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Applications of Additive Manufacturing in the Construction Industry

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Applications of Additive Manufacturing in the Construction Industry

by

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Thesis

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Master of Science in Engineering

The University of Texas at Austin

May 2018

Dedication

I would like to dedicate this work to my family who have been supportive through my entire education. Everything I have is because of the sacrifices and commitments of my family to give me a better and successful future. I am thankful to my mother for always thinking ahead and providing me with the best tools to excel in life. I am thankful to my father, for being there even in difficult times. And I am thankful to my sister, for being an inspiration to pursuing a higher degree.

Acknowledgements

I would like to acknowledge my advisor, Dr. Clayton, for her enthusiasm and motivating energy. Her support and guidance throughout the master's degree program has made this research experience positive, encouraging, and at the same time exciting.

I would like to recognize my co-advisor, Dr. O'Brien, for being the leader in our group and taking this emerging research on additive manufacturing in construction to new paths here at The University of Texas at Austin. His strategic thinking to look at the big picture and set objectives helped the team keep the main intent of this interdisciplinary group.

I would like to thank ExxonMobil as my employer sponsor for selecting me as the recipient of the prestigious GEM Fellowship and the University of Texas at Austin for participating as the university sponsor.

Abstract

Applications of Additive Manufacturing in the Construction Industry

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The University of Texas at Austin, 2018

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Additive Manufacturing (AM) or 3D printing, the process of fabricating components in a layer-wise fashion, has been increasingly applied in industries such as automotives and aerospace. In the 1990s, interest from the construction industry evolved through several experimental applications looking to reduce labor cost, waste material, or create complex shapes that are difficult to build using conventional construction methods. However, the full range of potential applications for construction have not been explored, and the industry's involvement with AM is still considered at its early stages. As a first step, this thesis provides an extensive literature review of AM as it relates to the construction industry. This research identifies the most significant AM processes, compared to subtractive or formative processes, as well as some technologies and materials being used. A recommendation is given for potential advancements in applications for construction. The thesis also explores the use of typical small-scale material extrusion desktop 3D printers to print and test customized fastener-free connections. The intent of these connection tests is to explore novel ways in which AM technology can be used for structural and non-structural applications using commercial polymers. The connections were inspired by traditional wood joinery and modern proprietary connections. A four-point bending test was used to evaluate their potential structural performance in bending and to identify connection types that could be used for future investigations. Before AM can realize its full potential, interdisciplinary research is still needed to provide new materials, reliable printed parts, and new and repeatable processes. This thesis provides initial steps toward this goal by finding research gaps, identifying research trends in the area, and by exploring initial benefits and limitations for non-structural and structural applications in construction using available small-scale AM technology.

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Chapter 1: Format of Thesis

Research in Additive Manufacturing (AM) for construction is still in its early stages. At the University of Texas at Austin, subject matter experts in the fields of mechanical engineering, construction, architecture, non-destructive evaluation, structural engineering, and materials began an interdisciplinary research team in this new field. This thesis represents the first stages of work from this interdisciplinary research team. First, an extensive literature review of AM in construction was conducted. After the research gaps and needs in the area were identified from the literature review, connections with complex geometries were manufactured using available AM technologies and tested for structural performance in bending as an exploratory investigation. This work results in preparation and publication of two papers on the previously mentioned topics. This research serves as a foundation for the AM in construction research program at the University of Texas at Austin that can grow into research on new materials, structural forms, and printing processes to be used in construction.

The thesis is organized in four different chapters. The first chapter provides an introduction clarifying the intent and the organization of the thesis. Two articles that were published or will be submitted for publication are presented in the following chapters. An extensive literature review article published in *Automation and Construction,* "Applications of Additive Manufacturing in the Construction Industry – A Forward-Looking Review", provides background on AM and how it relates to construction. This article is presented in Chapter 2: Literature Review. The paper that will be submitted for publication in the proceedings of the *29th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference 2018,* "3D Printed Fastener-Free Connections for Non-Structural and Structural Applications – An

Exploratory Investigation”, is presented in Chapter 3: 3D Printed Connection Tests. Lastly, Chapter 4: Conclusions provides a short list of the key findings from both papers and from this exploratory investigation.

Chapter 2: Literature Review

Applications of Additive Manufacturing in the Construction Industry – A Forward-Looking Review

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Contribution: Performed an extensive literature review and wrote the journal article. Other authors contributed by reviewing and editing the article.
Published in *Automation in Construction* 89; 110-119

ABSTRACT –

Additive manufacturing (AM), also known as 3D printing, fabricates components in a layerwise fashion directly from a digital file. Many of the early applications of AM technologies have been in the aerospace, automotive, and healthcare industries. Building on the advances in AM in these industries, there are several experimental applications of AM in the construction sector. Early investigations suggest that use of AM technologies for construction have the potential to decrease labor costs, reduce material waste, and create customized complex geometries that are difficult to achieve using conventional construction techniques. However, these initial investigations do not cover the full range of potential applications for construction or exploit the rapidly maturing AM technologies for a variety of material types. This paper provides an up-to-date review of AM as it relates to the construction industry, identifies the trend of AM processes and materials being used, and discusses related methods of implementing AM and potential advancements in applications of AM. Examples of potential advancements include use of

multi-materials (e.g., use of high-performance materials only in areas where they are needed), in-situ repair in locations that are difficult or dangerous for humans to access, disaster relief construction in areas with limited construction workforce and material resources, structural and non-structural elements with optimized topologies, and customized parts of high value. AM's future in the construction industry is promising, but interdisciplinary research is still needed to provide new materials, new processes, faster printing, quality assurance, and data on mechanical properties before AM can realize its full potential in infrastructure construction.

Keywords –
Additive Manufacturing; Construction Industry, 3D Printing, Productivity, Safety

1 INTRODUCTION

Additive Manufacturing (AM), commonly known as 3D printing, fabricates components in a layerwise fashion directly from a digital file. AM is a rapidly growing field that is having an impact on multiple industries by simplifying the process to go from a 3D model to a finished product. AM is unlike tradition manufacturing processes, such as formative processes that require the production of a mold to manufacture a product in mass quantities or subtractive processes that produce significant amounts of waste material as a solid piece of material is cut into the desired shape. AM can advantageously fabricate complex geometries with no part-specific tooling and much less waste material, filling a gap left by the other manufacturing processes.

Aerospace, automotive, and healthcare industries have explored the benefits of using AM in their businesses. Initial applications focused on rapid prototyping to reduce the time required to produce prototypes with complex geometries [1]. Since then, AM has evolved to include many types of functional end-use parts. Other industries, such as construction, are starting to follow the early adopters of these new AM technologies.

Experimental applications of AM in the construction industry started appearing in the late 1990's [2]. These initial proof-of-concept applications helped identify potential benefits and challenges for AM technologies in construction.

This paper provides an up-to-date review of experimental AM technologies in construction, identifies the trends in AM processes and materials for construction, discusses related methods of implementing AM and potential applications, and identifies research needs to foster more widespread use of AM in construction. It serves as a guiding point for researchers interested in the area, to understand what has been done so far and what needs to be done in the future.

2 Current Construction Industry and Potential for AM Technologies

To transform the current state of construction industry practice, innovations are needed in the way construction is performed. Challenges to construction include: work in harsh environments, decrease of a skilled workforce, safety during construction, production of large amounts of waste material, and transportation of materials to the site, among others [3, 4, 5, 6]. The construction industry tends to be very fragmented. With a large number of specialized small and medium-sized construction firms, many are cautious to share advantageous knowledge or technologies with others, further stifling potential innovations in the industry [7]. These challenges and limitations to innovation are seen as opportunities for AM.

One prominent motivation for AM construction technologies is worker safety, particularly in extreme environments [8]. When construction in harsh environments is unavoidable, the difficulty and risks increase, adversely affecting construction quality and human safety. For example, working in freezing temperatures may present challenges in excavation or concrete pouring, environments with very high temperatures could cause dehydration to construction workers, and sites with exposure to chemical or nuclear contamination may pose serious human health risks [9]. A solution used to address such issues has been off-site fabrication, where parts and assemblies are delivered to and assembled on-site, reducing the amount of on-site labor and often increasing construction quality and consistency. AM could provide services to the construction industry by reducing exposure of on-site workers to harsh environments and by automating some of the construction tasks.

Another opportunity for AM involves shrinking the supply chain, particularly for parts that need expedited delivery. AM allows customized parts to be printed on-demand from a 3D model without significant lead time. Using AM in construction could reduce the number of steps involved in the supply chain, bringing the supplier closer to the customer [10, 11]. Instead of having multiple companies or trades producing different structural or non-structural components, each component can be produced directly using AM after it is designed. This alleviates productivity problems caused by late deliverables to the job site, which are known to have several deleterious effects to productivity and safety such as working out of sequence [12].

Another motivation for AM is decreased availability of a skilled workforce. Contractors are finding it challenging to recruit a workforce with the necessary skills (e.g., experienced carpenters, heavy equipment operators, welders, and fabricators) [13]. The use of AM in construction should lower the demand for skilled craft while at the same time opening new opportunities for jobs with different skill sets than are in current practice.

Another potential benefit from AM is the reduction of formwork (and related temporary structures) used during construction. Concrete structures are commonly built using temporary formwork to maintain the desired shape of fresh concrete as it hardens, and formwork labor and material costs range from 35-60% of the overall cost of concrete structures [14, 15, 16]. The most common formwork is made from wood, using subtractive processes to cut it to the desired shape, producing waste material before it is even used. In the 19th and 20th centuries, formwork was produced for a single use only [14]. Currently, to decrease the cost of formwork and reduce material waste, formwork is being reused. Reducing formwork use not only reduces waste material produced during construction, which is considered to be about 23% of the total material wasted in construction [2, 17], but it also reduces the cost and time for placing and disassembling the formwork, largely by removing the need for formwork for direct placement of the construction materials. An alternate approach is to use AM techniques to fabricate the formwork – a recent practice example is using AM deposition of wax to create formwork molds that can be melted and reused [18].

Whether through design of complex forms or by direct deposition of final materials, AM techniques also allow architects and designers to produce complex interior and exterior geometries that would be difficult (or impossible) and costly to produce using subtractive and formative processes. This potential benefit offers opportunities for new designs and forms, giving more freedom to architects, without affecting the complexity and productivity during construction [6, 19].

Safety, reducing needs for skilled workers, replacing traditional supply chains, waste reduction, and new geometries are but a few of the potential applications for AM in construction, motivating further review of AM technologies and their possibilities.

3 Additive Manufacturing Processes

To understand the advantages that AM could bring to construction, it is important to understand the different AM processes. The American Society for Testing and

Materials (ASTM) International published a document in collaboration with the International Organization for Standardization (ISO) to define standard terminology for AM [1]. In this document, ISO/ASTM divided AM into seven different processes:

Vat Photopolymerization –A process of selectively curing a liquid light-activated polymer with a laser. An example of this process is stereolithography apparatus (SLA), a technique developed by Hull in the 1980's and commercialized first by 3D Systems [4, 20, 21].

Material Jetting –A process of selectively depositing drops of material in a layerwise fashion. An example of this process is PolyJet technology from Stratasys [21].

Binder Jetting –A process of depositing a powdered material layer upon layer and selectively dropping a liquid binding agent onto each layer to bind the powders together. Binder jetting was primarily developed at MIT in a process called 3D printing (3DP) [21].

Material Extrusion –A process of extruding material through a nozzle and depositing it layer-by-layer onto a substrate. The process was invented by Crump and commercialized by Stratasys as Fused Deposition Modelling (FDM) [21], but it now forms the basis for a very wide variety of inexpensive personal 3D printers.

Powder Bed Fusion –A process of selectively fusing a powder bed using thermal energy, typically in the form of a laser or electron beam. Selective Laser Sintering (SLS) was developed at the University of Texas at Austin for polymer materials and commercialized by DTM and 3D Systems [21]. Direct Metal Laser Sintering (DMLS) [21, 22] and Selective Laser Melting (SLM) are common versions of powder bed fusion for fabricating metal parts.

Sheet Lamination – A process of successively shaping and bonding sheets of material to form an object. An example of sheet lamination process is laminated object manufacturing (LOM) developed by Helisys Inc., in which paper sheets were trimmed to size and glued together [21]. Ultrasonic Additive Manufacturing (UAM), commercialized by Solidica Inc. fabricates metal objects using ultrasonic welding [21].

Direct Energy Deposition – A process of fusing materials with focused thermal energy that melts the material as it is being deposited. An example of this process is laser engineered net shaping (LENS), developed at Sandia National Laboratories [11, 21], which is particularly useful for repair of damaged metal parts [23].

Although all of these processes have been explored in many different industries, AM technologies in the construction sector are in the earlier stages of development and innovation diffusion, with initial applications primarily focused on material extrusion processes for large-scale components.

4 AM IN CONSTRUCTION

Table 1 presents examples of AM technologies used for construction and the companies using these technologies, categorized by materials and AM processes. ISO/ASTM 52900 [1] categorizes materials for AM as metallic, polymer, ceramic, and composite, where composite materials are defined as any combination of the other material categories. Because many of the technologies use composites (e.g., fiber reinforced concrete or fiber reinforced polymer), this paper divides the materials into categories by their binder material in the composites (cementitious, polymer, and metallic), to be consistent with commonly used terms for materials in the construction industry. Table 1 also separates AM technologies by the spatial delivery system for the materials used in the process, such as a gantry system, robotic arm, or other (to be discussed in more detail later).

Table 1. Example of AM Technologies in the Construction Industry

AM Process	Cementitious			Polymer			Metallic	
	Gantry	Robotic	Other	Gantry	Robotic	Other	Gantry	Robotic
Binder Jetting	Pegna [2] D-Shape [24]							
Material Extrusion	Contour Crafting [6, 25, 26, 27] Concrete Printing [28, 29, 30] WinSun [31] TotalKustom [32] BetAbram [33] 3D Concrete Printing (3DCP) [34]	XtreeE [35] CyBe [36] Apis Cor [37]	WASP [38]	BAAM [39] Qingdao Unique Products Develop [31] KamerMaker [40]	C-Fab [41] Digital Construction Platform (DCP) [42] FreeFAB™ Wax [43]	Mini-Builders [44]		
Powder Bed Fusion				Skanska* [45]			Arup* [46, 47] Permasteelisa* [48]	
Direct Energy Deposition								MX3D [49]

*Company using a technology

It can be determined from Table 1 that most of the work being done so far has been in cementitious material extrusion. As mentioned earlier, the material extrusion process is the most commonly recognized AM process with many affordable and often open-source, extrusion-based printers accessible in the mainstream. Many researchers and companies are leveraging the advances and ubiquity of these open-source platforms to start exploring the use of the extrusion process in construction at small scales at first and then applying the same concepts at larger scales. Most of the cementitious materials use portland cement, which is well known in the construction industry to provide reliable and suitable mechanical properties at a low cost. The lower price point makes cementitious materials more affordable to explore initially for AM applications than metallic materials and more functional than polymers for structural applications. There are some AM technologies that do not use portland cement such as D-Shape that uses sand with magnesium oxide and magnesium chloride as the binder [50], and World's Advanced Saving Project (WASP) that can use cement, but the main focus is on natural mixtures that contain terrain and straw [38]. It is worth mentioning these technologies, since they were considered on the cementitious group. Another advantage to initially exploring AM technologies using cementitious materials and extrusion processes is that these materials can already be extruded in conventional construction using concrete pumps. The difference is that AM technologies automate the process to extrude material in exact locations and with desired properties. Still, there are challenges associated with making concrete pumpable and extrudable while at the same time maintaining its shape and providing sufficient strength to support its self-weight post-extrusion. Lim et al. [51] called these main characteristics as "pumpability, printability, buildability, and open time".

As evidenced by their absence in Table 1, work in the area of vat photopolymerization, material jetting, and sheet lamination has yet to be explored in the construction industry to the extent of the authors' knowledge. For large-scale applications, vat photopolymerization would require large quantities of liquid light-activated polymer and a larger system, making this process complex and expensive to reproduce at larger scales. Small-scale applications using vat photopolymerization and material jetting processes for construction could be explored, since the precision and quality of the finished products are very good for non-structural components, but degradation of the polymer's properties over time often push this technology towards molding rather than final part production. For the sheet lamination process, Fabrisonic has developed a 1.8 m x 1.8 m x 0.9 m (6 ft. x 6 ft. x 3 ft.) ultrasonic additive manufacturing system, showing that a sheet lamination process is feasible for construction-scale metallic components. It has not been explored for construction applications thus far due to the high cost of fabrication [52].

Most of the technologies deliver material using a gantry system. Gantry systems are based on a Cartesian coordinate system, where the nozzle or building platform moves in three axes (X, Y, Z) [53]. Since it is commonly used for small-scale AM applications, this delivery method is relatively simple to mimic and enlarge for construction applications. Although gantry systems have been most commonly used, they do have limitations as discussed by others [8, 19, 35, 54], such as transportation, installation, orthogonal deposition, and size of the system. When producing a large-scale component, a gantry system must be larger than the component being built, complicating not only the design of the gantry system, based on the maximum build dimensions, but also the transportation and labor-intensive installation of such a system. Orthogonal deposition is another limitation, since a gantry system only allows extrusion of material perpendicular to the build surface, limiting curvature to the horizontal plane [8]. Some AM technologies have explored the use of a robotic arm (e.g., C-Fab) or other systems such as small robots that have specific tasks (e.g., MiniBuilders) [44] and delta systems that are similar to gantry systems without a fixed frame (e.g., WASP) [38]. Robotic arms increase freedom due to a six-axis motion and flexibility to program multiple tasks. Also, a robotic arm requires less space than a gantry system and can even be mounted to a transportable platform to provide on-site mobility, as is the case for MIT’s Digital Construction Platform (DCP) and CyBe.

No matter the method of material delivery or AM process being used, printing rate is an important drawback of AM, making scaling AM technologies to large-scale applications more challenging. Printing small-scale components already takes a significant amount of time, and printing larger volumes such as the ones in construction will require much greater deposition volumes. Layer thickness also plays an important role in printing time, with higher resolution requiring thinner layers and more printing time [51]. This challenge may limit AM's competitiveness with conventional techniques. Researchers at the Oak Ridge National Laboratory (ORNL) identified this challenge and have been able to increase polymer deposition rates for their Big Area Additive Manufacturing (BAAM) system to compete with conventional techniques. Now ORNL is looking to increase the deposition rate for metallic materials [52].

Additional information on key AM technologies and applications are provided in the following sections as categorized by the material.

4.1 Cementitious Materials

Initial concepts for producing elements for construction using AM were proposed in the late 1990's by Pegna [2]. One of the first to recognize its potential was the University of Southern California (USC), where Contour Crafting (CC) was developed [27]. BetAbram, Concrete Printing, and 3D Concrete Printing (3DCP) are other AM technology similar to CC. CC utilizes a gantry system to extrude thick layers of cementitious material to increase deposition rate for large-scale structures. The technology has trowels attached on the side of the nozzle to smooth the horizontal and vertical surfaces of the material being extruded [26]. CC technology was developed with the intent to print houses faster in a single manufacturing process [6]. NASA granted CC a research award to further develop the technology for space construction with the intent of using in-situ materials such as regolith rock found on the moon [55]. NASA's interest in research using AM for construction in space directly addresses the previously mentioned construction challenges of working in harsh environments and transportation of material, where stringent weight limitations are imposed for space exploration.

WinSun is a Chinese company that worked jointly with architectural and structural design companies such as Gensler, Thornton Tomasetti, and others to build an office building for the Dubai Future Foundation (Fig. 1), which was printed in Shanghai, shipped to Dubai, and then assembled on site. The office building was printed in segments in 17 days and required only two days to assemble on-site [56]. The cost of printing and assembling was around $140,000 USD for the 242 m^2 (2,600 ft^2) single-story building, and compared to conventional construction techniques the labor was reduced by 50 to 80% and construction waste was reduced by 30 to 60% [56, 57]. Apis Cor is another AM technology that has successfully printed a house on-site, claiming to reduce the costs compared to conventional construction [58]. While detailed information on the mechanical properties of their printed buildings is not publicly provided by WinSun, this innovation is a promising indication that industry partners are interested in the area of AM in construction. The city of Dubai expects to have 30% of their buildings printed by 2030 [56].

Figure 1. Dubai future foundation printed office building [59]

4.2 Polymer Materials

Material extrusion using polymers is one of the most pervasive applications of AM at the small-scale, an area where commercialization is rapidly growing. Although the use of polymers in construction is not as common as cementitious materials or metals, polymers could be used in construction for aesthetic purposes or structural applications when combined with other strength-enhancing materials.

Researchers at ORNL and Cincinnati Incorporated (CI) developed the BAAM system, which can print carbon reinforced (Acrylonitrile-Butadiene-Styrene) ABS polymer components with a deposition rate of 45 kg/hr (100 lb/hr) [60]. Qingdao Unique Products Develop and KamerMaker are other AM technologies that as BAAM system uses a gantry system to extrude polymer based materials. In collaboration with Skidmore, Owings, & Merrill LLP (SOM) and the University of Tennessee, the BAAM system was used to build the Additive Manufacturing Integrated Energy (AMIE) demonstration project [61]. AMIE was built to serve as an example of the capabilities of AM in the construction industry, producing an energy efficient building with less material waste. At the same time, this project shows the need and benefits of interdisciplinary research and collaboration with industry [61].

Skanska is another construction company that has utilized advancements in the area of AM by printing unique cladding for the Bevis Marks Building in London. Complex connections between structural elements using cast steel nodes were deemed to be too costly to construct and exposed welded steel connections between structural elements did not provide the desired aesthetic [45]. To address these concerns, designers decided to use conventional welded and spliced steel plate structural connections with some architectural covering to produce the desired appearance. The complex geometry of these connection regions made AM an attractive option for the architectural cladding, which had decorative purposes only (shown in Fig. 2). Using polymer materials, which are already commonly used in small-scale AM applications in other industries, for aesthetic purposes may provide a low-risk approach to introducing AM into the construction industry while ongoing work is being done to address the safety and reliability of AM technologies used in large-scale structural applications. This application by Skanska proves that AM can be used to provide unique architectural designs without requiring complex and costly production processes.

Figure 2. Bevis Marks roof (cladding) [62]

4.3 Metallic Materials

AM has been used to construct small-scale metallic parts in many industries, including antenna brackets for the aerospace industry [63], complex sand molds to cast a turbine wheel in a single piece for the energy industry [64], and gas turbine burner tip repair and modification for the energy industry [65]. However, when moving to larger scales, factors such as printing time and cost may limit the advantages of large-scale AM applications of metals. Table 1 shows that metallic material is the group least being explored, with two of the examples (those using Powder Bed Fusion) being small-scale applications funded by construction companies. The small-scale components built using powder bed fusion can exhibit comparable mechanical properties to conventionally manufactured components in some cases, but they are expensive with current AM technologies [46, 47]. The advantages of AM become more evident when building up structures or components with complex geometries designed to optimize weight and material use that would be difficult, if not infeasible, to manufacture using conventional techniques.

The Joris Laarman Lab and Arup are using MX3D technology, which uses gas metal arc welding (GMAW) attached to a robotic arm to weld small stainless steel segments [49]. As a proof-of-concept of the technology, MX3D is currently being used to print an 8 m footbridge in Amsterdam with complex 3D geometries, which was planned to be finished by summer 2017 [66]. Another example of using AM for optimized structural topologies was developed by Arup. The company investigated various geometries and manufacturing processes for a structural node element in a project in The Hague, the Netherlands that was used to connect strut and cables of a tensegrity structure used for street lightning [46]. In this project, Arup designed several variations of the node using conventional and AM techniques (Fig. 3) to demonstrate the potential savings that can be attained through topology optimization and AM. Although the structure was already built at the time of the investigation, Arup estimated that topology optimization and AM could reduce the weight of each node by 75% compared to the original design, resulting in an estimated reduction of more than 40% of the weight of the entire structure [47].

While the use of metallic AM applications in construction is one of the least explored areas (see Table 1) due to its high initial costs, this investigative project from Arup demonstrates the potential for small-scale metal components to have significant impacts on structural designs. Developing more robust industry and academic partnerships are important to advance research in the area and to identify and improve potential applications of AM using metallic materials.

Figure 3. Arup's optimized node [47]

5 Potential Advancements in Construction Applications of AM

AM is starting to gain attention in the construction industry based on the attention it is receiving in other industries such as aerospace, automotive, and healthcare. Several proof-of-concept experimental applications have already been implemented in construction, but further research is needed to develop and improve the technology fully. Some potential applications for AM technologies have been identified and are explained in more detailed next. The challenges and gaps that must be filled to develop and implement the technology in the construction sector fully are also discussed. Table 2 summarizes these potential applications, relates them to some of the existing experimental technologies, and comments on development needs.

Table 2. Potential Applications of AM in the Construction Industry

Potential Applications	Examples of Current AM Technologies	Future Development Needs
Novel Forms	D-Shape [24], Contour Crafting [6, 25, 26, 27], Concrete Printing [28, 29, 30], 3DCP* [34], XtreeE [35], CyBe* [36], Apis-cor [37], BAAM [39], KamerMaker [40], C-Fab [41], Skanska [45], Arup [46, 47], MX3D [49], DCP* [42], FreeFAB™ Wax [43]	Large-scale additive manufacturing Structural applications Faster printing On-site printing
Topology Optimization	D-Shape, Contour Crafting, Concrete Printing, 3DCP*, XtreeE, BAAM, KamerMaker, Skanska, Arup, Permasteelisa [48], MX3D	Standards and testing/Quality control Precision Large-scale testing Structural applications Bonding New design approach
Customized Parts	Skanska	Large-scale additive manufacturing Structural applications Faster printing On-site printing
In situ Repair		Identify areas that need repair Automation On-site printing Bonding
Tolerance Matching/Correcting		Identify areas that need repair Automation

*** Currently Under Development**

5.1 Novel Forms

Architects started using AM for small-scale building models as a way to present a concept of their design to a customer. Large-scale AM of end-use buildings and building materials is allowing architects to produce more complex interior and exterior geometries that would be difficult and costly to produce using conventional construction processes. AM allows architects to rethink their design and their forms, giving them more freedom without affecting complexity and productivity during construction [6, 19]. With AM, architects can design based on functionality with less worry about constructability of each part. As an example of conventional construction techniques, most of the designs made out of concrete are done by constructability (e.g., ease of casting concrete using standard formwork). As mentioned previously, formwork in construction accounts for 35-60% of the cost of a concrete structure. This large cost is due to factors such as labor and construction time required to assemble and disassembled the formwork. Using formwork with complex geometries increases the difficulty of construction, increases the time required to design and produce the formwork, and increases labor and construction time overall. Since the complex formwork is case specific, the formwork could potentially be used only once, increasing waste during construction.

While it is sometimes difficult to make an economic case for AM versus conventional fabrication techniques in other industry sectors [5, 9, 11, 20, 46, 48, 67], AM could start adding value to construction immediately, by using it to fabricate formwork with complex geometries, or end-use building materials with enhanced functionality, customized geometries, biodegradable materials, or reusability [42, 43]. A relatively easy approach to incorporate AM in construction is the production of complex molds, which is already done in other sectors like the automotive industry. Voxeljet produces sand-based molds for many industry applications; this type of manufacturing can be extended to the construction industry immediately to produce complex formwork for customized parts [64]. MIT suggested using DCP, which is intended to be used in designing, sensing, and fabricating a component on site for construction [42], to rapidly extrude foam as formwork. This leave-in-place foam formwork would provide additional functionality such as serving as insulation in the finished structure, or to provide a desired finish using subtractive methods. FreeFAB™ Wax, developed by Laing O’Rourke Engineering Excellence Group, proposed printing molds for reinforced concrete using wax material that can be created rapidly with low precision and can later be cut to the precise shape using milling techniques [43]. Wax would act as the mold during construction, and then it could be heated to recover and reuse the material for other molds.

So far, conventional construction techniques have promoted simple and rectilinear designs to facilitate construction. As AM allows for more unique designs and curved shapes, new structural forms need to be investigated that leverage the benefits of AM and maximize its potential in construction [19, 35, 42]. However, with these new geometries and materials, research is necessary to ensure materials and structures achieve levels of reliability and safety expected by current building codes.

5.2 Topology optimization

In conventional construction, designs that optimize the use of material and geometries for structural performance often result in complex or inefficient structures for construction (e.g. making each beam a different size based on its load demands). The designs are often optimized for construction simplicity, as it results in reduced construction time and costs and limits the opportunity for construction error. When using AM to automate the process of construction based on 3D model data, construction methods are less of a concern in the design phase, allowing optimization for reduced material/weight, and potentially a more cost-effective solution.

Topology optimization has shown benefits in other industries such as aerospace and automotive. For example, GE manufactured fuel nozzles as single components with AM, resulting in a 25% reduction in weight, five times increase in strength, and improved combustion efficiency for their new engines compared to nozzles produced using conventional methods [68]. As previously discussed, Arup explored use of topology optimization and AM for a structural node for their tensegrity structure project, resulting in significantly reduced weight and size. XtreeE has investigated optimizing an element by inserting voids where material is not needed for structural purposes and using those voids to provide additional functionality, such as thermal insulation and soundproofing

[9, 28, 35]. Other work has explored the use of such voids for utility access and pass-through in new construction [6, 51]. AM and topology optimization allow architects and engineers to rethink their design based on added functionality.

Several challenges arise when reducing the amount of material required for an assumed loading scenario, such as producing structures and components with reliable material properties and sufficient levels of safety. Significant work has been done to quantify the expected values and variation in material properties currently in use in the construction industry, and testing standards have been developed to verify performance. Building codes and engineering practices are based on the experience and data available from decades of testing and research on material and structural behaviors. Current research in the use of AM in construction largely consists of proof-of-concept studies, and detailed information about the performance of materials or finished structures is not always available [50]. To provide the levels of safety expected by modern engineering standards, more detailed information on material properties, uncertainty, and quality assurance protocols are needed.

To begin, standardized material and structural assembly testing methods should be established, and a database of mechanical properties of recent and new AM materials and assemblies should be compiled [11]. To assure quality and reliability of printed materials, real-time monitoring of environmental, material, and geometrical properties such as temperature, cooling rate, viscosity, defects, and dimensions of the material should be made. Further work is needed to correlate these factors, as measured during printing, to expected mechanical properties and performance of the finished product. Without sufficient data, it is unclear how imperfections or variations due to lack of precision during construction would affect performance of structures produced using AM [11, 34].

Another challenge is potential scaling effects when methods developed and tested at small-scales are applied to large-scale applications. AM has been shown to produce reliable products in the small-scale; however, when producing large-scale components, the structure may behave differently from a small-scale component either while it is under construction or in its final state. Thus, testing at the large-scale is required. Production of large-scale specimens requires special facilities that may not be available to every company. Currently, testing of small specimens is done to estimate material and element behavior, but scaling effects could result in very different behaviors for materials and elements produced at larger scales. The anisotropic behavior of assemblies produced using extrusion-based processes, due to the layered deposition pattern, makes the final element vulnerable to failures along the layer bonding interfaces [4, 16, 19]. For structural applications, work is needed to improve layer bonding performance or provide cross-layer reinforcement to increase resistance to loads acting across layers. For example, AMIE’s solution requires steel rods post-tensioned throughout the building to increase layer-to-layer frictional resistance and improve strength of the printed polymer layers [61].

5.3 Customized parts

Although construction cost can be minimized by reducing labor, material, transportation, and time required for a project, past studies have indicated use of AM in construction may increase costs [5, 46, 48]. Mrazovic stated in a study done for Permasteelisa [48], that 3D printing using powder bed fusion of metallic materials is possible but will likely be cost prohibitive, mainly due to the processing speed (30% of the cost of a steel component being the material and 70% being the processing time). Conversely, WinSun claimed that labor costs for the Dubai Future Foundation building, which is constructed from extrusion of concrete material, were reduced by 50 to 80% using AM [57]. Once the materials and machines become more common in the market, the cost associated with using AM may also be reduced through economies of scale [10]. Until now AM appears to be most economical for producing unique parts rather than parts that can be mass manufactured.

The benefits of being able to manufacture unique parts on demand without relying on an inventory of standardized parts can be leveraged to print customized parts for each project. Architects and engineers have limited their designs to standardized shapes and parts to smooth or reduce the construction time. When a unique part is required for a project, it takes more than just the design to make it a finished product. Extensive planning is required for manufacturing the part and testing it to meet current standards. Although using AM would still require testing to meet standards, it could reduce the manufacturing costs and time associated with converting the design into the finished product, making it beneficial for customized part production.

Every company and construction trade has different needs, some of them being very specialized. AM is ideal for specialized parts with uncommon dimensions or geometries that may not be cost effective to produce using other conventional manufacturing processes. The concept has already been demonstrated for non-structural applications, like the work done by Skanska to print unique claddings. Customized parts have been produced in small-scale in other industries and have shown a great reduction in cost and time; examples include customized tools for aircraft maintenance in the aerospace industry [69], customized dental prosthetic devices in the healthcare industry [70], and custom architectural models to present a design or an idea to a client [20, 21] . The construction industry should start exploring the use of AM for customized parts, beginning with small-scale parts that can be reliably fabricated using current AM technologies. Using AM, customized parts can also be built specifically for as-built dimensions, thereby enabling the delay of part design and production. Similarly, there may be cases in which components are lost or damaged and waiting on their replacements may cause construction delays. These examples are situations in which "last minute" production of components on-site using AM can add value in construction.

5.4 In situ repair

Much of the initial work investigating the use of AM in the construction industry has been on methods of constructing new elements; however, the potential benefits of using AM for in situ repairs of existing structures are significant. In the small-scale, other industries, such as the Siemens gas turbine burner tip repair [65], are already investigating the potential of repairing components using AM. Damaged areas are removed using milling techniques and then new layers of materials are added using AM to restore it to its original condition or to modify the component to meet current design needs. As they age, buildings often require maintenance, rehabilitation, and replacement. Maintenance or in-situ repairs could be done using machines that could scan the structure, detect the areas needing a repair, and do the repairs using AM techniques or even using hybrid systems. AM is already capable of using reverse engineering to scan an object and record its geometric data to produce a 3D model [21]. There is an opportunity to use the same or similar technology to measure other information such as material deformations or defects that could detect areas that need further maintenance.

Another potential application is repair of infrastructure that is damaged by a natural or human-made disaster. Often, it becomes dangerous for workers to enter these buildings to evaluate the level of damage and repair it. AM could be used to construct a temporary support structure inside the damaged building to allow for inspection and even restoration, decreasing the risk to humans. AM could also be used for the repair and maintenance of structures located in hazardous environments, such as chemical and nuclear facilities. AM with robotic arms could operate in limited access areas as well as in harsh environments, adding repair material where required with precise dimensions and avoiding worker exposure.

Future work is still needed to improve the automation process of placing material on an existing structure before moving to more complicated and multi-step tasks of detecting current conditions of a structure, using subtractive processes to remove damaged areas, and then repairing what is needed. Research that focuses on the bonding between new layers of material to the existing structure also needs to be investigated to assure a good performance of the repaired structure. Referencing Table 2, it can be seen that no research has been done that includes both the use of AM and automation of tasks for repairs in construction. Most of the existing AM technologies for large-scale applications are not suitable for changing working area conditions that may be encountered during repair situations. Further work is needed to develop AM technologies suitable for repair applications in a range of work conditions.

5.5 Tolerance matching/correcting

Another potential application is the use of AM for tolerance matching. The construction industry is often faced with the challenge of having elements or modules on the construction site that do not have precise dimensions or sufficient tolerance for assembling them, requiring on-site modifications, complicating the assembly process, and delaying construction. Matching issues with prefabricated components are due to the inability to maintain tight tolerances, introducing errors that propagate during construction that could risk the integrity of the structure [71, 72]. Tolerance issues can happen in many parts of the process starting from design all the way to assembly. Factors that create tolerance issues are human errors in the design, fabrication, or construction phase, changes in dimensions of the elements due to changes in temperature during fabrication or construction, or when the elements are damaged during transportation or installation to mention some [72]. As an example, Kalasapudi et al. [71] describe a bridge project in Iowa where misalignment issues caused rework for a prefabricated concrete girder; bending of steel bars at the ends was required to make the component fit within the space available.

AM brings the benefit of producing components with precise dimensions based on design drawings, which is important for modular construction, and at the same time the ability to match tolerances in real time by printing customized connectors or infill as needed on-site. AM opens the opportunity to accommodate wide tolerances for prefabrication and assembly, by then using AM to adjust to the required tolerances, possibly reducing the time spent during fabrication, construction, and on-site modifications.

Architectural detailing requires rigorous work on-site; the use of AM could ease the production of such details. AM can also be used to print customized sleeves, sleeve connectors, and piping hangers based on the space available on-site; these components are sometimes problematic because standard parts do not fit properly.

6 Potential Advancements in Methods of Implementing AM

Advances in AM processes themselves may also facilitate the realization of potential applications in the construction industry. These methods, including fabrication using multiple materials, using in situ resources, utilizing hybrid techniques that combine

AM processes with subtractive and formative processes, and expanding opportunities for both off-site and on-site fabrication, are discussed below.

6.1 Off-site/On-site Fabrication

AM is most commonly implemented in a controlled environment for high quality parts in both small and large-scale applications. The controlled environment is desirable as materials can react differently and provide different mechanical properties if the environment is suddenly disturbed. For example, in a common small-scale FDM system, enclosures are used for an ABS polymer like the one used in the BAAM system because the extrusion and material fusion processes are sensitive to temperature changes. The same problem occurs when printing with metallic and cementitious materials, which are also sensitive to temperature, humidity, and other environmental factors. The current on-site fabrication AM systems still require that certain environmental conditions be met for best results or that a type of enclosure is provided to keep desirable temperatures. For example, Rudenko [32] mentions that TotalKustom technology is likely to be ideal for warm regions.

Research is needed to develop more robust technologies and materials for AM that can facilitate on-site construction. Sensitivity of part properties to environmental factors during fabrication is an important topic of concern, as well as the finishing of printed components. Another issue is the transportation and setup of AM equipment at the building site and its ability to adapt to different applications with different geometries, access levels, and underlying materials.

6.2 Hybrid techniques

Hybrid systems that combine subtractive, formative, and additive processes could be implemented to facilitate the incorporation of AM in construction. Hybrid techniques can improve part resolution and surface finish without increasing printing time by, for example, utilizing AM for a low resolution base part that is then finished with a subtractive technology such as sanding, milling, or machining. Taking advantage of the benefits of each technique, while still exploring new materials, processes, and technologies provided by AM, will foster an environment for innovation in construction. An example previously mentioned is MIT's DCP which tries to incorporate additive, subtractive, and assembling techniques in one all-purpose construction system [42]. In construction, it could be advantageous, for example, to combine AM of a basic construction component, with finishing processes that provide the external appearance desired by the end customer.

6.3 In situ resources

Using locally available resources can reduce material transportation costs and provide more sustainable design solutions in locations that are difficult to access. CC and D-Shape are investigating the possibility of building structures using in situ resources such as regolith rock on the Moon, since sending raw construction material to the Moon is very difficult and expensive [55, 73]. Another technology known as WASP has focused on using AM technologies to build "zero-mile homes" that utilize on-site materials to create housing in places where it is hard to find access to construction materials [38].

Additionally, automation of construction using AM processes and local materials would allow for disaster relief construction in disaster-affected regions that may have limited workforce and construction material resources. By dropping a 3D printer and bulk supply of raw materials into the affected area or by using the in situ materials on site, a minimum number of workers would be needed to construct customized houses to satisfy personal living needs for those displaced by the disaster. Labonnote et al. [19] suggest the use of AM in construction of first response shelters that can be quickly deployable. The benefits of AM would provide unique and customizable 3D designs that could produce printed homes to meet the long-term needs of community members well after the disaster.

Research using in situ resources is still in its early stages, only proving the concept of building up layers of materials collected from surrounding areas. Further research is needed to decrease printing time, provide the desired structural properties, develop customizable designs, and ensure repeatability.

6.4 Multiple materials

Formative processes (e.g., casting of concrete in formwork) typically utilize a single type of concrete for a large portion of a structure. AM could allow multiple materials to be deposited during the construction process using extrusion based processes with multiple nozzles for different materials. Bos et al. [34] proposed a concept of material customization by location, for example, depositing ultra-high performance concrete where structural demands are largest, and low-strength concretes for finishes and areas where structural demands are lower.

Using multiple materials is not something new in construction. Concrete and steel are commonly used together due to their complementary mechanical properties and their similar thermal expansion behavior. Concrete exhibits high compressive strength at a relatively low cost, but it exhibits brittle failure and negligible tensile strength. It requires the integration of steel reinforcement to resist tensile stresses and to exhibit more ductile behavior. A combination of AM processes could allow simultaneous material extrusion and direct energy deposition processes to simultaneously deposit material for concrete and steel reinforcement, respectively, resulting in reinforced concrete structures similar to those used in practice today; however, using AM processes allows the concrete and steel reinforcement to take on geometries that are optimized for the structural demands and that may be challenging to produce using conventional techniques. In this approach, two nozzles could be used to fuse metals and extrude concrete separately. New cementitious and metallic materials developed for AM application may exploit the benefits of these common construction materials or may be completely new to the construction industry. Details on how this multi-material deposition process would be executed are definitely worthy of future research to address challenges such as temperature difference between concrete extrusion and metal fusion.

The potential of printing multiple materials, is something that could bring advantages in the construction industry, but research is needed to develop new construction materials that are optimized for use in AM while still providing desirable structural performance. These new materials can be developed for improved fresh-state and final-state properties depending on the desired AM process and application, such as viscosity (for extrusion processes), early strength gain after deposition, thermal expansion and resistivity, layer-to-layer mechanical bonding, ductility, reduced embodied energy, and more. At the same time, these new materials must be economical for AM to become a feasible alternative in construction [11].

7 CONCLUSION

AM is having an impact on many industries and growing as an alternative or complimentary approach relative to other manufacturing methods such as formative and subtractive processes. Aerospace, automotive, and other industries have explored the benefits of using AM in their day-to-day activities, finding new applications for different AM processes. The construction industry has become interested and has started exploring proof-of-concept AM applications that could be applied in the sector, looking to mitigate current challenges such as worker safety in harsh environments, decreases in skilled workforce availability, and waste materials. More broadly, AM is seen as a way of addressing construction productivity challenges.

While there are a range of AM technologies, most recent work in the construction industry has been focused on material extrusion process using cementitious materials for large-scale applications. Work with cementitious material extrusion is perhaps due to the experience of the sector with the material and the availability of material extrusion systems to experiment with. Other experiments with polymers have been effective for unique designs serving non-structural aesthetic purposes. AM applications of metallic materials for large-scale components are the least explored area due to high costs. While most of the applications explored so far are oriented to large scale applications, there is opportunity for small-scale applications finishing, repair, tolerance matching, and other applications.

Potential applications of AM such as optimized topologies, customized parts, in situ repair for construction in areas with limited access have been summarized and related to current AM technologies. These potential applications highlight opportunities in the construction industry that can be realized with AM. Interdisciplinary research is still needed to make AM a reliable and economically viable option in construction. To facilitate implementation of AM technologies and realize these potential applications, further work is needed to investigate ways to print using multiple materials, to use in situ resources, and to combine AM with other processes as hybrid techniques.

This field is still in its infancy, without standardized testing and quality control to compare or benchmark these recent advancements. Furthermore, many of these early projects and AM technologies are proprietary, lacking publically available, detailed information on the methodology and final part quality, making comparison or evaluation of new AM technologies more challenging. While much work is needed to fully realize AM as a cost-effective and reliable option in the construction industry, the potential benefits it can provide are worthy of further research and development.

8 ACKNOWLEDGEMENTS

An initial version of this paper was presented at the 34th International Symposium on Automation and Robotics in Construction on June 29 in Taipei, Taiwan [74]. The authors thank the reviewers and conference participants for helpful comments.

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Chapter 3: 3D Printed Connection Tests

3D Printed Fastener-Free Connections for Non-Structural and Structural Applications – An Exploratory Investigation

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Contribution: Designed, manufactured, and tested the connections presented in this paper. Analyzed the test data and wrote the conference paper.
On progress to submit to the *29th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference 2018*

ABSTRACT

Additive manufacturing (AM) or 3D printing, the process of fabricating components in a layer-wise fashion from 3D models, has been increasingly used in many industries such as automotives and aerospace. The construction industry has shown increasing interest in AM technologies and has successfully implemented various proof of concept projects using different AM processes. Much of the research on AM in the construction industry has focused on development of new large-scale extrusion printing systems and on development of cementitious materials for AM applications, whereas research exploring new applications of already existing AM technologies and materials suitable for construction applications has been scarce. This paper explores the use of existing, small-scale material extrusion 3D printers to create customized fastener-free connections that could be used in structural or non-structural applications. These fastener-free connections, inspired by traditional wood joinery and modern proprietary connections were printed using polylactic acid (PLA) material. The flexural strength of the connections was then tested using a four-point bending test to evaluate their potential structural performance and to identify connection types that warrant further research in this exploratory proof of concept study. Potential applications for these fastener-free

connections could be for formwork assembly, for architectural components, for rapid erection of scaffolds, to join beams to columns, or to form beam splices. This paper presents the 3D printed fastener-free connection concepts, provides a comparison of the test results, discusses limitations of current 3D printing technologies for structural and nonstructural applications, and discusses further work that can be done to explore more structurally robust materials and other AM processes.

Keywords – Fastener-Free Connections, Additive Manufacturing, 3D Printing, Material Extrusion, Polymers, Flexural Test

1 INTRODUCTION

Additive manufacturing (AM), the process of building up components in a layer-wise fashion from 3D models, has been increasingly used in many industries such as automotives and aerospace. AM is categorized into seven different manufacturing processes: vat photopolymerization, material jetting, binder jetting, material extrusion, powder bed fusion, sheet lamination, and direct energy deposition. These processes are explained in more detail in the ISO/ASTM 52900-15 Standard [1]. Current AM technology is generally used in smaller scale applications compared to the scales encountered in infrastructure construction project. When wanting to apply AM technologies to scales that are more common in construction, two major limitations, print volume and print time, become a challenge. The construction industry has shown interest in the use of more automated AM technologies and has started exploring proof of concept applications using different AM processes, mostly material extrusion processes using cementitious materials [2]. AM could be utilized in many ways in the construction sector such as producing novel forms, optimized structural topologies, customized parts, in situ repair, and tolerance matching [2]. Interdisciplinary research is still needed to make this technology reliable at larger scales and for construction applications.

In the construction industry, the most common types of materials used are wood, steel, and concrete. Wood is commonly used for low-rise residential construction and for formwork. Subtractive processes are often used to cut wood to specified dimensions and details using either CNC machines or manually, depending on the application. Steel is commonly used as a main structural component in industrial and high-rise applications, where structural components are typically fabricated using a combination of formative and subtractive processes (e.g., casting, rolling, cutting, drilling). Fabrication of reinforced concrete structural components requires the use of formwork, typically made from wood or steel, to shape the wet cementitious material after mixing and casting until it finishes curing. Both subtractive and formative manufacturing are common methods used in the construction industry. As it has done in other industries, additive manufacturing can provide an alternative construction process when challenges are present using these other two methods. For example, manufacturing reinforced concrete elements that have unique dimensions would require changing the mold/formwork or the milling tools used, which can result in prolonged manufacturing time, increased manufacturing cost, and potentially delayed delivery/construction. The use of AM could allow the designer and erectors to customize a design based on site-specific constraints without having to rely only on long-standing manufacturing and construction processes. For these reasons, AM has become an attractive option when dealing with unique single production needs. AM also has been used as a prototyping tool to check final design and assembly before mass production or before production at larger scales.

Much of the research on AM in the construction industry has focused on development of new large-scale extrusion printing systems and on development of cementitious materials for AM applications, whereas research exploring new applications of already existing AM technologies and materials suitable for construction applications has been scarce. This paper explores the use of AM to create fastener-free structural or non-structural connections of complex geometry that are well suited for AM process over conventional formative and subtractive processes used in construction. This exploratory research focuses on proving and testing the connection concepts at small scales and with commercially available 3D printers, such that promising connections can be identified and later explored at larger scales and with other materials. The connections in this study are inspired by traditional woodworking joinery and are manufactured using a material extrusion process. The flexural strength of the connections is evaluated using a four-point bending test. Potential uses for these fastener-free connections in construction could be for assembling formwork, for attachment of architectural components, rapid erection scaffolding, to join beams to columns, or as beam splices. The results of this study can inform future research that investigates the promising connections using different scales, materials, and other AM processes and technologies.

2 Inspiration for Fastener-free Connections

Erection and assembly of formwork and prefabricated structural and nonstructural components are some of the most time-consuming tasks on a construction site [3]. The time needed to make on-site corrections due to misfits and tolerance issues can further complicate and delay construction projects. Therefore, recent research in construction has focused on facilitating more rapid construction processes and more flexible on-site tolerance accommodation. These methods of construction have typically focused on improving efficiency using familiar construction techniques. For example, to reduce on-site construction time, modular structural or nonstructural subassemblies can be prefabricated off-site; reusable steel formwork is used to produce precast concrete off-site or for repeated concrete components, cast-in-place on the job site. For each of these methods, pre-fabricated components or subassemblies must be assembled and connected on-site, typically using fasteners such as nuts and bolts, screws, nails, adhesives, and more. This research aims to explore “quick connection” concepts that do not rely on conventional fastener techniques but instead rely on geometries that can be realized using additive manufacturing processes. Such connections can be utilized to assemble reusable formwork, to join beams to columns, to splice together beam segments, for rapid erection of scaffolds, or for attaching nonstructural architectural components, among other things.

Inspiration for these “quick connection” concepts was drawn from Japanese wood joinery and connection concepts from modern proprietary companies such as ConXtech Inc. and K’NEX. ConXtech Inc. connections are intended for structural applications in modern steel construction, while K’NEX serves more as an educational toy concept to enhance children’s creativity. These types of connections rely on steel CNC milling and plastic injection molding, respectively, to produce connection geometries capable of transferring loads. Japanese wood joinery, on the other hand, relies on historic woodworking techniques that have been passed down from generation to generation. In Japan, skilled craftspeople dedicated to connecting elements of a structure were considered master jointers [4]. The joints had to be able to transfer forces between members, typically without the use of fasteners, and at the same time had to be aesthetically pleasant [4]. This type of joinery is seen as a piece of art, and unfortunately difficult and time-consuming to reproduce by hand. Subtractive processes such as using CNC machines can help to facilitate fabrication of these complex joints, but some of the fine details of the connection are lost due to CNC tooling limitations. Using these types of fastener-free connections as inspiration, this research investigated types of fastener-free connections for structural or nonstructural applications that rely on complex geometries suitable for AM and that would otherwise be difficult to create using conventional subtractive and formative processes commonly found in construction. The three connection concepts that are explored in this study are the Kawai-tsugite, Kanawai-tsugi, and ConXtech connections.

2.1 Kawai-tsugite

The Kawai-tsugite connection [5, 6, 7, 8, 9] was created in the 1980s by Professor Naohito Kawai when he was a student at the University of Tokyo [8]. Kawai-tsugite is not a typical joint in Japan due to its complex geometry [9], and it was created primarily to test woodworkers' craftsmanship skills; thus, information and details about this specific joint are lacking in Japanese joinery books [9]. In the name, Kawai comes from the creator of the joint, Naohito Kawai, and tsugite is the name commonly given to describe a splice joint in Japanese.

Kawai-tsugite uses cube symmetry to join itself in three different ways, shown in Figure 4. A cube has a rotational symmetry of 120° about the axis going through opposite corners of the cube, meaning that when a cube is rotated 120° about this diagonal axis, the cube will appear to maintain is original geometry. Kawai-tsugite uses geometry in a complex way that is difficult to create or explain; thus, more details on fabrication of this connection can be found at [10].

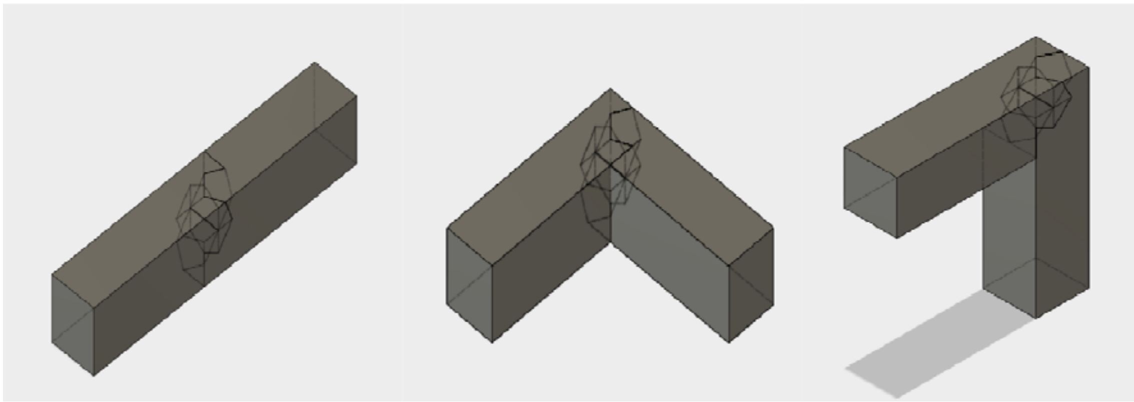


Figure 4. Assembly options for Kawai-tsugite

Figure 5 shows the dimensions used for the main connection based on a 37 mm x 37 mm x 37 mm [1.5 in. x 1.5 in. x 1.5 in.] cube. The two pieces being connected are geometrically identical but can be rotated in different orientations to produce splice joints and right-angle joints in different directions. This connection concept was selected for this study due to its complex geometry that is well suited for AM but is difficult to produce using conventional subtractive processes.

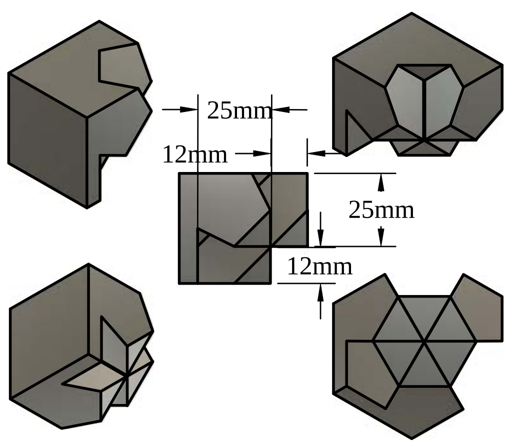


Figure 5. Kawai-tsugite concept joint

2.2 Kanawa-tsugi

Kanawa-tsugi is a splicing joint, described as a mortised rabbeted oblique splice by Suimyishi and Matsui [4]. There are many joints in traditional Japanese joinery that are similar to this one, such as the sashimono, shiribasami-tsugi, or the shippasami, with the main differences between each being small changes in the dimensions, angles, and layout of each part of the connection. This connection shows two identical pieces that fit together and slide parallel to each other to lock into place. This motion and dimensions of the connection leave a small gap (shown in Figure 6) in the middle, between the two pieces after they are locked into place. A pin is inserted in this small gap using friction to secure the pin and the connection. This type of splice, when made from wood, has an ultimate tensile strength higher than other traditional Japanese splice joints [4], hence its selection to be included in the current study for applications in construction. Figure 7 shows the Kanawa-tsugi connection used in this study.

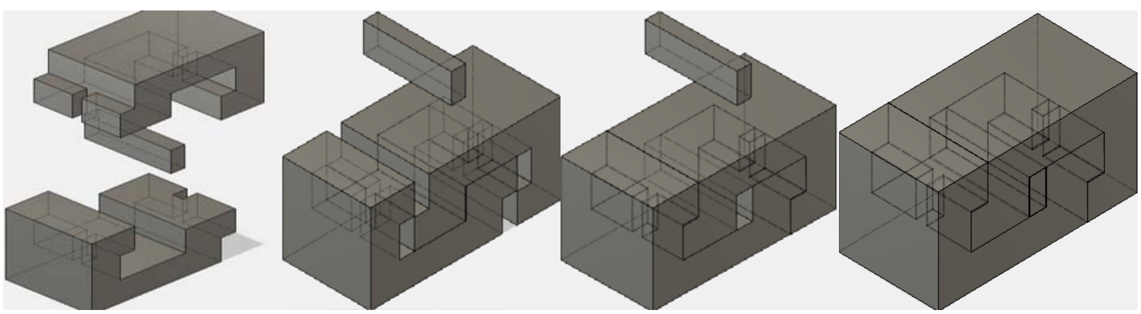


Figure 6. Kanawa-tsugi assembly sequence

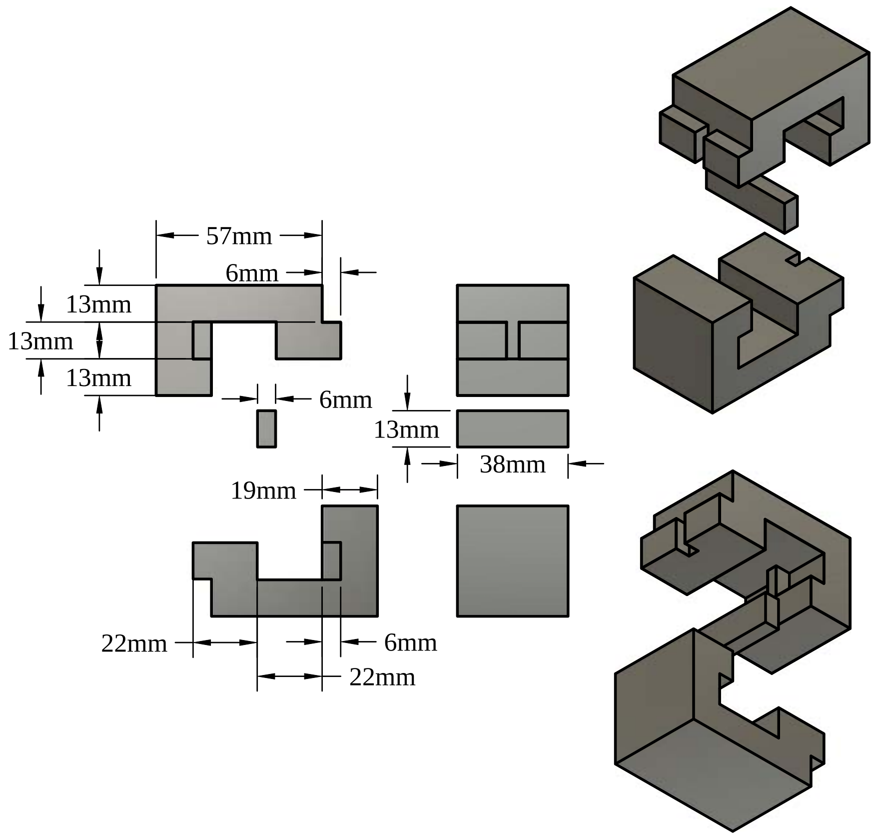


Figure 7. Kanawa-tsugi joint concept

2.3 ConXtech and K'nex

The final joint explored is inspired by connections produced by the company ConXtech Inc., which focuses on rapid and efficient modular construction using customizable steel connections for beams and columns [11]. These proprietary connections utilize tapered collar geometries to create gravity stabilized connections that can be "lowered and locked^{TM}" in-place and can be used to assemble beams and columns faster and safer, shown in Figure 8 [11].

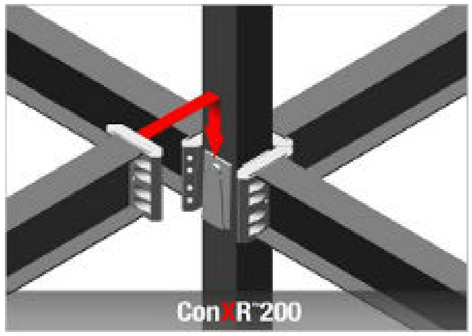


Figure 8. ConXR200 connection [11]

Bolts can be added to these connections as needed for structural resilience. Even though the company has three different connection styles called ConXR™, ConXL™, and ConXGravity™, the connection in this study was primarily inspired by the steel moment frame (SMF) ConXR™ connection. These connections are manufactured using subtractive processes such as CNC milling and using robotic welding, with predetermined dimensions that can be selected by the structural engineer [11]. A similar connection concept with a very different application came from K'NEX [12]. This company focuses on creating toys for kids with an educational purpose of enhancing creativity with a kit of parts that can be used to create buildings, bridges, roller coasters, and more. The kit of parts comes with multiple connectors and stick-type elements that could be disassembled and assembled as needed. The K'NEX concept of reusable and standardized kit of parts inspires future sustainable construction and design practices where buildings can be built, disassembled, reconfigured, and reused for future applications as needed. This connection concept was selected for this study due to its familiarity and use in modern construction and educational applications.

Figure 9 shows a 3-D model of this ConXtech/K'NEX inspired connection. The connection resists flexural demands through the mortise and the tenon, where the mortise is considered the reduced section or cavity that will receive the tenon, and the tenon is the portion of the joint that protrudes from the circular stub in the middle of the joint. A solid side was added to the tenon element to prevent rotation or twisting of the connection once in place.

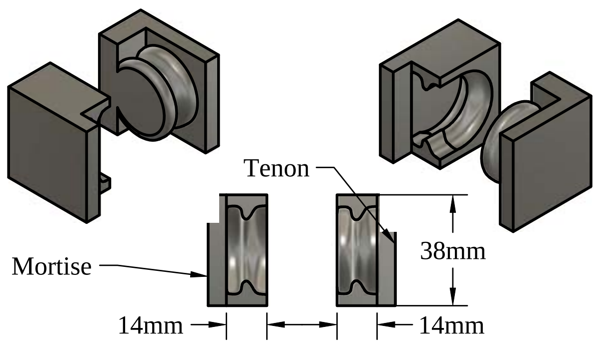


Figure 9. ConXtech concept joint

3 BACKGROUND ON 3D PRINTING

3.1 3D Printing Process

The 3D models of the connections shown in previous figures were created using Autodesk® Fusion 360™ software [13]. Models for AM applications can be created using a wide range of commercially available 3D modeling software such as SketchUp software [14], SolidWorks software [15], Inventor® 3D CAD software [16], AutoCAD® 3D software [17], 3ds Max® software [18], etc. Users interested in 3D printing can choose the software based on their expertise and preference. Autodesk® Fusion 360™ is a cloud-based 3D computer aided design, manufacturing, and engineering (CAD/CAM/CAE) software [13]. Fusion 360 allows users to convert a 3D model directly into an .stl file, which is the standard format for 3D CAD models that can be used in 3D printing software to slice the part into printable layers [19]. While many options are available, slicer software is typically developed to work best with specific printers and specific applications. Once the .stl file is imported to the slicer software, the user orients and sizes the model as needed. Inside the slicer software the user needs to specify the material being used. The most common materials for 3D printing or rapid prototyping are Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA). Other settings that need to be specified are: the extrusion temperature of the material, extrusion rate, nozzle travel speed, the layer thickness, infill ratio of the model, if the print will require supports, and many other case specific settings. Once those settings are specified, the software slices the model based on the layer thickness inputted and creates a .gcode file that contains all the information needed for the 3D printer. A .gcode file will send a set of commands one by one to let the printer know where and how much material will be extruded and the specific travel pattern, temperatures, and speed of the nozzle. G-codes are already used in subtractive processes such as CNC to automate machine tools and specify where to remove material from a solid block. The same concept is used for AM, but instead of removing material, AM adds material in a layer by layer fashion. More details about AM processes can be found in Gibson, Rose, & Stucker [19].

3.2 3D printing Design Considerations

3D printing is commonly used for rapid prototyping to test ideas, dimensions, and assembling processes before submitting final drawings or models for mass production. Rapid prototyping allows designers to present their concepts to others in a more realistic 3D format rather than simply showing 3D computer models or 2D drawings. Having a simple 3D prototype allows the audience to better evaluate and provide feedback on a design for future iterations. Prototypes can also be used for testing to quantify relative performance between different part geometries.

For construction, tolerances play a big role, where even a fraction of an inch of difference in a part's geometry can significantly increase construction time to make modifications necessary for the multiple parts to fit together. Due to the automation of 3D printers, parts can be manufactured to relatively tight tolerances, from submicron to micron tolerances [19], compared to the tolerances of about +/- 4 mm [0.157in.] for milled cross-section [20]. In this study, gaps were provided between the connecting parts to accommodate fabrication tolerances, and different gap sizes were explored in initial connection prototypes. Smaller gaps made connection fit-up difficult, while providing larger gaps made the connection lose the capability to stay in place. Ultimately, a gap of 0.508 mm [0.02 in] was provided between the parts in the connection. Exploring gap tolerances for conventional or 3D printed connections could be a research topic in and of itself and is thus considered outside the scope of this study. Potential research could study the effects of gap tolerance size as the scale of the printed part is increased or decreased. For example, if larger layer thicknesses are used in AM, by how much, if at all, should the connection tolerances be increased? For subtractive manufacturing processes, the tools used to carve material out of a solid block will govern the possible tolerances. For formative processes, tolerances depend on the formwork tolerances and correct placement.

For AM, different factors might affect the quality of tolerances. Since AM is a layer wise approach, the layer thickness will dominate the quality of the final print, especially for finer details. In the material extrusion process, a tabletop 3D printer typically uses a layer thickness of 0.2 mm [0.008 in.] with a standard nozzle size of 0.4 mm [0.016 in] diameter for a "normal" quality print [21, 22]. Higher quality will require smaller layer thicknesses that might also be able to meet stricter tolerances. Material extrusion processes are generally only able to provide reliable prints with a layer thickness of 0.1 mm [0.004 in.] or larger [22], compared to other AM processes such as vat photopolymerization that can give a layer height as low as 0.025 mm [0.001 in.] [23]. A drawback from producing prints with smaller layer thicknesses is the increase of number of layers required, which increases printing time. The increased number of layers might also increase the number of weak points in between the layers that could induce premature failure. As an example, smaller layer thicknesses have been shown to induce larger thermal strains that cause thermal stresses in 3D printed components [24]. 3D printing is evolving day by day. With the advantage of being open source technology, users can make modifications to their machines to improve their 3D printing experience and can share their knowledge to the 3D printing community. An example of this community-based improvement is the recent ability in some slicer software to change the layer thickness within an individual part depending on the quality that you want to get at different locations [25].

As mentioned before, the volume of 3D printed parts allowed in commercially available tabletop printers is quite small, around 285 mm x 153 x 153 mm [11.2 in. x 6 in. x 6 in.] [22], compared to the volumes you expect on a construction site. Although there is research focused on large scale printing, such as the work being done at Oak Ridge National Laboratory (ORNL) [26], small scale additive manufacturing is the most reliable and ubiquitous 3D printing technology currently available. Thus, this proof-of-concept paper on 3D printed connections focuses on smaller size connections printed using commercially available tabletop printers. As 3D printing technology advances and limitations in print scale and print time are addressed, fastener free connections identified in this study to have promise for structural and nonstructural applications can later be investigated at larger scales.

4 Evaluation of 3D Printed Connections

4.1 3D Printer and Settings

For this investigation, the Longhorn® Maker Studio facilities at the University of Texas at Austin were used for prototyping and final production of the different connections that were tested [27]. A CraftBot XL, which has a larger build volume of 300 mm x 200 mm x 440 mm [12 in. x 8 in. x 17 in.] [21], was used for this study. The material chosen was Hatchbox orange PLA 3D printer filament, with a dimensional accuracy of +/- 0.03 mm [0.0012 in.], and a diameter of 1.75 mm [0.069 in.]. PLA is a biodegradable thermoplastic commonly used in the 3D printing community due to its ability to heat and print with accuracy [28]. Another material that is commonly used for 3D printing is ABS, which is an oil-based thermoplastic with higher flexural strength, ductility, and durability [29, 30]. The challenge with ABS is that is more sensitive to temperature changes and produces fumes [30]. PLA was chosen as a starting point for this research as it is readily available and more reliable to produce quality prints, especially for components with large dimensions and higher infill. Future research could explore the variability of material properties and failure modes when different materials are used, as well as the limitations of using the other materials.

The settings used for this printer were the default easy mode settings by the Craftware software. A layer thickness of 0.2 mm [0.008 in.], considered as a high print quality was chosen. The travel speed was reduced from 180 mm/s [7.9 in./s] to 120 mm/s [4.72 in./s]. The infill speed was reduced from 150% to 100%. The reason to reduce the travel speed and infill speed was mainly to avoid issues like skipping steps during print that happens most of the times due to high speeds during printing. The type of infill selected was a square grid, which was the default, and the density was set to 70% infill to consider the parts being printed almost as solid. It needs to be noted that 3D printing is mostly done for rapid iterations or prototyping, meaning that a low amount of infill material is meant to be used to decrease printing time. The typical infill percentage is around 20% for 3D printing depending on the actual use of the 3D printed part. If the piece will be used for mechanical components, the infill percentage is increased, if the piece will be just one rapid prototype to check a design, lower infill is sometimes used such as 10%. Printing a part with 100% infill defeats the purpose of 3D printing using material extrusion and greatly increases the printing time. Therefore, a 70% infill, which might be already considered solid by most commercial software, was used to decrease material use and printing time without affecting the strength significantly [31]. Using CraftBot XL to print specimens with the dimensions shown in Figure 10 with the specified settings took around 19 hrs. to print each specimen.

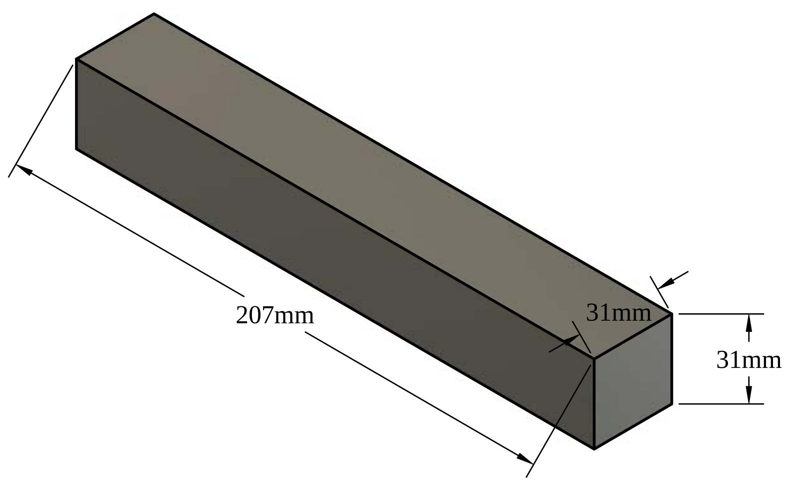


Figure 10. Dimensions for specimens

4.2 Testing Facilities and Equipment Used

The following tests used available test set ups and equipment at the Pickle Research Campus (PRC), Ferguson Structural Engineering Laboratory (FSEL). A Forney

FX 500 automatic machine with a maximum force capacity of 2224 kN [500 kips], which is most commonly used to test concrete specimens to characterize compressive strength, tensile strength, modulus of rupture, and modulus of elasticity, was used. The reason for using this machine was mainly due to the four-point bending fixture available for this machine. Linear potentiometers with a stroke of 50.8 mm [2 in.] were calibrated and used to measure the total displacement of the loading fixture during the test. A High-Precision Keysight Scanners 34980A data acquisition system was used to record the displacements.

Initially, the instrumentation plan included linear potentiometers measuring deflections of the specimen at mid space to characterize deformations in the connection, including one potentiometer for each side of the connection. Since the space available during test was limited by the machine, only the general displacement of the loading head was taken into consideration to provide a comparative estimate of specimen the deformation. Figure 11 shows the set-up configuration using the Forney machine and provides a model showing the general dimensions of the four-point bending test and specimen dimensions.

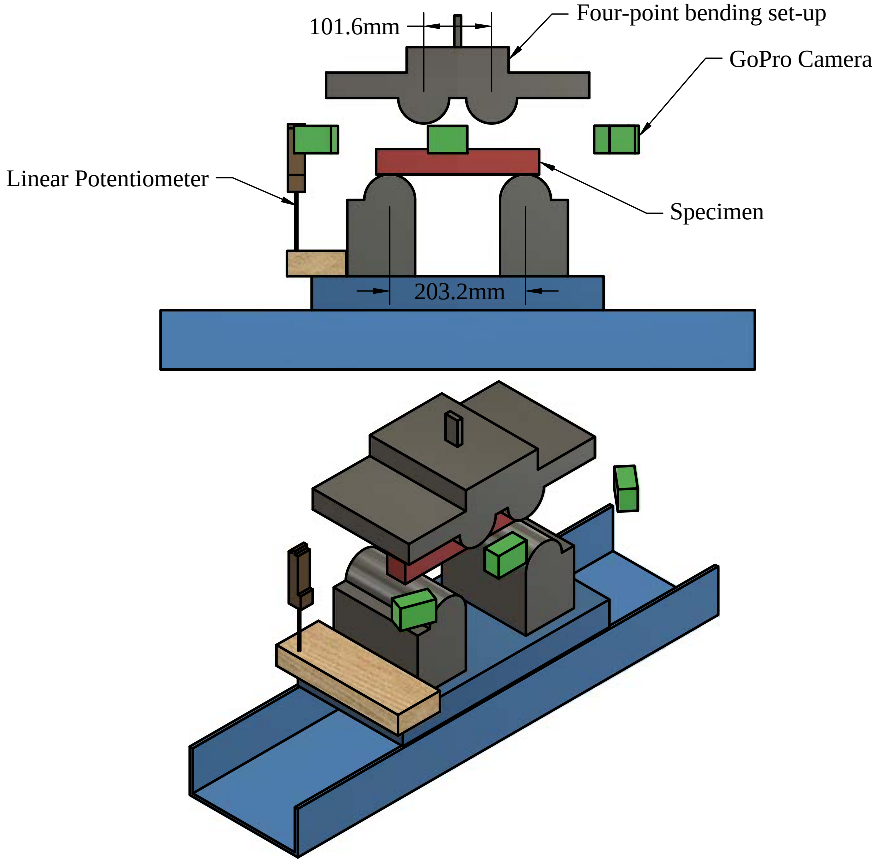


Figure 11. Test setup

4.3 4 Point-Bending Flexural Test

A four-point bending flexural test was used to explore the flexural capacity and the failure mode of each type of fastener-free connection. As illustrated in Figure 12a, four-point bending test consists of placing a beam with a bottom supports spaced at a length of L and a top loading points paced at L/2. A constant load rate is applied to the specimen until it fails, where flexural failure is expected to occur in the middle half of the beam where the bending moment is largest. As shown in Figure 12b and Figure 12c, the ends of the beams, between the supports and loading points, is where shear is non-zero and the middle portion of the beam exhibits a constant bending moment at its maximum value. Thus, the connections under investigation were placed in this middle part of the beam specimen, to test their capacities in pure bending. ASTM D6272 -17 [32] provides guidance to determine the flexural properties of unreinforced plastics by four-point bending. A difference in results is expected in these tests compared to current standards due to assumptions of having a completely solid and isotropic material, which is not the case with a material extrusion process. The material extrusion process is a layer by layer process, resulting in anisotropic material properties. Additionally, the additively manufactures specimens being tested have a specified 70% infill, which is not consistent with the solid infill assumed in the current standards. This difference highlights a need to develop new testing procedures, standards, and strength prediction equations for additively manufactures parts that do not assume homogenous and isotropic materials.

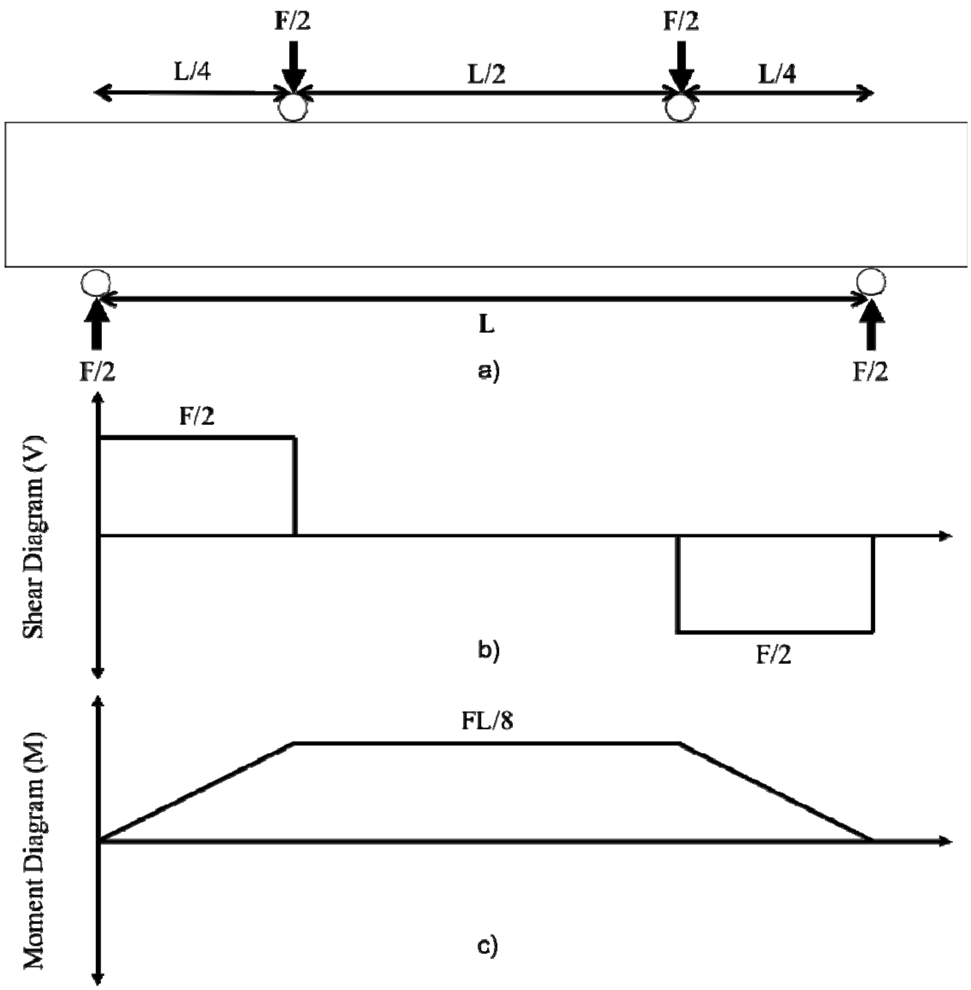


Figure 12. Shear and moment diagram for a four-point bending flexural test

5 TEST RESULTS

The results of the four-point bending tests for the 70% infill beams (with no connection) and specimens with the three different types of connections (Kawai-tsugite, Kanawa-tsugi, and ConXtech) are summarized below. At least three specimens were tested of each type, as indicated in the specimen naming convention by the number following the specimen type. All specimens were printed using the CraftBot XL printer with the same environment conditions. Thermoplastics are greatly affected by temperature difference in the room in which printing is done, which could cause some shrinkage of the material and cause warping of the 3D printed part. Some minor shrinkage was observed in the specimens. Other printing issues that arose with individual connection types will be discussed below, where applicable.

5.1 70% Infill Beam

To serve as a baseline for the capacity of the fastener-free connections, 70% infill beams, with no connections at midspan, were printed and tested. The testing machine used required an initial pre-load recommended to be no less than 445 N [100 lbs.] by the technicians. This preload is to ensure the loading fixture is engaged with the specimen. Figure 13 shows the load vs displacement of the 70% infill beams. The maximum loads on these beams were around 9200 N [2090 lbs.] with a max displacement of roughly 3.1 mm [0.12 in.] and they exhibited brittle failure. Figure 14 shows the failure mechanism of a 70% infill beam using PLA once the beam reached its peak capacity. The failure at the midpoint of the beam began at the bottom of the cross-section where the tensile stresses were largest and propagated up towards the top of the section.

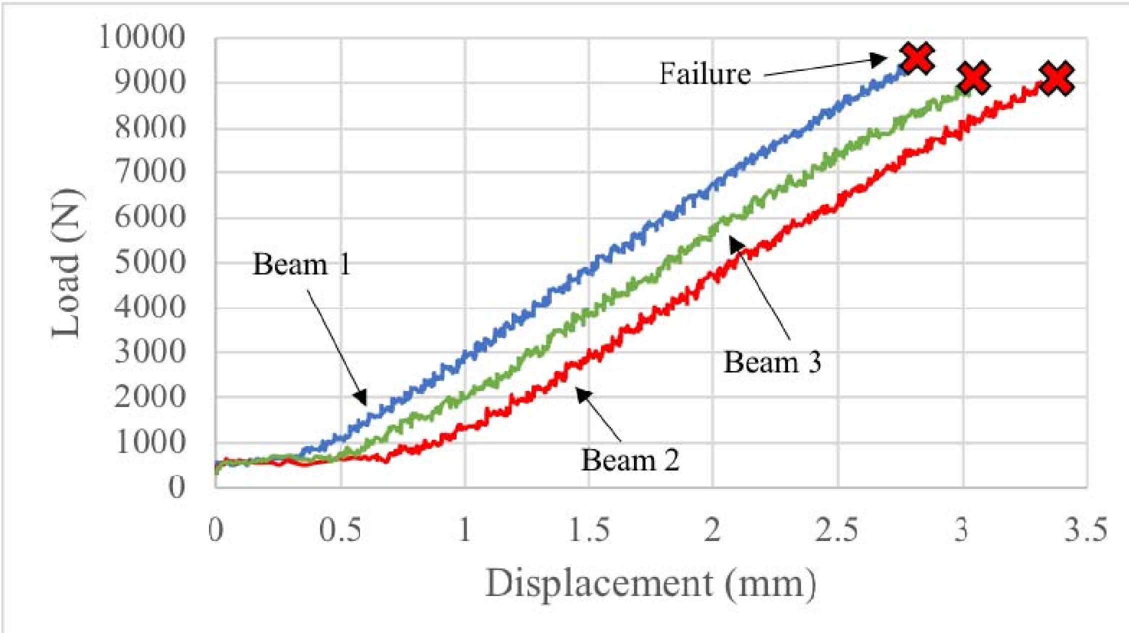


Figure 13. Load vs. displacement for a 70% infill beam

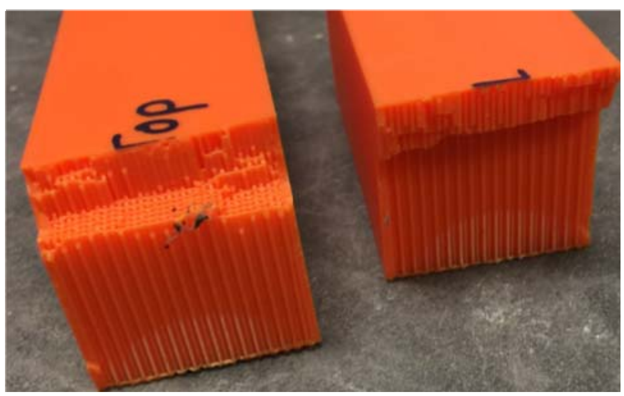


Figure 14. 70% infill beam after testing

5.2 Kawai-tsugite Results

Specific issues that were observed while printing this connection was stringing (shown in Figure 15) when the nozzle changed path causing strings of polymer to be left in places where it was not intended. Mill files were used to remove such imperfections in the specimens, which could affect the tolerances and fit-up of the printed parts. Stringing typically occurred in the side of the printer that was closer to the door and is believed to be caused by the colder temperatures on this side of the printer due to the very low room temperature outside of the printer (note, the specimens were printed when the university was on holiday break, and thermostats were set lower to conserve energy).

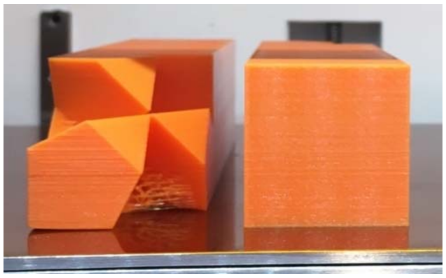


Figure 15. Stringing occurring during printing

Figure 16 shows the load vs. displacement relationship for the Kawai-tsugite connection. In Figure 16, an initial constant load applied to the connection can be observed, resulting in significant displacement of about 1 mm to 1.5 mm [0.04 in. to 0.06 in.] before the specimen begins to resist load with higher stiffness. It was concluded that such displacement might be due to the gap provided in the connections to accommodate tolerances, where an initial displacement is required for the connection to engage and resist the applied load. Kawai-tsugite 2 began to resist load at a smaller displacement, which is believed to be due to the removal of the excess material caused by stringing that occurred during printing, which might have reduced the gap in the connection, causing the connection to engage earlier. The maximum load that this connection was able to resist was around 2400 N [540 lbs.] with a maximum displacement of roughly 4.4 mm [0.17 in.], which is consistent with the other Kawai-tsugite specimens.

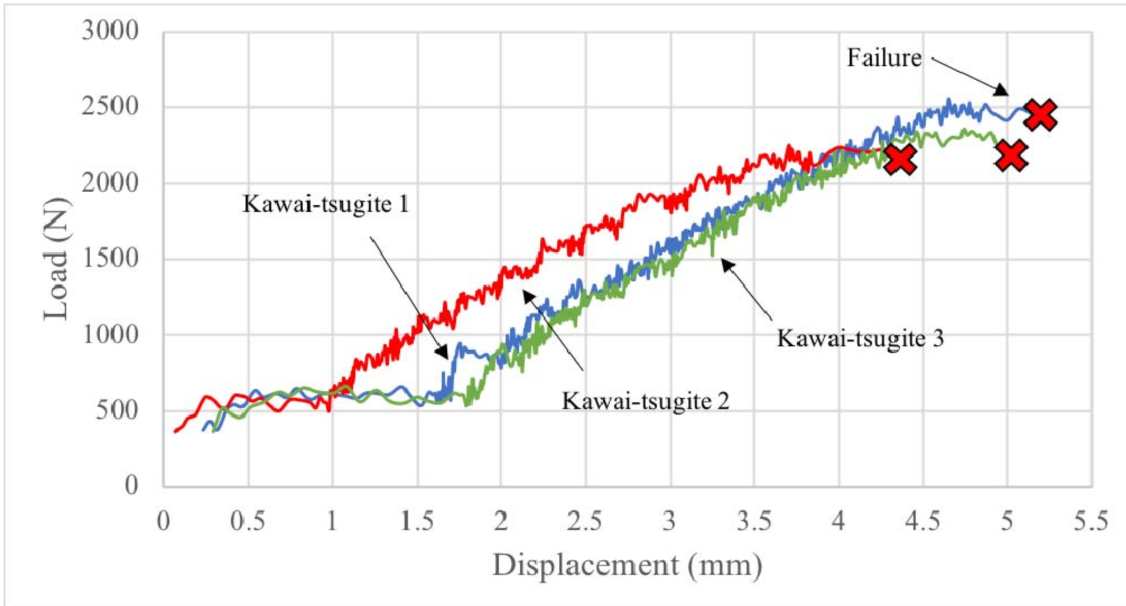


Figure 16. Load vs. displacement for Kawai-tsugite connection

Figure 17 shows pictures of the connection before and after testing, where the layer thickness is 0.2 mm [0.01in.] and the small gap of 0.508 mm [0.02 in.] between the printed parts can be seen to accommodate printing tolerances. Figure 17 and Figure 18 reveals the failure mechanism of this connection. An initial crack initially formed parallel to the layer orientation (perpendicular to the load) and continued growing perpendicular to the layer orientation until it failed in a brittle and unexpected manner.

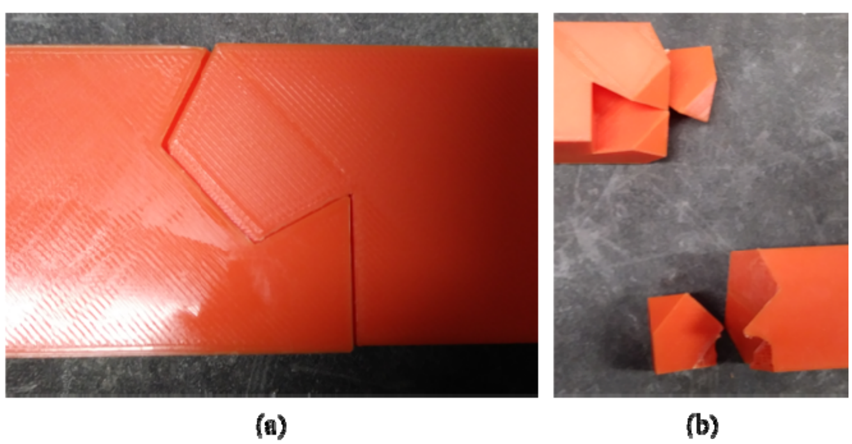


Figure 17. (a) before and (b) after testing

Figure 18. Four-point bending test for Kawai-tsugite connection from two different angles

5.3 ConXtech Results

It is worth mentioning that four ConXtech specimens were printed and tested; however, the ConXtech 3 specimen encountered several problems during printing, which ultimately affected its behavior and prompted the researchers to print and test a fourth specimen of this type. During printing, the ConXtech 3 specimen exhibited warping (an example of warping is shown later in Figure 23a), which is believed to have reduced the tolerance gap in the connection, causing the connection to engage earlier in the loading protocol. The warping is believed to be caused by the temperature differential between the printing environment and the surrounding room temperature, as previously described. Due to the cold room temperature, the printed parts, particularly ConXtech 3, did not properly stick to the print bed, causing subsequent layers to be detached and warped. In addition to the warping, other problems occurred during printing that are commonly observed in the 3D printing community. An example is a layer shift as shown in Figure 19, which is caused by the nozzle traveling too quickly, causing it to skip some steps and produce subsequent layers that are no longer aligned with the specified coordinates for the previous layers. ConXtech 1 and 2 were printed on the same printer as Kawai-tsugite, but ConXtech 3 and 4 were printed on a different printer of the same CraftBoxXL make and model that is referred to herein as Printer 2. Ultimately, ConXtech 4, which was printed without issues, exhibited behavior similar to ConXtech 1 and 2, indicating that the change of printer did not have a significant effect on performance when issues were not encountered during printing.

Figure 19. Layer shifting

Figure 20 shows the load vs. displacement relationship for the ConXtech connections. The maximum load that the connection could sustain was around 2,500 N [560 lbs.], similar to Kawai-tsugite. The connection starts resisting load after displacing approximately 1.3 mm [0.05 in.], when the connection engages. A major difference of this connection is that it had a more ductile failure compared to Kawai-tsugite.

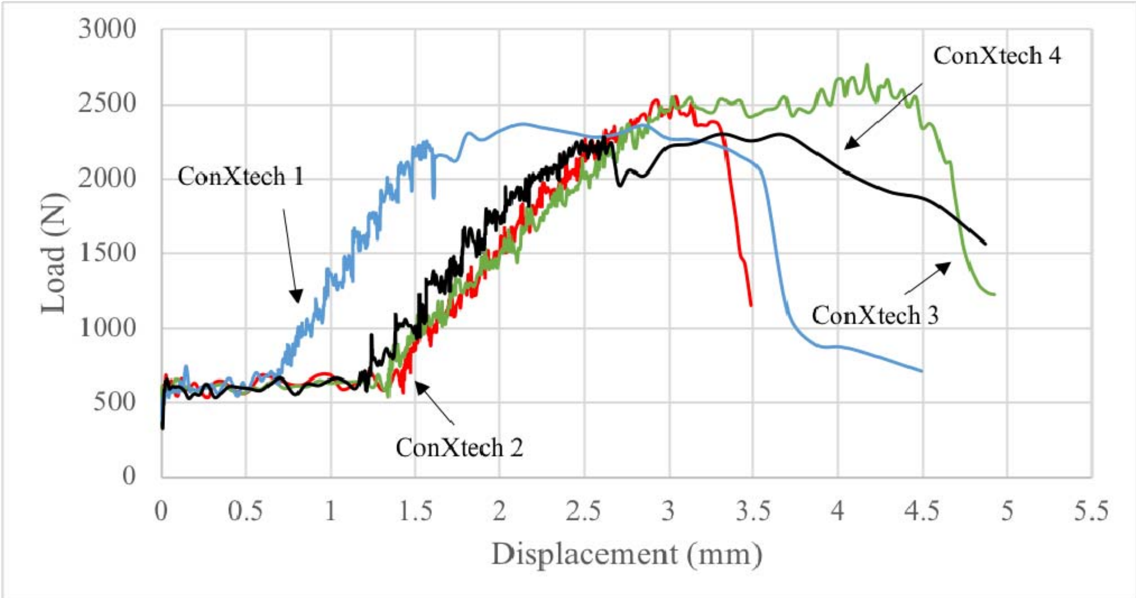


Figure 20. Load vs. displacement for ConXtech connection

Figure 21 shows before and after testing photos of a ConXtech connection where you can see the two different parts of the connection. The piece on the left in Figure 21a can be considered the mortise, since it has a void to receive a tenon. The tenon has a projection that is inserted to the mortise. In Figure 21 and Figure 22, the failure mechanism can be observed where the tenon fails abruptly in tension where its cross-sectional area is smaller. It can also be seen in Figure 21b and Figure 22 that the mortise formed a crack at the middle of the connection where it started to fail parallel to the layer orientation.

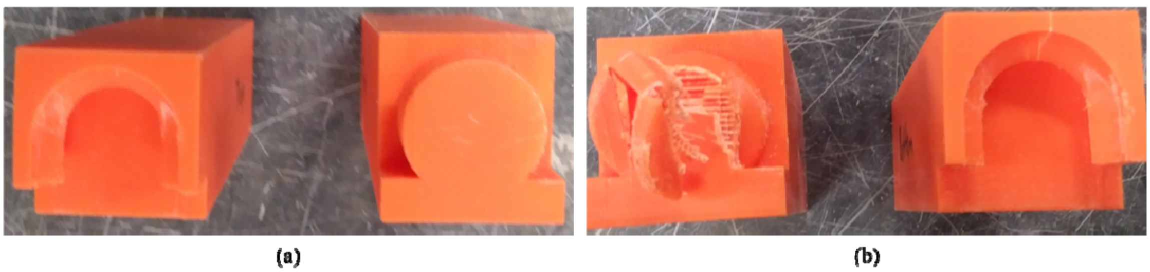
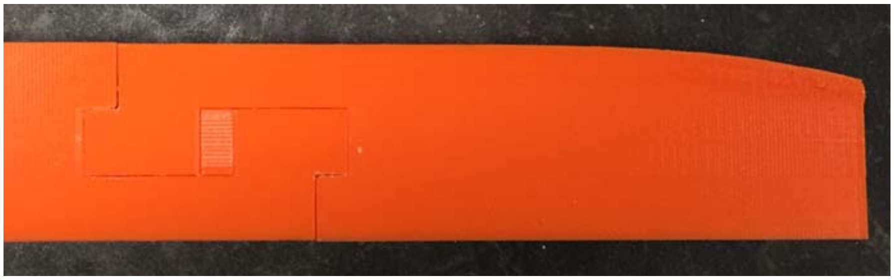


Figure 21. (a) before and (b) after testing

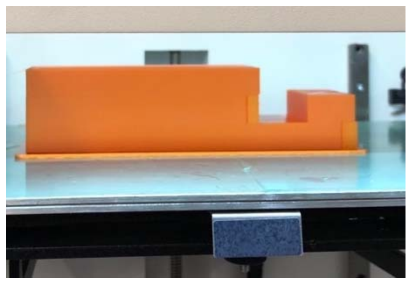
Figure 22. Four-point bending test for ConXtech from two different angles

5.4 Kanawa-tsugi Results

Several issues that are common to 3D printing were observed while printing the specimens for the Kanawa-tsugi connection, such as, bed leveling issues, electrical connection issues that caused the printer to stop, temperature differences causing the printed part to warp or not stick to the bed, and the nozzle hitting the printed part and causing it to fail. Due to the several problems that were encountered, it was suggested by [33] to add a raft (shown in Figure 23b) at the bottom of the specimen to increase attachment to the bed and decrease warping. The raft is removed prior to testing. Another suggestion was to print each piece of the connection separately to avoid failure of the entire print should an issue arise. It is believed that these differences in the printing process used for these specimens (i.e., the addition of the raft during printing and printing the different connection parts separately) did not significantly affect connection behavior. However, further research can investigate how differences in 3D model orientation and printing direction, as well as the effects of adding rafts or printing pieces in different stages, may affect behavior. Kanawa-tsugi had the greatest variability of results and the lowest capacity of all connection types, which is due to the reduction of effective cross-sectional area resisting the flexural demands within the connection. The depth of the effective cross-sectional area in the connection was a third of the gross cross-sectional area, reducing the moment of inertia compared to the other two connections, thus, reducing its moment capacity and maximum load.



(a)



(b)

Figure 23. (a) example of warping (b) added raft to decrease warping

Figure 24 shows the load vs. displacement relationship for the Kanawa-tsugi connection. Consistent with the responses of all the other specimens, a constant load is observed at the beginning of the test where the specimen displaces before the connection engages and begins to resist more load. The maximum load for this was about 1,600 N [360 lbs.] with a maximum displacement of 3 mm [0.12 in.]. All the Kanawa-tsugi connections were printed on a 3D printer of the same CraftBotXL make and model.

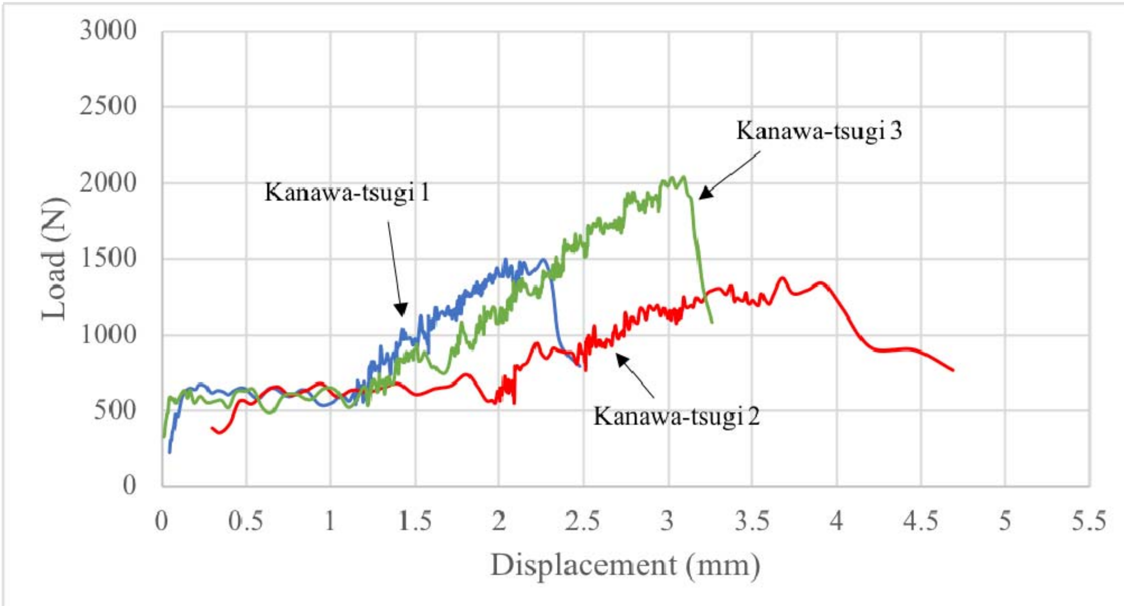


Figure 24. Load vs. displacement for Kanawa-tsugi connection

Figure 25 shows the connection before and after testing. The failure occurred in the reduced cross-sectional area at the top of the connection, which is the weakest point. The failure occurred perpendicular to the layer orientation where the tensile stresses are largest. Figure 26 shows the failure mechanism of the connection, which can be considered a brittle failure since the decrease in load capacity is rapid, although not as explosive or brittle as the Kawai-tsugite connection.

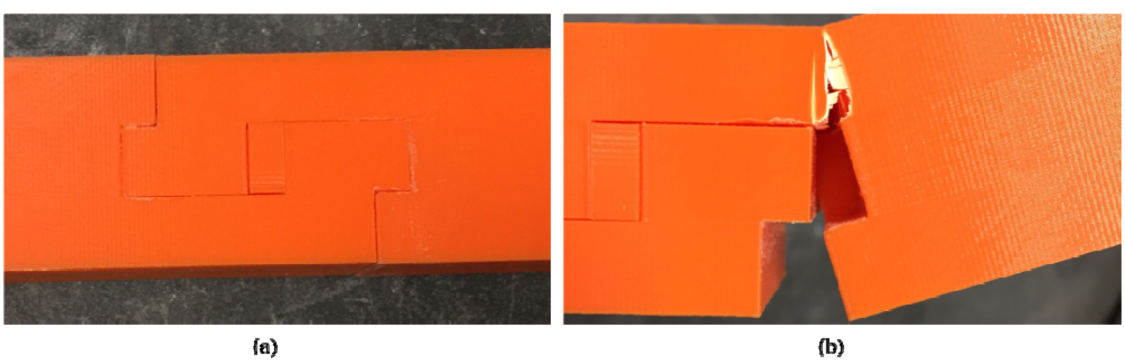


Figure 25. (a) before and (b) after testing

Figure 26. Four-point bending test for Kanawa-tsugi connection from two different angles

6 DISCUSSION OF RESULTS

After testing three specimens of each connection type and three specimens of the 70% infill beam with no connections, the average maximum load and deflection at the maximum load were calculated and are shown in Table 3. The ConXtech and Kawai-tsugite connections performed better that the Kanawai-tsugi connection, resisting a maximum load around 2450 N [550 lbs.] due to the better use of the total cross-sectional area compared to the Kanawai-tsugi connection. As expected, the connections had relatively large deflections, which are about L/67 to L/47 (where L is the span between supports in inches). For beams in building construction, the max deflection allowed is typically on the order of L/240 or L/360 [34]; thus, the deflections exhibited in the tested specimens, where the connections were placed at midspan, would not be permitted according to current codes for serviceability. However, a typical connection will likely be placed at the beam ends or at locations of lower moment demands, which would likely reduce the total beam deflection caused by connection rotations compared to the case where the connection is placed at midspan, the location of the maximum moment. Some of the initially deflection is partially attributed to the tolerance gaps of 0.508 mm [0.02 in.] provided in the connections that had to “close” before the connection was fully engaged, after which the deflections are primarily attributed to material deformations.

Table 3. Comparison of the average behavior of different connections

	Deflection at Max. Load (mm)	Max Load (N)	Max Moment (kN-mm)
70% Infill Beam	3.10	9,157	233
Kawai-tsugite	4.37	2,387	61
Kanawa-tsugi	2.95	1,639	42
ConXtech	3.51	2,539	64

It is worth noting that establishing an analytical expression to calculate the flexural strength of a 3D printed beam or connection is difficult due to the anisotropy associated with the printing direction and due to variations in print infill patterns. For example, uniaxial tests conducted on single strands of PLA filament, suggest that the material has a tensile strength of about 54 MPa [7,832 psi] [35]. For a solid beam made of this material, it would be expected to have a flexural capacity of 332 kN-mm [2937 lb-in] for a four-point bending test of the dimensions used in this study. The average flexural capacity of a 70% infill beam in this test is 233 kN-mm [2,062 lb.-in], or approximately 70% of the theoretical strength of a solid beam made of the isotropic PLA material. The reduction is strength caused by the requirement of an infill percentage and an infill pattern for AM construction. Choosing a different infill pattern and infill percentage will results in different strengths. Future work could include specimens with different infill patterns and infill percentages to investigate the impacts of these design parameters on beam and connection strength. When compared to the 70% infill beam, the specimens with the Kawai-tsugite and ConXtech connections exhibited a flexural strength that was approximately 27% of the strength of a simple beam with the same infill pattern and percentage. As expected, the introduction of splice connections does decrease the capacity of a beam, but the proposed fastener-free connection is still able to transfer significant load and could be suitable for non-structural applications. It is worth noting that the American Institute of Steel Construction (AISC) [36] references Hart and

Milek [37] who proposes "splices in fixed-ended [steel] beams be located at the one-sixth point of the span and be adequate to resist a moment equal to one-sixth of the flexural strength of the member, as a minimum". Also, typical bolted steel beam splice connections were tested in Mohr & Murray [38], some of them having a flexural strength of approximately 25% of the beam's nominal flexural capacity. Thus, the additively manufactured fastener-free PLA beam splice connections tested in this study have relative strengths, compared to a non-spliced beam of the same material and dimensions, that are comparable to splice connections used in conventional steel construction.

6 3D PRINTING LIMITATIONS

3D printing components introduces new design variables that can affect the strength or performance of an end product. These design parameters for material extrusion include, but are not limited to, percentage of infill, the type of infill pattern, scale of the part being printed, the layer and print orientation, the layer thickness, the speed of the nozzle, temperature of the nozzle, temperature of the bed, room temperature, material use (e.g., PLA vs. ABS), 3D Printer model, and even the manufacturer of the material. To ensure the quality of 3D printed parts used in industries such as construction, more tests must be done to better characterize the performance and variability of materials available in AM, to ensure environmental control and repeatability of results from a 3D printer, and to better predict properties of the end product based on the design parameters previously mentioned. For example, this study only considered one infill percentage and pattern (70% infill in a square grid pattern), which was consistent between all specimens so that these tests could investigate the effects of connection type on strength and failure mode of each connection. Other infill patterns, such as a honeycomb or cubic pattern, could further improve specimen strength and/or ductility by ensuring the infill crushes in compression before rupturing in tension.

One of the issues encountered with 3D printing components using common 3D printers is the cross-sectional area or the volume that can be attained by tabletop printers. For a 38 mm x 38 mm x 254 mm [1.5 in. x 1.5 in. x 10 in.] specimen, the printing time was around 19 hrs., which is considered a long print and uses a large amount of material. When considering large-scale construction applications, higher volumes of material will be used, and commonly available printers are not capable of producing components of such scale in the quick print time desired for most construction projects. Ongoing research such as Big Area Additive Manufacturing (BAAM) from Oak Ridge National Laboratory (ORNL) is focused on developing printers and materials suitable for reliable prints of large volumes. Will there be a relationship between the performance of a connection of 38 mm x 38 mm [1.5 in. x 1.5 in.] cross sectional area compared to a connection of 76 mm x 76 mm [3 in x 3 in.] of 305 mm x 205 mm [1ft. x 1ft.] cross sectional area? Further studies are needed to investigate scale effects in AM.

Additionally, only one-layer orientation was included in this study, mainly being aligned to the testing orientation or sometimes called 0°-layer orientation. Studying the behavior of a 45° or a 90° orientation and comparing the results may be able to corroborate previous research that states 45° is the best layer orientation for 3D printed components [35]. However, even if one print orientation is deemed to provide the largest strength, it may require supports during printing, resulting in a longer or less efficient print. Effects of each variable on print performance and final state performance must be carefully considered and weighed based on the needs for each particular application.

As discussed previously, layer thickness can play a key role in printing time, print quality, and final state strength, depending on the bonding between layers and the thermal strains being induced. There is research that suggest smaller layer thicknesses will increase thermal strains and stresses that could result in premature failure of 3D printed parts, which could be a major concern for structural applications [24]. Printing components as fast as possible to reduce printing time is sometimes required, but it affects quality of the final part and increases the likelihood of failure of the component because of skipping steps, warping, over extrusion or under extrusion of the material, etc. during printing.

Another issue that can affect performance is the temperatures required for the nozzle and the heated print bed depending on the material used. For example, PLA requires temperatures around 215 °C for the nozzle and 55 °C for the bed, but some material manufacturers recommend 210 °C and 60 °C for the bed. The 3D printing community has explored the variation of the temperatures that result in improved aesthetics, but work must also be done to investigate how the temperature variables affect the mechanical properties of the printed part.

Another thermal issue encountered while printing was the difference of temperature between the 3D printer and the room temperature or even building temperature. During winter, when the specimens from this study were printed, the thermostat in the building where the printers were stored was kept at a low temperature to conserve energy. During the time of printing from December 2017 to January 2018, the temperature in Austin had an average high of 16 °C [62 °F] and an average low of 5 °C [42 °F]. Thus, it is likely the room temperature was somewhere between those values. These low temperatures affected the printing quality as the heated bed and the nozzle during printing need to be around 60 °C [140 °F] and 210 °C [410 °F], respectively. This difference in temperature caused a “temperature shock” in some of the prints causing them to fail or warp. For this reason, many in the 3D printing community have built personal enclosures for their 3D printers to control their surrounding temperatures and reduce the temperature sensitivity of these materials. Even for 3D printing of concrete, which is being explored in the construction industry, some have provided a type of enclosure for their work to maintain a steady temperature and environmental control [39].

The connections in this proof-of-concept exploratory study were only tested in flexure. To better characterize structural performance of these connections, further tests could be done to look at the behavior of these connections in compression, tension, and shear. For example, Kanawa-tsugi is known to have a better performance in tension compared to other wood joinery [4].

As part of this study, the use of other materials and 3D printing processes was considered as a potential test variable. The use of ABS using material extrusion process and rigid resins using vat photopolymerization were investigated for use in this study; however, limitations in printing sizes and AM technical issues prohibited their use in this study. This planned phase of the study was intended to compare the performance and strength for one specific connection, Kawai-tsugite, when printed with different materials and/or AM processes. The first attempt to print a specimen using material extrusion of an ABS material was done using the same settings as the previous PLA prints, where the nozzle and print bed temperatures were adjusted to values recommended for ABS. The component failed at about a third way through the print due to warping in one of the corners. It was suggested to add rafts to the component to decrease warping, but after another attempt, warping was even worse (shown in Figure 27). For the third time, the components were printed one by one to reduce the amount of wasted material in the event the print failed, but the print warped once again and failed. It was concluded that the amount of infill percentage and the size of the 3D printed component were some of the main reasons the print continued to fail, despite attempts to mitigate the issues. The failures are believed to be due to the printer taking almost an hour to print the first layer, resulting in differential temperatures and shrinkage in some areas of the first layer that caused it to detach from the print bed.

Figure 27. Failed print using ABS

For vat photopolymerization a Forms 2 printer from Formlabs [40] was used to print the same Kawai-tsugite connection. Advanced settings were needed to place the supports required for the print instead of using the one-click print feature in the program. Using the one-click feature required our component to be printed in an almost 45° angle; however, this print orientation was not consistent with the goal of testing the component with a layer orientation similar to the previous PLA 3D printed connections. During the first attempt to print the connection in a 0°-layer orientation, the print kept failing within an hour after starting. Figure 28 shows images from the slicer software that suggested insufficient supports to hold the specimen in place while printing. Later prints were attempted with increased support diameters, support density, and adding manual supports, but the print continued failing. No further attempts to print the connections with other processes or materials are planned due to time constraints; however, the difficulties encountered in these attempts to print the same connections using different materials and different AM processes suggest more work is needed to improve printer reliability, design and process evaluation tools, and error detection. These topics, including exploration of connection behavior using different materials and processes, are suggested as future research.

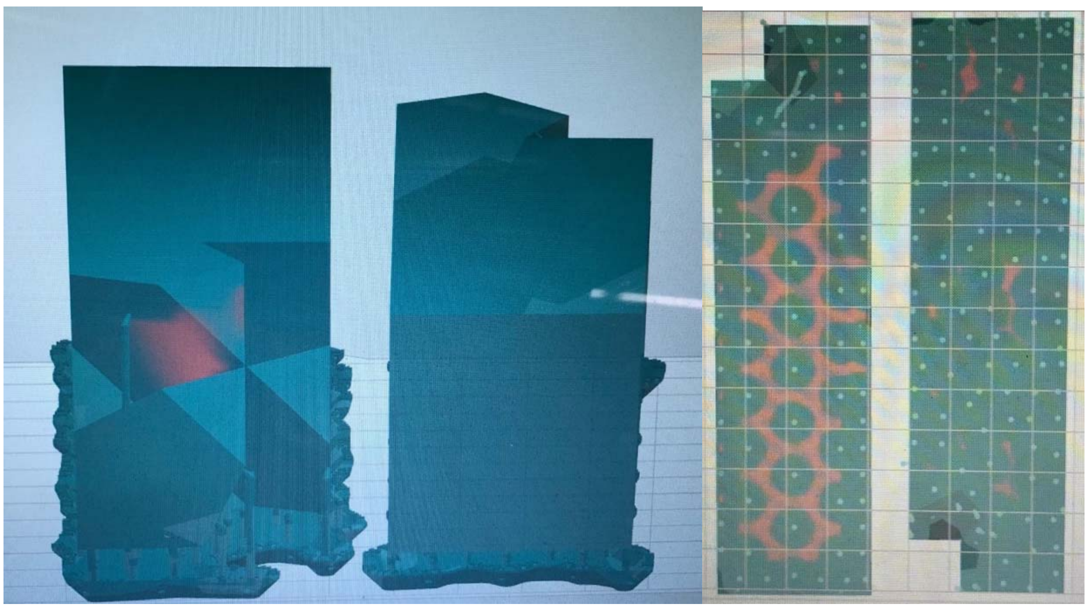


Figure 28. SLA slicer software

Lessons learned from this current study can be applied to future research investigating use of more reliable materials and AM processes more suitable for construction, such as using material extrusion for cementitious materials or powder bed fusion for metals. Connections are meant to resist and transfer bending moments as well as shear and axial forces from one element to another. These tests have shown 3D printed connections are capable of transferring bending forces and can be comparable to the performance of some splice connections used in conventional steel construction, as previously mentioned. Future research in the area of extrusion of cementitious material is needed to find clever and reliable ways of adding reinforcement to the material, as concrete and cementitious materials themselves are brittle and performing poorly when subjected to shear and tensile stresses. For cementitious materials, new connection geometries that take advantage of the material's high compressive capacity and minimize locations of tensile stress concentrations should be further explored.

Other materials such as fiber reinforced polymer or metals would be recommended for fastener-free connections due to their enhanced tensile strength and ductility. These materials are well known in AM and are being explored for other structural applications at smaller scales [41] . Information about material properties are available from the companies that produce these materials for AM, but the behavior of 3D printed components using these materials are not readily available and would require further testing. The performance of these materials are temperature dependent and are typically printed as solid pieces for mechanical parts. All materials currently used in AM, including cementitious materials, metals, and fiber reinforced polymers, all require a controlled environment to build reliable components. It is expected that with further research and testing, performance of connections printed using materials such as metals and fiber reinforced polymer, as well as adequately reinforced cementitious materials, can perform similar to or better than the connections printed and tested in this thesis.

7 CONCLUSION

The main focus on this study is the investigation of different fastener-free connection alternatives that could be utilized either for formwork, scaffolding, and other non-structural or structural applications such as beam-to-beam, beam-to-column, or beam splice connections. A PLA material was used in this study due to its availability and ease of use with commercially available 3D printers; however, this material is not considered reliable for structural or non-structural applications since it is biodegradable and is not considered to have a high strength necessary for structural applications. Investigation of different fastener-free connection concepts using this material is intended to provide some basic information on the relative strengths and properties expected of an anisotropic component due to the layer by layer processes using a material extrusion process and the expected failure modes of the different connections.

The purpose of this study is to test this concept of 3D printed fastener-free connections at a small scale and with current AM technology to explore the benefits, limitations, and potential uses of AM in construction. The extrusion AM processes used in this study are beneficial for generating the unique and customized geometries for the connections that would be difficult to generate using other formative or subtractive processes. Three types of fastener-free connection concepts were explored in this study—the Kawai-tsugite and the Kanawa-tsugi connections inspired from Japanese woodworking, and the ConXtech inspired connections. Each connection was tested in flexure and was compared to a plain beam specimen with no connection and comparable print parameters. Results showed that the Kawai-tsugite and ConXtech connections exhibit higher flexural strength than the Kanawa-tsugi connection. These findings confirm that Japanese joinery could be reborn for new applications in construction using AM process. Such fastener-free connections, like Kawai-tsugite, do not necessarily need to serve a structural purpose, but could be reliable enough to be considered as a type of quick-connect connection used for temporary structures like formwork to reduce assembling and disassembling time. Results from testing these additively manufactured connections have shown both the benefits and the limitations of 3D printing.

To encourage further applications of AM in construction, it is necessary to conduct further review and testing of new applications and improve and standardize testing procedures for components made using AM processes. The tests in this study were done using specific AM process settings, but variability of those settings such as layer orientation, infill percentage and pattern, tolerances, temperature changes, and scaling effects need to be considered. The exploration of connections that have been tested in this paper could be extended by using different materials available such as nylon, carbon fiber reinforced polymers, ABS, cementitious materials, and metals. Additionally, different AM processes beyond material extrusion can be explored, such as powder bed fusion that could be used for nylon and metals, vat photopolymerization, or direct energy deposition also used with metal powder.

Although AM is gaining recognition and applications in various industries, it still a work in progress where trial and error or tinkering is required. The technology cannot be considered reliable and repeatable yet, but the 3D printing community is constantly making advancements and new applications are being explored.

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Chapter 4: Conclusions

Key findings from the literature review on AM in the construction industry include:

- AM could mitigate some of the current challenges in construction such as working in harsh environments, decreases in skilled workforce availability, and waste material produced during construction.
- The use of additive manufacturing is still in its early stages in the construction industry, mainly being used for direct replacement of parts, rapid prototyping, and tooling applications.
- Most of current research on the use of AM in construction has been focused on the material extrusion process using cementitious materials on a larger scale.
- Some of the potential applications could be for optimized topologies, customized parts, in situ repair for construction in areas with limited access, and for tolerance matching.

Key findings on AM fastener-free connections include:

- Additively manufactured fastener-free connections investigated in this research were found to be suitable for non-structural applications with a low risk of failure repercussions. Further research is needed on AM before these connections are sufficiently reliable for applications that pose a risk to human safety.
- The performance of the connections in bending warrant further research in other failure modes, materials, print settings, and processes for possible structural applications.
- The material extrusion process is greatly affected by the surrounding environment and by the specified printer settings.

- Future investigations are recommended to continue exploring optimized forms specific to AM processes before AM can be used for low level production or even for mass production.

Based on the findings provided in this thesis, further research is recommended, including:

- Interdisciplinary research is needed to improve processes, produce reliable AM parts with repeatable performance, and to make AM an economically viable option in construction.
- New fields of study for AM in construction could emerge. For example, studies could focus on repair and retrofit options using AM technology, or explore the use of more advanced small-scale AM technologies for structural or non-structural applications in construction that have not yet been explored.
- There is a significant need to improve and standardize testing procedures for components made using AM processes. Such testing is necessary to ensure reliability and safety of AM parts used in construction.
- Extensive testing and collection of experimental data results is still required to explore the potential for different failure modes in AM parts and to increase the reliability of AM for structural applications.

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