

Challenges of Scale in Modelling Material Behaviour of Additive-Manufactured Nodes

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ABSTRACT

The application of Additive Manufacturing (AM) technologies promises much innovation across the manufacturing sector, and has generated great interest in the Architecture, Engineering and Construction (AEC) industry. This paper presents and reflects upon early prototypes for integrating AM in a construction application, through the design of a prototype frame structure with linear members connected by nodes of unique shapes. As an enabler for design, a system is developed and implemented to integrate expertise across architecture, structural engineering and advanced manufacturing in order to design and detail components for single layer canopies. This includes the topology optimisation and additive manufacture of nodes, both of which require the control of material behaviour at small scales. A scaled pavilion structure and full-scale node prototypes were successfully realised. However, this first stage of research presented a number of challenges to modelling material behaviour across scales – both the physical size and production volumes.

INTRODUCTION



Figure 1. Stainless steel prototypes of proposed construction nodes.

Amidst much excitement about the potentials of additive manufacturing to change manufacturing, the construction industry presents significant challenges of scale. These are both physical – related to the size of buildings - and also in terms systems design, related to

production volumes suitable to the project by project context of the AEC industry. The research presented here takes a clear position on each aspect of scale to explore a potential application for additive manufacturing in construction. To bypass limitations of physical size, additive manufacturing is targeted at the relatively small, connection components, so-called nodes as part of larger assembly. Embracing a manufacturing context of mass-customisation, each node is considered as a unique iteration derived from a common design system.

A team of experts from across architectural design, structural design, topology optimisation and AM was assembled to address the challenge of prototyping a design system and exemplar structure. The project aimed to integrate knowledge through connecting a series of existing technologies and techniques, namely Selective Laser Melting (SLM) for additive manufacture, Bi-directional Evolutionary Structural Optimisation (BESO) (Huang and Xie, 2010) for topology optimisation of node design, and parametric models with lightweight analysis tools for architectural and structural design of building form and detailing.

A digital workflow was implemented, linking modules across a design and production process. With these tools, both full-scale exemplar nodes printed in stainless steel (Fig. 1), and a pavilion structure at scale 1:5, constructed with timber beams linked by ABS printed plastic nodes (Fig. 4), were realised. These early prototypes offer promise that such a system might be feasible in the construction industry as technologies, in particular SLM additive manufacture, improve in terms of speed and cost.

Despite this promise, however, this early research raises significant further design questions. The project demands that node design incorporates the modelling of material behaviour in multiple contexts. Firstly, current techniques abstract material behaviour in order to optimise topologies in response to given load cases. While this reduces weight and material volume, manufacturing parameters are not considered. Secondly, AM requires that material behaviour is controlled to ensure successful results. For further development, the system needs to respond to manufacturing parameters to improve the design of nodes.

BACKGROUND

Additive Manufacturing in Metals

ASTM: F2792 - 12a (2012) defines AM as the "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". AM requires a Computer Aided Design (CAD) representation of the intended geometry. This CAD data has traditionally been represented in Stereolithography (STL) format (Gibson et al., 2010). However, enhanced data representations are under development, such as the Additive Manufacturing Format (AMF) (ISO/ASTM, 2014). This AM data is then converted to a sequence of two-dimensional scan paths (Zhai, 2014) that are sequentially processed by the AM process.

AM is an enabling technology with economic and technical attributes that allow design innovation including: reduced cycle times and unit cost (Ruffo et al., 2006), repair of high-value components (Shepeleva et al., 2000), and manufacture of high efficiency structures not compatible with traditional methods (Brandt et al., 2013). Plastic parts manufactured through Fused Deposition Modelling (FDM) are nowadays common and accessible to non-expert users. Metal-based AM systems are less common but provide opportunity for commercial benefit (Atzeni and Salmi, 2012; Atzeni et al., 2010).

Selective Laser Melting (SLM) applies a laser power source to selectively solidify powder in a powder-bed. SLM can process a range of useful engineering materials including: high-strength and alloy steels; light alloys, including aluminium, titanium and magnesium; and precious metals. Despite the associated design opportunities, SLM is subject to complex, dynamic manufacturing constraints. For example, SLM melt pool dynamics and is governed by over 130 parameters (Rehme and Emmelmann, 2006). Furthermore, the associated heat transfer is both spatially and temporally transient, resulting in significant challenges to the manufacture of commercially robust components (Gu et al., 2012); especially associated with optimisation of orientation and distribution of support materials (Brandt, et al., 2013; Leary, et al., 2014).

Node Precedents

Many in the AEC industry have identified that relatively small connection elements are key to the design of larger assemblies of parts. This includes key examples of pre-fabricated , modular housing systems (Wachsmann, 1946); space frames (Bardell et.al., 1996); and gridshell frames (Carlow and Crolla, 2013). This latter case presents particular challenges as nodes are highly varied to meet angles of adjacent members.

The design of connection parts has also received attention in high-value automotive and aerospace design. As SLM technologies have matured, designs have been proposed for key structural components in jet engine (Halchak et al., 2012), aerospace (Brandt et al., 2013), and automotive (Cooper et al., 2012) that are incompatible with traditional manufacturing methods. These are designed to replace existing components and exploit weight savings which can be achieved with optimised, additive manufactured parts. As though parts are produced for runs of vehicles, multiple versions and design prototypes can be produced and tested.

A first proposal for such an application of AM in construction has been proposed for application to a node in a tensegrity structure (Galjaard et al., 2015). This focusses on a case of a joint connecting a series of tension cables to a rigid member in compression. The design of the part employed optimisation techniques to reduce weight and a first prototype has been manufactured using SLM technology.

Design and Optimisation for Additive Manufacture

A number of preliminary studies have highlighted benefits of topology optimisation for additive manufacturing. Two techniques have received particular attention – BESO and SIMP (Aremu et al. 2010; Brackett et.al. 2011).

BESO routines, used here, develop optimal results through the iterative removal of inefficient material. A given design space is divided into spatial volumes, typically a grid of voxels, and results can be determined for stress, stiffness and other factors (Yang et. al., 2005, 957). This results in a minimisation of material volumes through specific and commonly freeform geometries. While these shapes present challenges to manufacture using conventional technologies, AM bypasses many common limitations.

THE SMARTNODES DESIGN SYSTEM AND PROTOTYPES

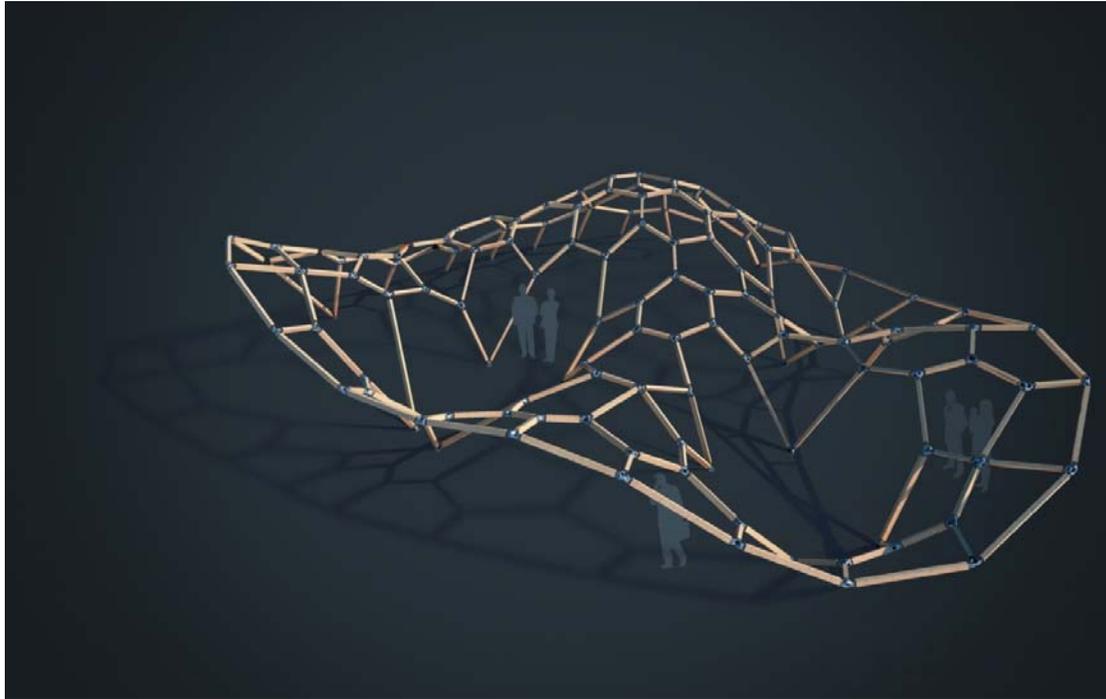


Figure 2. Proposed design of a single layer canopy with standard beams connected to customised nodes.

A design system was conceived to link modules across architectural design, structural analysis and design, topology optimisation of nodes and the generation of data for fabrication. Such a close linking a series of modules enables information to quickly flow both downstream and upstream, offering improved designs through iterative input across many project details. Key to these systems is consistent interfaces between modules, concisely defining data but with sufficient redundancy to enable flexibility (Marble, 2012, 130).

The design system was implemented, firstly, around a series of parametric models in *McNeel Rhinoceros*. In parallel to this, modules were developed to undertake more detailed structural analysis and topology optimisation of nodes (Figure. 2). Agreed interfaces in a neutral csv format describe firstly, the setout of axes across the form allowing them to be imported into GSA for structural analysis, and later, results from this analysis of the model which were interpreted into Abaqus tools for BESO algorithms.

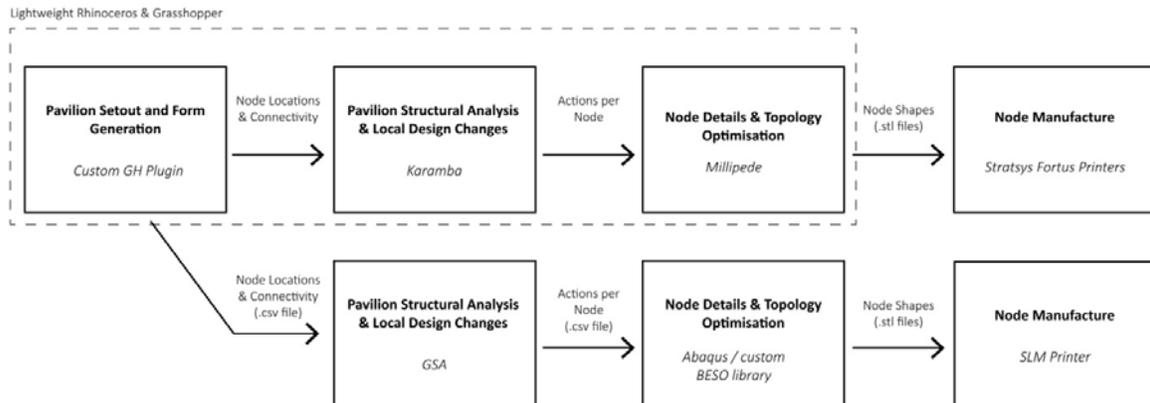


Figure 3. Key workflow structure showing modules and interface formats.

Through a custom interface created for *Rhinoceros*, a pavilion form was designed with linear members meeting at nodes. In order to accommodate a freeform shape, each node was assumed to have a unique geometric set-out, connecting between three and five beams in directions unconstrained by local conditions. The geometric setout was then exported in a neutral format for use in each branch of the workflow.

Structural analysis in response to gravity loads was generated. The results produced by *Karamba*, a plugin for *Grasshopper*, were compared to the results generated in the commercial structural design software *Oasys GSA*. The results correlated closely, with the latter providing verification for results from the lightweight tools.

Using the lightweight tools, the 144 nodes of the structure were topology optimised using *millipede*, a plugin for *Grasshopper*. In parallel, example nodes were identified and optimised in more detail for full-scale production. These parallel processes involved significant differences in resolution. For lightweight analysis, starting forms were modelled as spheres of 35,000 voxels. BESO algorithms were then run for six iterations, providing relatively simple topologies with crude levels of detail. This could be processed in only a few minutes on a desktop computer. The resulting forms were suitable for additive manufacture as demonstrator components at scale 1:5, providing minimum material thicknesses of 0.5mm. In some contrast to this, the BESO algorithms applied to the full scale prototypes used a starting mesh with greater than 500,000 voxels. The three node cases, one connecting each of 3, 4 and 5 members, each required over 48 hours to process 100 iterations. Results were of a much finer grain and offer significantly better outcomes, in terms of volume and weight, than the scaled versions.

The manufacturing of nodes through each of the parallel processes was undertaken. The scaled demonstrator nodes at 1:5 were printed using a *Stratasys Fortus* printer. Support material was generated using proprietary *Stratasys* software and manufacture required between 2 and 2.5 hours per part. At full scale, two of the three nodes were manufactured in stainless steel using an SLM printer. Print times of greater than 40hrs were required for these. As well, further skilled labour was required to orient the part, design support material and subsequently to remove this material after manufacture. Parts were successfully manufactured (Fig.1) however some minor problems were encountered.

DISCUSSION

Flexibility for Customisation in Construction

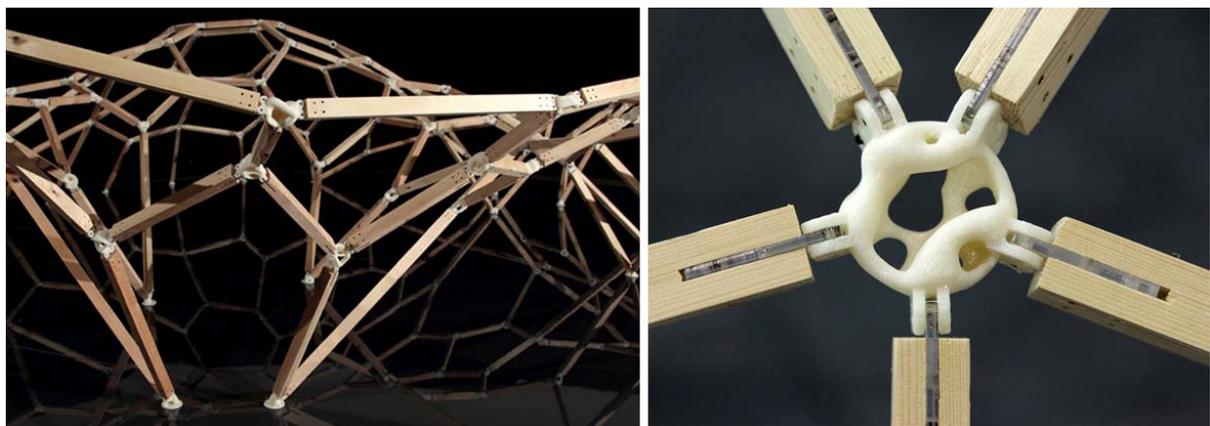


Figure 4. The fabricated pavilion prototype at scale 1:5 showing (left) a network of beams and (right) a typical node manufactured by an FDM machine.

The bifurcation of the project workflow into parallel streams was driven by pragmatic issues around managing levels of detail. As the project developed, large model sizes and lengthy processing times were identified as threats to both feasibility and flexibility for design. For example, taking the required BESO optimisation time of a full-scale node and applying it to the 144 node scenarios

across the pavilion would require many days using current computers. Even assuming improvements in computer processing, a relatively lightweight process is required to be feasible for a volume of parts such as this.

The manufacture of 144 nodes with FDM machines was straightforward, with all jobs successfully completed and parts within tolerance (Figure 4.). This demonstrates ‘file to factory’ principles which promise customised manufacture and flexibility in design.

In comparison to this, the SLM technology applied to the full scale parts is relatively new and caution has been advised in drawing simple comparisons between the two (Brewster, 2014). Given this context, it was unsurprising that some problems were experienced. Firstly, incorrect humidity levels caused failure through material slumping in one job. The second problem centres on difficulties in orienting the complex forms for printing. The design of an adequate support structure to ensure successful manufacture proved very challenging, and the proposals contained excessive amounts of material. As a result a prototype of a 5-sided node was not attempted.

These technical challenges to SLM demand further development of the technology for consideration in commercial construction. Much research is being pursued in this area and it is foreseeable that these issues will be largely overcome. Beyond this, however, human labour required for designing and removing support material is a significant impost to SLM manufacture. To enable flexibility for customised manufacture, this labour must be significantly reduced through algorithms using rules of thumb to automate orientation and design of efficient support structures.

Optimisation for Broader Criteria

BESO optimisation techniques are conceived to address a given set of load cases. Simulations typically use stopping conditions related to material stress or volume. While such optimisation techniques are highly sophisticated, the optimisation criteria addressed here reflect only a fraction of broader design issues being addressed. Simply, weight and volume are not directly proportional to economic issues underlying manufacture.

The challenges in SLM manufacture encountered in this research suggest that the inclusion of manufacturing parameters in optimisation processes would be of benefit. It is conceivable that suitable orientation of parts could be automated in response to geometric analysis. Once a suitable orientation is identified, support material could be generated for required areas using rules of thumb. Algorithms for generating efficient support structures for FDM printing are available through softwares such as *Autodesk Meshmixer*. Future research will explore whether similar ideas can be applied to SLM.

In opposition to this, however, this research also highlights significant computation time. As a result, the simple addition of further optimisation criteria and routines is not straightforward. Trade-offs between computation time for optimisation routines, and the material, labour and time for manufacturing must be negotiated. The consideration of broader criteria might alternatively lead to exploration of other optimisation strategies.

CONCLUSION

Through the study of parallel workflows applying both BESO and AM to the design of components at different scales, this paper highlights challenges in modelling material behaviour at an architectural scale. Scale parts using relatively simple optimisation routines and mature FDM technology were rapidly realised. This offers significant customisation and flexibility in the design of built form. However, for full-scale components using relatively complex BESO optimisation and SLM manufacture, technical challenges were encountered and design and production times were excessive.

This suggests that recent claims that AM allows architects to design at the scale of matter are overly simplistic. While it is possible to design highly detailed parts, the sheer size of a building requires that designers are strategic in identifying key components for such a level of attention. Further to this, the short production volumes and high degrees of customisation typical to construction demand flexibility in manufacturing. This requires robust processes (Piller, 2013) with many challenges still ahead for AM in metals to meet such a context.

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