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NUMERICAL MODELLING OF STRUCTURAL BAMBOO UNDER COMPRESSION

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Bamboo is a sustainable and eco-friendly material with great potential to replace traditionally available construction materials like concrete and steel. However, accurately predicting the behavior of bamboo is essential for improving the structural design codes, which will enhance the wider usage of bamboo as a structural member. In this study, the buckling of bamboo is modelled numerically as both cylindrical and tapered circular columns with varying elastic moduli across the cross-sections in ABAQUS®. Then, the results were compared with Euler's equation derived for the cylindrical and tapered circular columns having homogeneous cross-sections. Finally, it was observed that columns with varying elastic moduli across the cross-section have 1.5 to 2.3 times a lesser buckling load capacity than columns with homogeneous cross-sections with outer Young's modulus value (E_o). Also, compared to buckling load homogeneous cross-sections with inner Young's modulus value (E_i), varying elastic modulus cross-sections have 1.7 to 2.7 times higher buckling load. This study emphasizes the necessity of having a simple analytical equation with varying elastic modulus for calculating the buckling load for bamboo columns.

Keywords: Buckling, Natural FGM, Sustainable construction, Buckling load capacity.

1 INTRODUCTION

Bamboo, a naturally available structural member, has been used since ancient times for house construction due to its sustainability and potential to reduce carbon emissions. Bamboo is a unique unidirectional composite consisting of vascular bundles as reinforcement and parenchyma cells as the matrix. The density of bamboo varies depending on species, growing conditions, and position along the culm. The fibers, which are approximately 60-70 % by weight (Ghavami *et al.* 2003); determine their mechanical properties due to their unidirectional arrangement in the tissue and unique cell wall structure. To increase bamboo adoption in construction, appropriate building codes are needed to design the members for compression, tension, and bending forces. The bamboo design under compression is critical, as the member's failure would be buckling rather than material failure. This study focuses on understanding the buckling behavior of bamboo column members under pure axial compression and its relation to the microstructure. The study aims to idealize bamboo as a natural functionally graded material with varying Young's modulus from the inner face to the outer periphery of the bamboo rather than a homogeneous material (Harries *et al.* 2017). In the current work, the impact of varying elastic moduli on the buckling load of a bamboo column with cylindrical and tapered cross-sections was studied by finite element modeling in ABAQUS® software. Then the results were compared with the Euler buckling equation for the homogeneous cross-section. According to Harries *et al.* (2017); the modulus of elasticity (E) over the thickness of a bamboo column varies according to the volume percentage of the fibers and is determined by Eq. (1):

$$E = (1 - V)E_m + VE_f \tag{1}$$

where V is the fiber volume percentage, E_f is the elastic modulus of bamboo fibers, and E_m is the elastic modulus of lignin.

From above Eq. (1), one can easily observe that as the volume of fiber increases from the inner to the outer radius of the bamboo (as shown in Fig. 2) modulus of elasticity also increases from the inner to the outer radius of the bamboo. Also, the diameter varies along the length, as shown in Fig. 1, one needs to model the bamboo column as tapered instead of a cylindrical cross-section.

Fig. 1. Longitudinal section of Bamboo column.

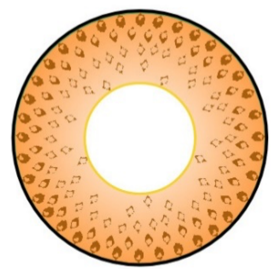


Fig. 2. Cross section of Bamboo column.

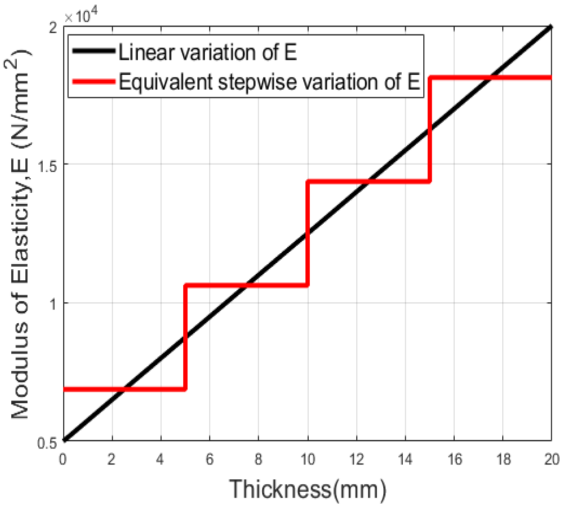
2 NUMERICAL MODELING

Three annular cylindrical columns with cylindrical cross-section and three tapered annular cylindrical columns with a D_o/t diameter to thickness ratio of 20, 10, and 5 are chosen to model the bamboo in the ABAQUS®, where D_o is the outer diameter of the column, and t is the thickness of the column. The outer diameter and length of the column were taken as 100 mm and 1000 mm. The tapering of 5° was given to the model tapered column. Three cases of linear, quadratic, and cubic variations of the modulus of elasticity (E) along the thickness of the bamboo were considered for cylindrical columns. Three cases of constant, linear, and cubic variations of the modulus of elasticity (E) along the thickness of the bamboo were considered for tapered columns. For the numerical model, based on the variation of the volume fiber, the following expression for the E across the thickness was adopted, which is given in Eq. (2):

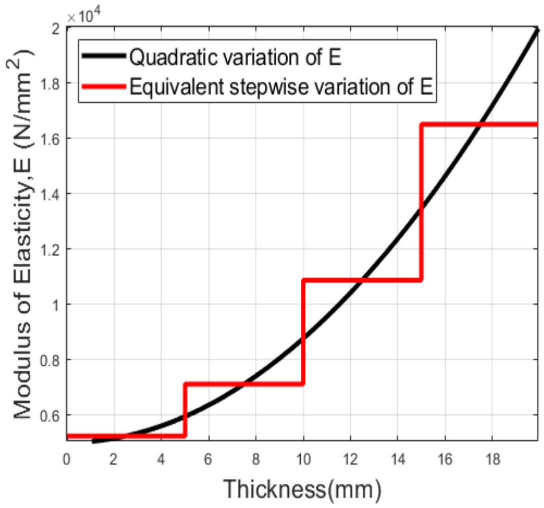
$$E(r) = (E_o - E_i) \times \left(\frac{r - R_i}{R_o - R_i}\right)^n + E_i \tag{2}$$

where E_i and E_o is Young's modulus of the inner and outer layer of the bamboo, R_i and R_o is the inner and outer radius of the bamboo.

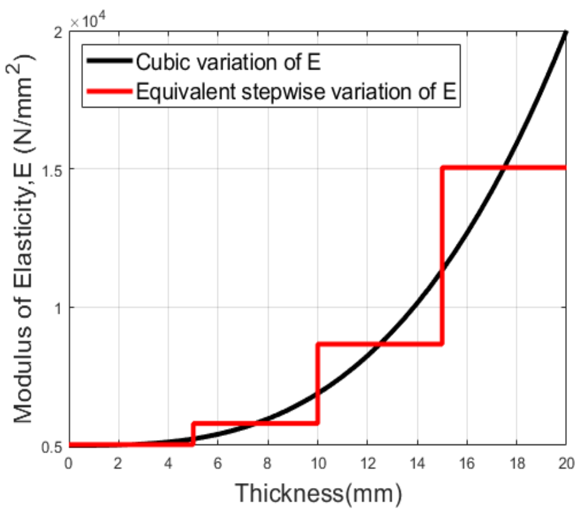
The value of E_i and E_o was taken as 5000 MPa and 20,000 MPa, respectively (Dixon and Gibson 2014). Depending on the value of n, the linear or non-linear variation of E along the thickness of the bamboo can be modeled. The geometry was created with four concentric cylinder parts, and each part was assigned a constant E value to get an approximate step variation of Young's modulus across the cross-section as compared to continuous variation, as shown in Fig. 3. Finally, all the parts were merged to get a single geometric model (refer to Figs. 4 and 5). The hinge boundary condition has been assigned at the top and bottom using MPC constraint at the centroid cross-section. The reduced integration of 20-node brick elements was used to model the column. The appropriate mesh for all the models arrived at after conducting the mesh convergence study such that the error between the buckling load corresponding to successive two trail numerical models (by varying coarse mesh to finer mesh) was less than 5% (Cook *et al.* 2001). Also, to validate the numerical models, the results of the cylindrical circular homogeneous columns were compared with the corresponding Euler's buckling equation, as reported in Tables 1 and 2. By comparing it with analytical results, the error was found to be less than 5%. The buckling analysis was performed, and the results are reported in the tables along with a comparison with the analytical equation of Euler buckling load.



a. Linear variation of modulus of elasticity.



b. Quadratic variation of modulus of elasticity.



c. Cubic variation of modulus of elasticity.

Fig. 3. Comparison of variation of E between analytical expression (Eq. (1)) and numerical modelling.

3 RESULTS AND DISCUSSION

Figs. 4 and 5 show the deformed shapes exemplifying the lowest buckling mode revealed through the eigenvalue analysis. The critical eigenvalues derived from this analysis act as pivotal buckling load factors. To ascertain the critical buckling load for the columns, these load factors are applied as multipliers to a nominal load of 1N. The results from the numerical models are listed in Tables 1 and 2.

Fig. 4. Model geometry with the meshing and first buckling mode of an annular cylindrical column.

Fig. 5. Model geometry with the meshing and first buckling mode of a tapered annular cylindrical column.

Table 1. Results of cylindrical column obtained from ABAQUS®.

D_o/t	Buckling load obtained from numerical analysis (kN)				Buckling load obtained from Euler's equation (kN) with E as E_i $P_{cr} = \frac{\pi^2 E_i I}{KL^2}$	Buckling load obtained from Euler's equation (kN) with E as E_o $P_{cr} = \frac{\pi^2 E_o I}{KL^2}$
	For constant modulus of elasticity with E_i	For linear variation of E	For quadratic variation of E	For cubic variation of E		
5	203	574.8	478	411	211	843.4
10	136	348	297	257	143	572
20	79	205	165	143.5	83	332

Table 2. Results of tapered column obtained from ABAQUS®.

D_o/t	Buckling value obtained from ABAQUS® (kN)			Result obtained from analytical expression (kN) (Gere and Carter 1962) with E as E_i $P_{cr} = \frac{P^* \pi^2 E_i I_A}{L^2}$	Result obtained from analytical expression (kN) (Gere and Carter 1962) with E as E_o $P_{cr} = \frac{P^* \pi^2 E_o I_A}{L^2}$
	For constant modulus of elasticity with E_i	For linear variation of modulus of elasticity	For cubic variation of modulus of elasticity		
5	1110	3076.7	2172	1117	4468
10	690	1756	1232	685	2740
20	345	904	629	348	1392

The results for the cylindrical column obtained from Abaqus were compared with Euler's equation for a homogeneous cross-section given by Eq. (3):

$$P_{cr} = \frac{\pi^2 EI}{KL^2} \tag{3}$$

where P_{cr} critical load of the column is, E is the modulus of elasticity corresponding to the inner or outer fiber layer of the bamboo, I is modulus of elasticity of column and L is the length of the column, K is the effective length factor, and for the pinned-pinned end boundary condition, its value is 1.

The eigenvalue obtained from numerical model results for the tapered column was compared with the analytical equation available in the literature (Gere and Carter 1962) as given by Eq. (4):

$$P_{cr} = \frac{P^* \pi^2 E_i I_A}{L^2} \tag{4}$$

where E is the Modulus of elasticity corresponding to either the inner or outer fiber layer of the bamboo, I_A is the moment of inertia at the smaller end of the column, L is the length of the column, p^* is the function of shape factor n, and the ratio of outer diameters at larger and smaller ends, respectively.

From the results that are tabulated in Table 1, it is observed that cylindrical columns with varying elastic moduli across the cross-section have 1.5 lesser buckling load for the linear variation of elastic modulus and 2.3 times a lesser buckling load capacity for the quadratic variation of elastic modulus than the columns with homogeneous cross-sections with outer Young's modulus value (E_o). Also, compared to buckling load homogeneous cross-sections with inner Young's modulus value (E_i), varying elastic modulus cross-sections have 1.7 lesser buckling load for the linear variation of elastic modulus and 2.7 times higher buckling load for the quadratic and cubic variation of elastic modulus. Similar results are also observed with tapered columns with varying elastic moduli across the cross-section. The reported results also showed that the bucking load of a column with a cross-section of a linear variation of E has a higher buckling load than a quadratic and cubic variation. From this, one can easily observe that the Euler buckling formula, originally developed for columns with homogeneous cross-sections, cannot be applied to predict the buckling load for a bamboo column.

4 CONCLUSIONS

In this study, a 3D numerical model was developed and analyzed to understand the effect of the bamboo cross-section with varying elastic modulus on the column buckling load capacity. Based on the above results, it is evident that accounting for variations in the elastic modulus results in either underestimating or overestimating the buckling load for cylindrical columns compared to assuming a constant modulus. Additionally, when considering tapered columns, which may reflect the actual geometry of the bamboo, there is an increase in the buckling load compared to that of cylindrical columns. In conclusion, considering variable elastic modulus values and the actual tapered shape of columns significantly underestimates or overestimates the buckling loads compared to assuming a constant modulus and cylindrical cross-section. This study prompts the development of an analytical equation to accurately predict the buckling load of the bamboo columns and, in turn, helps to advance the building design codes. Advancement of the structural design codes will lead to the large-scale adoption of bamboo in buildings by Architects and practicing engineers.

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