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# PRELIMINARY INVESTIGATIONS OF A DESIGN FRAMEWORK FOR LOW-TO-MIDRISE BUILDINGS WITH ROBOTICALLY SHAPED WHOLE TIMBER STRUCTURAL ELEMENTS WITH LOW-TO-NO STEEL JOINTS

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**ABSTRACT:** Following an exhaustive evaluation of the limitations of whole-timber carpentry connections in low-to-midrise buildings, recommendations therein have been extrapolated and applied to a small preliminary study of four beam-to-column connection details. These connections included two steel-free and two steel-minimised connections, each with compressive reinforcement. To understand the potential of each connection, fabrication trials and observational assembly tests were conducted. The complications of fabrication were workshopped across all stakeholders, and preliminary moment-rotation, pull-out, and gravity load observations were conducted to better understand how the fabrication frameworks and joint designs could be improved. The observations highlighted key successes as well as weaknesses in the design, fabrication, and construction methodologies, which were rectified. One connection that resulted from this revision is based on traditional interlocking dovetail mortise-tenon carpentry designs and the second is a blend of traditional mortise-tenon and contemporary connections with internal steel fasteners. The preliminary design and fabrications methods, as well as consequential changes, are discussed to provide a better understanding of the applications and limitations of natural-form structural elements and low-to-no steel beam-to-column joints in practice. The final connection designs and preliminary design framework is presented and upcoming sequential research is summarised.

**KEYWORDS:** whole timber, joints , robotic fabrication, carpentry connections, design framework.

## 1 – INTRODUCTION

In the process of devising a design framework for multi-level buildings that minimises embodied energy from fabrication, many avenues have been exhausted to consider viable solutions. The solution investigated in this project is the potential for whole tree trunks to be used as structural elements, of which the elements would be pre-fabricated for use in easily assembled interlocking beam-to-column connections that aim to minimise steel as much as practical. The motivation for this investigation is two-fold. First, the combination of minimally processed timber and little-to-no steel maximises the net-negative carbon potential of timber buildings and provides a more sustainable alternative to concrete, steel, and engineered timber buildings. Second, in response to the relatively high costs associated with engineered timber buildings and steel fasteners, the development of an alternate typology provides an affordable option while achieving notable sustainability outcomes in some cases. The potential for this alternative typology to provide an adequate design solution is foreseen for a range of commercial and residential design scenarios, of which the connections are designed to suit. For example, realistic implementation building layouts include roughly up to 5.5 m to 8 m column spacing in 3 to 6-level buildings considering floors with 2-directional load paths with a 4 m floor-to-floor level height. The applicable uses depend on a range of variables such as building use, building layout, and material availability. However, the absence of previous investigations of such connections means that to understand with certainty which design scenarios are workable, the connection behaviour must be observed. Only then can knowledge be gained as to what extent multi-level, whole-log, carpentry connection structures are a promising solution. An example of this building typology can be seen in Fig. *1A*, where a SOLIDWORKS model depicts a multi-level log structure with simply-supported, 1-way floors in

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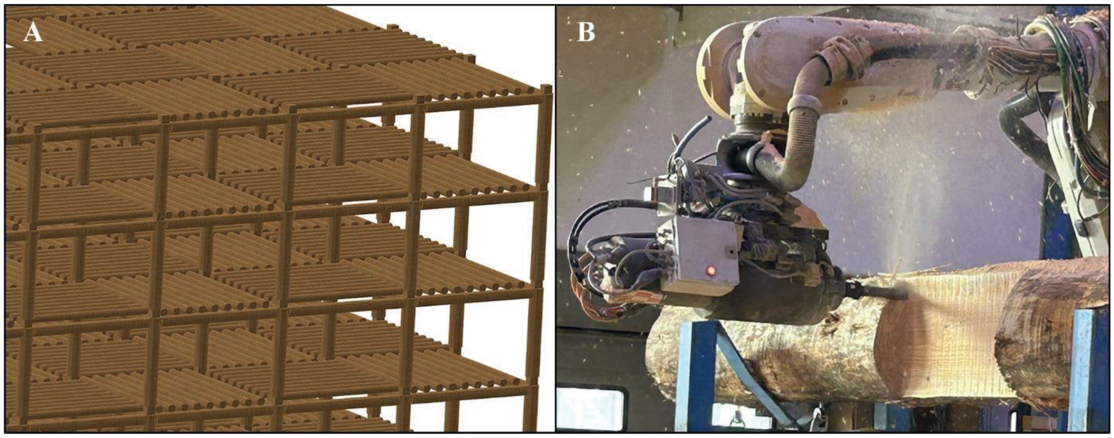


*Figure 1: (A) Idealised SOLIDWORKS model of a multi-level log building with a 2-directional load path floor system. (B) Six degrees of freedom robotic milling arm used to fabricate structural elements for both trial and final experimental analysis.*

alternating directions to create 2-way load paths to minimise log diameters and optimise cross-sectional area of elements.

To understand the extent of the potential for this typology, a systematic process of analysis has been undertaken with the intent of providing a framework for design and fabrication of this typology. The analysis included (1) literature review and case study investigations of connection options and adaptations, (2) compiling limitations and assessing the ability for connection designs to meet objectives within the limitations, (3) preliminary pre-test fabrication trials and observational tests, (4) design revision, and (5) experimental campaigns to evaluate connection behaviour. Herein, the design process used in the pre-test and observations (3) and revision (4) phases are recounted. The design decisions made from those phases and how they shaped the final designs are discussed, and an overview of the sequential experimental campaigns (5) are briefly explained, though work described in (1) and (2) can be found in [1] and [2], respectively.

## 2 – BACKGROUND

Sustainable methods have never been more important in construction, and consequentially many contemporary projects incorporate engineered timber in design as an alternative material to steel and concrete structural frames. However, the fabrication of more highly processed timber increases embodied energy, undermines the net negative $CO_2$ attribute of timber, and increases the cost of materials. Two ways to maximise the benefits of a timber building as a carbon sinkhole are to minimise the transformations of the timber and minimise the amount of steel used in connectors, thus minimising the energy used in making structural elements and components. Engineered timber products may be highly altered, including dried, cut, planed, joined, pressed, sanded, and glued, which implies both copious levels of transformations and transformation energy [3]. It is insufficiently investigated what feasible approaches to fabricating structural elements might better exploit the sustainability of timber.

While timber is commonly regarded as the key material of the future due to the sustainable qualities it offers, it is often forgotten that it is also a fundamental material of the past. Despite millennia of tradition providing countless civilizations with various structures, ancient methods involving interlocking carpentry connections, particularly with natural-form round timber elements, are largely dismissed in modern design and are almost exclusively seen only in cultural preservation of historic structures [1]. There are many reasons for this. For example, contemporary conventions in timber structures include the widespread use of timber of standardised dimensions connected by metal fasteners, which are generally accessible, affordable, and easy to use. This is unlike traditional connections, where a skilled carpenter considers the unique qualities and flaws of individual logs and then hand-crafts structural elements with practiced precision at a great cost of time, resulting in a building made of up many geometrically interlocking pieces. Today, this method is effectively impossible to achieve in most scenarios. Not only are there extremely few traditional carpenters with relatively limited knowledge of a widely forgotten skill, the cost to enlist such a carpenter would be great, the time to make a building long, and the cost-benefits of such structures for anything but cultural preservation is generally considered unjustifiable. Furthermore, as deforestation has intensified over the centuries, the availability of high-quality material trees with large diameters has been diminished and the possibility to shape large and strong structural elements with robust interlocking connections has dwindled. The unfortunate culmination of heightened


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levels of atmospheric greenhouse gasses alongside the loss of traditional methods begs the question if traditional techniques might be exhumed into a methodology that bridges the gap between ancient design and modern limitations such that more sustainable construction can be achieved within modern design demands and constraints for some buildings.

To answer this question, this investigation reimages traditional techniques to meet the structural and sustainability demands in a contemporary context by developing a framework for designing and fabricating beam-to-column wood joints for residential and commercial low-to-midrise sustainable structures. Within the proposed framework, structural elements undergo only the minimal transformations necessary to meet structural and practical requirements. This means that structural elements remain mostly in their relatively round but naturally flawed form, and are only made uniform at interfaces between elements. Subtractive fabrication, which is achieved by a process of milling away designer-nominated volumes of an element to substitute the work of skilled carpenters, is the primary fabrication method used. While this might be a relatively straightforward process with a structural element of uniform (rectangular or circular) geometry that is shaped by a computer numerical control (CNC) milling machine, the introduction of elements with natural geometries presents additional challenges. Therefore, precision milling of elements of irregular geometry are instead achieved in this investigation using a six degrees of freedom (DoF) robotic arm, as seen in Fig. *1B*. The conceptualisation of the connection designs incorporated many considerations, including the use of only locally available resources and materials, optimisation of log compressive areas in beams, optimisation of cross-sectional area in columns and beams, compliance with local building codes (to the extent that the Eurocode can be applied), design adaptation to robotic milling abilities and limitations, and accounting for necessary tolerances for design, fabrication, and assembly. A trial design and fabrication were first conducted to workshop outstanding flaws alongside industry partners before making final design decisions leading up to a large experimental campaign, which is presented in future work. The trials were instrumental in identifying the aspects of the methodology that might make the building typology appealing, or unfeasible, in practice. The discoveries made within pre-test fabrications are discussed herein, and the items determined to be essential to a design framework are presented.

## 3 – PROJECT DESCRIPTION

In this project, fabrication trials, assembly observations and troubleshooting, design revision, and an experimental campaign have been undertaken to determine the extent that log multi-level buildings with minimal steel might be used in practice for beam-to-column connections.

In preliminary fabrication trials, 4 connections were designed and milled using a six degrees of freedom robotic arm. Two connections were modified dovetail mortise-tenon style, drop-down, beam-to-column joints with either 12° or 17° angle heads, which is true to the aim of eliminating steel from the design. Alternately, the other two connections blended modern and ancient methods, and were anchored beams seated at the tenons and cut at 45° degrees on each end corner to fit 4 beams into a node where all beams rest on the column support and are fastened with either two or four 10Φ structural timber screws made to anchor the beam to the column. Examples of each type can be seen in Fig. *2*. In both cases, beams rest on a support at the outer edge of the column and designs neglect torsion as the beams and floors are assumed simply supported.

Due to the weak compressive strength of timber perpendicular to the grain, all samples are fit with compression reinforcing screws, which is a concession on sustainable targets that minimises necessary beam and column diameters and facilitates larger spacing between

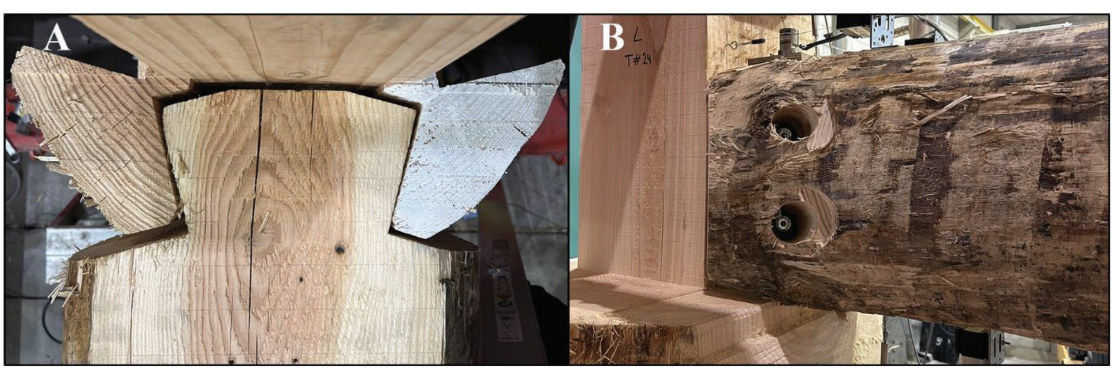


*Figure 2: (A) Top view of dovetail joint slotted into a whole log column element. (B) Whole log beam seated at the tenon on the column support and fastened to the column centre with structural screws and material volume removed below beam for access purposes.*

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columns or additional levels, increasing the possible building layout options. All steel is situated internally so to maintain a minimum 60-minute fire char layer before steel is exposed to fire. As brittle failures are seen as one of the largest shortcomings of wood connections and are frequently cited as the reason that wood is sometimes seen as an unreliable material, one additional objective is to observe deterioration in critical failures when the joints are pushed past their operable limits. Each connection was assessed for ease of fabrication and assembly, then observed in excessive gravity loading, moment rotation, and pull out to determine what design changes might be necessary.

Observational tests on pre-test trial fabrication samples provided insight into potential problems with the future samples or campaign. The results of the test, however, are only useful for qualitative observation and experience since these samples were often fabricated with defects while determining fabrication methods, and results on faulty samples could not be used for objective analyses. The observations made were simply used to improve connection design leading up to a sequential experimental campaign. The assemblies each included a 3-metre column segment with no column-column connection, and a 2-meter beam segment without secondary beams or a floor. The trial specimens in preliminary testing were designed as per the Eurocode in compliance with a 3-level building with a 6-metre column spacing in both directions with the assumption of a 2-way floor load path. Due to the length of tree trunks, a whole 3-level column without a column-column joint could reasonably be fabricated and transported. Otherwise, column-column analyses are recommended for future study. For more information on beam-beam log floor patterns and optimisation see [4]. The project herein focuses only on beam-column connections.

## 4 – DESIGN PROCESS

Following an investigative study of carpentry connections [1] and limitations to whole-wood structural elements with robotically fabricated joints [2], a preliminary framework was laid out for this emerging typology. Fundamental design factors incorporated were the outcome of a geometric analysis on the necessary minimum element dimensions and compressive surfaces for structural requirements as per the Eurocode building code. An analysis of 12 connection possibilities for commercial and residential buildings between three and six levels and with column spacing of 4 to 8 m highlighted the most promising building layout options to optimise elements and joints while meetings limitations imposed by building codes, material availability, robotic milling constraints, rudimentary char-layer fire protection, and a range of other practical limitations. The analysis of 1,632 scenarios was processed in a programme written in MATLAB to cross-check requirements for optimisation and provide design solutions. The analysis highlighted severe limitations to possibilities with natural wood compressive surfaces, and as a potential solution, 9Φ mm compressive reinforcement structural timber screws in four-beam nodes were introduced into the design. This diameter screw was selected due to the need to compromise between higher load resistance diameters resulting in increasing support length requirements. The automated design prompts the smallest and fewest screws possible. Nevertheless, this vastly increased the potential for column-to-column spacing by minimising beam and column diameters, of which 600 mm was considered to be the largest diameter that could be realistically specified in practice. Without compressive reinforcement, design options with widely available materials are extremely limited (i.e. few levels and close columns). For this reason, all connections proposed here contain three compressive reinforcement screws in the beam at the support, though it is not necessary in all scenarios. However, the reinforcement also meant that less compressive material in the middle of the joint was necessary, therefore increasing the material available on the sides of the beam for implementing a means of tensile and moment rotation resistance, which is a key unknown under investigation in this project.

Since the MATLAB programme could not possibly account for individual variations in geometry, the geometries recommended in the program are the minimum log cross sectional circular area necessary to meet structural and geometric demands. While irregularity of trees is natural, the minimum diameter cross sections must be abided by since extreme irregularity is troublesome at joint locations, resulting in missing sections or weak spots. Guaranteeing that this volume is available is straightforward with perfectly circular elements, but with irregular forms, this can be achieved with some time and effort if the log is digitised, for example, with form-capturing technology like lidar or photogrammetry. Due to the time and cost associated with individual log digitisation, trials incorporated a hand-measurement of the minimum circular area, however, increased quality only occurred after multiple attempts, and most early samples were severely flawed.

In cases where steel is to be used for fastening a beam to a column, the limited log diameter available and desire to reduce steel are, once again, great limitations. The beam was proposed to be horizontally anchored at 45° through the beam and into the column at staggered heights and alternating directions to (i) increase joint capacity compared to 90° orientation steel fasteners and


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(ii) avoid clashes of the steel in the column while still meeting penetration depth requirements. The original design considered 10Φ mm by 400 mm structural steel screws anchored to load distribution plates on planes cut 45° to the column surface, however, the threat of fire on exposed steel and the difficulty of fixing the plate to the correct location on an irregularly shaped log caused this design to be dismissed. The fabrication trial design was decided to move ahead with 60 mm anchor pockets milled into the sides of the beams where structural washers could be used for load distribution and commercially available 50 mm deep plugs can provide fire cover.

In carpentry style joints, it was found upon fabrication coordination that differences in which tools could be used for male and female parts meant that support areas could not be used as efficiently since the rounded curves of 90° turns meant that there is no contact possible on the sides of the joint. A smaller tool could increase the area, but at the cost of time and manpower, so this was not pursued. Furthermore, a range of access issues meant that a traditional dovetail mortise and tenon was impossible to replicate and many tolerances were incorporated. This resulted in the need for 5-sided beam head instead of a 3-sided beam head, the removal of extra material at the back of the joint to accommodate the extra milling plane on each side, the removal of beam-column volumes that clash on the sides at the bottom of the beams, and the removal of clashing volumes at the mouth of the connection at the column to increase robot access to mill all design planes. This final adjustment was also made commonly in anchored joint column fabrication.

Finally, some assembly issues highlighted a need for design changes. Initial column designs assumed that for anchored beams the beams could be swung in from the side and fit together if beam corners were removed, however, this meant that there was a very specific order of assembly to be followed to avoid clashes. Nevertheless, in practice some beams were very large which prevented easy assembly. This led to the adoption of the overhead clearance method used with the carpentry joint, where the interlocking of the joint was accomplished by the beam being slotted into place where a volume was removed from the column to facilitate assembly. Additionally, this enables secondary beams to be installed all the way up to the column centre, meaning that clashes between structural elements and floors is mitigated. The only problem highlighted with this design in the case of the carpentry connection was in the case that manufacturing errors or shrinkage resulted in a beam tenon height that is less than the beam mortise height, which would not allow for secondary beam installation.

With all considerations in mind, some basic design rules and recommendations have emerged throughout the design process framework. These findings are largely observational and are related to logistical design, fabrication, and construction assembly. Further design adjustments are foreseen following the final experimental campaign of the samples that resulted from these trials.

## 5 – RESULTS

Upon review, many aspects of the original design framework were found to be successful and were taken onboard when designing the final natural-form, whole-wood elements with robotically shaped joints:

*Design progression*: Use of a design program (in this case, written in MATLAB) for automated preliminary designs of different scenarios at different building levels proved to be the fastest way to standardise a joint to wide-range use and quickly understand individual geometric limitations of a joint. Additionally, the limitations could easily be adjusted, removed, or added as the development of the joint progressed, providing the ability to use the program in a feedback loop that generates new analyses immediately.

*Column area usage*: Use of the inner trunk for column load transfer and use of the outer trunk for beam load transfer was found to be a reasonable method in cases where columns were either (i) continuous trees, or (ii) connected at an adjacent location. The full diameter of the tree provides an exceptional char layer for fire resistance and the design enables a node to fit up to four beams in two directions, which is not the case when compressive areas for columns are external (for example, like with a *Nuki* joint).

*Satisfactory observation of compressive reinforcement*: Sunken head screws for compression reinforcement to increase beam load transfer capacity was observed to work as described in manufacturers recommendations in extreme gravity loading of three beams. This offers significant increase in possible building dimensions, making the typology more aligned with typical column spacing. For this reason, seated connections, like those described herein, when used with compressive reinforcement were found to be an acceptable alternative to a concrete, steel, or engineered timber counterpart.

*Assembly of seated-tenons anchored with structural screws:* Positioning the beam with a crane was very easy, and once seated the beam stayed in place. *S*ide screws at a 45°angle into the column were found to have easy access in assembly, though increased time and manpower is necessary compared to a slotted dovetail joint.

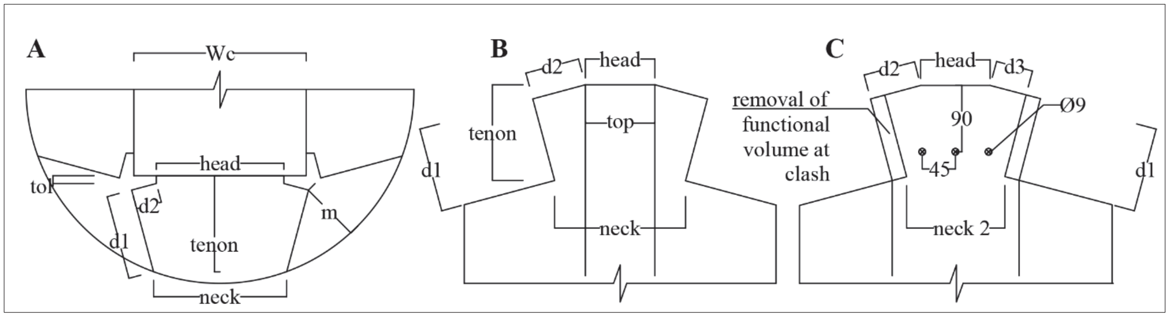


*Figure 3: Idealised sample dimensioning. Due to the tapering of the mortise and tenon and the removal of material to mitigate clashes, the geometries at the top and bottom of the mortise and tenon differ. Additionally, a volume of material for functional purposes is removed in line with the mortise neck in the column to account for a tolerance needed at the rounded edges of the milling plane. A second functional volume is removed from the bottom edges of the beam to account for the clash at the rounded edges along edge d1 of the mortise.*

*Observed failures*: In pre-test observations of all connections, even defective samples failed in a ductile manner for both dovetail mortise-tenons and seated-tenons in moment rotation and pull-out, which provided confidence in the design to move forward. With the observation of structural screws behaving as predicted by manufacturers, considerations of further pull-out and extreme gravity tests to test tensile and compressive behaviour were found to be superfluous. Furthermore, the steel compressive reinforcement was not seen to interfere with the failure mode of the samples as all failures occurred in the columns.

Key findings and changes applied to sequential design and fabrication:

*Milling defects*: Initially, logs milled without guidance from digitisation showed low delivery of complete samples free from milling defects, particularly among samples that were rotated or accidently moved during fabrication. However, after multiple attempts, defect-free samples became more common. It is unclear if this method might become more accurate alongside practice as human error decreases, or if digitisation is worth the outcome of all samples being within manufacturing tolerances.

*Steel installation method*: Trials of multiple types of structural steel screws with prescribed predrilling methods may be necessary to find what products in a designer's region can achieve a successful screw instalment with the available materials, as some combination of products and techniques trialled in this project caused screws to become stuck, damaging samples and risking that they become unusable. On this project, for kiln-dried C24 Douglas fir logs of moisture content often over 20%, Rothoblaas anti-corrosion VGS fully threaded structural timber screws with 3-thorn tip and countersunk head were used with predrilling and non-impact, anti-torque drilling, followed by hand-tightening to ensure that screws do not become stuck and the pre-drilling penetration does not become stripped. As this product only exists in 9Φ and 11Φ, with limited lengths available, this was taken as a design limitation.

*Timber screw detailing*: In the case of screw diameter, number of tensile screws, and where to put them, a trade-off exists. Due to the high risk of deflection of screw penetration at installation, as the number of screws or closeness of screw layers increases, the risk of clashes occurring inside the column increases. If a single row of reinforcement is used with 2 screws, clashes are very unlikely but the pull-out and moment-rotation resistance and connection confidence is significantly reduced. When two rows of anchors are used, the stiffness and pull-out was satisfactory. However, in this design a concession was taken where the distance between rows was increased to lower the risk of clash, resulting in increased slip in moment rotation. Three rows were not considered due to the high risk that clashes could occur, rendering the node unusable. However, if accuracy and precision of the installation could be increased, 3 layers might be used.

*Fire-isolation anchor pockets*: Though fire-isolation anchor pockets were found preferable compared to exposed structural screws on a flat surface for fasteners, there were many issues. Pockets required a custom-fabricated pre-drill guide, debris removal before screw installation, and, in cases of large diameter logs, removal of excess area around the pocket was necessary to enable robot access at the required pocket depth, which must be worked into initial designs and installation procedures. Likewise, logs that were smaller or off-centre risk that the pocket is not deep enough at the outside edge, meaning that it is not deep enough for the pocket to provide the design fire rating. This prompted the design change that the anchors are moved toward the centre of the log to provide the cover necessary, however, the anchor had to be tilted either up or down $10^o$ to centre the steel and avoid clashes. However, column compressive sections that are too small must be increased in some cases to meet the dimensions necessary for screw embedment.


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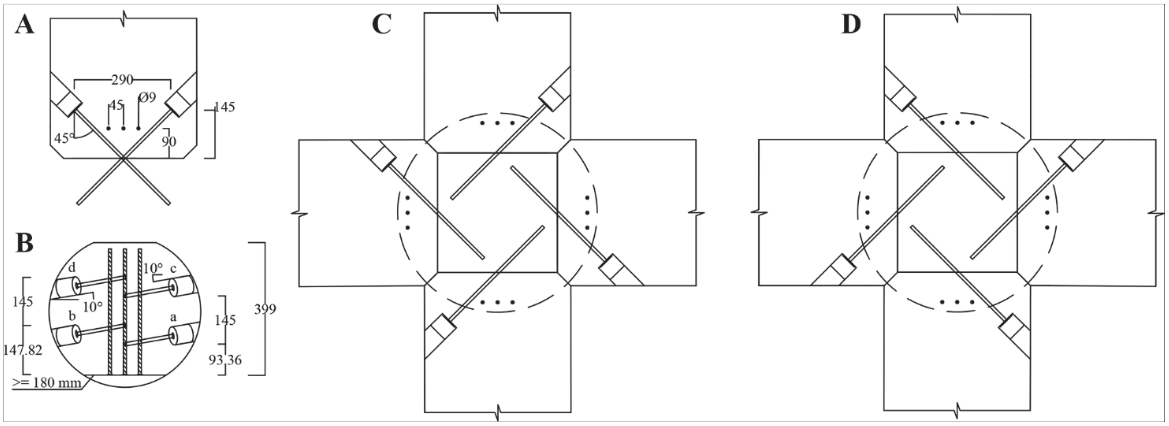


*Figure 4: Idealised detailing of the anchored seated-tenon. (A) Internal plan view and (B) internal front view of steel detailing, including 9Φ mm compressive reinforcement and 11Φ mm tensile reinforcement. Also seen in (B), angled isolating anchor pockets and predrilling for reduced fire exposure and clash risks. Column section and plan view of steel layer patters of screws a and c seen in (C), and screws b and d seen in (D).*

*Dovetail angles*: When selecting a dovetail angle, was is a trade-off between a well-interlocked larger angle resulting in removal of too much interlocking column material and a small angle increasing the gap into the column and allowing increased slip and rotation. A compromise of 15 degrees was taken after trials of 12 and 17 degrees were observed.

*Tapering of dovetail joints*: Drop-down connections were originally fabricated with 2 mm tolerance around and 5 mm in the back of the joint without tapering. Sequential joints were then fabricated with tapered tolerance cut from the bottom of the beam, which was found to facilitate ease of assembly and enabled tolerance on the sides and back to become 2 mm total. From the time of alignment, slotting the tapered beam into place with a crane took approximately 1-2 minutes. However, significant manufacturing flaws and shrinkage can cause the beams to become unable to fit into a joint or be too lose in a joint, therefore a tolerance inspection is recommended to avoid problems or delays.

*Flat-edged mortise*: In cases where excess volume was removed from the mouth of the joint at the column support for access, joints rotated more evenly and had less variability. It is therefore recommended to incorporate a straight edged gradient into the column at the mouth of the mortise, which facilitates both robot access and even rotation and distribution of forces.

*Table 1: Design dimensions of 15° dovetail mortise and tenon in mm.*

| Geometry Description | Mortise Top | Mortise Bottom | Tenon Top | Tenon Bottom |
|---|---|---|---|---|
| *head* | 173.07 | 173.07 | 94.27 | 94.45 |
| *neck* | 180.66 | 173.93 | 177.73 | 170.88 |
| *tenon* | 130.29 | 130.29 | 129.9 | 129.9 |
| *d1* | 114.67 | 114.67 | 114.67 | 114.67 |
| *d2* | 34.65 | 31.17 | 73.93 | 70.62 |
| *d3* | - | - | - | 50.45 |
| *tolerance* | 10.56 | 10.56 | - | - |
| *neck 2* | - | - | - | 132.36 |

*Assembly clearance*: In addition to the volume removed for the joint, and additional volume should be removed for assembly clearance. A clearance of the whole area around the compressive area of the column increases access and ease of assembly. A clearance of the height beam tenon plus 5 mm was found adequate.

*Aesthetics*: Due to the nature of the minimally processed elements, debarked trunks with connections of abrasive milling do not have the aesthetic appeal of engineered timber. For projects with exposed elements, further element transformations may be desired.

This investigation has resulted in the conception of two joints. The first is an interlocking joint that is effectively a modified dovetail mortise and tenon, referred to as a *slotted dovetail mortise-tenon* within parallel works. Geometries can be seen Table 1. for the resulting dimensions of the investigation, as seen in Fig. *3*. The dovetail of the joint has 5 sides to account for the milling limitations in the female part of the tenon. The head of the joint is wider in the end of the female component than the male component to account for a rounded edge that creates a milling clash. The cuts from the head to the joint and the joint to the neck form a 90° angle, as do the cuts from the joint to the neck and the neck to the outer beam. The use of multiple 90° cuts on the sides of the joint is intentional, as this reduces the cutting planes necessary in fabrication, however, the dovetail angle from the neck is 15°.

The dimensions found in Table 1 were modified from those exported from the scenarios run in the MATLAB program. While the height of the beam and the width of the neck were determined by the design shear area required, a post-analysis rework gave the dimensions seen here where the joint is tapered to increase ease of assembly. The removal of the bottom side edges of the male part were also reduced to align with these changes and mitigate another clash with rounded edges at the bottom sides. The minimum mortise

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thickness $m$ is currently a function of the column compressive width $Wc$, necessary tenon length, and fire cover, however, $m$ is always greater than the idealised value. Finding tensile and moment rotation capacities of mortises with different values of m is the focus of the experimental investigation.

Like the dovetail joint, many changes were made to the methodology of the anchored seated-tenon joint while the only minor changes were made to the connection detail. As seen in Fig. *4,* the concept of structural screws in fire pockets was maintained and four screws with interchanging angles were incorporated. The anchor screw diameter, however, was increased to 11 mm such that the most user-friendly screws trialled could be used. These screws were 400 mm long. The most notable change incorporated is the $10^{o}$ angle introduced for spatial dimensioning reasons.

In the case of both wood-wood and wood-steel, tenons are 399 mm deep. Reinforcing screws in beams at supports were easy to install when following manufacturer recommendations and 380 mm long 9Φ mm diameter screws enabled designers to minimise support length and element diameters while maximising beam compressive resistance to increase column-to-column spacing. The compressive reinforcement detailing shown in Fig. *4* is accurate for all samples, including dovetail tenons. Additionally, in both cases columns were fabricated with a 399 mm + 5 mm clearance over the joint for easy assembly.

## 6 – CONCLUSION

This investigation has shown that there is potential for use of whole timber logs with robotically fabricated low-steel and no-steel carpentry connections for some applications in modern construction. When conceptualising robotically-shaped joints into a natural-form structural elements, these key steps were identified:

1. Robotic milling arms are relatively new in fabrication, and access to different robots or milling machines and different milling tools may limit the possibilities in design. Furthermore, different companies and technicians may have different capacities to complete different kinds of works. This information should be determined early, as these limitations are fundamental design parameters.
2. Different regions have access to different materials and products. Planning for use of materials that are compatible with each other, widely available, inexpensive, and easy to use can result in a design that might be more realistic to fabricate and introduce into practice. Since some trade-offs exist between products, cost, availability, and user-friendliness, for example, some compromises may be necessary. This is particularly true with whole timber logs, since the variations in moisture content and material properties may not be compatible with some steel products, such as robot milling tools, structural screws, drilling augers, or drills. It is recommended to determine these limits early, as they may dictate what design possibilities exist.
3. Due to the large number of restrictive limitations in structural wood design, it is recommended to perform a comprehensive analysis to determine realistic scenarios of use. Such an investigation should incorporate the limitations found in (1) and (2) as well as local building code limitations and potential building scenarios to understand the scope under which a connection can be used.
4. When designing using subtractive fabrication, the volumes to be subtracted are nominated as per designer needs and robotic capabilities. A fundamental design and the removal of five types of connection milling volumes should be considered. Though many ancient connection types exist, like the mortise-tenon seen in Fig. *5*A, it is not necessarily the case that they could be fabricated without modifications such that the volumes to be removed

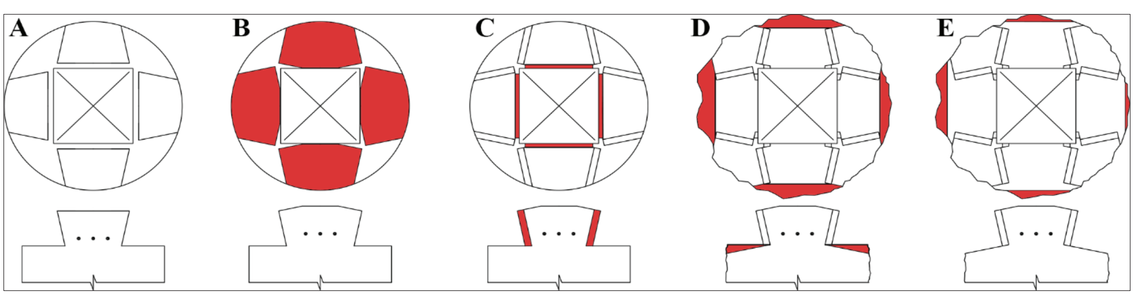


*Figure 5: Milling volume design process, where column section views and seen on the top detail and bottom view of beams are seen for each step and necessary changes are seen shaded. Idealised design conception (A) is made, followed by (B) traditional design adaptations to account for robotic limitation that result in a shape change. As a result of the milling process, some functional volume removals are required at clashes (C). When the idealised joint is applied to a natural form element, excess material volume removals are necessary (D). Additionally, volume removals for access areas creation for the robot must be made in some cases, though not all (E). Note that removal of assembly volumes (not pictured here) is also necessary, which is the column volume removal adjacent to the joint that makes joint assembly possible.*


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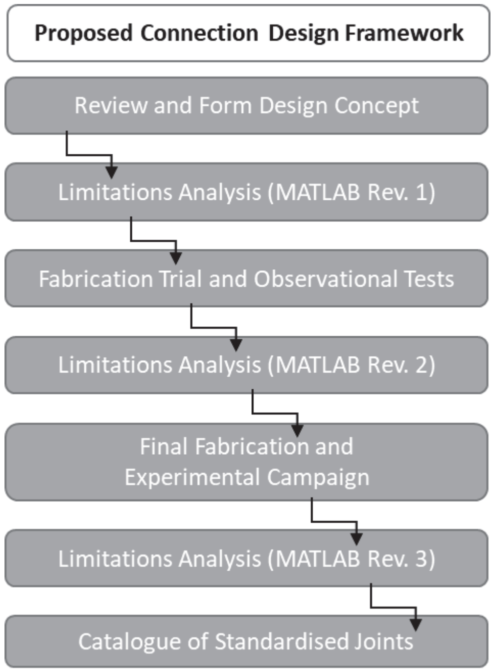


*Figure 6: proposed feedback loop in Design Framework used in design, fabrication, and validation of whole log structural element buildings with low-to-no steel structural joints.*

are adapted to the robotic milling capabilities. When modifications are applied, *design volumes* (Fig. *5B*) are fundamental volumes that must be removed to transform the log into a working connection, for example, the mortise and the tenon. F*unctional volumes* (Fig. *5C*) must be removed to account for the limitations of the milling tools and the robotic arm that might otherwise make the connection not interlock properly. These volumes may include removal of some edges where a rounded milling edge and a sharp milling edge clash, or other modifications necessary to make male and female parts compatible. Additionally, *excess material volumes* (Fig. *5D*) may need to be removed in the case where an element is significantly larger than the idealised design, causing adjacent areas to be inaccessible or making assembly impossible without first removing this additional volume. Next, *access volumes* (Fig. *5E*) include material removal either in the base design where the robot needs to remove volume to achieve the reach necessary to mill the design volume. For example, at the mouth of the mortise or at the mouth of an anchor pocket, which provides the robot arm additional reach to remove design volumes. While not part of the connection design, the final subtractive volume to be considered is the *assembly volume* (not depicted above). This volume in connection design was intended to facilitate node assembly, however, it should be noted that the removal of material around the compressive area of the column above the joint should be at the height of the larger of (i) the tenon height plus 5 mm, or (ii) the height of the secondary beam tenon plus all flooring to ensure that there are no clashes between the floor and the excess volume of the column.

5. Preliminary fabrication trials were helpful in this study in creating a feedback loop in design that increased confidence in sequential designs. In addition to this initial feedback loop, and secondary feedback loop is currently underway in which structural unknowns that cannot be predicted by available building codes or analytical models are evaluated in a series of structural tests. The results of the experimental campaign are anticipated to provide a scientific basis for analytical models to be reincorporated into the analysis described in (3). This is anticipated to be the final unknown in the design framework.

To organise these steps into a functional process, a preliminary framework can be used. Based on the trails and observations herein, the framework seen in Fig. *6* describes the steps identified during the development of the two joints presented in this project. First, potential designs were highlighted from literature of ancient and modern wood connections, and a workable version of the design selected was extracted and reworked to suit modern abilities and limitations. Next, any constraints foreseen from the local building code, supply chain, design needs, and other limitations were input into a program, and within that program connections were design as per the connection design with the application of the limitations. The generated connections were then fabricated, assembled and observed. The information gained from these trials was fed back into the design framework to improve the design, and a new design was conceived. This next generation of joints was fabricated for experimental testing. The results of these experiments are intended to provide insight to the unknowns about the connection behaviour (tensile capacity and joint stiffness), of which models can be used in the final version of the design program. Standardised joints designed to meet different structural needs are intended for export into a library of joints, or designers can use the program to input unique information and generate unique connection specifications. This method was instrumental in finalising the designs herein, which resulted one slotted dovetail mortise-tenon joint and one seated-tenon steel anchored joint.

## 7 – REFERENCES

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