Wood-based Columns Reinforced with Fiber-Reinforced Polymer: A Systematic Literature Review

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Fiber-reinforced polymer (FRP) is an external reinforcement solution for wooden structures, where several studies have shown its efficiency in maintenance and design. This solution is not yet among the main topics of literature, although its importance justifies new research on this relevant topic for construction. This systematic literature review involves the FRP as reinforcement in wood-based columns, using Engineering Village and Web of Science databases and PRISMA protocol to follow the procedures and ensure the quality of sampling. Reinforcement dispositions and types of assessments were identified so that the literature synthesis can contribute to identifying behavior models. Different methods of reinforcement sizing studied by the literature were synthesized and detailed as to their respective uses. A positive correlation between the reinforcement index and the increasing the load capacity of timber columns were discussed and statistically analyzed.

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INTRODUCTION

Columns are used in timber construction typologies, which are indispensable to erect post-and-beam, post-and-lintel, and stick-frame systems. Wood is a bioresource, which explains why it is subject to defects, cracks, and deterioration that influence its durability, load capacity, and stability (Chen and Guo 2017; De Araujo 2023). Studies have reported visible degradations in wood columns (Qiao *et al*. 2016; Li *et al*. 2021), where significant interventions were essential to ensure the structural safety and in-service performance of the degraded elements. According to Valle *et al*. (2013), the use of fiber-reinforced polymers (FRP) is a viable alternative for structural reinforcement of wooden elements.

The use of FRP in reinforced concrete structures has been widely investigated (Amran *et al*. 2018), with the possibility of adopting specific codes for the use of this solution in structural projects. When consulting the literature, there has been little research into the use of FRP to reinforce wooden columns, which has an impact on the evolution of the reinforcement method, creating a barrier to its use by designers.

The exposition of the current state of the art on the reinforcement of timber-based columns with FRP can present valuable information for the development of new studies, as well as contribute to more assertive evaluations of these elements through the elaboration of a synthesis of the analytical dimensioning proposals of this reinforcement method. Therefore, this study aims to carry out a systematic literature review and a bibliometric analysis using statistics on the use of laminated FRP composites to reinforce timber columns, as to the contribution to improving their mechanical performances.

METHODOLOGY: SYSTEMATIC LITERATURE REVIEW

The systematized review was carried out up to mid-2024. Three stages were used: study planning, analysis of collected publications, and data extraction. In planning, research questions, databases for identifying articles and the search string were defined.

For a wider search, words with similar meaning to the adopted terms were listed. The search was carried out based on the titles, abstracts and keywords of the publications. Two scientific database tools were adopted: Engineering Village and Web of Science. The used string was: (“timber” OR “wood”) AND (“strengthening” OR “reinforcement”) AND (“column” OR “pillar”) AND (“fiber reinforced polymer” OR “frp”). Two research questions were formulated: What is the influence of the physical and mechanical properties of FRP and timber on the column performance? What mathematical methods are adopted in the literature for the design of FRP-reinforced timber columns? After the exclusion of duplicate records in databases, those articles that answered the raised questions and that could contribute to this review were selected. In the selection filter, all titles, keywords, and abstracts of the articles extracted from the searches were read to identify those that are not eligible. In the eligibility filter, introduction, and conclusion sections of filtered papers were read. In the inclusion filter, all eligible articles were read in full and classified according to their suitability for the sample. The articles approved in the three filters were used to extract the data of interest. Using VOSviewer, all keywords were compiled to generate a map of relationship among topics of sampled articles. The final stage of the sample definition process consisted of data extraction, where the studies were classified according to the quality criteria presented in Table 1, aiming to analyze the sample qualitatively regarding the sample's capacity to answer the research questions.

Table 1. Criteria and Descriptions Analyzed in the Literature

Criteria	Description of Issues
Q1	Does the study characterize physical and mechanical properties of wood?
Q2	Does the study characterize physical and mechanical properties of FRP?
Q3	Does the study use any analytical method for analyzing reinforcements?

BIBLIOMETRIC AND QUALITATIVE ANALYSIS OF SAMPLES

After sampling process, 15 articles were selected, corresponding to 22% of the records from two databases, excluding duplications. Figure 1 presents a PRISMA flowchart. Articles not included in the sample were excluded because they did not use FRP as a reinforcement element or because they did not analyze timber columns.

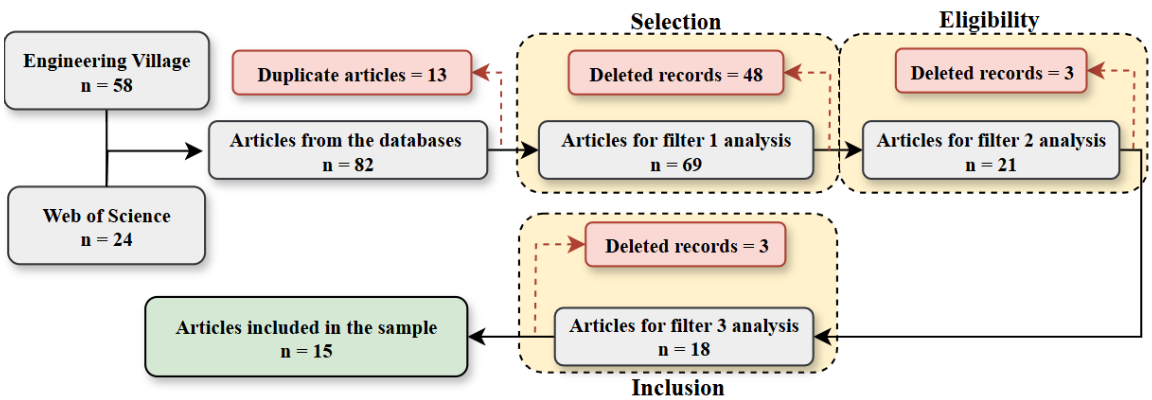

Fig. 1. PRISMA flowchart

Articles were obtained to recover other wooden elements like panels and beams, outside the scope of this review. Figure 2 shows the distribution of articles by year. The years 2015 and 2021 had more publications in the studied topic. Still, the small number of annual publications on the subject is verified.

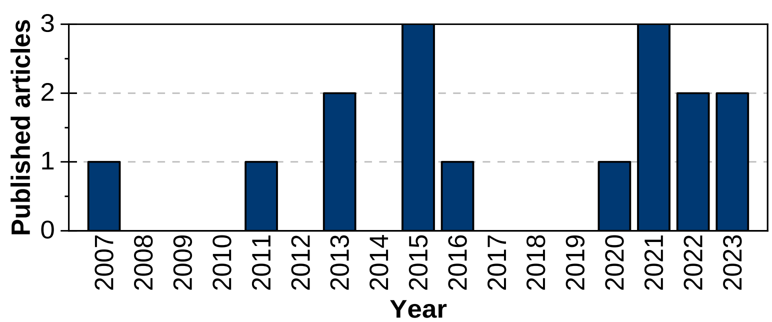

Fig. 2. Number of publications according to year for systematic literature review (SLR)

Regarding quality criteria (Table 1), the number of articles per criterion is presented in Fig. 3. Physical and mechanical properties of the FRP (Q2) were met by 100% of the sample, followed by criterion Q1, with 80% on wood properties.

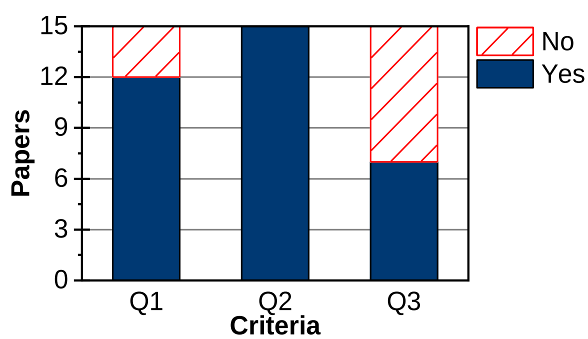

Fig. 3. Classification of studies according to quality criteria

The FRP was obtained from specialized manufacturers, having more production controls. This may explain the ease in obtaining and providing the values of the composite properties. Few studies performed a complete characterization. This may be explained by the difficulty in characterizing wood adequately, requiring several tests with distinct equipment to obtain different properties. Only longitudinal modulus of elasticity and compressive strength have been assessed. Criterion Q3 was met by 7 sampled articles (46.7%), indicating that there is a concern in proposing analytical design techniques for FRP-reinforced columns.

The map in Fig. 4 relates the keywords used together, showing the number of repetitions through the size of the word and the evolution of the terms adopted over the years. “Timber column”, “reinforcement”, and “composite reinforcement method” were the most frequently terms found. This indicates that the terms defined for the composition of the search string were suitable for this review, insofar as distinct terms adopted by the sample could emerge eventually. Although there were distinct groupings, keywords were similar, indicating axial compression tests, with variations in the type of fiber in the laminated composite and some indications of numerical simulations. The low number of articles (Fig. 1) and the similarity of the topics addressed (Fig. 4) indicate the importance of carrying out new studies that can elucidate possible topics not yet addressed.

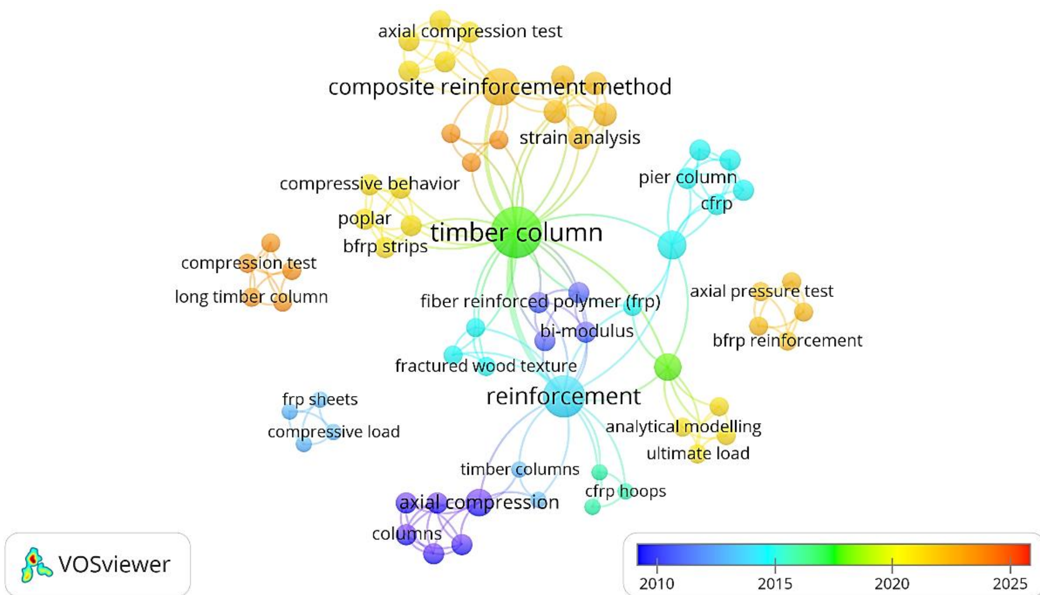

Fig. 4. Map of relationship of keywords of sampled literature

ANALYSIS OF MECHANICAL PERFORMANCE OF REINFORCED COLUMNS

Using the data from sampled studies, it was possible to establish physical and geometric indexes of the reinforced columns with the mechanical performance found by the authors. For this, the volumetric reinforcement (V_R) was obtained using Eq. 1, and the ratio between the elasticity modulus of the FRP and the wood (E_{FRP}/E_0),

$$V_R\,(\%) = \frac{V_{FRP}}{V_{timber}} \cdot 100 = \frac{A_{FRP} \cdot L_{FRP}}{A_{\text{timber}} \cdot L_{\text{timber}}} \cdot 100 = \frac{t_{FRP} \cdot p_{FRP} \cdot n_{FRP} \cdot L_{FRP}}{A_{\text{timber}} \cdot L_{\text{timber}}} \cdot 100 \qquad (1)$$

where A, V, L, t, p, and n denote, respectively, the cross-sectional area, volume, length, thickness, perimeter, and number of FRP layers. The consideration of V_R ratio to analyze the reinforcement in columns is considered adequate and is also used by Zhou *et al*. (2021), since it can be used both for columns with continuous reinforcement, covering the entire surface of the element, and for reinforcement with intervals, with FRP layers spaced apart. The reinforcement ratios of columns were related to the variation found for the load capacity (Δf) of structural element, as follows (Eq. 2).

$$\Delta f\ (\%) = \frac{\Delta f_{\text{reinforced}} - \Delta f_{\text{unreinforced}}}{\Delta f_{\text{unreinforced}}} \cdot 100 \tag{2}$$

Some properties, such as thickness, number of FRP layers or E_0, were not presented in the following studies: Chen *et al*. (2020), Dong *et al*. (2015a), Li *et al*. (2013), Najm *et al*. (2007), Xiong *et al*. (2016), and Zhu *et al*. (2013). Xiong and Su (2015) was not considered because it consisted of reinforcement in column joints by notch, using an intact column (without joint) as a reference model, and it was not possible to associate the results of the authors with the other studies. Even so, it was possible to obtain complete information on 42 columns tested in the laboratory. From these indexes analyzed, V_R ratio presented the highest levels of variation, with an average value of 5.05%, standard deviation of 8.52%, and coefficient of variation of 168.59%. This indicates that the literature has applied reinforcement with different proportions, which is considered positive because it allows evaluation of the impact of this variation on the reinforcement performance. Yang *et al*. (2021) adopted the highest V_R ratio, with 29.51%, in which a complete envelope of the external face of column was considered, as well as it was inserted the reinforcement in internal regions. The E_{FRP}/E_0 average ratio was 12.89%, with a standard deviation of 7.64% and coefficient of variation of 59.28%. The average indexes found can be considered as a starting point for reinforcement analyses in real timber columns.

The relation of reinforcement indexes (V_R and E_{FRP}/E_0) with Δf is shown in Fig. 5. Since these indexes are related to different quantities (V_R = geometric and E_{FRP}/E_0 = physical), their product was also considered. A higher concentration of models with V_R less than 5% and E_{FRP}/E_0 less than 20% was found. For reasons of graphic scale, in which the Δf data is grouped around V_R between 0 and 5% (Fig. 5a), this is a linear and unique behavior considering all individual results. Graphs did not show a clear pattern of dispersion, not even when considering the product of the reinforcement indexes.

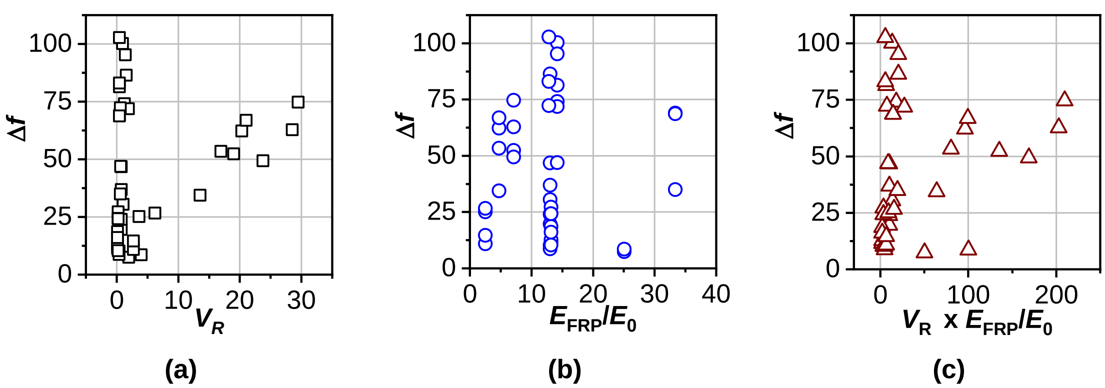

Fig. 5. Dispersion between reinforcement indices V_R (a), E_{FRP}/E_0 (b) and $V_R \cdot E_{FRP}/E_0$ (c) with Δf

It was possible to perform the correlation test by defining Spearman's correlation coefficient (r_s) to evaluate the non-linear relationship between the V_R and E_{FRP}/E_0 and Δf. These results are given in Table 2, where the bold values are those that presented correlation. Spearman's correlation test showed that there is a weak positive correlation between the product of the V_R and E_{FRP}/E_0 ratios and the increase in the load capacity of fully FRP-clad columns. The p-value indicates that this correlation is significant (α<5%).

Table 2. Correlation of Reinforcement Indexes with the Increase in Resistance

Coefficient	All data			Only full reinforcement		
	V_R	E_{FRP}/E_0	$V_R \cdot E_{FRP}/E_0$	V_R	E_{FRP}/E_0	$V_R \cdot E_{FRP}/E_0$
r_s	0.276	0.010	0.399	0.581	-0.159	**0.618**
p-value	0.077	0.952	0.009	0.005	0.480	0.002

r_s = Spearman's correlation coefficient; E_{FRP} = modulus of elasticity of FRP; E_0: modulus of elasticity of wood; V_R = volumetric reinforcement rate.

It should be noted that Fig. 5a shows two trends in behavior: one for $V_R < 3\%$ and the other for $V_R > 3\%$. Figure 6 shows a scatter plot for each group, accompanied by a regression model to predict Δf. The group of pillars with $V_R < 3\%$ (Fig. 6a) showed no correlation between V_R and Δf. On the other hand, the group with $V_R > 3\%$ (Fig. 6b) showed a linear relationship with Δf, with a high Pearson correlation and a regression model with R^2adj of 0.83. The pillars in Fig. 6b are made up of eight elements studied by Yang *et al*. (2021) and another three studied by Liu *et al*. (2022) and Wang *et al*. (2023).

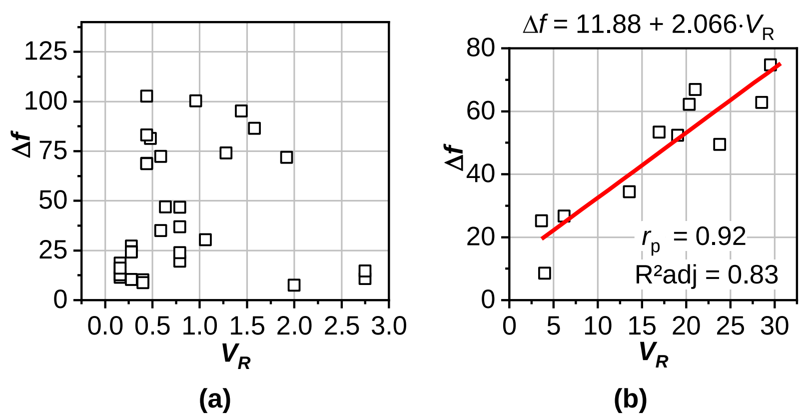

Fig. 6. Dispersion between the V_R with increasing column resistance: $V_R < 3\%$ (a) and $V_R > 3\%$ (b)

ANALYTICAL METHODS FOR DESIGN

Articles with design methods were analyzed and their approaches are presented and compared in this chapter. In total, 8 articles presented analytical methods for predicting the mechanical performance of FRP-reinforced timber columns. Most of these articles were dedicated to presenting formulations for predicting the load capacity. Some studies (Li *et al*. 2013; Xiong and Su 2015; Xiong *et al*. 2016) took as a basis formulations developed for confined reinforced concrete columns, being a material with a greater volume of study than wood columns. Li *et al*. (2013) adopted the study by Mirmiran and Shahawy (1997) on the confinement provided by FRP composites in reinforced concrete-based columns to discuss the results found in the laboratory. After adapting the formulation for the materials adopted, Li *et al*. (2013) presented Eq. 3 to predict the additional compressive strength provided by the reinforcement,

$$\Delta f = -\frac{t}{R} \cdot E_{FRP} \cdot \varepsilon_{FRP} \tag{3}$$

where R and ε_{FRP} denote the radius of wooden column (circular section) and the FRP deformation, respectively. Although aforementioned authors used Eq. 3 to justify the results found, where the columns reinforced with FRP with a higher modulus of elasticity showed a greater gain in strength.

Xiong *et al*. (2016) and Xiong and Su (2015) also substantiated the adopted equation in a study on concrete columns. Xiong's proposal adopts a confinement intensity coefficient (β) and a resistance reduction factor due to column cracks (γ). The adapted model is presented in Eq. 4, where b_{FRP} denotes the width of the FRP laminate and υ the Poisson's ratio of timber.

$$f = \frac{\gamma}{1 - \beta \cdot \frac{b_{FRP} \cdot t_{FRP}}{2 \cdot R^2} \cdot \nu \cdot \frac{E_{FRP}}{E_0}} \cdot f_{timber} \tag{4}$$

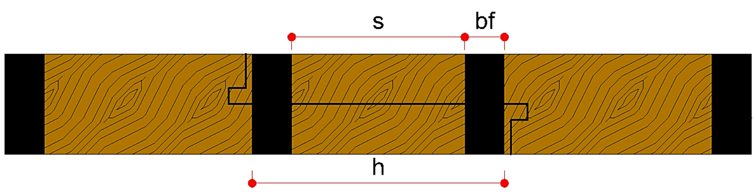

Fig. 7. Diagram of reinforcement

In Xiong and Su (2015), the modification of the calculation model, originally proposed for concrete columns (Richart *et al*. 1929), was performed to predict the compressive strength of FRP-reinforced columns with joints (Fig. 7). Equation 5 presents the proposed modification,

$$f = \gamma \cdot f_{c0} + \beta \cdot \frac{t_{FRP} \cdot \varepsilon_{FRP} \cdot b_f \cdot E_{FRP}}{r \cdot (b_f + s)} \tag{5}$$

where γ and β are, respectively, the column resistance reduction coefficient and the FRP restraint intensity coefficient, and r, b_f, and s denote, respectively, the column radius, the column reinforcement blade length and the spacing between the laminates (Fig. 8). The resistant force (P) of this connection was determined considering the calculation parameter presented in Eq. 6, resulting in Eq. 7.

$$\xi = \frac{b_f}{b_f + s} \tag{6}$$

$$P = \pi \cdot r^2 \cdot \left(\gamma \cdot f_{c0} - \beta \cdot \xi \cdot \frac{t_{FRP} \cdot \varepsilon_{FRP} \cdot E_{FRP}}{r} \right) \tag{7}$$

Dong *et al*. (2015b) proposed a formulation for determining the maximum load of FRP-reinforced timber columns, presented in Eq. 8, considering the following hypotheses: perfectly concentric loading until failure, no relative sliding between FRP and the column, and failure due to shear cracks,

$$P = \left[1 + \alpha \cdot \left(\frac{2 \cdot E_{FRP} \cdot \varepsilon_{FRP} \cdot t_{FRP} \cdot n_{FRP}}{R \cdot f_{timber}} \right)^{b} \right] \cdot f_{timber} \cdot A_{timber} \qquad (8)$$

where α is a regression coefficient defined as 0.61 and b is a conversion coefficient equivalent to -0.05. The proposed model requires few properties, most of which are geometric, as is the case with the model by Xiong and Su (2015) and Xiong *et al*. (Xiong *et al*. 2016), facilitating its use when equipment for a full characterization of the wood is not available. When comparing the experimental results obtained with those estimated by Eq. 8, Dong *et al*. (2015b) found errors of up to 20%.

Liu *et al*. (2022) observed that the sizing method present in the Chinese code (SAC 2017) does not present adequate results for the strengthening of glued timber columns with loss of cross-section.

This inaccuracy is evinced by Zhou *et al*. (2021). Thus, Liu *et al*. (2022) presented a modification of the calculation method in Eq. 9,

$$F_{aB} = F_a + \frac{79.45}{1 + 10^{0.02 \cdot 58.86 - \beta_B \cdot F_a}} \qquad (9)$$

where F_{aB} and F_a are the ultimate axial load capacity for hollow timber columns reinforced with BFRP and the ultimate axial load capacity of non-reinforced elements (kN), respectively; β_B denotes the adhesion coefficient of BFRP. Determined according to the Chinese code (SAC 2017), F_a is presented in Eq. 10 and β_B in Eq. 11.

$$F_a = \varphi \cdot A_n \cdot f_c \qquad (10)$$

$$\beta_B = \rho \cdot \frac{b}{b + d} \qquad (11)$$

From Eq. 10, φ is the axial stability coefficient (Eq. 12), A_n is the net cross-sectional area of the column, and f_c denotes the compressive strength of timber. From Eq. 11, ρ is the reinforcement ratio of the BFRP (A_{FRP} / A_{timber}), b is the length of the reinforcing blade, and d is the distance between the reinforcing blades, both relative to the longitudinal direction of the column, as shown in Fig. 7.

From Eq. 12, β, a_c, b_c, and c_c are correlation coefficients obtained from the Chinese code (SAC 2017), λ is the slenderness of the compressed element, and E_k and f_{ck} consist of the characteristic modulus of elasticity and compressive strength.

$$\varphi = \begin{cases} \dfrac{a_c \cdot \pi^2 \cdot \beta \cdot E_k}{\lambda^2 \cdot f_{ck}} & \text{if} \quad \lambda > c_c \cdot \sqrt{\dfrac{\beta \cdot E_k}{f_{ck}}} \\ \dfrac{1}{1 + \dfrac{\lambda^2 \cdot f_{ck}}{b_c \cdot \pi^2 \cdot \beta \cdot E_k}} & \text{if} \quad \lambda \le c_c \cdot \sqrt{\dfrac{\beta \cdot E_k}{f_{ck}}} \end{cases} \qquad (12)$$

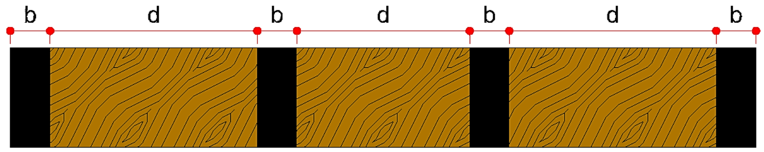

Fig. 8. Indication of the variables adopted for determining β_B

By adopting Eq. 9, Liu *et al*. (2022) estimated the resistance of the five reinforced columns studied, with an error ranging from -1.38% to 1.67%. The equation proposed by these authors is considered simple and is applied to columns with reinforcements at intervals. However, it depends on coefficients presented in the Chinese code (SAC 2017), which must be evaluated in order to be applied in other territories.

In the study conducted by Yang *et al*. (2021), where the reinforcement was considered in the internal region of the column, the proposed equation was based on the Tsai-Wu failure criterion, obtaining Eq. 13.

$$P = \frac{A_{timber}}{2F_{11}} \cdot \left\{ -\left(F_1 + 4F_{12} \cdot p_w\right) \pm \sqrt{\left(F_1 + 4F_{12} \cdot p_w\right)^2 - 4F_{11} \cdot \left[2\left(F_{22} + F_{23}\right) \cdot p_w^2 + 2 \cdot p_w - 1\right]} \right\}$$
$$+ \frac{A_l}{2F_{11}} \left\{ -\left(F'_1 + 4F'_{12} \cdot f_{t3}\right) \pm \sqrt{\left(F'_1 + 2F'_{12} \cdot f_{t3}\right)^2 - 4F'_{11} \cdot \left[2F'_{22} \cdot f_{t3}^2 + 2f_{t3} - 1\right]} \right\} + f_{FRP} \cdot A_{FRP} \quad (13)$$

where F_1, F_{11}, F_{12}, F_{22}, F_{23}, F'_1, F'_{12}, and F'_{22} consist of strength parameters calculated by the Tsai-Wu method, p_w is the restraining stress acting on the timber core (Eq. 14), A_l is the cross-sectional area of the internal reinforcement, and f_{t3} is the transverse resistance of the internal FRP. L_c is the length of the wood core segment and m is the confinement coefficient.

$$p_w = -m \cdot \frac{t_{FRP}}{L_c} \cdot f_{FRP} \quad (14)$$

To apply the method of Yang *et al*. (2021), a complete characterization of the wood and its reinforcement is necessary to determine the resistance parameters, which depend on the transverse and longitudinal tensile and compressive strengths of the wood, as well as the shear strength. Therefore, the method may be difficult to apply in situations where all this information is not available. Even so, the error found by the authors varied between -17.6% and 8.9%, being similar to the other models found in this review.

CONCLUSIONS

1. A weak positive correlation was found between the reinforcement ratios (product of the volumetric reinforcement rate and the E_{FRP}/E_0 ratio) and the increase in the load capacity of the fully FRP-clad columns.
2. The literature provides some calculation models for FRP-reinforced wooden columns with their accuracy varying by up to 20%, depending on the model.
3. In order to obtain results that allow conclusions to be drawn about the influence of reinforcement on the increase in compression load, parametric numerical simulations are needed to support a proposal for an equation that allows this increase in force to be estimated with greater precision.

4. Through bibliometric analyses, it was possible to identify gaps for further studies, including evaluation of the proposed models for estimating the load capacity of FRP-reinforced columns/pillars when adopting different types of fibers to reinforce the composite. Also needed are investigations into the use of hybrid FRPs in different applications, including degraded columns, with square cross sections, in joint regions, in glued wood-based elements, and others.

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