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Advancements in the Study of FRP-Reinforced Timber Columns under Axial Compression

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Abstract: FRP reinforcement technology, with its numerous outstanding advantages, has been widely applied to the strengthening of timber column structures, making related research of significant social and engineering practical relevance. This paper reviews the research achievements in the axial compression performance of FRP-reinforced timber columns from both domestic and international sources. It analyzes advancements in four aspects: types of FRP, number of FRP layers, the impact of knots, and models of ultimate compressive strength and finite element models. A comprehensive analysis and comparison of existing research shortcomings and unresolved issues are provided. Finally, some references and suggestions for further research and application of FRP-reinforced timber columns are offered.

1. Introduction

Wood, as a typical carbon-negative renewable building material, possesses notable environmental benefits[1]. Developing timber structure buildings is conducive to achieving the national goals of peaking carbon emissions and carbon neutrality. timber columns are the main compressive components in timber structure buildings, but natural defects in wood, such as knots and cracks, limit their application in timber column components[2]. Therefore, reasonable and effective reinforcement methods are crucial for timber column components.

Since the 1980s, Fiber Reinforced Polymer (FRP) sheets reinforcement technology has been widely used for the strengthening of timber column components due to its good reinforcement effect, simple construction, lightweight materials, non-destructive nature to the original structure, durability, and wide applicability[1]. FRP sheets enhance the load-bearing capacity of timber columns by restricting circumferential deformation with lateral confinement forces, which directly relate to the type and number of FRP layers[3]. Moreover, knots play a key role in the failure of timber structural components, and studying the impact of knots on FRP-reinforced components has significant practical engineering value[4]. Additionally, as FRP reinforcement technology has matured, practical demands have accelerated the research on models for the ultimate compressive strength and finite element models of FRP-reinforced timber columns.

Based on the existing research achievements in the axial compression performance of FRP-reinforced timber columns, this paper analyzes and summarizes the current research from four aspects: types of FRP, number of FRP layers, the impact of knots, and models of ultimate compressive strength and finite element models. This provides a reference for subsequent research on the axial compression performance of FRP-reinforced timber columns.

2. Types of FRP

Common types of Fiber Reinforced Polymer (FRP) include Aramid Fiber Reinforced Polymer (AFRP), Basalt Fiber Reinforced Polymer (BFRP), Carbon Fiber Reinforced Polymer (CFRP), and Glass Fiber Reinforced Polymer (GFRP). There are significant differences in material properties and synergistic working capabilities with epoxy resin among these fibers, resulting in varying reinforcement effects.

From 1998 to 2005, researchers such as Davalo[5], Chidiaq[6], Emerson[7], Taheri[8], and Nagaraj[9] conducted studies using GFRP and CFRP sheets to partially and fully wrap timber columns and performed axial compression tests. The results indicated that the ultimate bearing capacity of the reinforced timber columns increased by 8.00% to 90.00%, bending deformation of the columns decreased, and the ultimate strain increased by 15.30% to 65.00%, with GFRP showing a weaker reinforcement effect compared to CFRP.

Dong[10] et al. conducted axial compression tests on timber square columns reinforced with three different types of FRP sheets, studying their failure modes, bearing capacity, load-strain curves, ductility, and stiffness. The results showed that, compared to unreinforced specimens, the axial bearing capacity, peak compression strain, and stiffness of the reinforced specimens were improved, with the ultimate bearing capacity of FRP-reinforced specimens increasing by 68.9% to 100.2%; the ultimate displacement decreased by 46.1% to 56.9%, with specimens reinforced with two layers of BFRP showing the smallest ultimate displacement; specimens reinforced with two layers of CFRP and AFRP sheets exhibited greater ultimate displacement and stiffness than those reinforced with BFRP fabric.

de la Rosa[11] et al. used three different types of FRP sheets to reinforce square wild pine columns, including one type of CFRP fabric and two types of BFRP fabric with different gsm. The results indicated that the bearing capacity of the reinforced specimens increased by at least 96% compared to the unreinforced specimens, with the bearing capacity reaching up to 133% higher when reinforced with 600g/m2 BFRP fabric. The ductility of the reinforced specimens was lower than that of the unreinforced specimens; the tensile strength of the FRP fabric was almost unrelated to the ultimate strength of the reinforced specimens, but the stiffness and elastic modulus of the FRP fabric were strongly correlated with the ultimate strain of the reinforced specimens.

3. Number of FRP Layers

The number of FRP layers is one of the decisive factors affecting the lateral confinement force of FRP, and changing the number of FRP layers has a significant impact on the bearing capacity of the components and the reinforcement effect of FRP[3].

Cui[12] et al. conducted axial compression tests and numerical analysis studies on square hollow timber short columns, investigating the impact of FRP and wood material selection on structural performance through six different column types. The experimental results showed that as the number of GFRP layers increased, the failure mode of the section transitioned from buckling to crushing, with corresponding improvements in section strength and stiffness.

Pan[13] and others mixed carbon fibers and aramid fibers in proportion to study the axial compression performance of pine and fir columns constrained by carbon-aramid hybrid fibers of different layers. The results indicated that after reinforcement with hybrid fibers, the bearing capacity of the timber columns was significantly enhanced, and increasing the number of FRP layers could increase the extent of improvement in the bearing capacity provided by FRP.

O'Callaghan[14] et al.s investigated the axial compression performance of square timber columns wrapped with GFRP fabric, varying the fiber orientation and number of layers of GFRP. The study focused on the stress-strain relationship and failure modes after reinforcement. The experimental results demonstrated that, under an appropriate number of layers, FRP wrapping could prevent the most undesirable splitting and shearing failures in wood failure modes and the wood fiber fractures induced by wood defects. FRP wrapping significantly improved the post-peak performance of the timber columns, with FRP-wrapped specimens maintaining up to 61% of the peak compressive strength at higher strains, compared to only 41% for the control specimens. The FRP wrapping made the post-peak stress-strain relationship and failure modes of the reinforced timber columns more consistent, making the overall performance of the columns more reliable and uniform.

4. Impact of Knots

Knots are inevitable natural defects in wood, representing weak points in timber structural components and often playing a critical role in controlling the failure mode of full-size timber structural specimens in experimental studies[4]. However, in past research on FRP-reinforced timber columns, researchers often did not control the condition of knots in the specimens as a variable, and studies on the failure mechanisms of FRP-reinforced timber columns under the influence of knots are relatively scarce.

Xin[15] et al. investigated the compression failure mechanisms of full-length integrally connected plywood box columns, focusing on the interaction between knot defects, the overall box joint capability, and column strength. Through experimental observations and numerical analysis of different-sized knot defect sections, they identified a new critical failure mechanism, where the column load was controlled by the lateral load of the overall box-shaped joint caused by knot defects.

Qiao[16] et al. also tested square timber-filled steel tube columns (TFST), studying the impact of knots on the structural performance of TFST. The experimental results indicated that the presence of knots reduces the strength and ductility of the columns, with the ultimate compressive strength of the wood and TFST specimens decreasing by 10% and 11%, respectively.

Li[17] focused on the issue of poor load-bearing performance of timber columns due to the interruption of wood fiber texture at knots. Combining the superior physical and mechanical properties of FRP, they studied the axial compression failure mechanisms of six FRP-reinforced round timber columns, analyzing the impact of different fiber textures on the failure modes, displacement, and strain responses of reinforced short columns. The experimental results showed that the presence of knots reduced the axial ultimate bearing capacity of short round timber columns by nearly 23% and stiffness by more than 60%. After reinforcing short columns with knots using FRP, both their ultimate bearing capacity and stiffness were significantly improved, almost matching those of ordinary short columns without knots. However, the yielding stage of FRP-reinforced timber columns with knots was significantly shorter than that of unreinforced columns, leading to more abrupt failure. The improvement in ultimate bearing capacity and stiffness of FRP-reinforced timber columns with knots came at the expense of their ductility.

5. Strength Models and Finite Element Models

5.1. Strength Models

Currently, most scholars refer to the results of research on concrete columns and have established a series of strength models for FRP-reinforced timber columns based on existing axial compression tests of FRP-reinforced timber columns. The strength models researched by scholars domestically and internationally are shown as in Table 1-1. In these models, f_{cu} represents the ultimate compressive strength of FRP-reinforced specimens; f_{c0} represents the ultimate compressive strength of unreinforced specimens; and f_l represents the lateral confinement force provided by FRP.

Table 1-1. Strength Models for FRP-Reinforced timber Columns

Function forms	Strength models	Key parameters and notes
Linear function	$\frac{f_{cu}}{f_{c0}} = 1 + a_1 \frac{f_l}{f_{c0}}$	a_1 as the effective confinement coefficient, obtained from experiments.
Power function	$\frac{f_{cu}}{f_{c0}} = 1 + b_1 (\frac{f_l}{f_{c0}})^{b_2}$	b_1 and b_2 as the effective confinement coefficient, obtained from experiments.
Other functions	$\frac{f_{cu}}{f_{c0}} = 1 + c_1 \sqrt{\frac{f_l}{f_{c0}}} + c_2 \frac{f_l}{f_{c0}}$	c_1 and c_2 as the effective confinement coefficient, obtained from experiments.

Richart[18] was the first to propose a strength model for FRP-confined concrete represented by a linear function and defined the effective confinement coefficient a1 as 4.1. Following this, Lam and Teng[19, 20] adopted the form of this equation and made improvements on its basis. They simplified FRP as a unidirectional material, considering only the lateral force of FRP and providing circumferential confinement force only to the core concrete. They proposed a strength model that can be directly applied in design, revising the a1 value to 3.3. This model can reflect the influence of different types of FRP on the design stress-strain characteristics well.

Toutanji[20] proposed a power function represented strength model for FRP-confined concrete based on hoop-reinforced concrete, defining the effective confinement coefficients b1 and b2 as 3.5 and 0.85, respectively. Wei[21] applied this model to the study of FRP-confined timber columns, investigating the impact of fiber type, adhesion method, number of layers, adhesive type, and specimen size on the strength of timber columns. He proposed a formula that can reflect the influence of various parameters on the strength of timber columns, revising the b1 and b2 values to 9.4 and 1.2. Li[22] studied short columns of bamboo laminates confined with CFRP, researching the effects of distribution rate and FRP type on the ultimate strength, ductility, and Poisson's ratio of bamboo laminate short columns. Referring to the strength models for FRP-confined concrete columns and FRP-confined timber columns, he proposed a strength calculation formula for FRP-confined bamboo laminate short columns, revising b1 and b2 values to 0.18 and 0.7.

In addition to the aforementioned function forms, other scholars have defined the FRP-confined concrete strength model using different function forms. For example, Cai[23] proposed another strength model for FRP-confined concrete, and its expression is shown in Table 1-1.

5.2. Finite Element Models

As FRP reinforcement technology has matured, practical needs have led scholars to develop various finite element models (FEM) for FRP-reinforced timber columns under compression.

Oudjene[24] et al. established an elastoplastic constitutive model capable of describing the secondary hardening of wood under transverse compression and developed an algorithm for numerical simulation in ABAQUS. This model reflects the complex behavior of wood materials under load, including the effects of anisotropy and heterogeneity inherent in wood.

Zhang[25] et al. developed a finite element model based on experimental data to simulate and study the effects of various factors on the performance of reinforced timber columns. The finite element model considers five factors: column size, crack size, whether the crack is filled, FRP performance, and FRP spacing. Both experimental and finite element analysis results indicated that changes in different influencing factors lead to different failure modes; the impact of crack width on the load-bearing capacity of timber columns is the most significant, with the load-bearing capacity decreasing as the crack length and width increase; reducing the spacing between FRP wraps greatly enhances the restoration of load-bearing capacity in cracked timber columns.

Otoom[26] et al. conducted three-point bending tests on timber columns reinforced with a prefabricated GFRP wrapping system to evaluate the flexural performance of the reinforced columns. They developed both a theoretical constitutive model and a finite element model, comparing the load-midspan deflection relationship, longitudinal strain, and failure modes obtained from experiments with the analysis results from both methods. The results showed that the theoretical constitutive model and the finite element model predictions are in good agreement with the experimental findings, indicating the reliability and accuracy of these models in predicting the behavior of FRP-reinforced timber columns.

6. Conclusion

In recent years, scholars both domestically and internationally have conducted extensive experimental and theoretical research on the axial compression performance of FRP-reinforced timber columns. Based on an analysis of related research, this paper draws the following conclusions and suggestions:

(1) FRP improves the overall axial compression performance of reinforced timber columns by providing lateral confinement force. The type and number of FRP layers directly determine the lateral confinement force provided by FRP. However, comparative studies on different types of FRP are relatively scarce, and many comparisons do not control the gsm of FRP, leading to discrepancies in the evaluation of the reinforcement effects of various FRPs. For studies on FRP-reinforced timber columns with different numbers of layers, existing research has observed a phenomenon where the increase in ultimate bearing capacity diminishes with additional layers of FRP wrap, yet there has been no in-depth investigation or systematic summary of this phenomenon and its peak values.

(2) The presence and distribution of knots in FRP-reinforced timber columns directly affect the axial compression performance of the reinforced specimens. However, related research is rare, and the failure mechanisms of FRP-reinforced timber columns under the influence of knots are not yet clear.

(3) Most of the existing research results on the strength models and finite element models for FRP-reinforced timber columns under compression are based on specific FRP experimental data or related research on concrete columns. The applicability of these models to timber columns reinforced with different types of FRP still needs further investigation.

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