



Optimizing Structural Building Elements in Metal by using Additive Manufacturing

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Abstract

In order to explore the possibilities of using Additive Manufacturing (AM) techniques for the production of metallic structural elements for the Building Industry research has been carried out by the international engineering firm Arup.

The research is based on the redesign of an existing structural node which is part of a tensegrity structure. Offering much insight into different design steps and tools involved, as well as knowledge on materials, costs and structural characteristics. Earlier results in 2014 delivered the first structural building component designed and produced in metal using AM.

Based on these initial results the design process was fine-tuned focussing on product integration and improved control of the optimisation process. A full set of material tests was executed which should lead to a certification process required for specifying AM-produced products in the Building Industry. This paper shows our latest results.

Keywords: additive manufacturing, 3D printing, topology optimization, tensegrity structure, structural nodes, metal, product integration, weight reduction, material research, production rules.

1. Introduction

From 2008 till 2013 Arup was involved in the design of multiple tensegrity structures for the Grote Marktstraat in The Hague, the Netherlands, which were to be used as street lighting. One of the three larger structures is shown on the next page. Tensegrity - tensional integrity - is a structural principle based on the use of isolated components in compression inside a net of continuous tension, in such a way that the compressed members do not directly connect and the tension cables define the system spatially (Snelson [5]).



Figure 1: Artist impression of one of the original tensegrity structures in The Hague.
This design will not be built as such. Architect: ELV Architecten © Studio i2

Due to the intentionally irregular shape of the elements, the structural nodes, connecting the cables to the struts within the tensegrity, all have slightly different shapes. In all different elements together there are over a thousand variations in angle and position of the attached cables.

Conventional production of the nodes includes high labour intensity as it is literally a ‘one of production with very little rationalization. Each node will be made from six to seven unique machined steel plates, welded on a central tube in varying directions.

Funded by *Invest in Arup* we were able to explore novel methods of production in order to research opportunities to produce the nodes in a faster and smarter way. This research project has been executed separately from the original project and only after our work on it was finished.

1.1. Additive Manufacturing

The term Additive Manufacturing refers to a whole set of different production techniques, able to process different groups of materials like plastics, metals and ceramics. The American Society for Testing and Materials (ASTM) defines it as ‘a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining’ [1].

During this research project we focused specifically on Direct Metal Laser Sintering (DMLS). During the production process, powdered metal material is selectively melted layer by layer by lasers. Layers typically have a thickness of 20-100 μm . The metal is fully melted into a solid homogeneous mass. There is a wide variety of alloys available and new ones are continuously being developed.

Products produced by DMLS can have thin walls, deep cavities or hidden channels, but sometimes need support structures due to the weight of the solidified material and heat dissipation. The technique is mostly used in industries that benefit from weight reduction and where products are complex and produced in low quantities, like the aviation, aerospace and automotive industry (Diegel et al [3]).

2. Method

Our continued research focused on comparison of a structural element produced by traditional fabrication methods and one optimized for and produced by AM. Providing insight into the different design steps, tools used and a comparison of the outcomes on process, functionality, costs and structural characteristics. We formulated the following questions:

1. Design – How can we best incorporate the added value of AM and how does this influence the process and final design?
2. Tools – What do we expect from digital support tools when designing for AM and are these tools already available?
3. Material properties – What can we say about the behaviour of printed products and what further information and steps do we need to take so that AM products can be specified on building projects?

2.1. Design

We understood that the best optimizations are achieved taking the context into account. In addition to the function of connecting the structural elements, cables and struts, of the tensegrity structure and holding up the lighting fixture, we added:

The goal of this design exercise is to integrate as much functionality as possible in the node, in addition to the basic compression of the structure (struts), tension (cables) and lighting (fixture).

This means that the node should provide the connection to the cables, strut and lighting fixture, but also adjustability to make the cables longer or shorter and simplified data and power connection.

We focussed on a single node, but the design requirements were set up in a way that they could be used for all nodes in the structure. These would then be developed parametrically, based on the boundary conditions that were set.

2.2. Tools

Finding a topology optimised structure for AM is a process that relies heavily on the use of computational tools (Brckett et al [2]). Furthermore translation of a single set of design requirements in excess of a thousand slightly different configurations requires an automated process. With this in mind we tried to find a set of tools that could integrate attributes through simple interfaces.

The design process covers a wide range of techniques from parametric modelling, FEM analysis, optimization iteration, organic form modelling, digital sculpting, and mesh topology editing. It is obvious that no single design or analysis tool combines all of these different aspects. Closely coupled with the design process, various tools with different functionalities were evaluated and used for each design stage.

Altair's OptiStruct was selected as the program for the topology optimization of the node design. In addition other packages were used in the pre- and post-optimization process.

2.3. Material properties

Considering the evolution of the design and the context of this phase of the project, 1.4404 stainless steel (equivalent to 316L) was selected from the standard range offered by the manufacturer. The selection was based on the required performance and durability but also familiarity and experience in similar built environment applications.

The mechanical properties quoted by the manufacturer met the basic design requirements and a schedule of production testing was compiled not only to validate the properties, but to expand on the currently available physical and mechanical test data. The test schedule was developed to quantify some of the fundamental metallurgical properties of the material, resulting from the additive layer laser melting process. Properties investigated included dimensional repeatability, surface texture, hardness, tensile, impact properties and microstructure, considering expected anisotropy and the effect of thermal treatment.

Standardisation can only be applied loosely around the general parameters of the technology. As every item produced by AM is unique, it is necessary to quantify materials properties and performance on a case by case or project by project basis. By considering conventional products in the cast, wrought and fabricated condition, we had a basis to compare our results and expectations to attempt to validate the performance of our product.

3. Results

3.1. Design concept

In previous research we concluded that a substantial reduction of the weight of the node was possible, at least 30% and possibly up to 70% (Galjaard et al [4]). This weight reduction influences the forces in the tensegrity structure and might allow for a reduction in cable and strut sizes.

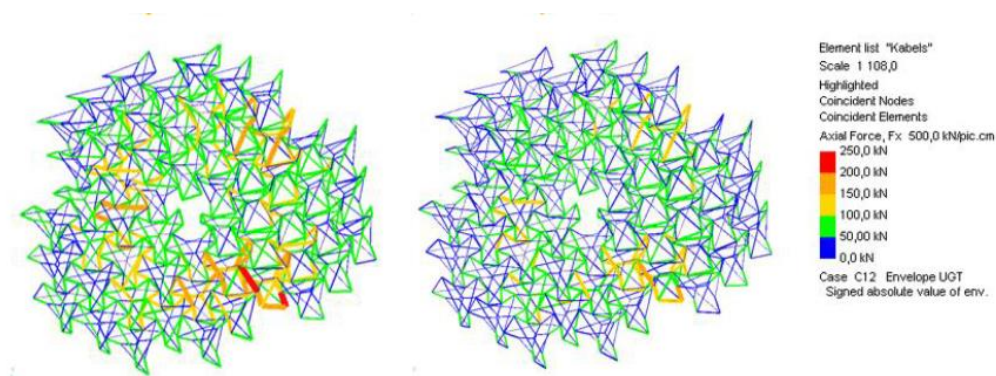


Figure 2: The forces in the cables compared after weight adjustment of the nodes.
Left original model, right new model.

The forces in the structure are determined by the pre-stress of the cables. The self-weight of the structure is a significant contributing load as the other live loads from wind, snow, temperature or maintenance are relatively small due to the open nature of the structure and its functionality.

A conservative reduction of 50% of the weight of the nodes was recalculated with the force density method using Oasys General Structural Analysis (Oasys GSA v8.6) to determine the influence on the pre-stress and sizes of the structural elements. A new equilibrium with smaller sized struts and cables was found. This model had similar overall behaviour when deflections and allowable stresses were compared. Both the compression in the strut and the tension in the cables is reduced by 20%, illustrated in figure 2 on the previous page. Because of the smaller elements the deflections from single load cases did increase, these were however found to be acceptable.

The connection of the cables to the node was the most challenging interface to develop as all different functions come together. The tension-only connection should compensate the lengthening of the cables, provide post tensioning to the system and allow for some rotation.

The original connection uses a pin & fork connection and an additional spanner per cable. Because of the standard detailing of the fork the connection to the node requires a considerable distance to the centre of the node. The functional integration of the turnbuckle and pin & fork leads to a smaller node and reduction of separate elements in the design. The selected concept is based on this approach, in which the cable is connected from the inside of the node as illustrated in the sketch in figure 3. The cable has a standard threaded end, fixed with a bolt which allowed for a simplified spanner option. This bolt in combination with the node now has a double function as a stopper and a spanner. This alternative provides sufficient room to access the bolt from within.

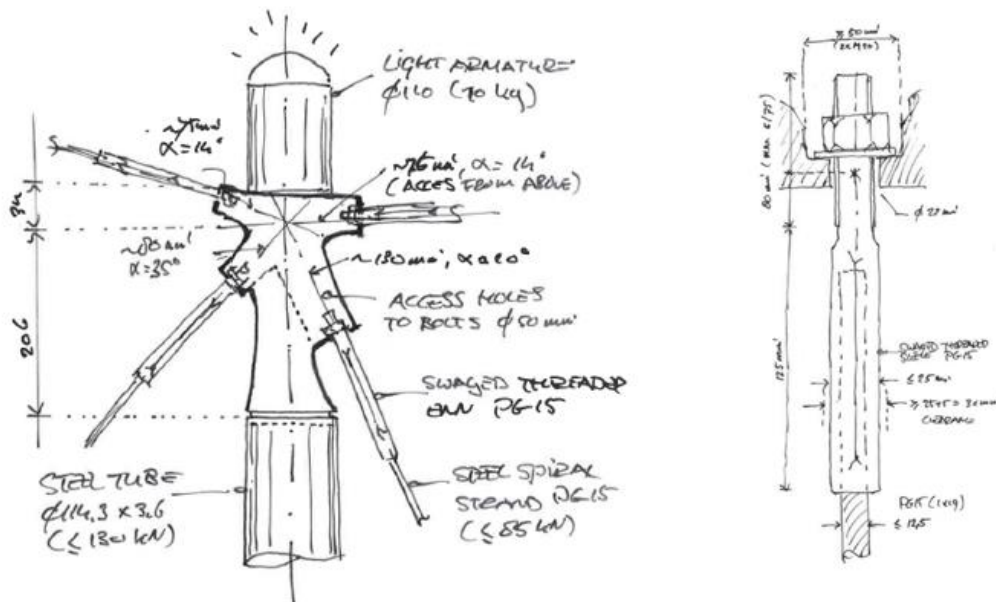


Figure 3: Sketch of the selected concept design with the different interfaces of the node, at the right detail of the swaged threaded end connection.

3.2. Designing with the software

Having determined the functional requirements and the interfaces, the design of the node was developed digitally in an iterative design process using the topology optimization method.

The design space was modelled in a Rhino/Grasshopper (Robbert McNeel v. 0.9.0075) environment (see figure below) which allows for setting up the model parametrically and adjusting the design space quickly in case of different cable configuration for another node.

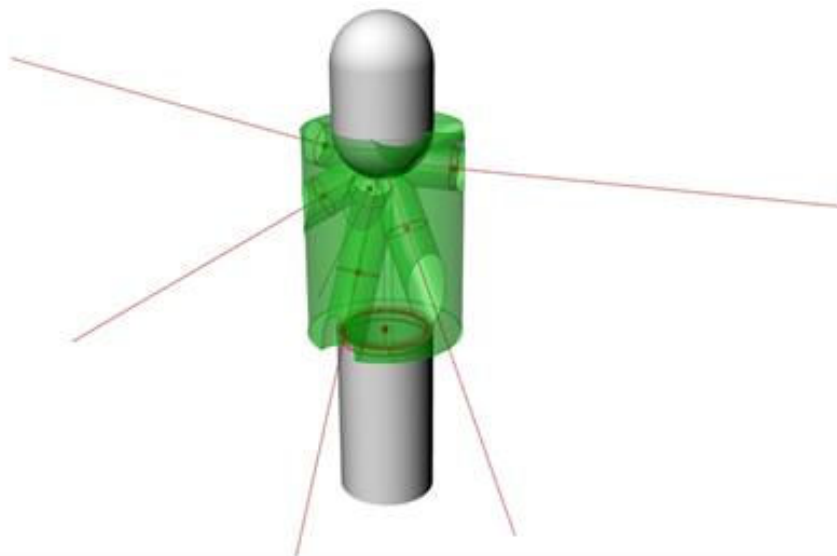


Figure 4: Parametric design space of the node allowing for all different configurations of the nodes.

3.2.1. The optimization approach

Given the design space and boundary conditions, a topology optimization was performed with OptiStruct (Altair Optistruct v11), which is a structural analysis and optimization package provided by Altair for our research. It features an optimization algorithm and an integrated FEM solver with multiple types of elements and analysis types available. Coupled with Hypermesh as the pre-processing interface, a topology optimization could be set up with a specified design objective in respect to the design constraints.

The geometry as defined previously was meshed with solid elements and the boundary constraints and load case were both applied. The material properties for the stainless steel has been applied with the stress limit set at 400 MPa, 80% of the maximum tensile strength.

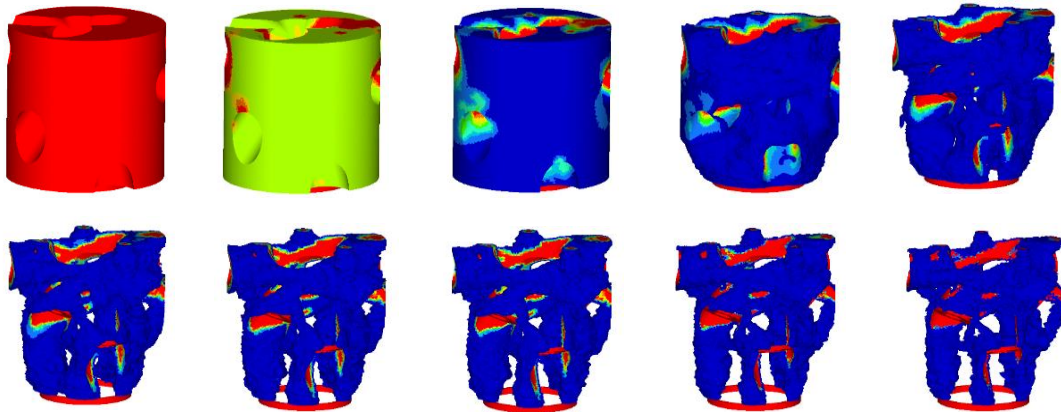


Figure 5: Topology optimization process of the node in OptiStruct.

A design space was then defined for the topology optimization as the maximum volume within which the optimization can occur by “removing” material when it is less loaded. The design objective is set to minimize the total structural weight. The Von Mises stress was analysed as a design constraint during the optimization process. The image above shows intermediate steps in the process.

3.2.2. Refining and preparing for production

The output of the topology optimization provides an optimal shape for the node within the boundary conditions and functional requirements, but only in a rough form. This form needs further refinement to incorporate the interfaces in detail and smooth the geometry. This is done by a mixed use of tools.

In order to produce the node, the design also needs to take the production requirements of the AM process into account. Based on an initial analysis by the producer 3D Systems, the optimal printing direction was determined from the bottom connection to the strut to the top.

The areas with a hangover angle less than 45° to the horizontal plane were then modified to increase the self-supporting features. The threaded end that inserted into the node and the 50 mm inner space needed for reaching the bolt as stopper and spanner both lead to horizontal surfaces that are more difficult to produce. The horizontal surfaces require support structure within the inner space which is then difficult to remove and ideally should be prevented as much as possible in the design. Figure 6 on the next page shows some of the modifications that were made.

Design priority was placed on the structural efficiency of the shape and the functional requirements defined for the node. The time consuming process of refining the shape would highly benefit from dedicated software with for instance intergraded production rules.

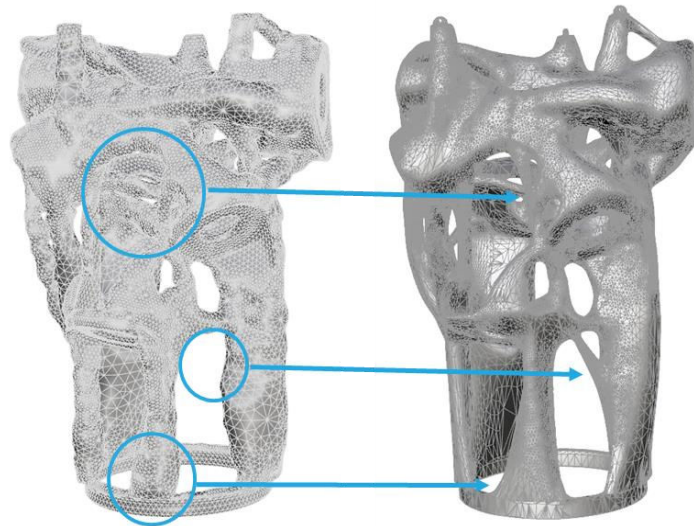


Figure 6: Comparison of the rough form (left) with the optimized-for-production model (right).

3.3. Material properties

The test results were in accordance with those quoted by the manufacturer and the alloy chemical composition met the requirements of the material standard (BS EN ISO 10088-1:2014). The 'as-built' tensile test specimens exhibited hardness, strength and ductility similar to cast, wrought and fabricated products in similar conditions. Room temperature impact test results were satisfactory and in accordance with the expected behaviour given the strength and ductility exhibited by the previous mechanical tests. Impact test specimens were built in the horizontal and vertical orientations to account for anisotropy, the measured toughness was uniform across the sample population and independent of build orientation.

Dimensional comparison of the impact test pieces exhibited reproducibility and repeatability with a maximum variation of 0.1mm in the transverse direction and 0.35mm in the longitudinal direction. The dimensional stability of the test specimens was unaffected by solution annealing heat treatment. The as-built microstructure was austenitic with negligible ferrite content, the grain morphology was columnar in the build direction and consistent with the feedstock of regular spherical gas atomised powder metal particles.

In summary, from the tests performed, the mechanical properties achieved were largely in accordance with typical wrought product forms, such as bars, plates, sheets and tubes in the solution annealed and mildly cold worked conditions. All of the test results conformed to the requirements of relevant international product standards for comparative products. The results were very encouraging in the context of the project and demonstrate that current selective laser melting techniques, applied to suitable materials present a valid technology for the production of components of satisfactory quality and integrity.

4. Discussion

After gaining some experience designing for AM, we took the design approach of a structural node one step further, focusing on uniqueness, weight optimization and product-integration. This resulted in a conceptual design process in which the implications of design decisions for production had to be foreseen. This isn't in essence different from a traditional design process, but in this case more complex because of our lack of experience with the selected production technique.

The design method with topology optimization and the production freedom of the AM technique allow for many new possibilities. However this also raised high level demands on computational skills together with the implementation of complex computational design tools. The topology optimization program that has been evaluated and used during our design process has shown robust performance with affordable design and computational time. On the other side, the post-optimization activities are still a time-consuming process. Better software support could well improve the efficiency of this process.

The latest optimized node is 75% lighter than the original and half the height. Taking weight reductions from the reduced struts and the now integrated connections into account, the structure as a whole could be more than 40% lighter because of these optimizations.

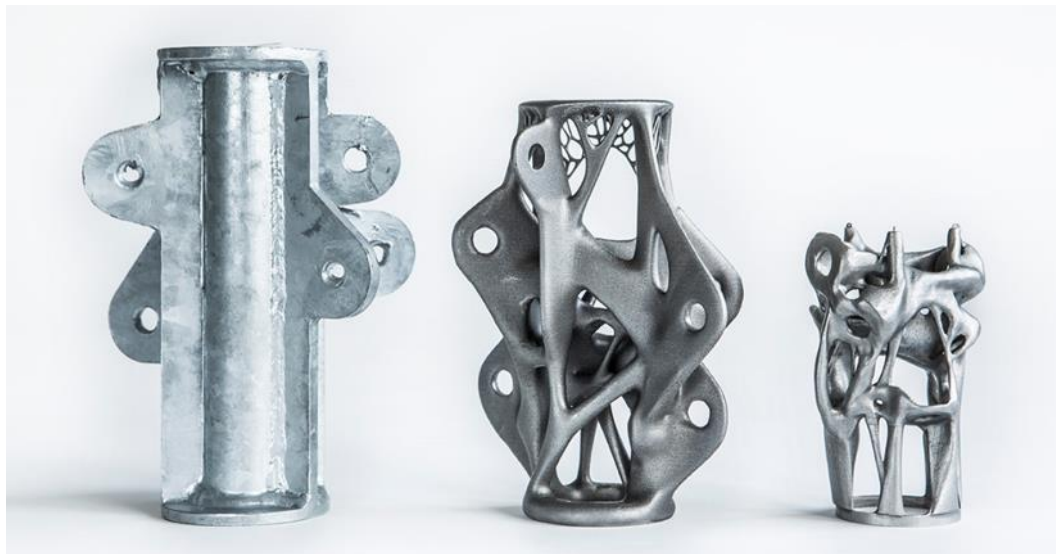


Figure 7: Models of the traditional node (left) and the two new nodes, in the middle the first node produced by AM in steel in 2014, at the right the latest optimization also produced by AM.

Incorporating production requirements required a lot of effort in order to deal with design conflicts between the optimal production shape with the functionalities and the structural efficiency. Printing and removing the support structure was a relatively expensive part of the production process. Depending on the requirements of the project, it would be beneficial to find a better balance between functional optimization and production.

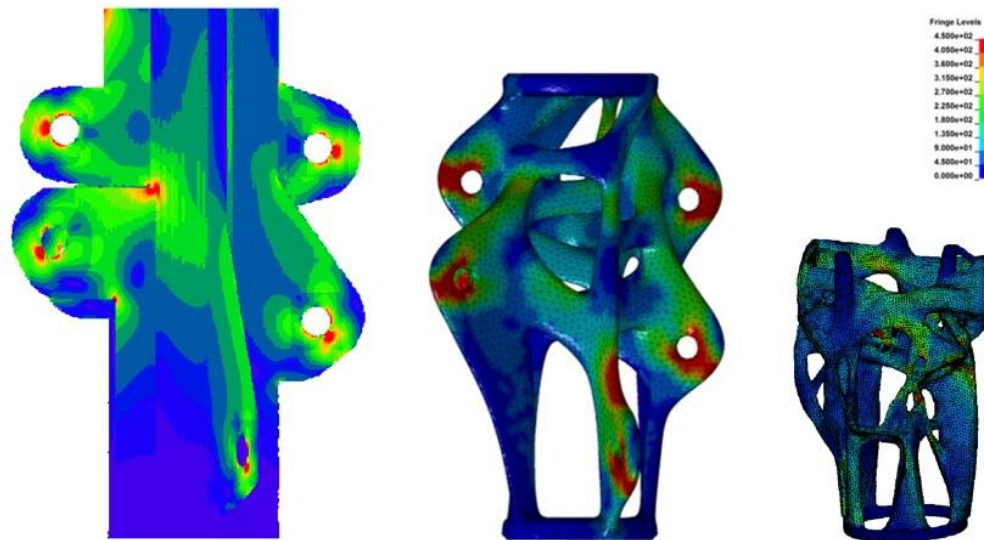


Figure 8: Plot of Von Mises Stresses in [MPa], the original design (left), the AM node 1.0 (middle), and the new design AM node 2.0 (right). Highest stresses can be observed in red, lowest in blue.

Structural comparison showed that all three designs were able to take the design loads. The Von Mises stresses are lower than the yield stress with the exception of local peak values which would be acceptable given the plastic behaviour of the steel.

The cost of the AM node are at present still higher than the traditional version. In the new design we included the functionality of the pin & fork and spanner, eliminating the need for these separate and relatively costly elements as illustrated in the render in figure 9 on the next page. These kind of advantages can be very decisive in selecting AM when successfully incorporated in the design. Other potential benefits include automatic generation of production files, reduction of (waste) material and labour, reduction of transportation cost and storage and lower maintenance and failure cost.

The material tests demonstrated that it is possible to achieve satisfactory mechanical and physical properties using powder bed laser melting technology. We must however recognise that different materials and alloys will behave in different ways, therefore it is important that each project and application is considered on a case by case basis. Stainless steel is widely understood in the context of fusion technology and responds well in welding and fabrication. Many of the characteristics of powder bed AM are comparable to welding technologies.

It is difficult to find examples of additive manufacturing applied to common engineering materials such as mild and carbon steels, aluminium alloys and copper alloys, simply because the technology is only beginning to find its way in applications in our industry. Future work in the context of the built environment should further address these materials and applications whilst continuing to showcase the other related benefits of the technology.

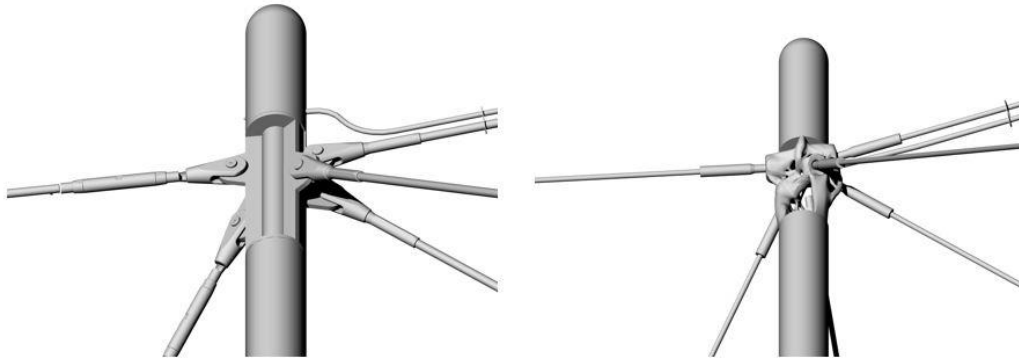


Figure 9: Render of the traditional design (left) and AM Node 2.0 (right) showing the nodes on the end of the strut with the connecting cables and light fixture.

5. Conclusion

By learning from the previous design process for AM we were able to approach the product from a new direction. Only with this new iteration we realize how close we still were to the traditional design regarding shape and design approach. This time we allowed ourselves to completely revise the design approach, resulting in a very efficient product with integrated functionality. The new design leads to a structure weighing almost half of the original design.

We looked at a whole range of available digital support tools to develop the design and automate the generative process for all nodes. The selected software showed good performance suitable for a specific task but lacked desired interaction and ease of operability for our design process. Automatic generative design of all the nodes in the structure is not yet possible in an efficient way. The whole process would highly benefit from appropriated software for an activity like this.

The stainless steel used in the AM production of the node showed comparable properties to other more conventional production methods and new materials and applications will likely come available for the Building Industry in the future. Standardisation of the general parameters of the technology should initially be accompanied by validating material properties and performance on project basis.



Figure 10: Image from the stainless steel AM node with connecting threaded swaged ends to the cables, the light armature and strut are not present.

References

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