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Bridging the Gap Between Traditional Japanese Fabrication and Advanced Digital Tools

Mohammed Makki[3], Masaaki Matsuoka[2], Ana Ilic[1], Lorenzo Franceschini[1], Jorge Beneitez[1]

[1]Architectural Association
London, United Kingdom
franceschini@aaschool.ac.uk

[2]Takenaka Corporation
Osaka, Japan
matsuoka.masaakia@takenaka.co.jp

[3]University of Technology Sydney
Sydney Ausralia
mohammed.makki@uts.edu.au

ABSTRACT

Traditional Japanese woodworking techniques have been inherited between generations in the past millennia through the Daiku, the master carpenter that teaches apprentices the precise and valuable skills of carpentry through methodical and time-intensive processes. Throughout the 21st Century, with the development of advanced construction methods, coupled with younger generations exhibiting little interest in following the Daiku, this valuable cultural artform is becoming less prevalent in Japanese culture. However, the development of advanced digital tools offers an avenue through which the knowledge and skills of older generations can be both transferred and developed by younger generations. In this context, the paper examines the relationship between traditional Japanese woodworking and advanced computational tools by bringing experts from both disciplines for the design and construction of a Japanese Pagoda, in which the significance of bridging the gap between both domains is highlighted across the design, fabrication and assembly of the project.

Author Keywords

Computation; Japanese Woodworking; Daiku; Evolutionary Computation; Pagoda

ACM Classification Keywords

I.6 I.2.8 Problem Solving, Control Methods, and Search (Heuristic methods); J.5 Arts and Humanities (Architecture); J.6 Computer-aided design;

1 INTRODUCTION

The historical development and evolution of traditional Japanese woodworking techniques spans many centuries. Primarily rooted in Japan's religious and geographic locale, the impact of climatic and environmental conditions on the territory's flora, and the deep respect of the Shinto belief of treating wood as a living organism, have played a primary and significant role in the use of wood (and the development of the intricate methods associated with handling the material) in Japanese culture [5]. Ingrained in this is the transfer of knowledge between generations, primarily through a master-apprentice relationship, in which not only were the methods and techniques taught (such as selection, cultivation, distribution, treatment, design and assembly), but also the respect and moral bond between the carpenter and the tree. The importance of the *Daiku* – master carpenter – went beyond simple construction, acknowledging and contributing to mental and emotional aspects of the trade, such as leadership, compassion and spiritual preparation [1]. Following the decline of the Edo period in which Western methods were actively pursued in Japanese construction, traditional methods remained heavily prevalent in ensuring the techniques and skills developed over centuries remained pivotal in Japanese woodworking approaches; more importantly, in ensuring the inheritance of this knowledge by future generations did not stop [10] (Figure 1).

Figure 1. The Horyu-Ji Pagoda is one of the oldest wooden structures in existence [9] and serves as a prime example of the woodworking knowledge inherited by Japanese master carpenters.

In more recent times, the transfer of this knowledge has showed signs of deterioration [4]. Attributed to a range of different causes, such as there being fewer *Miyadaiku* – carpenters who handle traditional Japanese structures through restoration by means of disassembly and re-assembly, less interest by younger generations in learning the trade, the development of advanced carpentry tools that have replaced traditional techniques and the use of digital tools for the purpose of expedited design and construction methods.

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While traditional knowledge continues to be used for shrines, temples, teahouses, and Japanese-style homes, they have ceased to become mainstream architectural techniques, and so the passing down and preservation of these methods has become at risk.

Advanced digital technologies developed in the last decade offer respite and an avenue for the preservation of traditional Japanese woodworking techniques. While the Daiku is primary in the transfer of knowledge, the use of advanced digital tools across a range of domains and disciplines allows for a streamlined sharing of knowledge through a feedback mechanism that is both relatable to younger generations as well as in line with the technological advancements of the 21st century, allowing greater opportunities to explore new formats and frameworks that effectively combine traditional techniques with contemporary methods.

In this context, the presented research examines the relationship between old and new by bringing experts in traditional Japanese woodworking techniques and experts in advanced digital technologies for the design and fabrication of a wooden Japanese Pagoda at the Takenaka Carpentry Tools Museum in Kobe, Japan. Additionally, the project is conducted with 28 participants from 16 different countries, in which the transfer of knowledge (both traditional and digital) played a primary role in ensuring the research examined the above relationship through varying skillsets and backgrounds.

2 BACKGROUND

The future of traditional Japanese woodworking techniques is at a crossroads. At one end, there is the preservation of "cultural heritage for the benefit of future generations", while on the other, the necessary acceptance and adaptation "to the inevitable future change" brought on by technological advancements [6]. In either case, the declining number of Daiku, coupled with a generation that is less interested in inheriting the techniques of previous generations, highlights the significance of bridging the gap between advanced digital design tools, which are in continuous evolution and change, and the artistry of traditional woodworking techniques. Most importantly however is the importance of demonstrating that the former does not diminish the role of the latter, as well as highlight that the latter is easily accessible through the former.

The project's aim is to design a traditional Japanese Pagoda through advanced digital tools; and utilise the expertise of a Daiku - Master Carpenter Akinori Abo - for the refinement of the design as well as the fabrication and construction of the final product. Most importantly, the project aimed to avoid linearity in its development, ensuring a feedback loop is developed between the application of digital tools for the design's development and the intricate fabrication processes and techniques inherent to Japanese woodworking. Through the use of Rhino 3D and Grasshopper 3D, in which structural analysis tools through Karamba [7], environmental analysis tools through Ladybug [8] and multi-objective evolutionary optimisation tools through Wallacei [3], the design of the Pagoda aimed to preserve its spiritual and historical significance and ensure it allowed for the application of the unique woodworking skills and techniques of the Daiku.

3 DESIGN ITERATIONS

Multiple design options were developed for the Pagoda, where several key characteristics played a significant role in the design process. First, the global morphological traits of a traditional Pagoda had to be respected, i.e. repetitive patterns, multiple levels and formal hierarchy. Second, the spirituality associated with the Pagoda is represented through its form. Third, wood is the primary and only material used in the structure's construction, more precisely, *Sugi* (Japanese Cedar) and Hinoki (Japanese Cypress) (Figure 2). Fourth, no fastening tools are used (i.e. screws, nails, etc..). Finally, to ensure an intricate and attentive use of joints between the wooden elements is considered; in which *Shiguchi* (joints between two members of different direction and function) and/or *Tsugite* (joints between two members in the same direction) [11] construction methods were utilised.

Figure 2. Sugi and Hinoki (Japanese Cedar/Cypress) is native to Japan and known for the wood's strength and durability. The wood used for the Pagoda was sourced from Mount Yoshino.

In this context, participants developed 5 different schemes that aimed to incorporate the above characteristics through a digitally driven design process. Utilising different approaches, the 5 schemes presented varying interpretations of the Japanese Pagoda, and the use of varying digital tools and their impact on the design of the Pagoda. Some of the schemes adopted a multi-objective evolutionary approach to their designs, where the pagoda was optimised for multiple conflicting objectives through the use of the evolutionary engine *Wallacei* (running the NSGA-2 multi-objective evolutionary algorithm developed by Deb et. al. [2]). In doing so, these schemes generated a population of different solutions with varying morphological characteristics driven by design objectives identified to be key in the traditional woodworking techniques used in a traditional Pagoda (Figure 3). Such objectives included the complexity of joints, the quantity of joints, the viewpoints of the different levels of the Pagoda, and the cross sections of the wood used in the Pagoda's construction. Through this process, the evolutionary model would derive the design objectives and morphological variables running the algorithm from the Daiku's expertise, allowing for the digital tools to be used within the framework of the traditional knowledge of the master carpenter.

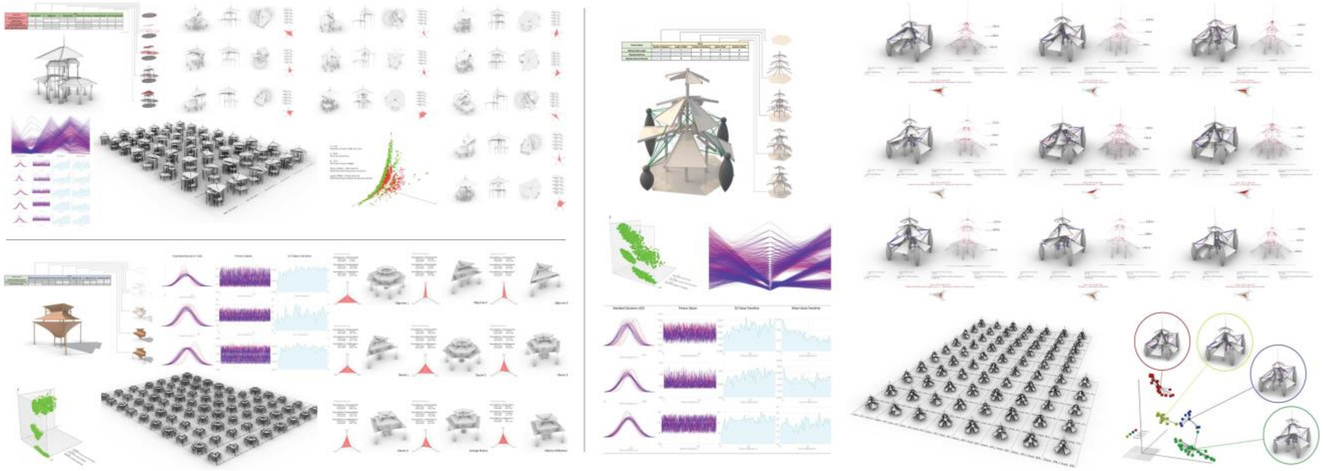

Figure 3. The application of multi-objective evolutionary optimization methods for the design of different Pagoda options.

In presenting the final designs to the Daiku, highlighting each scheme's development and underlying concepts, and the methods behind the application of the advanced digital tools for the design's development (Figure 4), one scheme was chosen by the Daiku as best representing a Pagoda that is both formally and structurally intriguing. In doing so, the design of the selected Pagoda was further refined in preparation for fabrication and construction.

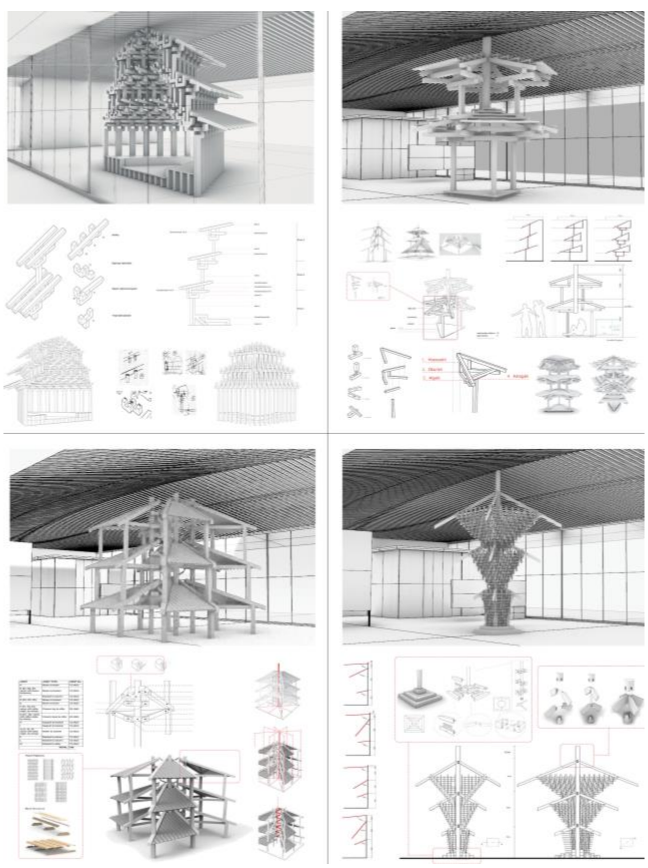

Figure 4. The different schemes developed of the Pagoda (the selected scheme is presented in the following section).

4 THE RECIPROCAL PAGODA

The selected scheme was a 3 level Pagoda structure comprised from a reciprocal pentagonal base through which each level recedes inwards (a feature found in traditional Japanese Pagodas). The structure's boundary sat within a 3m x 3m x 4m bounding box; in which the structural frame - comprised from columns, rafters and tension/compression rings - supported the linear roof slats located on each of the Pagoda's three levels.

4.1 Design Development

The primary aim of the design was to signify the central column of a Pagoda, one that holds significant spiritual significance for Japanese culture. However, rather than incorporating the column within the structure, it is rather representative as a continuous and uninterrupted void throughout the centre of the Pagoda. In doing so, the design is driven by 6 'rings' connected through 3 primary sets of rafters. The 3 larger and outer rings act in tension and join each set of rafters to one another; the 3 smaller and inner rings act in compression and join the centres of each set of rafters. Finally, the base columns lift the structure above ground level, in line with the design of traditional Pagoda structures.

The design of the roof followed the reciprocal morphology of the primary structure; where the objective was for the structure to be primarily fabricated using hand tools, the roof utilised digital fabrication methods – primarily the laser cutter. As such, the design was driven by the size of the laser cutter bed (60cm x 40cm) and developed through ruled surfaces that were independent from the primary structure; thus allowing for roof to be added onto the final built structure rather than incorporating it alongside its construction. In this context, the roof was designed as a gridded waffle structure comprised from primary (longer) slats and secondary (shorter) slats (Figure 5).

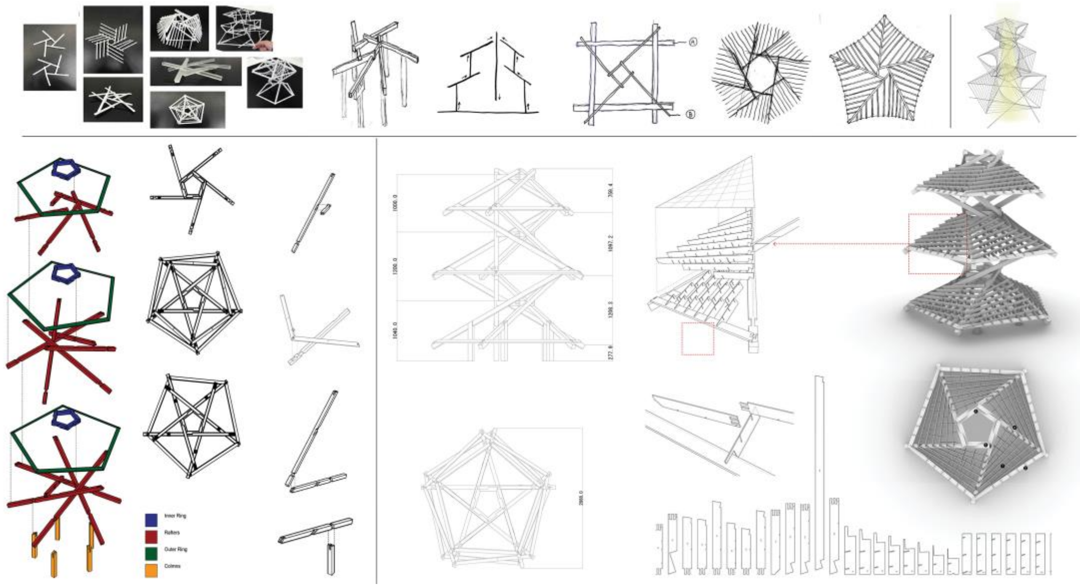

Figure 5. Design of the Pagoda selected for further development and fabrication

4.2 Optimisation

The design of the Pagoda was further developed using multi-objective optimisation methods through the use of the grasshopper plugin *Wallacei*. Where most recent applications of evolutionary computation methods have been applied for formal exploration, its application in this context was for the morphological refinement of the structure. The formulated design problem optimised for 3 primary objectives; First, to minimise the overall structural displacement of the Pagoda through using the structural analysis plugin *Karamba*. Second, to minimise the structure's weight by means of reducing the structure's overall size. Third, and in response to the impact of the first two objectives in decreasing the size of the structure, maximise the structure's overall volume. To optimise for the above, the variables inputted into the evolutionary engine were limited to the size and position (in the z-axis) of the compression and tension rings.

The results of the evolutionary simulation, presented through the fitness charts in Figure 6, demonstrate a successful optimisation run for objectives 1 and 2 (displacement and weight), however, seeing as how these objectives conflicted with the third fitness objective (volume), the simulation was less successful in optimising for the latter. However, through clustering the last generation of the simulation using the K-means clustering algorithm (function built into the Wallacei plugin), and analysing the morphologies of the associated cluster centres, the results demonstrate that the fittest solutions for objective 1 (displacement) did not retain the receded feature of the three levels of the Pagoda, instead favouring a linearly extruded form. This highlights the necessity of coupling the statistical analysis of the algorithmic output *with* the morphological analysis of the simulation's results; where the former may present a 'fit' solution according to its numeric attributes, the latter may highlight alternative results that were not defined through numeric analysis.

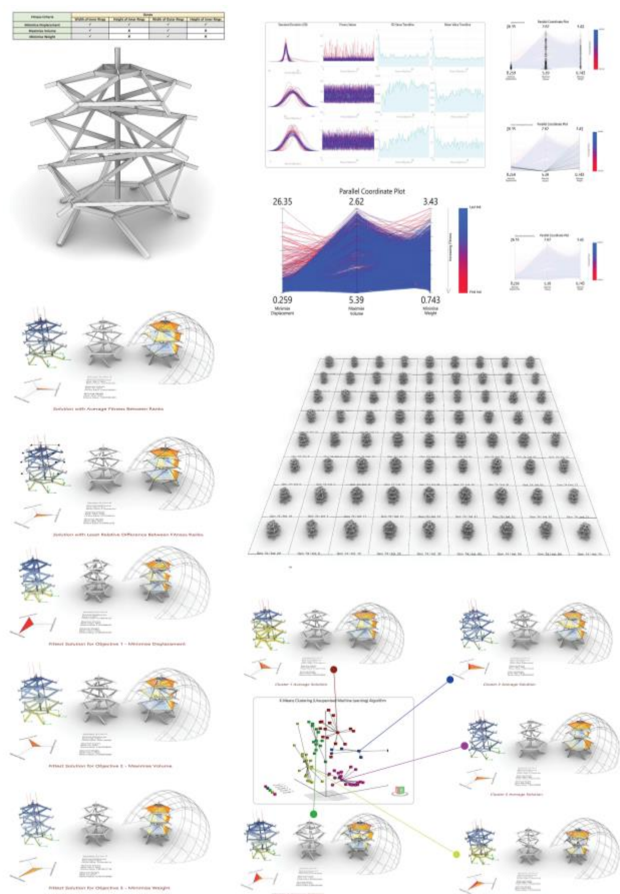

Figure 6. Results and analysis of the multi-objective evolutionary algorithm's simulation output (environmental analysis (ladybug) was also conducted on the simulation's output).

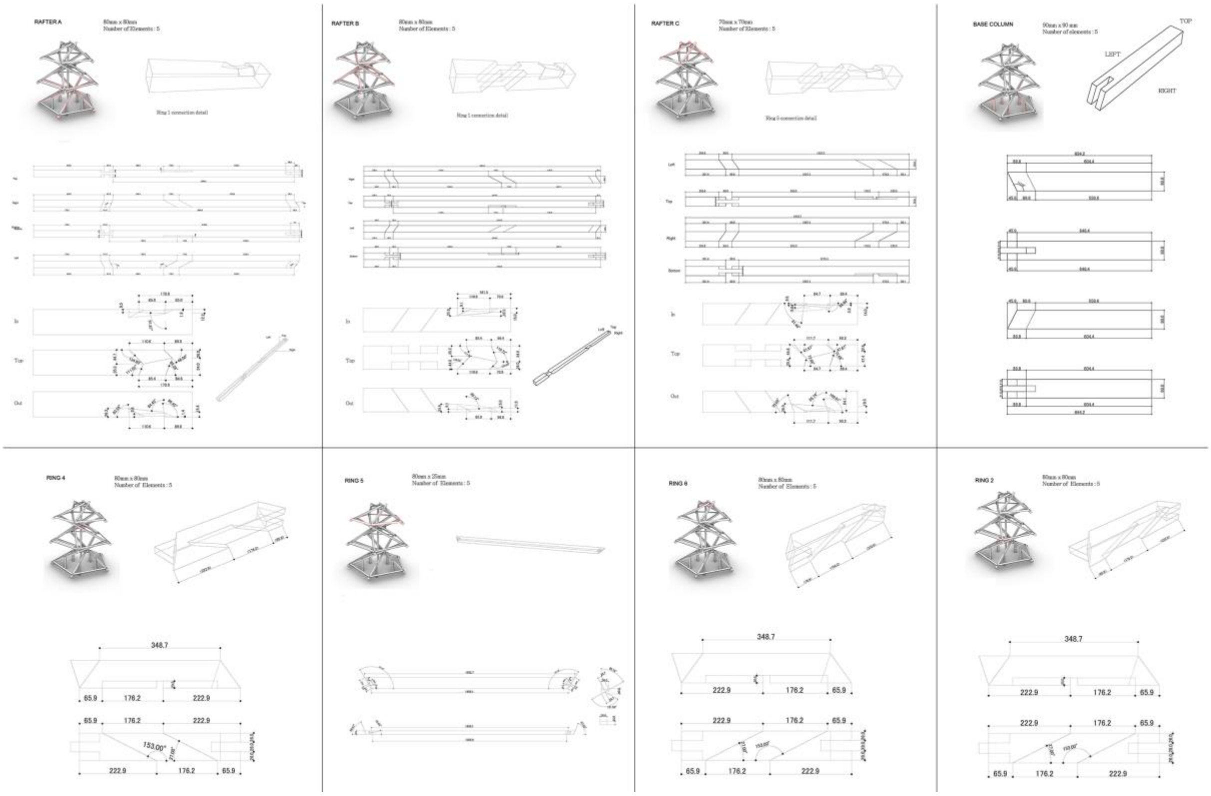

Figure 7. The complexity of the joints and the varying angles of connections demanded the production of highly detailed cutting files.

4.3 Fabrication

Throughout the design stage of the Pagoda, the influence of the Daiku was in translating the methods associated with preparing the wood for fabrication (i.e. selecting the wood, understanding its characteristics and properties, etc.) as well as understanding the methods and types of Japanese woodworking techniques, highlighting the importance of not using fasteners and relying on the friction between the joints to provide stability (thus signifying the type of joint and its relevance in the overall structure). However, in preparation for fabrication, the Daiku's influence grew exponentially, across multiple fronts which included preparing the wood, marking the wood, reviewing and informing the design of the joints, cutting the joints and finally, assembling the final form. It was at this stage that the gap between digital and master carpenter presented itself, where the simple act of marking the wood for cutting proved to be a challenging task for the digital experts. The precision and attention to detail demanded by the Daiku resulted in not only highly detailed cutting files (Figure 7), but also the understanding that the fabrication of very complex joints is achievable by non-experts through a careful translation from the digital to the physical (Figure 8).

Figure 8. The expertise of the Daiku was pivotal in realizing complex cuts and joints.

The Pagoda was fabricated over a timeline that spanned only 4 days; however, the actual assembly of the fabricated pieces spanned one afternoon. The primary challenge was cutting the joints between the rings and the rafters, where three timber pieces connected at 3 varying angles across three planes (Figure 9). While in the digital model the joints presented themselves as complex, translating them to the physical proved even more so. During this time, revisions were made to the digital model, primarily directed by the master carpenter, that revised the angles in which the rafters intersected the outer rings, with the primary intent to minimise the variation between joints and thus allow for repetition of similar joints at different locations in the Pagoda's design; and although this proved essential, the challenge to fabricate these complex joints continued to prove a difficult task (however imposing repetition did allow for inexperienced users to improve their skills). Although it was clearly evident that the Daiku's experience was vital to the success of realising the final built form (as was expected), what also emerged was the Daiku's influence on the development of the digital model and its translation to the physical, in which it served as a medium of communication between the two.

Figure 9. The assembly of the Pagoda exemplified the elegance (and challenge) of joint connections that avoided the use of fasteners between the timber elements.

5 CHALLENGES

The precision of the digital model was, mostly, successfully translated to the physical structure. However, due to the nature of the project (time limitation, lack of fabrication experience by the participants, absence of auxiliary joints,) and the tools used to fabricate different parts of the structure, there were several challenges in the Pagoda's fabrication. Two such challenges are highlighted below.

Firstly, the complexity of the connection joints between the tension rings and the rafters, primarily due to the deep timber cross section (25mm x 80mm), as well as the positioning and orientation of the timber elements, prevented the joints from securing a perfectly fit and tight connection. Although this was permissible in the scale that the Pagoda was being built at (considering it was a temporary and lightweight structure), the impact of this at a larger scale would have caused the connection joints to not withstand the occurring tension. This could have been avoided however should there have been another round of revision to the digital model, in which the orientation and cross section of the timber elements were revised to achieve a more secure and resolved joint (Figure 10).

Figure 10. Tolerances drastically increased during fabrication of complex joints.

Secondly, the fabrication of the roof plates using the laser cutter (Figure 11) (limiting the cut to one vertical cutting plane) resulted in 'linear contact' points to the multi-directional structural frame, as opposed to the 'surface contact' in the digital model. Although the thickness of the material (5mm) permitted an acceptable tolerance, thicker material sections would have resulted in a much larger tolerance (Figure 12). As before, further time in refining the digital model, so that it is more in line with the fabrication and woodworking techniques of the master carpenter would have allowed for the applied methods to function more efficiently at a larger scale. More importantly, engaging with the Daiku during the design phase in which his expertise in traditional fabrication methods inform the design's development, would allow for these tolerances to be addressed during the digital phase rather than the physical. The above highlights the significance of ensuring that the gap between advanced digital tools and traditional Japanese woodworking methods is based primarily on a feedback mechanism between the two artforms, ensuring a continuous transfer of knowledge between the two.

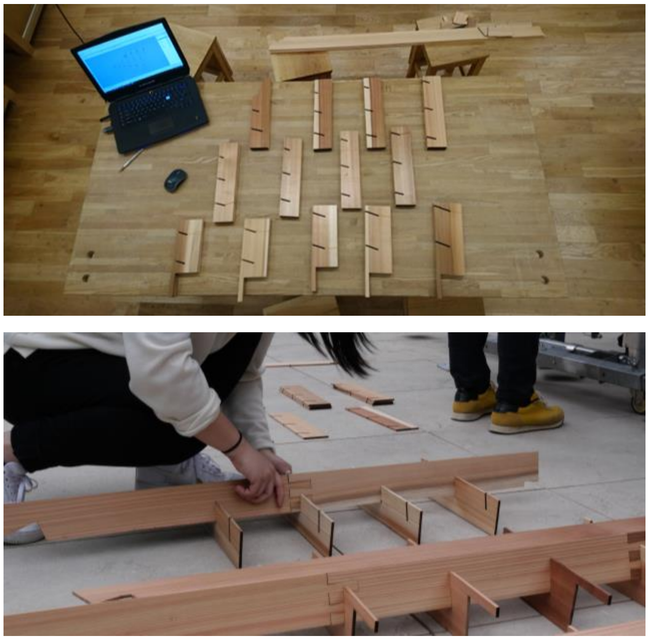

Figure 11. The roof of the Pagoda took full advantage of the laser cutter, in which all pieces were cut and labelled for pre-assembly before connecting to the structure.

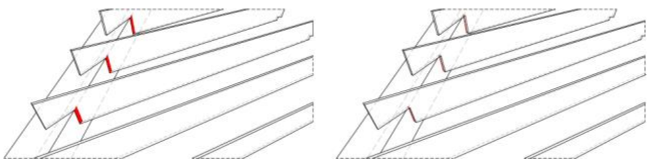

Figure 12. Comparison between surface contact points of the digital model (left), to the linear contact points in the final built form (right)

6 CONCLUSIONS

Traditional Japanese woodworking techniques have been gradually declining in recent years; their use has been limited primarily for the restoration and preservation of historic structures and in the construction of temples and shrines. The traditional craftsmen's manual labour continues to be eclipsed by the sheer volume and speed of machine production, with the presumption that the craftsmanship of the old is no longer applicable to the technological advancements demanded in the modern day. However, advanced tools in computational design and digital fabrication have allowed for the construction of non-identical, unique and complex architectural and structural morphologies, ones inherent to traditional Japanese architecture, easier and cheaper to conduct. Coupled with the younger generations' interest in digital tools and their consequential integration in the development and application of traditional Japanese techniques, facilitates the cultivation of craftsmen's apprentices as successors to the Daiku, preserving the knowledge gained over many generations through a symbiotic relationship with technological advancements of the 21st Century.

To achieve this relationship, the significance of the master carpenter's knowledge and its integration within the digital process is vital. Most evident was the Daiku's relationship with the wood, where his experience and knowledge of the wood's properties, - and most importantly, limitations - proved to be most beneficial, and in turn, the most difficult for the digital translation of the structure to replicate. Thus, highlighting the 'reciprocal' relationship that can be achieved between the master carpenter (and the knowledge of generations past) and the use of advanced digital tools. A relationship that has multiple advantages, most of which is the understanding that rather than advanced digital technologies acting as a hindrance to the transfer of traditional woodworking knowledge, it facilitates a mechanism of support and further evolution of the developed methods and techniques.

The project faced numerous challenges (Section 5), and although these challenges will be addressed in future work, the primary challenge remains in demonstrating that the use of advanced digital tools has a benefit to the preservation of traditional Japanese craftsmanship. Future work will further explore this in applying similar concepts to a larger structure that involves the master craftsman more heavily in the early stages of the design process, in which the contribution of digital tools to Japanese craftsmanship is examined more vigorously prior to fabrication rather than during it.

Figure 13. The final built Pagoda

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