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A LASHING-MORTISE-TENON TIMBER JOINT FOR AUTOMATIC ON-SITE ASSEMBLY

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Abstract

The automatic on-site assembly of timber components using robotic systems has emerged as a significant research focus, addressing challenges such as labor shortages and carbon dioxide emissions within the construction industry. However, existing timber joints utilized in current research often exhibit limitations, including reduced structural strength, limited reusability, and susceptibility to construction tolerances. In this study, we introduce an innovative timber joint concept specifically designed for on-site robotic assembly that addresses these limitations. This design combines the traditional mortise-tenon timber joint with glass fiber lashing in the tenon direction, thereby ensuring stiffness and strength in all loading directions. Additionally, post-installation prestressing of the glass fiber is employed to further augment the joint's mechanical properties. The proposed design presents several advantages for on-site robotic assembly, including reusability, installation efficiency, and insusceptibility to construction tolerances, without compromising structural strength and stiffness. The feasibility of the automatic assembly is validated through experiments with a bimanual robotic system, where a vision-based impedance control strategy is implemented to enhance the accuracy and robustness of the assembly process. The experiments show excellent efficiency and reliability in the automatic assembly of the proposed joint, demonstrating its potential for application in automatic construction of timber structures.

Keywords: automatic assembly, automatic construction, construction site, robotic assembly, timber joint.

1. Introduction

While the aging population and its impact on the construction industry, particularly the resultant labor shortage, is a pressing issue in many countries [1, 2, 3], automating construction with robots presents a promising solution to this challenge by leveraging advanced technologies to fill gaps in the workforce [4, 5]. As an important construction material for the reduction of carbon dioxide (CO_2) emissions in the construction industry [6], timber is also highly suitable for the automatic construction with robots, not only due to its high strength-to-weight ratio, but also because it can be prefabricated off-site into precise and desired shapes, which reduces the complexity of the automatic on-site assembly. Therefore, many works have investigated the automatic assembly of timber components with robots and achieved good results [7, 8], while the applied timber joints are still not perfectly suitable for the sustainable and automatic on-site timber construction. In [9, 10], the dowel connections with pre-drilled holes are installed manually in the robotic assembly process. The nailed joints in [11] and the lap joints in [7, 12, 13] are limited in load-bearing capacity. In [14], the glue-based connections are non-demountable and thus non-reusable, which limits the material circularity and is inconsistent with the objectives of sustainable construction. In [15], a reversible connection is developed for robotic assembly, whereas this connection with screw bolts requires high installation accuracy, which is very difficult to achieve in on-site assembly. The construction site is full of deviations, e.g. inaccuracy of measurements, deformations due to weather, or the inherent variability in the building materials [16, 17, 18]. The automatic construction system must have enough tolerance to be able to deal with these deviations without human interventions. The disadvantages of these timber joint types (lap joint, nail, glue, wood screw and dowel) are summarized in Table 1.

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Table 1. Disadvantages of timber joint types for robotic assembly on construction sites

Joint Type	Disadvantage
Lap joint	Structural strength
Nail	Structural strength
Glue	Reusability
Wood screw	Reusability
Dowel	Construction tolerance

With the aim to avoid the above-mentioned disadvantages and inspired by the traditional timber joint of mortise-tenon and the traditional bamboo joint of lashing, this work presents an innovative lashing-mortise-tenon timber joint specifically designed for the automatic construction with robotic systems while considering material circularity. The main contributions of this paper include the introduction of this novel timber joint design, which encompasses a detailed presentation of the applied methods, such as mortise-tenon, lashing, and prestressing, as well as the materials used, including glass fiber, along with a discussion of their respective advantages and limitations. Furthermore, this paper introduces the robotic assembly process and validates its feasibility, efficiency, and reliability through experiments conducted using a real bimanual robotic system. Directions for future research are outlined. A video showing the execution of the experiments is available at [19].

2. Design concept

The proposed lashing-mortise-tenon joint consists of pre-drilled holes, glass fiber and the prestressing device (Fig. 1 a). Due to the inherent flexibility of the lashing method, this joint can also be applied to many other joint types in timber construction, such as beam-to-post, post-to-beam and joist-to-beam (Fig. 1 b, c, d). The glass fiber threads are tied to steel shuttles for the lashing and prestressing processes. The prestressing device comprises a built-in liner, which is glued into a pre-drilled hole in the timber component, and a steel plate to fix the shuttles (Fig. 1 e).

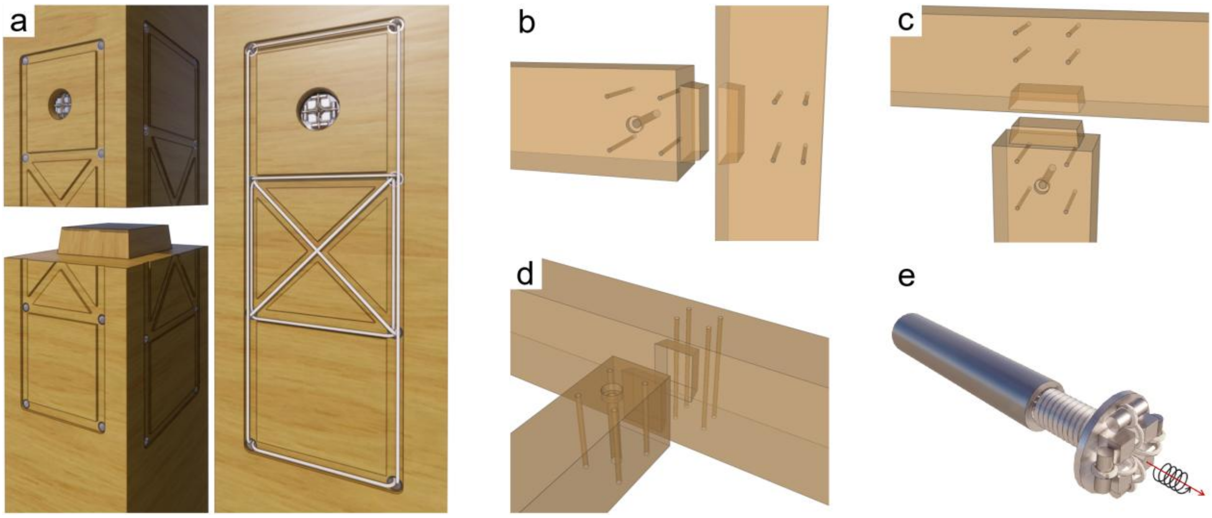

Fig. 1. (a) the proposed lashing-mortise-tenon joint (post-to-post); (b) beam-to-post joint; (c) post-to-beam joint; (d) joist-to-beam joint; (e) prestressing device.

The assembly of the proposed joint starts with the insertion of the mortise-tenon joint, which is controlled by measuring the position of the timber components using cameras and AprilTags. Afterwards, the lashing process is executed as the robot weaves the glass fiber threads around the joint through the pre-drilled holes and places the shuttles in the fixing plate. Then, for the prestressing process, the robot rotates the fixing plate (black arrow in Fig. 1 e), causing it to move along the liner (red arrow in Fig. 1 e) due to the screw mechanism. Thus, the fibers are tensioned with the resulting displacement of the fixing in the longitudinal direction of the built-in liner.

3. Advantages and limitations

The mortise-tenon joint is widely used in traditional timber construction [20], whereas lashing is widely used in bamboo structures [21, 22]. Some researchers have explored the combination of lashing and mortise-tenon joints for bamboo structures [23]. In this work, the combination of mortise-tenon and lashing joints is innovatively applied to timber joints to utilize the advantages of these two connection methods. The proposed lashing-mortise-tenon joint offers practical advantages in robotic assembly, disassembly and reassembly, construction tolerance and structural strength.

3.1. Robotic assembly

The mortise-tenon joint with chamfered edges provides auto-centering for the installation, which reduces the requirement on the accuracy of the robotic system to meet the capabilities of current robots. Besides, the connection method of lashing requires little direct contact between robots and building components, as the robots only need to drag the glass fiber threads through the pre-drilled holes of the building components. This significantly increases the success rate of the robotic manipulation, since robots excel at repetitive and structured tasks with high precision [24] and face significant challenges in executing contact-rich tasks, e.g. peg-in-hole tasks [25, 26].

3.2. Disassembly and reassembly

The mortise-tenon connection is inherently reversable and the disassembly causes nearly no damage to the construction parts. The lashing connection also provides convenience in disassembly and reassembly as it can be either untied or even cut open, which is why it is widely used in scaffolding or temporary construction in Hong Kong and South East Asia [23]. After being disassembled and reassembled multiple times, the damage to building components can be neglected and the frayed fiber threads can be replaced without significant effort, which further improves the reusability of the proposed joint.

3.3. Construction tolerance

The traditional mortise-tenon joint is highly sensitive to dimensional deviations, as the tenon width and the mortise width must align precisely to ensure both a smooth insertion and a tight connection. Even minor dimensional discrepancies at the millimeter scale can substantially increase the resistance force of insertion, potentially exceeding the maximum payload capacity of the robotic system. In this research, the shape of the tenon and mortise is modified to be trapezoidal, which ensures the insertion from size inaccuracies of the tenon and mortise. The resulting problem of having no tension bearing capacity in tenon direction is resolved by the lashing with glass fiber threads.

Dowels are commonly employed to provide shear and tensile load-bearing capacity in mortise–tenon joints. However, in contrast to fiber lashing, dowels impose stringent requirements on construction tolerances, as their load-bearing performance critically depends on a precise fit within the pre-drilled holes. In practice, deviations on construction sites can reach several millimeters, leading to misalignments between corresponding holes and rendering dowel insertion infeasible. In such cases, re-drilling becomes necessary, which not only delays the construction process but also adversely affects the structural integrity of the joint. Consequently, the use of lashings instead of dowels presents a significant advantage with respect to construction tolerance.

3.4. Structural strength

The interlocking nature of the mortise-tenon joint ensures satisfying structural stability and strength, which is why the mortise-tenon connection is applied to carry the shear, bending and torsion loads in the proposed joint. However, the mortise-tenon joints are only semi-rigid [27, 28] and usually lack the pull-out resistance in the tenon direction [20]. Besides, they inevitably have gaps due to the installation or the loading, which will affect the ultimate strength [29]. These disadvantages are avoided by the lashing and prestressing of the glass fiber threads, which also improves the overall strength and stiffness of the joint, as the chosen lashing material of glass fiber has high tensile strength (up to 3400 MPa) [30, 31, 32].

Another benefit of prestressing in timber construction lies in the fact that the tensile strength of wood perpendicular to the grain direction is weak due to anisotropy while in practice it is very difficult to avoid tensile loading in this direction, which may cause brittle splitting failure of the wood member [33, 34]. This problem can be solved by additional lashing and prestressing in the direction perpendicular to grain, as the fiber carries the unavoidable tension load and thus brittle splitting failures can be avoided.

3.5. Limitations

The proposed joint has several limitations that must be considered. First, it requires pre-drilled holes and pre-installed metal parts in the timber components, leading to increased production costs. Additionally, the maximum achievable prestressing force is limited by the payload capacity of the robotic system. Moreover, the applied prestressing force in the glass fiber threads is estimated indirectly through the robotic arms' torque sensors, making the accuracy of this estimation susceptible to factors such as rust and deformation of the prestressing device. Furthermore, long-term deformation of both the prestressing device and the timber components may lead to a gradual reduction in the prestressing force. External influences, such as dynamic vibrations caused by wind or seismic activity, may further impact the stability of the prestressing force over time. Consequently, long-term and dynamic testing are essential to assess the joint's performance in real buildings under various conditions.

4. Experiments

4.1. Hardware setup

The experiments with the real bimanual robotic system serve as a proof of concept focusing on the feasibility of the automatic assembly process of the proposed joint. The hardware setup is shown in Fig. 2 a. The bimanual robotic system consists of two collaborative robotic arms installed side by side, for which the model Franka Research 3 is chosen, which has seven degrees of freedom and a payload of 3 kg. The left arm is equipped with a tube to handle the steel shuttle, while the right arm has two 3D printed fingers to grasp the shuttle and a screw driver for the prestressing process. Both robotic arms are equipped with eye-in-hand cameras of the type Realsense D405 for the localization of the building components. The positions of the pre-drilled holes and prestressing device are pre-defined in reference to the AprilTags on the building component. An impedance controller [35] is chosen for the robotic arms to reduce the impact forces when the two arms are passing the shuttle and to tolerate position inaccuracies.

4.2. Experimental setup

The mortise-tenon joint is shown in Fig. 2 b. The installation of the mortise-tenon joint is no significant challenge for the bimanual robotic system due to the chamfered edges of the mortise-tenon design. Moreover, the feasibility of the robotic assembly of the mortise-tenon joint has been proven by many works [13, 26]. Therefore, this research will focus on the lashing and prestressing processes. The assembly of the mortise-tenon joint is shown in the video [19].

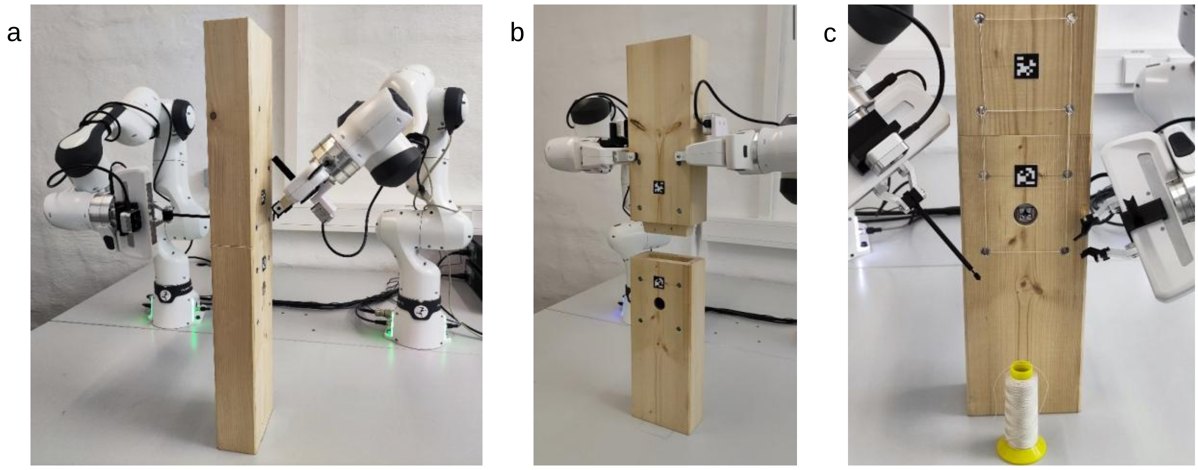

Fig. 2. (a) hardware setup; (b) mortise-tenon joint; (c) experimental setup.

The experimental setup is shown in Fig. 2 c. The joint type of post-to-post is chosen representatively. The cross-section of the post has the dimension 16 cm × 8 cm. At each post, four lashing holes of 12 mm diameter are pre-drilled and steel inner liners (outer diameter 12 mm, inner diameter 10 mm) are installed to protect the timber from stress concentration of the glass fiber. The applied glass fiber sewing thread has a PTFE coating and the diameter is 0.5 mm.

4.3. Lashing

As illustrated in Fig. 3 a, the lashing is accomplished by the two robotic hands passing the shuttle back and forth through the pre-drilled holes. There is no contact between the robot and the building components in this process, which simplifies the control of the robot and enhances the reliability of the process. The inner diameter of the pre-drilled holes (10 mm) is larger than the tube (8 mm) to compensate for inaccuracies of the robotic manipulation. After the shuttle has travelled through all planned holes, it is placed into the recess of the fixing by the robotic hand (Fig. 3 b).

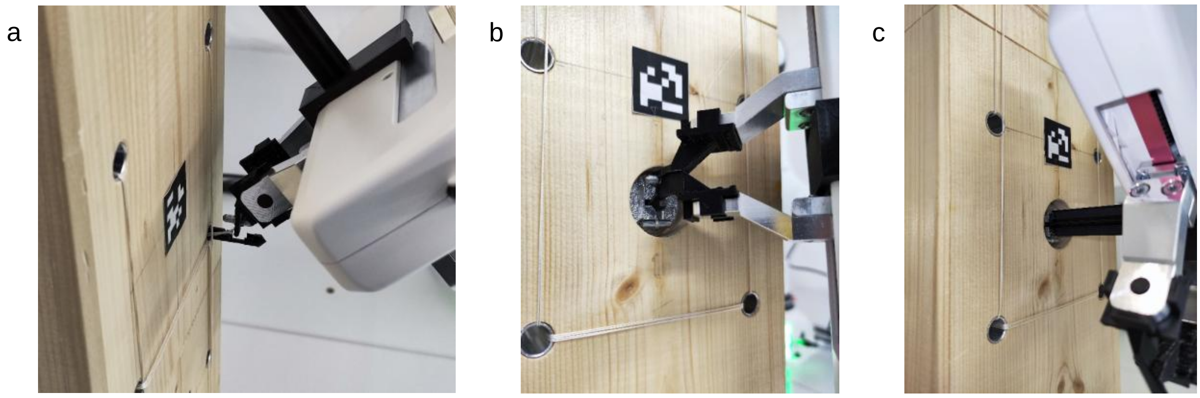

Fig. 3. (a) lashing; (b) placing the shuttle into the fixing; (c) rotation of the fixing.

4.4. Prestressing

After all the shuttles are placed in the fixing, the robot rotates the fixing (Fig. 3 c), making it move outwards and the glass fiber threads are stretched and tightened. By continuing the rotation, the tension force in the threads increases and the joint is prestressed. In this research, the prestressing force is only applied qualitatively. The robotic system is set to stop rotating the fixing at a predefined limit of the joint torques of the robotic arms, which indirectly ensures that the glass fiber threads are tightened.

4.5. Results

The automatic lashing and prestressing of the designed lashing-mortise-tenon joint for the post-to-post connection is executed effectively by the bimanual robotic system. The total inaccuracy of the robot's hardware and the AprilTag detection is around ±1 mm, which is smaller than the requirement of the proposed design and thus ensures the robustness of the assembly process. The designed automatic prestressing process of the glass fiber threads demonstrates satisfactory performance in the experiments with sufficient tension force being provided for the structural stiffness of the joint according to qualitative evaluations. The results of the experiments not only confirm the feasibility of the proposed joint, but also show its advantages in efficiency and reliability of the robotic assembly process.

5. Conclusions and future work

This study has introduced a novel lashing-mortise-tenon timber joint, which integrates the traditional mortise-tenon joint with prestressed glass fiber lashings, to address the principal shortcomings of existing timber joints for robotic assembly. By combining chamfered, trapezoidal tenons for self-centering insertion with flexible fiber lashings and an active prestressing mechanism, the proposed joint achieves reusability, installation efficiency, and insusceptibility to construction tolerances while maintaining sufficient structural stiffness and strength.

The feasibility of fully automatic assembly was demonstrated on a real bimanual robotic platform with Franka Research 3 robotic arms and eye-in-hand cameras for localization with AprilTags. Experimental results confirmed that the insertion inaccuracies remained below the tolerance threshold of the design and the contact-free lashing procedure significantly simplified robot motion planning and enhanced reliability. Furthermore, the prestressing approach produced adequate tension force to ensure joint stiffness. These outcomes substantiate the joint's applicability for automated timber construction, combining efficiency and flexibility with robust performance.

In the next research phase, the strength and stiffness of the lashing-mortise-tenon joint will be analyzed quantitatively with load tests, such as tension test, shear test and dynamic loading test. The results will be analyzed to derivate a model for the failure mechanism, which can then be used for the design calculation. Furthermore, the prestressing force of the fiber and its relation to the joint's stiffness and strength will be investigated. Methods will be developed for the robots to measure the applied prestressing force, e.g. with a special end-effector.

To increase the robustness and efficiency of the robotic manipulations in the assembly process for the real construction site, further development of the bimanual robotic system is necessary, including its upscaling and the development of task-specific end-effectors for the lashing, analysis of the accuracy of the positioning with AprilTags in on-site conditions and the application of more advanced control algorithms, e.g. force control, visual servoing, reinforcement learning etc. After the bimanual robotic system is capable of executing the assembly task autonomously, it will be either mounted onto a mobile base or implemented into a humanoid robot to allow for autonomous navigation and movement on the construction site.

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