Non-linear fabrication:

A dialogue between architecture and robotic wire-arc additive manufacture

BY

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Figure.0.01 Waam Fabrication

ABSTRACT:

Within architecture the joint is an integral part of a building's dialogue with its users and audience. Steel joints allow for the extension of members and fundamental changes between columns and beams. However, due to the limitation of traditional metal fabrication, highly parametric and computational informed designs are constrained by the conditions of mass production. High output low cost, limiting the highly variable nature of geometrical informed individual joints.

Through the fabrication of computational informed architectural steel connection in combination with non-linear geometric segmentation and 6-axis robotic wire arc additive manufacture (WAAM), this research aims to optimise the aesthetic opportunities and practical fabrication of large-scale steel architectural joints. Currently, there exists a disconnect between the dialogue of metal joints and architectural intent. Through the innovative use of non-linear fabrication and member informed multi-directional slicing, this research aims to construct a closed digital design loop through fabrication. Utilising the additive fabrication process of WAAM, to construct a mass-customisable metal node which still maintains an aesthetic architectural opportunity.

The aims of this research are to outline the potential of fabricating mass-customisable steel joints through the process of non-linear segmentation. Describing the methods and techniques used to fabricate a computational informed metal joint through the manufacturing process of WAAM.

SCAN ME

Video Title: Non Linear Fabrication: A dialogue between architecture and wire
arc additive manufacture

Notes

The document contains QR Codes, scan these with your smart device to watch a video. These videos act to aid the in communication of the research an example of the QR codes is above.

Additionally throughout this research the use of the words node and joint are interchangeable

The following thesis is part of the Advanced Manufacturing and Prototyping for Design Research Lab. AMPD aims to investigate and define innovative techniques and methods of modern construction applicable to the architecture and construction sector through the use of advanced tools of design, fabrication, and manufacturing. The fourth industrial revolution is core to our research exploring methods of improving information flow from design to fabrication—across the digital continuum—to design architecture that builds wellbeing for people and the planet. We can't keep doing what we have always done—our research questions the status quo by designing and constructing prototypes. You should consider the thesis within the larger body of research that AMPD Research Lab undertakes. Each thesis has focused on an aspect of AMPD's aim.

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01

Introduction

CHAPTER ONE

"figure out what's **good for printing** and leave the rest to the
regular way of building." - (Velden, 2020)

1.1 Introduction:

As one of the primary building elements within any industrial construction project, nodal joints are limited in their design, restricted to a role of functionality by the traditional methods of fabrication and bound by the manufacturing model of mass production. However, developments in additive manufacture, algorithmic design and robotic fabrication methods notable wire-arc additive manufacture (WAAM) have begun to challenge the existing role that steel nodes have with the surrounding architecture and occupants of the space. This can be achieved by presenting the opportunities for designers to use and digitally design structural nodes with regards to mass customisation instead of the traditional model of mass production.

WAAM is a large-scale metal fabrication process which utilises the multidirectional nature of a robot arm in combination with a welding torch, to additively fabricate geometries layer by layer. This process would transform the existing additive manufacturing methods from an architectural prototyping tool, into a viable manufacturing process for mass-customizable industrial sized metal joints. Unlike, alternative methods of additive manufacture which utilise metals, (SLM) select laser manufacture, WAAM is a large-scale manufacturing tool, which explores having an increased layer height, un-constricted print bed and high deposition rate to effectivity decrease the print duration and size limitations currently seen in existing additive manufacture.

Currently the model of metal joint fabrication for architectural design is built upon the idea that building joints are repeatable elements within the building and that the unique qualities and properties of a building are expressed through the interaction of the primary support members. Less in the expression of the nodes themselves and more in the expression of the larger architectural components. Wall, roofs, glazing panel, column and beams build the foundational integrity of the building expression for design and communication with the users. Whereas nodes and joints are commonly viewed and used as essential, often simplistic elements which connect primary members of the architecture together thus fulfilling the functional role of being a necessity, instead of an expressive option for design.

However, with the recent uptake of algorithmic design, digital fabrication and data driven computational design, architecture has begun to actively explore parametrically informed design structure, variable in nature and expressive in form. With this expressive shift in the architectural dialogue of buildings, there exists a problematic gap within the traditional mass production, fabrication model of structural steel joints. The production of mass-customisable steel joints, which are individually responsive, variably in nature and complex in design are not catered for by the current industry model. This exploration of feasibly constructing full scale mass-customisable joints for which respond to the complex angular nature of a parametric pavilion is where my research aims to situate itself.

FIGURE 1.02 WAAM FABRICATION

**WHAT ROLE DOES WIRE-ARC ADDITIVE MANUFACTURING, (WAAM) AS A DEVELOPING FABRICATION METHOD, PLAY WITHIN
THE ARCHITECTURAL DIALOGUE BETWEEN STRUCTURAL CONNECTIONS AND ARCHITECTURE?**

– Research Question

1.3 Aims + Objectives:

1.

The primary objective of this research is to fabricate a full scale architectural node which culminates in propelling the architectural potential of a pavilion structure. The nodal element will be used in a segmentation section of a pavilion, constructing constraints to physically inform the practical benefits and disadvantages of fabricating building nodes with WAAM.

2.

Additionally, this research aims act as a proof of concept research study of the additive fabrication process, WAAM with regards to computational informed architectural nodes, allowing architects and designers the design freedom to challenge the traditional notions of structural nodes within an architecture. It strives to present a physeable fabrication method for mass customisable joints within an actively responded pavilion.

3.

Furthermore, this research aims to increase the viability and effectiveness of mass customisable joints within an architectural expressive structure. Allowing designers to construct a digital design lead matrix of custom nodes, which are currently not covered by a larger section of the traditional fabrication industry.

1.2 Project Scope:

This research aims to develop a new algorithm approach to decrease the lead time of fabricating an algorithmic informed structural node whilst additionally providing validity to this systemic approach of fabricating mass customisable steel connectors within a proof of concept architectural structure. The end goal of the research is to produce a full scale section of a pavilion design with the fabricated steel node meanwhile allowing for physical demonstration of the impact which mass customisable joints have on the dialogue between architectural structure and the users interactions.

Before presenting the research it is important to understand the scope of the research and imposed limitations. This research will not be looking at generative design, topological optimisation to inform the aesthetic qualities of the joints as both of those systems remove architectural authorship from the design, an element of digital design which this research is striving to give back to the designer. Additionally, the fabrication of the full scale joint will be conducted through the use of a singular robot offsite. Due to the 'dirty' requirements of setting up an appropriate fabrication cell for the Victoria University of Wellington singular IRB 6700 robot, an external robot cell will be used. Restrictive access to the offsite robotic cell meant that fabrication time with the actual set up was limited during the research. This resulted in the exploration of segmentation methods, joints and prints being tested through conventional polymer 3d printing.

Additionally the scope of this project doesn't focus on the design outcomes of generative and topological optimisation. Whilst these systematic approaches to data driven design allow for optimal material placement, the scope of this research aims to provide the designer with a sense of authorship around steel nodes.

1.4

Methodology:

Design-led Research

This design – led research utilises a cyclic and iterative methodology to construct a four-step circular feedback loop, where iterative prototyping and reflective evaluation are used to dictate the workflow.

This thesis begins with background research and precedents studies, which act to establish the contemporary landscape as well as inform the iterative exploration of the four key phases.

Digital Design, Physical Fabrication, Onsite Assembly and Critical Reflection.

These four key phases established the digital design to fabrication workflow, where key elements of the workflow such as digital documentation, physical materiality and practical assemblage were able to be resolved and critically evaluated at a prototyping scale before the full-scale fabrication. Additionally, the workflow establishes a symbiotic relationship between the physical architecture and the computational informed design, where the both elements' limitations and constraints provide collective feedback into each other. Redefining the relationship between the architect and their design.

By establishing a workflow methodology and iterative feeding prototypes through the process, constraints and limitations were revealed which were not initially apparent. The use of a cyclic methodology, establishes a feedback loop where the identified constraints and limitations of each of the key phases feed back into each other. While each key stage of the workflow was critically evaluated with regards to their own criteria, the collective workflow was evaluated with regards to the aesthetic and technical elements it afforded of the full-scale proof of concept. This allowed for limitations and constraints identified within the later phase of the workflow to be resolved and addressed within the digital design phase. Collectively establishing a cyclic relationship between the designs where previous loops build upon each other to enhance the following loop.

02

Theoretical Framework

CHAPTER TWO

“In the early 1900s industrialism became dominant. Now components had to be mass produced. Products were stored, and customers could come by and pick up, for instance, a window. Which was now, however, invariably either “a little too small” or “a little too big”. On the other hand, significant amounts could be saved by buying larger volumes. Things were produced in a factory, under controlled conditions. Once the machinery was set for a specific product, one had to “exploit” this setup in order to rationalise and produce as many items as possible.” – (Christiansen, 2016, p. 49)

2.1

Background:

Within contemporary architecture, steel joints are considered an opportunity cost of the building, playing the functional role of a structural connector between architectural members. Due to the limitation of existing fabrication methods, steel joints and nodes offer limited architectural opportunities beyond their functional role as a connecting structural element, primarily acting as a perceived 'necessity' for a building's structural stability, these nodes attach beams to columns and columns to beams. Due to a combination of mass-production and fabrication methods, "steel joints" have been left in a position where they lack consideration for their design opportunities and inherent ability to propel the design intent of the non-standardised architecture.

This limited perception of relegating steel joints to an auxiliary role within the formal composition of a building's language, has not changed since the early 20th century. (Architecture - Iron and Steel, 2019) The perceived notion of steel joints is limited to roles of functionality being a direct bi-product of the traditional mass- production fabrication methods established within the early 20th century and still used within contemporary fabrication.

The driving principles of mass-production, standardisation and repetition shape both the outputs from the production line as well as functional use of joints within a buildings' design as the static design tools and fabrication methods used to construct steel joints, directly dictate their design intent and usability with architectural buildings.(Christiansen, 2016, p. 49) Currently the design intent of steel joints is shaped by the industrialised method of production and outdated static design tools creating a feedback loop where the design intent and fabrication model reflect each other resulting from the limited fabrication options for mass-customisable, variable responsive steel joints.

As such this chapter's focus is on establishing an overview on the current state of the fabrication methods and static digital design tools within the contemporary industrial fabrication of steel joints. As well as highlighting the emergence of computational design tools and fabrication methods which are enabling the shift away from mass-produced steel joints and towards mass-customisable steel joints which are parametric responsive toward the architecture.

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FIGURE.2.1 | *MASS PRODUCED STEEL JOINTS*

2.2 Literature Review:

2.2.1 Mass Production

Mass production in regards to the fabrication of architectural elements refers to a system based on the Henry Ford assembly line model, where the higher production volume of standardised parts is equated to a lower fabrication cost. (Banton, 2020) This model of fabrication was initially used in the automotive industry to repetitively fabricate standardised car parts in a manufacturing line. Initially these repeatable sequenced tasks were performed by humans, however contemporary mass production manufacturing lines have automated the process and utilise robotic arms. The impact of using the mass-production fabrication system within architecture is that steel joints can be produced at a larger volume, lower cost and at a higher precision with a catalogue of 'off the shelf' joints being produced to cater for the average building. The limitation of mass-producing standardised connections is that their high repeatability designs hold limited contextual responsiveness, since the designs of the joints are a reaction to the average demand and repeatability across a series of buildings.

The use of mass-production within the fabrication of steel joints has meant that the construction industry has standardised an element of the construction process ensuring that architects are no longer required to specialise in all areas of the construction process. However, the reliance on fabrication systems which utilises mass-production has created a void in the construction industry. Since mass-production fabrication systems only produce repetitive, standardised members, the construction of structures which contain mass-variation within its catalogue of steel joints is limited by the current method of fabrication. (Christiansen, 2016)

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FIGURE.2.2 | *VW MANUFACTURING LINE 1957*

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FIGURE.2.3 | *CONTEMPORARY STEEL PROCESSING LINE*

2.2.2 Fabrication Methods

Currently the primary methods of metal joint fabrication are categories as:

1. ADDITIVE FABRICATION
2. SUBTRACTIVE FABRICATION
3. FORMATIVE FABRICATION

Milling, casting and extruding currently make up the most conventional means of fabricating architecture joints and nodes. These subtractive and formative methods of fabrication can cater for a large range of geometric forms and structural supports, however the automation of assembly lines along with the economies of scale associated with mass-production systems results in standardised steel joints which are produced in large volumes as simplistic, repetitive geometries in order to produce an effective end product. (Busachi et al., 2017; Hopkinson & Dicknes, 2003; Ruffo & Hague, 2007)

However this doesn't mean that complex geometric architectural joints and structural pieces aren't seen within built structures with complex geometric joint designs being produced through the subtractive fabrication process of 5 axis milling (Figure.08) and the formative fabrication of Casting. (Figure.09) However the costing factor of machine time in addition to the material wastage means that these stylistically variable architectural joints are not commercially viable to use within a variable complex catalogue, and as such are rarely seen within architectural structures. This is where the additive manufacturing technologies (AMT) are thought to be the all-disruptive technology to remove our current bias towards economies of scale and repetitive use of identical construction elements. (Bechthold, 2016).

Unlike the traditional static 2d workflow of subtractive and formative steel fabrication, Additive Manufacture (AM) as a fabrication process requires the input of 3d mesh models in order to construct objects in a layer by layer process. Since additive manufacture is a fabrication process which is derived from the ideals of mass customisation, less focus is placed on the volume produced, and more on the complexity and variety of contextually respondent joints within the structure. (Dollahide, 2020)

Traditional steel fabrication methods of subtractive and formative fabrication follow a static 2d data transference within the design to fabrication workflow. Where the required fabrication inputs dictate that expressive 3d geometries are reduced down to linear static 2d CAD drawings by the architect, are then re-interpreted by the manufacture operator before being translated to machine G-code to be constructed. This static design workflow means that digital informed models are redundant to the fabrication method as the transmitted data is static in nature and can't be updated or changed in a respondent nature once the manufacturing process has begun. As a flow on effect of the traditional fabrication methods being designed and constricted to linear 2d CAD modelling tools, the systems of fabrication are also limited to these parameters restrictively impacting the design cycle too simplistic linear geometric forms which are a reflection of 2d CAD modelling tools. These geometries are then repetitively produced by the mass production model.

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FIGURE.2.4 | *Subtractive Fabrication - computer numerical controlled milling (CNC)*

FIGURE.2.5 | *Formative Fabrication - Material Deformation (Casting) Injections Moldings, Extrusion)*

FIGURE.2.6 | *Additive Fabrication - 3d Printing, Stereolithography, SLM, FDM*

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FIGURE.2.7 | *THALLUS INSTALLATION, ZAHA HADID ARCHITECTS, 2017*

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FIGURE.2.8 | *ZEPHYR PAVILION, MARC FORNES, 2019*

2.2.3 Computational Modelling

The transfer of architectural data and fabrication drawings is currently undergoing a paradigm shift with many of the traditional methods of data transference are being phased out of the construction site. Gone are the days of builders rolling out physical A1 sheets littered with human organised schedules and drawings, and in are the days of digital twins, collaborative BIM modelling and computational influence digital designs which allow for closed digital design workflows. Construction and fabrication drawings are being read through tablets and phones, containing a toolkit of 3d models, fabrication drawings and parametrically optimised buildings schedules. (Raspall & Banon, 2018) In the same way the CAD modelling tool, the Bézier curve created a paradigm shift in the modelling process and physical fabrication within the automotive industry in 1971, the inclusion of parametric digital design tools has shifted the architects' relationship between documentation and physical fabrication. (Bézier, 1974) Current developments in algorithmic data driven digital design are changing the way in which architectural fabrication drawings are communicated between industries. "Drawings are being augmented—if not entirely replaced—by processes that permit 3D fabrication of complex forms directly from architects' data." (Celanto, 2010)

With the inclusion of algorithmic data driven digital designs, the opportunity has emerged within the construction industry to further close the digital design loop reducing the need of 2d static CAD drawings which were traditionally required to begin fabrication, and instead utilising computational informed 3d mesh models. Such models are optimised by data driven constraints and factors, to elevate the level of contextual data which informs the digital design of the model along with toolpathing required to begin fabrication. This paramount shift from 2d CAD drawings to processes which optimise the fabrication of complex 3d geometries decreases the required human interaction throughout the fabrication workflow and lead time, whilst allowing the designer to input higher levels of design throughout the initial phases of the project.

The addition of 3d computational design into the digital workflow has shifted the relationship between digital architectural models and physical fabrication. Parametric software along with integrated visual based coding has been seen to shift the relationship between traditional digital architectural models and external data. Programmes such as Grasshopper and Dynamo, construct a visually responsive link between complex 3d buildings models and variable data analysis parameters. Once the variable parameters and data input conditions are set a seemingly infinite amount of respondent geometries can be generated. "Parametrism" affords architects the opportunity to algorithmically script complex repetitive task and operations whilst maintaining an organised schedule of data sets. (Schumacher, 2008) When translated to the fabrication of complex non-uniform geometries, the combined use of digital design tools and parametric design become the primary tool in establishing an automotive workflow as well as closed loop digital design. (Ercan & Elias-Ozkan, 2015)

"Integrating computer-aided design with computer-aided fabrication and construction [...] fundamentally redefines the relationship between designing and producing. It eliminates many geometric constraints imposed by traditional drawing and production processes—making complex curved shapes much easier to handle, for example, and reducing dependence on standard, mass-produced components. [...] It bridges the gap between designing and producing that opened up when designers began to make drawings." – (Mitchell, 1991, p. 195)

2.2.4 Robotic Architecture

With the emergence of algorithmic design and digital fabrication, advancement in robotic parametric fabrications have opened up the chance to reconsider the types of buildings we design and how we are designing them. (Gramazio et al., 2014)

Whilst in the past, robotic fabrication has been limited to the task of optimising factory floor fabrication and assembly lines, the multi-directional nature of robot arms in combination with emerging site respondent software means that robotic fabrication is becoming a viable means for precise mass customisable construction. Rather than looking at robotic fabrication as a means to increase production workflow, the architectural industry has started to view it as a 'master tool' which responds to any range of variable inputs, producing a lower number of units but at a higher precision and contextual response. (Gramazio et al., 2014)

Robotic fabrication has begun to decentralise the conventional norms of traditional fabrication workflows. As previously stated, architectural construction drawings are undergoing a paradigm shift in the method of communicating data, the same is said for robot fabrication. With the advent of file to factory workflows and closed looped digital designs, robotic fabrication presents the ability to feed back construction data into the fabrication process seamlessly merging the digital design process into the fabrication process allows for the same parametric software's which construct 3d models to directly be transferred into the robotic fabrication process. Thus creating a file to factory workflow where the reduced data transference establishes a more intuitive link between the architect's design intent and fabrication outcome. (Gershenfeld, 2012)

Industrial robots are generic robotic arms which respond to positional movement commands. Complex construction and fabrication are not a resulting factor of utilising robotics to automate the fabrication of parametric design, but rather a resultant factor of the multi-procedural sequenced tasks performed by a singular robot cell throughout the fabrication. The overall generic nature of robotic arms means they are not limited to the function of a singular operation, but rather become a 'toolkit' for variable tasks and operations when acquitted with the right tools and procedures. In the past several machines and stages of the assembly line were required to perform the itemisation, fabrication, post-processing and assembly of parts, however these tasks can now be more efficiently performed by a singular robot arm and a range of tools. (Wagner et al., 2020) In much the same nature as parametric design, robotic fabrication is less about the tools itself and more about the opportunities which it affords to contemporary construction and fabrication.

“Digital technologies are enabling a direct correlation between what can be designed and what can be built, ... By integrating design, analysis, manufacture, and the assembly of buildings around digital technologies, architects, engineers, and builders have an opportunity to fundamentally redefine the relationships between conception and production.”
(Kolarevic, 2003)

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FIGURE.2.9 | SPATIAL TIMBER ASSEMBLIES, ETH ZÜRICH, 2017

FIGURE.2.10 | *MULTITHREAD, WEISSHAAR AND KRAM, 2012*

FIGURE.2.11 | *3F3D; FORM FOLLOWS FORCES WITH 3D PRINTING, BAYU PRAYUDHI, 2015*

FIGURE.2.12 | *I LIGHT MARINA BAY, BAÑÓN AND RASPALL, 2017*

2.2.5 Additive Manufacture

The process of additive manufacture (AM), has gained significant interest from the general public and the industrial sectors for its ability to fabricate complex yet intricate forms in a diverse range of materials. The fundamentals of the process have existed since 1983 when Chuck Hull first created a 3d part using the stereolithography process. (Raspall & Banon, 2018) As a fabrication process AM refers to the process of constructing geometries by adding material in a layer by layer fashion where a cross-sectional slice of 3d CAD model is used to inform the toolpathing of the print nozzle, constructing an approximation of the digital model. Collective additive manufacturing processes work off the same fundamental principle of additively constructing geometries in a layer by layer process, however variations exist within the printing process with regards to materials use, toolpathing construction and layer binding methods. (Gibson et al., 2010)

As a fabrication process, AM caters for the model of mass customisation, combining the digital precision and repeatability of a manufacturing line, with the additional ability to fabricate variably complex geometric forms without the high-production numbers and tooling experience of traditional manufacturing processes. Offering no economies of scale and making the cost of customisation negligible. (Zhai, 2012) Traditional critiques of AM, initially relegated the fabrication process to an architectural prototyping method, suggesting that the “Cost, accuracy, and strength of 3d printed products need to be overcome before this technology can achieve widespread adoption.” (Sherman, 2009) However since then additive manufacturing processes have overcome these limitations, addressing gaps within the existing AEC commercial model with regards to fabrication speed, design complexity, lower cost and sustainable material usage at the same time the disestablishment of the need for mass-produce standardised building elements. Instead affording architects the geometric freedom to incorporate bespoke, custom-made elements that locally respond both to the structural requirements and contextual environment. “Build houses which are better designed for the emerging methods of Additive manufacture, rather than optimising them for existing models of design.” (Vassey, 2019) Furthermore, the implementation of design for manufacture and assembly (DFMA) in combination with AM could result in architects designing built environments being optimised to their users’ experience, instead of the existing model of fabrication. (Vassey, 2019)

2.2.6 Wire-arc Additive Manufacture

WAAM is a large scale metal additive fabrication process which utilises the multidirectional nature of a robot arm in combination with a welding torch to construct geometries in a layer by layer bases. Recently WAAM has gained significant research interest due to its ability to produce industrial scale building elements, unlike AM processes such as SLM and Polymer printers, which are restricted to being a prototype method of building elements due to their reduced deposition rate and print bed size. The increased deposition rates, layer height, reduced environmental impact along with relative cost efficiency means that as a fabrication process, WAAM is considered a more viable option of the fabrication of large scale construction elements. (Ding et al., 2014, 2015a, 2016) Alternatively, the increased deposition rate means that the fabricated geometries have a lower resolution finish than conventional 3d printing without the inclusion of post-processing into the workflow, finished geometries maintain a rough surface finish and low resolution of detail. With regards to the AM process WAAM is considered a viable economic and more sustainable solution for fabrication complex metal geometries due to its reduced material usage and fabrication time. Additionally WAAM is considered an alternative solution to subtractive fabrication due to its ability to easily construct complex mass-customisable geometries. (Zhai, 2012)

The most common materials substrate used in coloration with WAAM's is 308LSi, this creates layers with an average weld pool of 8mm in diameter and deposition rate of 5mm/s. These rates are dependent upon the type of metal used along with the wire thickness, as different grades of metal have varying effects on the printing properties. (Ríos et al., 2018, p. 653; Suryakumar et al., 2011) One of the unique properties of WAAM print is the need of cooling between layers. Unlike other forms of additive fabrication that allow continuous printing, the placement of molten metal requires either active systems of cooling or passive systems of interpass times between layers in order for the layers to build onto each other. (Ding et al., 2015b)

The costing model of industrial architectural fabrication of steel joints has limited the types of geometries which are viable and feasible to construct. However the costing model of mass-customisable large scale additive manufacture process such as WAAM, exists within an area which is currently not catered for by the model of mass production. Highly variable joints within a buildings catalogue, which are complex in geometric nature and limited in repetition are a target focus of additive manufacturers. WAAM's increased deposition rate over other forms of metallic additive manufacturing such as powder-based systems, primarily Selective laser melting (SLM) allows the opportunity for the fabrication of architectural joints which provide structural supports in a more cost effective time and scale.

FIGURE.2.13 | *3D PRINTING TOOLING (LINCOLN ELECTRIC, 2020)*

FIGURE.2.14 | *WAAM BRIDGE (MX3D, 2015) ADRIAAN DE GROOT*

2.3 Precedent Reviews:

2.3.1 Takenaka Joint

The Takenaka joint (2019) by MX3D looks at challenging the notion that 3d printed construction elements are not viable due to factors of material cost, scale and fabrication time. Through the fabrication of a series of proof-of-concept joints, this project has created the notion that through the use of WAAM variable mass-customisable joints can be used within buildings as a structural element.

The joint itself is a collaborative effort between MX3D and Takanaka, and is a test piece for a complex, parametrically informed tree like structural support. It utilises the fabrication process of WAAM to construct a hollow core shell print which stands at 500mm height and has a net weight of 40kg. Through the applied use of topological optimisation, the digital design loop was able to be further informed by data driven parameters, automating elements of the design as well as reducing the required amount of material in the print. The implication of this project acts as a proof of concept that mass customisable, additively process joints are a viable construction element. Utilizing visually variable joints in combination with WAAM fabrication to increase the discourse surrounding the viability of unique nodal construction within architectural structures.

One of the primary limitations with this system of design and fabrication is the limited range of angular range afforded to the connection members. Since the process utilised the base conditions of WAAM, the structural forms are restricted to a geometric form which can't branch further than 30-degrees.

FIGURE.2.16 | *TAKENAKA CONNECTOR (MX3D, 2019)*

FIGURE.2.15 | *TAKENAKA CONNECTOR (MX3D, 2021)*

2.3.2 Non-Planar Fabrication

As WAAM fabrication has begun to establish itself as a large scale fabrication process, the constraints and limitations of the process have been addressed through non-planar fabrication methods in combination with external manipulation affording the process the ability to print complex geometric forms. The use of mixed-layer adaptive slicing and cylindrical slicing utilises formal deconstruction and regrouping in order to fabricate complex geometric forms more efficiently. (He et al., 2019; Pan et al., 2018) Using a singular methodology to print forms in their most optimal method and removing the need for support scaffolding. The application of these non-planar methods allows for complex forms such as ship propeller and multi-direction joints to be fabricated.

The fabrication of the ship propeller provides strong evidence that non-planar fabrication extends the practical fabrication of complex geometries allowing for the additive production of parts to directly compete with the existing mass-produced fabrication model. (Zhao & Guo, 2020) The inherent limitation of these two precedents is that they focus on a singular fabrication approach, aiming to directly compete with the existing fabrication of mass-produced standardised components instead of producing forms that are enabled by the process. While the fabrication of the multi-joined pipe presents a methodology of extending the printable range of a part through external manipulation of the print base. The resulting form is an existing standardised component that is more efficiently produced through existing mass-production methods regarding cost, fabrication time, and material usage.

The implications of these precedents demonstrate the possibilities that WAAM fabrication can construct complex geometric forms. Additionally demonstrating that the fabrication process's limitations and constraints lead to innovative solutions challenge the contemporary mass-produced fabrication model.

FIGURE.2.17 | *MIXED-LAYER ADAPTIVE SLICING (2020)*

FIGURE.2.18 | *CASE 8 PIPE JOINTS (2020)*

2.3.3 Other Precedents

The structural joining element of a 'node' has become an un-optimised, underutilised component within architectural structures. However these precedent projects looked to construct joints which challenged this inherent nature. Utilise additive fabrication to construct mass-customizable connection joints for their irregular highly parametric designs. Centralising the joint itself as an aesthetic option within the structure's dialogue, expressing the highly individualised nature of connection over the traditional joint methods which aim to hide the nature of a connection. Additionally some precedents expanded upon the role of the joint within a building and applied structural modelling to inform both the print time and material usage of the node. Designing the joints for manufacture whilst expressing the opportunities of computation design and saving material algorithms.

FIGURE.2.19 | *MANGROVE STRUCTURE, DENEGRI BESSAI STUDIO, 2015*

FIGURE.2.20 | *GROTE MARKTSTRAAT, ARUP, 2015*

FIGURE.2.21 | *AIRMESH PAVILION, AIRLAB, 2019*

FIGURE.2.22 | *SYDNEY OPERA BAR VIP CENTERPIECE, UNSW CoDe, 2016*

FIGURE.2.23 | *6 BEVIS MARKS, ADRIAN PRIESTMAN, 2013*

FIGURE.2.24 | *NODE, TIDA, 2019*

FIGURE.2.25 | *SMARTNODE PRIVILLION, RMIT UNIVERSITY 2019*

03

Digital Framework

CHAPTER 3

FIGURE 3.01 DIGITAL PLANNING

3.1

Introduction:

This chapter establishes the digital parametric model which is used to construct a range of contextual respondent connections throughout a series of complex non-linear structure. The aforethought model takes into consideration the discretised elements of a 3d structural model to computational inform the design of the joints. In combination with the parametric tools, a range of nodal connections are afforded the potential for full customisation with regards to both the computational response to the structure and the parameterised variables within the digital model. Furthermore, the digitalisation of this parametric workflow enables large amounts of itemised data and digital relationships to be organised, scheduled and transferred through the design to fabrication workflow.

3.2

Prototyping Materiality

Due to the offsite limitation of using WAAM's larger scale printing process, polymer printing was used as an initial prototyping method within the earlier stages of the research. The use of polymer 3d printing meant that the research was able to rapidly explore joint designs with regards to aesthetics, printability and concepts of segmented printing before printing the final designs. Standardised 1.75mm ABS 3d filament at a print height of 0.2mm was used within the initial stages of the project allowing for a scaled test of additive printing principles before physical fabrication. In the same manner as architects use 3d printers as a conceptual driver to establish a link between physical materiality and digital designs, printing prototypes through the use of polymer allowed this research to evaluate printing methods and critique elements of the digital design before printing the final versions in metal.

Individual Lines
- Beams and Columns

3.3 Digital Discretization

Throughout this research there will be a digital reduction on the level of architectural members mentioned and displayed throughout the research. This is due to the heavy computational strain that it places on a computer when calculating every element of a structural model. Instead, architectural members and elements will be digitally reduced to their simplistic and data transparent methods of communication. The 3d modelling method of the node-element model will be used, where complex non-conventional structural forms will see beams and columns digitally reduced down to individual lines and nodal joints will be reduced to connection points. (Madenci & Guven, 2006) This is to reduce the complexities of the digital models as well as improve the display characteristic of the model.

Support
Members

Intersection
Nodes

Digital
Model Data

Whilst the process of digital discretization reduces the level of visual data communicated throughout the model, the established link between the base digital elements of the structural model, allows for the model to easily draw elements and parameters from the complex structural mode without having to fully visualise the process.

Additionally, this established link between the full structural model and the digitally discretized data means that variable parameters attached to the structural model can be changed without impacting the logic of the model. Parameters such as the dimensional conditions, material properties and member type can be fundamentally changed without impacting upon the computational load of the digital model or development of the workflow.

3.4 Parametric Nodes

The digital parametric model used throughout this research constructs nodal joints based off the discredited digital elements of a 3d structural model. Using the digital data of end profile, centreline and node collision points to inform and localise the connection within an existing 3d architectural model. These three key discretised elements of digital data are the only variable parameters manually fed into the parametric model. Beyond specifying these discretised architectural elements, a model of closed loop design is constructed. This methodology of a closed digital design ensures that whilst the repetitive task of constructing mass-customisable joints is running, the designer is able to productively work on other elements of the design without having to continuously feed inputs back into the digital model.

Joint-specific parameters such as the body hull, distortion of the surface, length of the members and mesh smoothing increased the level of design freedom and customisation. Through manual control over these aesthetic parameters the designer is afforded design control over the form of the joints without impacting upon the computationally driven stage of the joints' design.

The key computational stage of the joint design where:

1. Localising the intersection points and relevant connecting members
2. Retrieve the defined end profiles sizing dimensions of structural members, adjusting variable length placement to avoiding localised mesh collisions
3. Extrude end profiles to a central point to construct transitional limbs between intersection interface and the node
4. Construct a convex hull for the body of the joint
5. Define and place chosen joint interface between member and node
6. Smoothing resultant body for seamless edges and aesthetic fluidity

1.

2.

3.

4.

5.

6.

3.4 Parametric Nodes

One of the key errors that frequently occurred during early versions of the script, was the continually overlapping and distortion of the finalised smoothed mesh. This error occurred when input members were too close together, resulting in a collision of the mesh's body and limbs. The implemented solution saw the digital node algorithm respond by adjusting the variable lengths of the limbs to allow for a seamless transition between node terminals and the convex hull body of the joint. This simple error check to the digital design model removed repeating errors within early iterations of the mesh models, whilst providing quality assurance that the mesh model could be carried through to the fabrication process without requiring manual intervention to fix flip faces or overlapping geometries.

The initial design constraints of the process allowed for a variable array of structural nodes to be digitally generated and changed with regards to the centrelines of structural members and design grids. This meant that the process for constructing an array of nodes throughout a structure could be locally individualised and contextual respondent, without the manual production time of a human producing the individual designs for local nodes. With the digital parametric model, a series of mass-customisable joints could be produced in an instant with regards to both the localised member constraints as well as the aesthetic conditions desired by the designer. Additionally, due to the parametric nature of the script itself, any component with variable parameters can be optimised and changed in order to better respond to the designer's desired outcome. The implementation of digitally responsive node generation meant the joints and, by extension, the structural form were unrestricted by the limitation of standardised connections which primarily only provide a singular 2d plane of freedom. Instead, the parametric joint connections are afforded 6 degrees of design freedom to respond to any angular range of member inputs. In instances of mass-customisation this means that as long as a structure is reduced to the simplistic discretised nature of lines and connection points, the digital model can universally respond to any range of contextual angular inputs.

Structural design A {10} series

3.5 Digital Itemisation;

For this research itemisation of building element relationships along with the collective nesting of individual structural elements was an essential part of driving the research forward. By itemising the data relationships between mass-customised design components within the early stages of the design workflow sets of complex relationships such as the sorted list of data connections, sorted arrays of timber members, node to member relationship, onsite assembly sequencing and assembly itemisation were able to be adaptively sorted, scheduled and later referenced in the digital design to fabrication workflow.

The use of digital itemisation streamlined the file to factory workflow ensuring that there was a direct data transmission between the architectural design, fabrication procedures and onsite assembly. Additionally, this linear transitional of scheduled data relationships meant that a direct digital feedback loop was able to be constructed where elements of fabrication and assembly process could directly be translated to the relevant itemised relationship within the digital design process. Without the tagging and scheduling of building elements and nodes connective assembly and further steps throughout the digital to fabrication workflow would have been liable to error and mis-assembly.

FIGURE 3.10 DIGITAL SCHEDULING AND ITEMISATION OF PAVILION NODES

3.5.1 Data Sequencing

{ Plan - Rapid Scheduled Outputs

- 17 Unique Length of Timber Supports
- 12 Unique Custom Joints Connections
- 7 Unique Foundation Custom Joints Connections
- 4 Unique Roofing Custom Joint Connections
- 11 Unique Roofing Panels
- 466m Lengths of Timber

FIGURE 3.12 PLAN VIEW; SUPPORT MEMBERS SCHEDULED
WITH RELATIONSHIP TO CONNECTION NODES

Node
A {201}

Node
A {202}

Node
A {203}

Node
A {207}

Node
A {301}

Node
A {302}

Node
A {306}

Node
A {307}

Node
A {308}

FIGURE 3.13 DIGITALLY ITEMISED SCHEDULE OF NODES
FOR PAVILION STRUCTURE SERIES N.1

FIGURE.3.14 RANGE OF POLYMER PRINTED SCHEDULE OF
NODES FOR PAVILION STRUCTURE SERIES N.1, SCALE 1;10

3.6

Computaion Reflection

In order to physically understand the materiality of additive fabrication, polymer scaled prints were used and developed to explore the systems of design. While the scale prints, visual lack the weight of a full scale connection, the apparent design freedom and ability to construct complex non-linear structures with regards to mass-customisation became self-apparent. The polymer test prints were printed as full body mesh shells, where the prints were given an infill of 20% to compensate for the 0.2mm layer thickness and required need for scaffolding. Across the range of printed node series and iterations, the amount of support scaffolding ranged from 33.2% to 61.2%.

Node A201

– Series A (ABS Print)

Volume - 751.5 mm³
Weight (kg) - 82.5 grams
Print Time - 7h 24m
Input members - 5
Layer Hieghts - 0.2mm
Layers - 110
Required Supports - 39.3%

FIGURE.3.16 POLYMER PRINTED NODES_A201; SUPPORT STRUCTURE

3.7

Preliminary Node Evaluation

The digital design model which allows the construction of a range of mass-customisable joints is a foundational part of this research, as it allows for countless tests of modellings, forms and aesthetic options without the manual labour-intensive process of digital modelling singular responsive joints for complex structures. The early establishment of this script meant that less time was spent repetitively modelling customised joint designs and instead was focused on the physical means of fabrication along with the digital design to fabrication workflow.

The variable parameters which controlled aesthetic design factors in combination with the 6-degrees of angular freedom allowed for an array of aesthetical design options to be produced. This afforded the joint connections, mass-customisation in regards to both the design of the joints and contextual structural response. Through the physical practise of additively printing scaled prototypes of the nodes, development of the digital design to fabrication workflow was enabled. Visually constructing a link between the digital data drive design and physical materiality, where the properties of physical print feed back into the digital design and vice versa construct an open loop workflow.

Now that the means of digital design and physical prototyping has been established the focus of the research shifts towards exploring the capabilities of full scale print through the process of WAAM. Shift the dialogue from scale polymer prints towards industry scaled additive production, where further developments in the file to factory workflow allow for collaborative feedback between the digital design and fabrication process capitalising on the benefits of additively producing mass-customisable joints.

FIGURE 3.17 *NODES_A201; SUPPORT STRUCTURE CLOSE UP*

04

Segmentation

CHAPTER 4

4.1

Established Design :

Having previously worked with the fabrication process of WAAM, Tida Node (2020). There was already an established level of knowledge surrounding the initial setup, physical limitation and resulting materiality from the prints. These previous research which saw the collective collaboration between industry partners of Tida and MX3d, allowed for this research to have an established understanding of the fabrication process. Removing the primitive research need to produce test prints exploring the material properties and unique characteristics for the fabrication process.

Instead of focusing on the material science side of the fabrication, an element of fabrication which has already been established during the Tida Node (2020) research. This research will focus on exploring how complex architectural joints can be fabricated through the use of multi-direction segmentation. Enabling an additive algorithmic approach to printing 'unprintable' geometries and the opportunities it affords the fabrication process.

FIGURE 4.19 *TIDA NODE* (2020)

SCAN ME

Video Title: Tida Node - WAAM
Singular Print Layer Fabrication

WAAM Print Layer

The video below is not the most accurate representation of base WAAM fabrication due to the nature of the footage being sped up as well as the use of spheric slicing, however it acts to provide an overview of how WAAM as a fabrication process works. Highlighting the scale of the print layers, surface finish and range of procedural tasks executed within a single print layer.

4.2 WAAM Limitations:

Like all fabrication processes, WAAM is restricted by constraints and limitations that define the viable geometric form that are physically constructible. Many of these constraints are a follow-on effect from the limitation seen in AM. Although WAAM is considered a newly emerging larger-scale additive fabrication process, it is fundamentally limited by four elements that restrict the 'printable' geometric forms:

Overhang angle (30-degrees)

Print Size (Range of Print bed)

Wait Time (Interpass time between printed layers)

Torch Alignment (Vertical to the print layer)

These fundamental limitations define the viable geometric forms produced through base fabrication, framing the fabrication scope regarding the rate of production, size of production and printable geometric 3d forms. Without the current ability to print support structures (scaffolding), WAAM is highly restricted in the geometric forms that it can produce, being restricted by the material substrate and planar slicing properties. These restrictions, primarily the overhang angle of 30-degrees and wait time between layers, are addressed within this research through non-linear segmentation, allowing for the construction of mass-customisable geometric nodes digital constructed in the previous chapter.

Wire - Arc Additive Manufacture Fundamentals

- 1: Weld Torch Nozzle
- 2: Nozzle TCP
- 3: Current Print Layer Move Targets
- 4: Previous Weld Based Layers
- 5: Vertical Weld Torch World Aligment
- 6: Print Base Plate
- 7: Weld Deposition Direction
- 8: Current Layer Home A{Node Tag}_{Current_Layer}Home

4.3

Localised Angles

A key aspect of fabrication limitation is that complex geometric forms such as the digital constructed mass-customisable nodes are considered 'unprintable' through traditional methods of planar slicing. The angular responsive nature of the nodes means that the majority of the connective limbs exist within a global reference range $0^\circ - 360^\circ$. As such when planar slicing is implemented with regards to the global Z axis, a significant proportion of the nodes geometry exceeds the 30-degree overhang constraint, with certain sections of the print requiring material to be deposited in empty space. In order for the research to progress a methodology of constructing these 'unprintable' areas was needed, as otherwise the printable nodes would only be able to connect structure members which act within a 30° angle cone.

FIGURE 4.22 DIGITALLY LOCALISED ANGULAR PARAMETERS OF NODES

Joint A {3;0}
Connection Members
 - { 1;0 }
 - { 2;1 }
 - { 2;2 }
 - { 2;3 }

**Angular responsive design of the nodes
well exceeds the 30-degree overhang
limitation of WAAM**

**Node
A {302}**

Node
A {201}

$$\text{overhang angle (X)} = (\theta) - 90^\circ$$

Where (θ) = angle between mesh face normal and global Z axis

4.4

3D Angle Checker

In order for this research to deal with the issue of unprintable node geometries a visual toolkit was developed to allow for a connective link between what was conceivably printable and what pushed the range of fabrication. The initial integration of the visual toolkit was used as a post design check before polymer prototypes were fabricated, occurring during the fabrication stage of construction the 3d printers tool paths. This method of overhang angle checking compared the current print layer, (N) against the next print layer (N+1) and highlighted sections of the print volume and layers that where areas of concern for the fabrication process.

While this methodology defined and highlighted problematic areas of the print volume, the evaluation of data occurred too late within the digital workflow limiting the amount of integrated inclusion within the design process. In response to the static nature of the visual toolkit, it was reworked to evaluate the surface normal of the mesh geometry during the computational construction of the nodes.

This additive toolkit meant that the visualisation of the problematic areas occurred during the design process instead of the fabrication process. Evaluation of mesh model before the construction of print tool paths allowed for the computational model to respond to the nodes design as well as construct a visual link between digital 3d mesh models and the resulting prints which are physically constructible.

The final version of the digital angle checker used within this research evaluated the mesh face normal against the global print nozzle orientation and assigns a visual colourisation between unprintable geometries and potential areas of print errors, affording designers a collaborative link between the fabrication process and design intent. Closing the loop of digital data transferred and collaboratively linking the physical nature of the fabrication process with the digital design. The implantation of a visual design toolkit meant that the digital design of the nodes changed with regards to the 3d mesh model surface slope instead of the static 2d planar tool paths.

Overhang Angle - Medium
- 12 ° to 35 °

Total mesh Faces - 1825
- 32.5 %

Overhang Angle - Easy
- 0 ° to 12 °

Total mesh Faces - 578
- 10.2 %

Node
A {201}

Node
A {202}

Node
A {203}

Node
A {207}

Node
A {301}

Node
A {302}

Node
A {306}

Node
A {307}

Node
A {308}

Node
A {204}

Node
A {205}

Node
A {206}

Node
A {303}

Node
A {304}

Node
A {305}

Node
A {309}

Visual Angle Checker:

- 45 - 90 ° { *Unprintable* } - 45.1 %
- 35 - 45 ° { *Considerable Overhang* }
- 25 - 35 ° { *Medium Overhang* }
- 0 - 25 ° { *Easy Overhang* }

On average 45.1 % of a node is 'unprintable'

4.5 Non-linear Slicing

In order to fabricate mass-customisable joint geometry used to construct parametrically informed architectural structures, a methodology of construction which disregarded the imposed limitations of WAAM, primarily the restrictive limitation of a 30-degree overhang angle, was needed to be addressed in order to construct a range of joints which connected structural members at a greater global angular range than -30 degrees to +30 degrees. In order to overcome the exposed limitations of WAAM's fabrication, a methodology of generating non-linear print paths to realise the design potential of fabricating mass-customisable nodes through the process of WAAM was used. This methodology addressed the key limitation of overhang build angles and vertical torch orientation in order to realise the fabrication of geometric nodes which act in the 'unprintable' fabrication range. An additional benefit of this non-linear fabrication methodology was the increased production speed and reduced fabrication time.

The methodology uses nonlinear slicing to segment the node members into printable sections, similar in theory to mixed-layer additive slicing which deals with the decomposition and aligned printing of pipe-based structures. This method of non-linear slice constructs tool paths with regards to the relevant directional input of the structural members, not requiring the use of an external manipulator to re-orientate the building planes of the part in order to continually build up the geometry.

This method of non-linear slicing looks at the decomposition of architectural nodal forms through the use of existing digital data established within the digital construction, using the directional norm of the input member (structural support) centrelines to reference the localised build planes. These build planes dictate the geometric slicing direction of the node informing the fabrication tool paths. The resulting collision points from the intersecting tool paths construct the seam lines which segment the print volume. Through the implementation of this non-linear slicing method, the decomposition of the node results in segmented print volumes equal to the amount of member inputs. For a visualisation purpose the mesh geometry was segmented and oriented to the global build planes. However, with regards to the fabrication process, the tool paths are the only part of digital data that is re-orientated and fed through the fabrication process.

Node A201
Timber Multi-Directional Joint

SCAN ME

Animation of
Non-Linear Slicing

Video Title: Animation
explaining Non - Linear Slicing of
a multi-direction node

4.6

Itemised Segmentation

By rational slicing the geometry with regards to the amount of member inputs, an array of printing tool paths is constructed, with each of them being relevant to the number of connections interfaces. A joint with $N=4$ member connections will have 4 resulting slicing directions and tool paths and a joint with $N=5$ member connections will have 5 resulting slicing directions and tool paths. These slicing tool paths act as a foundational piece of digital data, informing both the fabrication tool paths and the digital schedule used to reconstruct the segmented sections relationship to each other. Through digitally labelling the N number of tool paths a relationship between the segmented sections and structural members is itemised allowing for ease of assembly post-fabrication.

There are a few inherent benefits of using this method of non-linear slicing over traditional planar slicing. The first is that the print geometry itself is able to be printed without the need for scaffolding and the second is that the fabrication process is afforded a continuous printing process, ensuring the print paths are long enough. This means that the robot is able to print all segmented sections of the node continuously without having to impose an interpass time between layers as passive cooling is applied to the printed layer whilst the other sections of the node are being printed. This reduces the interpass time between layers by a minimum of $\frac{1}{4}$ and at best completely removes it from the fabrication process.

This methodology of non-linear slicing and segmentation addressed the key limitation of overhang build angles and vertical torch orientation in order to realise the fabrication of geometric nodes which otherwise would be considered 'unprintable', additionally, increasing the production speed while reducing fabrication time.

A key challenge of multi-directional segmentation for additive manufacturer is the development of geometrical capable algorithms which respond to any range of geometric forms (concave, convex). The algorithmic segmentation should be capable of accurately automating the equal segmenting of the 3d mesh model into a set of additively printable bodies which do not require support structures and align along the segmentation line. The idea behind segmenting the node geometry was to increase the range of printable geometric forms by segmenting the node part along a localised seam and reconstructing them post-fabrication. Unlike traditional methods of segmentation where the part is split along random seams, this method of segmentation is defined and self-contained within the design loop, requiring no additional inputs from the manual operator.

Node_A {308}

- Series B (ABS Print)

Volume - 751.5 mm³
Weight (kg) - 120.1 grams
Print Time - 8h 32m
Input members - 4
Layer Hieghts - 0.2mm
Layers - 192
Required Supports - 45.7%

Digital Segmentation

Digitally segmenting Node_A {501} results in the initial node geometry being increased from a singular mesh body to 4 individual segments responding to the number of input members. The deconstruction of the initial mesh is split apart along a singular continuous seamline which act to inform both the point of disassembling and assembly.

Whilst other additive fabrication methods can construct 3d models which exceed the overhang limit, if the mesh form of joint A {501} was to be printed through the process of WAAM, 45.7% of the geometry would be in excess of 30° and be considered unprintable. However, though non-linear segmentation the geometry is afforded the ability to overcome the fabrication constraints and be printed through WAAM.

Node Joint
- A501

4.7 Joint Interface:

The initial stage of the design constructed a digital framework script which allow for the parametric construction of node, up until this point in the research little consideration was given to the physical connection interface between the joint itself and the timber support member, until after the segmentation of the joints was solved. All of the polymer prototypes regarded the connection interface as an expansion of the 3d mesh geometry. In the instances of solid mesh node, the connection interface, saw the two faces being glued together and in the instance of shell mesh node, a socket joint was used.

Due to the additive nature of the fabricated print, the segmented node is afforded the ability to utilise a variation of connection interfaces between the support members and node. The possible range of connection interfaces, such as base plate bolting, external flanges and socket joints, allows for a variety of different member to node interactions with regards to materiality, onsite/offsite assembly and the sequenced assembly of non-regular building components. While this digital concept was never developed or realised through the fabrication process of WAAM, it became a necessary consideration towards to the industrial applications and onsite assembly of parametric structures.

05

CHAPTER 5

Fabrication Establishment

5.1

Toolpath Creation

In robotic fabrication tool paths refer to a sequence or array of positional movement points which are used to inform where the location of the TCP. In this research the tool paths are extracted from the digital model through non-linear slicing and then translated into a series of arrays to inform the print layers and sequence order of points.

These points inform direction and sequenced order that the welding torch should move through in order to construct the print layers. Additional movement positions are added to the tool path to inform stages of the printing process.

Due to the print process not being continuous in nature these additional movement positions are tied to procedural operations which occur throughout the course of a singular print layer. The creation of the tool path are detailed in the key steps below.

1. Non-linear Layer Slicing

In order to additively construct the intended digital node model, relevant curves space at 3.2mm where need to create the physical geometry. These were obtained through non-linearly slicing the digital model into 2d CAD slices, obtaining the base representation curves which were used to inform the print paths.

2. Simplify Toolpath (Point Spacing)

The representation curves obtained through non-linear slicing are an approximation of the digital geometry and potential contain critical errors with regards to the print part and material properties of the deposited weld pools. As such to reduced the error rate as well are reduced the unnecessary data being transferred to the robotic controller, the obtain curves are smoothed and simplified, normalising the function of the tool path curve, reducing the deviation and unnecessary noise which results in areas of rise and slump within the print layer.

3. Movement Planes (Global Positioning)

In order to construct the movement positions for the weld torch to move through, global planes are needed to inform the end effector of its directional orientation as well as its position in space. As such the simplified curves being divided at 2mm point spacing to construct an array of movement planes. Additional global home positions are independently added between layers allowing for welding torch to transition between print layers without hitting the printed volume.

4. Toolpath Direction

A common error within WAAM printing is the slump and rise of print layers due to variable rates of cooling across a whole layer. With the same continuous printing direction resulting in one end of the print being higher than the other. As such print layers alternated toolpath directions every second curve to reduce the total distortion across the whole print.

5. Staggered Start Points

Due to the visible appearance of start points welds, the start points of the print layers are randomly alternated throughout the print volume to reduce the visual impact. As not staggered the start points result in a visually noticeable seamline. The random shifting of start and end points throughout the print is purely a visual element to reduce the visual appearance on the surface finish. Additionally, the start and end points are tied to the procedural operation of arc-on / arc -off.

Closing Statements

These toolpaths are just points array of movement commands which are uploaded to the ABB controller in an RAPID procedural module. Whilst the construction of the toolpaths only tells the robot where to move, the order of the movement commands along with the positional order allows for additional external procedures to occur within the array. With key positions in array inform when automated tasks such as gas flow, arc on and wire feed should occur. Additionally the movement array acts to inform which stage of the printing process is occurring, visual signifying if the cell is live or not acting as an additional safety factor.

5.2

Fabrication Simulations

Digital pre-print simulations were used to check and ensure that there were no errors during the printing process or the movement of the joints. The digital workflow used an inverse kinematics solver to ensure that none of the independent joints' parameters ran through singularities or collided with the surrounding environment. During the process of visual simulation, the printing process acted as a final safety check to detect potential errors, collision or missed print layers within the modules.

SCAN ME

Scan to See digital Simulations
Of the Print Procedures Occuring
During robot fabrication

Video Title: Fabrication Simulations

FIGURE 5.35 *PRE-PRINT CALIBRATIONS PROCEDURES*

Working Enviroment :

5.3 Robotic Environment

Fabrication of the metal joints was done at an offsite robotic cell external, due to the 'messy' setup and establishment of a working WAAM cell. Printing joints through the process of WAAM was not able to be performed on-site at Victoria University of Wellington. As such, this research used Tida's established robotic cell in order to test the methods of printing architectural nodes through the process of WAAM.

Due to the nature of constructing layers with a MIG welder there are a number of variable components within a WAAM welding cell which are unique and unnecessary in other processes of robotic printing. The setup used within this research utilises a 6 axis ABB robot in conjunction with an external manipulator to establish the robotic parts of the cell. Attached at the end, the robot's arm is a MIG welding torch acting as the effector. Much like free form printing, the MIG welding torch acts as an extrusion tool as well as the end effector. The Tool Center Point (TCP) is established at the tip of the nozzle, with the additional variable of the wire length and distance from the nozzle tip being taken into consideration during the digital calibration of the toolpaths.

The location of the work surfaces and surrounding cell environment were also digitally established parameters. This meant that the location of the external manipulator, and in turn the build plate, were established conditions within TIDA's work cell. A machine steel plate which was bolted on top of the external was used as the build plate and worksurface for the print. Due to the previous calibration and established accuracy of the work environment, preliminary checks were run before the print to ensure that the robot's accuracy was still within 0.1mm. These preliminary checks ensured that the accuracy of the prints was not changed as a result of the un-evenness of the plate.

In addition to the standard components which make up the robotic cell, the wire feeder, ABB robot control and welding gas supply, there are the additional safety requirements from the process of welding. An extraction vent is located above the build plate and welding nozzle acting to remove possible toxic gas from the cell. In addition, the exterior of the welding environment is covered in UV protectant screens which act to dissolve the rays of the welding torch. Additional safety factors, which are not apparent in the design of the robot cell, are the use of lab coats, welding suits and welding masks which have to be worn if any physical interaction is required within the robot cell.

Welding Torch

Welding Nozzle

Cell Camera

6 Axis Welding Robot

Wire Cleaner

Welding Helm

Welding Gloves

Base Plate

Work Bench

Welding Screen

FIGURE 5.38 WELDING CELL SETUP

5.4 WAAM Materiality

Building upon the prototyping materiality of ABS polymer, the full-scale prints used stainless steel wire due to its corrosion resistance, mechanical printing properties and applied use within the construction industry. From this point on in the research 0.8mm 316 stainless steel wire will be the primary material of investigation.

FIGURE 5.39 *STAINLESS STEEL PRINTING WIRE*

5.5 Accuracy:

Whilst the TCP was established and set to an acceptable global tolerance of 0.01mm before the printing process, the variable nature of printing layers onto a malleable molten surface meant that the layers accuracy needed to be constantly monitored and the variable adjusted to ensure a consistent and accurate print throughout the printing process. The inaccuracies within the tolerance throughout the process of the print were a resulting factor of push and pull welds, as well as the general wear caused by the wire on the contact tip.

Unlike other methods of robotic fabrication where the TCP is established and left unchanged throughout the course of the procedural operations, the variable nature of printing on an uneven and malleable surface (molten stainless steel) which is prone to slump or rise due to external factors, means that consistent accuracy checks are required to ensure that the constructed layers throughout the print are within an acceptable range of accuracy. As factors such as push and pull welds wear on the feedhole of the contact tip and shift the wire tip by considerable amounts, the additional factor of the wire extending 40mm for the TCP means that wear at the end of the contact tip presents significant change in the placement of the wire's tip and resulting print geometry if left unchecked.

Certain levels of tolerance are built into the digital toolpaths and inaccuracies within the print are considered acceptable since the process of WAAM produces rough end products which can be post-processed to a near net perfect shape. That being said the contact tip is changed regularly throughout the course of the print to ensure that the print sits within a range of 1-2mm of the digital model.

FIGURE.5.40 *PRE-PROCEDURAL ROUTINE CALIBRATION*

FIGURE.5.41 *MANUAL TCP ACCURACY CHECK*

5.6 Pre-Printing Procedures

Manual preparation of the base plate by grinding the surface layer ensures that no dirty materials from the plate cause issues with the arc failing to strike and error or affect the porosity of the initial weld layer. Once the task is completed, the calibration and accuracy of the print has been established and the final task in the pre-printing procedures is to switch the robot into automatic and begin printing modules.

FIGURE 5.42 PREPARATION OF THE BUILD PLATE TO ENSURE THE FIRST LAYERS DON'T HAVE AN ELECTRICAL IMPEDANCE, CAUSING AN ARC STRIKE ERROR.

FIGURE 5.43 *ESTABLISHED PRINTING ENVIRONMENT*

06

Fabrication - Node V.1

6.1

Pre-fabrication Introduction;

This section culminates the collective research of the polymer prototyping prints and digital design to finalise the geometric structure of a node in a full-scale metal printed joint. Therefore, acting as a proof of concept for the possibilities for non-linear slicing and segmentation to reduce the print time as well as print what was previously considered 'unprintable' geometries.

Over the next two chapters, two nodal joints which were fabricated through the process of WAAM, explore the physical characteristics of the resulting print form and fabrication process. While both digital joint designs were produced through the same methods of non-linear fabrication and segmentation, each node looked at different options for functional connection inputs between the joints and support members, as well as highlighting the possibilities of mass-customisation and the resulting aesthetic finishes afforded by WAAM fabrication.

6.2 Foundational Print Layers:

During the early stages of the printing process, print layers were actively monitored to ensure that the distortion of the build plate, resulting from continuous heating and cooling of the print layers, did not result in the build layers slumping or rising. This system of active monitoring occurred until 5 layers were printed, where the responsive layer heights had corrected any areas of slump/rise caused by the distortion of the build plate. At this point in the fabrication process the print modules were left to automatically run whilst being actively monitored through a camera in the robotic cell. The implantation of error procedural messages which resulted in the fabrication process spotting whenever an arc-on or gas error occurred, reduced the level of manual intervention and ensured that layers were not skipped during the printing process. This meant that the print could be passively monitored only requiring active intervention when an error procedure occurred or procedural task required human intervention. This system of passive monitoring has the potential to construct a closed fabrication loop with the implementation of control systems and automated procedures, that will further improve the reliability and repeatability of the process whilst reducing the necessary manual intervention. Additional systems such as active cooling, automated tool cleaning station, machine learning and robotic procedural task for wire, gas and ignition start errors, would optimise the fabrication process allowing for more industrial viability.

FIGURE 6.45 ACTIVE MONITORING OF THE INITIAL PRINT LAYERS, ENSURING NO ERROR WITHIN IN THE PRINT LAYER RESULTING FROM BUILT PLATE DISTORTION

FIGURE 6.46 MANUALLY RECORDING THE MATERIALS PROPERTIES OF THE PRINT LAYER WELD POOL

SCAN ME

Video Title: Node_1 ; Fabrication
Timeline

Print Properties:
Node _5.0'

Node Printing
Timelapse

Weight (kg) - 23.1 Kg
Arc On Print Time - 9 h 48 m
Interpass Time - 4- h 7 m
Input Member - 4
Layer Hieghts - 3.2mm
Print Layers - 119
Total Toolpaths - 479
Print Length - 158.1m

6.3 Print Fabrication Process:

Due to the hardware limitation of the ABB controller's memory, (data limit of points / file size) every module contained on average 10,000 points, equating to 20m of executable print length as the average spacing between movement points is 2mm. While it is possible to upload 20,000 points to the controller or directly upload print modules through the server and disregard the data limitation, the manual operation of uploading of the print module procedures every 20m, coincides with the manual operations and checks that it needs to be run during the printing process. As a result, the manual loading of the modules acted as a safety precaution to ensure that the manual procedures were not forgotten and occurred at the right time.

Whilst the actual fabrication time of the node was only 18 hours, in order for the robotic fabrication process to occur, two people were needed for on-site monitoring and health and safety reasons. In combination with pre-printing procedural operations, the actual fabrication process of the node occurred over the span of 4 working days and 8 printing modules. On average every module contained around 15 print layers or 60 individual toolpaths, with the average toolpath length being 284mm. Toolpaths with a smaller print length than 10mm were removed to avoid errors within the printed substrate. Consequently, the shortest toolpath print length was 10mm and the longest was 375mm.

6.4 Procedural Operations

Print modules uploaded to the ABB controller consisted of an array of movement positions and procedural commands which ran through a looping function. This ensured that if predefined error operations or values were triggered as a result of gas flow, arc strike errors, wire feed or extraction vent, the printing process would stop immediately within the looping array. This allowed for the error to be fixed and the print layer to resume from the point of stoppage without running through the rest of the print layers, or manually having to find the point of stoppage within the positional movement array.

The array of movement commands is run through a looping function which defines the order of procedures within a single layer. In addition to the movement positions, variable speed data is also predefined within the module order. Each print layer runs through the loop of:

```
Start Global Home Position (Location in space above Print geometry)
MoveL Layer Home (Location 60mm above layer start)
Run procedure Arc Start
Wait time 0.5s
MoveL Start Position of Layer
Run through Movement Array when Procedure Arc Weld Operational
MoveL Array of Points
Arc Off
Arc MoveL Z height to Home (New)
Wait Time (Interpass passive Cooling) // 40 seconds

Repeat Operation { Module list array; n+1 }
```

Due the average print length of the node being 284mm and no system of active cooling being implemented, the temperature of the previous print layer (n-1) didn't reach the appropriate temperature of 120 degree, in order to construct the next print layer. As a result, an interpass time had to be implemented to ensure the previous layer substrate was cool enough to print on. Whilst the length of the print layer toolpaths was not long enough to completely remove the need for an interpass time, a total reduction of 30% interpass time was achieved. This could have been further reduced with more separation between the segments on the build plate.

FIGURE.6.48 *PRINT LAYER FABRICATION LOOP*

SCAN ME

Video Title: Node_A50_Print_Layer

Movement Commands and
procedural operations occurring
in a singular print layer

FIGURE.6.49 *CLOSE UP WAAM FABRICATION*

FIGURE.6.50 *NODE V.1 - MID PRINT LAYER*

6.5

Manual Operations

While the fabrication process is not fully optimised and automated, there are still manual procedural operations which need to be performed during the printing process. These procedures occurred at different stages as a result of their required frequency, however all operations were timed to be performed between the change of printing modules to reduce the impact on printing sections. The manually procedural operations performed during the printing process were:

- Changing the weld tips every module
- Cleaning the nozzle tip twice per module
- Check on the gas flow rates
- Changing the wire role
- Managing and recording the build plates' temperature and distortion
- Measuring the print layers' temperature to ensure passive cooling is working
- Checking weld for areas of slumping or rising
- Changing the gas bottle.

FIGURE.6.51   *NODE V.1 - MID PRINT LAYER*

FIGURE.6.52   *NODE V.1 - MID PRINT LAYER*

6.6 Data Feedback Welds

Throughout the printing process weld layers and their deposition were constantly being informed by data feedback parameters taken directly from the MIG welders' outputs. This data was used to ensure that printed layers maintained a level of consistency across the whole print and were variably updated to compensate for external factors which caused imperfections in the deposited weld pool. These imperfections, commonly areas of slump or rise, were caused by factors such as the rate of cooling, push and pull welding, along with distortion of the wire feed caused by wear and tear on the welding tip.

While the process of data feedbacks only saw the MIG weld vary its control parameters to adjust the current layer height (amount of substrate deposited) as a response to previous layers ($n-1$), the process was constantly monitoring and recording data to ensure accuracy was established and handled throughout a singular print layer in response to the previously printed layer. Currently the method of data feedback adjustments is a real time responsive system where only the previous layer ($n-1$) is used to ensure consistent layer accuracy.

However, further development into this system, in combination with a catalogue of previous print data, would see the process being further automated and optimised. Through recording and active evaluation of digitally recorded data, desired aspects and aesthetics of previous print layer could be used to digitally inform to improve and enhance future prints, thereby acting as a feedback system where the performance of physical parts informs and builds knowledge around the next digital informed models.

FIGURE.6.54   *NODE V.1 - MID PRINT LAYER*

FIGURE.6.55   *NODE V.1 - MID PRINT LAYER*

FIGURE 6.56   *NODE V.1 - FINALISED PRINT SEGMENTS*

FIGURE.6.57 *NODE V.1 - FINALISED PRINT SEGMENTS*

FIGURE.6.58 *NODE V.1 - FINALISED PRINT SEGMENTS*

6.7

Segmented Assembly:

In order for the segmented sections to be assembled, there was some required manual post-processing. This saw the use of grinders to remove excess numb and tags with occurred along the seam line as well as positioning rigs set up to create a connective interface between the between two members at a time. Segmented sections where added one at a time, and tack welds where used to hold the segments sections in place before a weld bead was constructed along the seam line. Due to the digital tagging and itemisation established within the digital stage of the design, positioning and assembling the segmented sections was an easy task as each segment was able to reference to the digital model and placed within physical space accordingly.

FIGURE 6.60 *ASSEMBLED NODE V.1 SEGMENTS*

FIGURE 6.61 *INTERNAL MANUAL SEAM WELD*

6.8 Post – Fabrication Assembly;

Within the digital design model additional sizing around the exterior of the slot section was added and allowing for the offset of the weld pool to be a condition of the structure itself. Therefore, the digital model was compensating for the sizing of a 90x90, however was designed with the considerations of an 8mm weld pool, meaning the digital model was a 98x98mm cross section on the end terminal.

Whilst this consideration was taken into account and allowed for the net internal dimension of the node to represent a simple socket joint, the overall roughness and inconsistency of the welded layers resulted in a socket section which required additional human intervention and machining to slot the joint and timber sections together.

In order to assemble the timber members into the joint, manual post-processing was needed to construct a workable connection between the two members. This process involved manually smoothing the insides of the metal socket sections with a dremel to remove the imperfection and tolerances created during the fabrication process. In an ideal setup, these tasks would be performed within the closed fabrication loop, the existing digital data would allow for highly precise machining tolerances if variable attachment heads were attached to the robot's end effector.

Two bolt holes were drilled through the socket connections to further increase the connection between the timber member and joints. Without the incorporation of a joining system the timber would move and slide out, as it was not perfectly machined to be held in by friction.

FIGURE 6.62 *SQUARE SOCKET SECTION, CLOSE UP*

FIGURE 6.63 *SQUARE SOCKET, 90 X 90 ROUGH INTERNAL DIMENSIONS*

The overall imperfection of the internal dimensions of the socket, meant the timber members were required to be manual machined to effectively slot into place. This machining varied throughout the length of the member and across each of the members. Knots and scratches on the timber members are a result of the movement which occurs between the metal interface and the timber members.

Critical Reflection:

While the design for this node was initially constructed during the polymer prototyping phase, it wasn't until the physical full construction was finalised, that the overall volume and aesthetic appearance of the node become apparent. Once the segments were assembled the volume seemed clunky and visually bulky as a result of the extruding square socket sections. The whole form became a larger structural element than intended, asserting visual dominance over the whole structure. While an area of this research was to explore the possible visual importance of a joint within a structure's dialogue, the aggressive formal weight of the square socket sections drew unnecessary attention, overpowering the aesthetics of the structure.

While the node achieved the goal of constructing a mass-customisable large scale additive node joint which responded to the contextual relationship of the surroundings, the next development within this research needed to address the areas relating to the aesthetic qualities of the full-scale prints as well as the collaborative dialogue that the joints maintain with the surrounding built environment.

07

CHAPTER 6

Node v.2 - Post-Processing

7.1

Node V.2 Introduction:

The second node didn't challenge or change any elements of the fabrication process or file to factory workflow. Rather it acted as a validation of the workflow, seamlessly translating the digital design intent to robotic fabrication modules to physical printing without any errors or bumps in the process.

SCAN ME

Singular Print
Layer

FIGURE.7.01 *NODE v.2, SINGULAR PRINT LAYER*

Video Title: Node_A60_Print_Layer

FIGURE.7.02 *NODE V.2 - MID PRINT LAYER*

FIGURE.7.03 *NODE V.2 - MID PRINT LAYER*

7.2 Modelling Errors

Upon completion of the fabrication of the full-scale metal joint, a few key areas which were not addressed within the polymer prototyping or digital modelling became apparent. These problematic areas weren't limitations or errors within the theory of the workflow but rather areas which could benefit from further development. The primary area which could improve from further development surrounded the connective nature of the seam line. Whilst no issues were present during small scale testing, the larger layer thickness of WAAM fabrication presented issues around the connectivity of segmented sections along the seam line requiring additional manual post-processing in order for the parts to be aligned and connected.

The increased layer print width of WAAM (8mm) was not taken into consideration during the polymer prototyping phase. This increased physical offset of the layers meant that the edges of the print layers occupied the same space, and didn't seamlessly join along the seam line like the polymer models. In future prints this issue would be addressed through treating the physical translation of scale within the digital workflow. This saw the digital workflow take into consideration the material print width and offset the print layers by half of the width. Instead of treating the toolpaths as a digital slice of the geometry they were updated to be considered with regards physical properties of the print layers, thus treating the toolpath with regards to the size of the printed material and constructing them as centrelines to achieve a better approximation of the digital geometry.

Additional possible improvements to the seam lines connective nature revolve around the idea of implementing connection tags to allow for more seamless connection between the segmented sections. Much in the same manner that timber joinery used tags/nubs as an effective joinery method, a method of printing jagged tab edges in accordance with the layer heights may allow for better alignment without the intervention of manual operations. However, this was a theorised idea during the assembly of the node, and as such was not a realised part of this research for its possible benefits or unforeseen issues.

These unaccounted factors concerning the connective nature of the seam line only became apparent during fabrication and assembly, resulting in a connection between the segmented sections which was not machine perfect and required human intervention to manually machine sections and tack the part together before welding the seam lines. If robotic fabrication was to be used to weld the segmented sections together, either further print accuracy or post-process machining would be required to effectively construct a seam line joining the sections. At the current stage of research, the end product is too 'raw' to effectively produce a structural weld bead connection without manual intervention.

FIGURE.7.04 LACK OF CONSIDERATION FOR THE PHYSICAL PROPERTIES OF THE MATERIALS PRINT WIDTH, RESULTED IN LAYERS ALONG THE SEAMLINE OCCUPYING THE SAME SPACE AND REQUIRING MACHINING TO ACHIEVE A SMOOTH CONNECTION THAT COULD BE WELDED TOGETHER

7.3 File to Factory Workflow

The file to factory workflow used within this research saw a direct data translation of digital design to robotic toolpathing code and fabrication procedures. This direct translation of data allowed for the workflow process to be autonomously optimised without having to move and integrate through different programmes and model types. This meant that the digital design, toolpath curation and procedural command were proceeded through the same digital model and allowed for the expertise of the fabrication operator to feedback into the digital design.

Within a traditional design to fabrication workflow, data translation follows a linear process where static data is progressed through a series of stages requiring manual operators. This linear process results in alteration in the design resulting from fabrication limitation, having to be linearly translated back through the workflow. Consequently, this research created a closed digital design to fabrication workflow, which incorporates feedback loops throughout the process to optimise the process for future production projects. The feedback loops throughout the process, draw on the experience and expertise of previous prints to further optimise the fabrication process and workflow.

Where alteration and variation were required in order to ensure quality to the print these were able to be done at any stage of the workflow without impacting the flow of data or requiring repetitive manual intervention. In the case of physical fabrication, the nodes required the addition of base print layers at the bottoms of the joint to lift the print off the plate and ensure an adequate zone to cut the print off the plate. Since the data set was localised to the singular model, simple variation at the start of the process was performed and immediately transferred as a print module without the need for additional transfer of data between softwares.

FIGURE.7.07   NODE V.2 - POST-FABRICATION MACHINING

FIGURE.7.08   NODE V.2 - POST-FABRICATION MACHINING

FIGURE.7.09   *NODE V.2 - POST-FABRICATION MACHINING*

7.4 Critical Reflection:

The primary difference between the first and second iteration of the full scale joint, saw more exploration of the design opportunities and dialogue offered by an additively produced node. The aesthetics' of the second node looked at twisting the formal composition and inserting reduction into the mesh's body to provide elements of visual interest and variance to the surface finish. Additional building upon the lack of visual interest offered by the square socket joints, the second iteration utilised a repeating curved profile and clean intersection face to reduce the visual weight of the connection.

The design of the second node performed the task of constructing a visually aesthetic element better than the first node. If given the chance, to reproduce the first node a different method of connection interface between the timber connections and the joints would have been used. This would have allowed a visual cohesion between the two structural elements, or a symbiotic relationship where the visual weight of the joints didn't overpower the design.

A604

Node _6.0' Print Properties:

Weight (kg) - 5.4 Kg
Print Time - 8h 52m
Input members - 4
Segments - 4
Layer Hieghts - 3.2mm
Layers - 247
Required Supports - 0%

08

A close-up, high-contrast photograph of a woven basket. The texture is highly detailed, showing the intricate patterns of the weaving. The lighting is dramatic, with strong highlights and deep shadows, emphasizing the three-dimensional quality of the weave. The background is dark and out of focus.

Conclusion

CHAPTER 8

8.1

Critical Reflection:

Overall, the variation in aesthetic conditions between the first and second node saw a successful exploration of unconventional formal topologies, with particularly the second node challenging and pushing against the traditional notion that structural connections should only act as a functional connection member.

That being said further developments in this research would have explored the design opportunities afforded to full-scale printed joints within a full structures dialogue. While the second node introduced elements of surface manipulation and distortion to create visual interest between the intersection interfaces and body of the node, this visual aesthetic could have been taken further to explore ideas of negative voids and 3 dimensional depths to the joint. Additionally, the intersection between the node and structural member could have been tapered so that the connection interface wasn't a singular flat line but rather a fluid transition between the two architectural elements.

This research needed to be established in order to validate the construction process of fabricating mass-customisable architecture joints through WAAM. The printing of two full-scale joints acted as a proof-of concept. However, building upon this the next research would begin to explore a large range of formal node connections within a complete structural form, primarily highlighting the visual cohesion between structural members and the possible designed form of the joints. This further research would allow for the construction of a seamless dialogue between the two building elements where neither element overpowers the design intent of the building, developing upon the overwhelming visual dialogue seen between the node v.1 and the timber members within this research.

8.2 INDUSTRIAL FABRICATION

One of the key elements brought to light throughout this research is the level of under optimised design with regards to mass-customised steel joints with architectural structures. The fabrication of two full steel joints that explored the possibilities of introducing contextual respondent nodes, in addition to aesthetic possibilities, this research has offered some input surrounding the dialogue of how architectural forms are constructed along with their designs.

Whilst the models and methods of traditional fabrication, such as subtractive and formative fabrication, still hold value within the construction industry for their ability to process mass-produced standardised joints, in regards to fabrication of mass-customisable joints, additive fabrication processes such as WAAM afford optimised material-efficient methods of producing complex nodal forms. Additionally, with the emergence of computational aided design tools which have led to architectural designs being parametric and computationally informed, the industrial assembly and fabrication of building should change to embrace and utilize the parametric and generative forms they can produce instead of reproducing mass-produced standardised elements which diminish the digital design intent.

Future development into the fabrication process, which optimises the lead time and reduces the time required need for manual interaction, will see the increased practical viability of using WAAM to produce industrial scale architectural nodes. These optimisations are the by-product of commercial scaling, as elements such as the increased number of robots on the fabrication line, would allow for multiple nodes to be produced at the same time, reducing the production time.

Additionally, the automation of manual tasks which were required to be performed in between print modules and upon completion of the part, would close the fabrication process. The possible implementation of automated post-process machining through either an additional end effector attachment or another robot, would allow for the segmented prints to be robotically assembled without the required intervention of a manual process. Onsite ready nodes could be produced, instead of raw products which still required manual post processing before being integrated into the assembly process of a building.

FIGURE 8.03 *NODE V.2 - FINALISED PRINT SEGMENTS*

FUTURE RESEARCH

IMPROVEMENTS TO THE FABRICATION PROCESS:

The physical welds pools used to construct the two nodes were to a higher degree than most human welds. The integration of data driven analysis would allow for further optimisation of the print structure as well as allowing custom control over the process. Optimal control over the weld pool would allow for the curation of aesthetic ornamentation within the weld layers and print conditions, in a similar manner currently being explored in concrete and clay additive printing. Currently the deposited weld pools which are used to construct the layers have slightly imperfection seen in the current fabrication process. These imperfections, such as the start and end lumps along with slump and rises in the deposited layers, are a result of external factors. Whilst the imperfections are visual problems and could be machined off, the integration of additive print control, informed by previous print data, is the next step in improving and controlling the constructed layers.

Through the incorporation of programmed robotic responses to known procedural errors, such as an automated cleaning station and nozzle tip replacement procedure, the fabrication process would be afforded the ability to decrease the required manual intervention. The fabrication system would maintain a higher level of accuracy and assurance across the printing process, possibly leading to a reliable printing system where architectural nodes could be produced without human supervision, allowing for the fabrication process to take only the arc –on time of 11 hours instead of 4 working days.

POST-PROCESSING:

Due to the additive nature of the fabrication process the joint connection types themselves are afforded the ability to be universal, and cater to the surrounding context or the structural requirements. Beyond the standard bolt connections and socket joints, used within this research, the ability to add material to the joint connections means that unconventional means of connection interfaces can be explored. Throughout the fabricated joints in this research, print layers were constructed from a base plate and then cut off the base plate. However, there is potential for printing additional structure on the bottom of the base plate, not limiting the base of the connection to a flat interface, offering the potential to hide the connection method or create a visual transition between the joint and the structural member.

Additionally, the post-process machining of joint intersection or interfaces should become an integrated element of the fabrication process. As shown in the research, the node required significant hours of manual machining to reach an acceptable surface tolerance to assemble the timber members within the socket sections. Currently the imperfections in the printed layers result in a raw surface finish which is a representation of the digital model. However, with the inclusion of post-process machining the threshold condition between the joint and structural member would fall within an acceptable tolerance allowing for efficient on-site assembly without the required need for manual intervention. Alternatively, further research could look at a collective response between multiple fabrication processes to increase the accuracy of the joint interface whilst reducing the required post processing needed for onsite assembly. The possible combination of WAAM fabrication and external joining conventions such as a base plate, external flange or machined sockets, would reduce the required onsite assembly time through ease of assembly.

It is acknowledged that some form of post-processing is required in order for this research to be integrated within the construction of a building. However, what level of post-process should be implemented is an area of research which hasn't been explored. While there is an inherent aesthetic quality procured by the method of fabrication which is removed when part is fully machined the lack of practical assembly, resulting from the imperfection of the print layers means that some level of post-process machining is required. The author suggests the notion that post-process machining should only occur around the required areas and interfaces relating to other building members, thus reducing the material wastage and machine time of the fabrication process, while allowing for the fabrication of a building node which allows for ease of assembly and still depicting the method of fabrication through the raw surface finish.

FIGURE 8.04 *NODE V.1 - ASSEMBLED PRINT*

FIGURE 8.05   *NODE V.2 - FINALISED PRINT SEGMENTS*

CONCLUSION

This research utilised a digital design to fabrication workflow in combination with the fabrication process of WAAM to construct mass-customisable nodes, which responded to both the surrounding structural members and offered an opportunity for the aesthetic design for the nodes. Digital design tools were used to construct a parametric model that informed the nodes' design, establishing a link between complex non-conventional structural forms and the localised elements of mass-customisable joints. The parametric nodes were first released through iterative polymer prototyping, this establishing a workflow loop between the physical materiality of the additive fabrication process and the computational informed digital designs. The initial scaled polymer prototype prints acted to inform the digital design to the additive fabrication process before full-scale fabrication of the nodes was conducted through WAAM.

The series of polymer prototyping integrated a feedback loop at the end of each iterative stage, allowing for constraints and limitation of the workflow to be critically evaluated before being addressed and allowing the workflow model to improve and close the file to the factory workflow loop. This workflow allowed for the identification of key fabrication constraints which restricted the geometric freedom of the angular responsive digital designed nodes. The limitations of the 30 degree-overhang and the lack of support scaffolding were critical evaluated before being addressed through the use of digital segmentation and non-linear slicing. Implementing a non-planar printing methodology enabled the fabrication of the mass-customisable node, affording the fabrication process the ability to print angles in excess of 30-degrees whilst additionally reducing the fabrication time.

Throughout the research, there was an intentional attempt to shift away from traditional documentation and data transfer methods to between designers and fabricators.

3d modellings and a closed-loop file to factory workflow, used within this research, challenged the traditional 2d static CAD drawings. With the idea presented within this research that 3d models themselves are the only required form of documentation, providing a higher representation and communication level than traditional 2d static CAD drawings. Through the process of automated digitalisation and sequencing, loops within the digital design to fabrication workflow were constructed. As a result of the digital model existing within the same workflow as the fabrication data outputs, allowing for further considerations of the practical material properties and printing process to be directly feedback in the design without a static translation of data between the design and technician.

The realisation of the full-scale printed joints offered some dialogue in the practical nature of the onsite assembly process, further closing the digital design to fabrication workflow loop established throughout the research. While the realisation of the two full-scale nodal prints saw an exploration of aesthetic opportunities and interface connections, the continuous nature of the cyclic research methodology used throughout this research presented areas for further development and improvement, which could be feedback into the workflow and improve the digital design to fabrication to assembly loop.

These evaluated areas highlighted the potential for future research to explore the levels of integrated post-processing, aesthetic dialogues and interfaces connections regarding the fabrication of mass-customisable node through the process of WAAM.

The use of non-linear slicing and segmentation within this research showed that mass-customisable large scale architectures are able to be printed through the fabrication process of WAAM. Fundamental this changes the relationship that conventional architectural structures have with structural joints and nodes. Instead of only being able to integrate standardised mass-produced connection, the structure and, by extension, architectural design are afforded the possibility to incorporate contextual responsive joints that enable the structural design of complex computational and parametrically informed structures. The purpose of this research was to explore the potential dialogue options that mass-customisable metal nodes fabricated through the process of WAAM afford architectural structures. While there are still currently unresolved areas of research relating the integration of WAAM fabricated nodes within the complete dialogue of an architectural structure through the realised printing of two full architectural joints this research suggests that this is an area of research worth further exploration.

FIGURE 8.06

FINAL SOCKET SECTION PRINT LAYERS

8.5

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8.6

FIGURE LIST

** All Figures not attributed are authors own

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