Form Finding Nodal Connections in Grid Structures

Citation for the original published paper (version of record):
Tsigkari, M., Aish, F., Olsson, J. et al (2018). Form Finding Nodal Connections in Grid Structures.
Proceedings of the IASS Symposium 2018

(article starts on next page)

IASS 2018 BOSTON, JULY 16-20
CREATIVITY IN STRUCTURAL DESIGN

Proceedings of the IASS Symposium 2018
Creativity in Structural Design
July 16-20, 2018, MIT, Boston, USA
Caitlin Mueller, Sigrid Adriaenssens (eds.)

Form Finding Nodal Connections in Grid Structures

Francis Aish[c], Mats Ander[a,b], Eduard Hryha[b], Jens Olsson*, Martha Tsigkari[c], Chris J K Williams[a]

*Chalmers University of technology, Dept. of Architecture and Civil Engineering, 41258 Göteborg, jens.olsson@chalmers.se
[a] Chalmers University of technology, Dept. of Architecture and Civil Engineering
[b] Chalmers University of technology, Dept. of Industrial and Material Science
[c] Foster + Partners, Applied Research + Development (ARD)

Abstract

Nodes for grid structures are often manufactured in a rather material intensive and inefficient way, increasing the weight of the structure and thus the load. Recent development of additive manufacturing techniques, have resulted in a rising interest in large-scale metal 3D printing. Topology optimization has become the obvious companion in the design of structural parts for 3D printing, and rightfully so. The technique is demonstrably able to provide material efficient solutions and is well suited for a manufacturing technique with few formal restrictions. However, from a designer's perspective one could argue that topology optimization have some limitations. Like other "automated processes", it tends to take over and does not leave much room for other form drivers.

This paper presents an alternative method for designing material efficient nodes in grid structures that builds on the conventional form-finding techniques, usually applied to create minimal surface tensile structures or gravity shell like structures. The technique works by modelling the node as a hollow shell with a mesh, applying a set of tensile forces derived from the structural action from elements adjacent to the node (where compression is converted to tension) and running a form finding simulation. After the simulation, the shell is then thickened and analysed for the real load case (which consider both tension and compression) using FE-analysis.

The benefit of such technique is that the designer has control over the topology of the design which enables more creative control and free exploration of a range of design variations. The form finding is done using dynamic relaxation and introduces spline elements with bending capability to control deviation from the pure spring network solution.

Keywords: Structural nodes, topology optimization, form finding, space frame, additive manufacturing.

1. Introduction

The idea of studying material efficient and expressive structural joints has grown out of the experience of working on the design of a number of space frames, including that of the new international airport for Mexico City. The structural concept for the latter was motivated as a response to the challenging site conditions with soft soil in a highly seismic area. The ambitions were to create a light weight structure, built on a massive raft that would be floating on the wet soil, which efficiently caries both its self-weight but more importantly is stiff for later loads imposed on the structure during a seismic event. The roof structure was designed as a double curved shell structure with a highly efficient tetrahedral space frame configuration, where the 300 000 unique nodes are created from solid steel spheres. The nodes became a major concern in the roof design because they account for the majority of the structural weight, and are also important for the experience of the interior space as the structure is completely exposed.

Thus, much of the design work with the roof structure was centred on making sure the angles between adjacent members were not too small, which would result in larger nodes [7]. When the nodes become larger the weight increases leading to larger bar diameters which is the other parameter that also drive the node size to increase.

When the design phase for Mexico City airport was finalised, the question was raised of what could be the next step in the design of such space frame structures. An obvious answer was to further explore the node design in order to improve on material efficiency, weight savings and design quality.

2. Background

This section gives a short background on additive manufacturing and topology optimisation and how the two are related and can work in synergy. It also discusses the application of topology optimisation in the design process. But first of all a definition of the term topology is given, since it is frequently used in the paper to discuss design outcome and user control in the design process.

2.1 Topology

Topology is used here as the mathematical concept for the properties of an object that are preserved through deformations like twisting, and stretching [6]. However, it may be helpful to distinguish between what is here referred to as geometrical topology and topological connectivity. Geometrical topology can be explained as the number of holes in an object irrespective of whether the object is continuous or discrete. (The torus and coffee cup have the same geometrical topology). Topological connectivity on the other hand refers to the discretization of an object, and changes in the topological connectivity may or may not change the geometrical topology.

Topology optimization changes at least the topological connectivity of an object with the removal of elements in a FE mesh, which may or may not alter the geometrical topology. Form finding on the other hand only deforms the object through stretching (and potentially twisting) thus leaves both geometrical topology and topological connectivity intact. From a design perspective the question then becomes who controls the two aspects of topology for the object, the designer or the optimization.

2.2 Additive Manufacturing in Construction

Additive manufacturing (AM) is considered to be one of the key drivers in current industrial revolution. AM provides virtually unlimited freedom of design, optimization of resources, manufacturing strategies as well as distribution to the end users. There is a common understanding by many industries that AM is a game changer and benefits identified include increased production flexibility, design for function, customisation, reduced lead-time, efficient material utilization, reduced weight, etc. The application of AM in architecture and construction started from the first days of the AM development in early eighties as an excellent tool for making scale models. During the last three decades a number of AM technologies have expanded their capabilities from sheet lamination technology utilizing glued paper, to high-performance medium-size metal components using e.g. powder based techniques, and macroscale 3D printing of full-scale buildings utilizing extrusion of low-slump concrete. Taking into account still considerably high cost of the AM hardware and AM material in comparison with the conventional techniques utilized in construction business, the most promising AM applications are originating based on the utilization of the customisation, improvement of the traditional techniques and supply chains as well as product development work-flows.

Steep increase in metal powder based additive manufacturing technologies during last couple of years – about 30% per year staring from 2011 – indicate transformation of the metal additive manufacturing from the technology for rapid prototyping to manufacturing of the complex-shaped high-performance components, characterised by low to medium size and required in rather low volumes. Material properties offered by AM at the current state-of-the-art are comparable or higher than obtained by casting and in many cases are similar to the ones offered by wrought metals alloys. Hence, taking into account almost unlimited design flexibility, this technology provides a huge potential for broader application in construction industry that can utilize its freedom of design, functional design, lightening as well as other advantages, mentioned above.

It can be argued that at the current state-of-the-art of powder based metal AM, rather slow build rate, limited material choice, especially cheap structural materials, and production capacity is hampering industrial implementation of this technology in construction industry to the full extent. However, significant research and development efforts focused on these aspects in combination with steep industrial growth in different chains of these technology will definitely change the material and process flexibility as well as manufacturing costs, resulting in expansion of the technology in areas as architecture and construction. Therefore, implementation of the technology for the design and development phase for specific components e.g. nodal connections, is a must for the early and successful implementation of the technology, as was done by medical, aerospace and energy sector decade during the last decade.

2.2. Topology optimisation

Topology optimisation which is sometimes called shape optimisation has proven to become a suitable method for design in relation to additive manufacturing technology. The algorithms for TO have been around for quite some time but have always been ahead of the manufacturing capabilities since the resulting shapes are often difficult to manufacture by conventional means. Recent development of TO has focused on introducing shape control functionality such that the resulting object can in fact be manufactured using conventional techniques like casting, extrusion etc. [4]. But with the development of AM there is a potential shift towards new manufacturing paradigm with few formal restriction. The question which remains unanswered is then to what extend this process can be scaled up to work for mass production.

The biggest difference from a designers perspective of adopting topology optimisation as part of the workflow is the shift in sequence between analysis and design. Instead of taking a best guess of what an object should look like the designer can work by defining the boundary conditions, working envelope, load cases and material properties to let the TO process make the first design iteration. The designer then continues working from there with reasonable confidence that the design will perform in later stages of analysis.

The TO influenced design process works really well for well-defined problem where weight savings is the top priority and that may be a reasonable approach for many machine part design applications. However, in the field of architecture where formal expression and multi-objective functionality is often desirable one can question if the TO should be given the privilege of making the first design iteration, or if that should be left to the designer.

3. Case Study

The exploration of methods for designing material efficient nodes started with adopting a topology optimisation approach, which later on led to the developed of an alternative approach based on the mass spring simulation using dynamic relaxation. For this particular case study the methods are applied and tested on a node in a tetrahedral space frame as illustrated in Figure 1, but the aim is to explore an approach to material informed design in a broader sense.

3.1 Set up

The set up for the analysis for the global geometry was done using a simple double symmetric tetrahedral space frame roof. Each side of the hexagonally shaped roof boundary measures 15 m and the longest span becomes 30 m, the bars are on average 2 m long for each of the two layer that are separated with a distance of 1 m. The node which is chosen for the study is the one at the inner layer on the top of the dome which is exerted to symmetrical conditions both in terms of geometry but also in terms of reaction forces from adjacent elements. The roof is shaped into a domelike structure using form finding of the inner layer under the influence of a gravity load case.

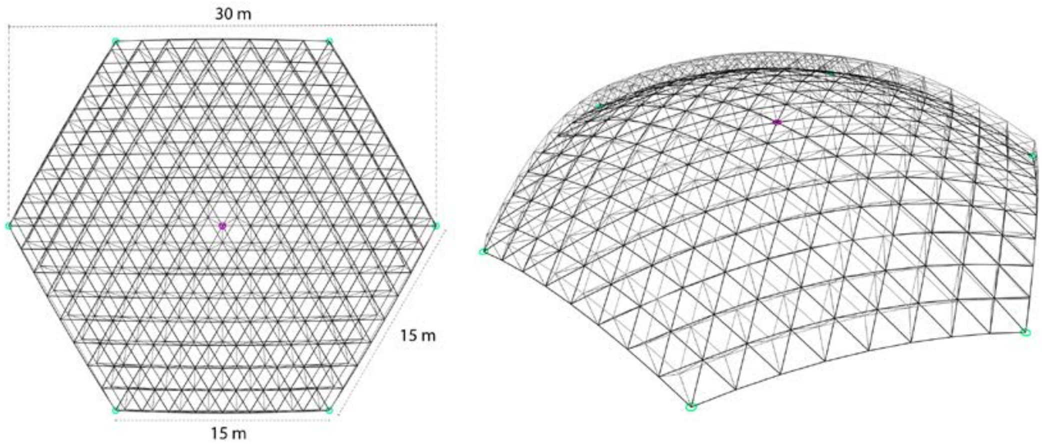

Figure 1: The setup of the space frame geometry where the green circles indicate nodes that are locked for translation, and the purple circle indicate the node of interest for this case study.

The structure is modelled with steel bars with circular hollow cross section under the influence of a gravity load case which is applied as an amplification of the self-weight of the structure by a scale factor. Linear FE analysis are then carried out to get the forces acting on the nodes, which are then brought into the optimisation environment. Figure 2 show some of the results from the analysis in terms of forces acting on the nodes. (Exact details of the set up is regarded beyond the scope for the paper).

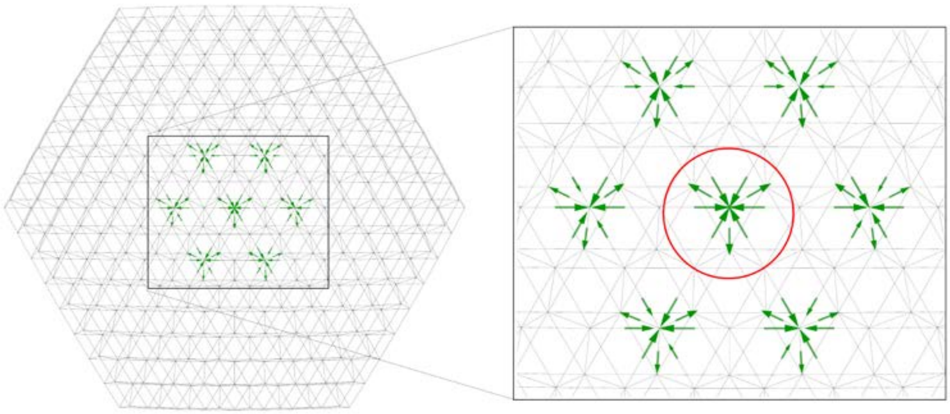

Figure 2: Showing the force acting upon 7 nodes at the top of the dome. The node which is at the centre is exerted to close to symmetric loading, and is chosen as target for further studies.

3.2. Topology optimization approach

The topology optimisation was initially carried out as a series of tests to get familiar with the process and understanding of how to set up the boundary conditions such that they do not become stiff supports that attract stress and thus accumulate mass. The final set up is illustrated in figure 3. The 6 members that attach to the node in close to a horizontal plane are all pushing with a compressive force, whereas the 3 remaining attachments are pulling with a tensile force, just like the results indicate from the space frame analysis show in Figure 2. The dead load is then applied onto the node as a vertical force distributed over all the 9 bar attachments, such that the sum of all the forces lead to equilibrium. The material for the node is specified to be steel and the optimisation goal is to maximise stiffness with a target mass of 15% of the initial mass.

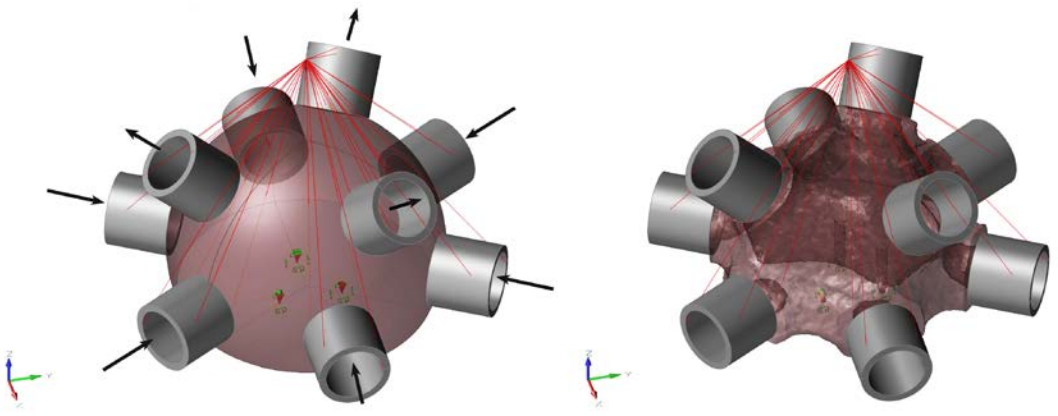

Figure 3: Topology optimization setup to the left, where the node is initially modelled as truncated sphere. Three vertices at the cut plane are locked in a total of 6 degrees of freedom (tx, ty, tz, rx, ry, rz) to ensure numerical stability. The force applied on each bar attachment is indicated with the black arrows, and the resulting shape is shown to the right.

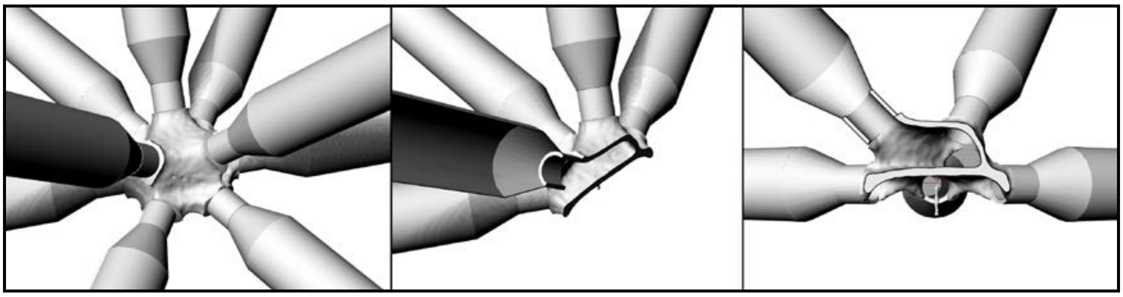

Figure 4: Results from the TO simulation with a symmetric load case. Only a weak strip of material is left as an attachment to the locked nodes that provide support for numerical stability, which indicated little stress has traveled this way and the boundary conditions described in Figure 3 seems to have worked.

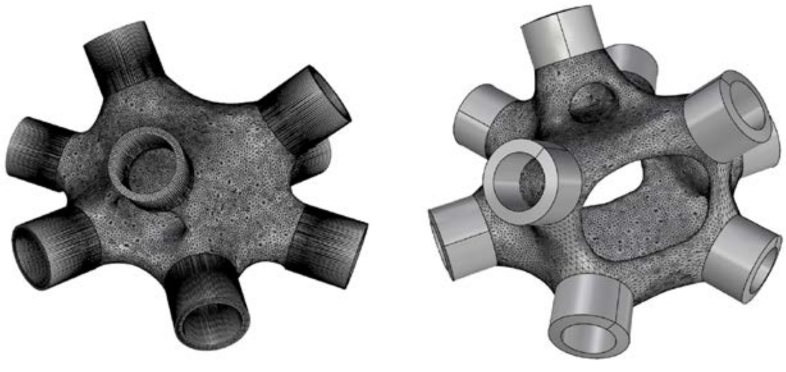

Figure 5: Resulting geometry from two different TO attempts after the geometry has gone through a cleaning process using mesh smoothing. The node to the left comes from a symmetric load case (as described above) and the one two the right is optimized with an envelope of 4 different asymmetric load cases.

The results from the TO approach was found to be satisfying in the sense that material was removed in a convincing way. The resulting shapes were often found as shell like structures (Figure 4, 5), not dissimilar from what one would expect from a minimal surface. The main issue with this method was found to be the lacking of control in relation to design outcome. The method dictates the geometrical topology as well as the resulting form and the designer is left with having try to steer the outcome with rather abstract parameters, like the TO algorithm settings. Thus initiative was taken to look at a different way of shaping the nodes where the process of optimisation is not subtractive but rather alters the shape of the node such that the topology stays intact.

3.3. Form finding approach

The aim with this section is to describe the exploration of an alternative method to TO for creating material efficient expressive structural nodes. The method builds on the assumption that the node will be modelled as a shell where the designer is in control over the geometrical topology (as well as topological connectivity) which is defined in an interplay with the form finding simulation. The whole process can be broken down in a few steps as shown below, some of which are further explained in the following sub sections.

- Global analysis for the governing load case
- Defining the geometrical topology of the shell like node
- Subdividing the node mesh, thus defining the discretised topological connectivity
- Form finding the node
- Applying thickness properties and analysing the node

3.3.1. Defining the topology

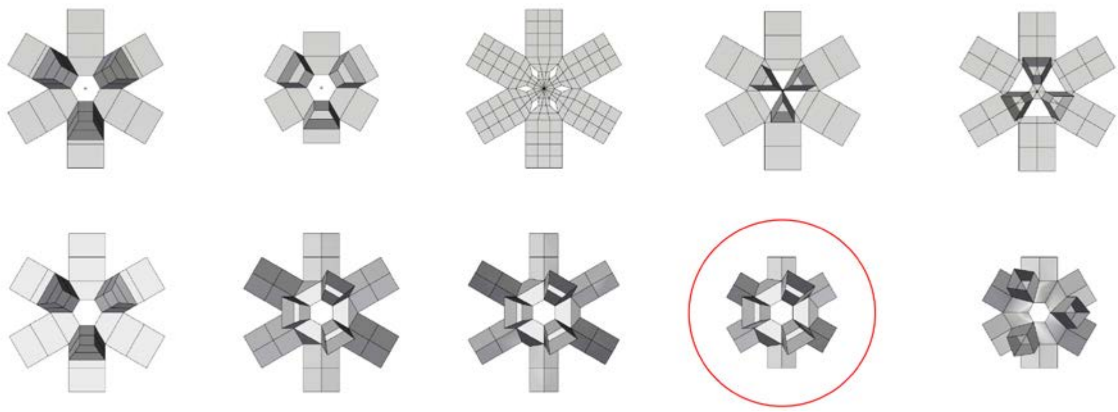

Figure 6: Variation of geometrical topology for the node design which sets the premises for how the node develops in the form finding process. The option in the red circle is used as the example in this article.

The fact that the topology is unchanged in this process is regarded as one of its potential strengths, because that gives the control back to the designer to have a say in the overall expression of the design. Needless to say, not all topologies will work in the form finding process, but that is a constraint which is found reasonable in favor of material efficiency. There for, it was found a necessity for the exploration of possible geometrical topologies to happen in interplay with the form finding process. However, there is also a step in between defining the geometrical topology and the form find, namely the definition of the topological connectivity which is done using subdivision. Two different subdivision schemes were tested for this purpose, a primal quadrilateral quadrisection (PQQ) subdivision [8] paired with the Laplacian smoothing to round of the shape, and a Catmull-Clark subdivision [3], where the later proving to work better and became the method of choice.

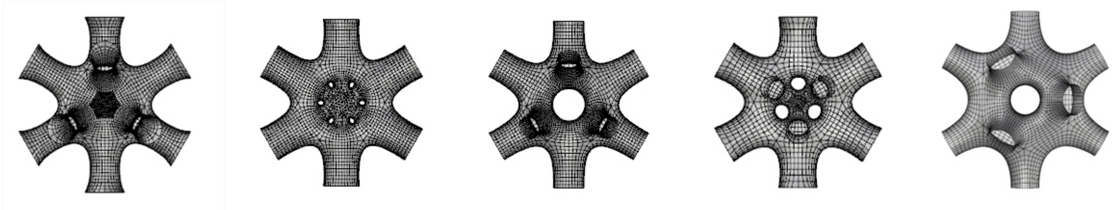

Figure 7: A selection of the initial node geometries are then subdivide into finer meshes using PQQ-subdivision and Catmull-Clark subdivision.

3.3.2. The form finding

This application of form finding in this context is based on the idea that the nodes in the grid structure are exerted to loads that are either tensile or compressive. Each adjacent force is then converted to a tensile force in the form finding process. Since the line of action would be the same the main difference is understood to be the final stress distribution in the node and potential of buckling where the bar transitions to the node. The form finding model is set up using regular spring elements that are given a rest length that is 0.9 x initial length, to prevent the geometry from wrinkling.

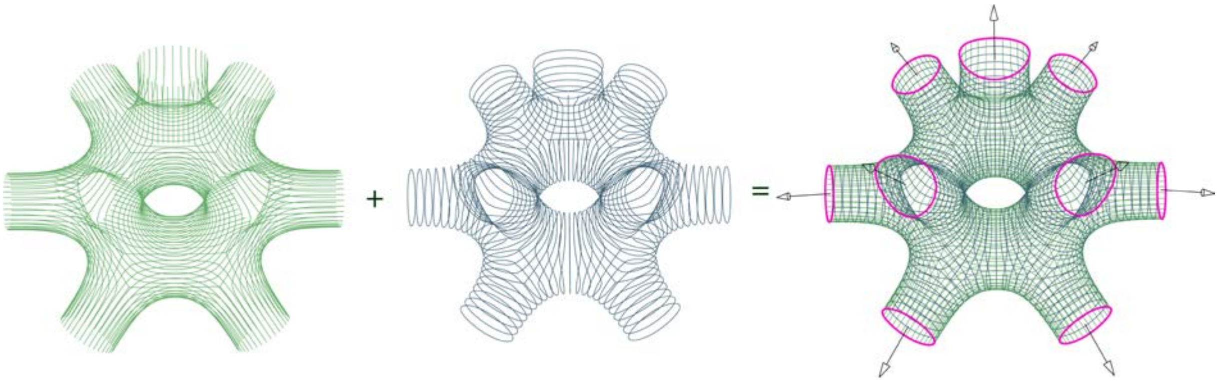

Figure 8: Illustrating the set up for the form finding of a node where tensile forces are applied at the bar attachments. Also showing the buildup of the node geometry which is described using a mix of bi-directional spline elements with bending capabilities and regular springs.

The springs are also sorted in continuous polylines to enable bending capability according to the spline theory as described in [1] which is used as a tool for shaping the node. The bending is useful in the form finding process to avoid that the transition of the shaft to the bar attachment gets a “waist” in the form finding process. It is also found useful to control how much the node flattens when it is stretched by the pulling forces.

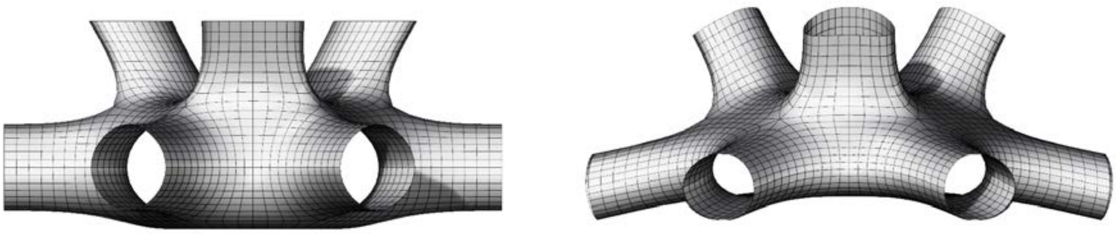

Figure 9: Showing the geometry before (left) and after (right) the form finding.

3.3.3. Analysis check

A proper assessment of the node performance would require non-linear analysis, buckling studies and potentially even fracture and failure simulations, also including a variety of load cases. For the purpose of early stage design development however, analysis here are carried out using a simpler linear FEA solver [2] where the geometry is represented by shell elements with a thickness of 3 mm. The diameter of the node is 0.3 m and with a volume of 4.16e-4 m^3 the total weigh the nodes is 3.4 kg if it is built of structural steel. The load applied on the node consist of a distributed load of 20 kN, a compressive 5.3 kN acting on element attachments e_1 – e_5 and a tensile force of 5.5 kN acting on e_7 – e_9 as shown in Figure 10. The results are checked for maximum and minimum principle stress, which are then compared with the yield limit of steel which is around 250 MPa. For the 3 mm thickness the max absolute value of the principle stress is around 58 MPa for the given load case. Even a shell thickness of 1 mm turns out to pass the yield limit for this case, but is likely too thin for both buckling and additive manufacturing.

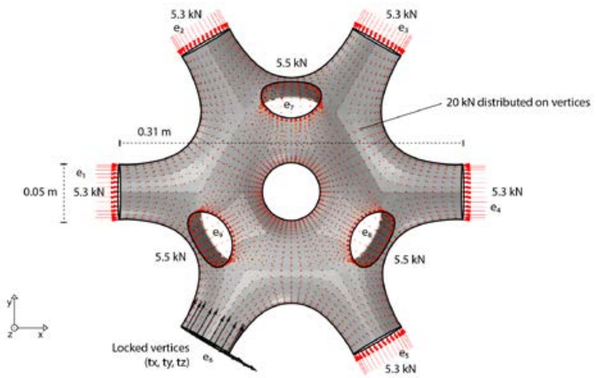

Figure 10: Showing the setup for the analysis where bar end e_6 is locked for translation bar ends $e_1 – e_5$ are loaded with a compressive force, ends $e_7 – e_9$ are loaded with a tensile force, and an external load is distributed over all the mesh vertices in the negative z-direction.

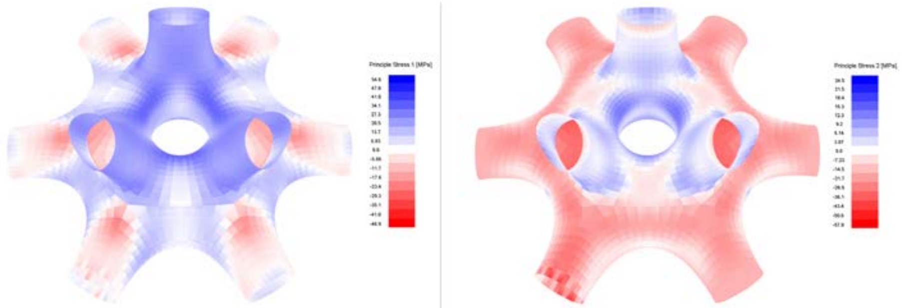

Figure 11: Showing the principle stress distribution in the node which reaches a maximum of 58 MPa in compression and 55 MPa in tension.

4. Discussion

This paper suggest a way to approach shaping of material efficient structural components where the designer remain in control of the topology. The results from the case study is convincing but more test cases in terms of nodal configuration paired with more sophisticated analysis need to be performed to establish a better understanding of the usefulness of the method. In the application of the method in a large scale situation it is suggested that the form finding is performed using prescribed displacements of the nodal bar attachments rather than forces. That would allow for better control in relation to geometrical constraints. It also seems reasonable to combine the two methods which in this example worked well to come up with the final design. Finally the possibilities to manufacture the nodal joint by AM should also be tested and evaluated.

References

[1] Sigrid Maria Louis Adriaenssens. *Stressed spline structures*. PhD thesis. University of Bath (2000)

[2] Preisinger, C. (2013), Linking Structure and Parametric Geometry. Archit Design, 83: 110-113. doi: 10.1002/ad.1564

[3] E Catmull, J Clark, *Recirsively generated B-spline surfaces on arbitrary topological meshes* Computer Aided Design 10, 6 (1978), 350–355.

[4] Sandro L. Vatanabe et al. *Topology optimization with manufacturing constraints: A unified projection-based approach*, Advances in Engineering Sofware 100 p.97-112 (2016)

[5] Grégoire Allaire et al. *Casting constraints in structural optimization via a level-set method*, 10th World Congress on Structural and Multidisciplinary Optimization, Orlando, (2013).

[6] http://mathworld.wolfram.com/Topology.html, (2018-04-29)

[7] Martha Tsigkari et al. *The Computational Challenges of a Mega Space Frame*, ACADIA (2017)

[8] Oswald, Peter and Schröder, Peter, *Composite primal/dual √3-subdivision schemes*. Computer Aided Geometric Design, 20 (3). pp. 135-164. ISSN 0167-8396 (2003).