Application of Topology Optimisation to Steel Node-Connections and Additive Manufacturing

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Abstract. Structural Topology Optimisation (STO) is a prevalent optimisation technique used nowadays to reach desired weight-to-stiffness ratios via highly complex and efficient designs unable to achieve otherwise. Additive manufacturing (AM) is widely known in the manufacturing industry and provides designers with a higher degree of freedom in realising highly optimised designs through a layer-based fabrication process. This paper focuses on reticulated structures and proposes using STO and AM to design and fabricate alternative connection designs with outstanding bespoke performance and drastically reduced weight. It studies the optimisation of a conventional node-connection found in reticulated timber structures under four loading cases, to producing state-of-the-art optimised connection designs, each capable of withstanding one of the four selected loading cases. The results are compared with the conventional node-connection, and the optimised configurations achieved up to 46.9% weight reduction. A selection of the highly bespoke scaled-down designs was additively manufactured in two different materials (metallic and polymer) as a proof of concept for the capacity of the technologies available for future testing.

Keywords: Structural Topology Optimisation · Additive Manufacturing · Structural connections · 3D printing · Reticulated structures · Advanced manufacturing

1 Introduction

1.1 Background and Critical Review

Reticulated roofs are highly versatile structures and are widely used for large and landmark projects. Otherwise known as spatial structures, such structures achieve a cost-effective span-weight ratio for roof constructions while reducing the number of intermediate column supports required. Their numerous applications range from stadiums to warehouses to aircraft hangers [1]. Fundamental changes and improvements have been undertaken on such structures over the years to increase their structural capacity, simplify their fabrication and erection techniques, and improve the performance of their node-connections. Yet, the fundamental worldwide shift in architectural

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perspectives from modular and repetitive to free-form and unique is imposing critical challenges and limitations, most of which are related to the connections of such structural systems.

Recent attempts by researchers aimed at exploring the potential of using Structural Topology Optimisation (STO) as a mean of creating bespoke node-connection designs which can accommodate the variability of the tie member directions and angles in free-form shapes [2–4]. The node-connection designs achieved had the major benefit of attaining significant weight reductions which on a large scale can result in an improvement to the overall structural performance. Such node-connection designs were observed to have geometrical complexities and curvature patterns which were highly challenging to construct using traditional fabrication methods such as milling, casting or using subtractive manufacturing. Additive manufacturing emerged as the ideal fabrication solution for this challenge.

1.2 Background and Critical Review

Additive Manufacturing (AM) allows designers to create physical models through depositing and joining thin layers of a material together based on a three dimensional computer model [5]. Research institutions and the industry worldwide are investing in AM due to its high precision and minimal fabrication limitations when compared to traditional manufacturing. The technology has been industrialised since the 90 s through improving the fabrication processes and allowing fabrication using a wider range of materials which include metals, ceramics, and polymers [6]. From the literature, it is apparent that manufacturing industries related to aerospace, automotive, and medical (e.g., prosthetics) have declared strong interest in attaining the full potential of AM, unlike the construction industry which seems to be moving at a much slower pace for a number of reasons (e.g., size of printed elements, high load bearing, long lifespan, etc.) [6]. This paper aims to support the research in bridging the gap between AM and its application in the construction industry through the adoption of additively manufactured node-connections for reticulated structures.

1.3 Research Objectives

The aim is to build upon previous research attempts through optimising single-layer node-connections, and testing against several loading cases that allow for a deeper understanding and interpretation of the optimised designs. The need for creating several connections is to allow for a fair comparison between a range of results and a conventional connection that provides inherent robustness previously associated with the uncertainly of loading cases and simplistic designs. Meticulous optimisation studies and numerical analyses with specialised and sophisticated software tools are employed to carry out this research.

2 Selection Criteria of the Connection Design

A comprehensive study was undertaken to identify practical node-connections commonly used in the industry and choose the potential candidate which would represent the control sample. Simplicity was the key part of the research, therefore, a list of questions was prepared which helped decide upon the joint type which is likely to be the simplest to model and optimise. Yet, that will yield significant weight reductions which then translate to reduced carbon emissions and a more sustainable design. The questions considered include the following:

- What is the total volume occupied by the connection?
- What is the material percentage in the total volume occupied by the connection?
- How simple would the connection be to create, model, and test?
- How simple would the connection be to predict its behaviour upon modelling?
- Does the connection need to have any internal bolting or welding?
- How are the tie members attached to the connection?
- How much commercial knowledge is available to judge upon the typical loading capacity and dimensions of the connection?

3 Conventional Node-Connection Design Concept

Given the above questions and after reviewing numerous connection types, the Splice Node-Connection "POLO-1" shown in Fig. 1 has been chosen as it represented the ideal candidate for this research study [7, 8]. The applications employ this connection range from geodesic domes to reticulated structures. The connection consists of a central thick RHS core with several splice plates welded to it. The tie members attached to this connection are fabricated with a fork-shaped ending which fits in between the plates of the connection. The central RHS region provided the large volume needed for the freedom to apply the shape formation with the optimisation algorithm and easily interpret the formed designs and structural behaviour. Furthermore, eliminating any bolts from the core part of the connection and keeping the bolting to the external splice steel plates, provide further simplicity while running the analysis.

Fig. 1. Splice node-connection "POLO-1" [9, 10].

3.1 Connection Anatomy

The structure of the connection was divided into two regions, the design domain and non-design domain. The design domain region as shown in red in Fig. 2, is the region which was optimised by the software. The non-design domain region, not optimised by the software, consists of the connecting splice steel plates indicated in grey, and the semi-cylindrical members indicated in green which were added to allow for improved stress flow and shape development within the design domain area. Similar model division has been undertaken in the conventional connection design to ensure a fair comparison between the stress and strain level of the results of both the conventional and optimised connections.

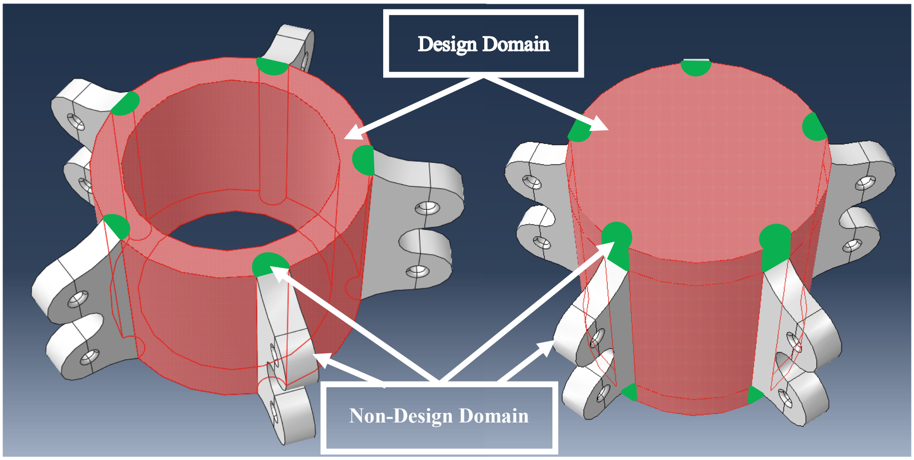


Fig. 2. Design anatomy of the conventional node-connection and “Connection A”.

3.2 Design Dimensions

The dimensions and geometries of the connection of reticulated structures are commercial design ‘secrets’ which are usually developed through years of development and testing. As a result, only limited design information concerning these connections are provided by the manufacturers. The research team herein adopted case studies from the industry to select representative connection dimensions which are suitable for connecting to available structural strut options. A practical case study is the Eden Project dome which was designed using a bespoke type of semi-spherical nodes known as the top chord “bowl” node [11]. The node had a diameter of 400 mm, a plate thickness of 40 mm, a weight of about 80 kg and a chord tube diameter of 193.7 mm. Following the same design indications provided in the case study, a POLO-1 node with similar dimensions was produced as shown in Fig. 3. The node-connection can practically connect a 300 mm deep timber joist or a steel circular/rectangular hollow section using fork-like fin-plate connection as indicated below in Fig. 4 below. The conventional node-connection design weighted around 127 kg per joint in full scale.

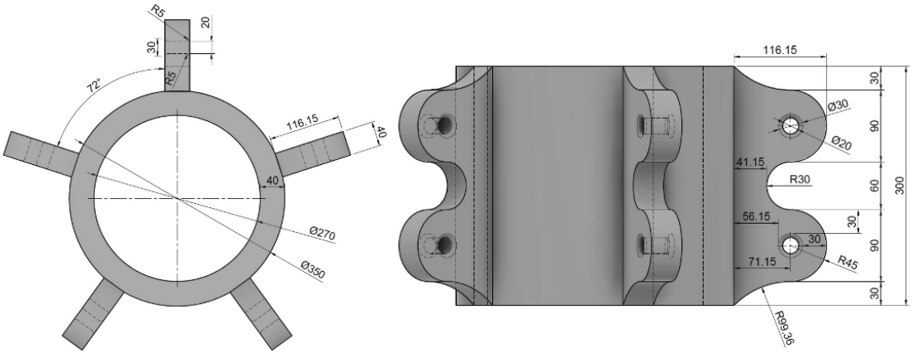


Fig. 3. Dimensions of the conventional node-connection.

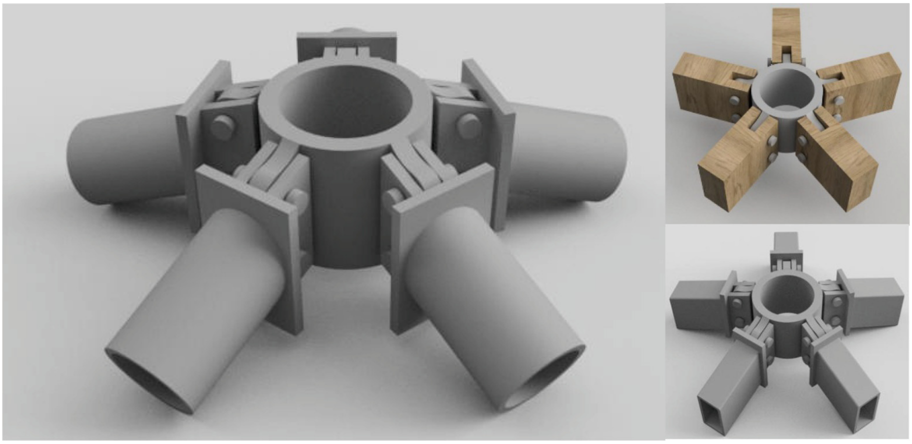


Fig. 4. Visualisation of the conventional node-connection with tie members.

3.3 Load Cases

The four connection test samples were analysed each against one of the four loading cases as shown in Fig. 5. These loading cases have the benefit of simulating a spectrum of asymmetrical loading scenarios and provide the variations required in the loading types (tensile/compressive) and magnitudes. Even though this connection type has some inherent moment capacity to it, industry practices were followed in this research through only applying axial loads in the optimisation process. The resultant of all the applied loads in each of the four loading cases sums up to zero, thus in equilibrium.

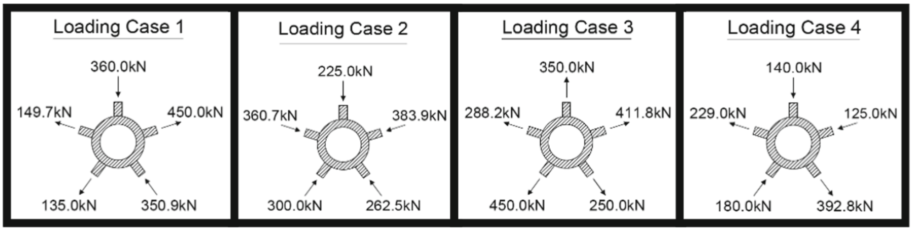


Fig. 5. Loading cases applied to the node-connections.

3.4 Methods and Tools

Three software packages were used throughout the various stages of this research. Fusion 360 was the main design tool which was used to create the connection designs and undertake shape improvements. ABAQUS/CAE was used for the FE analysis testing and the STO stages. MeshMixer was then used to post-process and refine the rough and low-quality connection designs extracted from ABAQUS to more printable structures.

4 Optimisation Process

The optimisation process used in this research, as shown in Fig. 6, contains the core elements from the processes established by previous relevant research [12, 13]. Steps 1 and 2 in the design process started by creating the conventional connection model in Fusion 360 and visually optimise its shape [14]. A modified version of the conventional connection shown in step 3 was created with the central void filled with material. This modified version which is referred to as “Connection A” was utilised during the optimisation task. “Connection A” was imported into ABAQUS, meshed and analysed separately against each of the four loading cases considered, as shown in steps 4 and 5. “Connection A” was then optimised in step 6 at a specified weight percentage against one loading case at a time to obtain the final optimised results after roughly three hundred trials. To obtain “Connection B” which was optimised simultaneously against the abovementioned four loading cases, step 6 was re-undertaken with the four loading cases input into the software rather than one single case. Designing one joint against one loading case early on, is a step in the process of attaining and analysing the resulted “Connection B”. The structural integrity and robustness along with the manufacturability of the produced optimised connections in step 7 were visually assessed using engineering intuition and an understanding of the AM processes involved. As a result, a continous trial and improvement cycle was undertaken between stages 3 and 7 to indentify the optimal design parameters which produces some highly robust and producable connections. In steps 7 and 8, the produced designs were then exported from ABAQUS to MeshMixer for post-processing and smoothening to prepare for the AM process. Finally, in step 10, the modified conventional connection design was imported into ABAQUS and applied the same conditions, and tested against the aforesaid loading cases in order to act as the control sample in this research.

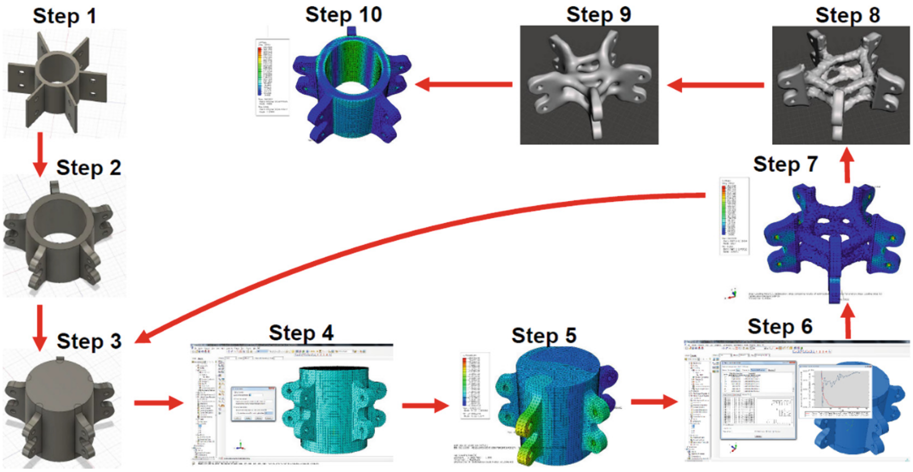


Fig. 6. The design process.

4.1 Design Modifications

Initial modifications to the design of the splice steel plates were introduced through adding the semi-circular shape shown in Fig. 7 around the bolt holes in all the considered models and filleting the sharp edges of the holes. Such modifications allowed for a further reduction in the overall weight of the connections, allowed for a better stress flow through the structure and utilised the full fabrication potential of AM through introducing complex geometry.

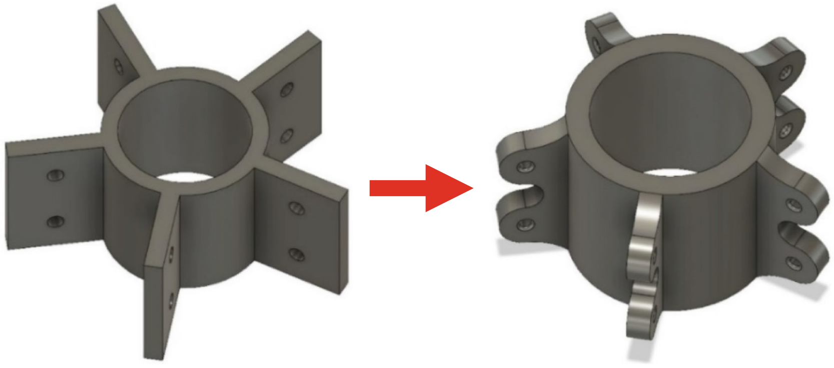


Fig. 7. Splice Node-Connection “Polo-1” before and after design modifications.

4.2 Material Properties and Permissible Stress Levels

For all the node-connections in this project, a steel grade of S355 was used to define the material properties; 210GPA was chosen as the Modulus of Elasticity and 0.3 as the

Poisson's ratio. An early assumption was made regarding the permissible stress levels in the node-connections (permissible strain energy is used in the design of free-form reticulated structures). A linear-elastic analysis was undertaken; therefore, it was assumed the stress levels in the design-domain region of the connections shall not exceed 355 N/mm^2. The loading cases and percentage weight reduction considered were achieved through trying a number of iterations while monitoring the maximum stress levels observed.

4.3 Meshing

"Connection A" was imported in ABAQUS and the properties were assigned as well as the loads and boundary conditions were applied. The FE mesh of the connection is shown in Fig. 8. A free meshing technique using quadratic tetrahedron element (Element type: C3D10) was employed due to the model's complex geometry. The mesh size was chosen as 12 (unit less) and remained constant across all the models undertaken in this research to avoid accuracy-related variations. The number of elements and nodes obtained in the model are 148,438 and 212,127, respectively.

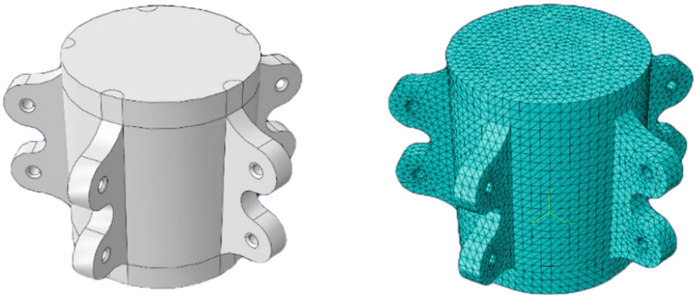


Fig. 8. FE mesh of "Connection A" for the optimisation

4.4 Weight Percentage

The weight percentage target of "Connection A" to be used in the optimisation tasks was set in the analysis tool as 53.1% (reduce weight by 46.9%), which produced optimal designs that consistently remained within the linear elastic range. Increasing the weight reduction percentage in most of the optimisation tasks resulted in the failure of the resulted optimised joint designs. The optimised real-size connections weighted approximately 67.5 kg on average, achieving a weight reduction of 59.5 kg compared to the conventional connection. Studying the stress flow within the connection and applying further modifications could help reduce the weight even further.

The few initial loading cases considered when optimising "Connection A" were excluded either due to excessively high stress levels or minimal material formation in certain areas. This minimal material formation in the optimisation study was later linked to low applied loads, which resulted in low straining, and since the STO tool is driven by increasing strain, minimal or no material was formed throughout the design-domain region. Based on that, loading cases with high enough magnitudes were selected. These loading cases utilised a significant capacity of the splice steel plates and resulted in a reasonable material formation throughout the design-domain region.

4.5 Optimisation Approach

A stiffness-based structural topology optimisation process has been adopted in this research which allows the addition of material only in the regions displaying noticeable displacement in the structure. Thus, the design-domain region in "Connection A" has been filled with material as shown in Fig. 8 to undertake the optimisation work.

Following the model preparation, the design-domain region was defined in ABAQUS and "Minimising the connection volume" of the target volume was introduced as the optimisation objective, while "Minimising the maximum design response values" of the strain energy was taken as the optimisation constraint. For each of the loading cases, an optimised design has been obtained as shown in Figs. 9, 10, 11 and 12. In order to obtain "Connection B" which is shown in Fig. 13, the optimisation objective remained the same, while the optimisation constraint was changed to account for the maximum strain value associated with each loading case. The maximum number of cycles allowed in each optimisation trial was taken as 200 cycles, which was proven adequate to allow the software to reach the optimal design, achieving the highest stiffness at the target volume specified. The actual number of cycles ranged from 28 to 50.

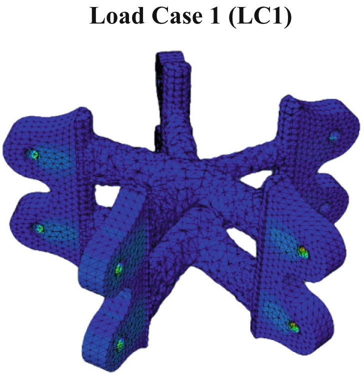


Fig. 9. LC1 optimised design.

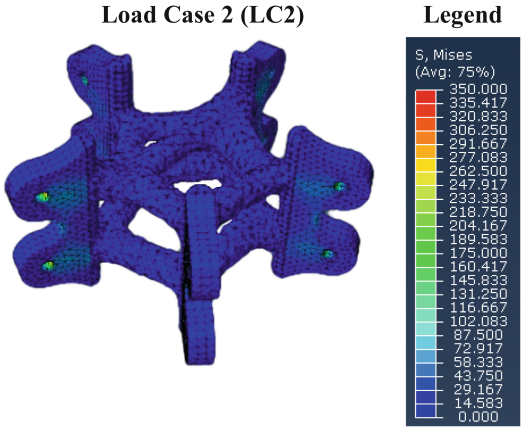


Fig. 10. LC2 optimised design.

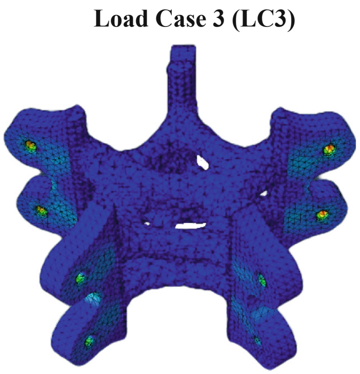

Load Case 3 (LC3)

Fig. 11. LC3 optimised design.

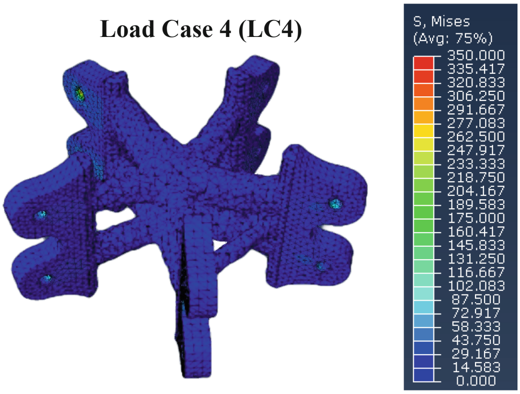

Load Case 4 (LC4)

Fig. 12. LC4 optimised design.

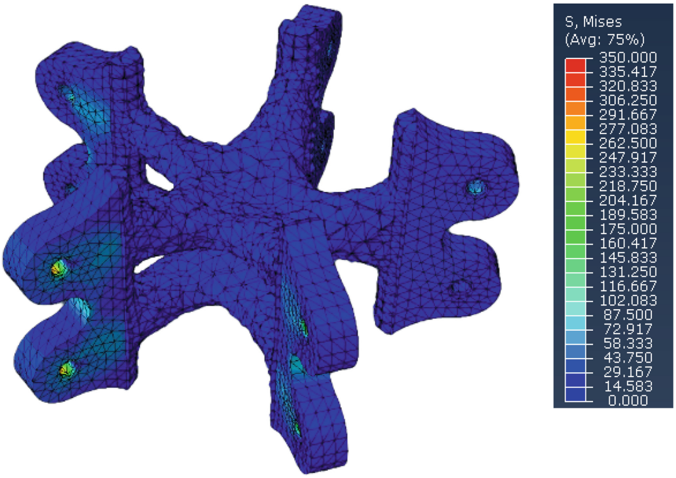


Fig. 13. FEA structural testing of “Connection B” against LC1

4.6 Comparative Study

Once all the optimisation work has been undertaken, the same load cases used in the optimisation tasks were applied to the reference connection. Figure 14 shows the Von Misses stress contour plot of the conventional connection against load case 1. Identical dimensions, features, and meshing techniques were used to avoid accuracy-related variations. Moreover, the stress and strain levels were measured at the design-domain region of the conventional connection to allow for a fair comparison.

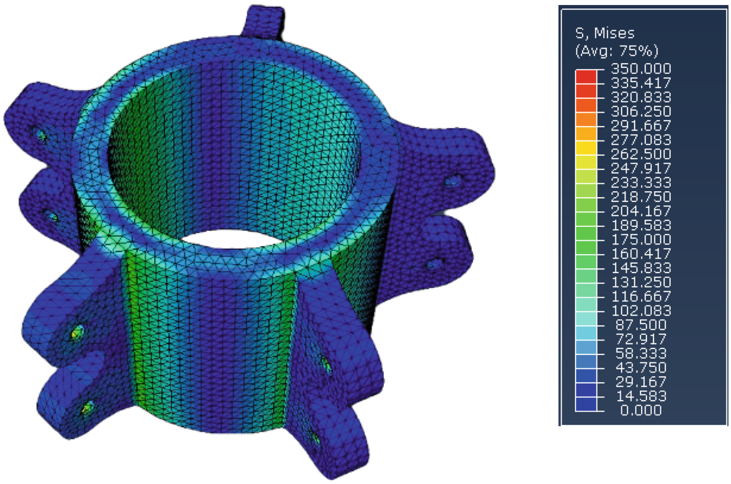
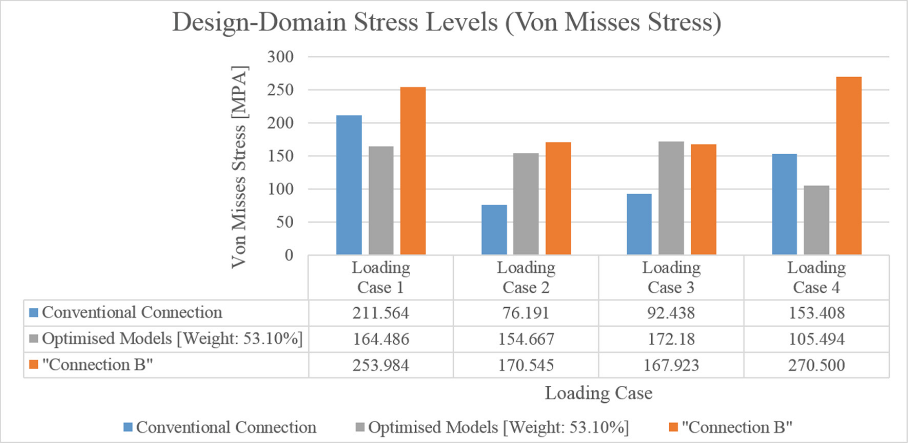


Fig. 14. FEA structural testing of the conventional node-connection against LC1.

5 Optimisation Process

Figures 15 and 16 demonstrate a comparison between the recorded stress and strain levels in the design-domain area in the reference conventional connection, the optimised designs, and "Connection B". The non-design domain stress and strain levels are not important for this research study; therefore, their values were not presented.

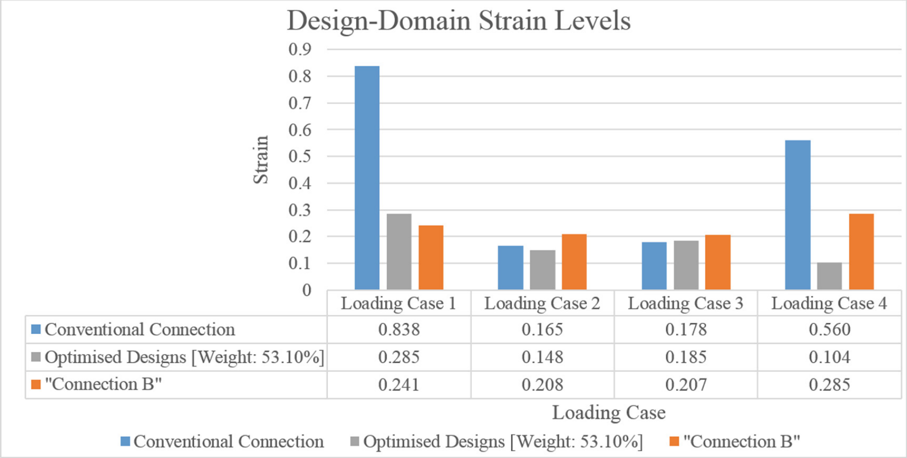
In loading cases 2 and 3, which consisted of only tensile or compressive forces in one case, with different magnitudes acting on the splice plates, the conventional connection displayed the lowest stress levels and significantly low strain levels. As for loading cases 1 and 4, which consisted of a combination of tensile and compressive



	Loading Case 1	Loading Case 2	Loading Case 3	Loading Case 4
■ Conventional Connection	211.564	76.191	92.438	153.408
■ Optimised Models [Weight: 53.10%]	164.486	154.667	172.18	105.494
■ "Connection B"	253.984	170.545	167.923	270.500

Fig. 15. Recorded stress levels.

loads on the splice plates, the optimised models had better performance with lower stresses than both the reference connection and “Connection B” while displayed relatively low strain levels. As “Connection B” was optimised to all of the four loading cases, the ideal shape formed was not specific towards a single loading case, rather, all of them. Therefore, the resulted “Connection B” contains the highest stress levels in three out of four of the cases and some varying strain levels.



	Loading Case 1	Loading Case 2	Loading Case 3	Loading Case 4
🟦 Conventional Connection	0.838	0.165	0.178	0.560
⬜ Optimised Designs [Weight: 53.10%]	0.285	0.148	0.185	0.104
🟧 "Connection B"	0.241	0.208	0.207	0.285

Fig. 16. Recorded strain levels.

6 Manufacturing Process

The optimised designs extracts from ABAQUS inherently experienced low mesh quality and required further refinement in preparation for the AM process. In total, four scaled-down optimised designs with bespoke and complex geometries were manufactured. The fabrication of these prototypes showcases the capability of AM in producing intricate shapes and its advantage through eliminating many of the traditional manufacturing constraints.

6.1 Post-processing and Preparation for the Additive Manufacturing

The post-processing steps undertaken on the optimised designs ‘prepared’ them structurally and geometrically for the AM process. These steps involved creating smoother curves, removing any weak regions likely to develop during the printing, and reducing the number of sacrificial structural supports required. Moreover, the modifications undertaken improved the mesh quality to allow for better fabrication as shown in Fig. 17. Care was taken while using MeshMixer to maintain the original design-domain geometry of the connections, while allowing for improved overall curvatures in the shape.

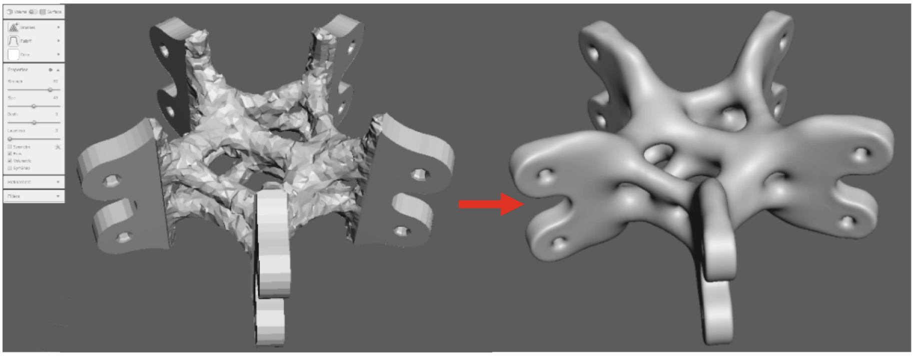


Fig. 17. An optimised node-connection before and after post-processing.

6.2 Additively Manufactured Designs and Material Properties

Two different materials were used in constructing the designs as the desired material is not commonly adopted in the AM markets. The first material is a metallic alloy formed through a combination of 420 Stainless Steel (60%) with Bronze (40%), while the Bronze component consists of 90% Copper and 10% Tin. According to the manufacturing company (i.materialise based in Leuven, Belgium), this alloy with a density of 7.86 g/cm^3 has a Modulus of Elasticity of 147GPa, a 0.2% offset Yield Strength of 455 MPa, along with an elongation of 2.3%, and an ultimate tensile strength of 682 MPa [15]. Thus, the research team adopted this material in the three geometrically most complex designs to showcase the limitless fabrications capabilities of AM and the aesthetical benefits gained, as shown in Figs. 18 and 19. These connections could be involved in future lab-based testing and validation studies for analytical models. Ongoing research focusing on refining the geometry of the connections. Moreover, the true metallic properties and any anisotropic effects will be characterised after coupon tests to allow for more reliable and accurate FEM validation.

The second choice is a polymer-based material, trademarked under the name of “nylons” and referred to as “polyamide” by the manufacturer. This material was selected as a showcase (demo) material for the fabrication of the reference connection and the complex design generated with a weight reduction of 46.9%.

The designs printed in the metallic alloy were manufactured through the “Binder Jetting” Technology while the polyamide designs were printed through trademarked process referred to as “Multi Jet Fusion Technology” (MJF).

Fig. 18. Additively manufactured node-connection designs.

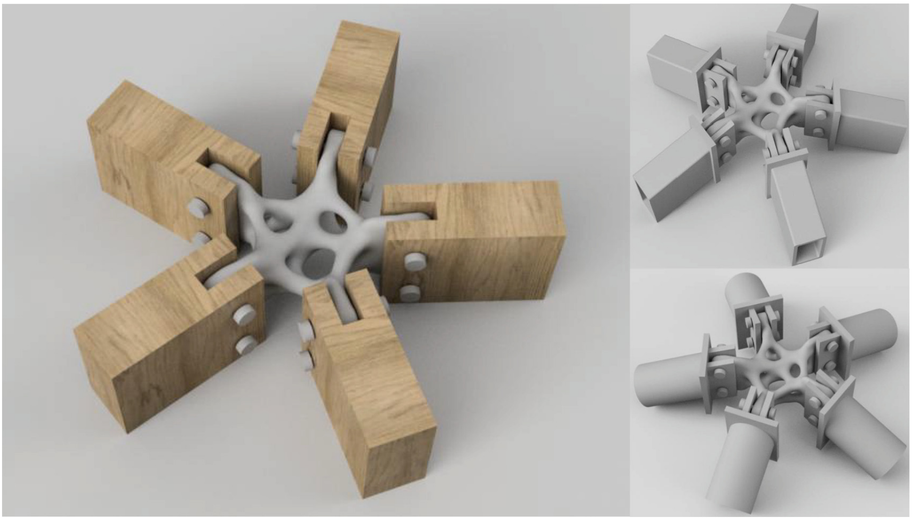


Fig. 19. Visualisation of the assembled optimised node-connection with strut members.

6.3 Cost Comparisons

The three most pressing factors for the introduction of AM in the construction sector are the limiting fabrication dimensions, printing time, and high cost. The first factor can be considered early on in a project by controlling the maximum object/connection size to meet the print volume of the available metallic printer. With 3D printing patents lapsing, more companies will develop newer and bigger printers for the construction industry needs. The second factor can be met by allowing enough time in the construction programme for fabricating the connections ahead of erecting the superstructure. Since structural components can be prefabricated and stored in the warehouse, the exposure time on-site can be significantly minimised and well managed. The third factor requires more research on to present in-depth statistics. AM can be considered an expensive process for the typical mass-production but an ideal solution for highly-optimised and bespoke designs. The main reason for considering AM connections is that they are typically labour intensive and may require a heavy and expensive fabrication either using injection moulding or welding tailored to each connection specifically. As the AM market will open after the lapsing of 3D printing patents, competition will be increased, also leading to lowering costs.

An exact cost for each connection type could not be obtained from the suppliers, as the design of such joints is yet considered a commercial secret by its manufacturers and is very much dependent on the complexity, quality, and number of the designs. Therefore, any figures and cost estimations presented are solely based on case studies attained from the literature and industrial experience of the researchers. The cost of the manufacturing the scaled down metallic connections (scaled down by 75%) ranged between \$635–680 per node. Scaling up the metallic connections would result in an approximate fabrication cost of 2.4 times higher ($0.75^3 = 0.42$, i.e., 42% of the volume), thus ranging between \$1,510–1,620 per node (£1,210–1,300). The two slightly smaller demo Polyamide connections (as in Fig. 18) were fabricated with a much lower price tag of £35–47 per node.

Adopting the case study of the New Trade Fair freeform reticulated structure in Milan [16], the total roof weight is around 77,000 tonnes and for an average steel price of around £900 per tonne, the total steel tonnage cost of the roof is £69,300,000 (excluding design, manufacturing, and transportation costs). The connections typically account for 20% of the frame from experience and as a result, the connections in the project would cost £13,860,000 (£770 per each of the 18,000 nodes). As anticipated, the optimised AM connections remain higher in cost; however, considering the weight reduction of the entire structure, not only due to the connection weight reduction, but also the cost reduction as a result of the shape optimisation on the roof structure, could account for 46.9% of the connections cost (i.e., 53.1% of the initial cost). This would reduce the cost per connection to £410 per node (£70 per connection times 0.531), assuming direct correlation between steel tonnage and cost. No definitive conclusions can be drawn from this, since more detailed cost-related studies are required to assess the feasibility of this design and fabrication method for the joints of large-scale reticulated structures, but they present descent indicative costs.

7 Conclusions and Ongoing Research

Recently, structural topology optimisation (STO) together with additive manufacturing (AM) have been employed for various structural applications in the Civil Engineering sector [17, 18]. This study enhances this knowledge by investigating the application of STO and AM for the design optimisation of node-connections found in reticulated structures. A conventional node-connection is optimised against individual four loading cases at a percentage weight reduction of 46.9%. In addition, an optimised connection design “Connection B” is achieved, being capable of withstanding each of the four loading cases. A comparison of the design-domain stress and strain levels between the reference conventional connection and the optimised connections is also presented in this paper. Finally, a selection of the generated highly bespoke and complex optimised designs has been manufactured in metal and polyamide.

Ongoing research is focusing on improving the complexity of the node-connection model by using the multi-material components, validating the results through experimental testing as well as considering a wider range of adverse loading cases in designing “Connection B” and comparing its performance to the conventional connection. Research also focuses on studying the cost-effectiveness and environmental impact of the additively manufactured connections to the entire reticulated structure.

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