Design for Repair and Reuse, and Digital Fabrication of Traditional Japanese Timber Joinery: a *Daimochi Tsugi* case study

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Abstract -

Construction, renovation and demolition activities generate 30–40% of global solid waste. Yet, buildings are rarely designed for repair and reuse. Traditional Japanese timber joinery offers a historically grounded counter-model. *Daimochi tsugi* is a shear-resistant load-bearing scarf joint used in the roof structures of temples, shrines and *wagoya* buildings since the *Kamakura* period (1185–1333). This work takes it as a case study to investigate how its geometric design embeds logic for repair and reuse, including structural continuity when a supporting column is temporarily removed. Experimental testing further reveals a gravity-locking behaviour: the roof load actively closes the joint, allowing it to recover and sustain additional load even after partial failure. To further understand how it can be fabricated in current practice, the joint is digitally modelled, analysed using finite element methods and fabricated at 1:1 scale by both traditional handcraft and by CNC milling. Structural testing shows handcrafted joints sustain ∼40% higher peak load than CNC counterparts, due to fabrication precision and contact quality. The study demonstrates how vernacular construction logic can inform contemporary design-for-deconstruction principles and circular construction practice, and shows how traditional joinery can be translated into machine-readable geometry for digital fabrication.

Keywords -

Design for X (DfX); Repair and Reuse; Japanese Timber Joinery; Robotics; Digital Fabrication; Circular Construction; Construction History

1 Introduction

1.1 Repair, Reuse and Circular Construction

Waste in the Construction Industry: Construction, renovation and demolition waste is one of the largest global waste streams, accounting for 30-40% of solid waste generation globally. By countries, this waste accounts for 23% of the total waste in the U.S., around 20% in Japan and 40% in China. In Europe, this waste accounts for more than one-third of all waste. Approximately 10-15% of this waste is generated during construction, while 85-90% come during demolition or replacement. The use of materials accounts for around one-third of total CO_2 emissions. The circularity of materials has dropped from 31% in 2018 to 20% in 2023. This decline can be attributed to factors such as rapid urbanisation and population growth, driving the expansion of residential and commercial buildings, as well as public infrastructure projects [1, 2, 3, 4].

Landfilling remains the main disposal method globally, causing environmental harm through leachate and gas emissions while consuming finite physical capacity. Japan's Ministry of the Environment announced in 2023 that the available landfill capacity will be exhausted by 2045 [5, 6]. The removal of waste through the 3R concept of reduce, reuse and recycle therefore represents the optimal mitigation strategy [7].

Under the umbrella of design for X (DfX), design for manufacture and assembly (DfMA), design for disassembly, design for repair and design for reuse each aim to minimise the time, labour and cost of their respective processes [8, 9].

Design for Repair and Reuse: Recent scholarship has increasingly examined design for disassembly and reuse, in particular, in timber construction. Recent research indicates that commonly-used non-reusable or irreversible connections or joinery, such as those in concrete or timber buildings, between building components cause construction waste and permanent material loss in the building's afterlife, as well as extensive processing to reuse these components and materials [10, 11]. *Wet joints* in timber structures, such as glued parts, make them harder to disassemble or reuse compared to *dry joints*. Akinade et al. [12] reveals that currently only 1% of existing buildings are fully demountable. One crucial reason is that current design and construction methods make deconstruction economically unattractive and technically unfeasible [13]. In addition to rethinking demolition, maintenance and repair have recently undergone a paradigm shift in the built environment to maintain a healthy building life, save materials and reduce waste [14]. For example, in Europe, the European Green Deal introduced the renovation wave strategy in 2020 to increase renovation rates and reduce energy consumption by 2030. This envisions supporting local supply chains and maintaining existing building stocks to meet current building standards. Similarly, a renovation project involves the processes of inspection, repair, replacement and retrofitting. Appropriate renovation work can precisely diagnose the problematic building-parts and repair or replace those parts without wasting other healthy parts. Therefore, it is important to focus on the root cause of the design of connections/joinery that hinders the deconstruction and reusability of a building for repair and reuse. Cost-effective and efficient waste management is needed to facilitate a circular economy in construction, and economic disincentives remain the main barrier to reuse in practice [15].

1.2 Design for Repair and Reuse from History

The topic of *Design for Repair and Reuse* is not new. Japanese temples and shrines have the tradition of constant repairs and rebuilds. Buddhist temples are designed for repair. For example, Hōryūji Temple, constructed in 607 AD over 1,300 years ago, contains the world's oldest surviving wooden structures and endures due to constant maintenance and repair. Shinto shrines are designed for deconstruction. For example, Ise Shrine (*Ise Jingu*), which has a history of 2,000 years, has a tradition of rebuilding every 20 years [16]. *Miyadaiku* refers to a specialised profession of Japanese carpenter and craftsmen (*shokunin*), who design, fabricate and repair traditional timber joinery for castles, temples and shrines. They traditionally undergo at least ten years of training through apprenticeship under a master (*daiku tōryō*), similar to the European traditional *Meisterklasse* system [17]. Their profession ties not only to the built environment but also to the cultural landscape, including religions, by perceiving timber materials as spiritual to preserve with respect. Also, their carpentry tools have been designed according to specific usages. In history, a *miyadaiku* could entrust and commission an allied blacksmith to make a uniquely designed tool specifically for their use for a particular dedicated purpose. A small-scale building project can use a minimum of 72 tools [18].

The longevity of these structures is not incidental but is a direct consequence of design decisions embedded at the joint level. Traditional Japanese timber structures are designed so that individual components can be removed, repaired and reinstated without compromising the standing structure, which is a principle that is now recognised as a precursor to contemporary design for deconstruction [19]. The continuity of this repair logic over centuries is maintained through the apprenticeship system, in which craft knowledge, including the geometry, sequencing and structural behaviour of individual joints, has traditionally been transmitted directly from master to apprentice alongside through written documentation [18].

Fastener-free joinery: Japanese timber joinery, namely *kigumi* , refers to a traditional connection that does not utilise any metal fasteners or adhesives to join wood and allows for timber structures of limited lengths. In Europe, some historical joinery appeared similarly without metal fasteners to different extents [20]. This *kigumi* connection and its construction technique, namely *dentō kōhō*, can be traced back approximately 4,000 years, with ideas imported from ancient China. *Kigumi* is designed in response to Japan's warm and humid climate, as well as earthquakes, there are gaps within joints that absorb seismic forces and resist vibrations.

Because only wood is used, *kigumi* is less likely to rot and lasts longer compared to connections with iron nails, which rust and weaken the wood due to humidity. *Kigumi* and its *dentō kōhō* are well recognised for sustainability and de-constructibility [19]. There are over 4,000 *kigumi* on record; some are not recorded. The design of *kigumi* is generally related to the architectural styles and fashions of that time, as well as the skills and preferences of the carpenters, the tools used, the wood sources and their availability during that time, along with the structural and aesthetic requirements. Amongst all, there are two major types of joints in *kigumi*, *shiguchi*, referring to the right-angle joint, and *tsugite*, referring to the scarf joint that connects two pieces longitudinally [21]. These joints have a tradition of design for deconstruction and repair [18].

1.3 Carpentry and Digitalisation

Today, the modern method, namely *zairai kōhō*, has become more popular since the post-war reconstruction due to Western influence. The joining with bolts and fasteners complies with the current building codes in Japan.

The traditional *kigumi* faces several challenges in the modern world for several reasons. Amongst these challenges, the investment in training a traditional *miyadaiku* is too high and the aging population of *miyadaiku* leads to a loss of knowledge and skills in the industry. Nevertheless, existing castles, temples and shrines still require constant maintenance and rebuilding. Furthermore, according to a report by the Nomura Research Institute in 2023, by 2030, the productivity of each carpenter must increase by 1.4 times to keep up with the demand for new housing [18].

Researchers have recently explored ways to bridge traditional joinery techniques with modern technologies to different extents, including the digital fabrication of traditional timber joints using various technologies, such as CNC milling machines and robotic arms [22, 23, 24]. While CNC machines typically operate using multi-axis milling tools based on predefined toolpaths to offer high geometric precision and repeatability, robotic fabrication systems provide greater flexibility in tool orientation. This allows for more complex joinery geometries and adaptive fabrication processes based on the analysis of traditional manual parts processing [24]. However, differences in tool control, machining strategies and tolerances between these technologies significantly influence surface quality and dimensional accuracy. In timber joinery, where structural integrity is based on tight fit and friction between surfaces, these fabrication-induced variations can directly affect the overall structural performance and load-bearing capacity of the joint [25].

2 Research Questions and Methodology

To understand the principles related to repairability and reuse in current practice, this work refers to historical precedents rather than proposing a new design concept from scratch. Traditional Japanese timber joinery offers a relevant example of a construction logic developed to support maintenance, repair and long-term reuse. The goal is not to propose that contemporary construction should directly replicate historical practice, but to investigate what can be learned from this joint and how it can be interpreted and fabricated using current methods. Thereby, this work takes one typical *tsugite* scarf joint, *daimochi tsugi*, as a case study to answer the following three research questions.

RQ1 How does the design of *daimochi tsugi* embed logic for repair and reuse, in particular, how does its geometry support structural continuity when a supporting column is temporarily removed for repair or replacement?

RQ2 How can *daimochi tsugi* be modelled and fabricated using contemporary digital design and fabrication methods?

RQ3 How does the structural performance of digitally fabricated joints compare with traditionally handcrafted joints and what factors contribute to any observed differences?

This work is structured as follows. This section presents the points of departure for this research. Section 3 answers RQ1 and presents *daimochi tsugi* design in correspondence with repair and reuse in architecture and structural significance in structural joinery. Section 4 answers RQ2 by presenting the digital design and fabrication process. Section 5 answers RQ3 through a comparative study of (i) traditional handcrafted joints and (ii) CNC-fabricated joints, including their structural performance. Section 6 discusses the ideation of *Design for Repair and Reuse* , learning from construction history and vernacular architecture, the limitations of this work and potential future research directions. The last section concludes this work with insight into the overarching topics of research on Construction 5.0. This work is curated based on the thesis by Wang [18] on *daimochi tsugi* digital modelling, structural tests and fabrication comparisons.

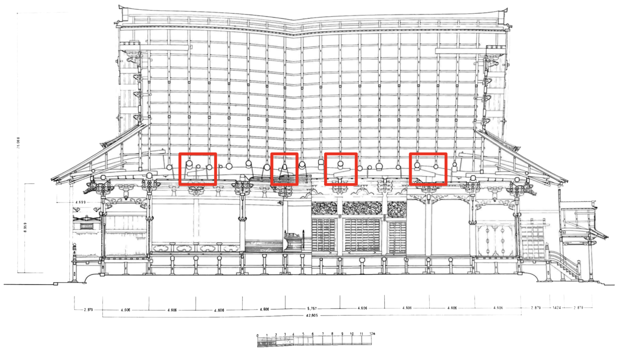

Figure 1. An example of *daimochi tsugi* in existing building: a section drawing of Mieidō Hall at Senjūji Temple in Mie Prefecture, where several *daimochi tsugi* are found as squared in red [26].

3 *Daimochi Tsugi* Joint

Daimochi tsugi appears in structures built as far back as the *Kamakura* period (1185–1333) or earlier and is found extensively in the Edo period (1600-1868). This joint can be found in 21% of a survey of 104 structures from a general archive in Kyoto [18].

Figure 1 shows this joint in use in temples such as Mieidō Hall at Senjūji Temple in Japan [26]. It is also used in today's small timber buildings with the Japanese shed structures, namely *wagoya*. Reinforcement can be made using bolts instead of dowels; however, this discussion is not included in this paper.

It is a load-bearing and shear-resisting stub tenon scarf joint with high lateral strength. In the Japanese language, *dai* means platform; *mochi* means "to hold up". It is commonly used in a roof truss system of *wagoya* structures as a joint above the laying beam, which is connected to a column, with the roof ridge resting directly on top. Figure 2 illustrates how this joint is used in a sketch [27] and in a 1:1 timber structure [28]. There are also different forms and variations of this joint due to, for example, the fashion of the time, location, or preference of the *Miyadaiku* , or the performance requirements of that building. It is a versatile joint that can also be used anywhere supporting a roof and requires a long span, which cannot be achieved with a single span of wood.

Design for Repair and Reuse: It is defined in such a way that the upper piece (*uwaki* as the shed beam in the figure) and the lower piece (*shitaki*), each with diagonal

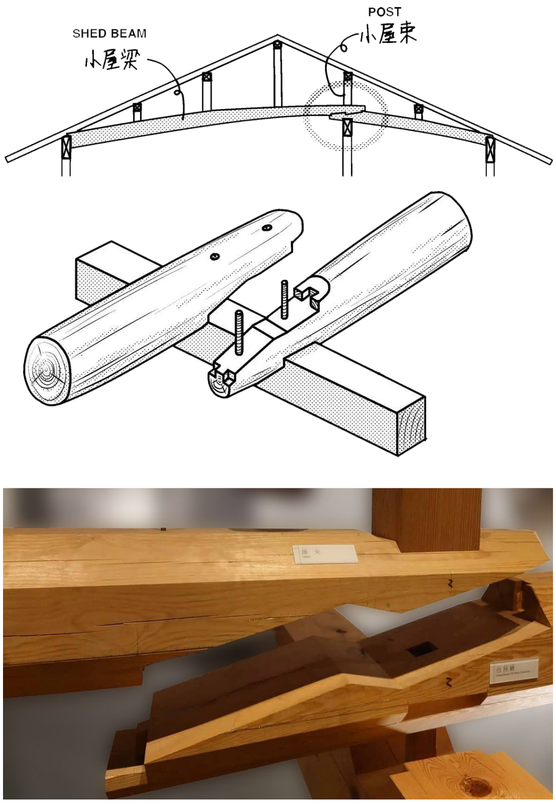

Figure 2. top: *Daimochi Tsugi* in a structure using logs in a sketch [27]; bottom: a 1:1 timber structure from the Takenaka Carpentry Tools Museum [28]

cuts of long stub tenons with steps to impede the breakage of material across the grain in shear, are connected with dowels to prevent horizontal misalignment [18]. This joint is designed not only for structural performance in a building but also for its functional purpose, which allows the entire structure, of which it consists, to remain stable and structurally sound while a supporting column is removed.

The geometric basis for this stability can be understood as follows. The diagonal stub tenon cuts on both the *uwaki* and *shitaki* resist sliding in the direction of vertical shear, so that even without the column's direct support, the interlocking scarf faces continue to transfer vertical load between the two beam members. The dowels prevent lateral separation of the joint under any asymmetric loading that develops once the column is absent. Critically, the roof load acting downward on the *uwaki* keeps the joint in compression against the *shitaki*. The weight of the structure above actively closes the joint rather than opening it. This gravity-locking behaviour is consistent with the experimental observations in Section 5, where the joint consistently attempted to return to its original position under sustained load even after partial failure. A formal mechanical model of load redistribution during column removal is identified as important future work.

In Japan, it is not uncommon for castles, temples and shrines to undergo repair, deconstruction and reconstruction, either partially or entirely on a building scale. For example, the over 400-year-old Himeji Castle in Hyōgo Prefecture has undergone disassembly, deconstruction, repair and reconstruction during the Shōwa Restoration, which was completed in 1964, as well as partially from 2009 to 2015 [29]. In large or small restoration projects, it is often the case that the building elements are disassembled and individually inspected. Many traditional joinery techniques are designed to be disassembled and reassembled piece by piece without destroying each element or reducing its purpose-built structural performance. Like many other traditional Japanese joinery, the design of *daimochi tsugi* offers a relatively convenient configuration that supports a non-destructive repair process. For example, in a case where a column requires repair, the damaged column is disassembled from the rest of the structure, repaired off-site and reassembled into the standing structure; or if a column requires a replacement, the damaged column is replaced with a new one in the existing standing structure; meanwhile, the standing structure, with the column removed, can also be inspected and repaired without the support of that removed column, or it can be temporarily supported by a newly placed column underneath.

4 Digital Modelling and Digital Fabrication

This work further explores how a joinery design for repair and reuse, such as this *daimochi tsugi*, can be fabricated in current practice. This section summarises Wang [18] work on a comparative study of handcrafting a 1:1 *daimochi tsugi* joint and digitally fabricating the 1:1 joint with CNC. Both 1:1 prototypes have a 3.5"×3.5" (≈ 9cm×9cm) cross section using southern cypress wood. Both processes involved subtractive fabrication. In this paper, information on the digitally fabricated joint is presented primarily. Although knowledge about carpenters' tools and craftsmanship is very diverse and valuable in construction history, it is out of scope and will not be included in this paper.

3D Modelling: The 3D model of the *daimochi tsugi* joint was developed in Rhinoceros 3D based on geometric descriptions from Wang [18]. The modelling process primarily serves as a geometric basis for subsequent fabrication and analysis. Its role is to enable consistent comparison between handcrafted and CNC-fabricated joints by ensuring identical geometry across fabrication methods.

Finite Element Analysis: The modelled joint in Rhinoceros 3D was imported into Abaqus as a .stp file

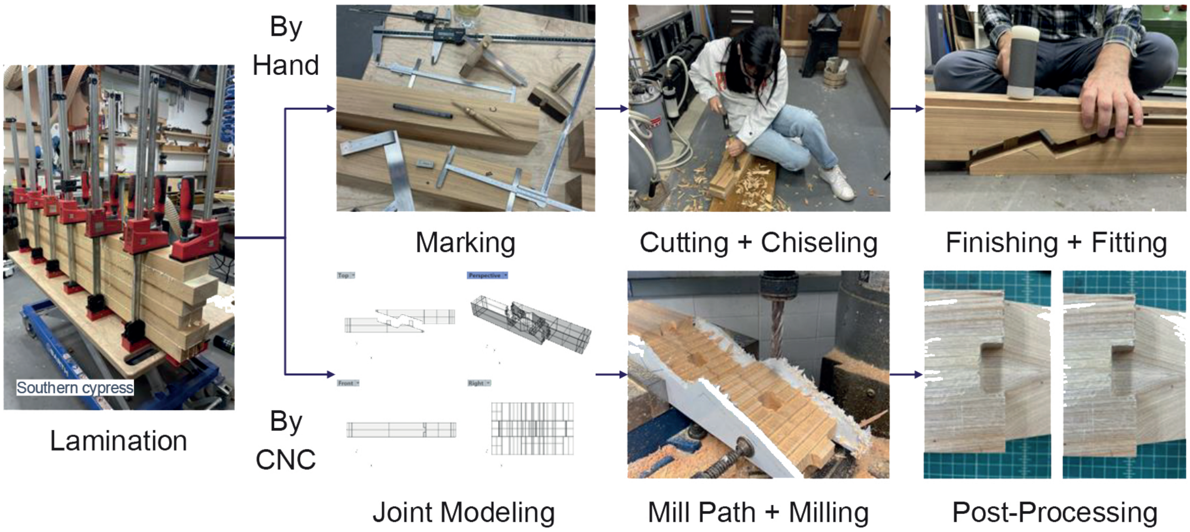

Figure 3. The two fabrication workflows compared in this work: traditional handcraft (top, from marking and chiseling to fitting) and CNC milling (bottom, from joint modelling to post-processing), starting from the same laminated southern cypress blank [18]

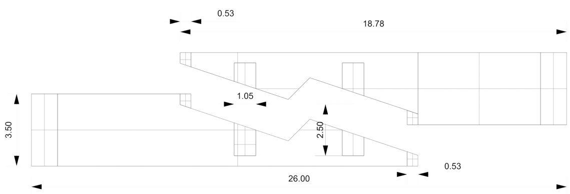

Figure 4. The 3D model in Rhinoceros 3D of the 1:1 *daimochi tsugi* prototype in this work with a 3.5×3.5 in^2 square profile cypress wood [18].

Table 1. The maximum values of requested outputs for each simulations [18]. S_{max} refers to maximum principal stress, *dy* refers to vertical displacement and P_{max} refers to maximum contact pressure.

Loading Condition	S_{max} ($\pm$10 psi)	*dy* ($\pm 10^{-4}$ in)	P_{max} ($\pm$1 psi)
4-Spring	1.651e+05	1.014	7.348e+04
6-Spring	1.720e+05	1.190	8.918e+04
% increase (4 → 6-Spring)	∼4%	∼16%	∼19%

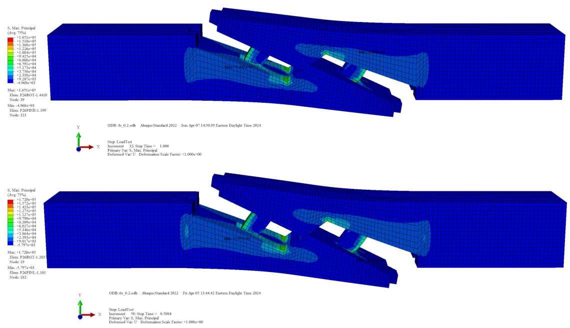

Figure 5. Top: Maximum principal stress (S_{max}) in the 4-spring model. Bottom: S_{max} in the 6-spring model. Both show maximum stress in the corner of the scarf and the pins. The 6-spring shows higher stress comparatively and the light black indications at the outer edges of the joint [18].

in four separate parts - *uwaki*, *shitaki* and the two dowels. The parts were meshed and assigned linear elastic material properties for computational simulations and load tests. Only the key assumptions and results relevant to the interpretation of the experimental behaviour are presented here; more details are available in the thesis [18]. Table 1 shows the test information, with the results presented in this work. Figure 5 shows the results of the maximum principal stress in the 4-spring model and in comparison with the 6-spring model. Both show maximum stress in the corners of the scarf and the pins. The vertical displacement for both the 4-spring and 6-spring models shows similar results, with a maximum at the tip of the *uwaki* and a minimum at the tip of the *shitaki*. The highest contact pressure is shown where the dowels meet the inner diagonal contact surface of the joint [18].

In this study, the linear model is employed primarily for its numerical stability and computational efficiency, especially in light of the complex contact behaviour and geometry of the *daimochi tsugi* and is intended as a complementary qualitative tool rather than as a predictive design model.

The results show that the model successfully predicts the locations of the experimentally observed crack initiation, particularly at the scarf interface and around the dowel regions. This indicates that despite its simplifications, the linear elastic model captures the dominant stress pathways governing the initiation of failure.

Figure 6. The clamping setup of the joint with the Laguna CNC [18].

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Nevertheless, the timber joints exhibit highly nonlinear behaviour, including orthotropic material response, contact slip and progressive damage such as cracking along the grain. Advanced approaches in the literature incorporate nonlinear material behaviour, contact mechanics and damage modelling to simulate timber joint response more accurately [30]. Such approaches typically require user-defined material models and significantly higher computational effort, which is part of the authors' ongoing work.

Mill Path and Milling: The CNC machine used was a 4-axis machine, but this fabrication work only utilised 3 axes. The milling was conducted in three subtractive fabrication steps, the last step involving the finishing and smoothing of the cut surfaces with a 1/4" end mill. The prototyping shows that the radii hinder the fitting process because some square edges could not be fabricated. Figure 6 shows the clamping setup. Light filing and chisel work were performed to alter the geometry for fitting. Also, the CNC-fabricated pieces tended to chip at the edges because the toolpath strategy did not account for the tendency of wood to chip or crack along the grain [18].

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5 Handcraft VS Digital Fabrication

A total of five *daimochi tsugi* joints, two handcrafted joints, two CNC-fabricated joints and one continuous solid timber control specimen of the same wood as a control were subjected to axial tension tests by Wang [18] to compare the performances of the handcrafted and digitally fabricated joint prototypes. The joints were set with constraining plates on both ends, with a 4-spring and a 6-spring clamp, respectively. Figures 7-9 show the results

Table 2. Summary of the maximum load and maximum deflection of each *daimochi tsugi* joint [18]. L_{max} refers to maximum load, d_{max} refers to maximum displacement, T_{UF} refers to time at ultimate failure, d_{UF} refers to displacement at ultimate failure. The handcrafted 6-spring specimen did not reach a defined ultimate failure during the test, hence T_{UF} and d_{UF} are not reported. For the continuous control specimen, T_{UF} and d_{UF} correspond to the point of testing fixture failure rather than specimen rupture.

	Loading Condition	L_{max} ($\pm$ 0.1 lbf)	d_{max} ($\pm 10^{-5}$ in)	T_{UF} ($\pm 10^{-6}$ min)	d_{UF} ($\pm 10^{-5}$ in)
Hand-crafted	4-Spring	4,879	1.0700	10.445	1.0443
	6-Spring	6,513	2.2758	N/A	N/A
CNC fabricated	4-Spring	4,131	0.4767	4.615	0.4613
	6-Spring	4,683	0.4356	3.43833	0.3436
Control	-	36,137	0.6211	6.06833	0.6066

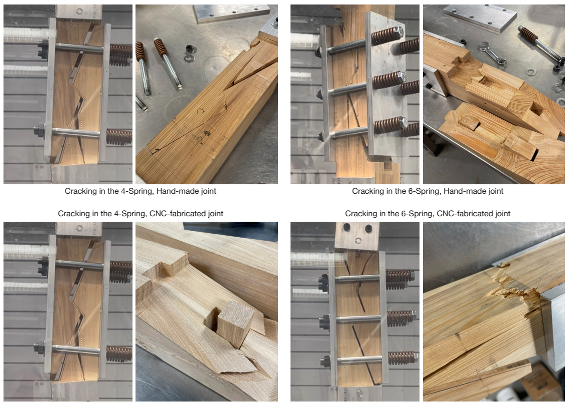

Figure 7. Comparison of the testings between the handcrafted and the CNC-fabricated in 4- and 6-spring clamping systems respectively [18].

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of the tests of the two handcrafted joints and the two CNC-fabricated joints in 4-spring and 6-spring configurations, respectively. A consistent pattern in all four cases is that cracks tended to initiate and propagate from the tip of the angled scarf. Only the handcrafted joint in the 6-spring configuration showed shear failure across the scarf in the opposite direction to the other cracks [18].

The load-displacement curves for each tested joint show that each of them experienced about 2–3 areas of maximum loads; the load dropped off due to cracking, alleviating some stress. In all cases, the joints were able to recover and take on additional loads. Additionally, all four tests indicate that once the joint failed, as long as the roof load is still present, the joint attempted to return to and fail into the original position. Thus, heavy loads in the roof structure above the joint prevent the joint from opening. This behaviour is also directly relevant to the repair scenario described in RQ1. The gravity load from the roof actively closes and stabilises the joint during the period in which a column is temporarily removed, suggesting that the joint's geometry and loading condition work together to maintain structural continuity. This shows the *daimochi tsugi* design is well suited to delaying the failure of the beam-column joint.

Furthermore, the handcrafted specimens showed a higher load-bearing capacity than the CNC-fabricated specimens in both test configurations (Table 2). The comparison in the 6-spring configuration further amplifies the

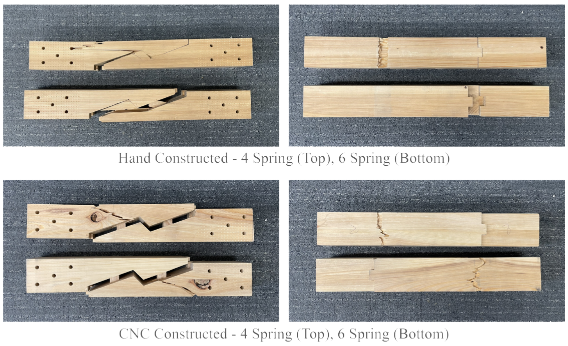

Figure 8. Visual comparison of the failure patterns of the handcrafted and the CNC-fabricated in 4- and 6-spring clamping systems respectively [18].

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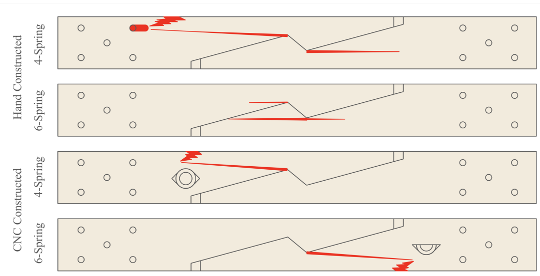

Figure 9. Schematic of the major crack patterns observed in the four tested daimochi tsugi joints (top to bottom: handcrafted 4-spring and 6-spring; CNC-fabricated 4-spring and 6-spring). Red lines indicate crack initiation and propagation paths from axial tension testing [18].

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difference in performance between the handcrafted and CNC-fabricated joints.

The observed differences in structural performance between the handcrafted and CNC-fabricated joints can be attributed to several fabrication-related factors. First, the handcrafted joints were iteratively adjusted using chisels and planes to achieve tight-fitting contact surfaces, which is critical for effective load transfer and friction resistance. In contrast, the CNC-fabricated joints required geometric clearances to ensure assembly and early milling iterations resulted in gaps and non-flush surfaces. Second, limitations of the milling process prevented the formation of sharp internal corners, leaving unavoidable radii that altered the intended interlocking geometry of the joint. Third, the CNC process introduced local defects such as edge chipping, which can act as stress concentrators and initiate cracking under load. Finally, variability in the timber material, including the presence of knots in the CNC-fabricated specimens, further contributed to reduced structural performance. Together, these factors indicate that the difference is not due to the fabrication method itself, but rather to the current limitations in machining precision, toolpath strategy and material control in the CNC process compared to the adaptive refinement achieved through handcraft.

Moreover, the tests show that this joint regained strength in almost all cases even after a degree of failure up to the ultimate failure. The four tests show yielding patterns characterised by both brittle and ductile fracture behaviour. The FEA models were able to qualitatively predict the principal regions of experimentally observed failure. In the two CNC-fabricated joints, both crack predominantly in one direction from the middle of the scarf near where the dowel resides [18], indicating some deviation from the idealised stress distribution predicted by the model.

6 Discussion

Beyond the specific case of *daimochi tsugi*, this study suggests three broader implications. First, historical joinery can embed repair-oriented design logic that remains relevant to contemporary practice. Specifically, *daimochi tsugi* demonstrates the principle that a joint can be designed so that gravity loading itself stabilises the connection during partial disassembly. This is directly analogous to contemporary design-for-deconstruction principles, in which connection geometry controls load paths rather than relying on temporary structure. Second, the comparison between handcrafted and CNC-fabricated specimens shows that reproducing joinery geometry alone is insufficient; structural performance also depends strongly on contact quality, tolerance control and material continuity. Third, digital fabrication remains promising for repair and reuse, but its implementation must be sufficiently refined so that fabrication efficiency does not compromise structural durability.

This work presents a curated part of Wang [18] on *daimochi tsugi*, focusing on design for repair and reuse, digital modelling, fabrication and comparative structural testing. The main limitations of this work and the corresponding directions for future research are as follows.

- This work addresses RQ1 through geometric interpretation and experimental observation; a formal mechanical model of stress redistribution during column removal, including boundary condition assumptions and contact mechanics, remains an important direction for future work and would further validate the repair logic attributed to this joint's design. Future publications will present the repair and reuse processes and performances in comparison to other traditional joinery and modern joinery, as well as a comparison between the conventional repair process and the digital repair process with robotics, respectively.

- The structural testing in this work is based on a limited sample size and should be interpreted as indicative rather than statistically conclusive.

- This work presents only one example of a traditional Japanese joint associated with repair and reuse. More studies on other types of joinery are needed to investigate how different traditional designs facilitate repair and reuse to different degrees. Also, future work on joinery configurations and kit-of-parts could support computational design and optimisation.

- This work emphasizes historically grounded knowledge on joinery design for repair and reuse rather than contemporary repair-oriented design in concrete or steel construction. A broader comparative study of materials and construction systems would be a valuable future research direction.

- The weaker performance of CNC-fabricated specimens should not be taken to mean that digital fabrication is inherently unsuitable for repair or reuse. Rather, it reflects the limitations of the specific CNC workflow used in this study. Digital fabrication therefore remains promising for repair and reuse, provided that machining precision, tolerances and material quality are better controlled.

7 Conclusions

This work investigates design for repair and reuse by combining a literature review with a case study of daimochi tsugi, a traditional Japanese timber joint examined through historical, computational and experimental perspectives. The archival and geometric analysis reveals how the joint's design embeds logic for non-destructive repair, including gravity-assisted stability during temporary column removal. The digital modelling, finite element analysis and CNC fabrication demonstrate that this joinery can be translated into machine-readable geometry and reproduced using contemporary tools, while comparative structural testing shows that handcrafted joints outperform CNC-fabricated counterparts due to fabrication precision and contact quality. Beyond the specific case, the design principles embedded in daimochi tsugi, including gravity-assisted joint stability, fastener-free disassembly and component-level replaceability, offer concrete precedents for circular construction and design-for-deconstruction practice. The findings suggest that vernacular joinery is not only of heritage value but a practical resource for the automation and sustainability agendas of Construction 5.0.

References

[1] L. Ruiz, X. Ramón, and S. Domingo. The circular economy in the construction and demolition waste sector: A review and an integrative model approach. *J. Cleaner Production*, 248, 2020.

[2] C.K. Purchase et al. Circular economy of construction and demolition waste: A literature review on lessons, challenges, and benefits. *Materials*, 15, 2022.

[3] M. Gebhardt, J. Maksimainen, and S. Reiter. From trials to triumphs in building materials circularity: Takeaways from davos. McKinsey, Feb 2024.

[4] B. Tang et al. Demolition waste from the infrastructure network in china: Retrospective and perspective. *Resources, Conservation and Recycling*, 219:108272, 2025.

[5] I Jahan et al. Circular economy of construction and demolition wood waste—a theoretical framework approach. *Sustainability*, 14:10478, 2022.

[6] M. Osmani. Construction waste. In *Waste*, pages 207–218, 2011.

[7] UNEP. Reduce, reuse and recycle concept (the "3rs") and life-cycle economy : note, 2004.

[8] M.S. Ng, D.M. Hall, M. Schmailzl, T. Linner, and T. Bock. Identifying enablers and relational ontology networks in design for digital fabrication: a systematic literature review. *Automation in Construction*, 144:104592, 2022.

[9] M.S. Ng, T. Bock, and T. Linner. Robotization: Design for fabrication, assembly, disassembly and the circular built environment with robot-oriented design. In *Proc. 22th Symposium on Construction Robotics in Japan*, Tsukuba, Japan, 2024.

[10] P. Crowther. Re-valuing construction materials and components through design for disassembly. In *Proc. Unmaking waste in production and consumption: Towards the circular economy*, pages 309–321, Adelaide, Australia, 2015.

[11] C. Grüter et al. Design for and from disassembly with timber elements: strategies based on two case studies from switzerland. *Front. Built Environ.*, 9:1307632, 2023.

[12] O.O. Akinade et al. Design for deconstruction (dfd): Critical success factors for diverting end-of-life waste from landfills. *Waste Management*, 60:3–13, 2017.

[13] T.O. Chiletto, E. Knapen, and R.N. Passarelli. Design for disassembly and reuse: A synthesis for timber construction. In *Proc. Conf. Earth Enviro. Sci.1363*, page 012040, 2024.

[14] S. Langenberg, O. Kasap, and M. Brenner. An intergenerational shift in mindset. *Ardeth*, 15:125–143, 2024.

[15] F. Karaca et al. Stakeholder perspectives on the costs and benefits of circular construction. *Sci Rep*, 14:30039, 2024.

[16] J. Cali and J. Dougill. *Shinto Shrines: a guide to the Sacred Sites of Japan's Ancient Religion*. University of Hawai'i Press, 2013.

[17] M.S. Ng. *German influence on art education reform and school design in 19th-century England*. Master's Thesis, University of Cambridge, U.K., 2015.

[18] A. Wang. *Join(t)ing the Past and Present: a dive into the History, Construction, and Structural Properties of the Traditional Japanese Daimochi Tsugi Timber Joint*. Senior Thesis, Princeton University, U.S.A., 2024.

[19] L.-M. Ottenhaus et al. Design for adaptability, disassembly and reuse: a review of reversible timber connection systems. *Construction and Building Materials*, 400:132823, 2023.

[20] M.S. Ng and J.W.P. Campbell. The unpublished carpentry archives of cecil hewett (1926-1998): a survey of his letters and drawings in the essex record office in chelmsford. In *Proc. 5th Conf. Construction History Society*, pages 475–486, Cambridge, U.K., 2018.

[21] H. Sato and Y. Nakahara. *The Complete Japanese Joinery*. Hartley & Marks, 1995.

[22] M. Heesterman and K. Sweet. Robotic connections: Customisable joints for timber construction in blucher design. In *Proc. XXII CIDSIDGD*, page 644–652, 2018.

[23] M. Larsson, H. Yoshida, N. Umetani, and T. Igarashi. Tsugite: Interactive design and fabrication of wood joints. In *Proc. 33rd ACM Symp. on User Interface Software and Technology*, 2020.

[24] H. Takabayashi, K. Kado, and G. Hirasawa. Versatile robotic wood processing based on analysis of parts processing of japanese traditional wooden buildings. In *Robotic fabrication in architecture, art and design*, pages 221–231. Springer, 2018.

[25] T. Tannert and F. Lam. Design guideline for rounded dovetail connections. In *Structures Congress 2008: Crossing Borders*, pages 1–7, 2008.

[26] JACAM. *Report on the Repair Works of the Mieidō Hall at Senjū-ji Temple, an Important Cultural Property*. 2008.

[27] H. Hidaeaki. Daimochi tsugi: Diagonal dovetail joint. mikao dairy, 2021.

[28] Takenaka Corporation. *Takenaka Carpentry Tools Museum Permanent Exhibitions Catalog*. Takenaka Corporation, Kobe, Japan, 2014.

[29] Kajima Corporation. Himeji castle main keep, 2022.

[30] C. Sandhaas, A. Khaloian Sarnaghi, and J.-W. van de Kuilen. Numerical modelling of timber and timber joints: computational aspects. *Wood Science and Technology*, 54, 2020.