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From Pagodas to Printed Homes: Exploring the Flexural Strain, Deflection, and Relative Strength of 3D Printed Japanese Joinery

Kevin Slattery
The American School in Japan, Japan
22slatteryk@asij.ac.jp

Abstract

Large-scale 3D printing, a recent technological advancement, is a cost-efficient and eco-friendly method of construction. However, its products suffer from poor aesthetics, which drive away many potential buyers. Refraining from using any nails, screws, and adhesives, traditional Japanese joints truly depict the beauty of Japanese nature. The application of traditional Japanese joinery may solve the poor aesthetics of large-scale 3D printed structures. Furthermore, these joints are historically earthquake resistant and may improve the safety of 3D printed structures against natural disasters. This study explores the potential uses and limits of 3D printed Japanese joinery when applied to large-scale structures. Four traditional joints were 3D printed using Poly Acetic filament (PLA) at 10 % infill. Three-point flexural tests were analyzed using digital image correlation (DIC) to determine each joint's strain to failure, deflection, and relative strength. The Kanawa Tsugi joint had a significantly higher flexural strain than the other joints tested. Moreover, there were various statistical differences observed among deflection measurements of each joint. 3D printed Japanese joinery could be applied for quick assemble purposes, such as for building formwork.

Keywords: Japanese Joinery, Flexural Strain, Deflection, 3D Printing, Digital Image Correlation

Introduction

Traditional Japanese carpentry is a form of wooden architecture and joinery that originated around 1400 years ago during the Asuka era（宮大工の歴史, 2021). The work of Japanese carpenters, known as the Daiku, mainly revolves around visual aesthetics that spotlight the theme of Japanese nature. The Daikus' refrain from using any nails, screws, or glue to connect joints allows the creation of a natural look that results in a visually pleasing product. The works of the Daiku are seen in shrines, temples, and pagodas throughout Japan. Traditional Japanese carpentry is also seen in residential structures, which are performed by the Sukiya-Daiku (数寄屋大工).

Although Japan is an earthquake-prone nation, before the Meiji Restoration (1868), Japanese carpenters did not focus on earthquake-proof architecture. Instead, the focus of the Miyadaiku was on the visual aesthetics of their final product. According to Clancey (2006), as foreign engineers began to observe the structural flaws of Japanese architecture, Daikus faced the dilemma of having to favor either aesthetics or improve the structural integrity in their work. Scottish civil engineer RH Brunton, who the Meiji Government hired in 1868, criticized the ways of Miyadaiku carpentry as "unfit to earthquakes due to its unnecessarily heavy roof and weak framework."

Brunton described Japanese architecture as "worst adapted to withstand heavy shock" (Clancey, 2006). The foreign criticism of Japanese carpentry led to a shift in the Daikus' focus. They incorporated aspects of western technology such as diagonal braces and iron fittings within Japanese frames. This helped improve the rigidity and strength of Japanese structures, significantly improving protection against earthquakes.

Importance of Joinery to Earthquake Resistance

Even without Western technology, Japanese pagodas built centuries ago are earthquake-resistant. One example of this is the Five Storied Pagoda at Horyu-Ji, a wooden pagoda built in the year 607. The Five Storied Pagoda (Goju-no-to) at the Horyu-Ji temple is the oldest pagoda in Japan. Since the pagoda was initially built, the Goju no To has experienced earthquakes with magnitudes greater than 7.0 at least forty-seven times (Horyuji: A Brief History). Yet, the beautiful pagoda still stands today. Theories attempting to explain the earthquake-resistant characteristic of pagodas have long been debated.

The initial theory explaining this phenomenon focused on the pagoda's vibrational period. The approach was that the structure's naturally long vibrational period is well-matched to the seismic frequency of the ground during an earthquake, allowing the pagoda to "slide" in a flexible manner at the approximate frequency of the accelerating ground waves (Majima, 1927). According to this theory, the matching vibration of the ground and the pagoda allows resonance and minimal stress throughout the structure. However, measurements have shown a significant difference in the natural period of the pagoda and the average period of ground acceleration during an earthquake. The period of the pagoda is far longer than that of the ground acceleration. Therefore, the possibility of resonance with ground acceleration waves causing this phenomenon is minimal. Thus, the "ground wave resonance" theory does not serve as an explanation of the pagoda's structural resistance to earthquakes (Tanabashi, 1960).

A new theory was formed to replace the "ground wave resonance" theory. This theory focused on the shin bashira, the central wooden column of the pagoda.

During the early stages of seismic study in Japan, the structural purpose of the shin bashira was not well understood by Japanese architects since the concept of the shin bashira was passed through the Korean Peninsula carrying Chinese and Indian roots. The shin bashira is not a Japanese innovation (Ooi, 2012). Japanese engineers developed the "Pendulum Theory" to explain the structural purpose of the Shin-Bashira. The theory states that the shin bashira sways in the opposite direction of the mainframe during an earthquake, resulting in movements to "counteract" each other. This results in less stress applied to the overall structure. However, this theory is not accepted today due to the discovery that the shin bashira does not directly play a role in protecting the tower, but rather the joints and connections that surround it do (Abe, 2018).

The seismic resistance of pagoda structures can be described through 3 characteristics made possible by the wooden joinery surrounding the shin bashira.

1. Ability to withstand large lateral loads.
2. High deformation limit until complete failure of the structure.
3. A large amount of structural damping.

Pagodas are capable of undergoing a large amount of plastic deformation before failure: a permanent distortion resulting from high load or stress. A pagoda with considerable lateral strength throughout its body and a large limit of lateral deflection indicate that a large amount of potential energy can be stored before the structure's complete failure (Tanabashi, 1960).

Today it is accepted that the frictional damping of traditional Japanese joinery within the pagoda provides earthquake resistance. The frictional damping provided by each joint is key to an earthquake-resistant structure (Nakahara, 2000). These joints that connect the shin bashira to the outer wooden columns allow for a flexible "spine-like" support that efficiently absorbs seismic stress caused by the earthquake (Hanazato et al., 2004).

The seismic performance of flexible traditional Japanese joinery is seen not only in pagodas but also in other Japanese structures. According to Yamada (2004), "Traditional Japanese wooden buildings are typically composed of wooden frames with joint connections and plaster walls to enclose the buildings and separate rooms". In modern wooden houses, the walls and braces play essential roles in resisting earthquakes. With the use of traditional Japanese joinery, structures are strong and flexible. Similar to the structure of a pagoda as a whole, Japanese joints have a high deformation limit. These characteristics of traditional Japanese joinery play into the damping of the structure. The frictional damping of each wooden joint in the structure allows for absorbing stress that protects the structure from collapse (Nakahara et al., 2000).

Among traditional Japanese joinery, a few stand out for their structural performance as well as aesthetics.

Types of joints

Kanawa Tsugi (金輪継):

The Kanawa Tsugi is considered one of the strongest traditional joints and is used to connect columns, beams, and girders because it provides strength in all directions. The joint is made of two identical pieces with a staggered pattern, fixed by a draw pin inserted in the joint's midspan (Sumiyoshi, 1989).

Koshikake Aritsugi (腰掛蟻継)

The Koshikake Aritsugi is called the sitting-ant joint due to its trapezoidal shape that looks like the head of an ant. The Koshikake Aritsugi is placed horizontally within the frame and is the strongest in the perpendicular axis. However, the Koshikake Aritsugi is most commonly used in groundsills throughout Japan (Sumiyoshi, 1989).

Kama Tsugi (鎌継):

The Kama Tsugi, similar to the Kanawa Tsugi, is the most common joint used in structural application. The Kama Tsugi is often used in beams and girders. Furthermore, the complex shape of the Kama Tsugi results in a stronger joint than the Koshikake Aritsugi, especially in the perpendicular direction (Sumiyoshi, 1989).

Shiho Kamatsugi (四方鎌継):

The Shiho Kamatsugi, also known as the "impossible joint," requires skillful craftsmanship to fabricate. Each piece is inserted in the oblique direction (45 degrees), which allows for an identical gooseneck motif to be found on all joint faces. The joint is primarily used to demonstrate the beauty of traditional Japanese joinery, and its application within structures is minimal (Sumiyoshi, 1989).

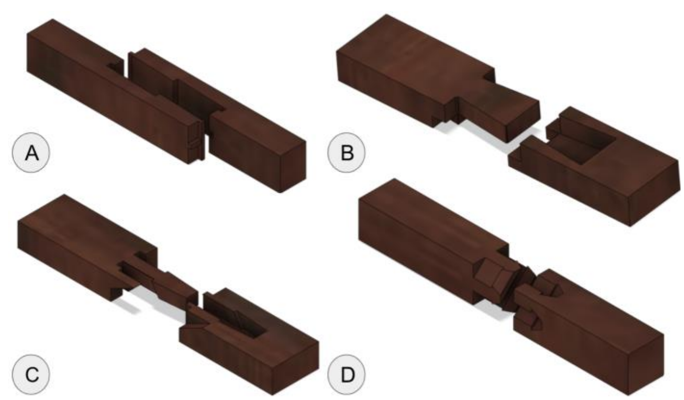


FIGURE 1: CAD representation of Kanawa Tsugi (A), Koshikake-Aritsugi (B), Kama Tsugi (C), Shiho-Kamatsugi (D)

3D Printed Structures

AM, which stands for additive manufacturing, describes construction methods that involve adding layer-upon-layer material. Much of the recent AM construction developments focus on large-scale printing systems, such as the commercial 3D printed housing system by ICON. To reach the goal of commercializing sustainable housing that takes “half the time” to build and “half the price” to buy, 3D printed housing has become a new technology on the rise (ICON: Becoming Iconic). A cementitious filament is used to print these houses. An initial concern with the concept of 3D printed housing was its ability to withstand natural disasters. However, the cementitious material has been tested to be quite durable against natural threats. ICON has tested its cementitious material to be compressed to 6000+ psi, making it far more durable than wood (ICON: Becoming Iconic). Furthermore, wood is susceptible to weathering and damage over time, whereas cement is more resistant to aging issues such as mold.

3D printed housing is cheap, environmentally friendly, and, most importantly, structurally safe. However, a significant issue of 3D printed housing now lies within its design. 3D printed housing is currently not visually appealing to most. This is where traditional Japanese joinery could play a role in the future of 3D printed structures. 3D printed Japanese joints could be applied to 3D printed housing in the future to provide the visually pleasing natural aesthetics of a wooden house while maintaining sufficient structural stability and support against earthquake threats, especially in nations such as Japan.

Research Purpose

The purpose of this study is to explore the potential uses of 3D printed traditional Japanese joinery in structural applications, focusing on its unique ability of earthquake resistance. A three-point flexural test of each joint will be analyzed to determine whether the joints are possible for an application at a larger scale. The strain to failure, deflection, and relative strength of each joint will be analyzed and compared.

Methods

The Autodesk Fusion 360 software was used to create the four traditional joints shown earlier (Kanawa-Tsugi, Koshikake-Aritsugi, Shiho-Kamatsugi, and Kama Tsugi). Autodesk Fusion 360 is a 3D computer-aided design software. On Fusion 360, each joint was scaled to a width of 12.5 millimeters. Furthermore, each connection was designed with a 0.5 mm offset so that pieces could interconnect smoothly without the need for excessive sanding. After each model on Fusion was converted to a .stl file, the joints were 3D printed at a 0.4 mm nozzle size. The common polylactic acid (PLA) filament was used to fabricate each joint, with a percent infill of 10%. PLA was used in this study due to its high availability. However, PLA is biodegradable and unreliable when applied to structural purposes (Kawashima, 2021). Yet, this study does allow testing of different joint configurations and their relative characteristics under a load.

DIC (Digital Image Correlation)

Digital Image Correlation (DIC) was used to analyze each joint’s deformation and strain when countering a load. DIC allows for a full field strain and displacement analysis of the measured specimen. Frame by frame images of the specimen was taken by the test camera at regular intervals. DIC measurement could then allocate each pixel of the image to a coordinate. The changes in the stochastic pattern on the surface of the specimen within each frame allowed the DIC software to compute strain and displacement at each specific coordinate point (Sun, 2021). The GOM Correlate software was used in this study to analyze DIC measurements (GOM Metrology).

Joint preparation

Each joint was cleaned so that there was no oil on the joint surface, allowing for optimal measurements. Before applying a stochastic pattern, the joint surface was primed with a layer of white paint, allowing for better contrast with the pattern throughout the filming process. Using black paint spray, a stochastic pattern was applied on the joint surface so that the deformation of the surface could be analyzed on GOM correlate. A stochastic pattern is necessary for GOM Correlate to analyze surfaces, as the changes in the pattern must be computed to produce strain and deformation values (GOM Metrology).

FIGURE 2: Stochastic pattern applied to Koshikake-Aritsugi joint via black spray paint.

Setup

Each joint was held stable between wooden columns using clamps. The joints were firmly clamped in place at two contact points. There was one camera placed parallel to the joint, facing the connection. Another clamp was attached to the midspan of the joint. This is the third contact point, where the middle clamp will be tightened until failure of the joint is observed.


FIGURE 3: Experimental Setup

Data Collection and Processing

The GOM software generated a strain field, in which the degree of strain throughout the joint surface was analyzed as a function of time. All measurements of strain were calculated by the quotient of the change in length and the reference length. This is called the technical strain. The strain to failure was recorded for each joint. Strain to failure, also known as flexural strain, is the nominal fractional change in the length of an element of the outer surface of the test specimen at midspan, where the maximum strain occurs. Moreover, vertical displacement of the joint was measured as well. The vertical displacement, also known as deflection, measures the maximum displacement on the joint's surface before reaching failure. Although the load was not measured in this study, the relative strength for each joint was recorded. The number of clamp rotations necessary to make the joint reach failure was recorded. The number of rotations correlates to the load applied to the joint.

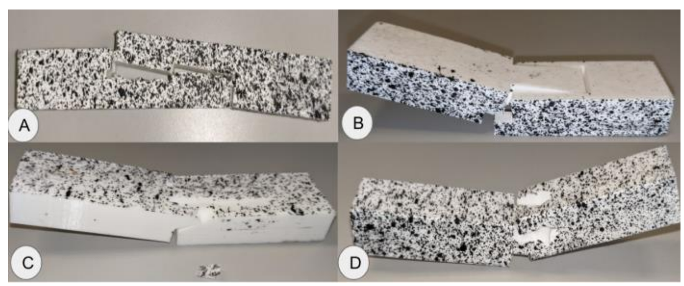


FIGURE 4: Joints after testing: Kanawa Tsugi (A), Koshikake Aritsugi (B), Kama Tsugi (C), Shiho Kama Tsugi (D)

Furthermore, the significance of data was analyzed with a statistical method known as one-way ANOVA (one-way analysis of variance). The one-way ANOVA tests whether the difference between means of samples is statistically significant. Tukey's honestly significant difference test (HSD) was used to determine which means were statistically different.

Results and Discussions

Overview of PLA material

Overview of PLA material PLA is a glassy polymer characterized by its high stiffness and non-crystalline structure (Lee, 2019). Therefore, PLA materials have a poor elongation at break. The flexural strain of PLA materials at 23 degrees celsius ranges from 0.5 to 9.2 percent. (Lanzotti, 2015).

Three-point flexural test results

Kanawa Tsugi:

The Kanawa Tsugi experienced an average flexural strain of 21.6 % before failure, exceeding the flexural strain's estimated limit for PLA materials. However, the Kanawa Tsugi performed poorly in terms of deflection and strength. The low deflection limit of the Kanawa Tsugi seems to be caused by its strain distribution. As seen in Figure 6A, the configuration of the Kanawa Tsugi results in strain being concentrated at a singular point. Therefore, the joint suddenly reaches a high strain value (FIG 5A Top) before failing at a relatively small load. Furthermore, the Kanawa Tsugi had an average deflection of 1.97 mm, which is relatively low among the joints tested. The deformation of the joint before failure is low, causing the Kanawa Tsugi to undergo brittle failure. Lastly, the Kanawa Tsugi failed at an average of 2.7 rotations of the clamp. This makes the Kanawa Tsugi the weakest joint tested, failing at the smallest load.

Koshikake Aritsugi:

The Koshikake Aritsugi experienced an average flexural strain of 1.28 %, the lowest among the joints tested. As seen on FIGURE 6B, the high strain was concentrated at the engagement point between the two pieces. Furthermore, the joint experienced an average deflection of 3.2 mm. As seen in Figure 5B, the joint reaches a peak in the strain at approximately 30 seconds into testing (when the failure occurs). The failure of the Koshikake Aritsugi was not as sudden as the Kanawa Tsugi but was still brittle due to its relatively low plastic deformation (deflection) before failure. The joint failed at an average of 5 rotations of the clamp, which places the Koshikake Aritsugi as the second strongest joint tested in terms of strength.

Kama Tsugi:

The Kama Tsugi experienced an average strain of 2.2 %. As seen on FIGURE 6C, the strain was relatively evenly distributed throughout the surface. Furthermore, the Kama Tsugi experienced a rather large deflection, with an average of 7.9 mm. As seen on FIGURE 5C, the joint failure occurs approximately 28 seconds into testing, where there is a sudden change in the displacement vs. time graph slope. At this point, the joint has already undergone significant plastic deformation. A relatively large deformation indicates a ductile failure. The joint failed at an average of 5.3 rotations of the clamp, making the Kama Tsugi the strongest joint tested.

Shiho Kama Tsugi:

The Shiho Kama Tsugi experienced an average flexural strain of 3.56%. As seen on FIGURE 6D, strain is concentrated on the gooseneck of the joint. The strain is concentrated at the gooseneck, which is a thin piece of the joint. Furthermore, the Shiho Kama Tsugi experienced the largest deflection among the joints, with an average of 9.2mm. Although the joint underwent a sudden failure, the failure is considered ductile due to the relatively large amount of deformation endured by the joint. Lastly, the joint failed at an average of 3 rotations of the clamp, making the Shiho Kama Tsugi a weak joint.

One-way ANOVA tests for flexural strain and deflection were significant ($p << 0.001$ for each). The post-hoc Tukey HSD test revealed that the Kanawa Tsugi had a significantly greater flexural strain than the other joints tested ($p = 0.001$). Furthermore, the Tukey HSD test revealed significant differences between the deflection measurements of the Kanawa Tsugi & Kama Tsugi ($p=0.001$), Kanawa Tsugi & Shiho Kama Tsugi ($p=0.001$), the Koshikake Aritsugi & Kama

Tsugi (p=0.002), and the Koshikake Aritsugi & Shiho Kama Tsugi (p=0.001).

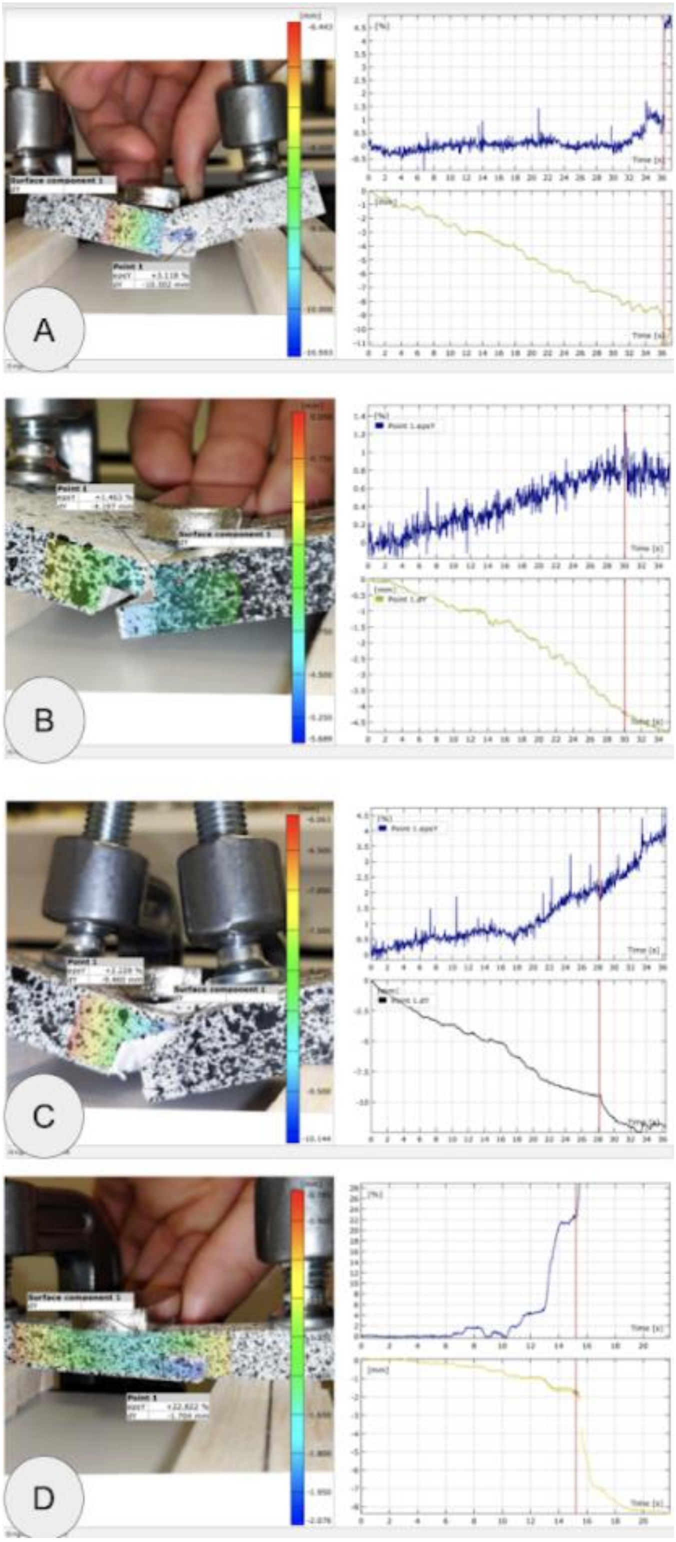


FIGURE 5: Displacement Mapping (left), Displacement vs. Time graph (top), Vertical Strain vs. Time graph (Bottom): Kanawa Tsugi (A), Koshikake Aritsugi (B), Kama Tsugi (C), Shiho Kama Tsugi (D)

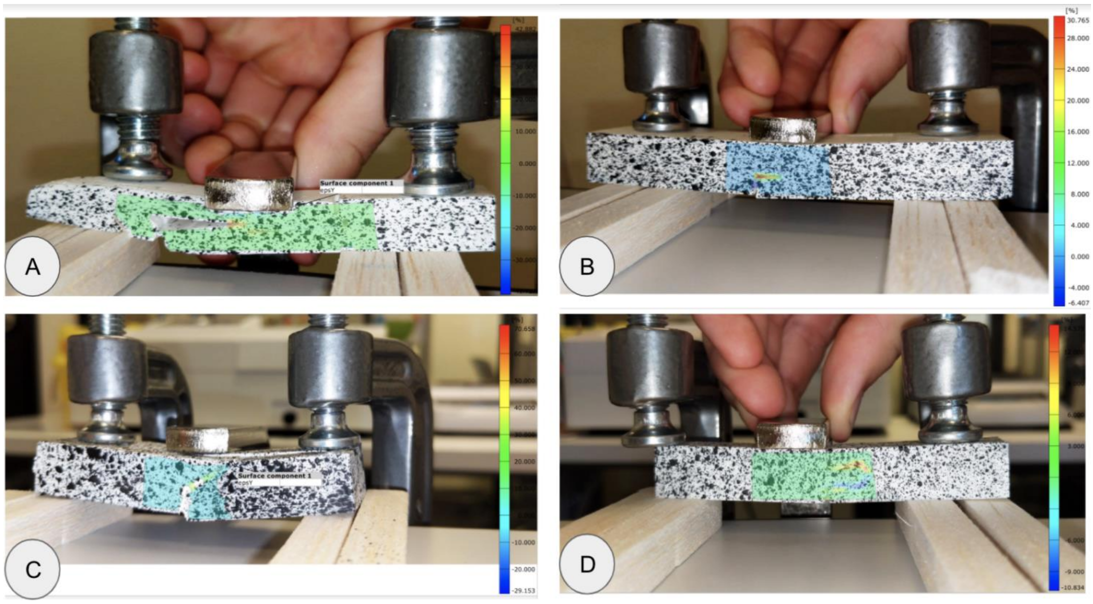
Potential error and inaccuracy

Since each connection is separated with a 0.5 mm gap, the displacement measurement for each joint does not only measure the deformation of the joint but also includes the distance of the movement of the upper piece until it makes contact with the bottom piece. This results in each measurement being approximately greater than the actual deformation limit of the joint.

Comparison to real-world applications

Consider L to be the distance between the two place-holder clamps for each test. Using the scale function on GOM Correlate, length L was measured. For beams in building construction, the max deflection allowed for serviceability is typically on the order of L/240 or L/360 (American Society of Civil Engineers, 2017). Therefore, the deflections exhibited in all tested joints do not meet serviceability limits in current building codes. However, instead of being applied within a structure, these joints could potentially serve as an option for formwork to reduce assembling and disassembling time.

The strain to failure of concrete beams in structural use is 0.004% and 0.02 % for standardized steel (Sun, 2021). The strain to failure of these commonly used materials in construction is nominal compared to the recorded measurements of each joint. However, the material difference must be considered. PLA filament is a naturally more flexible material than steel or concrete, and further research is necessary to correlate strain data for PLA material to standard codes used for construction.



For future study

Although all joints used in this study are made with 10 percent infill PLA, joints may respond differently to the same load when made with different percent infills. Finding the optimum percent infill for structural performance could be the focus of a future study.

Furthermore, wood PLA, which is commercially available and relatively inexpensive, could potentially be an alternative for PLA when producing “wood-like” joinery. The powered wood within the filament creates a “flexible” material that might be better suited for Japanese joinery. The effect of different filaments should be further explored.

The Kanawa Tsugi especially should be further investigated due to its ability to withstand high strain limits, which could be helpful in structural applications. The high strain limit of the joint, which is a result of its high deformation limit, correlates to the earthquake-resilient properties of the joint. Further testing with the GOM ARAMIS program would allow an in-depth study into the flexural properties of the Kanawa Tsugi.

Through this study, I hope to have expanded future research about the applications of traditional Japanese joinery in settings that would help improve both the visual aesthetics and the structural integrity of the structure.

References

Abe, M. and Kawaguchi, M. (1995). Structural Development of the Japanese Timber Pagoda. Structural Engineering International, 5(4). https://doi.org/10.2749/101686695780600836

Abe, M., & Kawaguchi, M. (2002). Structural Mechanism and Morphology of Timber Towers in Japan. Journal of Asian Architecture and Building Engineering, 1(2), 25–32. https://doi.org/10.3130/jaabe.1.2_25

American Society of Civil Engineers. (2017). Minimum design loads and associated criteria for buildings and Other structures: Asce/Sei 7-16.

Camacho, D. D., Clayton, P., O'Brien, W. J., & Jung, K. Y. (2018). 3D Printed Fastener-Free Connections for Non-Structural and Structural Applications – An Exploratory Investigation. E 29th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference.

Clancey, G., (2006). Earthquake Nation: The Cultural Politics of Japanese Seismicity, 1868-1930. University of California Press; First Ed. (ISBN 13: 9780520246072; ISBN 10: 0520246071)

Fusion 360 | 3D CAD, CAM, CAE & PCB Cloud-Based Software | Autodesk. (2021, August 6). Autodesk. https://www.autodesk.com/products/fusion-360/overview

GOM [GOM Metrology]. (2016, May 13). GOM Training Webinar - 2D Digital Image Correlation with GOM Correlate [Video]. YouTube. https://www.youtube.com/watch?v=pGXuXg7dRlo

Hanazato, T., Fujita, K., Sakamoto, I., Inayama, M., & Ohkura, Y. (2004). Analysis Of Earthquake Resistance Of Five-storied Timber Pagoda. 13th World Conference on Earthquake Engineering, Vancouver, Canada.

Hōryūji: A Brief History. Hōryūji. www.horyuji.or.jp/en/garan/.

ICON. (n.d.). Our Story | ICON. ICON build. Retrieved August 14, 2021, from https://www.iconbuild.com/about/

Kawashima, N., Yagi, T., & Kojima, K. (2021). Pilot-Scale Composting Test of Polylactic Acid for Social Implementation. Sustainability, 13(4). 1654. https://doi.org/10.3390/su13041654

Lanzotti, A., Grasso, M., Staiano, G., & Martorelli, M. (2015). The impact of process parameters on mechanical properties of parts fabricated in PLA with an open-source 3-D printer. Rapid Prototyping Journal, 21(5), 604–617. https://doi.org/10.1108/rpj-09-2014-0135

Majima, K. (1927) On the Problem of the Earthquake-resistant Structures, Jour. of the Architectural Institute of Japan.

Miyauchi K., Masuda M., & Murata K. (2006). Analysis of Strain Distributions of Wooden Dovetail Joints Using Digital Image Correlation Method. Journal of the Society of Materials Science, Japan, 55(4), 367–372. https://doi.org/10.2472/jsms.55.367

Nakahara, K., Hisatoku, T., Nagase, T., & Takahashi, Y. (2000). EARTHQUAKE RESPONSE OF ANCIENT FIVE-STORY PAGODA STRUCTURE OF HORYU-JI TEMPLE IN JAPAN. 6.

Ooi, F. (2012). ORIGINALITY OF CENTRAL COLUMN IN JAPANESE PAGODA. 2nd International Conference, Mukogawa Women's Univ., Nishinomiya, Japan.

Sin, L. T., & Tueen, B. S. (2019). Mechanical Properties of Polylactic Acid. Polylactic Acid, 167–202. https://doi.org/10.1016/b978-0-12-814472-5.00005-4

Sumiyoshi T. and Matsui G., (1989). Wood Joints in Classical Japanese Architecture. Japan: Kajima Institute Publishing Co.

Sun, F. F., Ran, M. M., Li, G. Q., & Wang, Y. B. (2021). Welded connections. Behavior and Design of High-Strength Constructional Steel, 565–612. https://doi.org/10.1016/b978-0-08-102931-2.00012-7

Tanabashi R., (1960) Earthquake Resistance of Traditional Japanese Wooden Structures. Disaster Prevention Research Institute, Kyoto University.

Yamada, M., Suzuki, Y., & Gotou, M. (2004). Seismic Performance Evaluation of Japanese Wooden Frames. 13th World Conference on Earthquake Engineering, Vancouver, Canada.