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Research Progress of CFRP in the Protection of Wooden Components: From Mechanical Enhancement to Cultural Heritage Adaptation

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Abstract. Carbon fiber reinforced plastic (CFRP) have become a key technology for the maintenance of wooden components in ancient buildings due to their lightweight, high strength, corrosion resistance, and concealed construction characteristics. This paper systematically reviews the research progress of CFRP in the maintenance of wooden components from three dimensions: conditions, reinforcement methods and process parameters, and performance evolution after reinforcement. Addressing the core contradictions in current research, such as the obstruction of wood "breathing," interface creep, concealed damage, and irresponsibility, and combining emerging technologies such as modular connection components, it points out that future research should shift from simple chemical bonding to mechanical assembly, and from passive reinforcement to active control, in order to achieve an organic unity between improving mechanical performance and the principles of cultural heritage protection.

Keywords: CFRP, wooden components, ancient building protection, reinforcement, reversibility, durability

1. Introduction

Timber structures are the core carriers of historical buildings such as palaces, temples, and residences in my country, carrying extremely high cultural and scientific value. However, due to natural defects in wood and environmental factors, timber components commonly suffer from problems such as decay, insect infestation, and cracking. The "Technical Standard for Maintenance and Reinforcement of Ancient Timber Structures" (GB/T 50165—2020), promulgated in 2020, has raised higher requirements for the verification of the load-bearing capacity of timber frames. Traditional iron reinforcement methods easily damage the architectural style and are difficult to replace, while CFRP technology, especially the embedded reinforcement method, can significantly improve the performance of components without significantly changing the appearance, conforming to the principle of "restoring the old as it was," and has gradually become a hot topic in research and application. Reviewing the research of the past decade, the academic community has expanded from a single mechanical performance examination to multiple dimensions such as seismic resistance, creep, and damage monitoring. Chen Qingjun et al. and Zhou Qian et al. verified the seismic

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reinforcement effect of CFRP on mortise and tenon joints [1-4]. Wu Jianguo and Huang Junjie et al. revealed its enhancement mechanism on the axial compression performance of wooden columns [5, 6]. However, Xu Kai et al. pointed out that existing studies mostly focus on mechanical enhancement and ignore the potential negative impact of CFRP on the control of wood moisture content and long-term durability [7]. Based on this, this paper systematically analyzes the technical bottlenecks of current research from the perspectives of intervention conditions, reinforcement technology and performance evolution, and looks forward to future development directions in conjunction with cutting-edge dynamics such as modular assembly technology.

2. CFRP reinforcement of timber components: conditions, methods, and performance

2.1. Conditions and applicability of CFRP intervention in the maintenance of wooden components

The intervention of CFRP technology is not unconditionally applicable. Its decision depends on the accurate diagnosis of the damaged morphology and a deep understanding of the biological characteristics of wood. Damage to wooden components is common. Survey data shows that the cracking rate of beam structure components is generally as high as 85%, as shown in Figure 1. The basic form and scale of shrinkage cracks in ancient building wooden components. This provides a realistic background for CFRP reinforcement. However, the reinforcement effect shows a significant condition dependence. Zhang Lu et al.'s four-point bending test showed that the location of the defect determines the reinforcement effectiveness: the knots in the tension zone will greatly weaken the bending strength, and the effect of pasting CFRP cloth at the bottom is significant; conversely [8], if the defect is located in the compression zone, the reinforcement effect is negligible. In addition, the geometric parameters of the component are also a key constraint. Wu Jianguo's research pointed out that the CFRP hoop can improve the bearing capacity of wooden columns by about 5%~20% [5], and the effect is better for short columns with a small slenderness ratio, while the improvement is limited for columns with a large slenderness ratio. As shown in Figure 2, the slope of the load-displacement curve of the reinforced beam increased significantly, indicating that the CFRP fabric effectively improved the stiffness of the wooden beam; the increase in ultimate load confirmed the strength enhancement effect; the expansion of the curve envelope area reflected the simultaneous improvement of the bending and deformation performance of the wooden beam. It is worth noting that the characteristics of old wood with low shrinkage and stable dimensions provide CFRP reinforcement with better application conditions than new materials, effectively avoiding the risk of hoop loosening caused by wood shrinkage. In addition to the mechanical compatibility, the principle of cultural relic protection constitutes another layer of limitation for intervention. Xu Kai raised a particularly critical question using the Quxi Tower of Liuyuan Garden as an example: CFRP, as an airtight inert polymer material [7], will block the "breathing" channel of the wood when fully wrapped or hooped, causing moisture to accumulate at the interface between the wood and the adhesive layer. This will not only cause the adhesive layer to bond, but also accelerate the internal decay of the wood, which goes against the original intention of the maintenance project to "extend the life". Therefore, before deciding whether to intervene, it is necessary to comprehensively assess the component damage status, stress mechanism and dynamic balance requirements of wood moisture content, and avoid using mechanical performance improvement as the only intervention standard.

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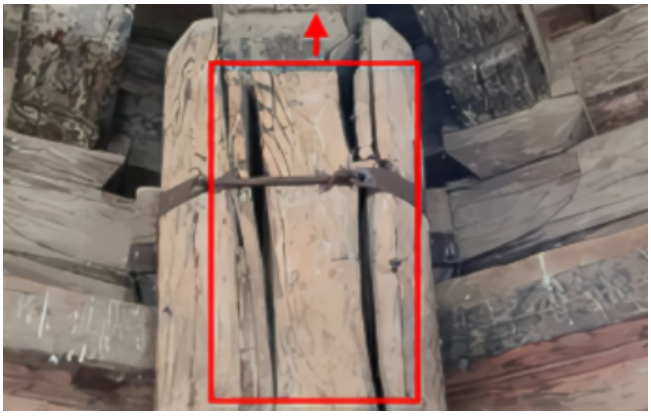


Figure 1. Cracking morphology of wooden components in ancient buildings

Note:Adapted from [J]. Research Progress on the Cracking Mechanism, Assessment, and Reinforcement of Wooden Components in Ancient Architecture. Wood Science and Technology, 2024,38.

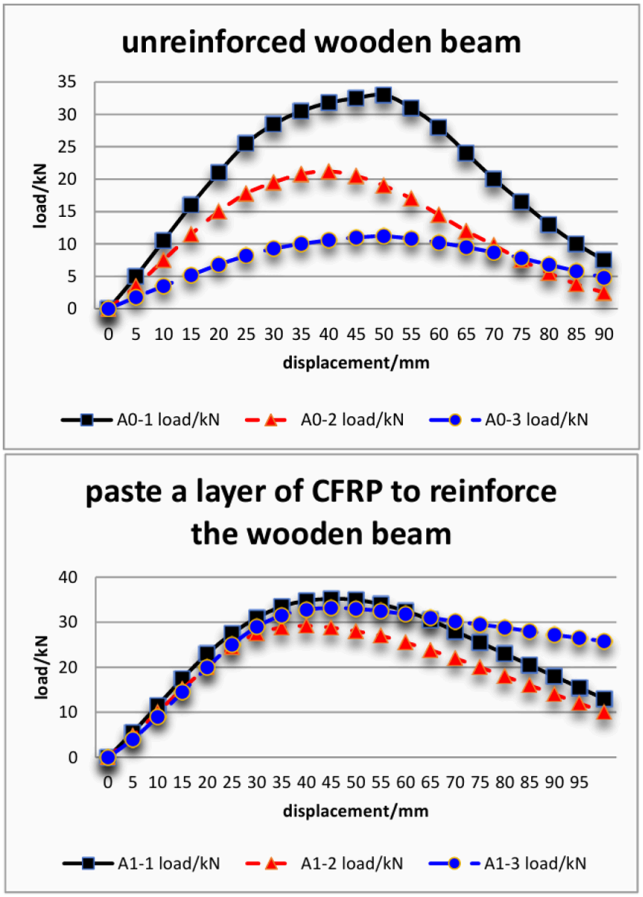


Figure 2. Load-displacement curve. a: Unenforced wooden beams b: Paste a layer of CFRP to reinforce the wooden beam.

Note:Experimental study on the reinforcement of defective wooden beams using carbon fiber composite materials [J]. Journal of Forestry Engineering, 2018,3(3); Data from Figure 3 is re-drawn.

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2.2. Optimization of CFRP types and process parameters for strengthening wooden components

For different damage forms, CFRP reinforcement is mainly divided into surface bonding method and embedding method. The fine control of its process parameters is the core to ensure reinforcement effect and durability. In terms of reinforcement methods, it is necessary to treat the symptoms according to the characteristics of the damage. For typical diseases such as splitting, opening, decay and half-butt joint as shown in Figure 3, the experiment has established differentiated treatment schemes: split components need to be wrapped with CFRP cloth after bonding; opening components need to be filled with mortar and then wrapped with wide CFRP cloth; decayed components need to have the decayed parts removed, new materials inlaid and then wrapped with the whole length. The experimental data confirms that the constraint effect of full-length wrapping is significantly better than that of local hoop constraint, the latter is prone to damage outside the constraint area. In terms of parameter optimization, Guo Xuan et al. [9] clarified the key influencing factors of end U-shaped CFRP reinforcement through orthogonal experiments and found that the number of CFRP layers and the angle of wood missing corner have the most significant impact on shear performance. Huang Junjie et al. further quantified the relationship between reinforcement and performance through acoustic emission monitoring: with the increase of the number of winding layers and angle (winding method as shown in Figure 4) [6] , the ultimate bearing capacity of the wooden column can be increased from 112.63 kN to 161.21 kN, and the displacement ductility coefficient can be increased from 1.44 to 1.72. However, when the reinforcement angle is increased, the ultimate bearing capacity of the wooden column can be increased from 112.63 kN to 161.21 kN, and the displacement ductility coefficient can be increased from 1.44 to 1.72. When the angle reaches 90° and the number of layers exceeds 4, the failure mode of the wood itself limits the high strength of CFRP, and the material is prone to wrinkling rather than breaking. Yang Xiaojun et al. proposed a process red line from the perspective of interface mechanics: the larger the thickness of the bonding layer [10], the more significant the shear creep deformation. It is recommended to apply a pressure of more than 0.05 MPa during construction to reduce the thickness of the adhesive layer, and control the shear stress of the bonding layer within 50% of the ultimate stress to ensure long-term service safety.

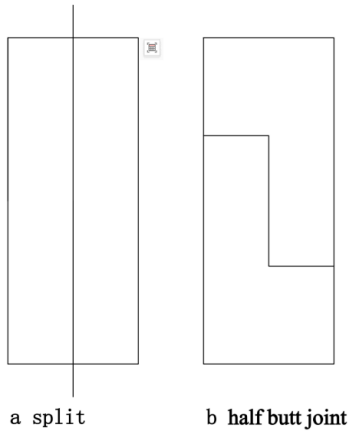


Figure 3. Schematic diagram of split and half butt joint (Adapted from literature [5])

Note:Adapted from the literature "Experimental Study on the Compressive Performance of CFRP-Reinforced Wood Members." Sichuan Journal of Building Science and Technology, 2017,43(4). Figure 1

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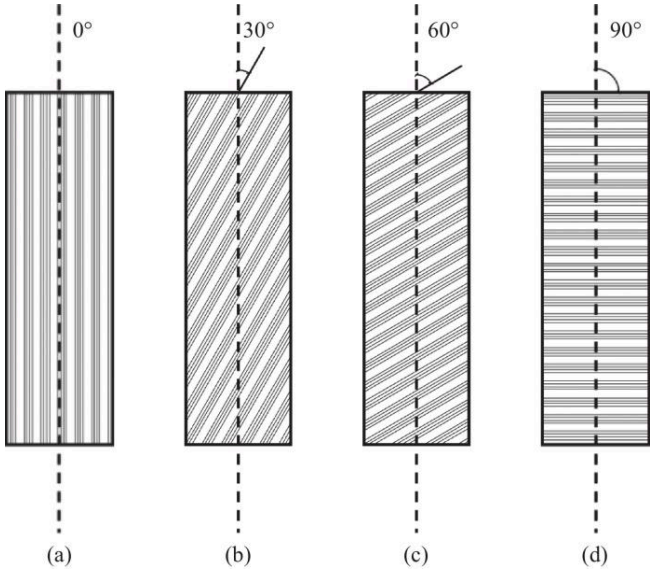


Figure 4. Schematic diagram of winding angle

Note:Adapted from [J]: "Experimental Study on the Axial Compression Damage Performance of CFRP-Reinforced Wooden Columns." Journal of Composite Materials, 2024,41; Figure 3

2.3. The performance evolution mechanism of wooden structural members and joints before and after reinforcement

CFRP reinforcement achieves a leap in mechanical properties by changing the stress mechanism and damage evolution path of wooden components. This process can be revealed through macro- and micro-scale experiments and numerical simulation. In terms of macro-mechanical properties, the enhancement of the axial compression performance of wooden columns by CFRP is manifested as the improvement of initial stiffness and ductility. Wu Jianguo confirmed that combining traditional repair technology with CFRP ring hoop can greatly improve the bearing capacity of defective columns [5]. Chen Hao et al. used the refined finite element model established by ABAQUS to further reveal the reinforcement mechanism: the number of embedded CFRP plates and ribs has a linear relationship with the reinforcement effect [11], while the contribution of the outer CFRP cloth to the ultimate bearing capacity is the most prominent; under the same configuration rate, the reinforcement effect of CFRP plates and ribs is almost the same. Based on this, the researchers derived the theoretical calculation formula of the yield bearing capacity of axially compressed wood, and its value is in good agreement with the simulation results. At the level of microscopic damage evolution, CFRP plays an effective role in inhibiting damage. Huang Junjie et al. combined acoustic emission and digital image technology to find that unenforced specimens mostly cracked along cracks or knots [7], while the cumulative ring count of acoustic emission inside reinforced specimens decreased significantly with the increase of reinforcement (from 1.4×10^{6} to 2.0×10^{5}). This shows that CFRP effectively reduced the overall damage of the component by limiting the initiation and propagation of cracks. In addition, in terms of bending and shear performance, the studies of Zhang Lu et al. and Guo Xuan et al. respectively confirmed that CFRP reinforcement targeting defects in the tension zone can significantly improve the bearing capacity of wooden beams, while the U-shaped CFRP at the end can delay the shear fracture of wood [9, 10], making the failure process change from sudden brittleness to a gradual failure with warning signs.

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3. Existing technical bottlenecks and future prospects

Although CFRP reinforcement technology has achieved significant results, it still faces severe challenges in engineering applications, such as material compatibility, stress concentration, detection and evaluation, and cultural heritage ethics. Technical bottlenecks are mainly reflected in three aspects: First is the "breathing" barrier effect. The sealing of CFRP blocks the normal evaporation of moisture inside the wood, leading to the deterioration of the interface environment and accelerating the aging of the material. Second is stress concentration and damage concealment.The cut-off point of the CFRP cloth is prone to peel stress, and once the pasting is completed, the cracking and bonding of the wood inside will be completely concealed. The accuracy of existing non-destructive testing methods in complex wood structure environment still needs to be verified, which may lead to the component being in a dangerous state of "outer intact, internally rotten". Finally, there is the conflict of cultural heritage protection ethics. Existing epoxy structural adhesives are difficult to remove without damaging the substrate after curing, violating the "reversibility" principle in international cultural relic protection guidelines. Furthermore, the extremely high strength of CFRP, if used improperly, can easily cause wooden components to transition from plastic to brittle failure, or trigger secondary disasters due to sudden changes in stiffness. In response to the above bottlenecks, future technological breakthroughs will show the following trends: One approach is to move from "chemical bonding" to "mechanical assembly." The patent for "easy-to-assemble and disassemble CFRP connecting components" proposed by Changsha University of Science and Technology provides an engineering prototype: this component achieves rapid alignment, connection, and disassembly through a ball-and-groove joint and a pin fixing system; its modular structure allows for independent production and transportation of each part, requiring only simple assembly on-site. The core value of this design concept lies in upgrading CFRP from a "disposable adhesive material" to an "Assemble-able connecting element"—by pr-setting standardized interfaces (such as pr-embedded sleeves and slotted inserts) on wooden components, CFRP plates/ribs are connected to the wood through mechanical interlocking rather than chemical bonding. Future maintenance allows for complete disassembly and individual replacement, fundamentally meeting the reversibility requirements of cultural relic protection. Meanwhile, the spherical hinge joint can transform the concentrated peeling stress easily generated at the edge cut of traditional CFRP fabric into multi-directional uniform transmission, effectively alleviating the problem of end stress concentration. Although this patent is in the proof-of-concept stage, its production approach of "standardized CFRP connection components + special interfaces for wooden components" provides a detachable, replaceable, and inspect-able solution framework for typical working conditions such as tenon joint removal, wooden column pier joints, and reinforcement of the tension zone at the bottom of beams. Second, from "passive reinforcement" to "active control". Xue Meihui et al.'s research on CFRP reinforced finger-jointed wooden beams revealed the key mechanism: CFRP increases the reinforcement strength of finger-jointed wooden beams by 70% [12], but only by 22% for solid wood beams. The fundamental reason is that CFRP restricts the slippage effect of the finger joint, and the existence of the internal damage structure of the material changes the original crack propagation mode. This finding suggests that future reinforcement design should not pursue the excessive goal of "defect-free restore to-new", but should actively utilize the damage structure of wood to achieve the synergistic work of "defect-CFRP".

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4. Conclusion

The application of CFRP technology in the protection of wooden components has moved from simple mechanical reinforcement to complex systems engineering involving multiple disciplines. Future research should, while ensuring structural safety, pay more attention to the physical and chemical compatibility between materials and the ethical requirements of cultural relic protection. By introducing modular and reversible assembly technology, optimizing reinforcement process parameters, and establishing a long-term performance monitoring mechanism, CFRP technology will surely play a more crucial and sustainable role in the scientific protection of ancient wooden structures.

References

[1] Chen, Q., Zhang, Y., Lei, J., et al. (2024). Study on seismic performance of CFRP reinforced wooden structure with damaged mortise and tenon joints in ancient Guangfu architecture. *J. Xi'an Univ. Archit. Technol. (Nat. Sci. Ed.), 56*(5), 642–649+659.

[2] Zhou, Q., Yan, W., & Zhang, B. (2011). Seismic test of CFRP-reinforced wooden frame in ancient architecture. *J. Shandong Jianzhu Univ., 26*(4), 327–333+347.

[3] Zhou, Q., Yan, W., Ji, J., et al. (2011). Shaking table test of CFRP-reinforced mortise and tenon joints in ancient architecture. *J. Guangxi Univ. (Nat. Sci. Ed.), 36*(1), 37–44.

[4] Zhou, Q., Yan, W., Li, Z., et al. (2011). Shaking table test study on the reinforcement method of mortise and tenon joints in ancient buildings. *J. Sichuan Univ. (Eng. Sci. Ed.), 43*(6), 70–78.

[5] Wu, J. (2017). Experimental study on compressive strength of CFRP-reinforced wooden components. *Sichuan Archit. Sci. Res., 43*(4), 38–44.

[6] Huang, J., She, Y., Li, M., et al. (2024). Damage evolution of wooden components reinforced with different carbon fiber cloths. *J. Northeast For. Univ., 52*(1), 115–123.

[7] Xu, K. (2020). Exploration of the applicability of CFRP material in the field of ancient building timber structure protection—Taking the reinforcement and restoration of Quxi Tower in Liuyuan Garden as an example. *Archit. Cult.*, (2), 102–103.

[8] Zhang, L., Zhou, A., Sheng, B., et al. (2018). Experimental study on the reinforcement of defective wooden beams with carbon fiber composites. *Trans. Chin. Soc. For. Eng., 3*(3), 128–135.

[9] Guo, X., Zhang, Z., Huang, H., et al. (2025). Orthogonal experimental study on the shear performance of wood with U-shaped CFRP at the end. *Guangzhou Archit., 53*(5), 79–84.

[10] Yang, X., & Sun, Y. (2012). Study on shear creep properties of the bonding layer of carbon fiber wood composite. *J. Zhejiang A&F Univ., 29*(2), 192–196.

[11] Chen, H., Zhang, H., Huang, Y., et al. (2025). Finite element simulation of axial compression performance of CFRP-reinforced timber columns. *Civil Eng. Green Build., 1*(2), 18–21+50.

[12] Xue, M. (2019). *Study on mechanical properties of CFRP-reinforced finger-jointed timber beams* [Master's Thesis, North China Univ. Technol.].