Growth and Iteration: Exploring Tectonic Design with Natural Tree Branch Materials from the Perspective of Tree Morphology

Zhixin WEN[1] , Congcong REN[2,*] , Xin YAN[3]

Abstract: The growth process of trees embodies efficient and ingenious structural characteristics, where high-strength fibers grow along the axial direction of branches, making it a biologically smart material that is difficult to simulate. For a long time, due to various factors, a large amount of unconventional lumber, such as natural tree branch materials, has not been utilized in the construction of buildings, resulting in the wastage of its unique organic structural morphology and mechanical properties. Based on the perspective of tree morphology, this study analyzes and learns from the growth patterns, structural forms, and environmental adaptations of trees. It proposes an iterative algorithm for simulating growth structures based on the Grasshopper platform, and elaborated on the issues of data transformation and control. In terms of subjective control methods, a manual adjustment method and an automatic generation method were innovatively proposed and tested to varying degrees. Regarding digital construction, the study focused on simplifying joints and innovating mortise and tenon structures, conducting preliminary construction experiments. This research initially explores a method for the design and construction of wooden structures using natural tree branch materials from the perspective of tree morphology. It is dedicated to finding new wooden structural forms that fully utilize the organic structural characteristics of trees.

Keywords: Natural wood, Tree morphology, Computational design, Design-to-fabrication, Traditional structure.

1 Introduction

1.1 Background

In recent years, wood, as a traditional building material, has regained attention and undergone a revival globally. However, the mainstream wooden architecture still primarily uses standardized straight components as the core structural elements. Looking back at history, instances of unconventional wood usage, though existing, are relatively few. For instance, in 17th-century Europe, the shipbuilding industry had a history of utilizing curved wood (Vial du Clairbois 1783) , while in China, some non-standard wood was employed in the construction of southern pile-dwelling houses and northern open-timber roof structures (see Fig. 1) (Yang 2016). Nevertheless, due to the historical predominance of orthogonal or beam-column systems in architecture, and the tendency for architectural volumes and structural demands to favor straight components, this limited the widespread application of unconventional wood.

Since modern times, influenced by the development of concrete and steel structure buildings, wooden architecture technology has also made progress, such as the development of high-quality cross-laminated timber (CLT). However, the application of unconventional wood, such as natural forked materials, is still insufficient. The potential of the research for this part is huge.

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[1] Z. Wen, Beijing University of Civil Engineering and Architecture, No.1 Exhibition Hall Road, Beijing, China, e-mail: wenzhixin0509@163.com

[2] C. Ren (🖂), Beijing University of Civil Engineering and Architecture, No.1 Exhibition Hall Road, Beijing, China, e-mail: rencongcong@bucea.edu.cn

[3] X. Yan, Beijing University of Civil Engineering and Architecture, No.1 Exhibition Hall Road, Beijing, China, e-mail: yanxin@bucea.edu.cn

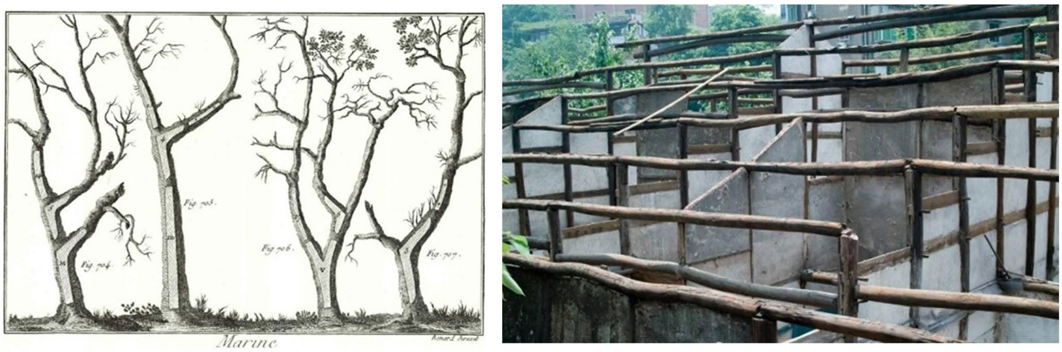


Fig. 1 Curved wood used in European shipbuilding in the 17th century (left) and unconventional wood application in Chinese pile-dwelling houses (right)

1.2 Related Research

First, it is necessary to review traditional tree morphology. Halle founded a school dedicated to related research in the 1970s and summarized 23 types of tree development (Hallé et al. 1978), marking a significant research milestone. Before the introduction of computer technology, tree morphology primarily involved typological analysis of trees from a botanical perspective. Starting with Honda's pioneering use of parametric methods to create simple tree shapes (Honda 1971), computer simulation of tree morphology emerged as a research direction in the field of ecology. In 1999, CIRAD released the Amapsim software, which became a versatile tool for plant structural modeling. In recent years, the topic of computer-simulated tree morphology has begun to integrate with newer technologies and has expanded into interdisciplinary fields such as 3D scanning and AI (Cardenas 2022). The objective of these studies is to better simulate and demonstrate real growth patterns, unrelated to the design or development of structures using these branching materials. Nevertheless, these explorations in tree morphology provide valuable insights for design.

Despite the absence of work in the architectural field that designs and constructs developments from a tree morphology perspective, studies have shown that the geometric and mechanical advantages of tree canopies can be applied to architectural design (Bao. 2022). In recent years, many research teams have conducted studies on the utilization of unconventional wood materials (branches). These studies mainly focus on the combination of structural optimization and form-finding in branch wood structure with robotic digital construction. In this regard, these researches tend to first adopt general methods to design an original structure and then use specific methods and material libraries for matching. For instance, a geometric matching method, which was based on a Vierendeel-style arching truss, was implemented (Mollica and Self 2016). Additionally, a matching approach that originated from ParaGen was put to use (Von Buelow et al. 2018). Other research teams either adopted the Hungarian algorithm-based matching method (Amtsberg et al. 2020) or implemented a matching technique anchored in graphic statics (Chai et al. 2024). The essence of such practices is to make unconventional wood and topological form-finding methods adapt to each other, with the tectonic logic based on preexisting design methodologies. However, the unique characteristics of unconventional wood originate from its growth process, including its structural properties and organic forms. To better utilize this material, rather than just reducing construction waste, it is necessary to explore a tectonic logic and method from tree morphology that align with its growth process and leverages its structural and morphological features.

2 Analysis of Tree Growth in Nature

The growth direction and morphology of trees are the result of multiple factors, including both environmental and internal factors.

2.1 Environmental Factor: Light and climate

Research has shown that trees adapt to their environment primarily through secondary growth processes, which determine their survivability. Among the environmental factors in nature, the photoperiod is the most stable, playing a dominant role in controlling the start, stop, and speed of tree growth processes (Saderi et al. 2019). On the side with sufficient light, tree branches tend to grow towards the light source to maximize photosynthetic efficiency. This phototropic growth results in branches forming larger angles in the direction of light, making the tree canopy more open. The size difference in the gaps formed during tree growth largely determines the success of branch growth. A larger gap provides a greater advantage, increasing the likelihood that the branch will eventually reach the canopy layer and contribute to a lush growth (Poorter 1999).

In the context of global warming, temperature and climate are important factors that affect tree growth, and continuous climate change will trigger a geographical redistribution of growth responses to climatic factors (Babst et al. 2019). Among these factors, rain and snow can cause mechanical damage to tree branches, affecting their growth direction and morphology. Therefore, in areas with more rain and snow, trees often develop more resilient and flexible branch structures to adapt to this stress. Meanwhile, wind plays a crucial role in the changes during tree regeneration and succession stages. Under strong winds, trees can reposition themselves, reconfigure their canopies, or shed leaves and branches to reduce resistance (Gardiner et al. 2016). In areas with stronger winds, to reduce wind resistance and enhance stability, trees often grow lower and have smaller branch angles to minimize the impact of the wind.

2.3 Internal Factors of the Plant

From a microscopic perspective, axial growth indeed occurs along the fiber direction within the tree, and this growth pattern plays a crucial role in the tree's resistance to various natural forces, thereby maintaining its stability. The fiber direction of tree branches is primarily longitudinal, arranged parallel to the main axis of the branch. Additionally, the tensile and compressive strength of wood along the fiber direction (i.e., axial direction) is much greater than its strength under transverse (radial and tangential) forces (Hoadley 2000). This arrangement allows them to better distribute and resist pressure when subjected to gravity or external impacts, making the tree more stable when withstanding natural forces such as wind and snow pressure.

In summary, the various factors influencing the transformation of a sapling into its final form through the growth process have long contributed to the environmental adaptability of trees. Through this adaptability, trees can overcome survival difficulties under different conditions and form stable macro and micro structures. This project embarks on a tectonic exploration from the perspective of tree morphology. The aim of this study is to imitate and simplify the tree growth process into quantifiable geometric parameters by extracting geometric features. Utilizing these geometric parameters, we seek to simulate the tectonic logic of tree growth and control the structural form of constructions, thereby better exhibiting the inherent characteristics of unconventional lumber.

3 Iterative Algorithm for Simulating Growth Structures

Through the analysis of tree morphology, two simplified geometric features have been identified as essential for representing tree growth patterns. Firstly, the direction of extension must be axial. Secondly, the angle of growth varies to adapt to the environment.

The axial direction, as a critical component of tree growth, refers to the characteristic of trees to extend along the branch angle after each bifurcation. In the absence of human intervention, such as pruning or suppression, most tree branches maintain a relatively stable extension angle before undergoing the next bifurcation, without sudden angle changes. This characteristic plays a decisive role in the unique mechanical properties of the tree's fiber structure. Preserving the axial growth logic is particularly important when utilizing unconventional lumber to construct structures that can fully leverage its performance. This viewpoint has been widely recognized in previous related studies (Amtsberg et al. 2020) (Von Buelow et al. 2018).

The angle of branch development, which determines the direction of each bifurcation, influences the growth trend before the next bifurcation. The core of the simulated growth algorithm lies in transforming the natural variation of tree growth angles into easily controllable algorithmic parameters. Unlike previous studies that initially searched for shapes and then matched them, this study approaches the problem from the perspective of existing unconventional lumber objects and constructs based on a digital material library, utilizing growth iteration logic.

There are mainly two challenges in this approach. The first challenge is how to extract the angles from existing unconventional lumber for iteration, rather than for matching (*Data Conversion Issues in Existing Material Libraries*). The second challenge is determining the method to control the direction of each iteration (*Control Issues in Iterative Algorithms*). The following are two issues elaborated separately.

3.1 Data Conversion Issues in Existing Material Libraries

In projects involving construction with existing components, material database establishment issues in material libraries are quite common, and relevant research provides valuable references (Amtsberg et al. 2020) (Chai et al. 2024). Initially, discarded tree branches were collected from the horticultural departments of Beijing Zoo and Zizhuyuan Park after pruning, which served as raw materials. The excess parts of them were then trimmed at the Beijing University of Civil Engineering and Architecture's woodworking workshop. Following this, 3D scanning technology was employed to digitally model these branches. The Mesh models underwent post-processing, were centrally numbered, and a database was established (see Fig. 2).

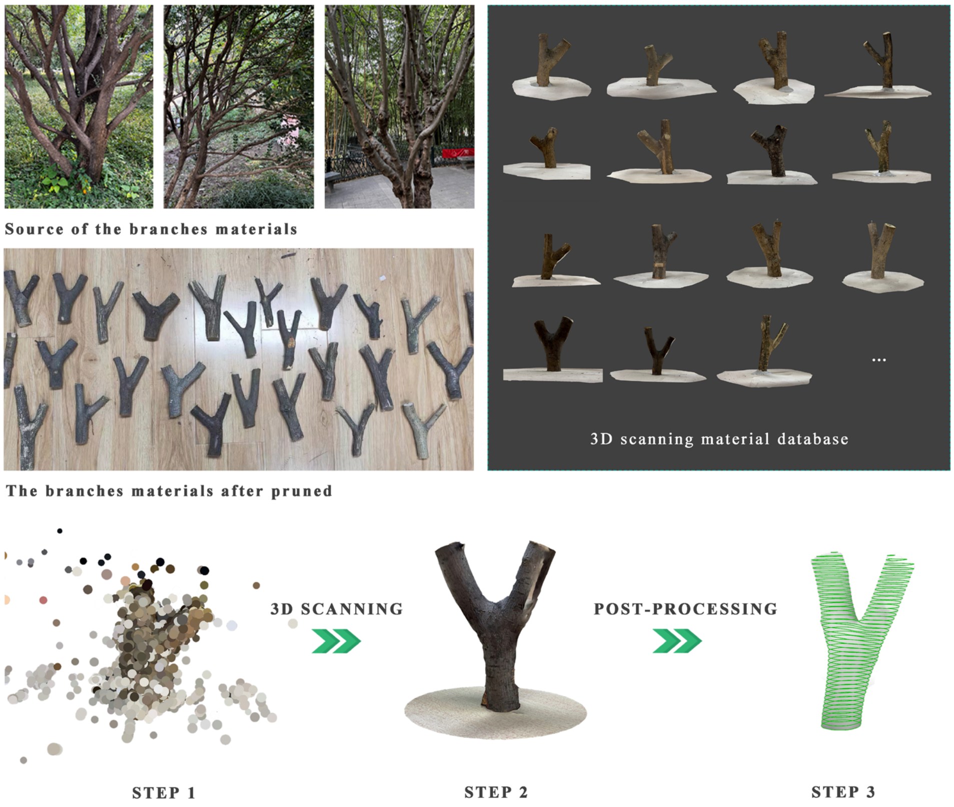


Fig. 2 Data conversion issues in existing material libraries (Including the whole process from material collection to 3D scanning)

To facilitate the extraction of required geometric data from the material library, Rhino's Grasshopper parametric design platform was utilized. By analyzing the center points of the cross-sections of tree branches, the complex material models were simplified into linear models. This approach was derived from an understanding of wood cross-sections. The simplified linear models contain 'n' length data points and 'n+1' angle data points. Additional angle data was obtained by setting a special plane with its origin at the bifurcation point.

3.2 Control Issues in Iterative Algorithms

Subsequently, based on the constructive logic of growth iteration and the simplified linear model, we designed a geometric variation method that simulates growth for data conversion in the material library. This method also serves as the core of the iterative algorithm, influencing its control logic (see Fig. 3).

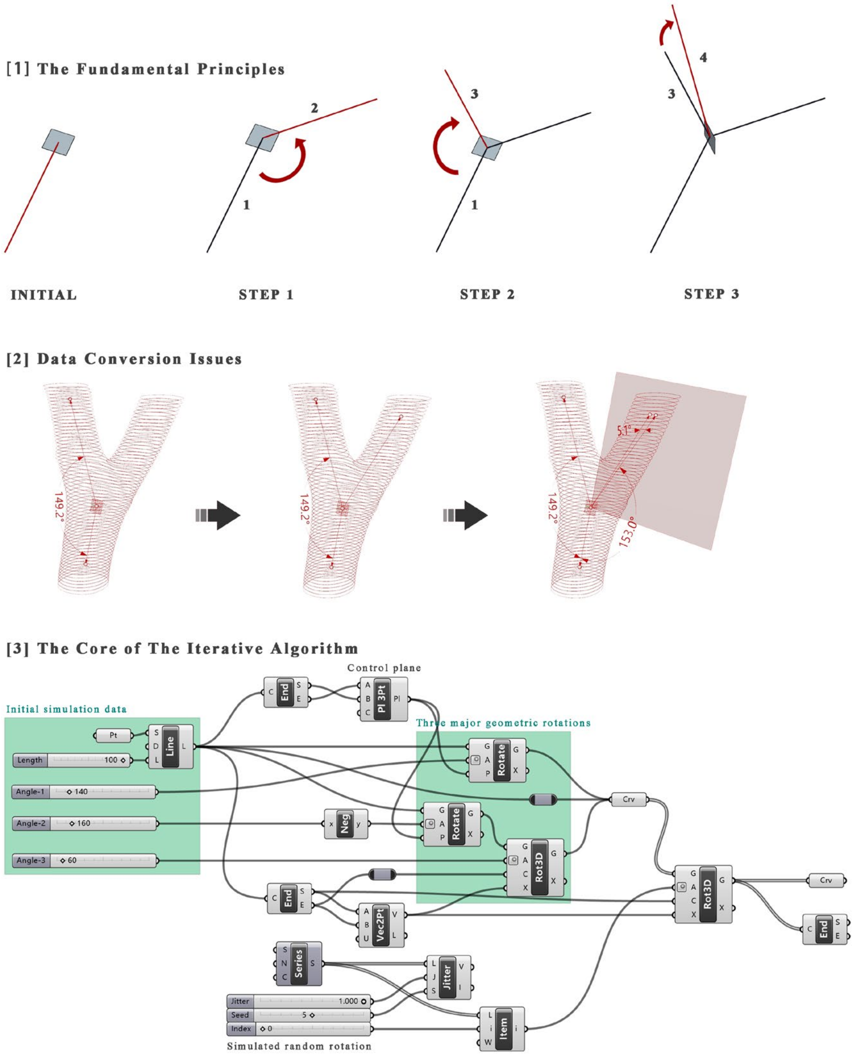


Fig. 3 The geometric variation method applied to both data conversion and control issues in the iterative algorithm

This approach consists of a three-step process:

1. Using the line extended from the previous iteration as Line 1, perform the first rotation on a specific plane by an angle of 'a' to obtain Line 2.
2. Rotate Line 1 on the same plane for a second time by an angle of 'b' to get Line 3.
3. Rotate Line 3 on a plane perpendicular to the original plane by an angle of 'c' to generate Line 4.

Ultimately, a new tree branch is formed by Lines 1, 2, and 4. The entire process can be fully represented by just three angle data points: a, b, and c. This also implies that with these three data points, both data conversion in the material library and control of the iterative algorithm can be achieved (see Fig. 3).

Using this method, a large number of tree branch models in the material library can be converted into sets of three data ports, including a switch to adjust the positive or negative connection of the branches. It should be emphasized here that adjusting the positive and negative orientation of tree branches involves remodeling the tectonic logic. On one hand, pure biomimicry is disrupted, as the iterative algorithm does not merely imitate tree growth; on the other hand, it facilitates designers to create new forms. In subsequent research, the algorithm demonstrates that regular combinations of positive and negative orientations can create structural forms with principles of spaced growth and logical order.

During the algorithm's execution, the data ports of the tree branch models are inputted into multiple steps of the algorithm in the form of GH components. Ultimately, controlling the growth iteration algorithm can be accomplished by simply changing the number of each newly grown tree branch and adjusting its axial rotation angle. Additionally, a method is provided to select the branches that need to continue growing after each iteration, allowing the rest to stop growing and preventing uncontrollable data situations (see Fig. 4). The paper provides a flowchart analysis of the algorithm to offer clearer insights into the methodology for future researchers (see Fig.5).

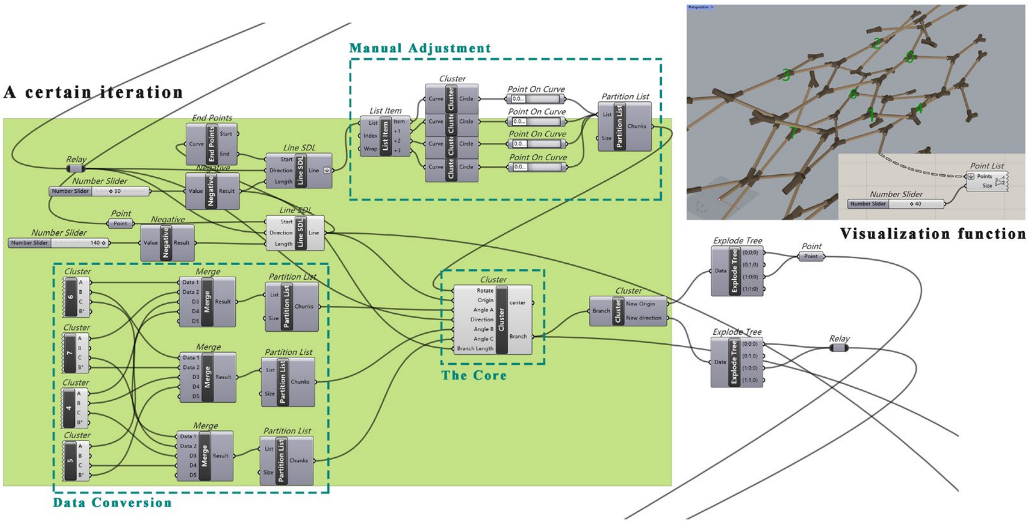


Fig. 4 Iterative algorithm process and visualization capabilities based on the GH platform

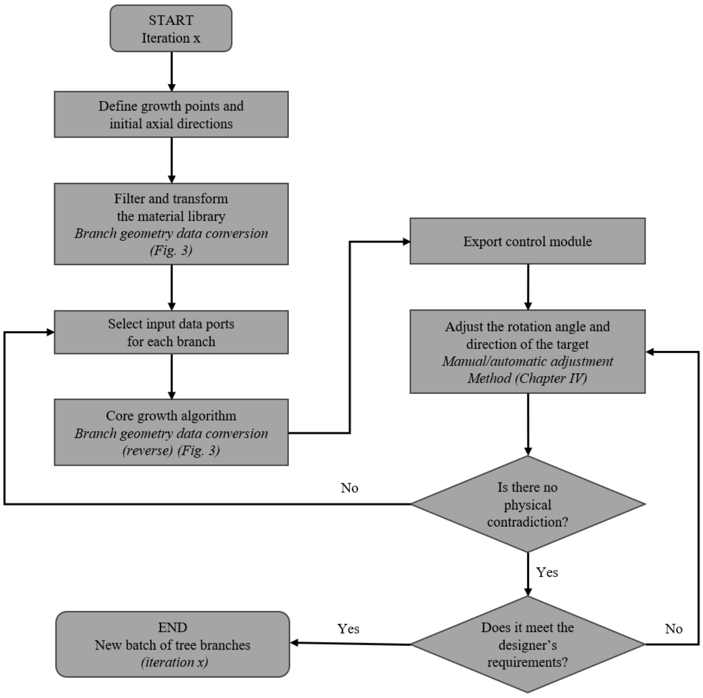


Fig. 5 Flow chart analysis of iterative algorithm

4 Subjective Control Methods and Construction Exploration by Designers

After completing the design of the simulated growth iteration algorithm, its tremendous potential in construction has been recognized, representing a unique design approach and tectonic logic. Initially, through initial experiments, such as adjusting axial rotation and directional changes, various structural forms have been created (see Fig. 6). Although these structures meet certain usage requirements and have passed structural calculations, they cannot be effectively controlled, and there are some contradictions in the details. Expecting them to be better utilized by designers or to create more fascinating structural trends necessitates special control methods to meet subjective demands.

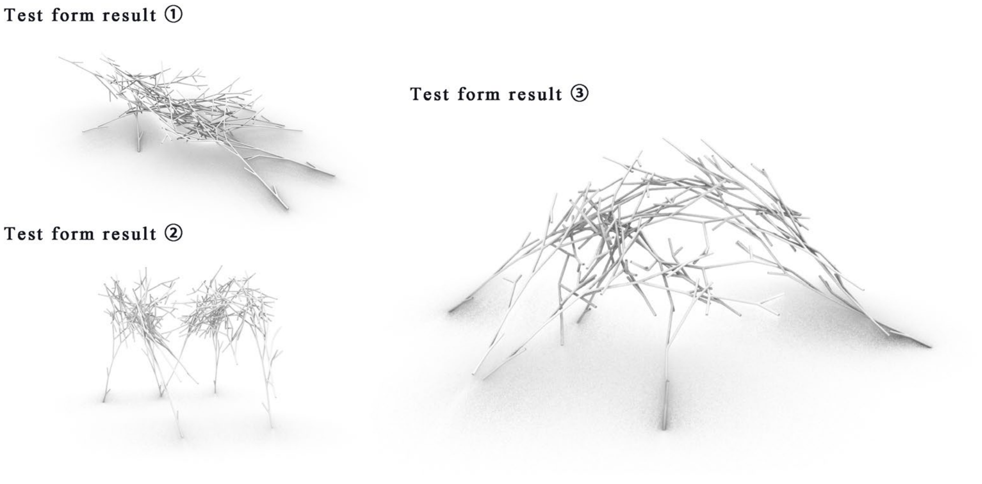


Fig. 6 Structural forms of three early tests

In this regard, some preliminary exploratory research has been conducted. Two potential solutions are proposed: Manual adjustment and Automatic generation: *Manual adjustment* and *Automatic generation*. Among them, this article focuses on elaborating manual adjustment. The manual adjustment method allows designers to make detailed adjustments based on personal needs, enabling flexible control over the morphological trends of different stages and parts during the growth process, thus achieving free manipulation of the entire growth form. However, this method is more suitable for smaller-scale branch structures. In contrast, the automatic generation method needs to be combined with other algorithms to control morphology by finding optimal data that meets specific requirements, making it more advantageous when dealing with larger-scale branch structures, this method is still in the initial exploration stage.

Based on the simulated growth iteration algorithm, adjustments have been made to enable precise positioning of each branch through labeled serial numbers, allowing individual rotation and directional changes. Designers can gradually control the shape of the structure according to the iteration sequence. This regulation method, known as the manual adjustment method, is suitable for integration with AR-assisted construction technology. This approach enables designers to experience the construction process in a tactile manner and closely observe the geometric transformation of each branch.

The study has conducted multiple tests on this method and successfully designed a structural unit. This unit can be presented as an independent installation art or integrated into a larger-scale architectural structure as a crucial component of a column. To verify its structural stability and practicality, structural tests were conducted, and a 1:50 scale 3D-printed model was further produced to visually demonstrate its final presentation (see Fig. 7).

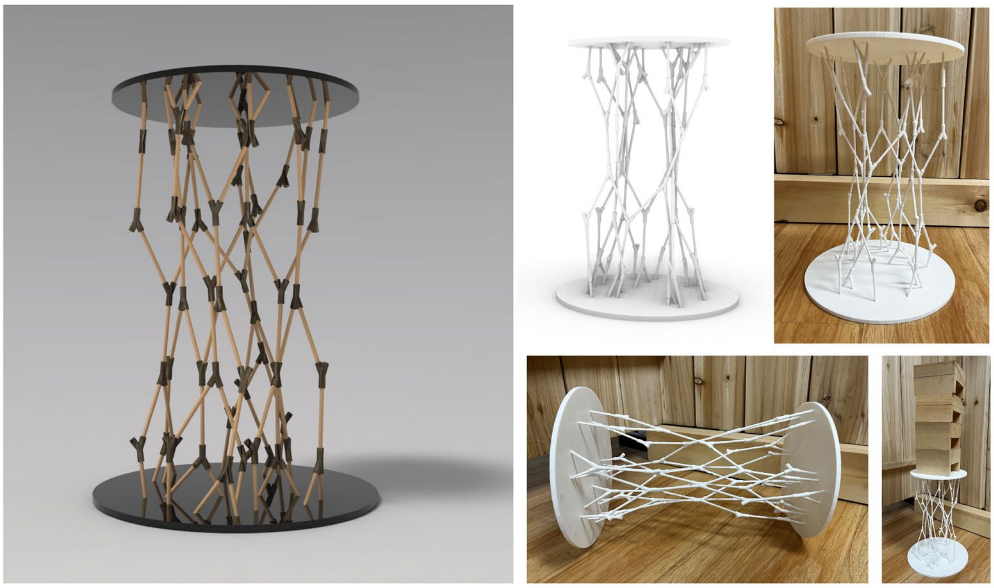


Fig. 7 Manual adjustment case and a 1:50 scale 3D-printed model

The other regulation method is the automatic generation approach, with the aim of enabling the growth iteration algorithm to extend along a specific surface to achieve a particular form. Currently, the simulated annealing algorithm has been adopted for initial testing. This algorithm can locate the closest point to the surface during each iteration, assisting numerous branches to precisely pinpoint the most suitable position on the surface. Nevertheless, certain contradictions and issues arise during the actual operation process, necessitating continuous optimization and enhancement of this advanced algorithm in future research.

5 Construction Attempts of Mortise and Tenon Joints in Timber Structures

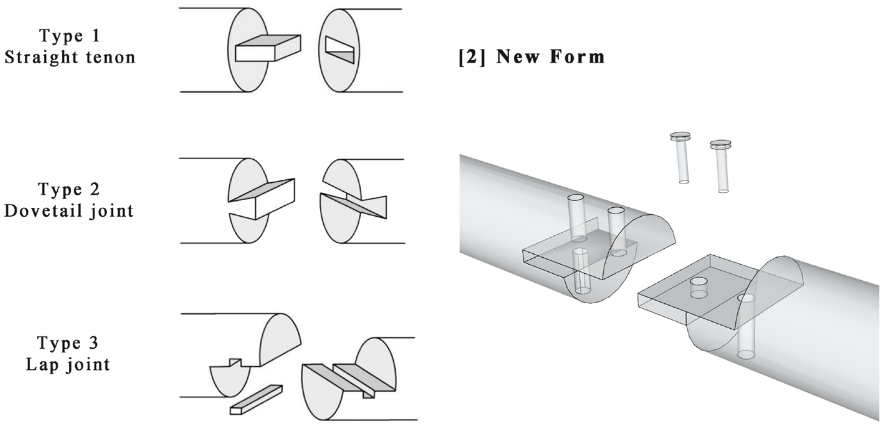
In the design process of timber structures using natural tree branches, the exploration of joint design and construction methods is also crucial. In the previous section, the paper has elaborated on the value of unconventional lumber as a construction material from the perspective of tree morphology, as well as the construction logic that can maximize these values and advantages. In fact, besides a generative algorithm that can assist design, matching joints and construction methods are also an indispensable part of realizing its value.

In past related studies, most research teams have focused on utilizing digital manufacturing techniques to process unconventional lumber, such as milling operations performed by robotic arms, this is primarily due to the complex shapes and difficult positioning of unconventional lumber. However, the high capital costs and technical thresholds make it difficult for ordinary designers to access and apply. Our team has been dedicated to the modern interpretation of traditional construction techniques and structural forms, using them as a lubricant in the initial exploration of digital construction to address the widespread transitional issues in current architectural practices (Yan. 2023).

This study focuses on enhancing the performance of unconventional lumber by optimizing wooden joints while simplifying the complexity of digital fabrication. Therefore, while advancing the integration of digital manufacturing with unconventional lumber, study have focused on simplifying the processing difficulty at the joint level. Among the various techniques for connecting members in traditional construction, such as straight tenon, dovetail tenon, and lap joint, each has its advantages and disadvantages. For these joints, our team has conducted research and practical tests in recent projects (Wen. 2024). The straight tenon, for instance, is the most straightforward but often requires pins to prevent detachment. The dovetail tenon is suitable for connecting members, but its complex shape can affect the strength of smaller-diameter tree branches after processing. The lap joint is easy to process, locate, and mill, but its aesthetic appeal may be affected when connecting natural and conventional materials.

Utilizing the woodworking workshop at Beijing University of Civil Engineering and Architecture, digital modeling and physical processing were conducted for these three types of joints, and structural units were built to test the connection effectiveness (see Fig. 8). Currently, preference is given to a new type of mortise and tenon joint that combines the straight tenon and lap joint for unconventional lumber construction. This structure offers ease of location, simplicity in milling, aesthetic appeal, and reliable strength. With this structure, standard woodworking equipment can complete special angle processing, and the required operator skill level is not high. Future research plans include exploring the construction practices of unconventional lumber structures and implementing the aforementioned digital construction achievements.

[1] Traditional mortise and tenon joint



[3] The testing process of joints

Fig. 8 The design and manufacturing experiment process of translating traditional mortise and tenon structures

Conclusion

From the perspective of tree morphology, this study conducted an exploration of the impact of environmental factors on tree morphology, as well as the growth logic and structural characteristics of tree forms, through the analysis of natural tree growth. Based on this understanding, an iterative algorithm was proposed to simulate growth structures, and elaboration was provided on the data conversion of existing material libraries and the control issues of the iterative algorithm. In terms of subjective control methods, a manual adjustment method and an automatic generation method were innovatively proposed and tested to varying degrees. Regarding digital construction, the study focused on simplifying joints and innovating mortise and tenon structures, conducting preliminary construction experiments.This study not only provides a new perspective and approach for the use of unconventional lumber in construction but also offers designers a flexible and creative simulation method during the creative process.
However, the current research still has certain limitations and its potential awaits to be unleashed through new research initiatives. In terms of the algorithm itself, the automatic adjustment modules requires further optimization, including new functionalities such as selecting iterative targets, avoiding other branches and

optimizing structures automatically. Through such optimization, the growth-iterative algorithm can better handle the construction process of large-scale naturally branching materials, and reducing errors. Meanwhile, the research will also continue to make attempts in practical construction. Using the optimized algorithm to design and construct 1:1 small-scale indoor structural installations will further demonstrate the architectural and structural practical value of the algorithm.

Lastly, attention should also be drawn to the potential and value of this research from a general architectural perspective. Firstly, the use of unconventional wood brings new possibilities to sustainable building materials, by leveraging algorithms to design and construct using unconventional materials. This is a significant approach that can be extended to a wide range of unconventional building materials, such as natural irregular materials, recyclable building materials and other industrial wastes. At the same time, the potential link between the use of unconventional materials and modular, discrete architecture cannot be overlooked. New materials, tectonic logics, and workflows will create novel forms and architectural languages. Just as parametric design has brought new variations to the morphological expression of wooden structures, the possibilities offered by unconventional materials are equally anticipated.

References

1. Amtsberg, F., Huang, Y., Marshall, D., Gata, K. M., Mueller, C., Amtsberg, F., ... & Mueller, C. (2020). Structural upcycling: Matching digital and natural geometry. Advances in Architectural Geometry.
2. Babst, F., Bouriaud, O., Poulter, B., Trouet, V., Girardin, M. P., & Frank, D. C. (2019). Twentieth century redistribution in climatic drivers of global tree growth. Science advances, 5(1), eaat4313.
3. Bao, D. W., Yan, X., & Xie, Y. M. (2022). Fabricating topologically optimized tree-like pavilions using large-scale robotic 3D printing techniques. Journal of the International Association for Shell and Spatial Structures, 63(2), 122-131.
4. Cárdenas, J. L., Ogayar, C. J., Feito, F. R., & Jurado, J. M. (2022). Modeling of the 3d tree skeleton using real-world data: a survey. IEEE Transactions on Visualization and Computer Graphics, 29(12), 4920-4935.
5. Chai, H., Zhou, X., Gao, X., Yang, Q., Zhou, Y., & Yuan, P. F. (2024). Integrated workflow for cooperative robotic fabrication of natural tree fork structures. Automation in Construction, 165, 105524.
6. Cárdenas, J. L., Ogayar, C. J., Feito, F. R., & Jurado, J. M. (2022). Modeling of the 3d tree skeleton using real-world data: a survey. IEEE Transactions on Visualization and Computer Graphics, 29(12), 4920-4935.
7. Gardiner, B., Berry, P., & Moulia, B. (2016). Wind impacts on plant growth, mechanics and damage. Plant science, 245, 94-118.
8. Hallé, F., Oldeman, R. A., & Tomlinson, P. B. (2012). Tropical trees and forests: an architectural analysis. Springer Science & Business Media.
9. Hoadley, R. B. (2000). Understanding wood: a craftsman's guide to wood technology. Taunton press.
10. Honda, H. (1971). Description of the form of trees by the parameters of the tree-like body: Effects of the branching angle and the branch length on the shape of the tree-like body. Journal of theoretical biology, 31(2), 331-338.
11. Mollica, Z., & Self, M. (2016). Tree fork truss. Advances in architectural geometry, 2016, 138-153.
Saderi, S., Rathgeber, C. B., Rozenberg, P., & Fournier, M. (2019). Phenology of wood formation in larch (Larix decidua Mill.) trees growing along a 1000-m elevation gradient in the French Southern Alps. Annals of Forest Science, 76, 1-17.
12. Poorter, L. (1999). Growth responses of 15 rain-forest tree species to a light gradient: the relative importance of morphological and physiological traits. Functional ecology, 396-410.
13. Vial du Clairbois, H. S. (1783). Encyclopédie méthodique marine. Panckouke, Paris, 1783.
14. Von Buelow, P., Oliyan Torghabehi, O., Mankouche, S., & Vliet, K. (2018, July). Combining parametric form generation and design exploration to produce a wooden reticulated shell using natural tree crotches. In Proceedings of IASS
15. Annual Symposia (Vol. 2018, No. 20, pp. 1-8). International Association for Shell and Spatial Structures (IASS).
16. Wen, Z., Yan, X., Ren, C. (2024). Digital Translation of Traditional tectonics: A Study on Parametric Design and Construction of Mortise and Tenon Timber Pavilion. Southern architecture (05), 50-57.
17. Yan, X., Bao, D. W., Ren, C., & Xie, Y. M. (2023, October). Constructing topologically optimized spatial structure using innovative mortise-and-tenon joints. In Proceedings of IASS Annual Symposia (Vol. 2023, No. 19, pp. 1-12). International Association for Shell and Spatial Structures (IASS).
18. Yang, C. (2016). Analysis on the Characteristics of Ancient Chinese Architecture. Cultural Relics Publishing House, Beijing, 2016.