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ORIGINAL ARTICLE

Development and investigation of a hybrid built-up column made of small diameter logs originating from juvenile trees

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Abstract

Small diameter logs from juvenile trees are heavily produced during the management of artificial forests around the world. As a kind of plentiful and inexpensive natural resource, the potential was not fully explored. So far the small diameter logs are mainly used as raw materials for products other than building materials. To utilize these small diameter logs originating from juvenile trees as structural members into wood construction, a kind of hybrid built-up column was developed and the performance was investigated experimentally and theoretically. It was found that column had good load-carrying capacity. To apply the developed member in wood construction, the prediction method of the column was proposed. The effective slenderness ratio which took the shear deformations due to the bending of limbs and slip of nail connections between U-shaped nails and limbs into consideration was derived based on mechanics theory. The proposed prediction method was found to have good accuracy in predicting the load-carrying capacity of the hybrid built-up column. This paper can promote the structural application of the small diameter logs originating from juvenile trees.

Keywords Load-carrying capacity · Juvenile round timber · Built-up column · Effective slenderness ratio · Timber structure

Introduction

Large quantities of juvenile trees exist in forests, especially in planted forests [1]. Not only do these overstocked stands increase the risk of insects, diseases, catastrophic fire potential, but they are costly to manage [2]. Increasing management emphasis on forest health forces the forest managers to seek economical treatments such as thinning to improve the stand condition. Parts of these juvenile trees are removed to make room for the growth of others, thus a large quantity of the juvenile small diameter logs are produced. The traditional processing methods fail to recognize the juvenile tree's full value, as a kind of plentiful and inexpensive natural resource, the potential is not fully explored. So far small diameter logs from juvenile trees are mainly used as raw materials for products other than building materials, e.g. used as pulp to make paper or wood strips to make furniture panels, they are even used as firewood in some areas, thus economical and value-added methods are urgently needed.

There are still some problems existed in engineering application of the small diameter logs. Difficulties are met in designing the connections between these logs which have small and strongly varying diameters. Moreover, the mechanical properties of small diameter logs from juvenile trees are different from timbers from mature trees, thus the design values listed in the design code are not suitable to the small diameter logs. Much effort has been made to increase the economic efficiency of this kind of material. The physical and mechanical properties of small diameter logs from juvenile trees were tested by researchers around the world, for example, Boren and Barnard [3] tested the bending and compression strength and stiffness of small diameter logs from juvenile Scots pine. Bao et al. [4] compared the properties of timber from juvenile and mature trees of four kinds of structurally used species in China. Olarescu et al. [5] investigated the mass loss, swelling coefficient and dimensional and shape stabilization during heat treatment of wood originating from juvenile and mature trees from the same forest parcel. Series of studies were conducted by researchers in

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Forest Products Laboratory to investigate the mechanical properties and the potential of the small diameter logs as structural members [6–10]. Stern [11] reviewed the effective connecting methods for small diameter logs to encourage the use of these timber as construction materials. Fredriksson et al. [12] utilized small diameter logs to produce cross laminated timber panels, in which the logs were sawn along the edge into tapered shape. Komariah et al. [13] determined the physical and mechanical properties of glued laminated timber manufactured from small diameter logs of three tropical species. Chrisp et al. [14] applied small diameter logs into the structural frame of a single story residential center. From the literature it is found that there is still no effective way to utilize the small diameter logs from juvenile trees as structural materials, a simple, economical and efficient way to make use of this kind of forestry by-product is still needed.

The authors of this paper has developed one method to apply the small diameter logs from juvenile trees into the light wood frame construction as shearwalls [15] in which the small diameter logs were used in the form of hybrid built-up column. The lateral performance of the shearwall studded with the built-up column was investigated by experiment and finite element modeling. Built-up columns are widely used in steel structures [16], as for timber structures, to increase the section modulus and bearing capacity, built-up column and beam are also used. National design specification (NDS) [17] provides guidelines to calculate the load-carrying capacity of nailed and bolted built-up column. Eurocode 5 [18] also contains some provisions about calculating the effective slenderness ratio of spaced and lattice columns.

In the present work, the vertical performance of the developed built-up column was investigated by experiment and theoretical analysis. The results of this work contribute to application of small diameter logs as structural members, and can promote the value-added application of small diameter logs from juvenile trees.

Experimental investigation

Formation of the developed hybrid built-up column

There are usually two kinds of built-up timber columns used in the field of building engineering, i.e. the spaced column and the lattice column. As shown in Fig. 1, a spaced column is composed of two or more limbs intermittently connected with packs or gussets, the limbs cannot rotate at the fix point because of the restrain of packs or gussets. A lattice column consists of usually two limbs connected by diagonals continuously anchored to the limbs by nails or glue.

To apply the small diameter logs from juvenile trees into timber structures, a kind of hybrid built-up column was developed. The hybrid built-up column, which utilized pairs of crossing placed diagonals between the two limbs, was different from both spaced and lattice columns. A pair of crossing diagonals could be treated as a quasi-gusset plate, and the segment of column covered by the quasi-gusset could be

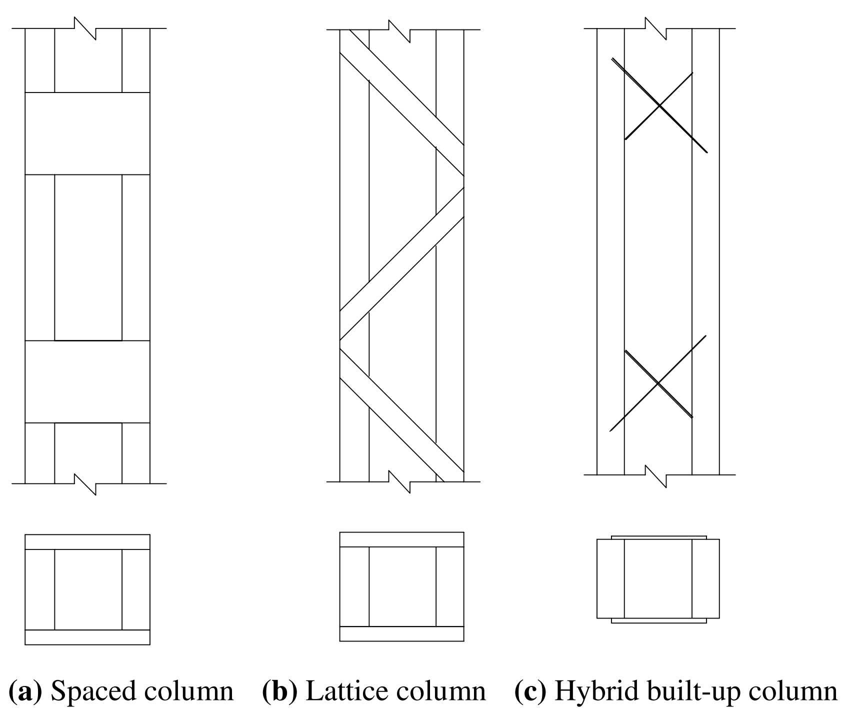


Fig. 1 Built-up columns

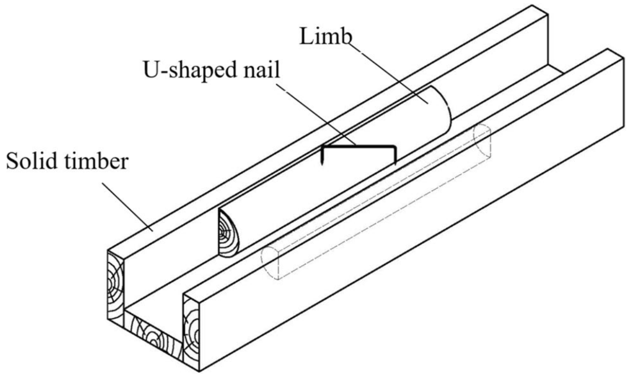


Fig. 2 Channel-shaped apparatus used to assemble the built-up column

treated as lattice column, thus the developed built-up column was a kind of hybrid built-up column.

A piece of small diameter log can be sawn into two halves to obtain two semicircular limbs. To assemble these two limbs into a built-up column, a channel-shaped apparatus was made by nailing 3 solid timber together, as shown in Fig. 2. The apparatus had an inner space whose width was the same with the built-up column. Two limbs were insert into the channel with their flat surfaces closely contacted with the solid timber, then U-shaped nails were driven at corresponding positions by hammer. Turn the half-finished build-up column and nail the other side up, a built-up column was manufactured. The hybrid built-up column was easy to manufacture and it converted irregular logs into regular members with two parallel surfaces, the hybrid built-up column was similar to dimension lumber and can be used as stud of shearwalls.

Materials and methods

To investigate the performance of hybrid built-up column, specimens were manufactured with Northeast China larch (*Larix gmelinii* (Rupr.) Kuzen) whose diameters ranging from 40 to 100 mm, a sketch of the hybrid built-up column is shown in Fig. 3.

The limbs of the hybrid built-up column were manufactured with semicircular cross section small diameter logs, which can be manufactured easily by splitting a round timber into two halves. The U-shaped nails, also named staple, were adopt as the diagonals. The crown of U-shaped nail was about 160 mm in length with tapered slope whose maximum diameter was about 8 mm, the leg of the U-shaped nail was about 35 mm long with a diameter around 3–4 mm. The U-shaped nail was made by commonly used Q235 low-carbon steel per Chinese code, with a characteristic yield strength of 235 MPa. The position of the U-shaped nails was determined before test based on the concept that the limbs

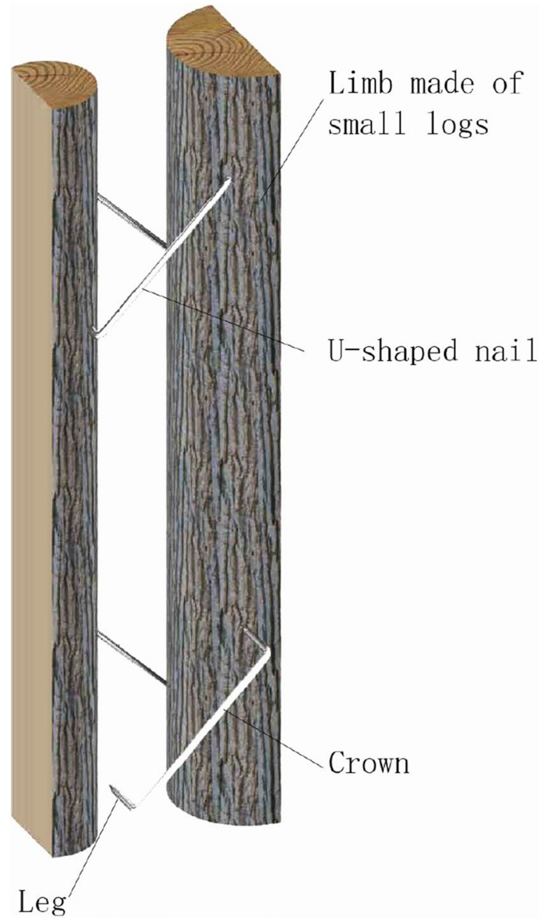


Fig. 3 A picture of the hybrid build-up column made of small diameter logs

should not bulked before the integrated column. The angle between the axis of the column and the crown of U-shaped nail was about 45°, this angle was chosen based on design concept of V-truss lattice column, the diagonal works in an optimum way in this situation, as indicated in equation C.18 in Eurocode 5 [18].

36 hybrid built-up columns were manufactured and every 3 of them were assembled together as one wall-type model. Thus, 12 test models were manufactured, 6 of which were loaded axially and designated as C1–C6, the other 6 were loaded eccentrically with an eccentricity of 35 mm and designated as E1–E6. 8 U-shaped nails were applied to both sides of the built-up column at a distance of 575 mm. The 3 built-up columns in one model were linked together by 2 in. × 6 in. SPF (Spruce-Pine-Fir) dimension lumber top and bottom plates and some 9.5 mm thick oriented strand board (OSB) panels discontinuously sheathed at the outside of the column. The OSB panels were sheathed discontinuously to function as in-plane lateral supports for 3 built-up columns while not affecting their load-carrying capacity. Built-up columns in the test model can only buckle out of

the wall plane under vertical load. Both ends of the built-up column were connected to top and bottom plates by four 3.8 mm × 80 mm nails. The OSB panels were connected to the limbs with 2.8 mm × 50 mm nails. All of the nails were hand driven. The height of the built-up column plus the top and bottom plates was 2440 mm (8 ft.), which was same as the height of a sheathing panel typically used in light wood frame construction.

As shown in Fig. 4, a one-way steel hinge was placed at each end of the test model, the total height of the test model and two hinges was 2550 mm. The models were axially loaded by a universal test machine at the speed of 2 mm/min. The vertical load and displacement were recorded at the frequency of 1 Hz by a computer controlled data acquisition system.

Besides the load-carrying capacity, the sectional dimensions at two ends and two-third-point of each column in every test model were measured, totally 72 groups of dimension data were obtained. The sectional properties including the average area of a single limb A_{limb}, the average area moment of inertia of a single limb to its weak axis I_{limb}, the average sectional area of a column A_{column} and the average moment of inertia of column I_{column} were calculated and listed in Table 1.

The bending strength and modulus of elasticity of the small diameter logs were determined by testing 16 pieces 2000 mm long round timber via Metriguard 312 bending proof tester (Metriguard Inc., Washington, USA). The tensile strength of the small diameter logs was determined by testing 16 pieces 2000 mm long round timber via Metriguard 412 tension (Metriguard Inc., Washington, USA) proof tester, and the compression strength of the timber was determined by testing 13 pieces 300 mm round timber by a universal test machine. All of the test were conducted in accordance with ASTM D 4761 [19]. It must be pointed out that the round timber used to determine the mechanical properties were sawn to the desired length and no extra processing was made, thus the determined mechanical properties were thought to be representative.

Fig. 4 Photo of a model in testing

Test results

It was found that all of the test model buckled under vertical load, as shown in Fig. 5. There was no lateral displacement noticeable before buckling. After the peak load, load dropped swiftly and local failures were observed in the test model. However, these post-buckling phenomenon did not affect the load-carrying capacity of the hybrid built-up column.

The load-vertical displacement curves of the axial compression models are shown in Fig. 6, C1 was not included for the sake of malfunction of the vertical displacement gauge in the process of testing, however, the vertical load was recorded and the peak load of C1 was 71.01 kN. The load-vertical displacement curves of the eccentric compression models are shown in Fig. 7.

The minimum load-carrying capacity of the axial compression models was 65.05 kN and the maximum is 82.95 kN, the average was 73.85 kN with a coefficient of variation of 8.12%. The tested load-carrying capacity was then divided by 3 to calculate the bearing load-carrying capacity of a column. The average of a built-up column was 24.62 kN. While the load-carrying capacity of the test models under eccentric load ranged between 52.65 and 70.95 kN, with an average of 64.78 kN and coefficient of variation of 9.04%. The average of a built-up column under eccentric load was 21.59 kN.

Table 1 Cross-sectional properties of the hybrid built-up column models

Loading type	A_{limb} ($\times 10^3$ mm^2)	I_{limb} ($\times 10^5$ mm^4)	A_{column} ($\times 10^3$ mm^2)	I_{column} ($\times 10^7$ mm^4)
Axial compression models	2.78	4.68	5.57	1.36
Eccentric compression models	2.74	4.12	5.48	1.42

Fig. 5 Failure of test models

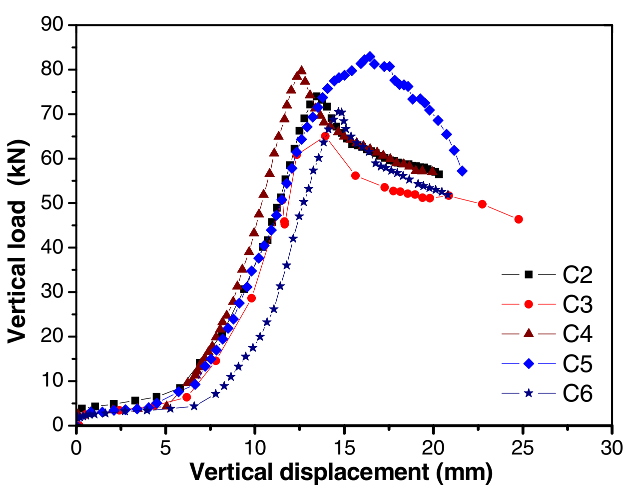


Fig. 6 Load-vertical displacement curves of axial compression models

The average compression strength of a 2 in. × 4 in. SPF dimension lumber of No. 2 is 28.25 MPa [20], the computed buckling average load-carrying capacity of a SPF stud with a length of 2550 mm and hinge supports at two ends was 27.16 kN as per Chinese timber design code GB50005 [21], but mean value of the lumber strength was taken, instead of

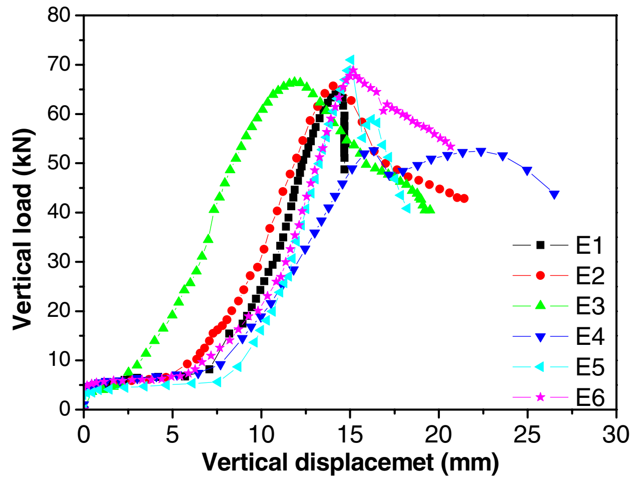


Fig. 7 Load-vertical displacement curves of eccentric compression models

the design value. This indicated that the hybrid built-up column can be used as a substitute of 2 in. × 4 in. SPF dimension lumber as they have similar bearing capacity.

Theoretical investigation

Derivation of the equation of effective slenderness ratio

The load-carrying capacity of the hybrid built-up stud was obtained by experiment, however, to utilize the column in engineering practice, the prediction method of the load-carrying capacity of the member needs to be proposed.

Vertical load imposed on a built-up column will induce shear deformations due to the bending of the chord members, deformation of web member and deformation of the connection between web member and chord member. To predict the load-carrying capacity of the built-up column, the effective slenderness ratio of the built-up column needs to be worked out. The Euler formula can be expressed as [16]:

$$N_{cr} = \frac{\pi^2 E A_{tot}}{\lambda^2} \tag{1}$$

where N_{cr} is the Euler buckling load considering shear deformation; E is the modulus of elasticity of the limbs of the built-up column; A_{tot} is the cross sectional area of the built-up column; λ is the slenderness ratio for a solid column with the same length, the same area and the same second moment of area as the built-up column, can be calculated by Eq. 2:

$$\lambda = l_E / i \tag{2}$$

where l_E is the effective length of the built-up column and i is the gyration radius of the column, i is known as:

$$i = \sqrt{I_{tot}/A_{tot}} \tag{3}$$

In which I_{tot} is the second moment of area of the built-up column. When considering shear deformation, λ is replaced by λ_{ef}, which is the effective slenderness radio of the built-up column, can be written as:

$$\lambda_{ef} = \lambda\sqrt{1 + \gamma N_E} \tag{4}$$

In which N_E is the Euler load without considering shear deformation; γ is the shear deformations caused by unit shear force.

A segment of the hybrid built-up column is shown in Fig. 8a, by analyzing the formation of the column, it can be found that the shear deformations γ of the column under unit shear force consists of 3 parts:

As shown in Fig. 8b, a pair of crossing placed U-shaped nails is regarded as a quasi-gusset between the two limbs, then the built-up column is considered as a multi-storied rigid frame, i.e. the spaced column. In this frame, the quasi-gussets are treated as beams and the limbs are treated as columns. For spaced column, the shear deformation γ_1 is rises from the bending of limbs, and the effective slenderness ratio considering this part of shear deformation can be expressed as [18]:

$$\lambda_{ef} = \lambda\sqrt{1 + \gamma_1 N_E} = \sqrt{\lambda^2 + \eta\frac{n}{2}\lambda_1^2} \tag{5}$$

where

$$\lambda_1 = \frac{a}{\sqrt{I_1/A_1}} \tag{6}$$

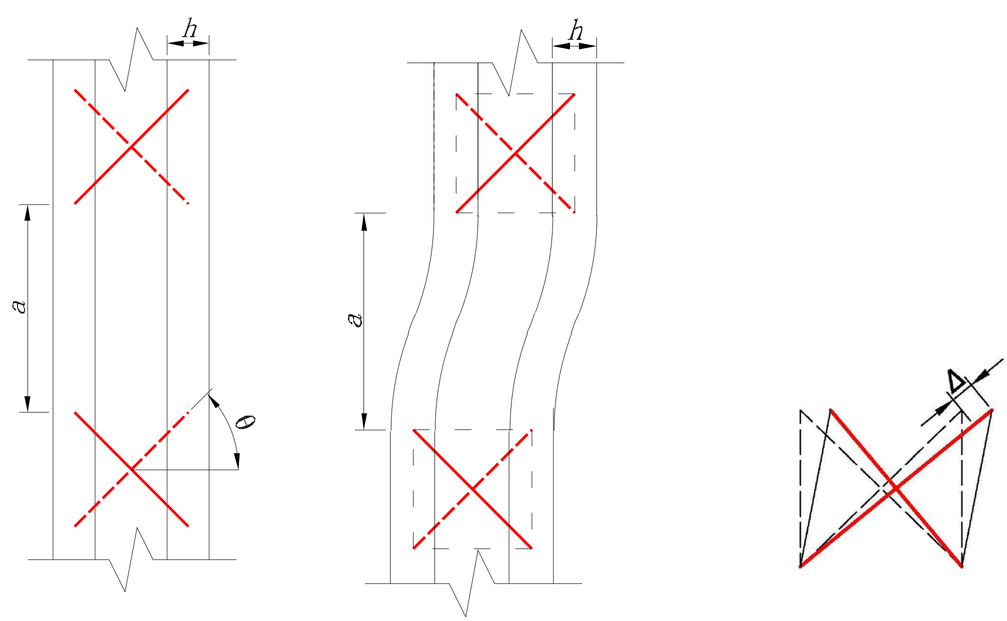
where λ_1 is the slenderness ratio for the limbs; I_1 and A_1 are area moment of inertia and the cross-sectional area of a single limb, respectively; a is the length shown in Fig. 8; n is the number of limbs; η is a factor which can be taken 4.5 per Eurocode 5 [18].

Besides in the hybrid built-up column, the pseudo-gussets are not actual gussets, they can actually deform under shear force due to slipping of the connections between the U-shaped nails and the two limbs and elongation or contraction of the U-shaped nails, as shown in Fig. 8c. The stiffness of the U-shaped nails is much higher than that of the nail connection, thus the shear deformation due to the deformation of U-shaped nail can be neglected. To calculate the contribution of the slip of the connection between the U-shaped nails and limbs Δ, the built-up column within the U-shaped nails can be treated as a V-shaped lattice column. For lattice column, the shear deformation γ_2 rises mainly from the slip between diagonals and limbs, and for a nailed connection, the effective slenderness ratio can be expressed as [18]:

$$\lambda_{ef} = \lambda\sqrt{1 + \gamma_2 N_E} = \lambda\sqrt{1 + \mu} \tag{7}$$

In which

$$\mu = 25\frac{hEA_1}{l^2 n_n K \sin 2\theta} \tag{8}$$



(a) A segment of the column **(b)** Shear deformation due to bending of limbs **(c)** Shear deformation due to bending of limbs

Fig. 8 Shear deformation of a segment of the hybrid built-up column where n_n is the number of nails contributing to the shear deformation in all diagonals. h is thickness of the limb along the direction of deformation. A_1 is the area of a limb. θ is the angle between the axis of crown of U-shaped nails and the column. K is the slip modulus of one nail connection, which can be expressed, according to Eurocode 5 [18], as:

$$K = \rho^{1.5}\frac{d_L{}^{0.8}}{80} \tag{9}$$

where ρ is the mean density of the wood member; d_L is the diameter of the leg of the U-shaped nail.

Based on the derivation above, for the hybrid built-up column the effective slenderness ratio taking into consideration of the shear deformations resulting from bending of the limbs and slip of connection can be expressed as:

$$\lambda_{ef} = \sqrt{\lambda^2 + \eta\frac{n}{2}\lambda_1^2 + 25\frac{hEA_1}{l^2 n_n K \sin 2\theta}\lambda^2} \tag{10}$$

Prediction of load-carrying capacity of the built-up column

To calculate the load-carrying capacity of a hybrid built-up column, the stability coefficient needs to be worked out. As introduce in Eurocode 5 [18], the stability coefficient k_c can be expressed as:

$$k_c = 1/\left(k + \sqrt{k - \lambda_{rel}^2}\right) \tag{11}$$

In which

$$k = 0.5\left(1 + \beta_c(\lambda_{rel} - 0.3) + \lambda_{rel}^2\right) \tag{12}$$

$$\lambda_{rel} = \frac{\lambda}{\pi}\sqrt{\frac{f_c}{E}} \tag{13}$$

where λ and λ_{rel} are slenderness ratios and relative slenderness ratios corresponding to bending about the selected axis, respectively. To calculate the stability coefficient of the hybrid built-up column, λ needs to be replaced by the effective slenderness ratio λ_{ef} in Eq. 10. β_c is a factor for members within the straightness limits, i.e. 0.2 for solid timber.

For the test models, the gyration radius i of an equivalent solid column was calculated as 49.5 mm, thus the slenderness ratio λ was 51.5; The gyration radius for a limb was 13.0 mm and the calculated slenderness ratio λ_1 was 44.4; n was taken as 2 and n_n was taken as 4; The average compression strength parallel to grain was 42.0 MPa, obtained from compression tests of 300 mm small diameter logs specimens; For U-shaped nails with 3.5 mm-diameter legs, the slip stiffness K was calculated as 493 N/mm; θ was 45° for the test models; The effective length was taken as 2550 mm for the hinged column. Substituting these parameters into Eq. 10, the effective slenderness ratio of the hybrid column was 159.1. Then substitute the calculated effective slenderness ratio into Eq. 11, the stability coefficient was worked out as 0.099.

The load-carrying capacity of the developed hybrid built-up column can be calculated as:

$$F_c = \sigma_c A_{tot} \tag{14}$$

where σ_c is the critical stress due to buckling, which is often expressed by Eq. 15 in the design code of most countries:

$$\sigma_c = k_c f_c \tag{15}$$

where f_c is the compression strength parallel to grain. It should be point out that mean value of lumber, instead of the design value, was taken to make a comparison between the prediction and experiment. The stability coefficient for the axial compression model k_c was 0.099, and the calculated load-carrying capacity considering buckling was 23.31 kN, which was very close to the test result of 24.62 kN, the error was only 5.3%.

For the eccentrically loaded built-up column, bending stress due is introduced, in Eurocode 5, the governing design function was provided as [18]:

$$\frac{\sigma_c}{k_c f_c} + \frac{\sigma_m}{f_m} \le 1 \tag{16}$$

where f_m is the bending strength, mean value of 67.2 MPa is taken here, which was obtained from bending tests of 2000 mm long small diameter logs specimens. σ_m is the bending stress due to eccentric load, can be worked out as:

$$\sigma_m = \frac{F_c e y_{max}}{I_{column}} \tag{17}$$

where e is the eccentric distance, 35 mm. I_{column} is the average moment of inertia of column, listed in Table 1, y_{max} is the maximum distance from neutral axis, 70 mm. Substitute Eqs. 14 and 17 into Eq. 16, and take the area properties listed in Table 1, the stability coefficient k_c for the eccentric compression model was 0.093. The maximum load bearing capacity of the eccentrically loaded built-up column can be worked out as 20.29 kN, which was very close to the test result 21.39 kN, also. The error was 5.56%.

Conclusions

To efficiently utilize small diameter logs originating from juvenile trees as structural materials, a hybrid built-up column fabricated with small diameter logs was developed and the performance was investigated experimentally and theoretically. The results of this paper can contribute to application of small diameter logs as structural members. The main conclusions are list as follows:

1. The derived equation of effective slenderness ratio, in which Eurocode 5 [18] equations were used and combined in a previously not presented manner to take into consideration of the shear deformation due to bending of limbs and slip of connection between U-shaped nail and limbs, had good accuracy when used to calculate the stability coefficient and to predict the load-carrying capacity of the hybrid built-up column developed in this paper.
2. The developed hybrid built-up column can be manufactured easily, and had good load-carrying capacity under vertical load, thus it provided an effective way to utilizing the small diameter logs originating from juvenile trees as construction materials.
3. The failure mode of the developed hybrid built-up column was buckling under vertical load, no local failure was observed before peak load.
4. The mean load-carrying capacity of the developed hybrid built-up column of 2440 mm height was 24.62 kN with the given configuration, which had the potential be used as a substitute of the dimension lumber stud.

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