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

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Abstract

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 fastener-free connections that could be used in structural or non-structural applications. These 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.

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 used increasingly in many industries such as automotive 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 projects. 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 either manually or using CNC machines, 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. As advancements continue to be made in AM processes and materials, there are likely to be more structural and nonstructural AM components used in construction. These components may include architectural claddings [3], formwork for concrete components of complex geometry, permanent or temporary structural elements such as beams and scaffolding, and much more. Even as large-scale AM technologies allow for full-scale components, and even monocoque structures, to be printed, it likely that multiple structural components and architectural finishing will be printed on- or off-site and will need to be connected to form the final product. While traditional connection methods using fasteners such as bolts, screws, welds, epoxies, or un-bonded post-tensioned elements [4], can be used to connect these AM components, there may be novel connection methods amenable to AM that have otherwise considered impractical or uneconomical in conventional construction practices.

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 processes 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 most 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 [5]. 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 cast-in-place concrete components. 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.

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 joiners [6]. 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 [6]. This type of joinery is seen as pieces 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 [7, 8, 9, 10, 11] was created in the 1980s by Professor Naohito Kawai when he was a student at the University of Tokyo [10]. Kawai-tsugite is not a typical joint in Japan due to its complex geometry [11], and it was created primarily to test woodworkers' craftsmanship skills; thus, information and details about this specific joint are lacking in Japanese joinery books [11]. 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 1. 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 [12].

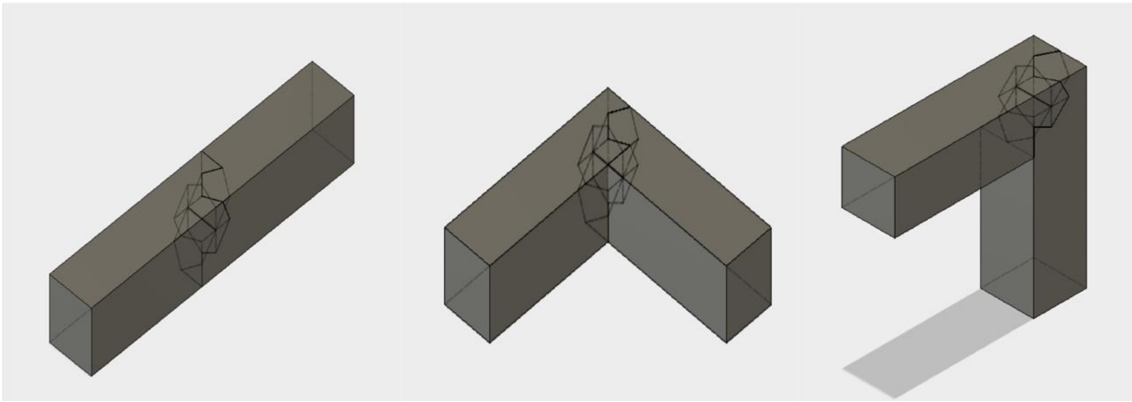


Figure 1. Assembly options for Kawai-tsugite

Figure 2 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.

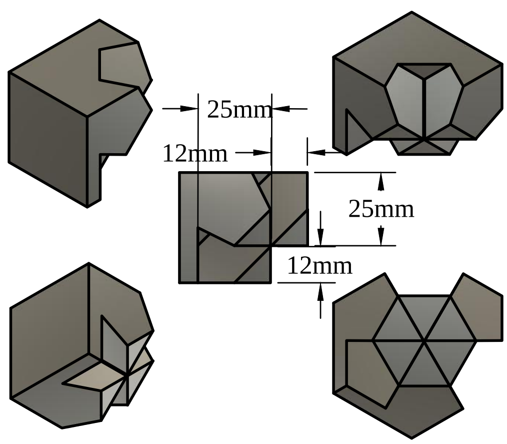


Figure 2. Kawai-tsugite concept joint

2.2 Kanawa-tsugi

Kanawa-tsugi is a splicing joint, described as a mortised rabbeted oblique splice by Suimyishi and Matsui [6]. 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 3) 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 [6], hence its selection to be included in the current study for applications in construction. Figure 4 shows the Kanawa-tsugi connection used in this study.

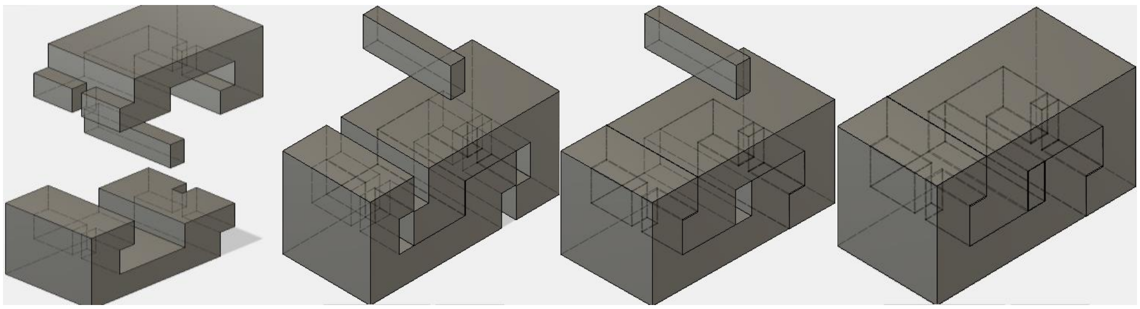


Figure 3. Kanawa-tsugi assembly sequence

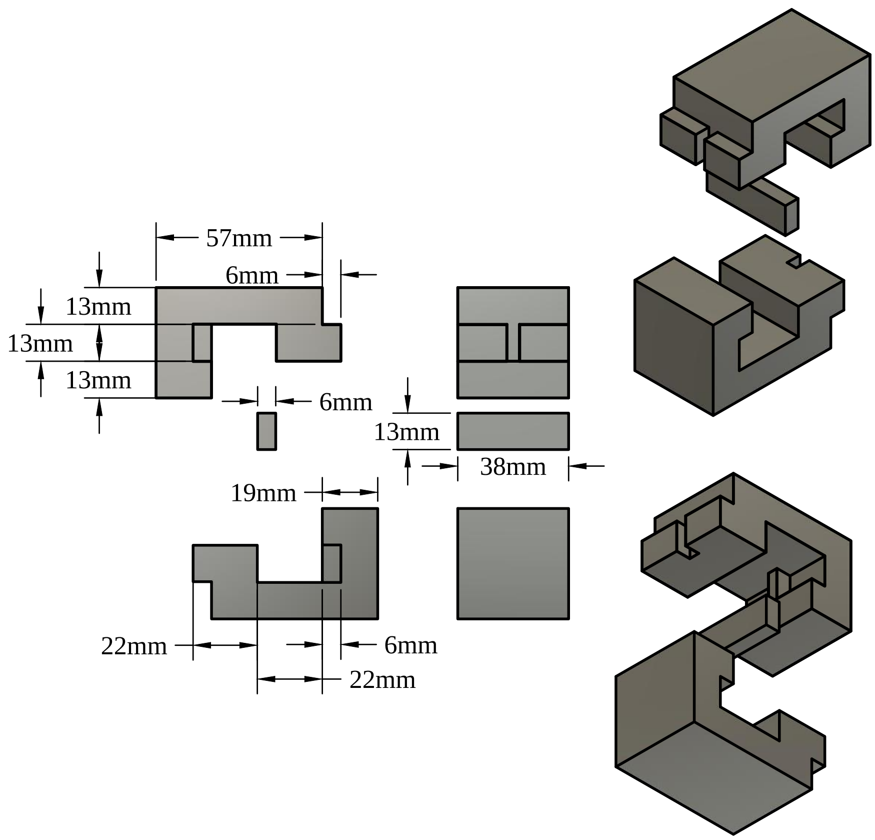


Figure 4. Kanawa-tsugi joint concept

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 [13]. These proprietary connections utilize tapered collar geometries to create gravity stabilized connections that can be "lowered and locked™" in-place and can be used to assemble beams and columns faster and safer, shown in Figure 5 [13].

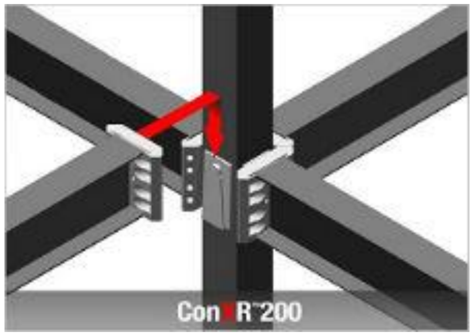


Figure 5. ConXR200 connection [11]

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-resisting frame 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 [13]. A similar connection concept with a very different application came from K'NEX [14]. This company focuses on creating educational toys for kids 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 re-assembled as desired. 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 6 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.

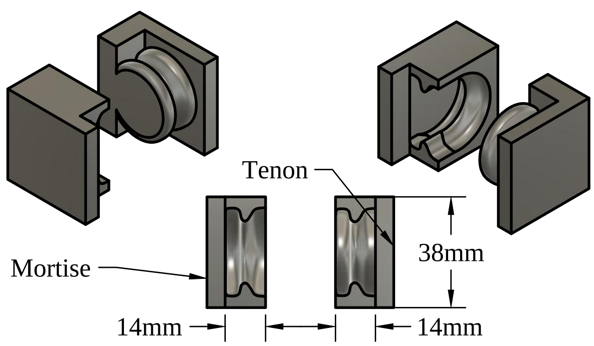


Figure 6. ConXtech concept joint

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 [15]. Models for AM applications can be created using a wide range of commercially available 3D modeling software such as SketchUp software [16], SolidWorks software [17], Inventor® 3D CAD software [18], AutoCAD® 3D software [19], 3ds Max® software [20], 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 [15]. Fusion 360 allows users to convert a 3D model directly into a .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 [21]. 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 [21].

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, which is the prototyping application being used in this study.

For construction, tolerances are an important factor in fabrication and performance, where even a fraction of an inch of difference in a part's geometry can significantly increase construction time required to make modifications necessary for the multiple parts to fit together. For example, the layout of structural concrete and light-frame wood construction components are suggested to be within ±6.4 mm [1/4 inch] of specified locations [22, 23], and any finishes or additional components connecting to these elements must be fabricated to accommodate these tolerances. 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. Due to the automation of 3D printers, parts can be manufactured to relatively tight tolerances, from micron to millimeter tolerances depending on the print scale [21], compared to the tolerances of about ±6.4 mm [1/4 inch] for hot-rolled steel cross-sections traditionally used in construction per the American Institute of Steel Construction [24]. 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. Comprehensive exploration of 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 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 [25, 26]. Higher quality will require smaller layer thicknesses that might also be able to meet stricter part geometry 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 [26], compared to other AM processes such as vat photopolymerization that can give a layer height as low as 0.025 mm [0.001 in.] [27]. A drawback from producing prints with smaller layer thicknesses is the increase of the number of layers required, which increases printing time. The increased number of layers might also increase the number of weak points or slip planes 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 [28]. 3D printing is evolving rapidly and potential improvements in print processes are readily available. 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 [29].

As mentioned before, the volume of 3D printed parts allowed in commercially available tabletop printers is relatively small, around 300 mm x 200 mm x 440 mm [12 in. x 8 in. x 17 in.] [25] for the tabeltop printers used in this study, 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) [30], small scale additive manufacturing is the most 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 build volume of 300 mm x 200 mm x 440 mm [12 in. x 8 in. x 17 in.] [25], 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 [32]. Another material that is commonly used for 3D printing is ABS, which is a petroleum-based thermoplastic with higher flexural strength, ductility, and durability [33, 34]. The challenge with ABS is that is more sensitive to temperature changes and produces fumes [34]. PLA was chosen as a starting point for this research as it is readily available and a commonly used material in tabletop 3D printers. Future research could explore the variability of mechanical 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. The platform bed and the printer head were heated to 60 °F and 215 °F, respectively. The build plate was also coated with hair spray to improve adhesion of the initial printed layers. A layer thickness of 0.2 mm [0.008 in.], considered as a high print quality for fused filament fabrication (FFF), 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 layer offsets during printing, which can often occur 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. The infill pattern and density was kept constant for all prints in this study, and was therefore not investigated as an experimental variable. A 70% infill was used instead of a solid print (100% infill) to decrease material use and printing time. Using CraftBot XL to print specimens with the dimensions shown in Figure 7 with the specified settings took around 19 hrs. to print each specimen.

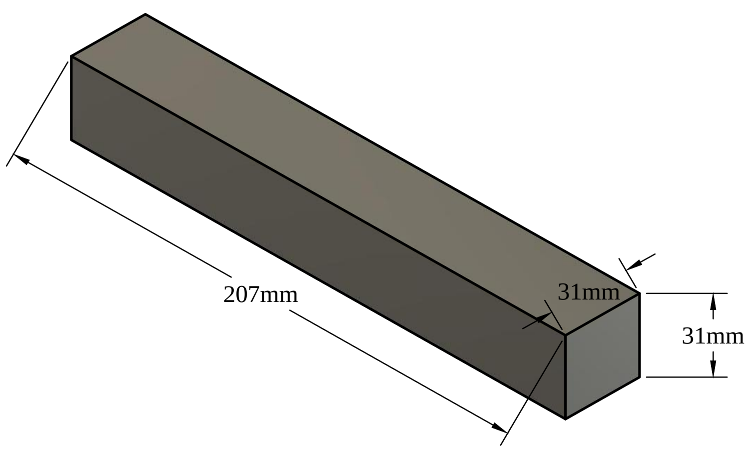


Figure 7. Dimensions for specimens

4.2 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 8a, four-point bending test consists of placing a beam on bottom supports spaced at a length of L and with top loading points spaced 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 8b and Figure 8c, 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 [35] provides guidance to determine the flexural properties of unreinforced plastics via four-point bending tests, assuming the tested part is made of completely solid and isotropic material. The FFF material extrusion process is a layer by layer process, resulting in anisotropic material properties; thus, results are expected to be different than those assumed in the ASTM standard. Additionally, the additively manufactured specimens being tested have a specified 70% infill, which is not consistent with the solid infill assumed in the current standards.

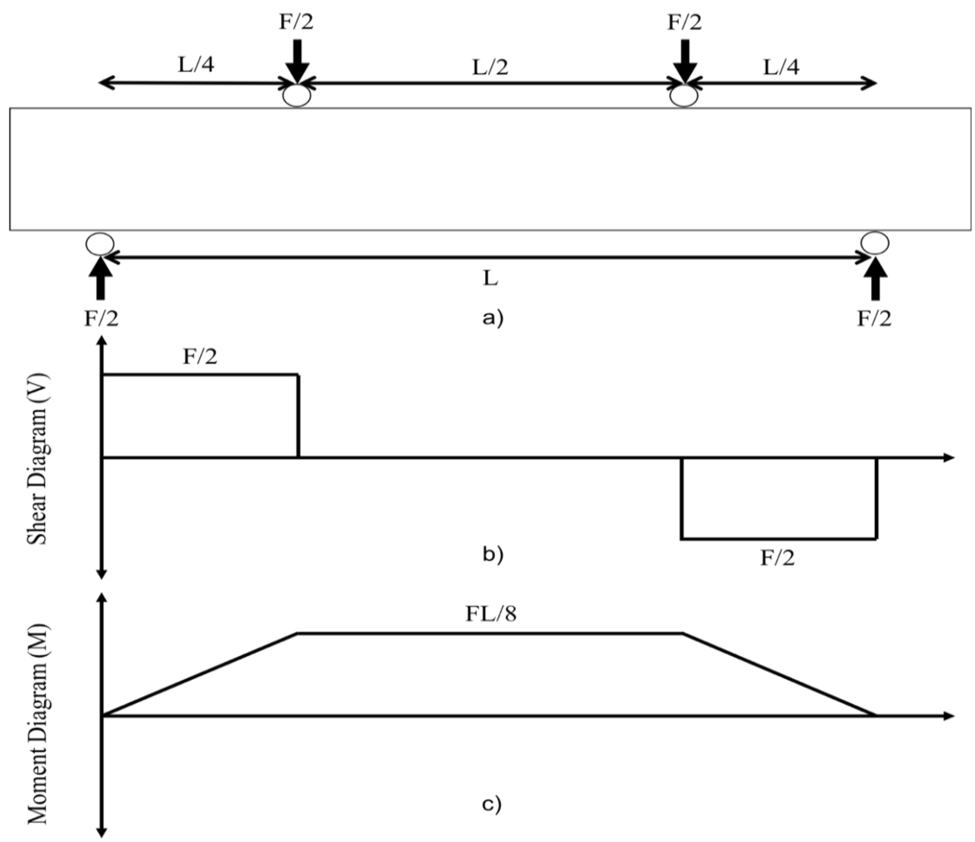


Figure 8. Shear and moment diagram for four-point bending flexural test

5. Test Results

The results of the four-point bending tests for the reference beam specimens (with 70% infill and 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 in the Longhorn® Maker Studio facilities at the University of Texas at Austin. 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. It is worth noting that all specimens for this project were printed from December 2017 to January 2018, when University classes were not in session and building thermostats were set to lower temperatures to conserve energy; thus, the researchers were unable to control the ambient room temperature. 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 Reference Beam

To serve as a baseline for the capacity of the fastener-free connections, reference beams, with 70% infill and 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 9 shows the load vs displacement of the reference 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 10 shows the failure mechanism of a reference beam after it 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.

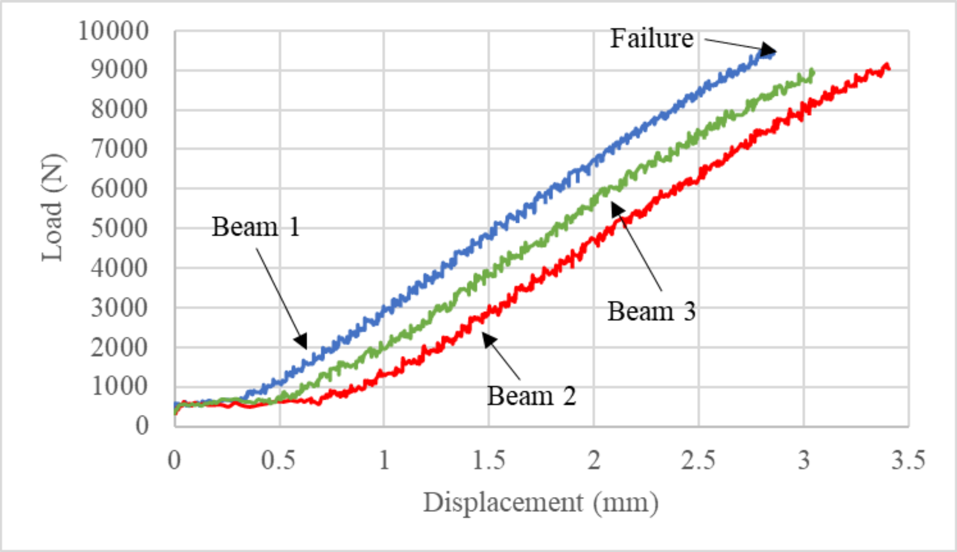


Figure 9. Load vs. displacement response for reference beams

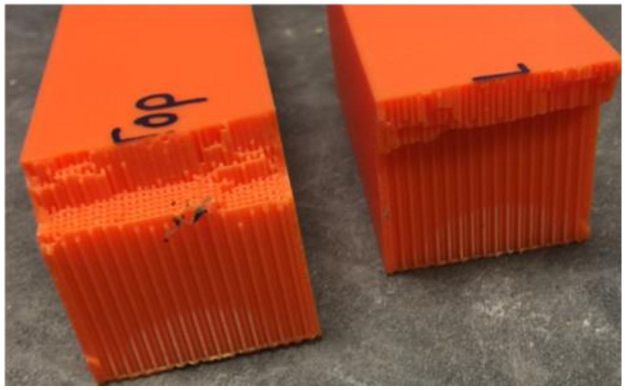


Figure 10. Reference beam after testing

5.2 Kawai-tsugite Results

Specific issues that were observed while printing this connection was stringing (shown in Figure 11) 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).The excess material from the stringing was removed and tested, and no changes were made to the printing process to mitigate stringing.

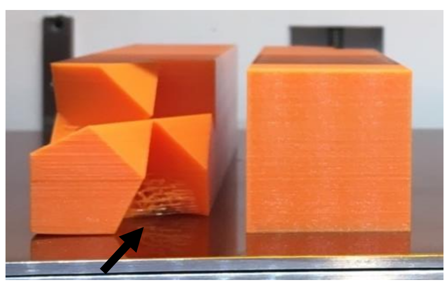


Figure 11. Stringing occurring during printing

Figure 12 shows the load vs. displacement relationship for the Kawai-tsugite connection. In Figure 12, 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 excess material caused by stringing that occurred during printing, which, even after being removed, 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.

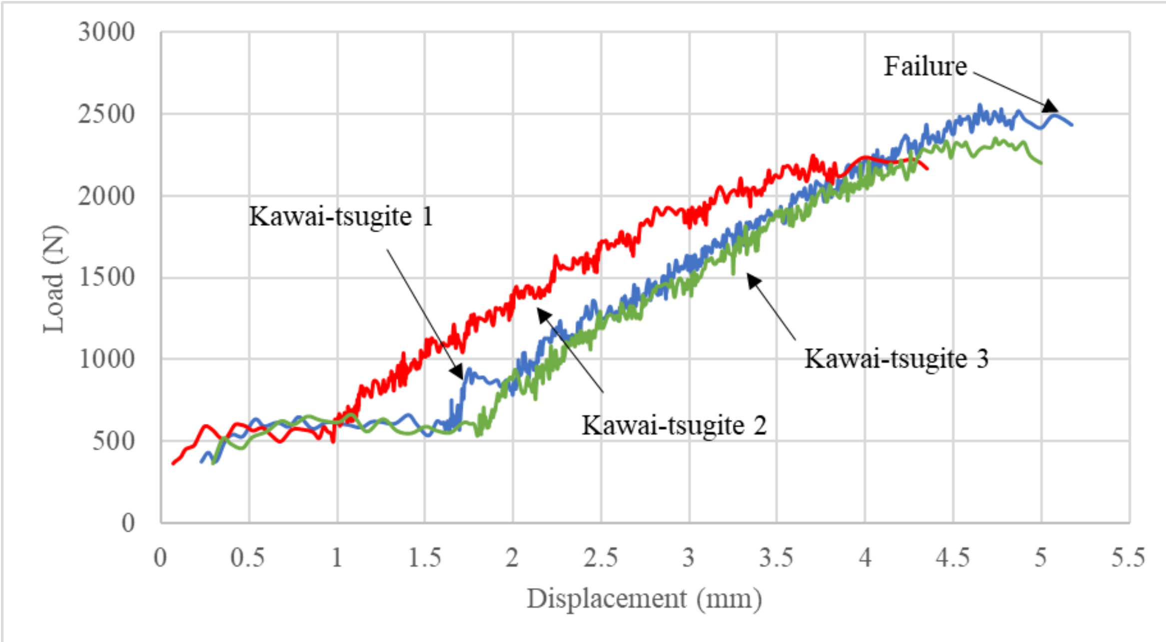
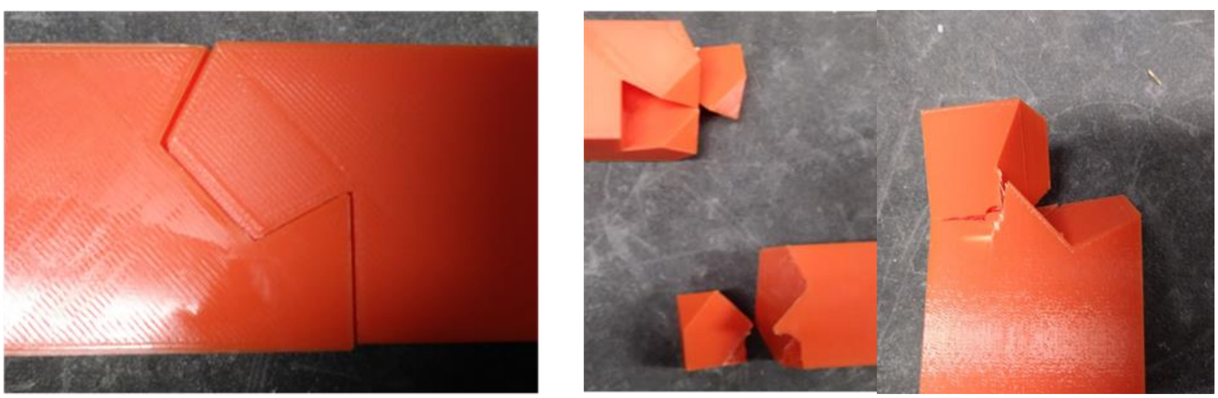


Figure 12. Load vs. displacement response for Kawai-tsugite connection

Figure 13 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 13b and Figure 14 reveals the failure mechanism of this connection. A 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 sudden, brittle manner.



(a) (b)

Figure 13. (a) Before and (b) after testing

Figure 14. Four-point bending test for Kawai-tsugite connection from two different angles

5.3 ConXtech Results

A total of 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 19a), 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 15, 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 the Kawai-tsugite specimens, 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 15. Layer shifting

Figure 16 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, as indicated by the reduced stiffness and increased plastic deformations prior to failure, or loss of load carrying capacity.

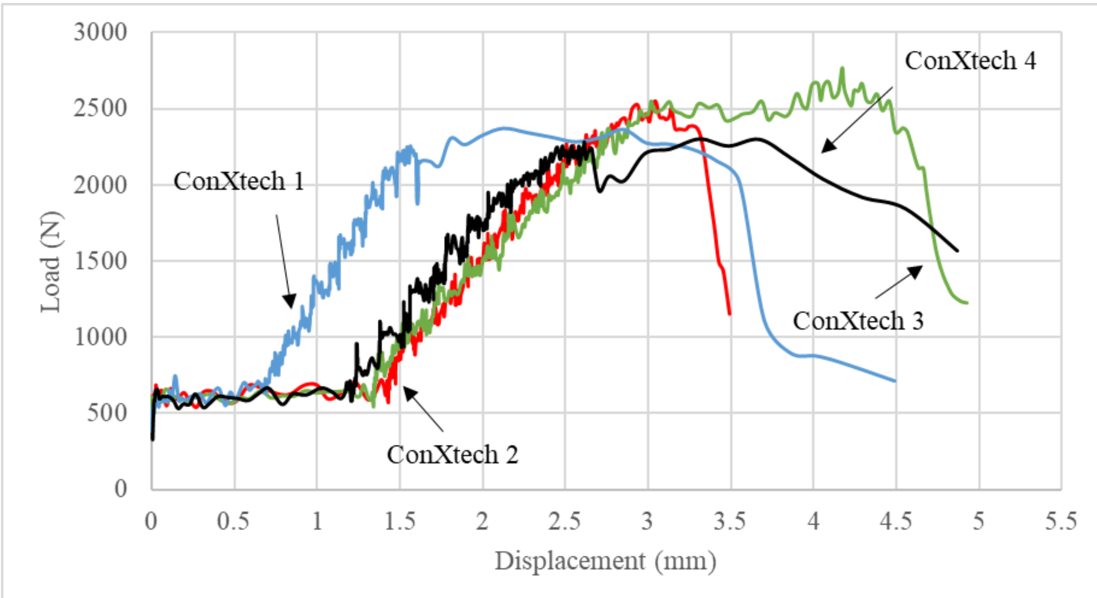
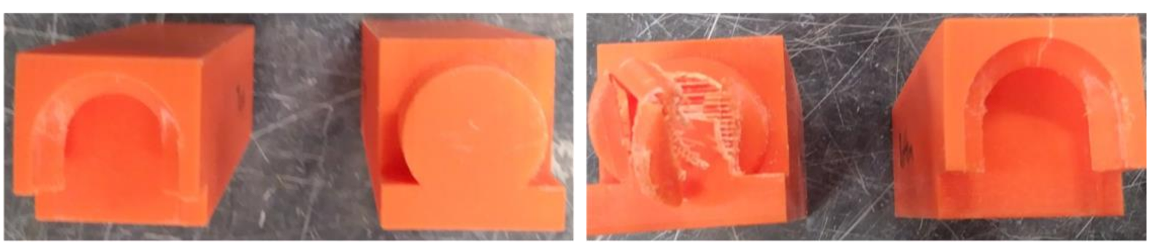


Figure 16. Load vs. displacement response for ConXtech connection

Figure 17 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 17a 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 17 and Figure 18, the failure mechanism can be observed where the tenon fails in tension where its cross-sectional area is smaller. It can also be seen in Figure 17b and Figure 18 that the mortise formed a crack at the middle of the connection where it started to fail parallel to the layer orientation.



(a) (b)

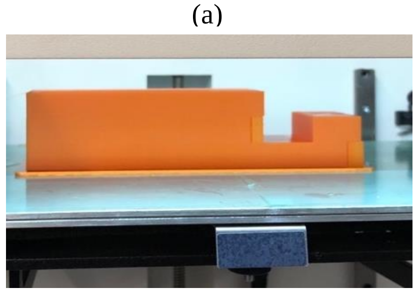
Figure 17. (a) Before and (b) after testing

Figure 18. 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 [36] to add a raft (shown in Figure 19b) 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, since the added material was removed before testing. Kanawa-tsugi specimens 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. It is unclear whether the variability in response of the Kanawa-tsugi specimens is due to the connection itself or due to variability in the printed part. 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 19. (a) Example of warping, and (b) an added raft to decrease warping

Figure 20 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.

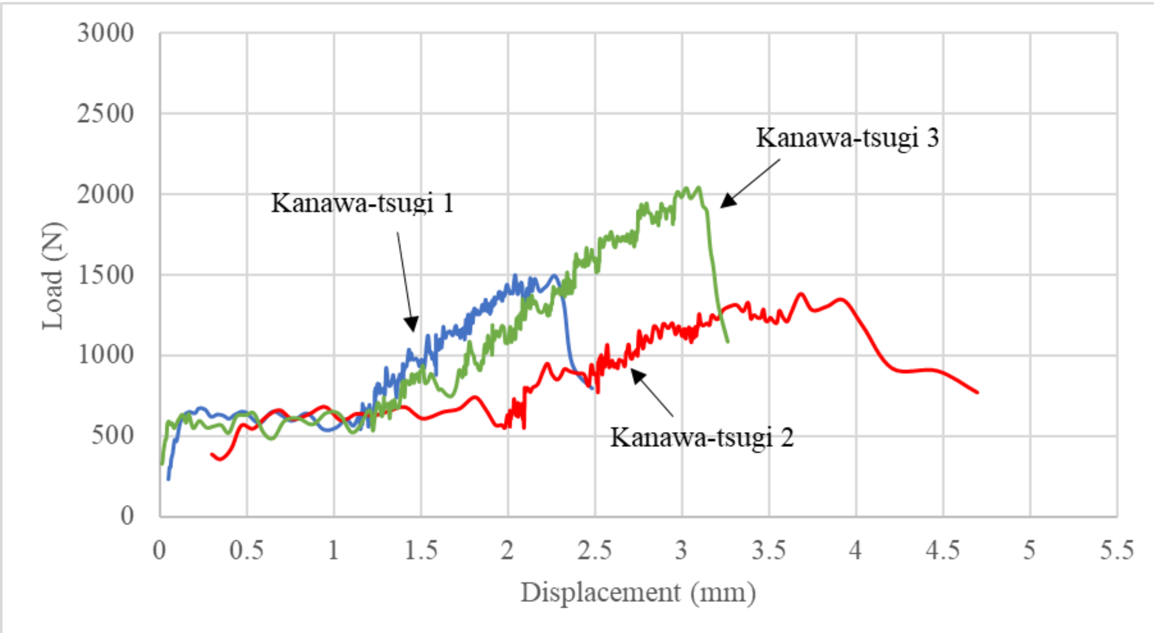
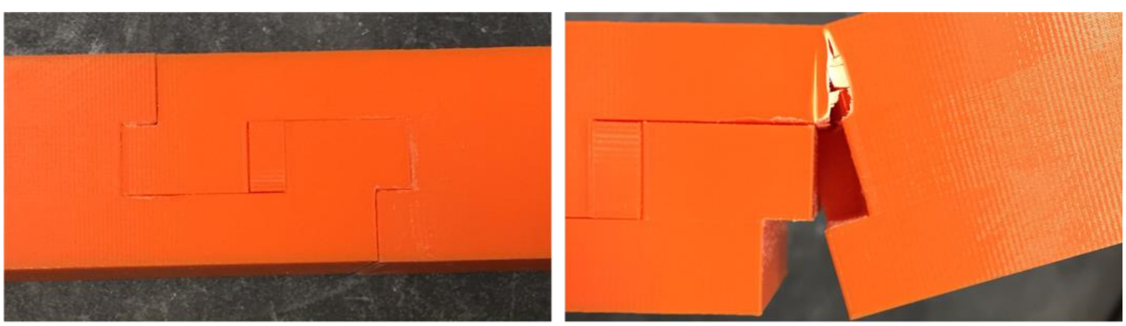


Figure 20. Load vs. displacement response for Kanawa-tsugi connection

Figure 21 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 22 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 sudden or brittle as the Kawai-tsugite connection.



(a) (b)

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

Figure 22. 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 reference beam with no connections, the average maximum load and deflection at the maximum load were calculated and are shown in Table 1. 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 at failure, which are about L/67 to L/47 (where L is the span between supports in inches). For reference, for beams in building construction, the max deflection allowed for serviceability under service (i.e., not ultimate) loads is typically on the order of L/240 or L/360 [37]; thus, the deflections exhibited in the tested specimens, where the connections were placed at midspan, may not be capable of meeting serviceability limits in current building codes. 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 initial 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 1. Comparison of the average behavior of different connections

	Deflection at Max. Load (mm)	Max Load (N)	Max Moment (kN-mm)
Reference 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] [38]. For a solid beam made of this material, it would be expected to have a flexural capacity of 332 kN-mm [2937 lb-in] per the ASTM D6272-17 standard [35] for a four-point bending test of the dimensions used in this study. The average flexural capacity of a reference beam (with 70% infill) 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. Choosing a different infill pattern and infill percentage will result 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 reference 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) [39] references Hart and Milek [40] who propose that "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, Mohr & Murray [41] tested typical bolted steel beam splice connections, some of which exhibited flexural strengths 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. These fastener-free "quick connections" can therefore be considered as an alternative to conventional fastening methods for connecting additively manufactured parts, which could potential reduce the labor and time required to connect parts in the field.

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, temperature of the room, material use (e.g., PLA, ABS, nylon, etc.), 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 fully characterize the performance and variability of materials available in AM, to ensure environmental control and repeatability of results from a 3D printer, and to reliably 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 percentages or 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 may be considered too long for on-site printing on a construction job site. 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. Other institutions and companies, such as Big Area Additive Manufacturing (BAAM) from Oak Ridge National Laboratory (ORNL) [30] and Thermwood Large Scale Additive Manufacturing (LSAM) [42], are developing printers suitable for large-scale prints, and this is an ongoing area of research. 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.] or 305 mm x 205 mm [1ft. x 1ft.] cross sectional areas or larger? 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 referred to as 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 [36]. 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. For example, some applications, such as attachment of small architectural finished, may have minimal strength requirements (e.g., only supporting a relatively small self-weight) and a designer may favor printing efficiency and speed over structural performance. In other applications, such as load-bearing structural elements, part strength and quality may be of utmost concern. 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 reduce strength of 3D printed parts, which could be a major concern for structural applications [28]. 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 due to 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 and mechanical properties, but further work must still be done reliably characterize and qualify mechanical properties of printed parts based on such printing variables.

Another thermal issue encountered while printing was the difference of temperature between the 3D printer and the surrounding room 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 should be around 60 °C [140 °F] and 210 °C [410 °F], respectively. The researchers were unable to print the parts at another time of year due to limited availability of Longhorn® Maker Studio printers for research purposes during the academic sessions. 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 [43].

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 [6]. Additionally, further work can be done to optimize the geometries and dimensions of specific connections to minimize stress concentrations and improve structural performance under various loading conditions.

As part of this study, the use of other materials and 3D printing processes were 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 of the 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 23). 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 23. Failed print using ABS

For vat photopolymerization a Forms 2 printer from Formlabs [44] 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 24 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. As such, exploration of connection behavior using different materials and processes is suggested as future research.

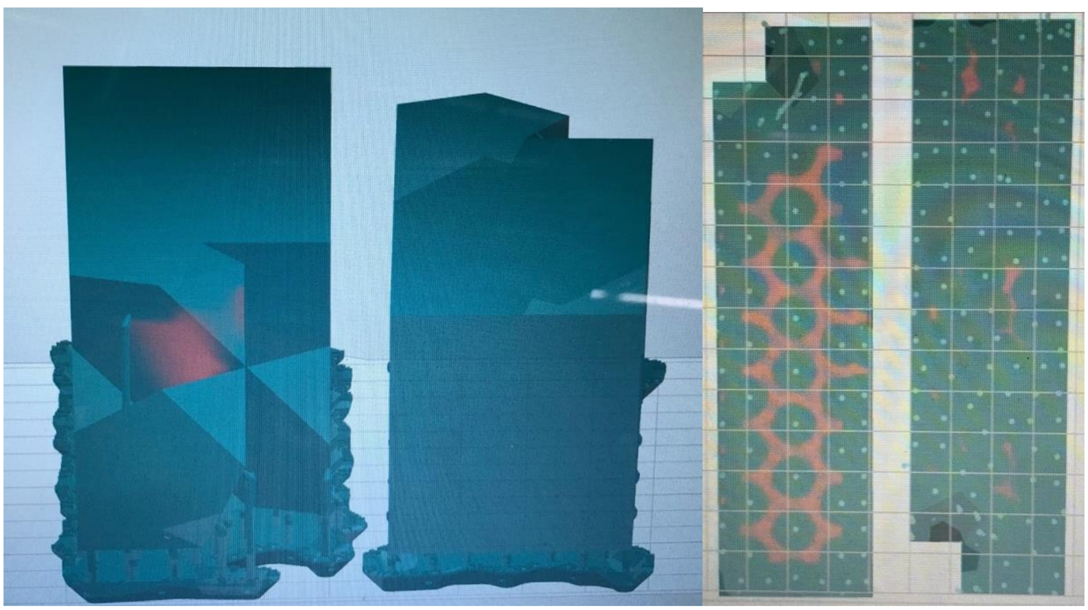


Figure 24. SLA slicer software

While the current study was focused on connection of structural and nonstructural AM components for applications in the construction industry, lessons learned from this study could be applied to other AM connection applications. Additionally, the connection concepts investigated using PLA in the current proof-of-concept study study can be applied to future research investigating use of other 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 [45]. 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, architectural fixtures, 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 such connections in structural and nonstructural applications. 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 reference 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 used 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, further research is necessary to develop and test new applications and improve and standardized 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.

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