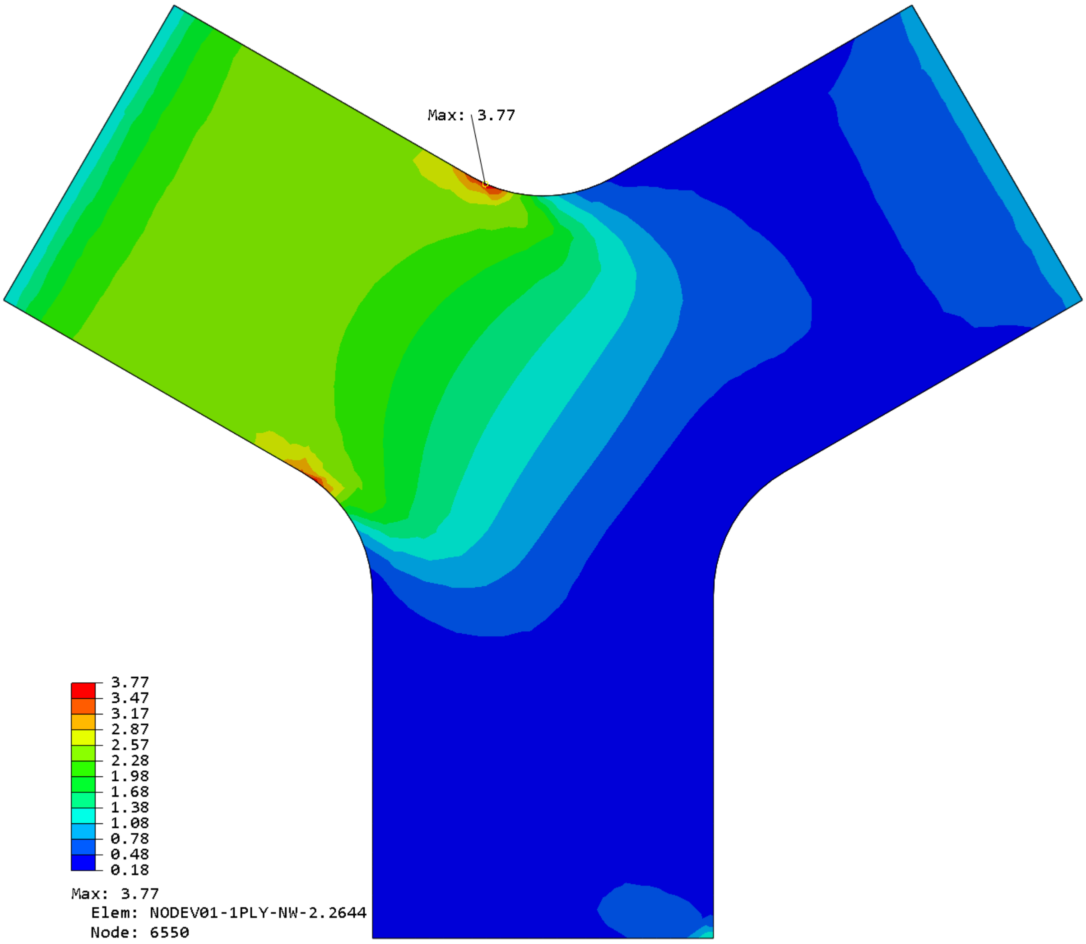


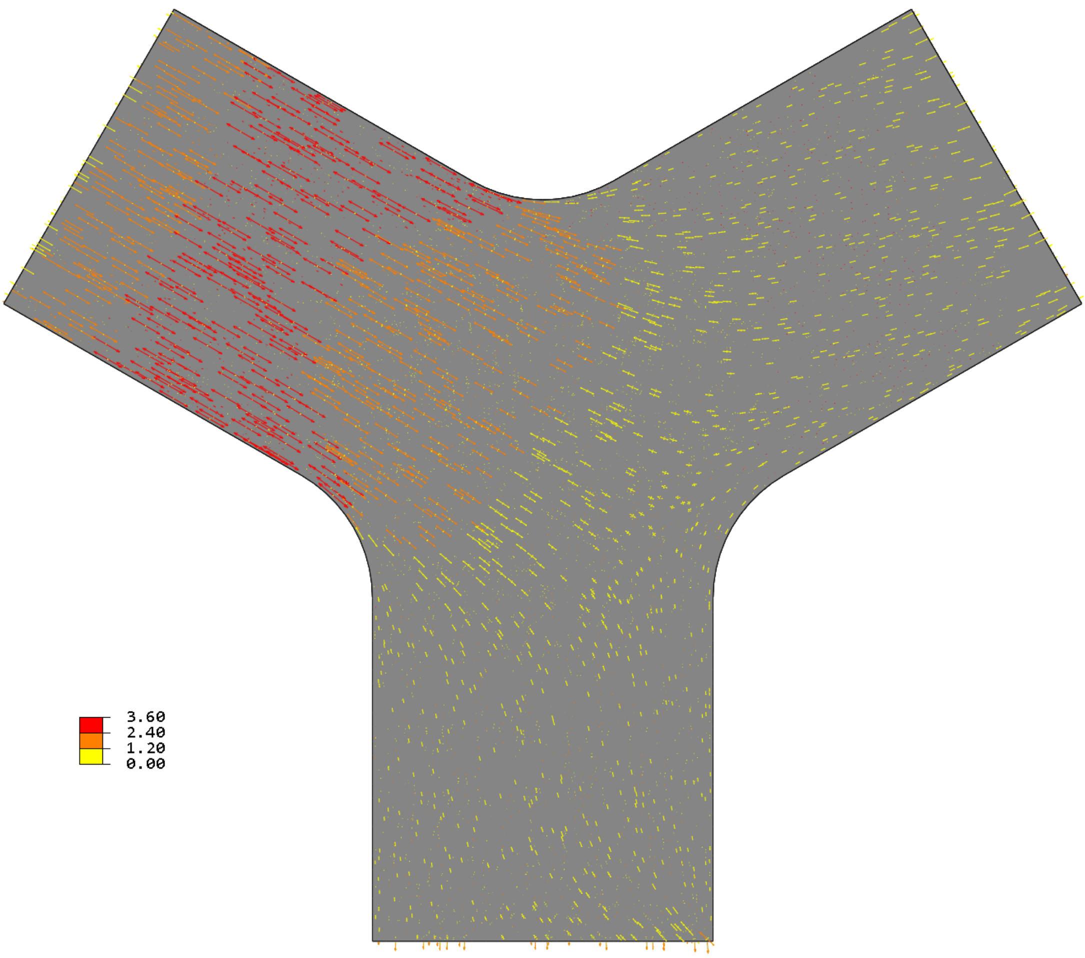

Max: 3.77
3.77
3.47
3.17
2.87
2.57
2.28
1.98
1.68
1.38
1.08
0.78
0.48
0.18
Max: 3.77
Elem: NODEV01-1PLY-NW-2.2644
Node: 6550


3.60
2.40
1.20
0.00

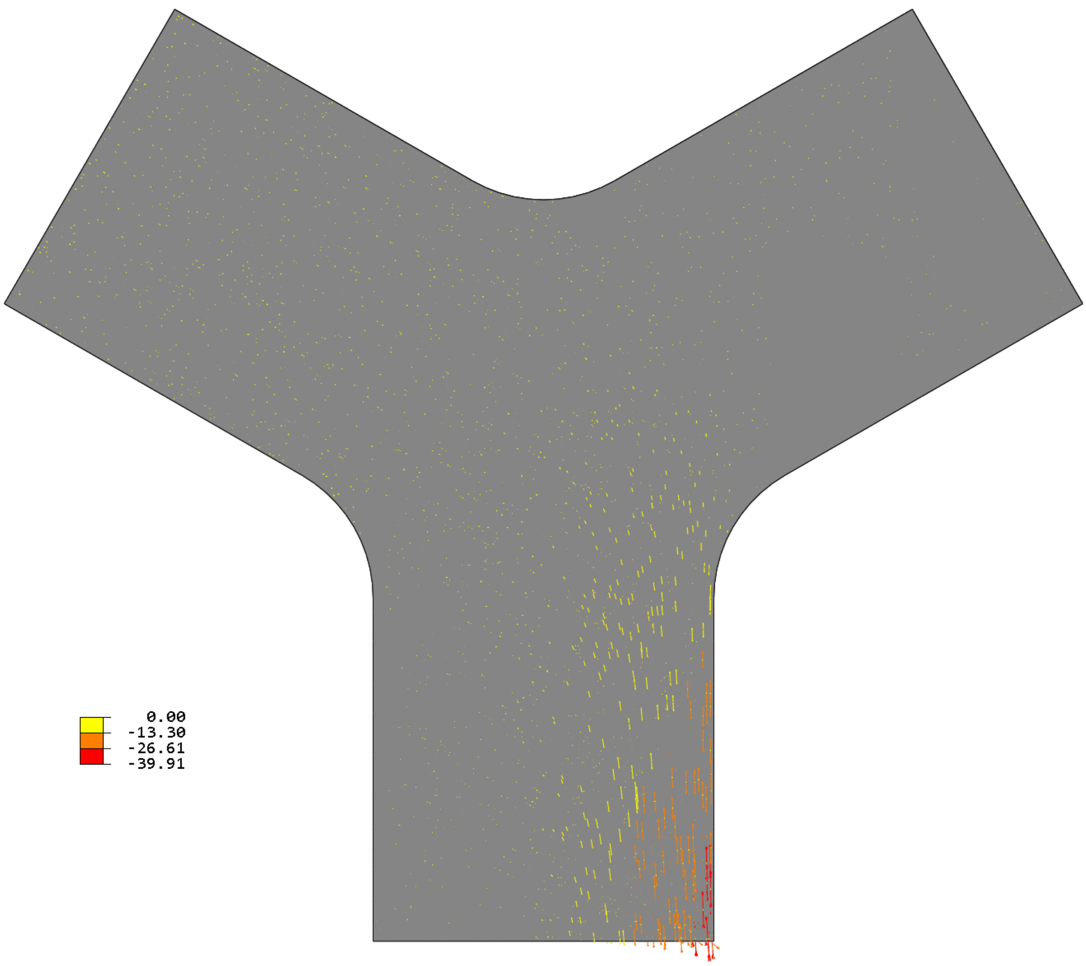
v1.2 7ply Tensile load (Alt section - ply 3)

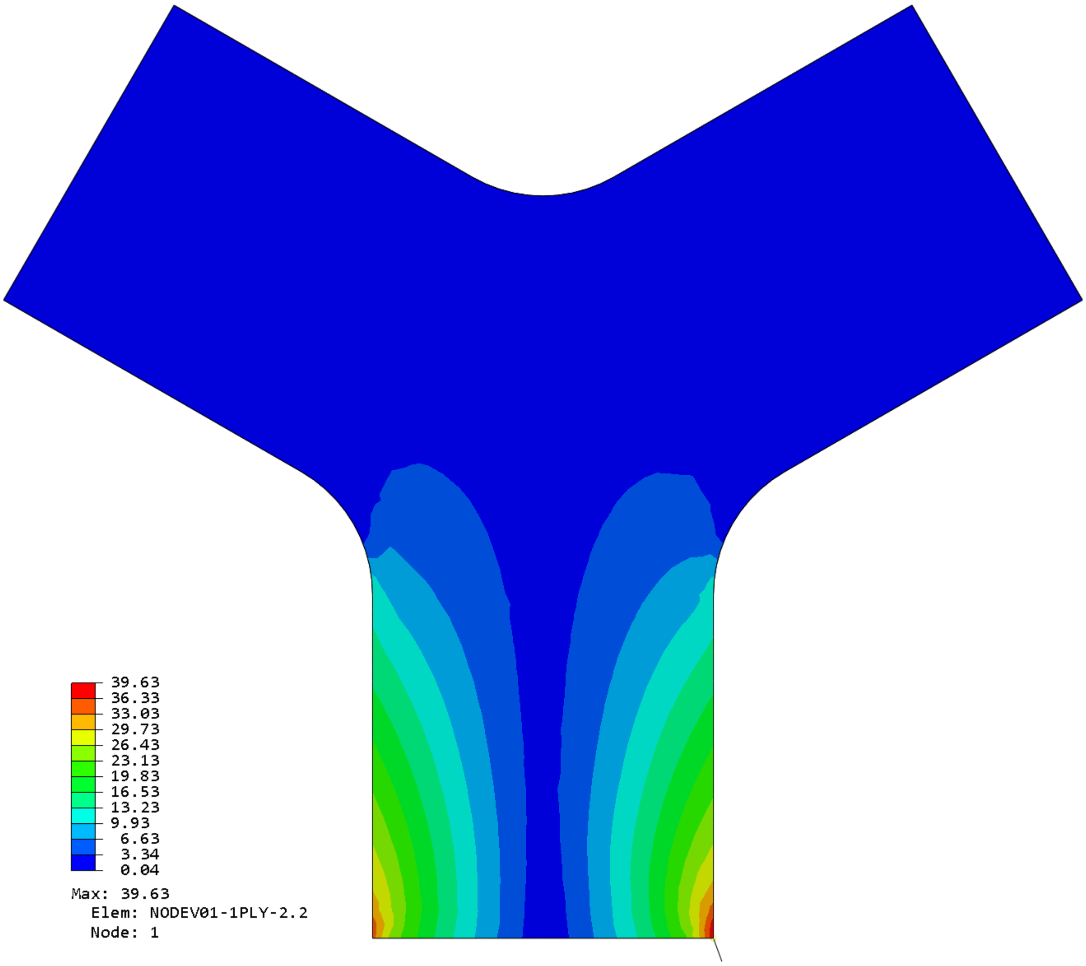


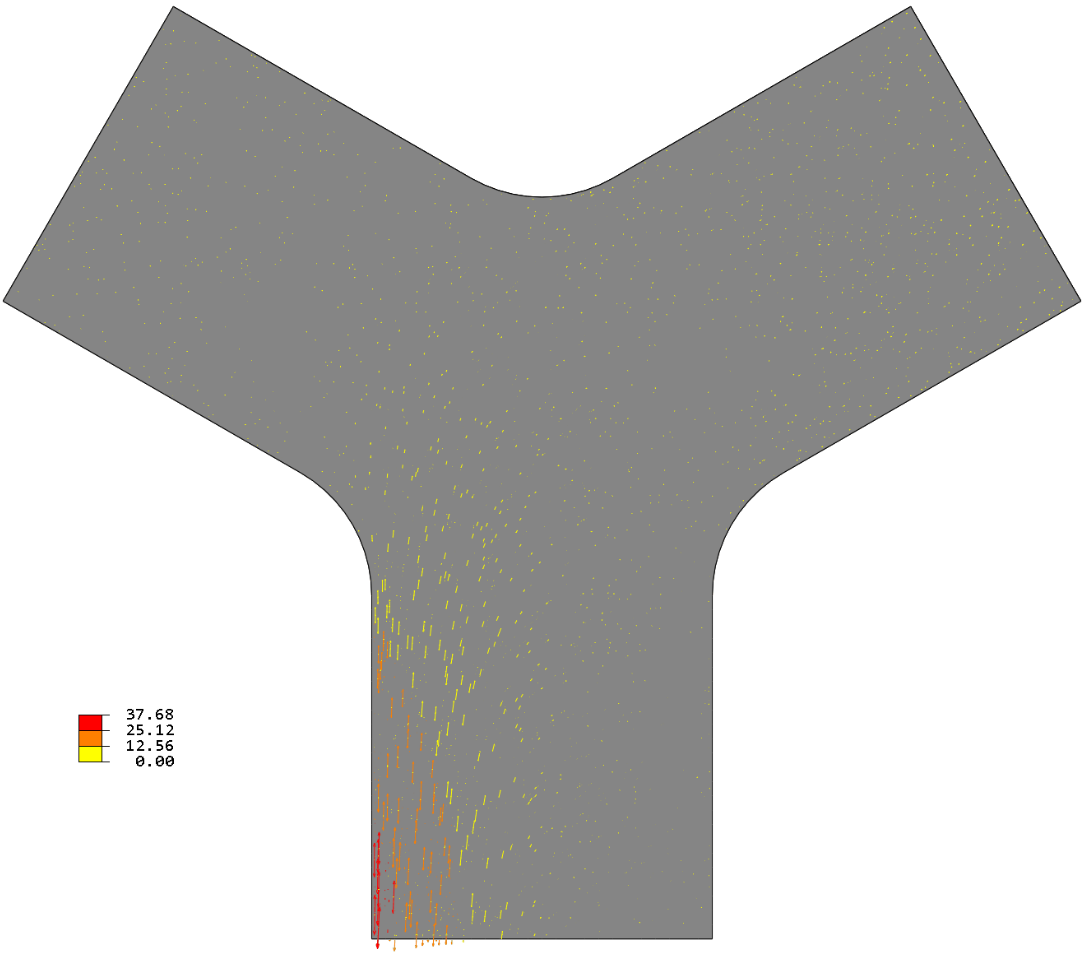

Max: 3.77
3.77
3.47
3.17
2.87
2.57
2.28
1.98
1.68
1.38
1.08
0.78
0.48
0.18
Max: 3.77
Elem: NODEV01-1PLY-NW-2.2644
Node: 6550


3.60
2.40
1.20
0.00

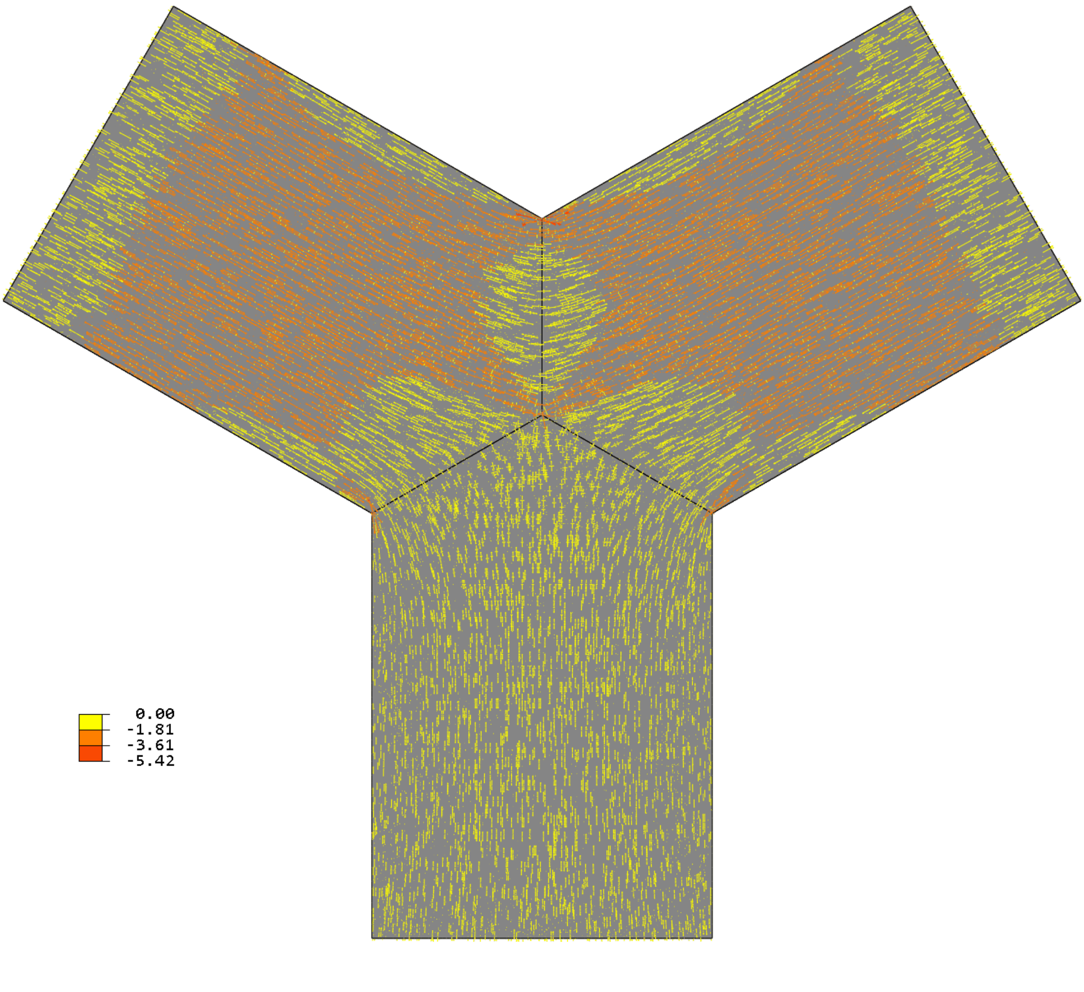
v1.2 7ply Compressive + tensile load

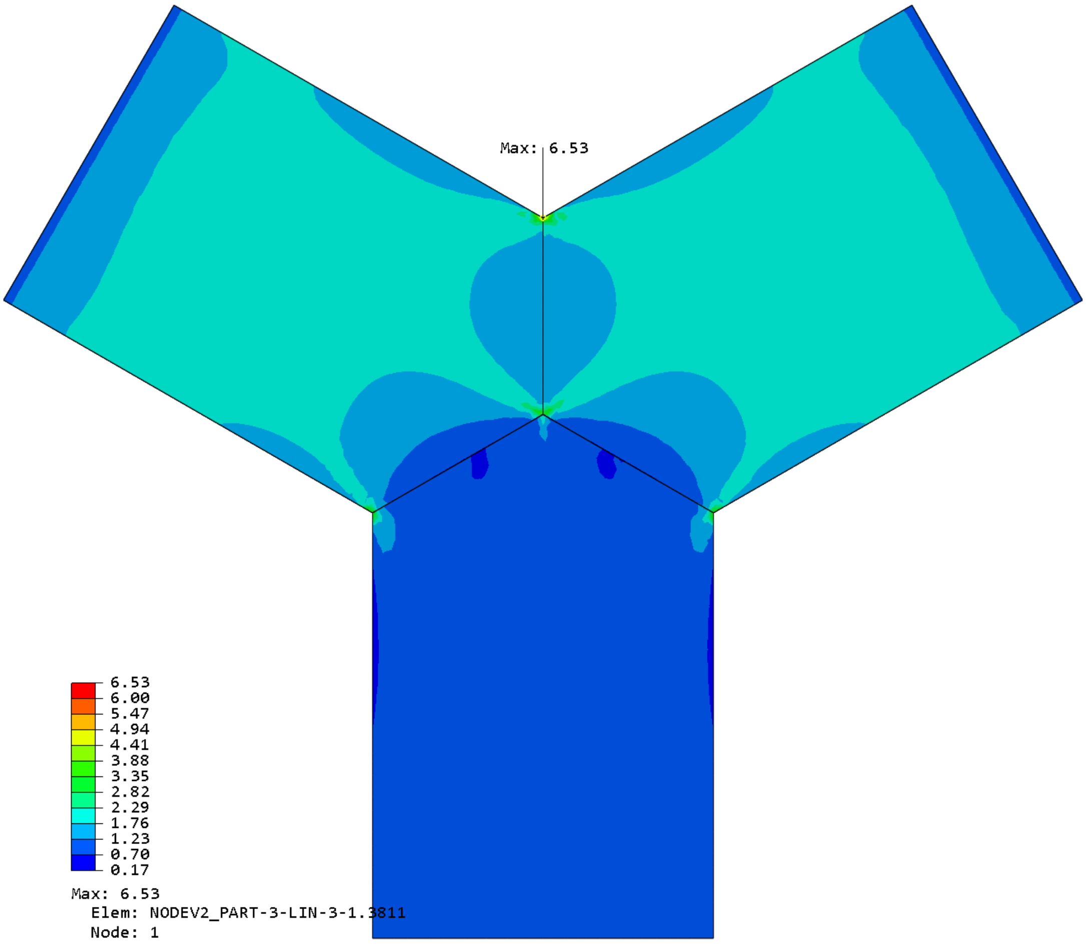


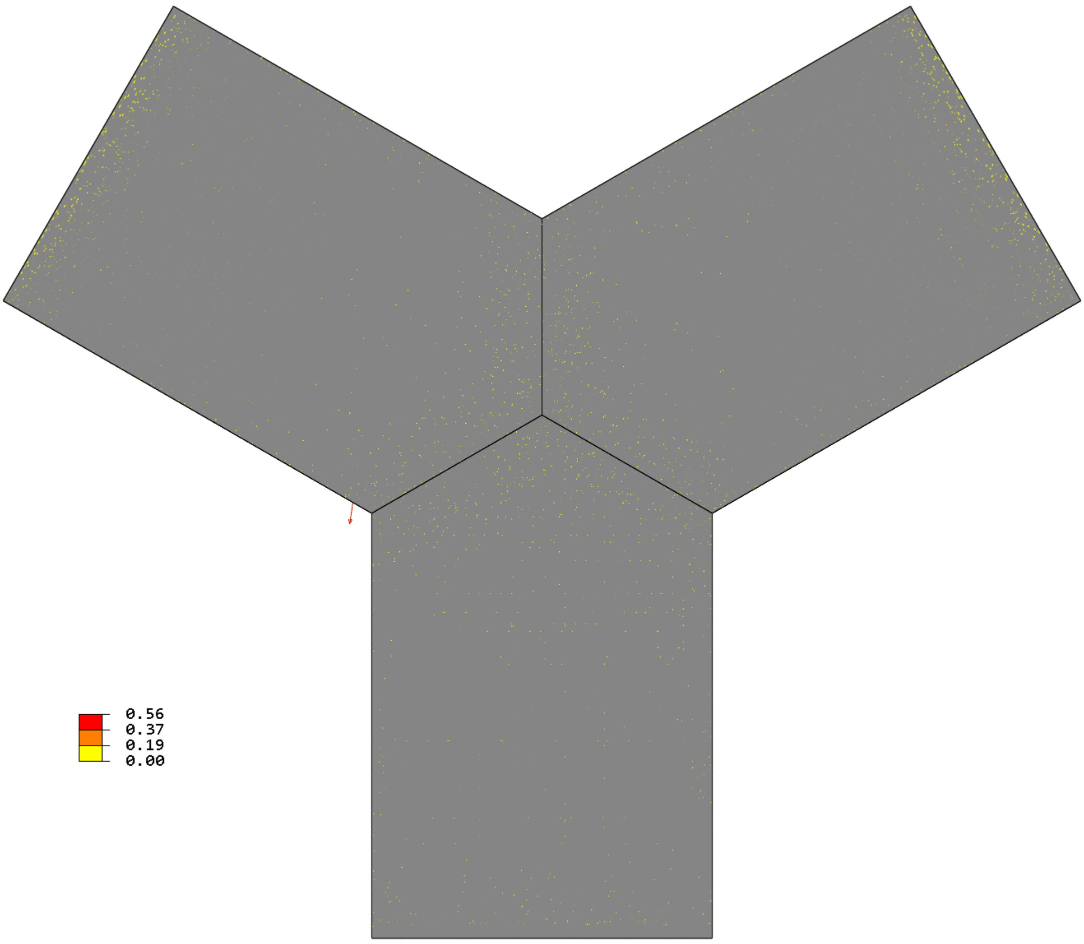

39.63
36.33
33.03
29.73
26.43
23.13
19.83
16.53
13.23
9.93
6.63
3.34
0.04
Max: 39.63
Elem: NODEV01-1PLY-2.2
Node: 1


37.68
25.12
12.56
0.00

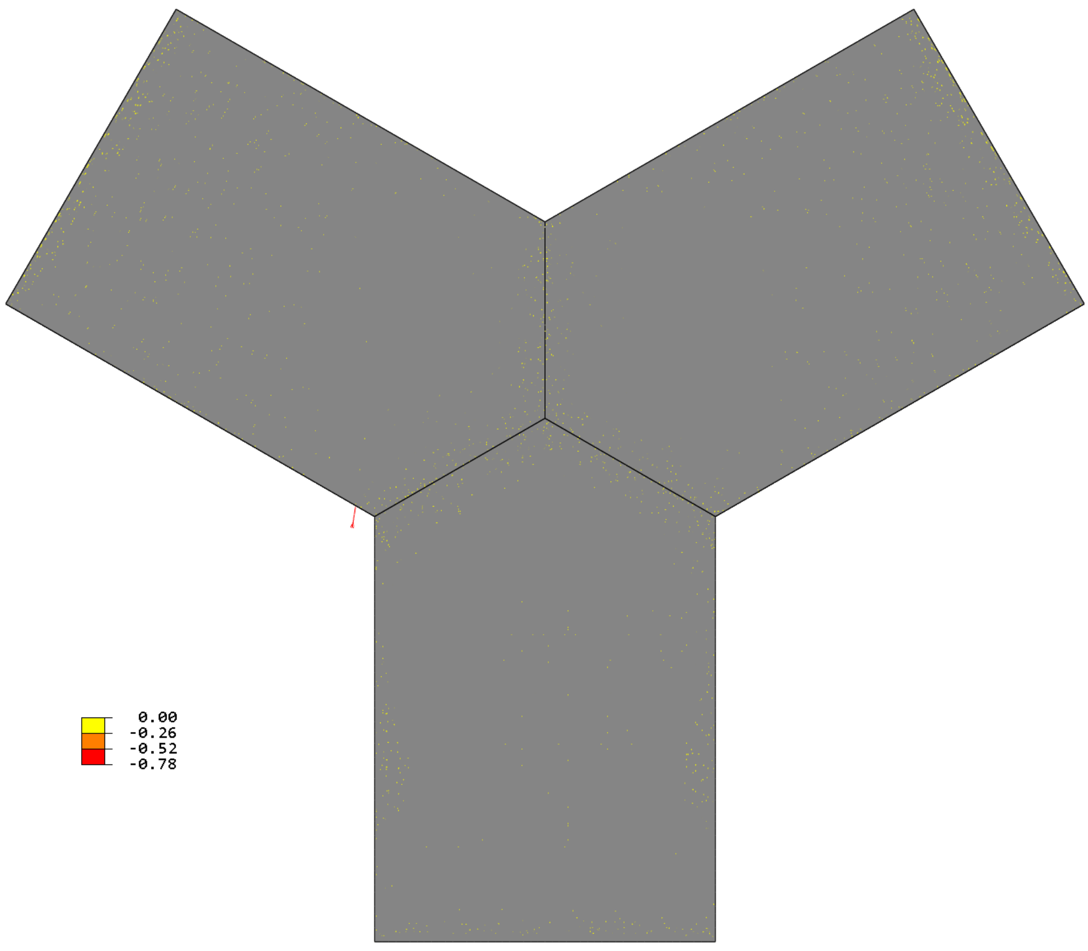
v2.1 7ply Compressive load

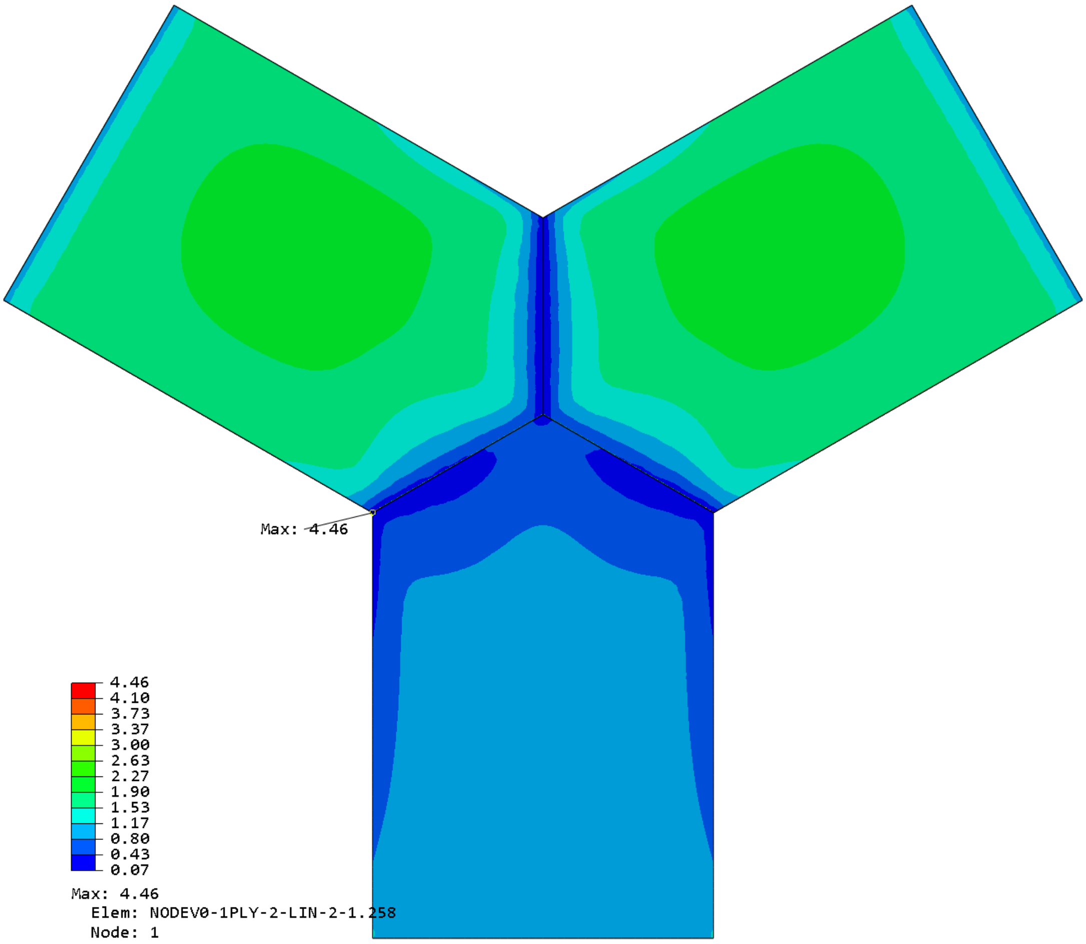


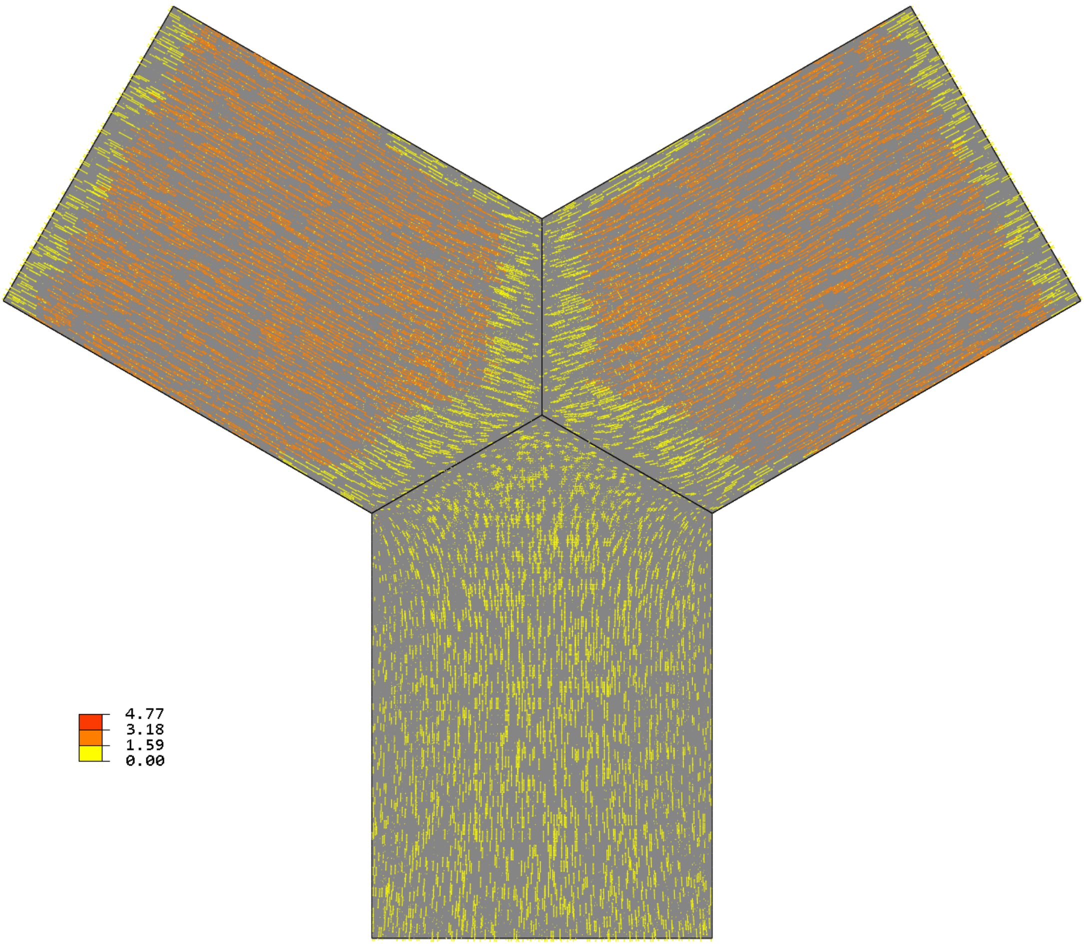

Max: 6.53
6.53
6.00
5.47
4.94
4.41
3.88
3.35
2.82
2.29
1.76
1.23
0.70
0.17
Max: 6.53
Elem: NODEV2_PART-3-LIN-3-1.3811
Node: 1


0.56
0.37
0.19
0.00

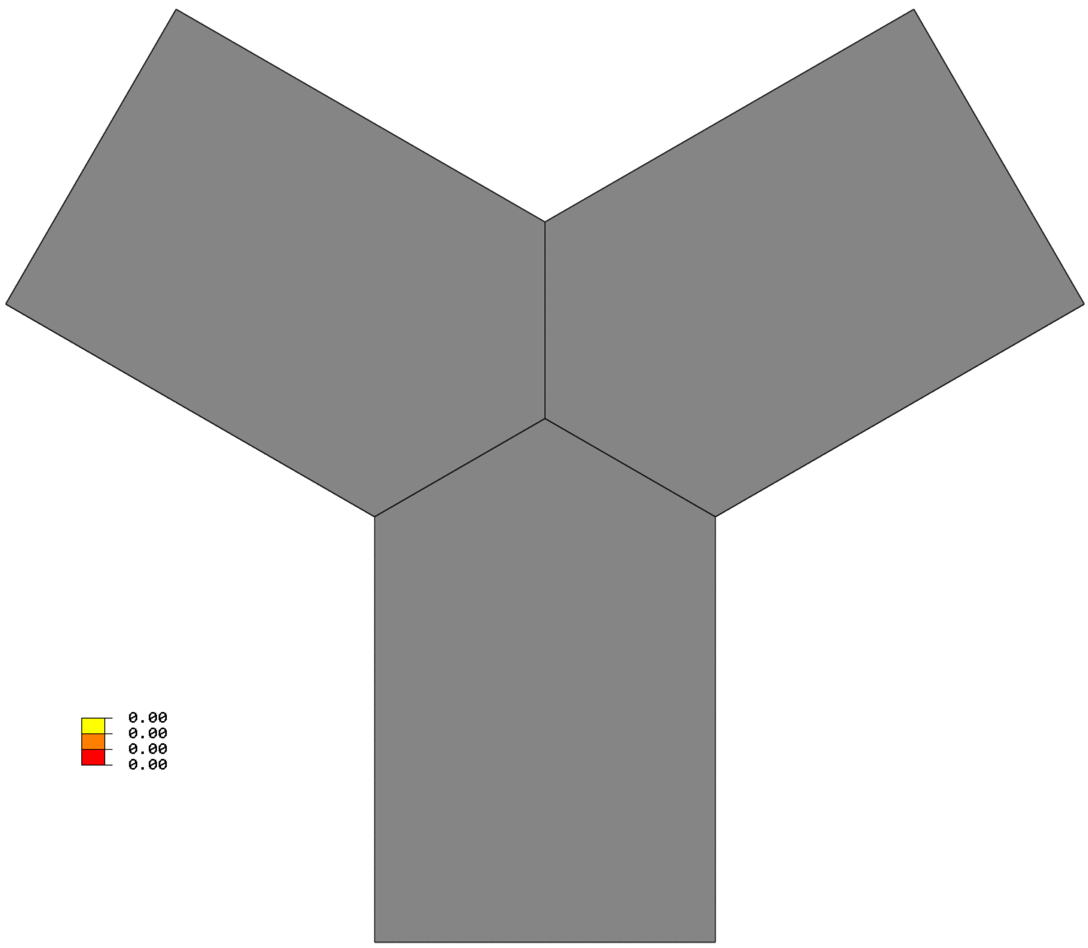
v2.1 7ply Tensile load

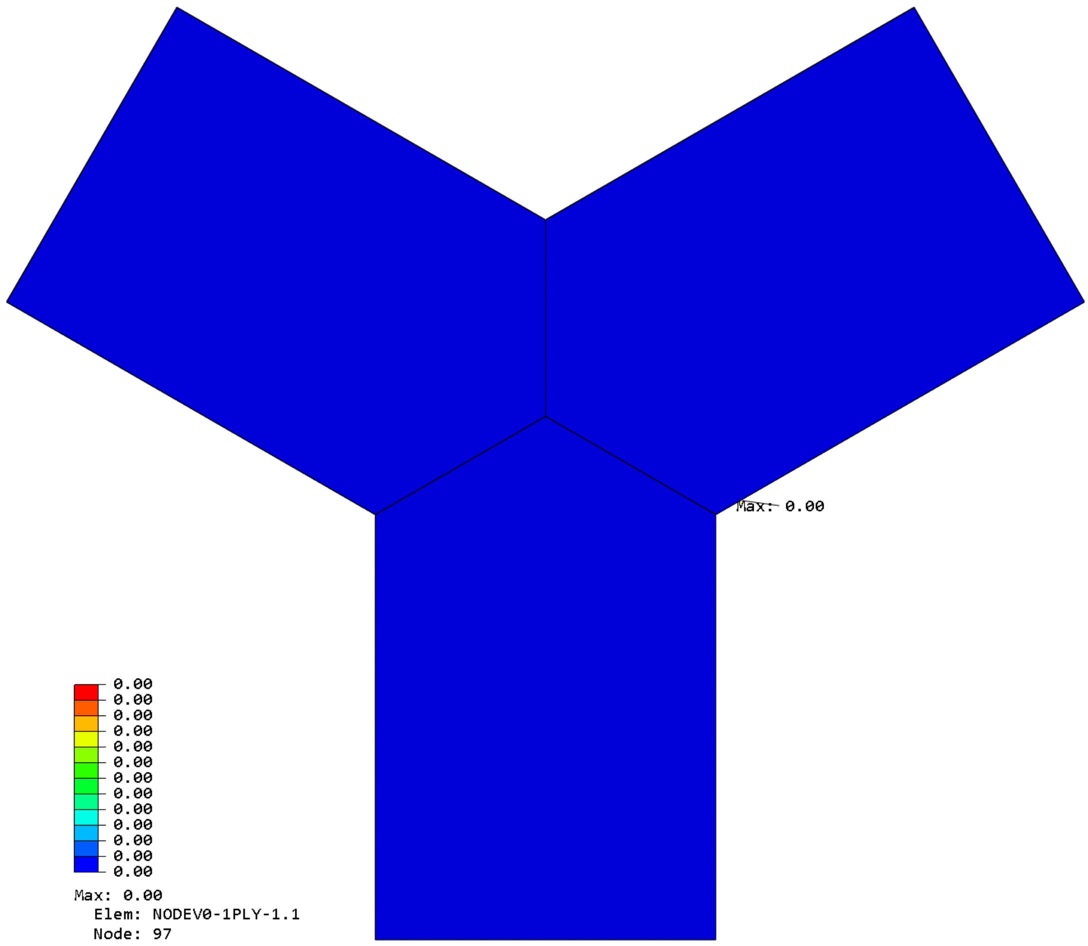


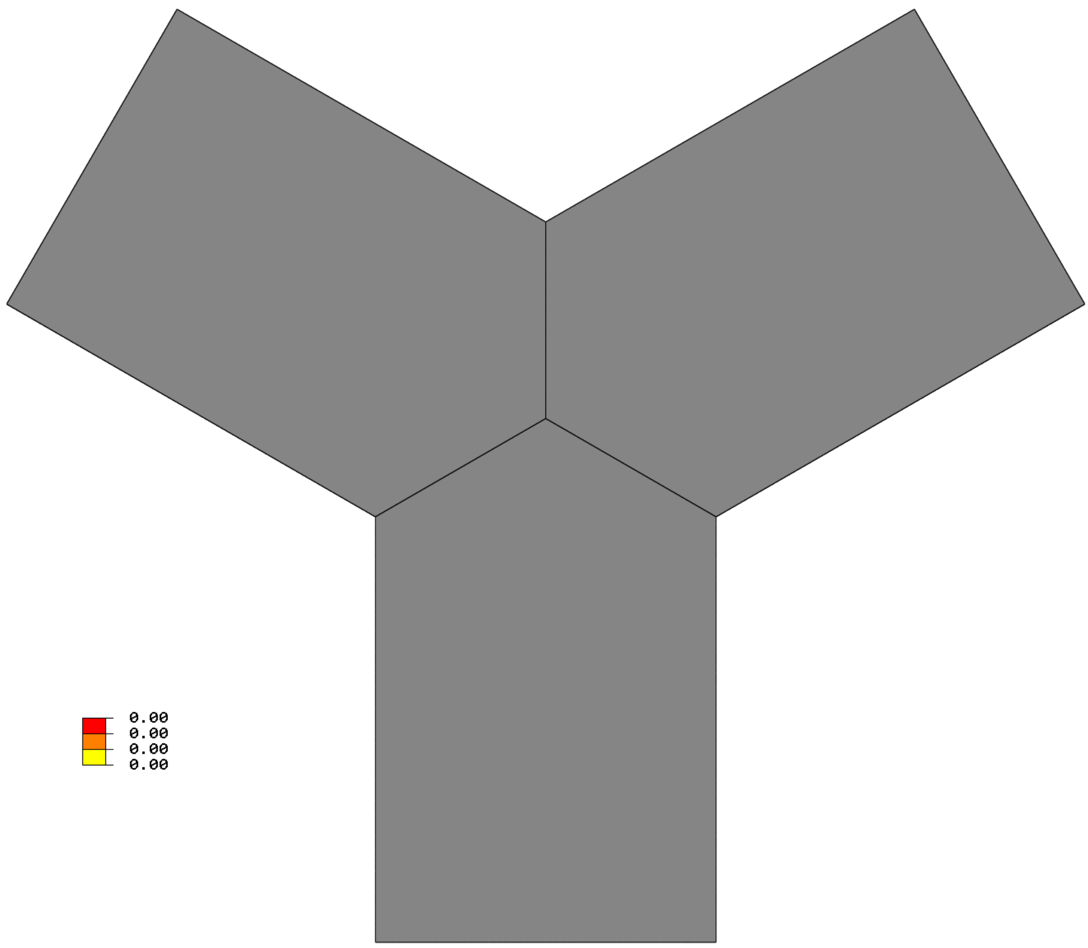

Max: 4.46
4.46
4.10
3.73
3.37
3.00
2.63
2.27
1.90
1.53
1.17
0.80
0.43
0.07
Max: 4.46
Elem: NODEV0-1PLY-2-LIN-2-1.258
Node: 1


4.77
3.18
1.59
0.00

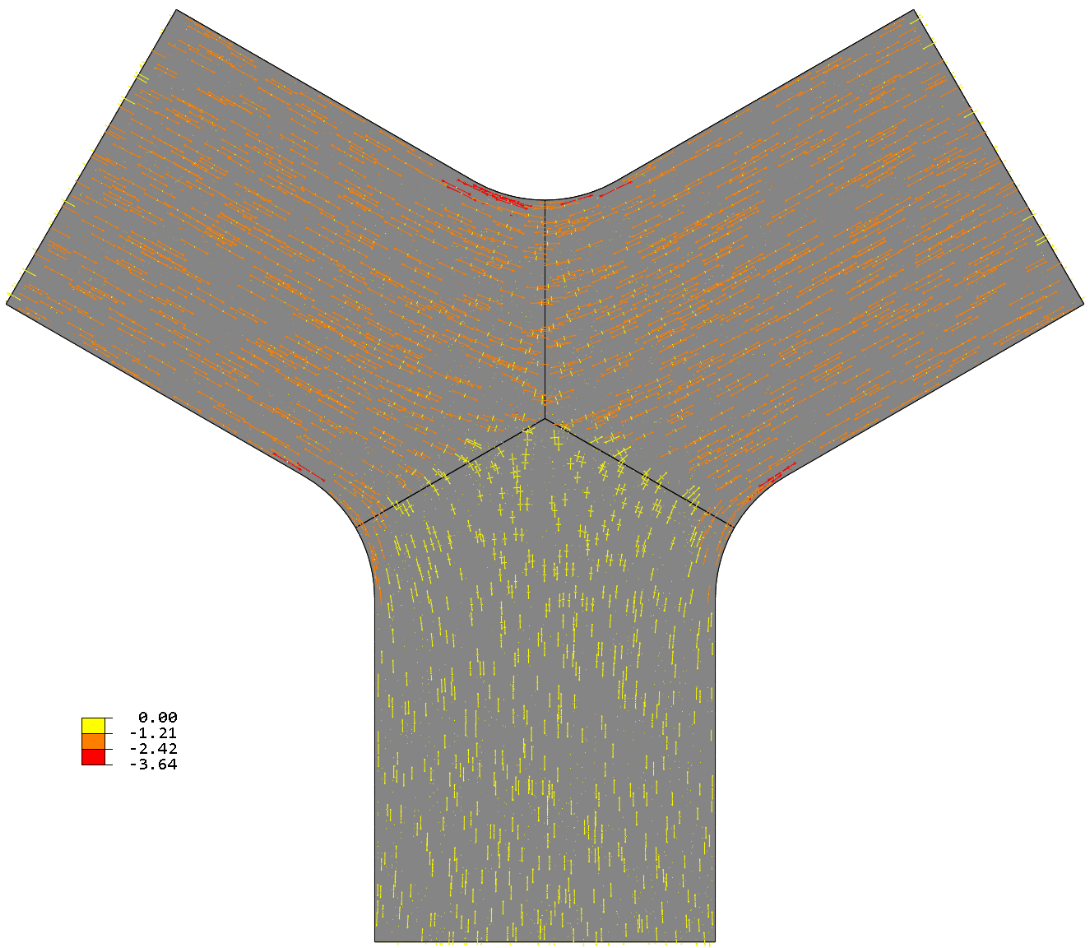
v2.1 7ply Compressive + tensile load

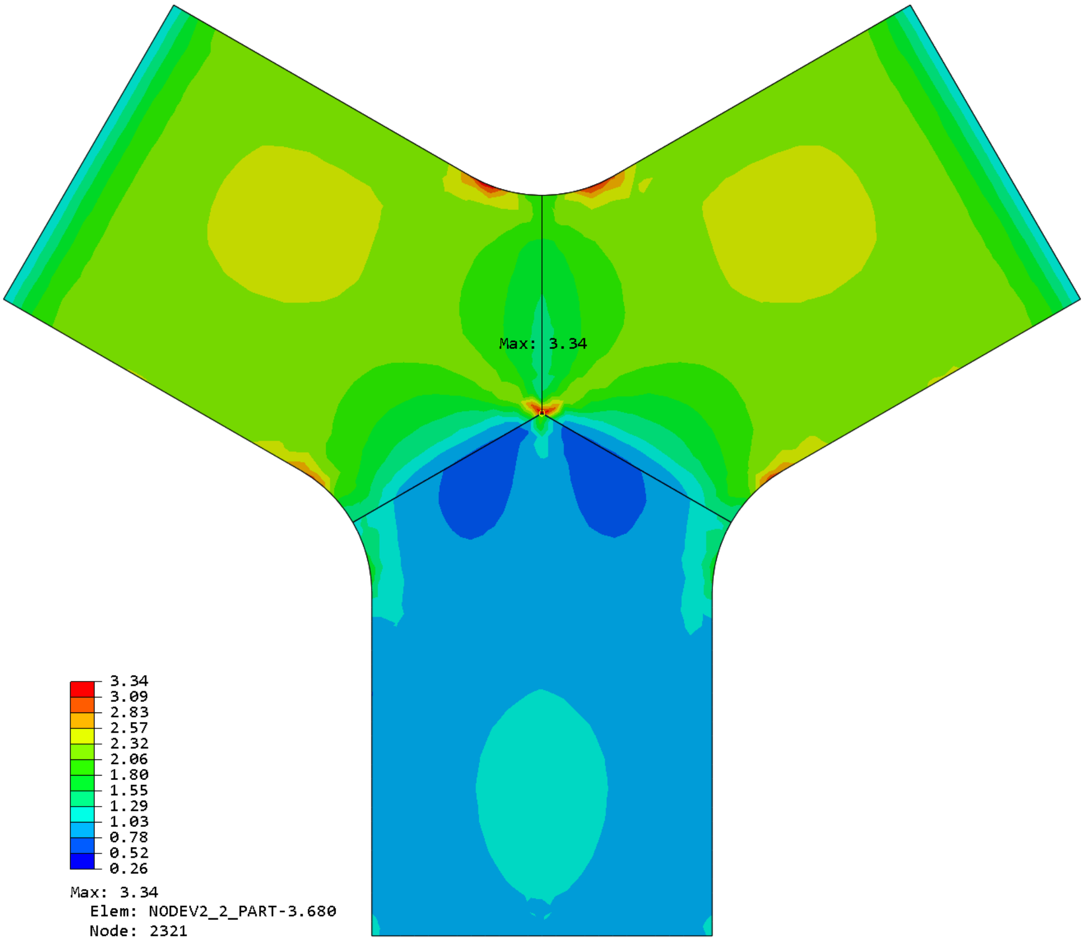


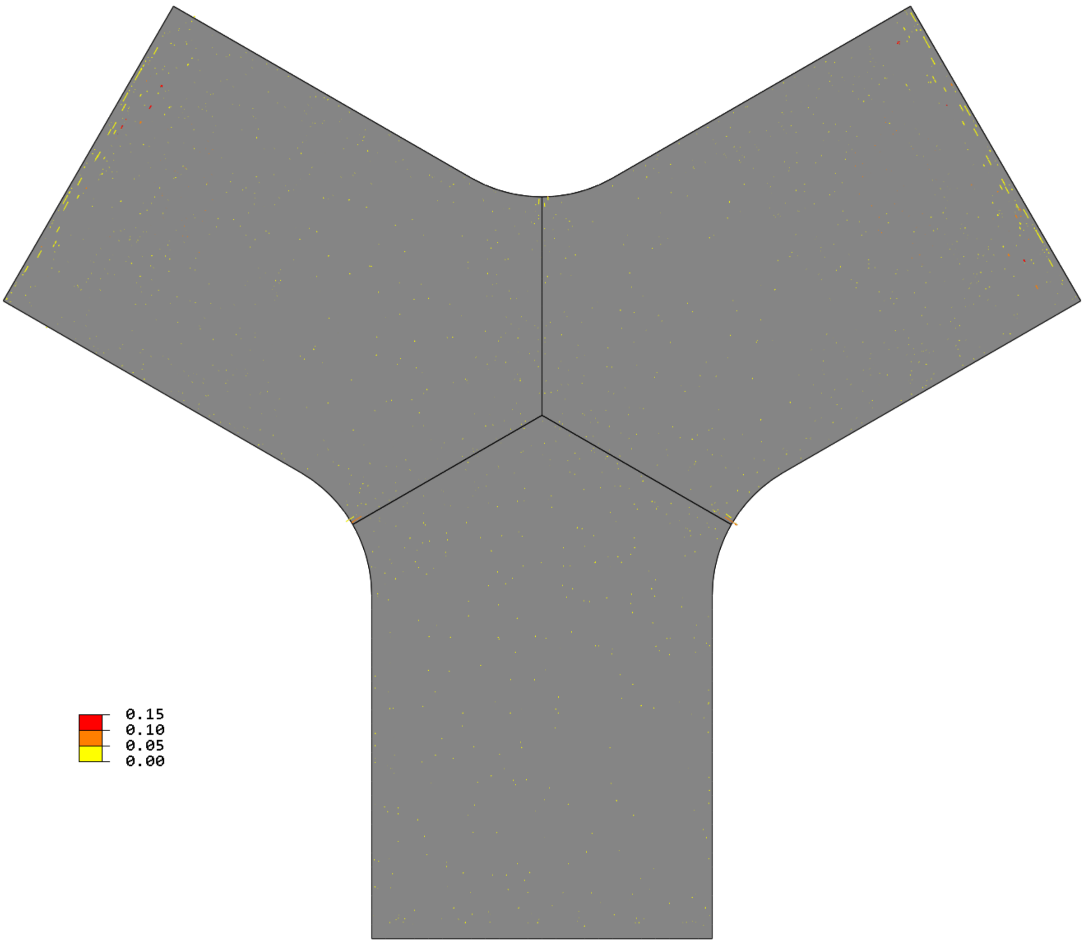

Max: 0.00
0.00
0.00
0.00
0.00
0.00
0.00
0.00
0.00
0.00
0.00
0.00
0.00
0.00
Max: 0.00
Elem: NODEV0-1PLY-1.1
Node: 97


0.00
0.00
0.00
0.00

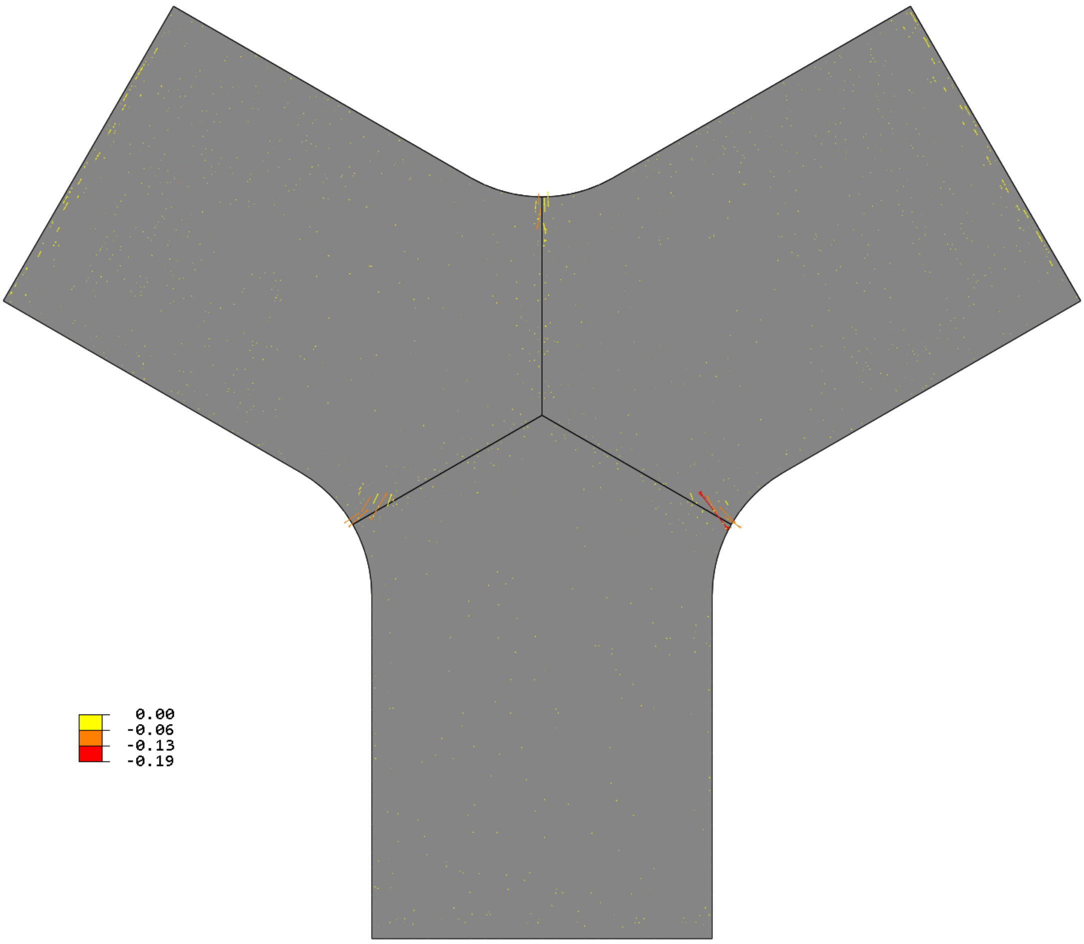
v2.2 3ply Compressive load

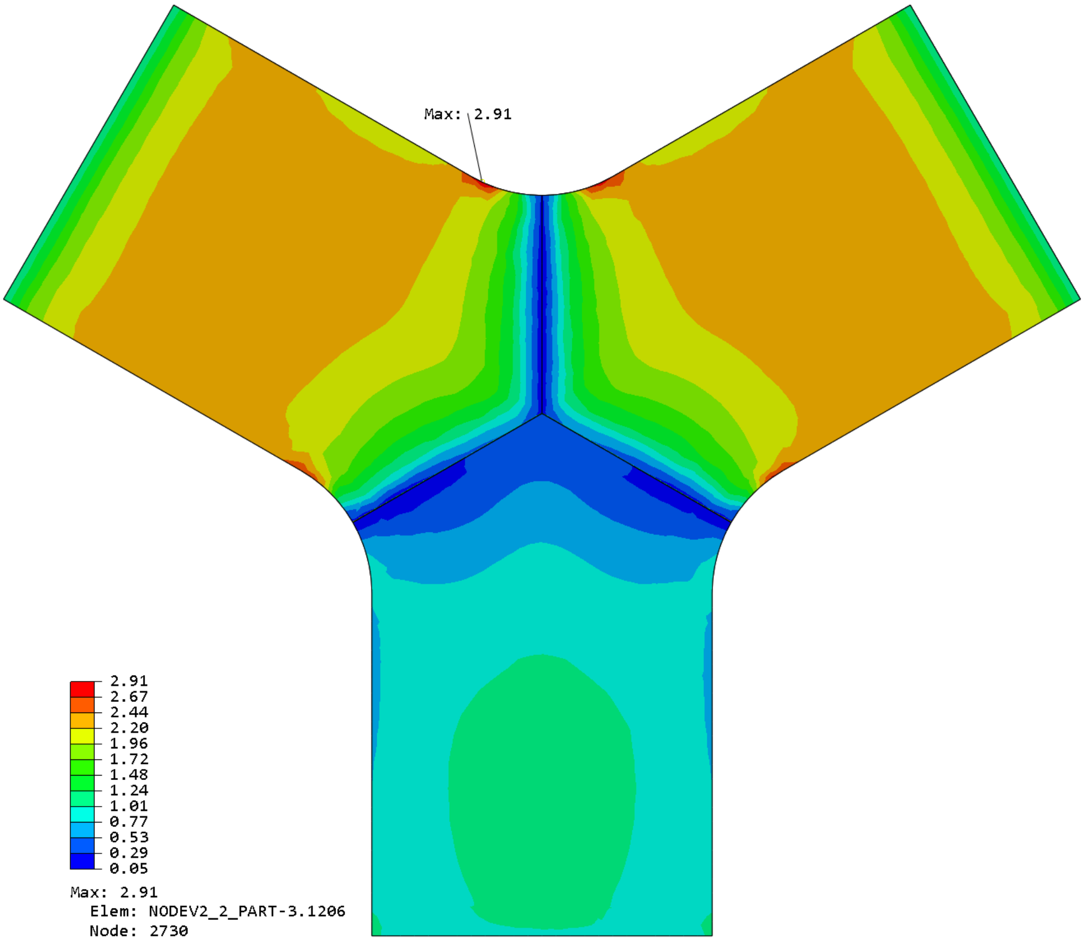


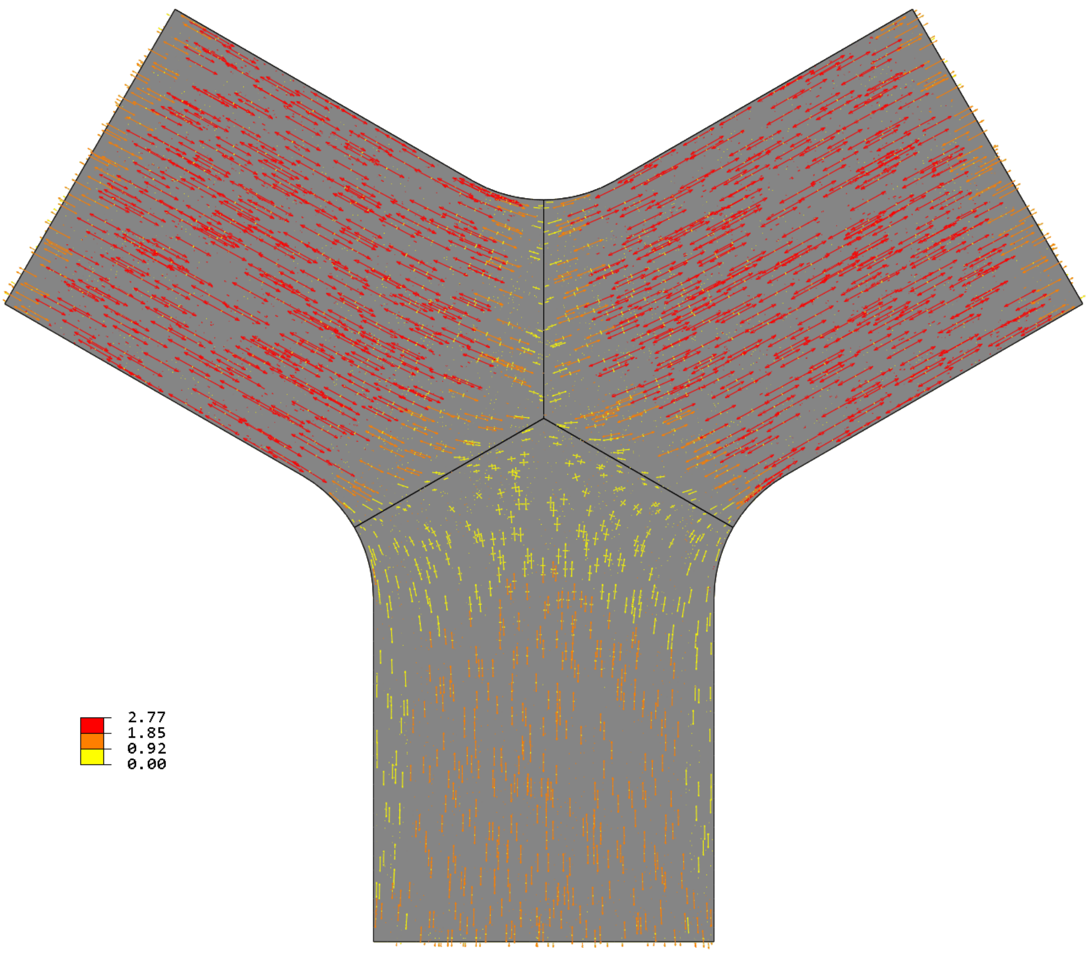

Max: 3.34
3.34
3.09
2.83
2.57
2.32
2.06
1.80
1.55
1.29
1.03
0.78
0.52
0.26
Max: 3.34
Elem: NODEV2_2_PART-3.680
Node: 2321


0.15
0.10
0.05
0.00

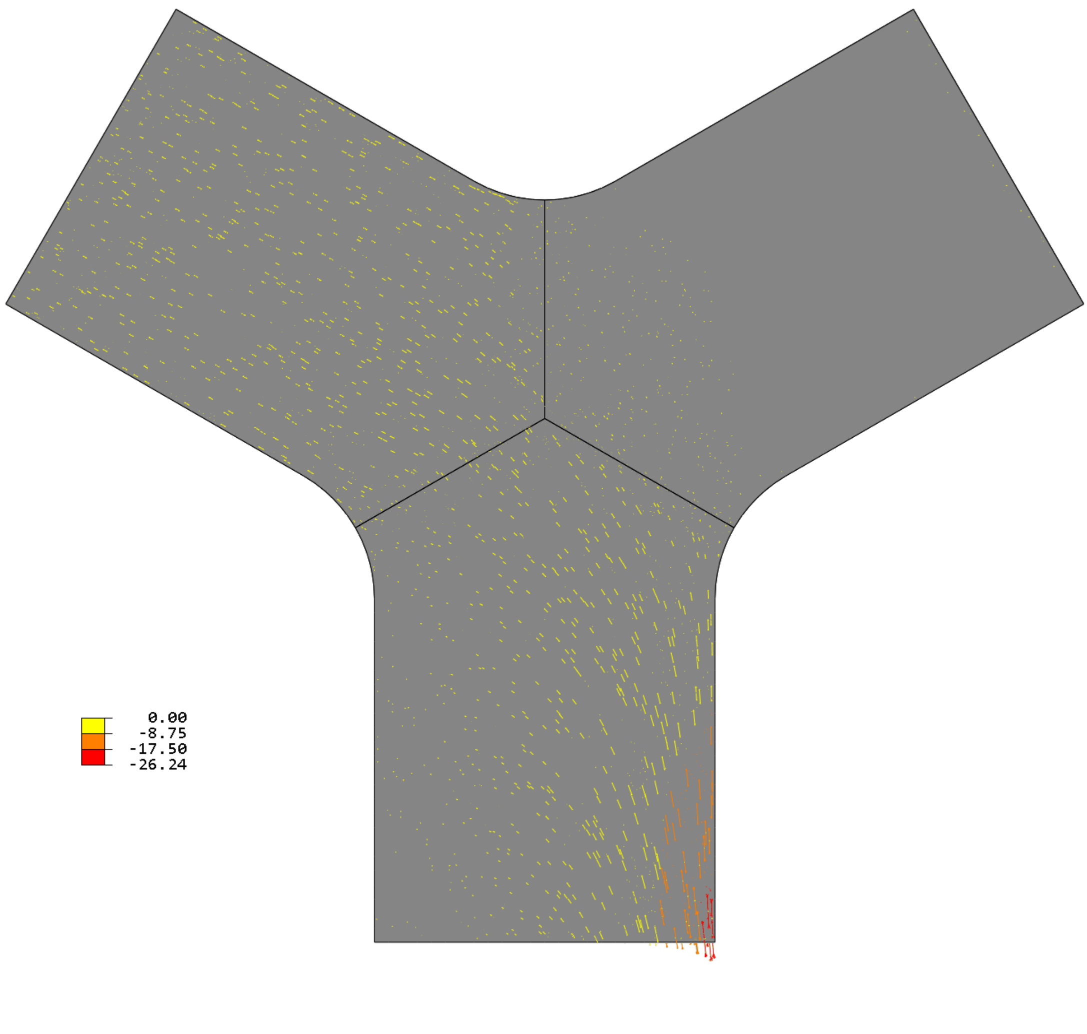
v2.2 3ply Tensile load

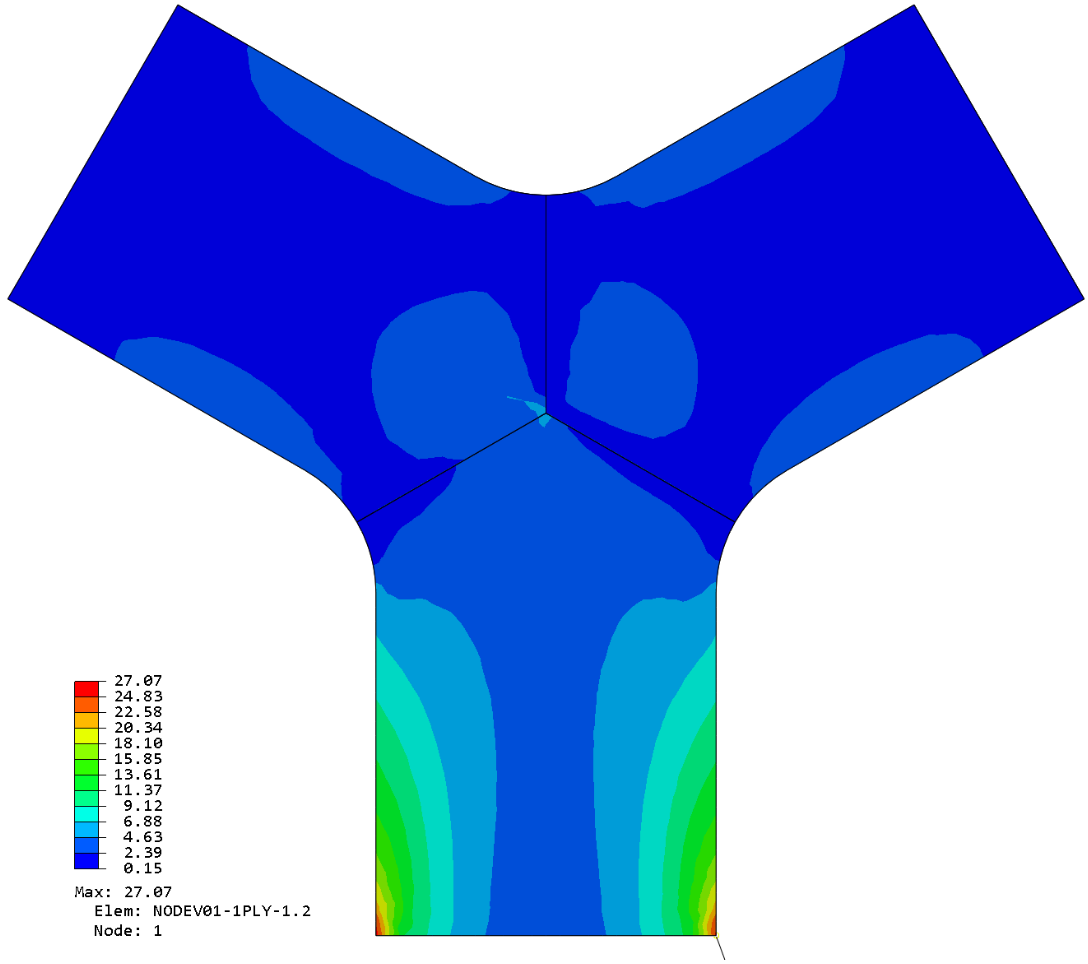


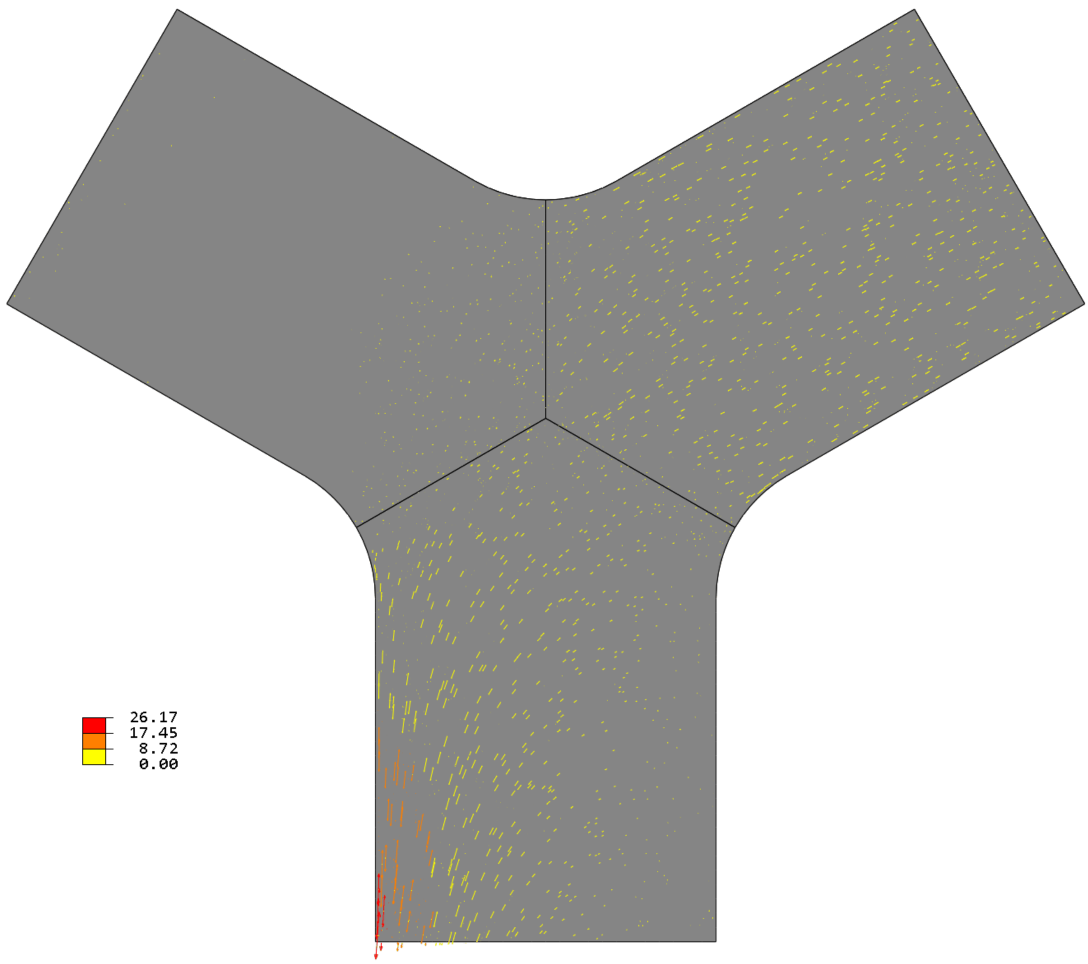

Max: 2.91
2.91
2.67
2.44
2.20
1.96
1.72
1.48
1.24
1.01
0.77
0.53
0.29
0.05
Max: 2.91
Elem: NODEV2_2_PART-3.1206
Node: 2730


2.77
1.85
0.92
0.00

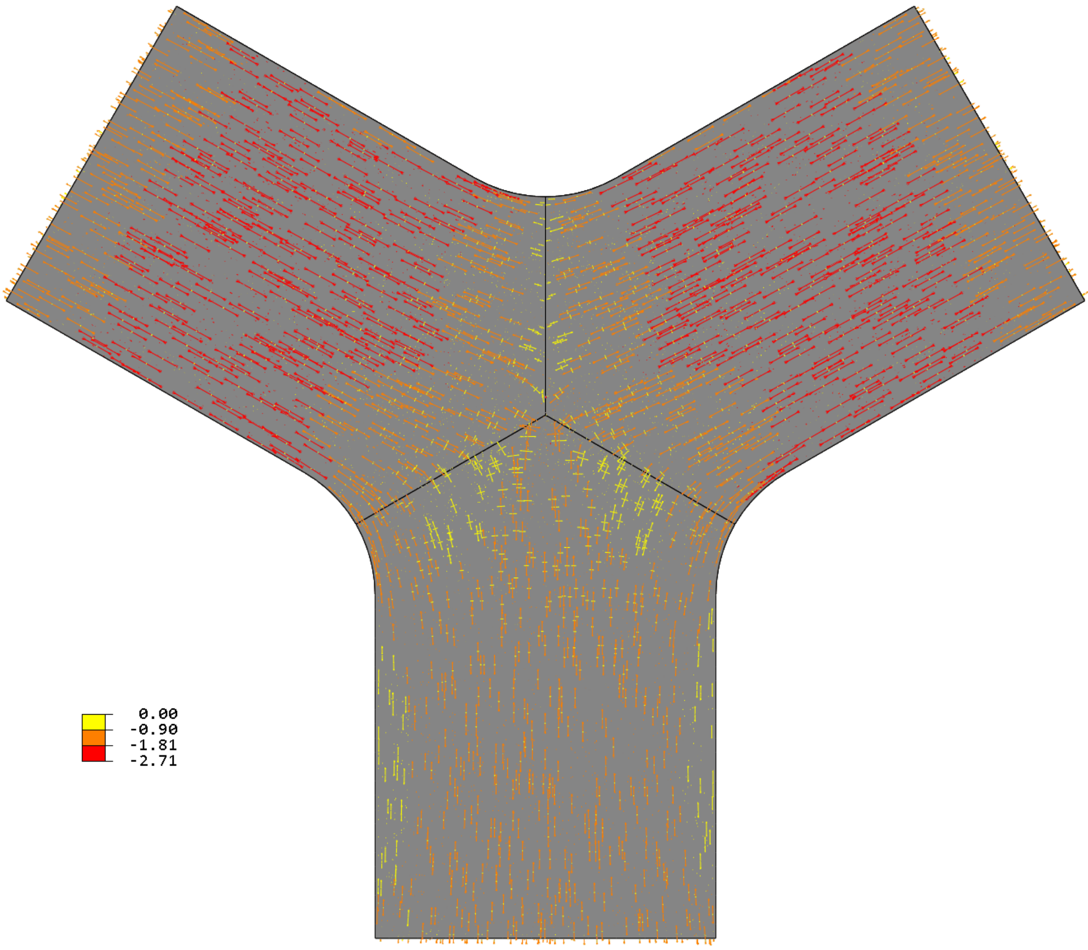
v2.2 3ply Compressive + tensile load

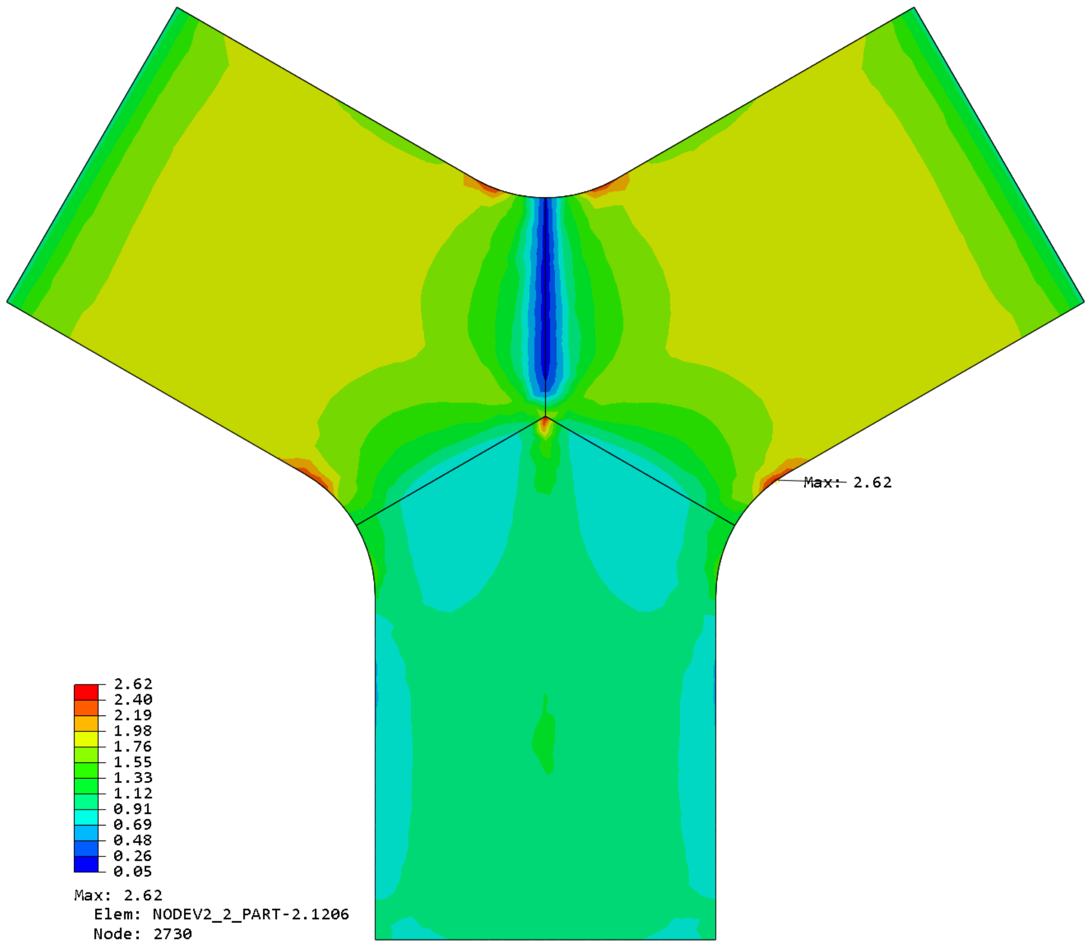


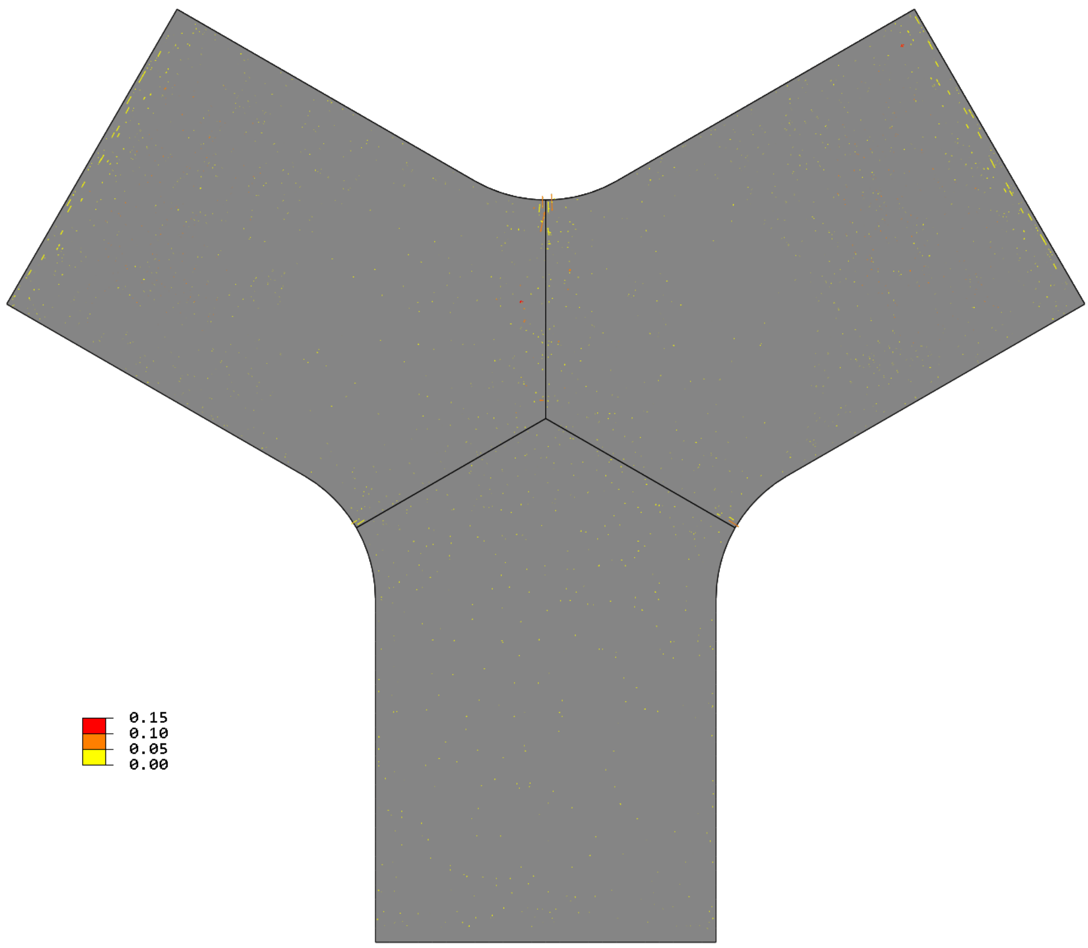

27.07
24.83
22.58
20.34
18.10
15.85
13.61
11.37
9.12
6.88
4.63
2.39
0.15
Max: 27.07
Elem: NODEV01-1PLY-1.2
Node: 1


26.17
17.45
8.72
0.00

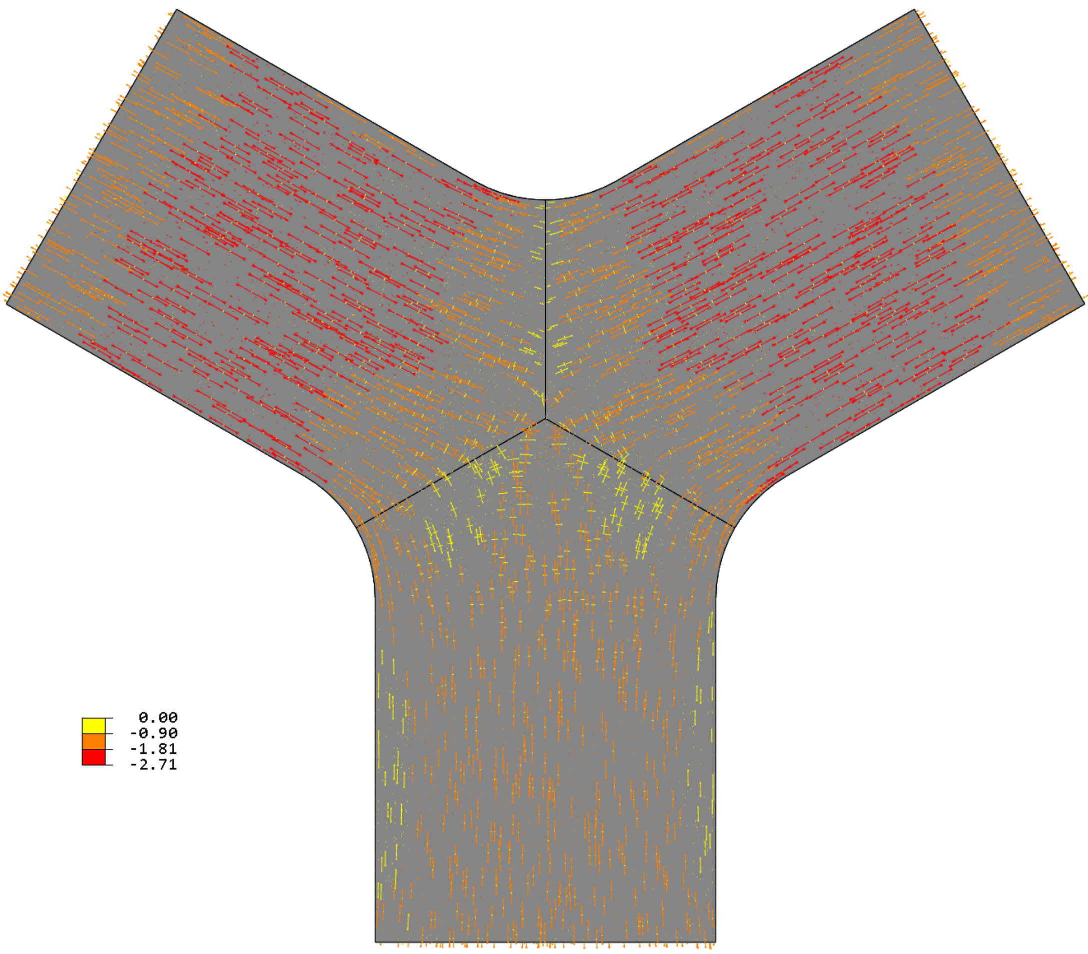
v2.2 7ply Compressive load

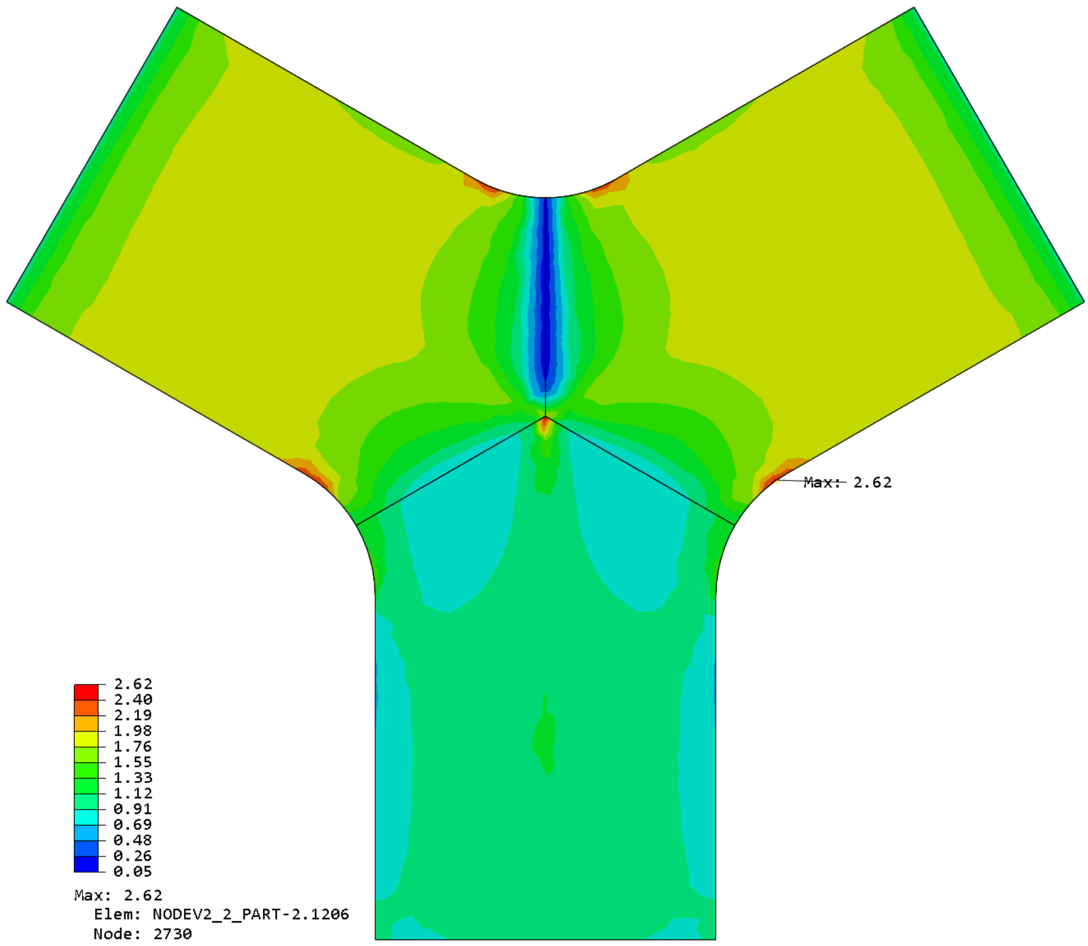


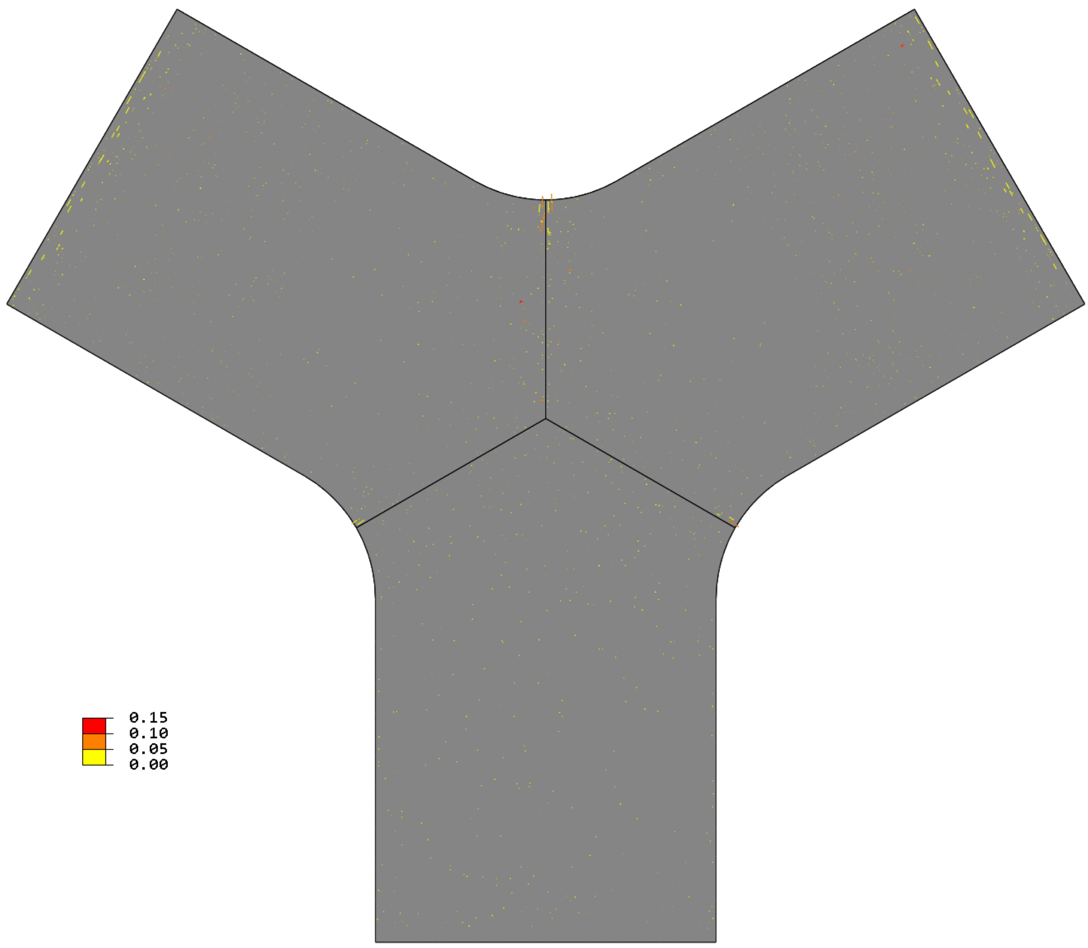

Max: 2.62
2.62
2.40
2.19
1.98
1.76
1.55
1.33
1.12
0.91
0.69
0.48
0.26
0.05
Max: 2.62
Elem: NODEV2_2_PART-2.1206
Node: 2730


0.15
0.10
0.05
0.00

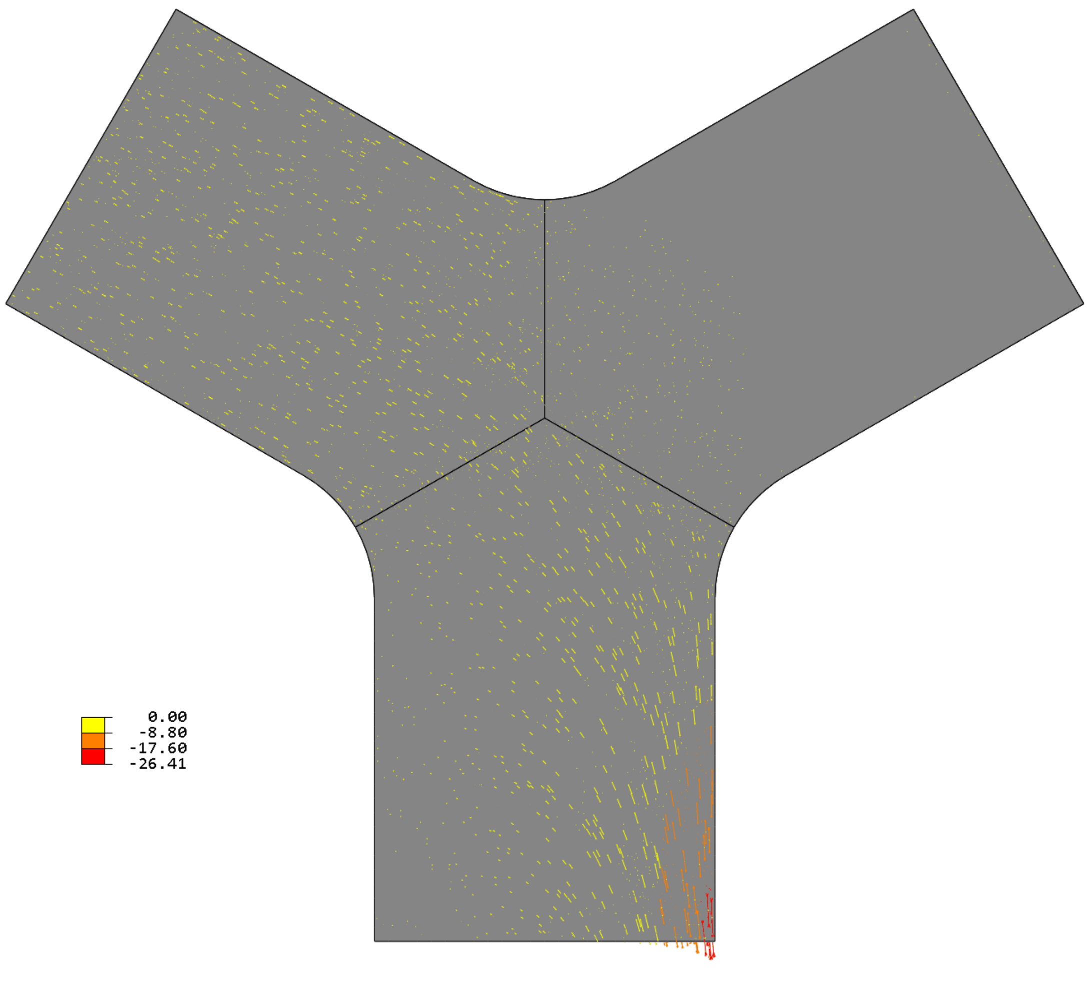
v2.2 7ply Tensile load

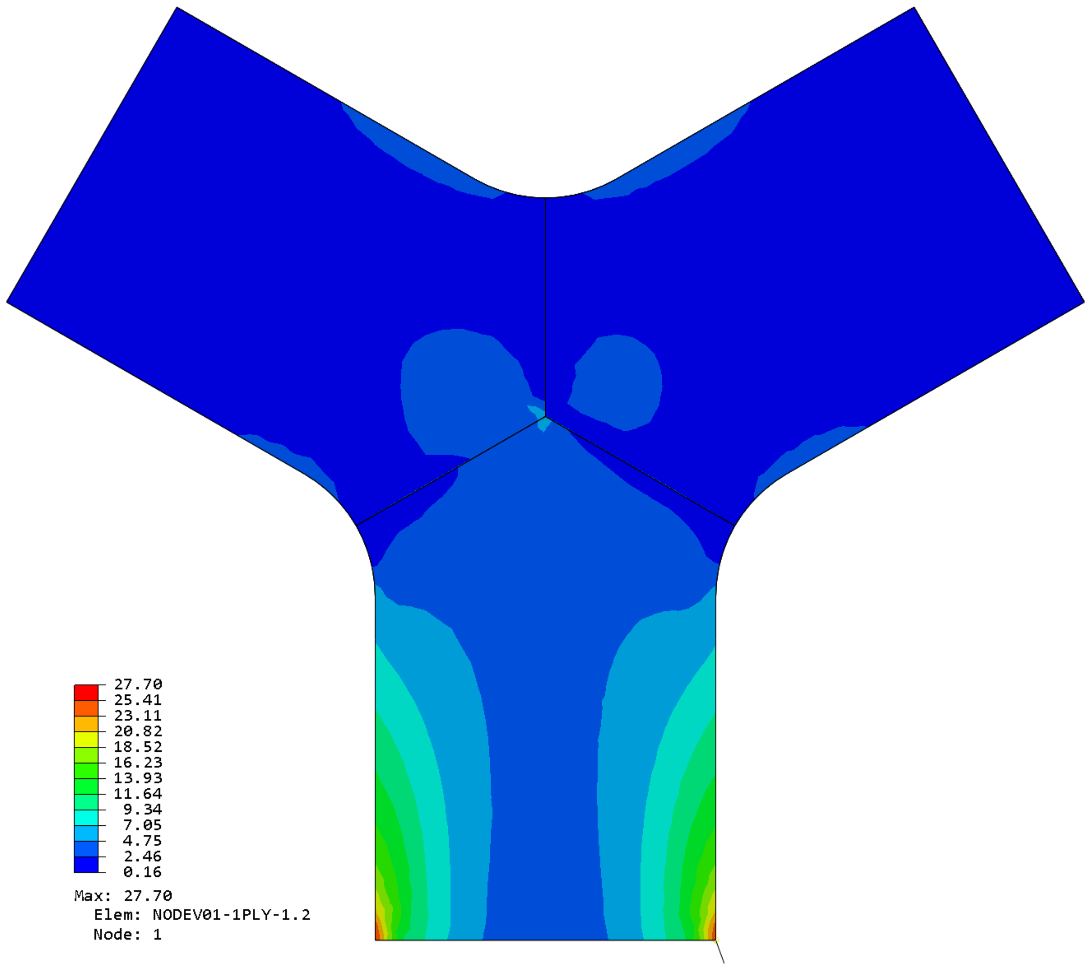


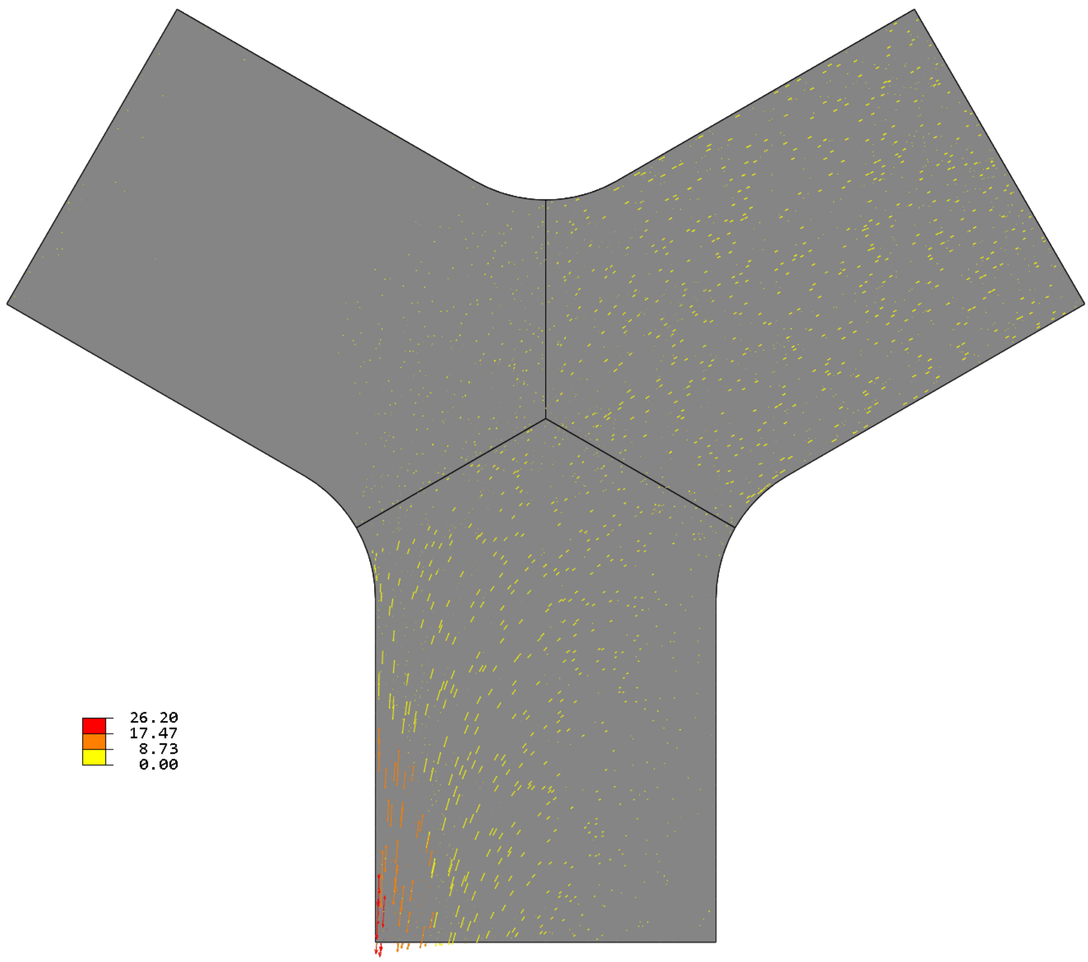

Max: 2.62
2.62
2.40
2.19
1.98
1.76
1.55
1.33
1.12
0.91
0.69
0.48
0.26
0.05
Max: 2.62
Elem: NODEV2_2_PART-2.1206
Node: 2730


0.15
0.10
0.05
0.00

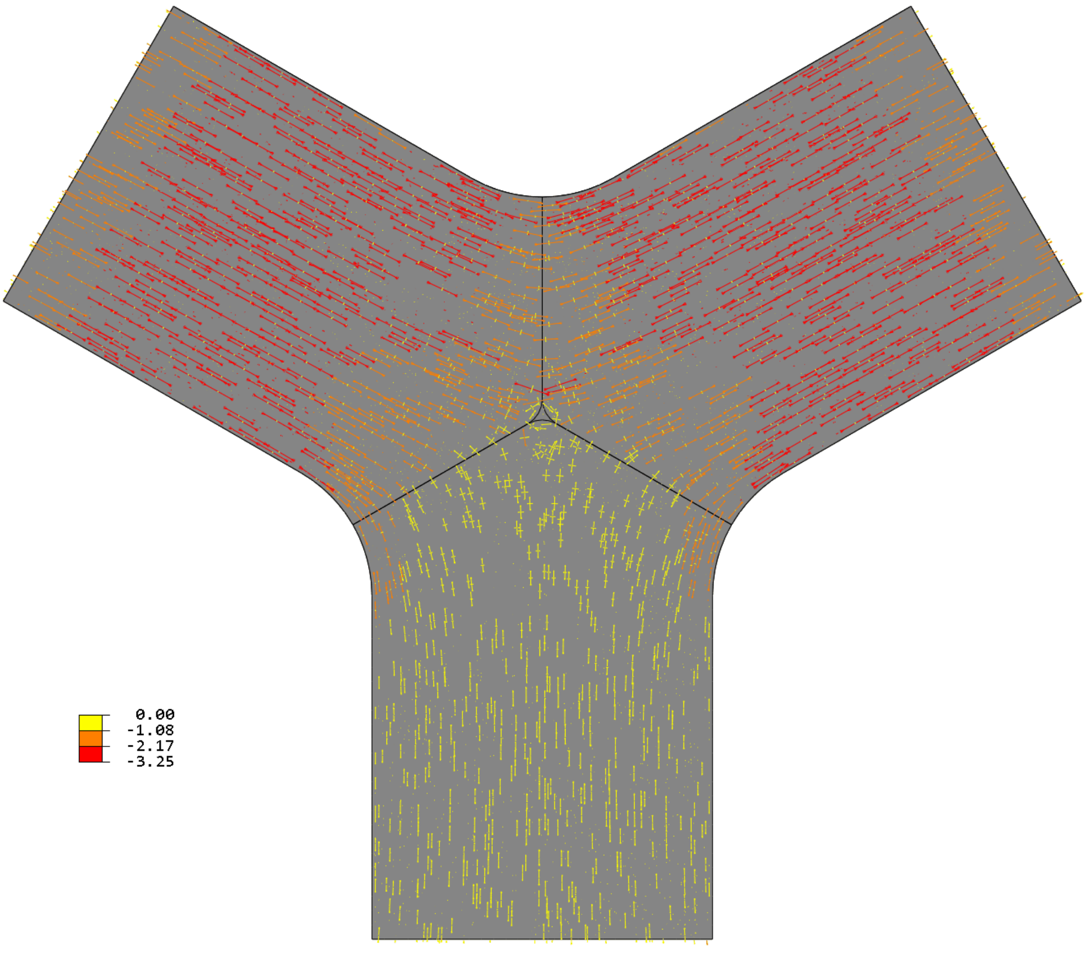
v2.2 7ply Compressive + tensile load

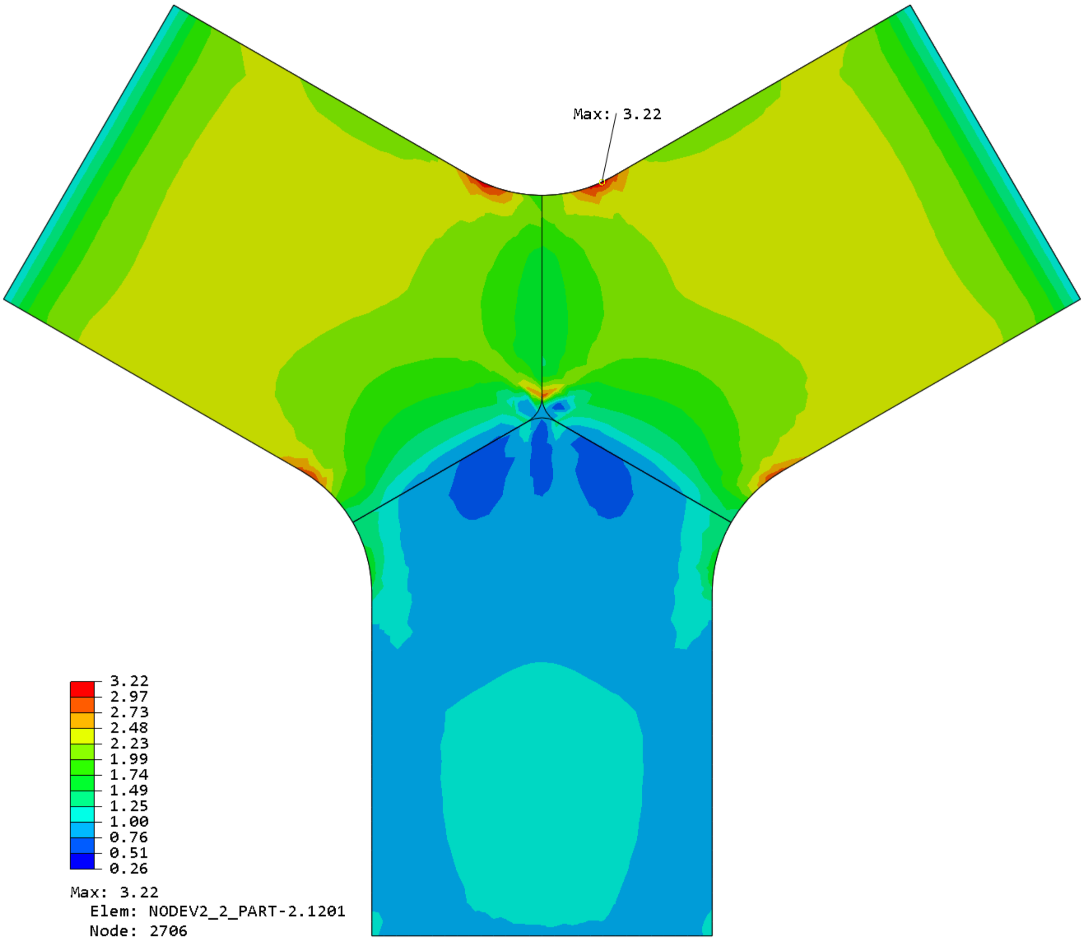


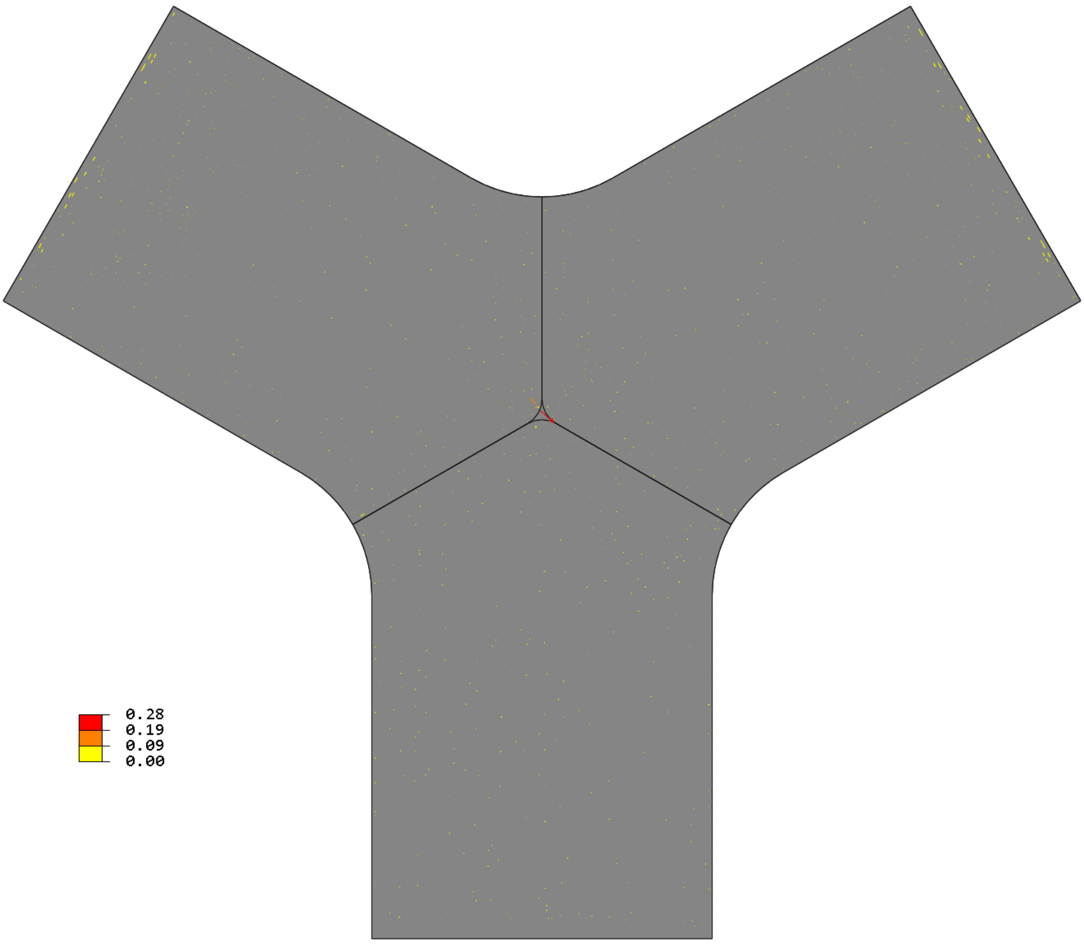

27.70
25.41
23.11
20.82
18.52
16.23
13.93
11.64
9.34
7.05
4.75
2.46
0.16
Max: 27.70
Elem: NODEV01-1PLY-1.2
Node: 1


26.20
17.47
8.73
0.00

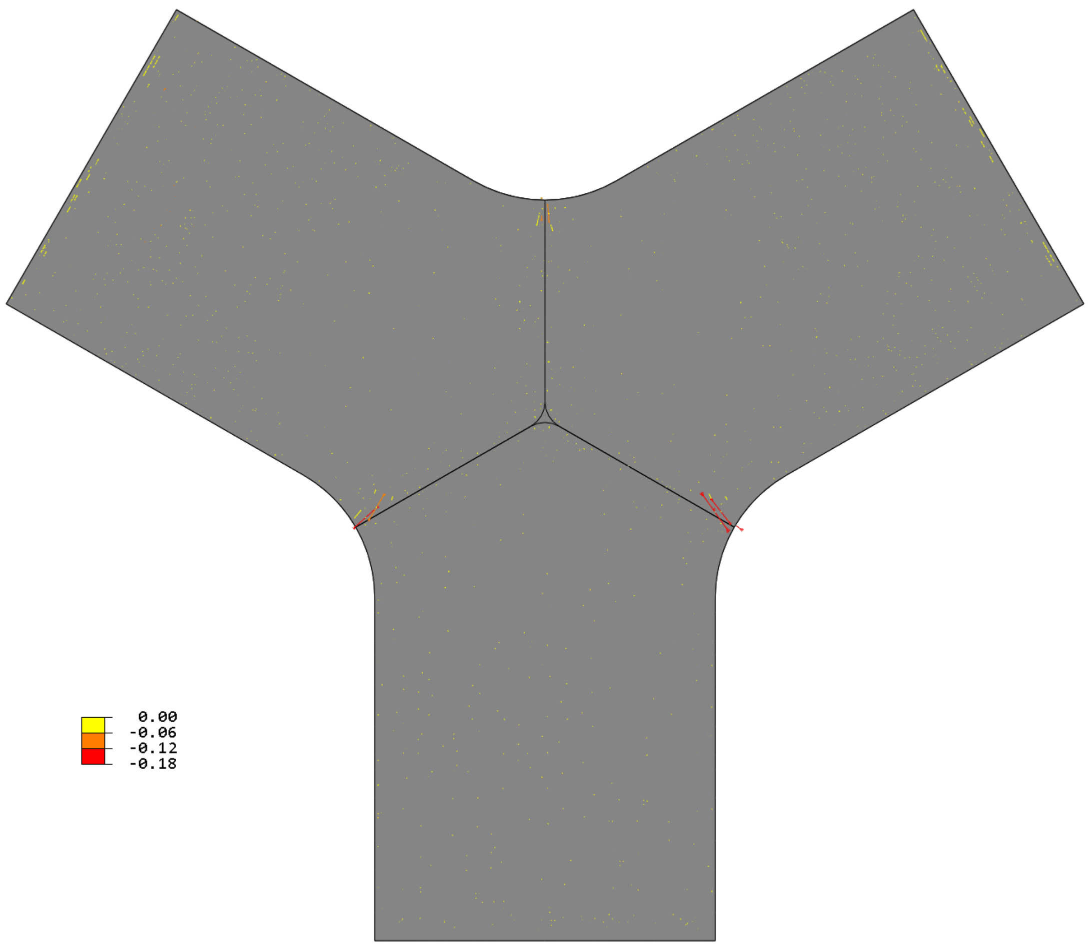
v2.3 3ply Compressive load

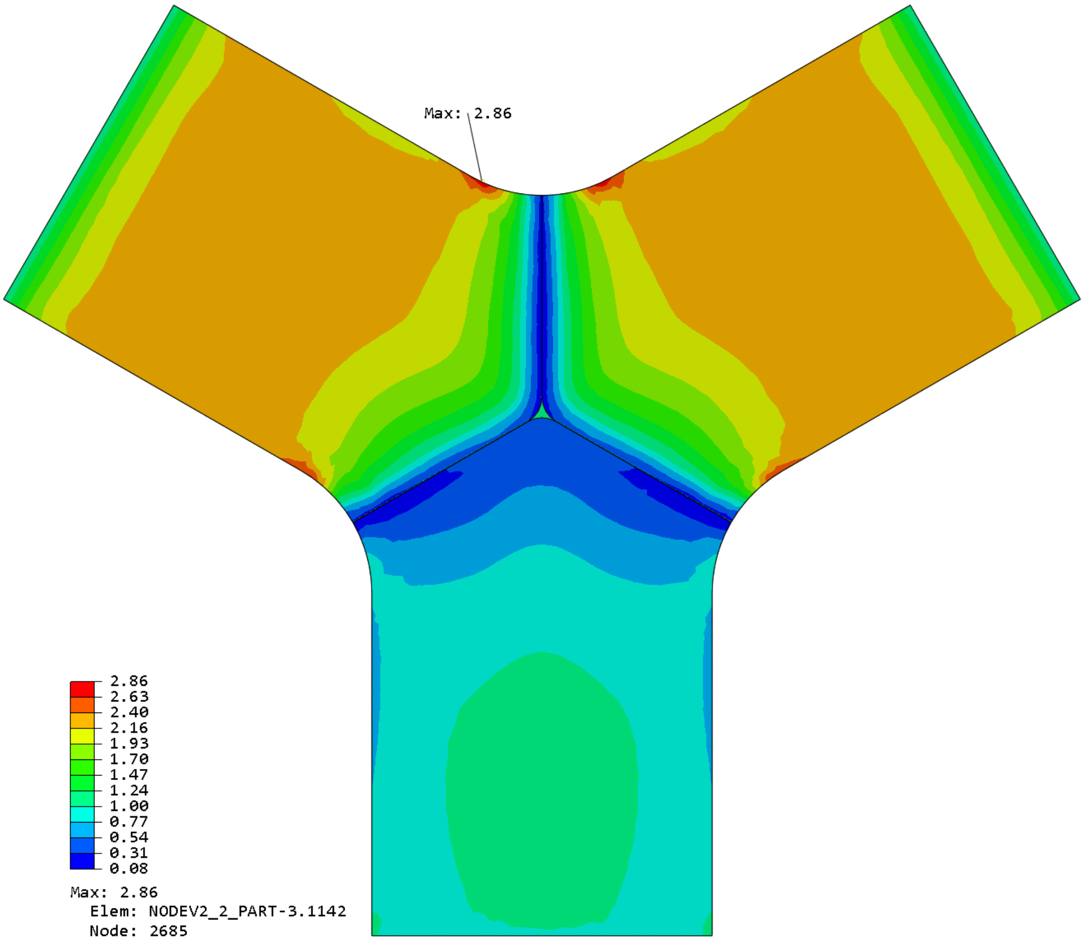


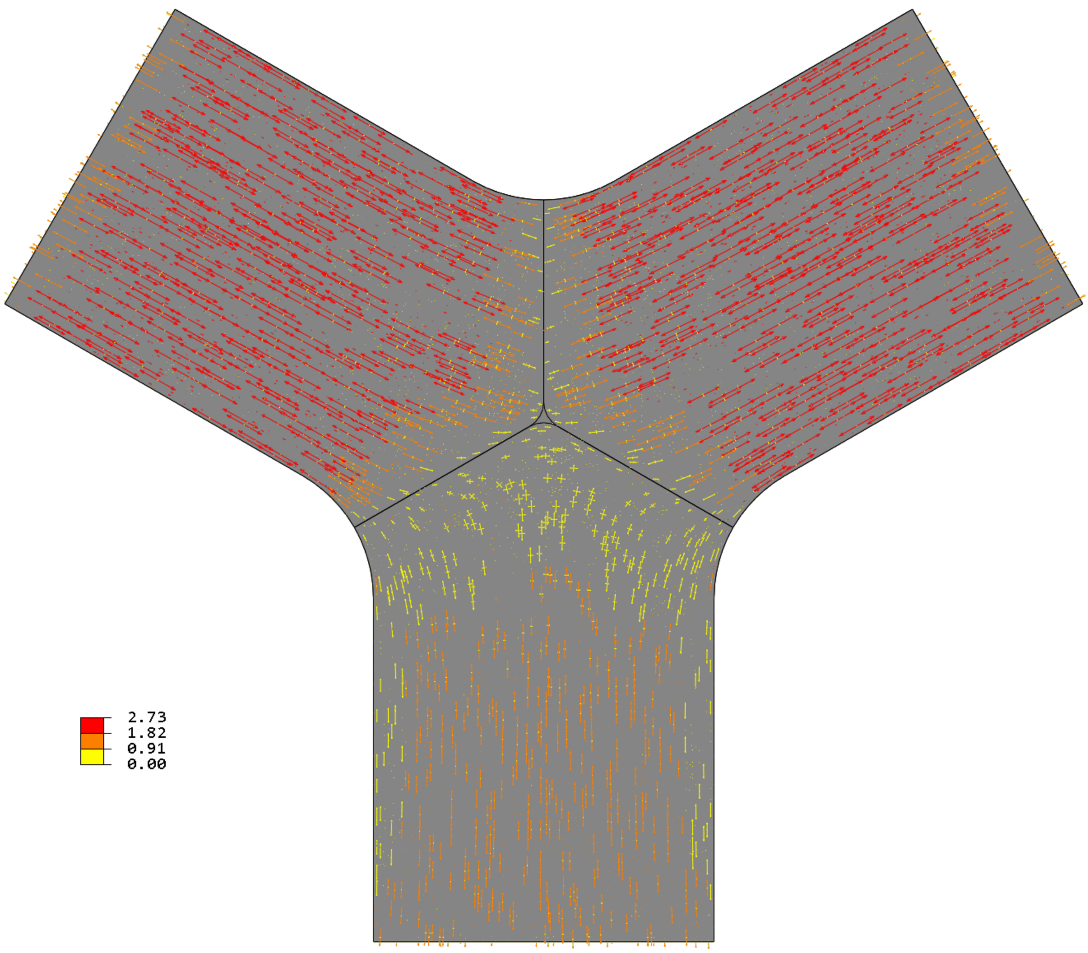

Max: 3.22
3.22
2.97
2.73
2.48
2.23
1.99
1.74
1.49
1.25
1.00
0.76
0.51
0.26
Max: 3.22
Elem: NODEV2_2_PART-2.1201
Node: 2706


0.28
0.19
0.09
0.00

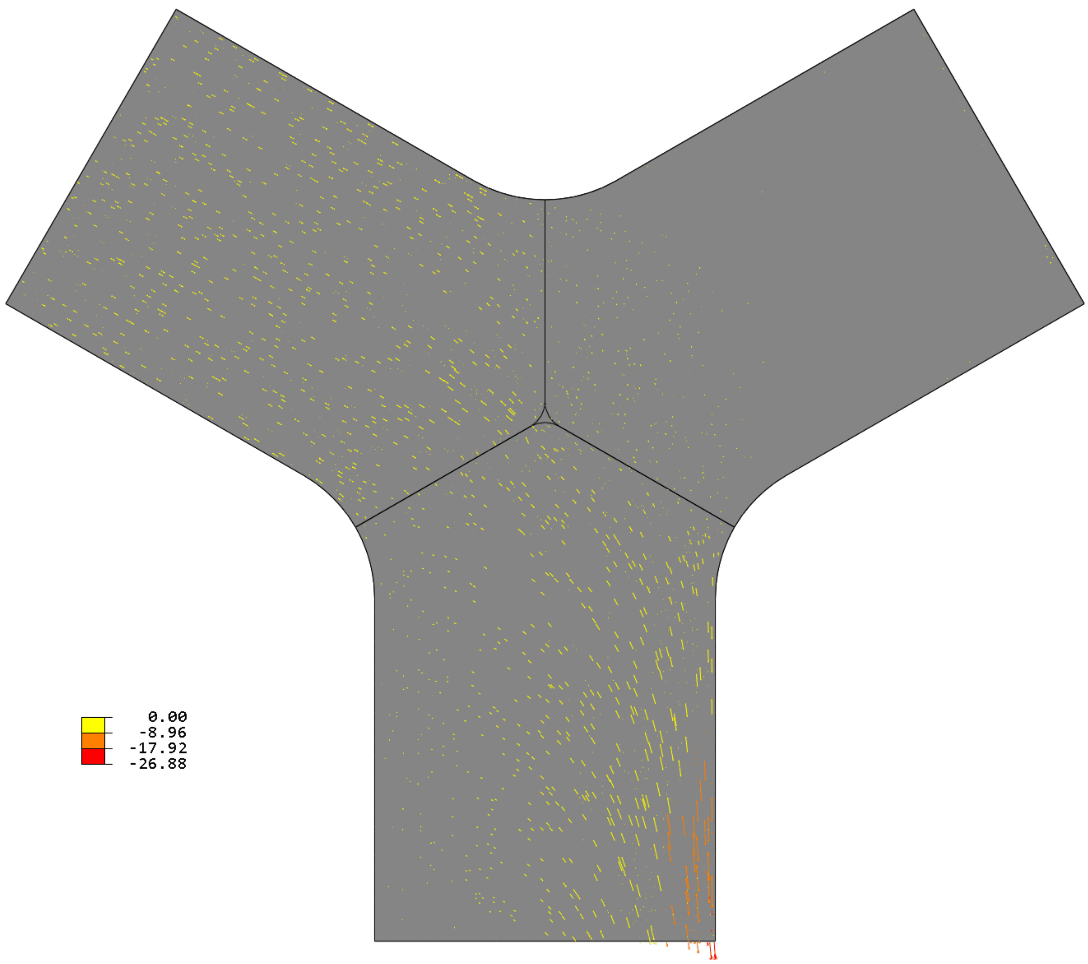
v2.3 3ply Tensile load

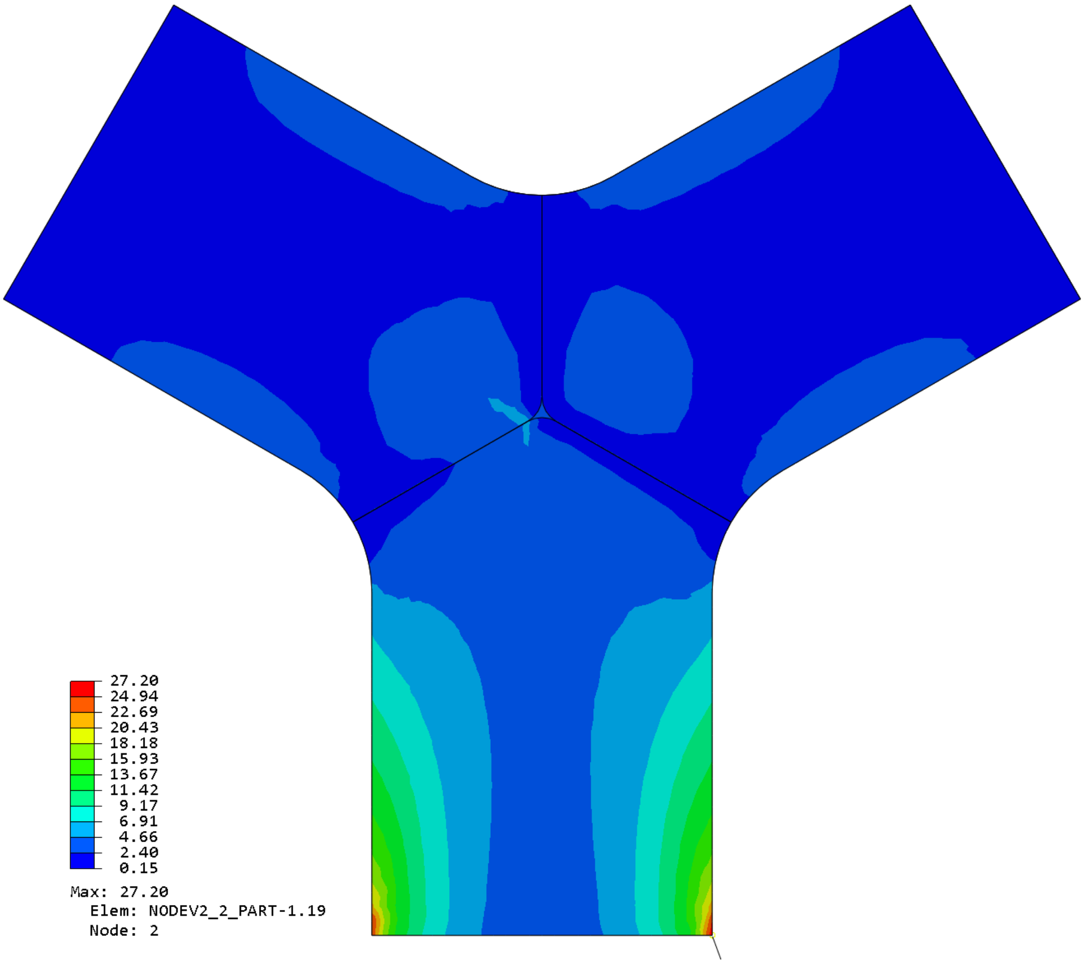


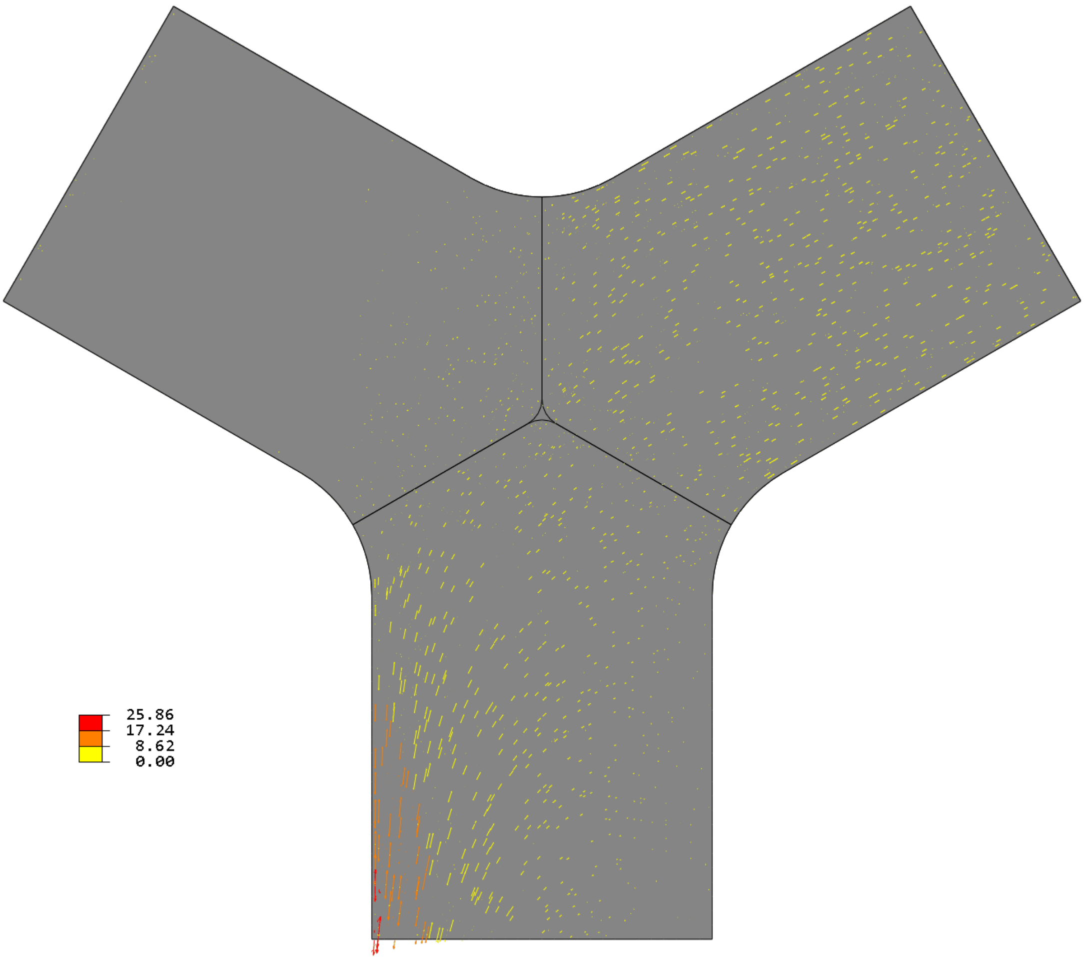

Max: 2.86
2.86
2.63
2.40
2.16
1.93
1.70
1.47
1.24
1.00
0.77
0.54
0.31
0.08
Max: 2.86
Elem: NODEV2_2_PART-3.1142
Node: 2685


2.73
1.82
0.91
0.00

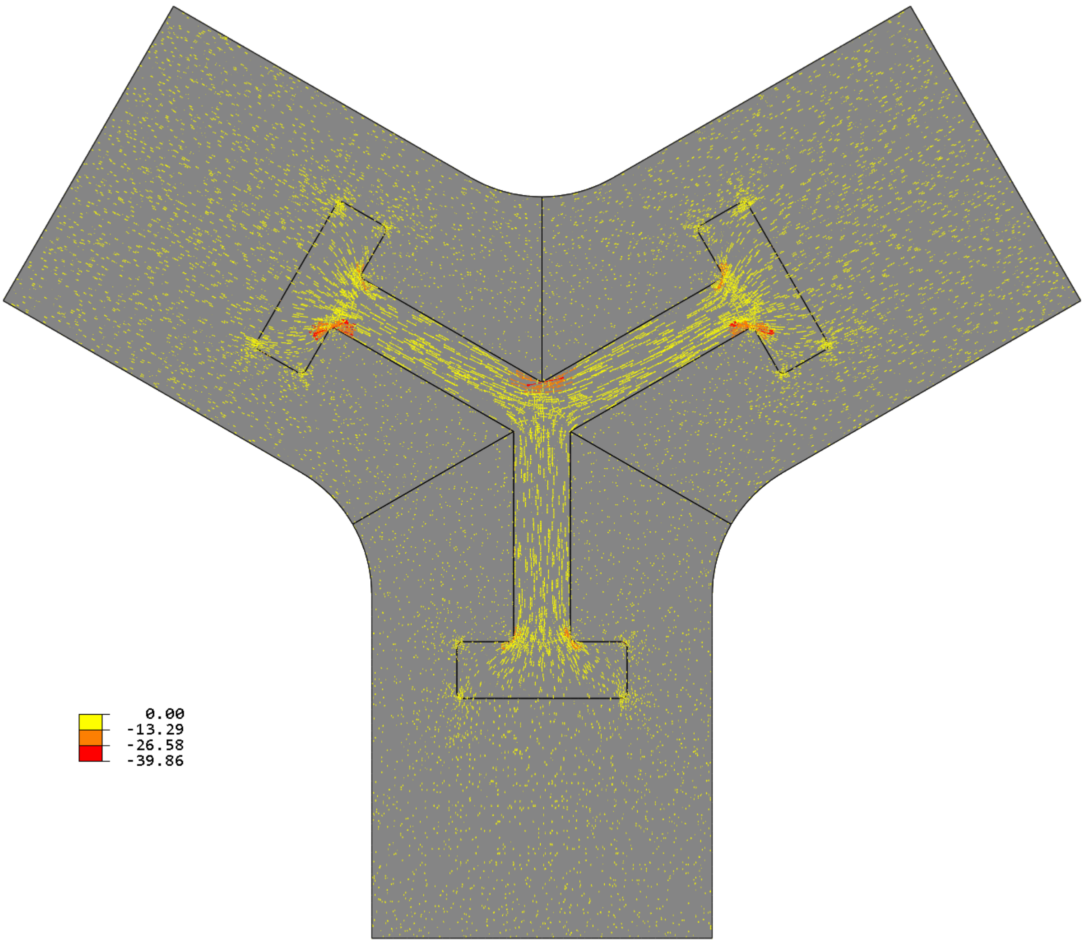
v2.3 3ply Compressive + tensile load

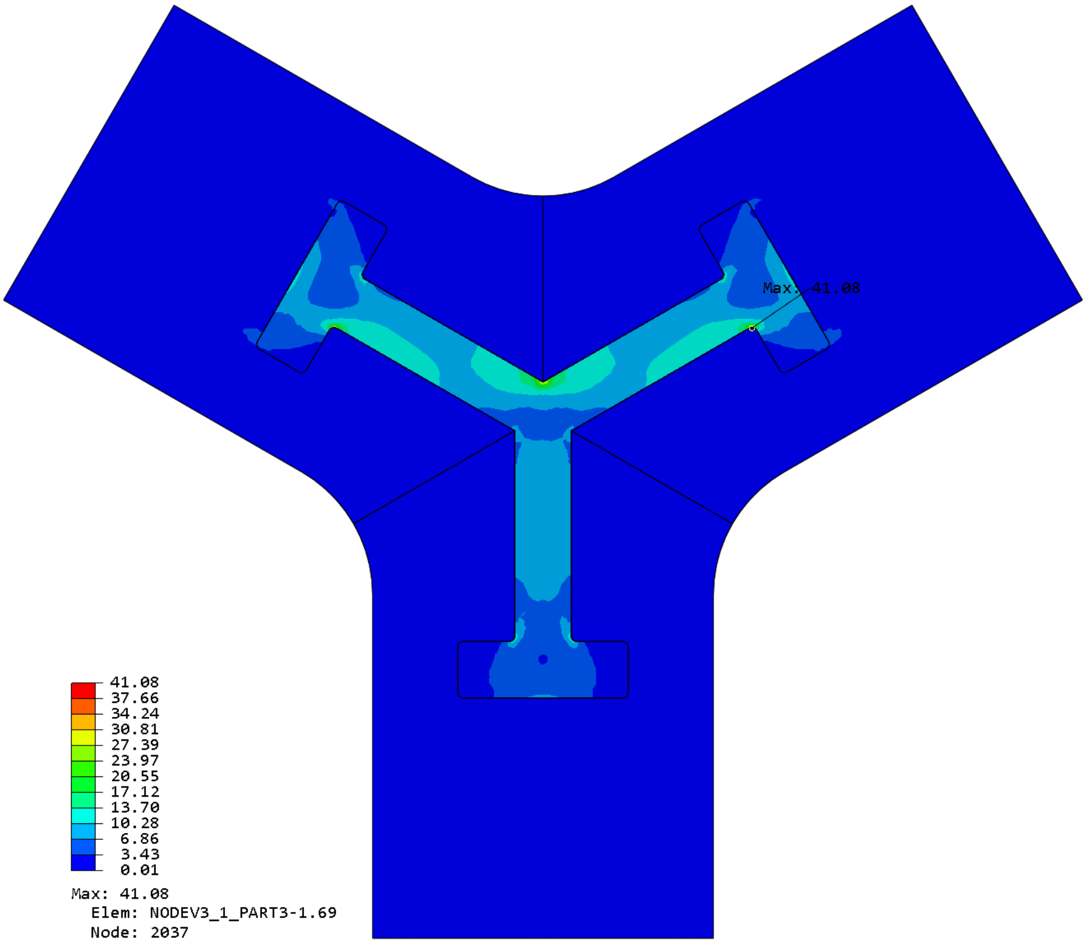


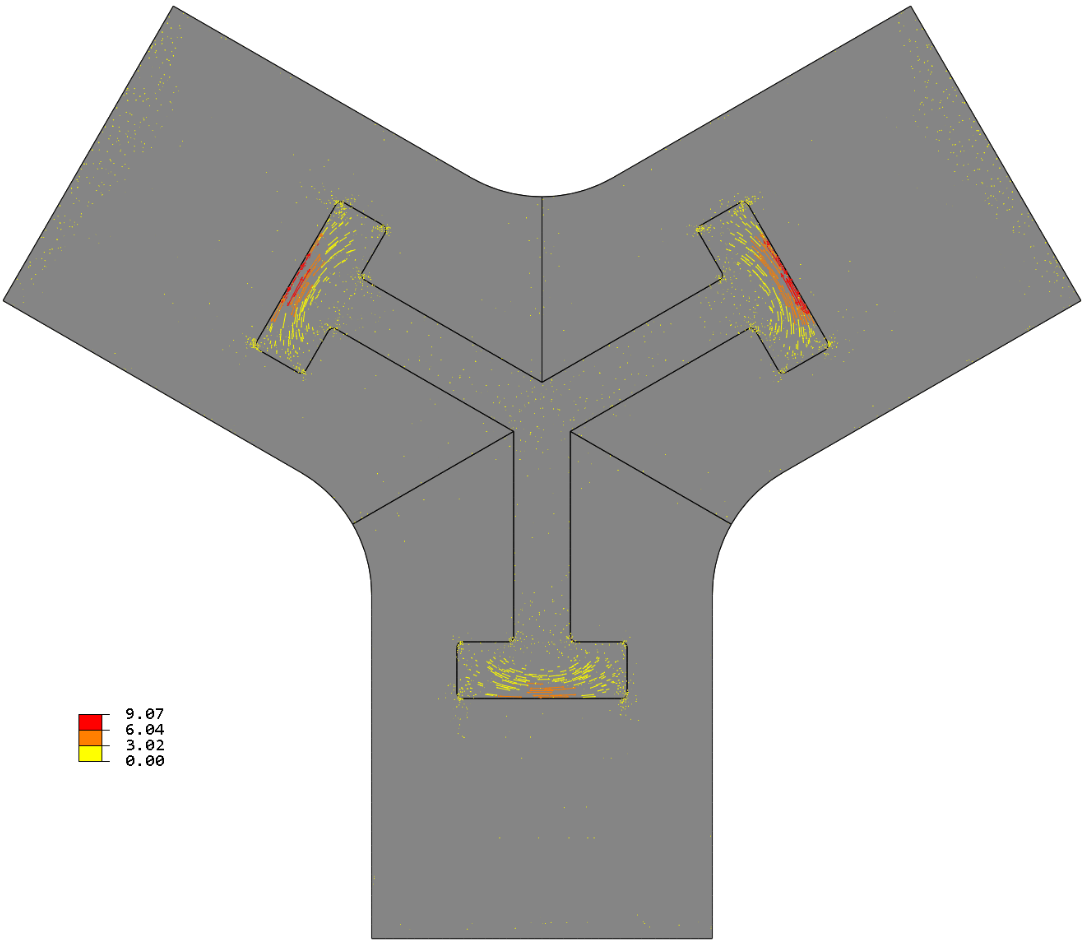

27.20
24.94
22.69
20.43
18.18
15.93
13.67
11.42
9.17
6.91
4.66
2.40
0.15
Max: 27.20
Elem: NODEV2_2_PART-1.19
Node: 2


25.86
17.24
8.62
0.00

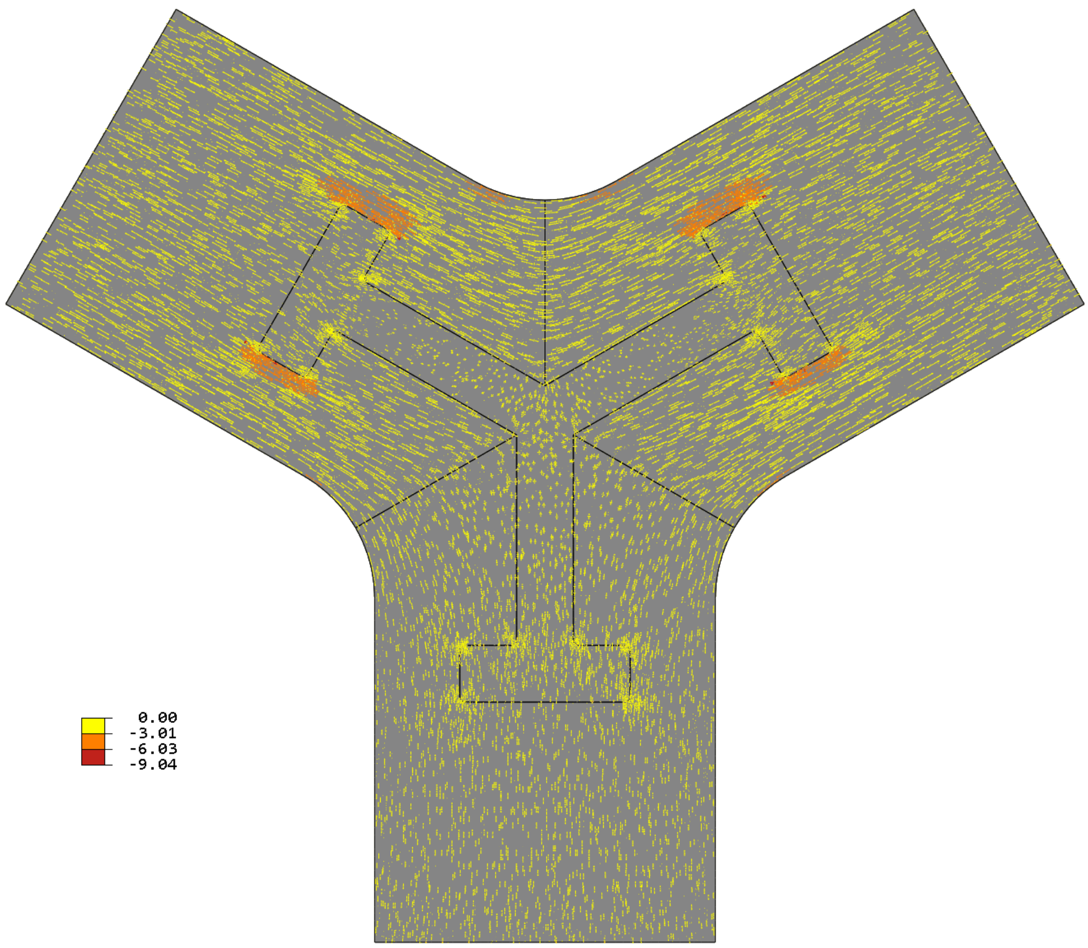
v3.1 3ply Compressive load

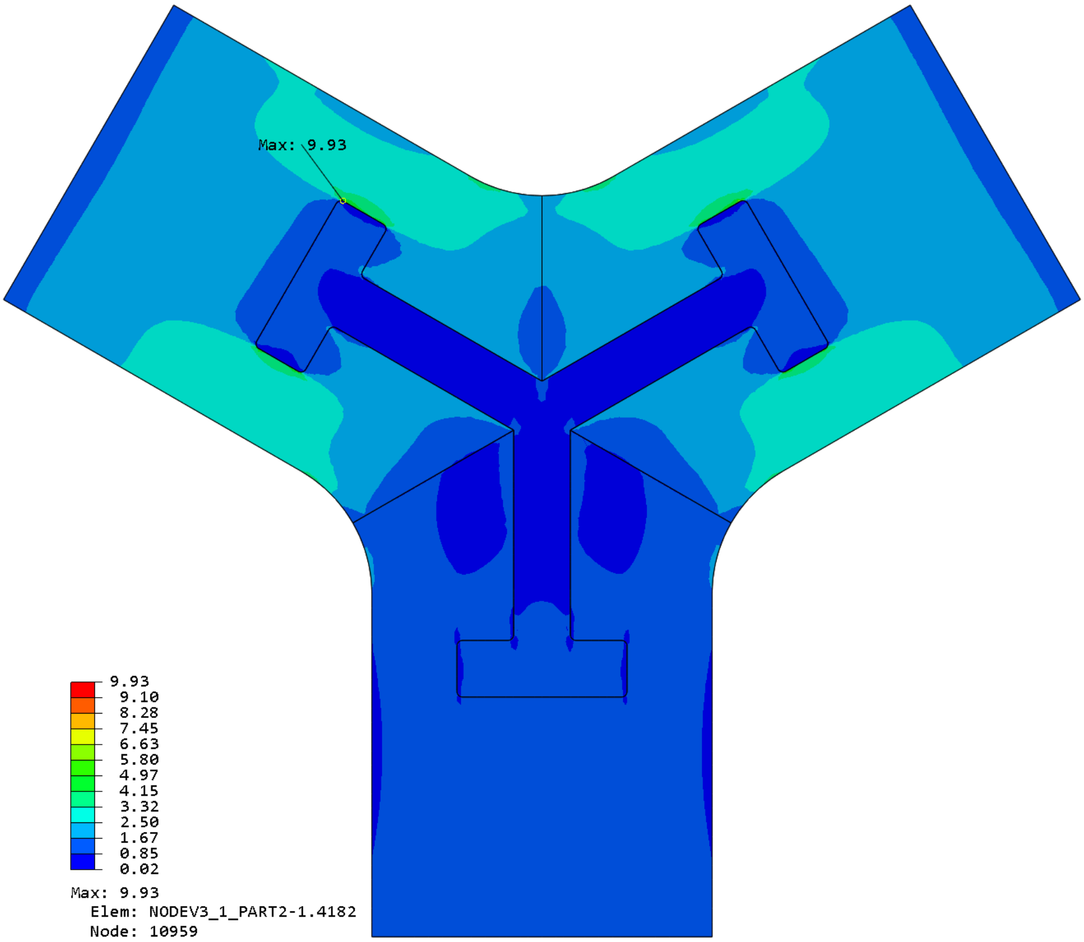


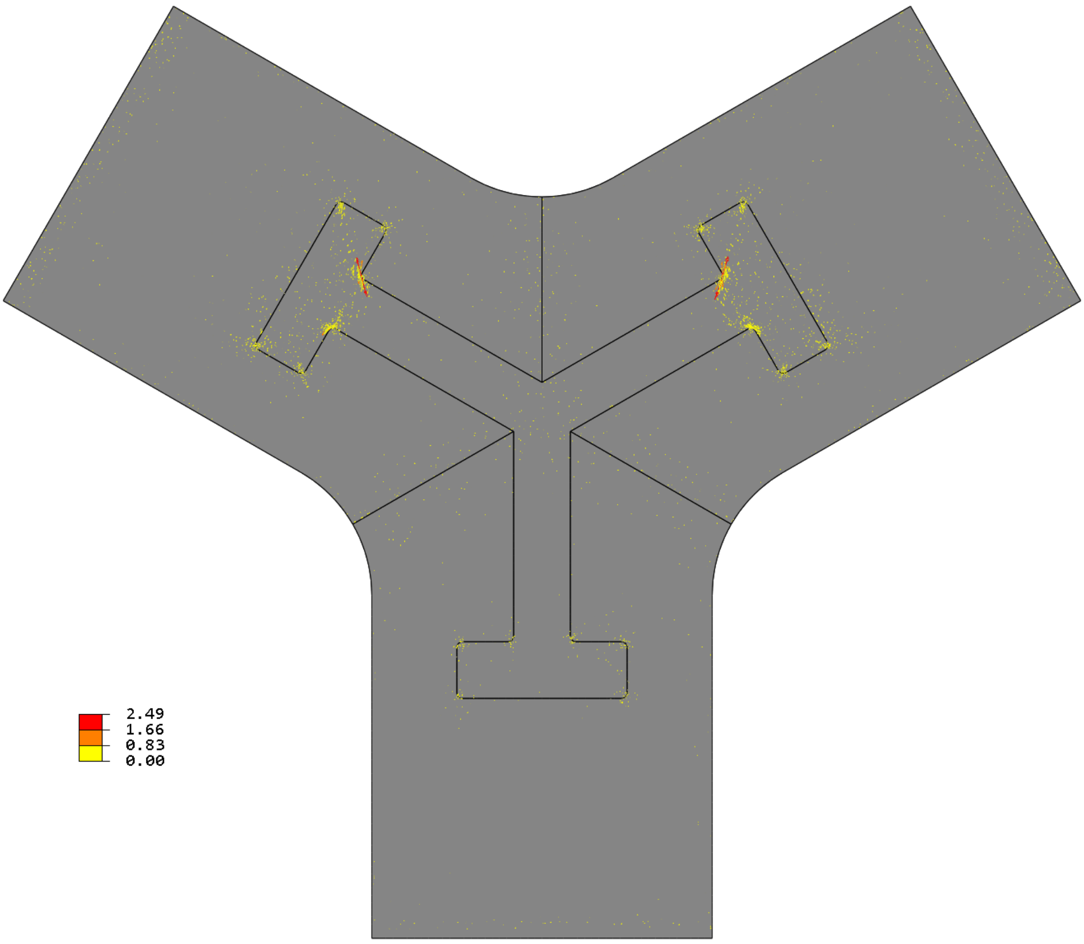

Max: 41.08
41.08
37.66
34.24
30.81
27.39
23.97
20.55
17.12
13.70
10.28
6.86
3.43
0.01
Max: 41.08
Elem: NODEV3_1_PART3-1.69
Node: 2037


9.07
6.04
3.02
0.00

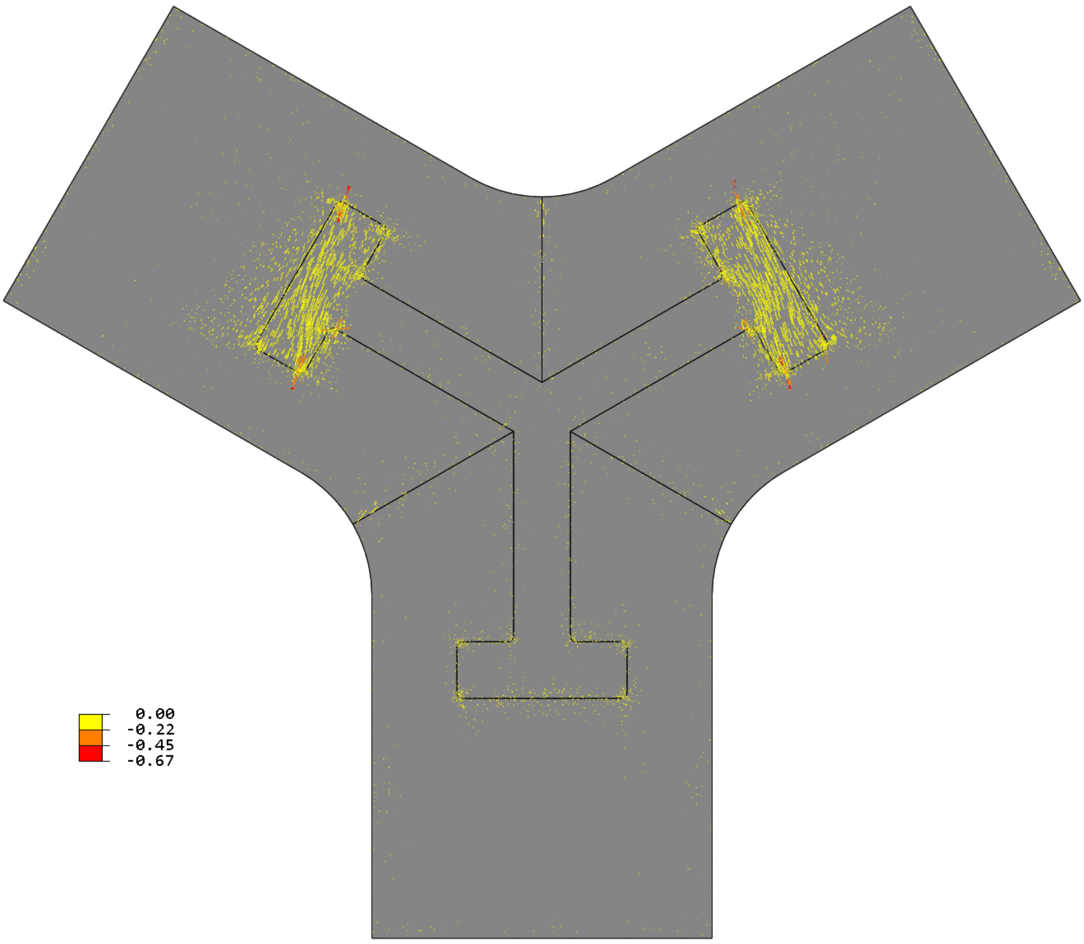
v3.1 3ply Compressive load (Beech reinforcement element)

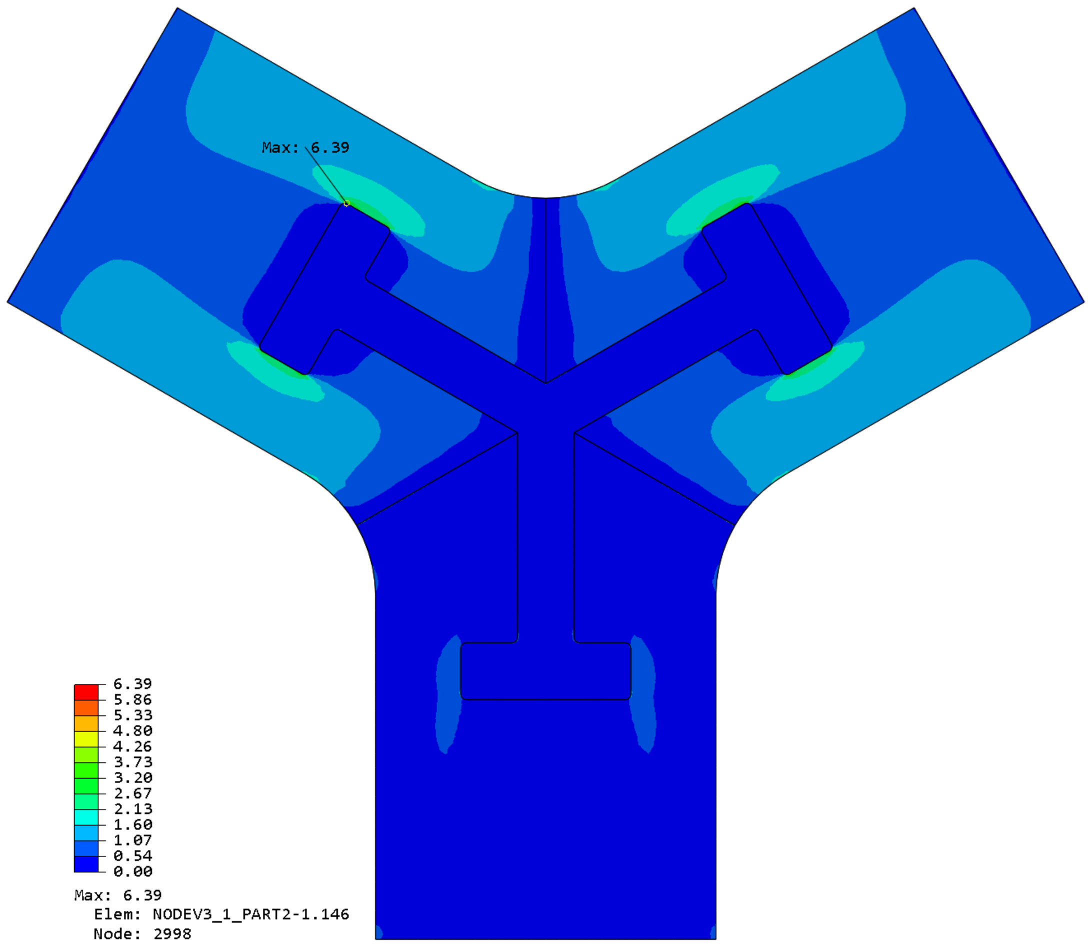


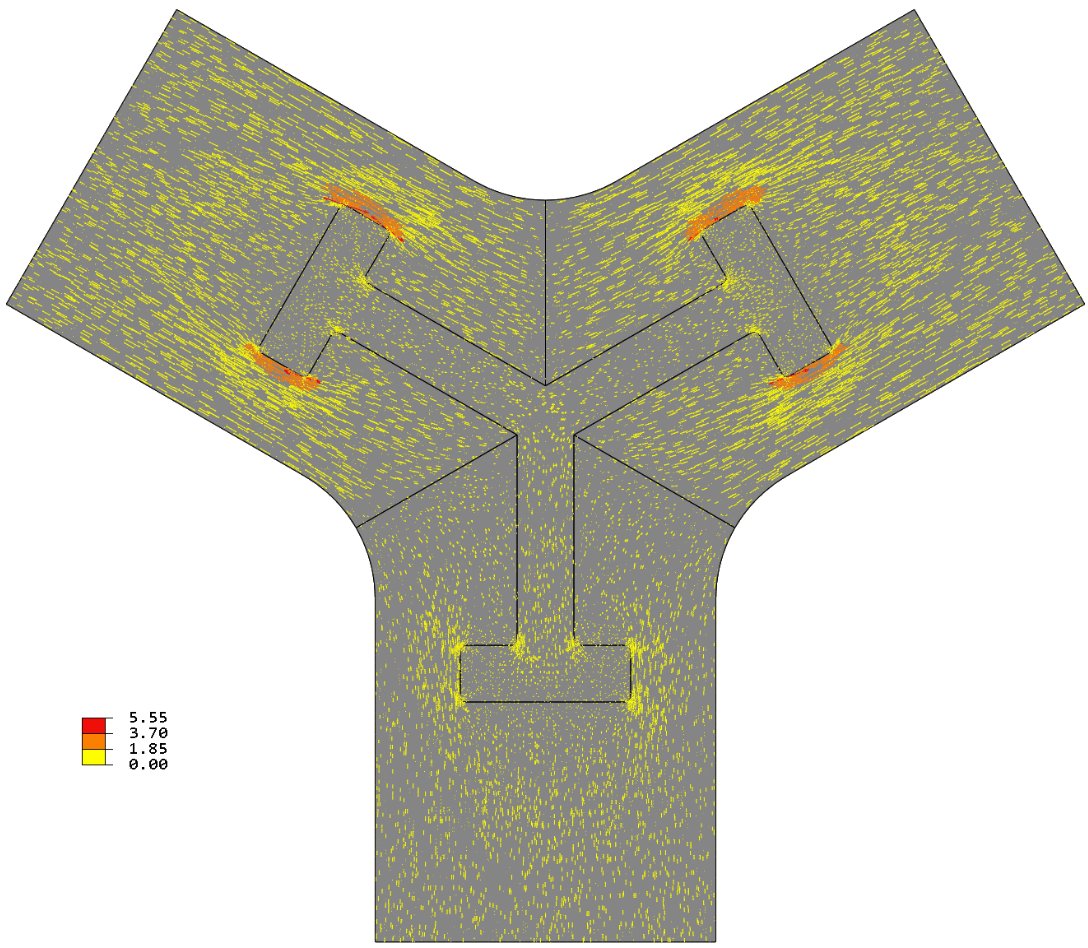

Max: 9.93
9.93
9.10
8.28
7.45
6.63
5.80
4.97
4.15
3.32
2.50
1.67
0.85
0.02
Max: 9.93
Elem: NODEV3_1_PART2-1.4182
Node: 10959


2.49
1.66
0.83
0.00

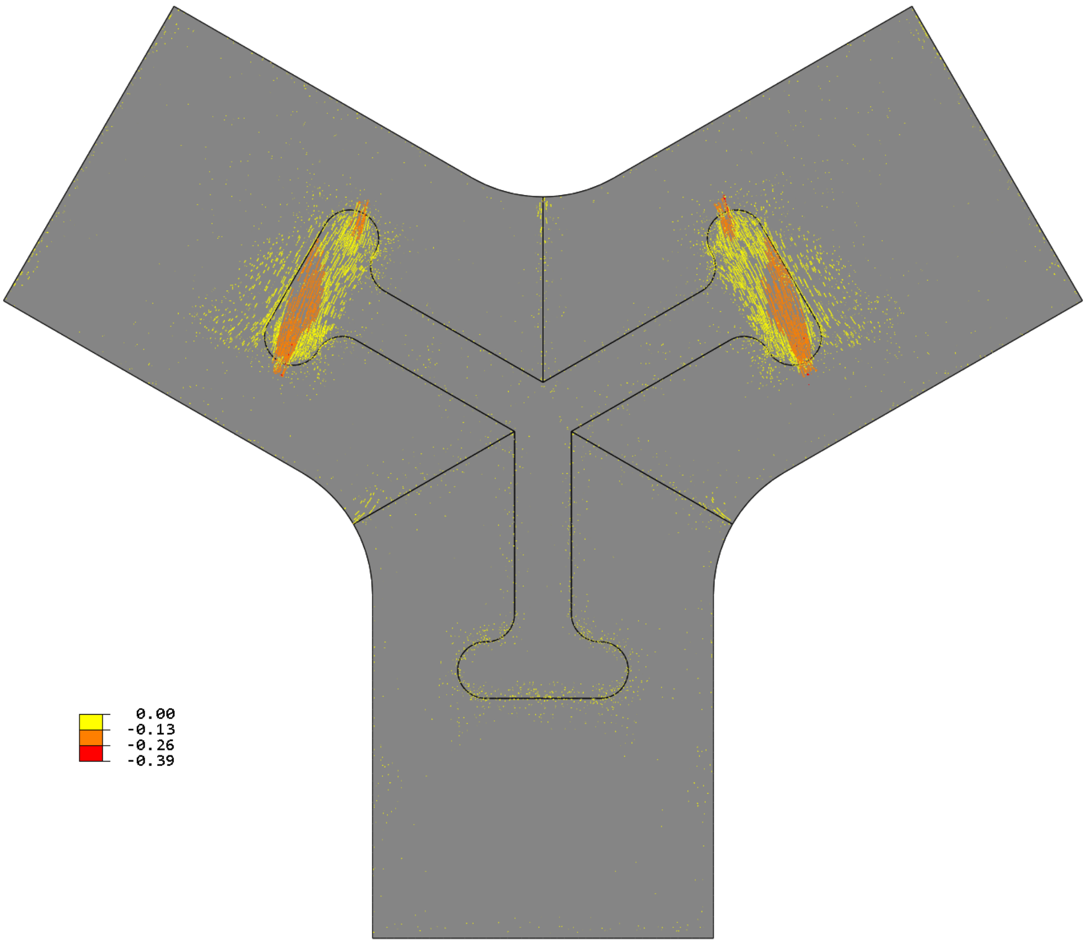
v3.1 3ply Tensile (Beech reinforcement element)

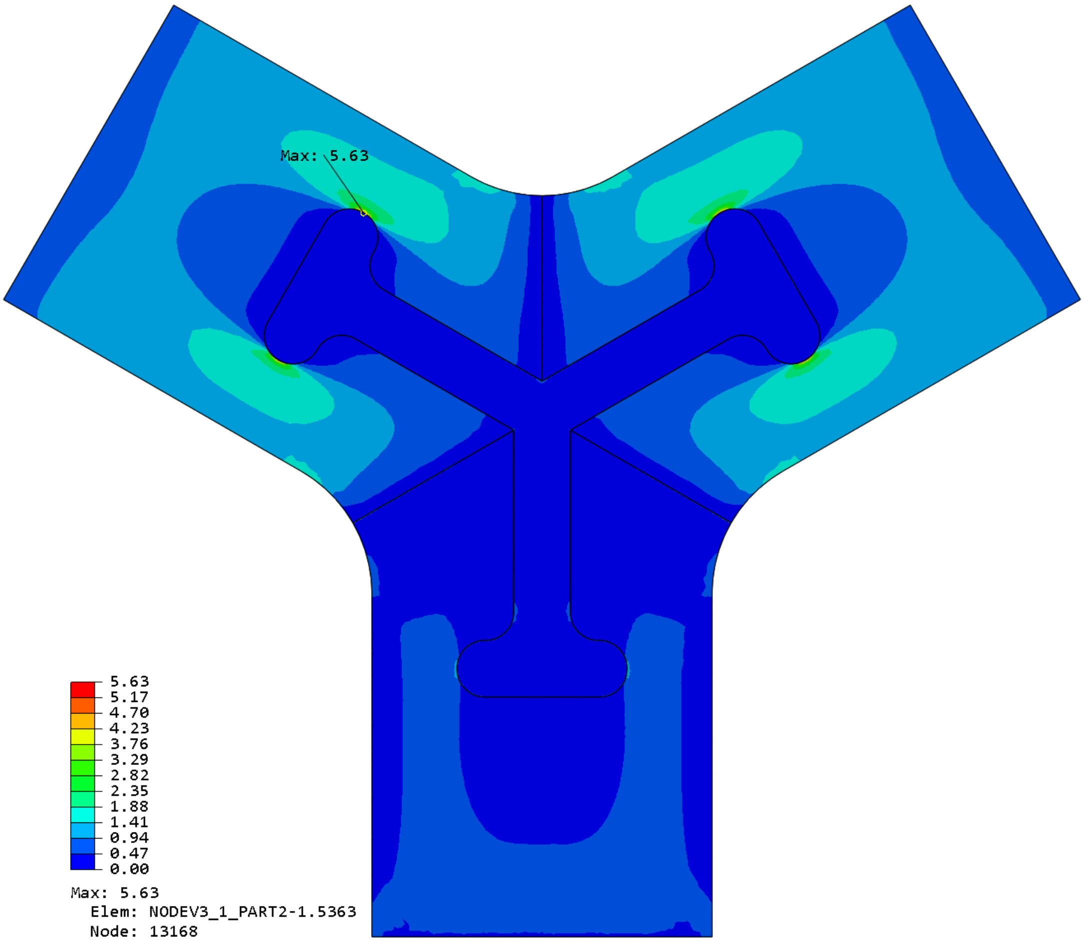


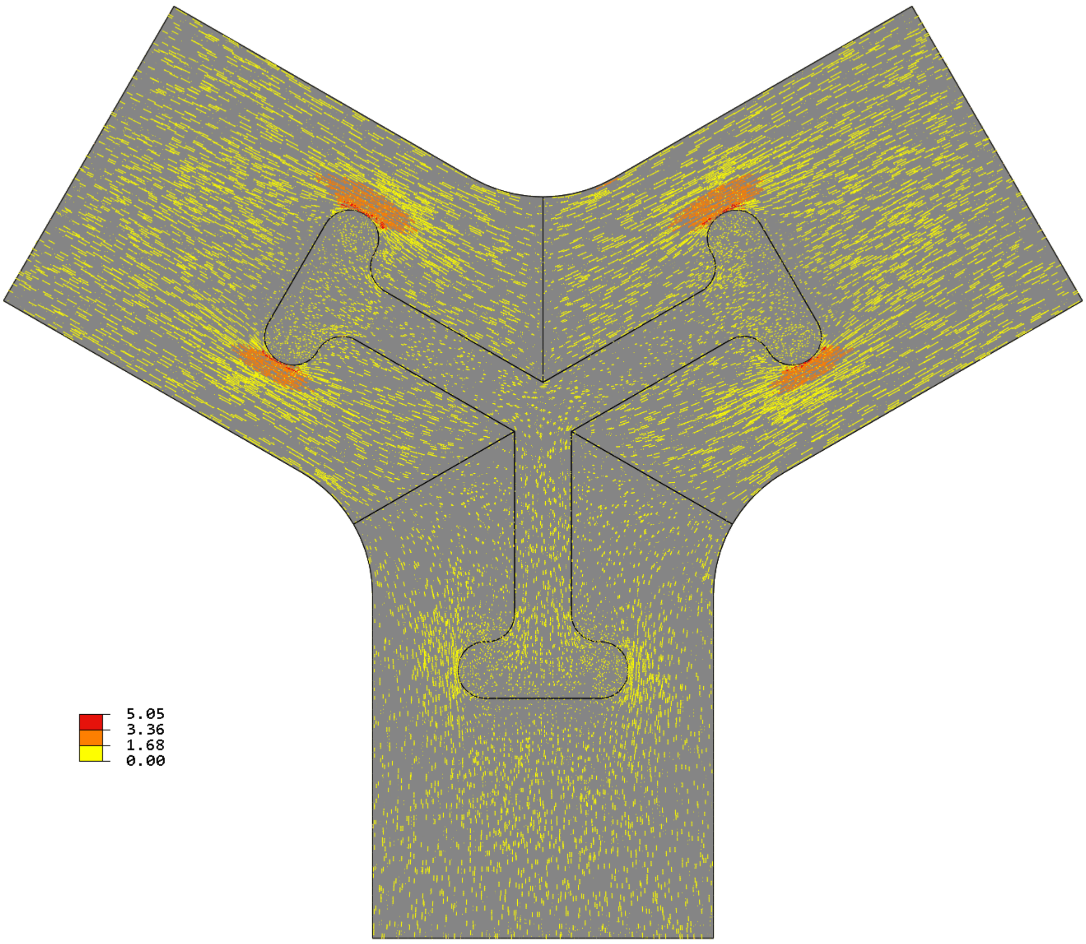

Max: 6.39
6.39
5.86
5.33
4.80
4.26
3.73
3.20
2.67
2.13
1.60
1.07
0.54
0.00
Max: 6.39
Elem: NODEV3_1_PART2-1.146
Node: 2998


5.55
3.70
1.85
0.00

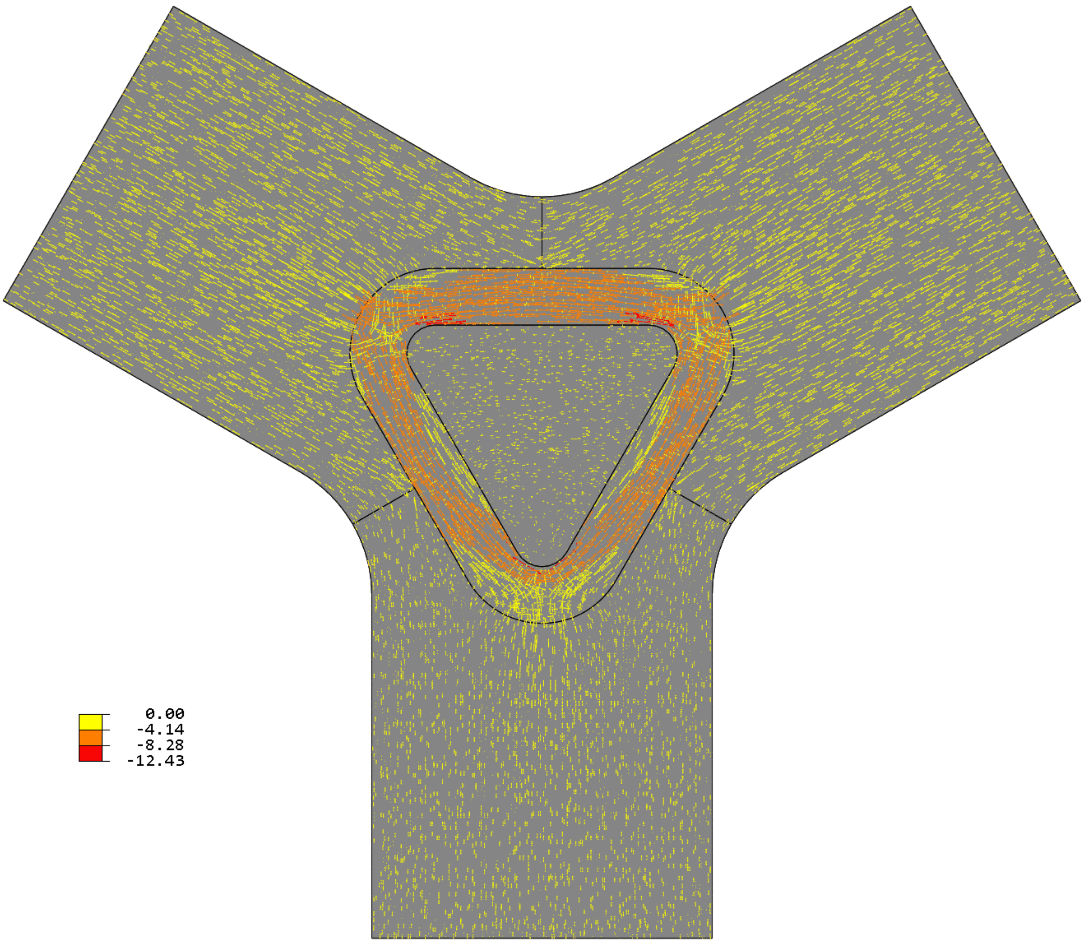
v3.2 3ply Tensile load (Beech reinforcement element)

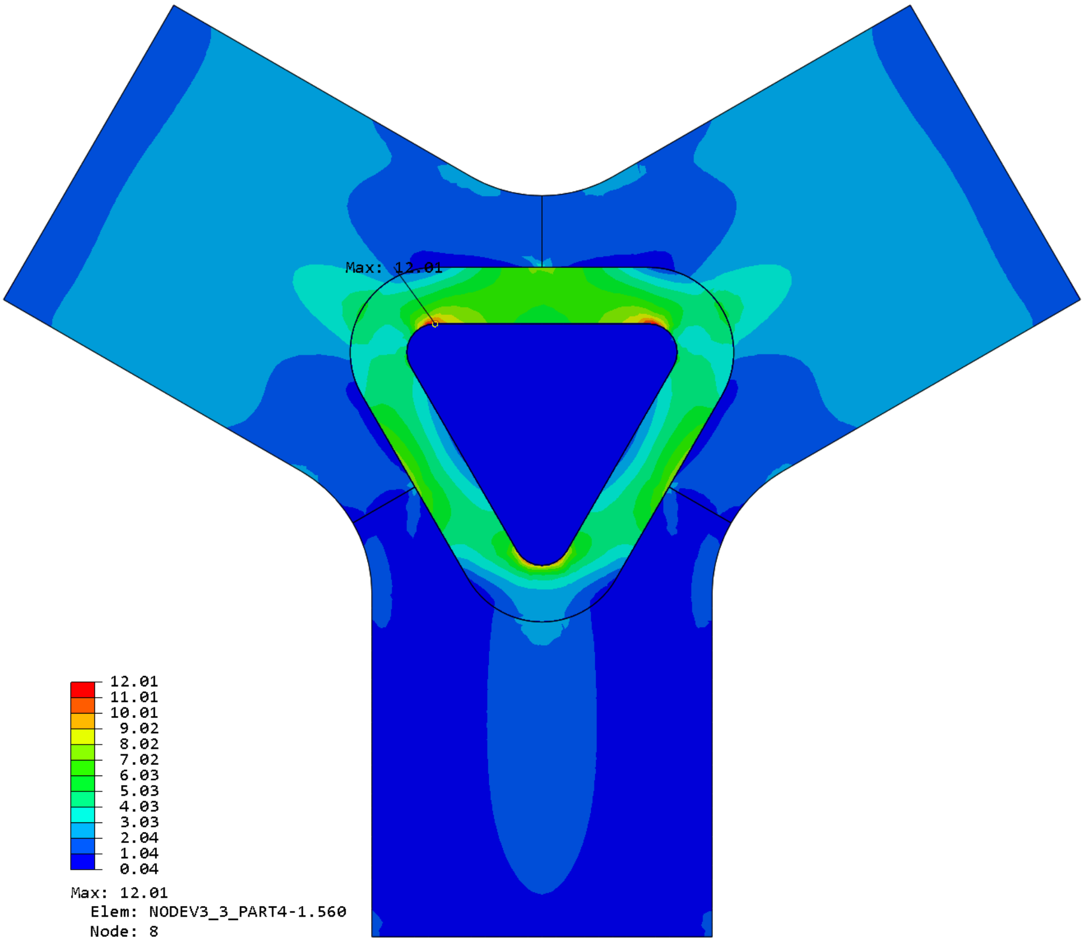


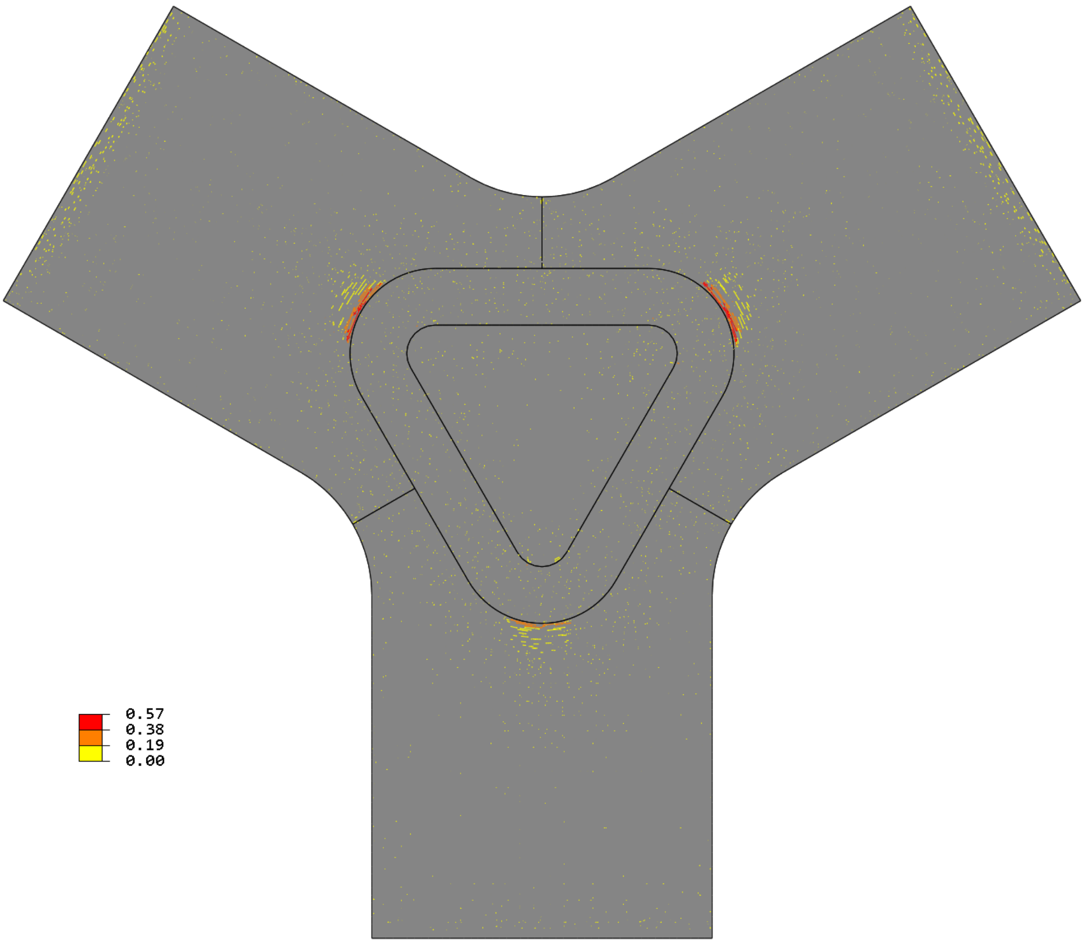

Max: 5.63
5.63
5.17
4.70
4.23
3.76
3.29
2.82
2.35
1.88
1.41
0.94
0.47
0.00
Max: 5.63
Elem: NODEV3_1_PART2-1.5363
Node: 13168


5.05
3.36
1.68
0.00

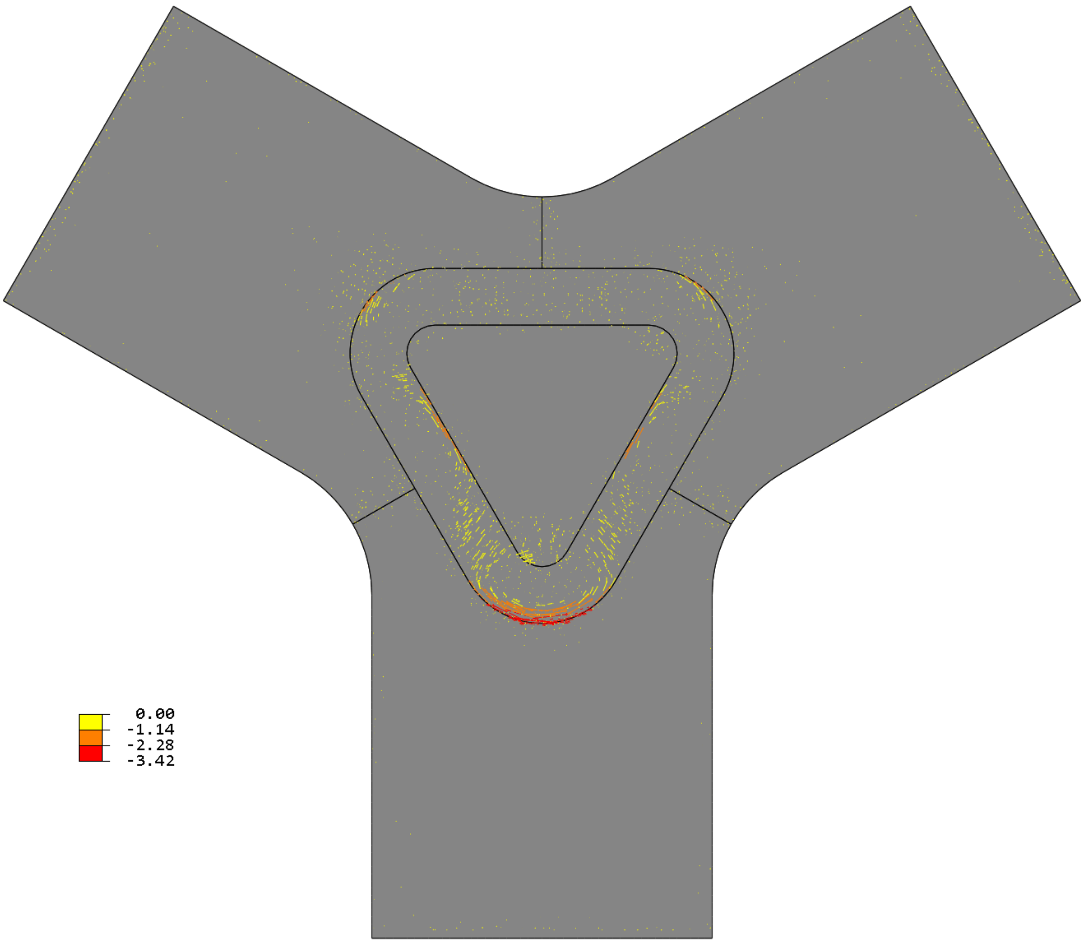
v3.3 3ply Compressive load

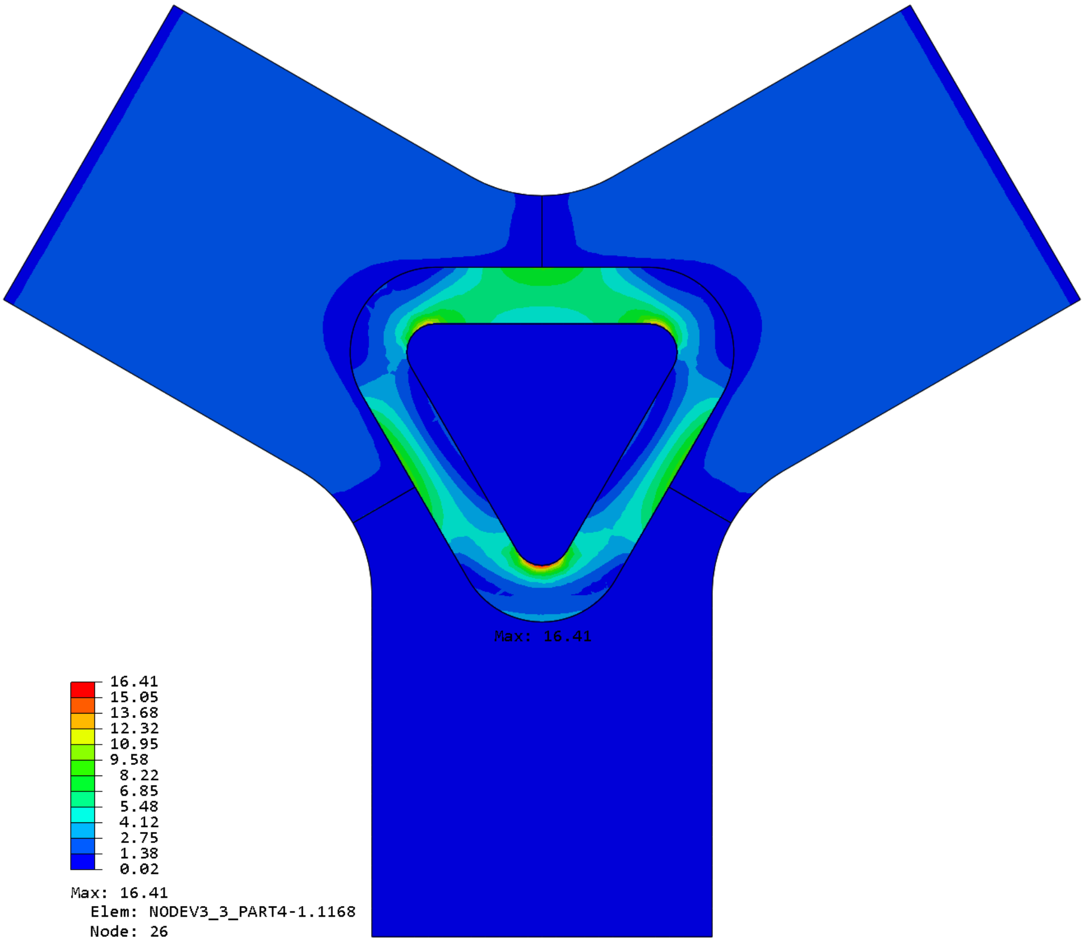



Max: 12.01
12.01
11.01
10.01
9.02
8.02
7.02
6.03
5.03
4.03
3.03
2.04
1.04
0.04
Max: 12.01
Elem: NODEV3_3_PART4-1.560
Node: 8

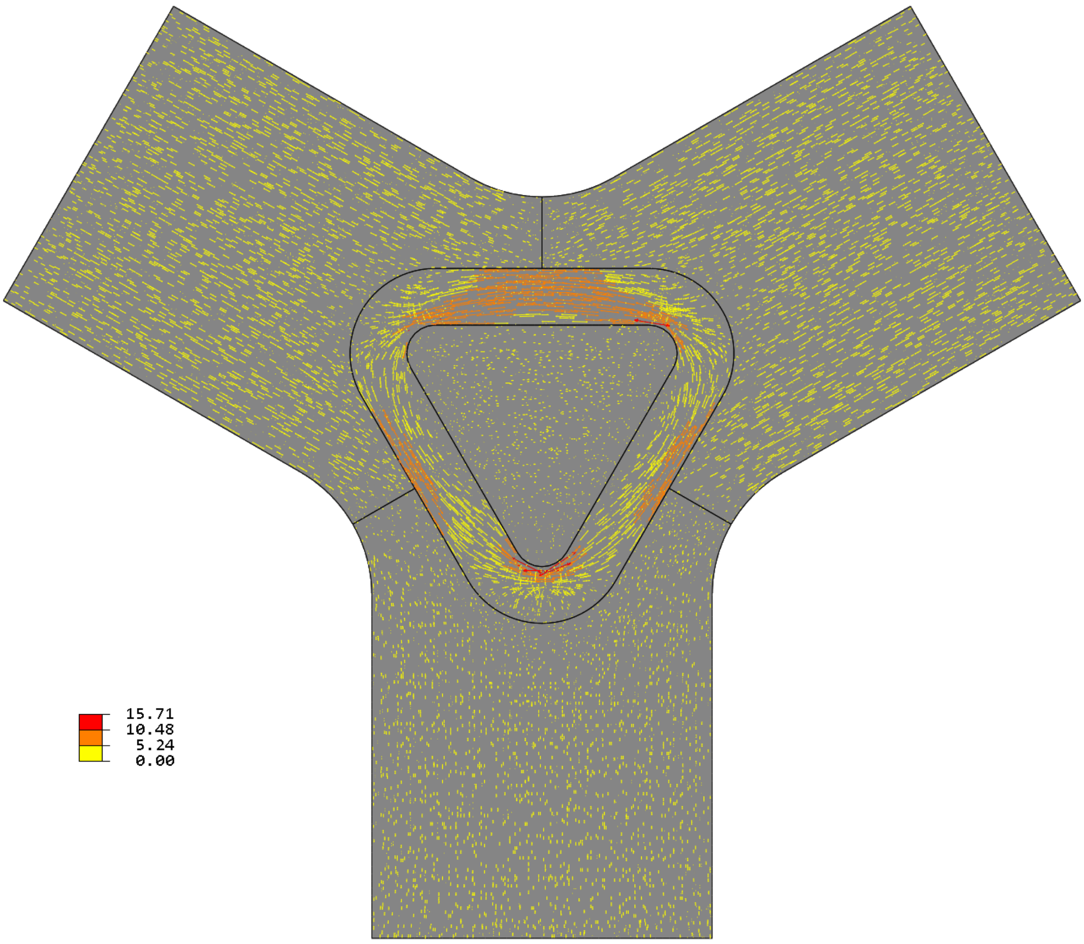

0.57
0.38
0.19
0.00

v3.3 3ply Tensile load



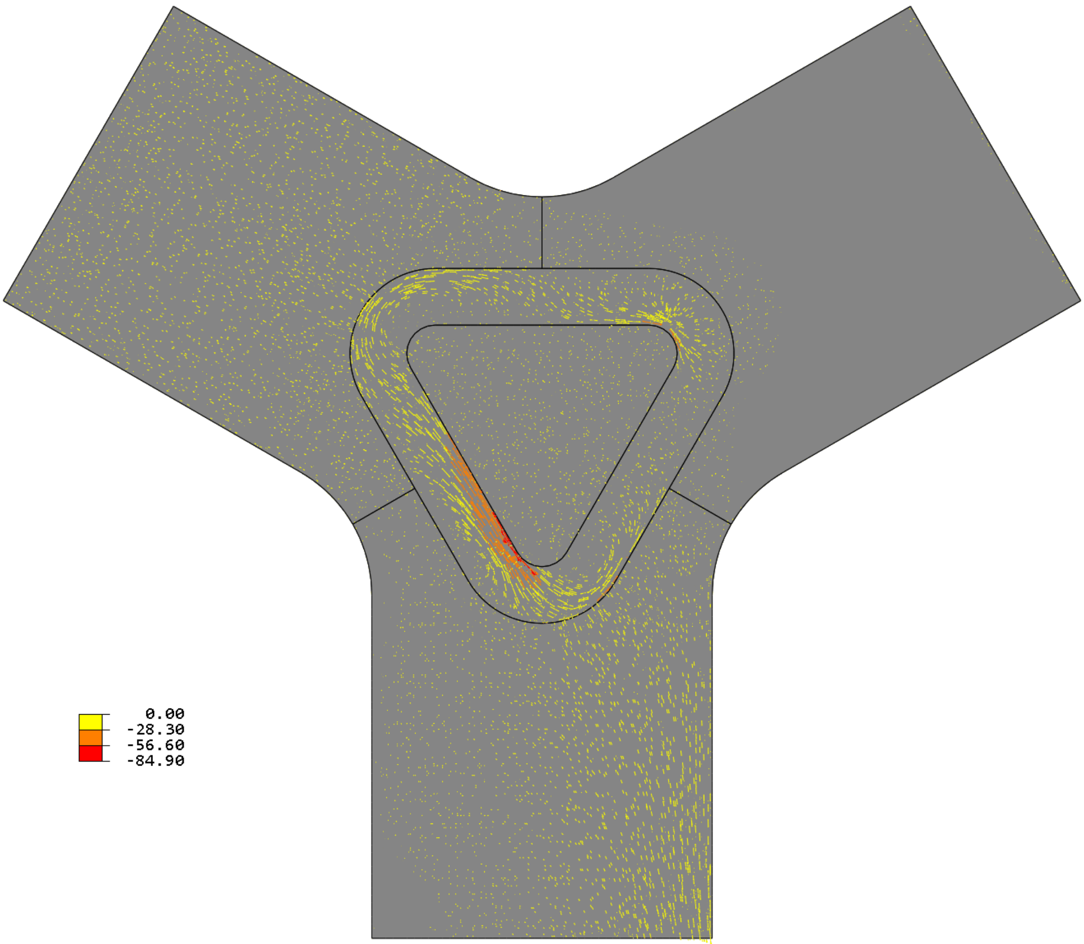


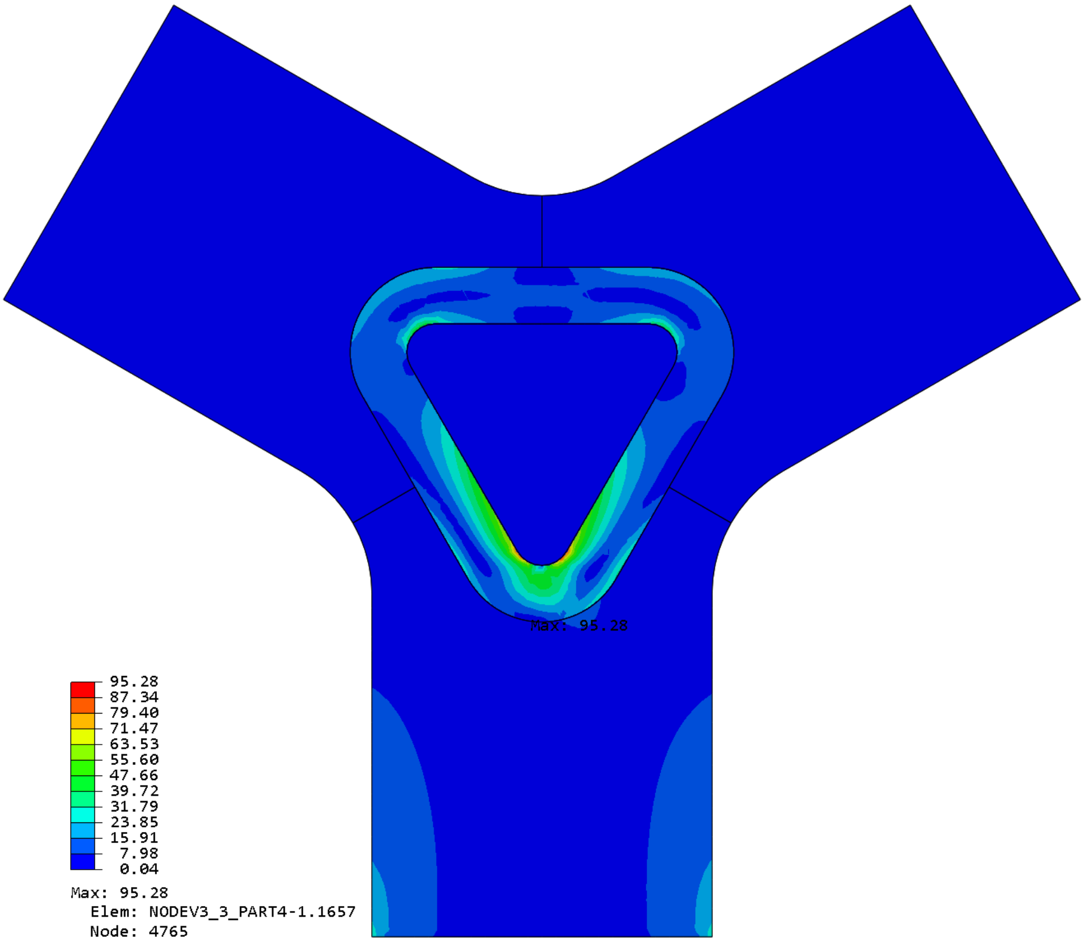
Max: 16.41
16.41
15.05
13.68
12.32
10.95
9.58
8.22
6.85
5.48
4.12
2.75
1.38
0.02
Max: 16.41
Elem: NODEV3_3_PART4-1.1168
Node: 26

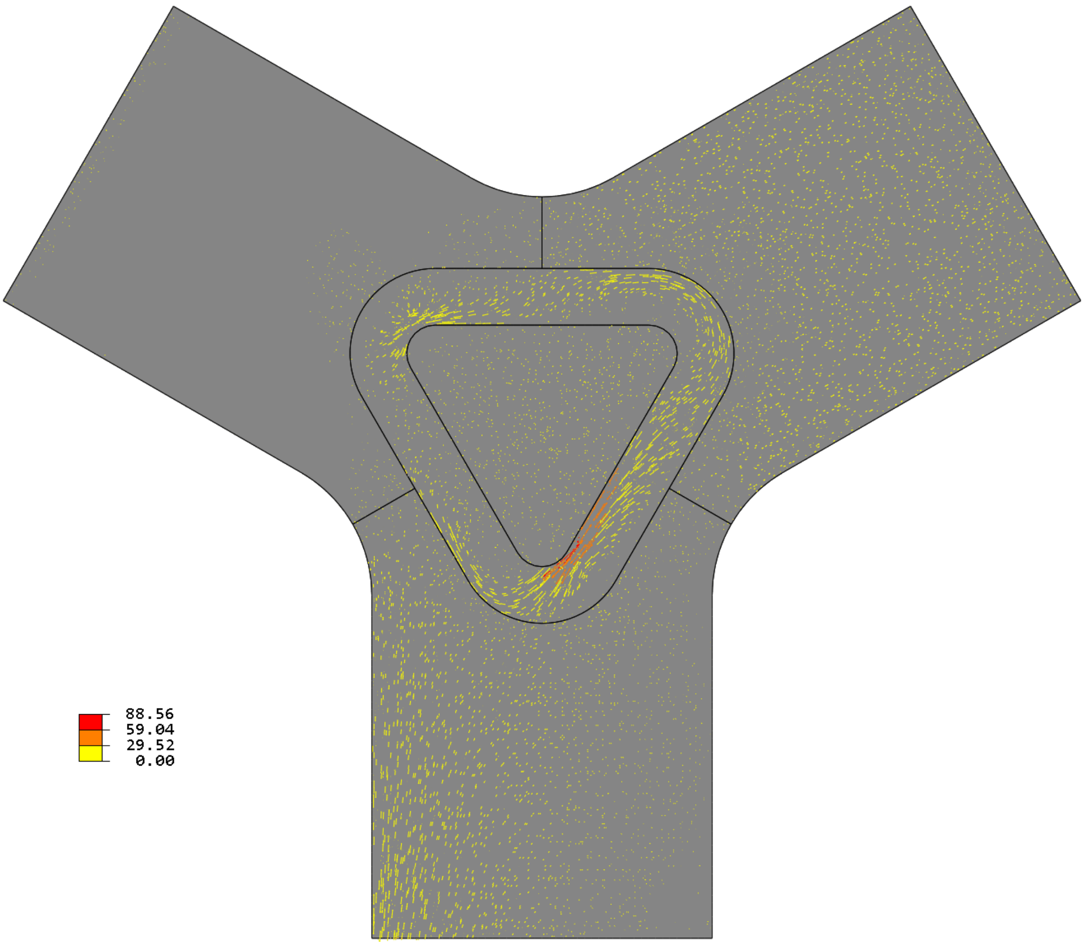


15.71
10.48
5.24
0.00

v3.3 3ply Compressive + tensile load




Max: 95.28
95.28
87.34
79.40
71.47
63.53
55.60
47.66
39.72
31.79
23.85
15.91
7.98
0.04
Max: 95.28
Elem: NODEV3_3_PART4-1.1657
Node: 4765


88.56
59.04
29.52
0.00

Appendix IV

Grasshopper model