THE EFFECT OF SPECIFIC GRAVITY ON EMBEDDING STRENGTH OF GLUED-LAMINATED(GLULAM) BAMBOO: NUMERICAL ANALYSIS AND EXPERIMENT

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Abstract

Glue-laminated (glulam) bamboo potentially used to be a substitute for wood as a building material, because it can be produced within four to five years of planting. Mechanical properties of glulam bamboo should be well understood by support the wider application of this new material in structural components. This study focused on embedding strength evaluation of glulam bamboo, were required to evaluate lateral resistance of dowel-type joints. The evaluation was carried out using experiment according to ASTM D5764 and numerical analysis performed with ADINA™. Material were considered in the experiment consist of bolt 12.2 mm diameter, a range of specific gravity of glulam bamboo from 0.57 to 0.79 and moisture contents varies from 11.14% to 12.45% were considered in the experiment. There were three groups of specimens: group A parallel loading to grain radial; group B parallel loading to grain tangential; and the last was group C perpendicular loading to grain. Glulam bamboo were modeled as an orthotropic nonlinear material whiles the dowel was assumed as perfectly rigid material. Contact condition between dowel and laminated bamboo was considered and the numerical model was solved under the plane stress assumption with deformation control. The experimental result was indicated that embedding strength parallel to grain (group A and B), it was significantly higher than group C. This phenomenon was apparent in the numerical study as well. The embedding strength of laminated bamboo (F_e) could be well predicted as 78.4G for parallel to grain radial, 72.79G for parallel to grain tangential; and 69.96G for perpendicular to grain radial, where G is the specific gravity.

Keywords: Connection, Contact condition, Dowel, Embedding strength, Laminated bamboo

Introduction

The connection needs major concern in most timber buildings/ constructions as weakest link. Research on connection therefore has become one of the most interesting topics for many timber engineers and scientists since a couple decades ago. In timber construction, there are some factors that decrease the connection resistance: reduction of cross-sectional member area, angle of loading-to-grain are often not parallel, and limited effective area for connection placement due to fasteners spacing requirement [1]. Previous studies [2-4] had indicated that the lateral resistance of dowel-type timber connections was governed by connection geometry, embedding strength of timber member, and bending yield strength of the dowel. The embedding strength of timber member can be evaluated according to ASTM D5764 [5] where it depends on specific gravity, moisture content, dowel diameter and angle of loading-to-grain.

Recently, bamboo has been applied in some constructions such as residential houses, bridges and buildings. As bamboo has pipe-like cross-section, problems appear especially in connection parts. To overcome this difficulty, glued-laminated bamboo (glulam bamboo) is now fabricating in our laboratory. Glulam bamboo is made from multiple bamboo straps which are arranged in the same direction, glued and pressed together. This paper is a part of a comprehensive study to examine the application of glulam bamboo as structural elements. Focus of this paper is investigating the influence of specific gravity of glulam bamboo on its embedding strength.

Literature Review

Glulam Bamboo

Originally glulam bamboo is based on similar technology applied in glued laminated timber. Glued laminated timber consists of relatively thin wood layers were combined and glued together in such a way as to produce a beam of various sizes and lengths [6]. Our previous study [7] summarized in Table 1 showed that glulam technology increased mechanical properties of glulam bamboo. Glulam technology also becomes solution of cracks or deformation due to bamboo drying activities because glulam bamboo consists of thin laminas that dries easily. In addition, glulam technology allows the manufacture of large and stable structural members because all laminas are dried before assembling process. [6]

Table 1. Mechanical Properties of Bamboo and Glulam Bamboo [7]

Mechanical properties	Bamboo	Glulam Bamboo	Increased %
Compression ⊥ fibre	11 MPa	15 MPa	36.6
Compression // fibre	52 MPa	71 MPa	36
Tension	247 MPa	350 MPa	41
Shear	4.5 MPa	9.5 MPa	111
Bending	118 MPa	175 MPa	48

Embedding Strength of Wood

Dowel connection generally functioned to support a perpendicular load to longitudinal axis. Connection strength is determined by embedding strength of wooden, bending strength of dowel, and slenderness value (ratio of length of dowels on main timber with a diameter of dowel). When slenderness is small, dowel becomes very stiff and stress distribution embedding strength of wooden under dowels will occur evenly. The higher slenderness of dowel, it will begin to buckle and embedding strength of wood unevenly distributed. Maximum embedding strength occurs on side of main timber [9].

Embedding strength of wood depend on water content, spesific gravity of wood, and diameter of dowel. Test results by Rammer [4] showed that embedding strength in water content of 15%, 12%, 6% and 4% were respectively at 1.23; 1.36; 1.63; and 1.72; times embedding strength of wood at 20% moisture content. Awaludin [1] perform testing of wood with some varies of specific gravity values are classified on softwood and hardwood. The results showed that the embedding strength of wood increased along with the increasing specific gravity of wood. Angle of loading-to-grain has also been investigated by Soltis and Wilkinson, who later adopted the regulations on wood National Design

Specification (NDS) for timber construction and ASTM D 5764 [5,8], with testing setting direction of loading to direction of grains such as Figure 1.

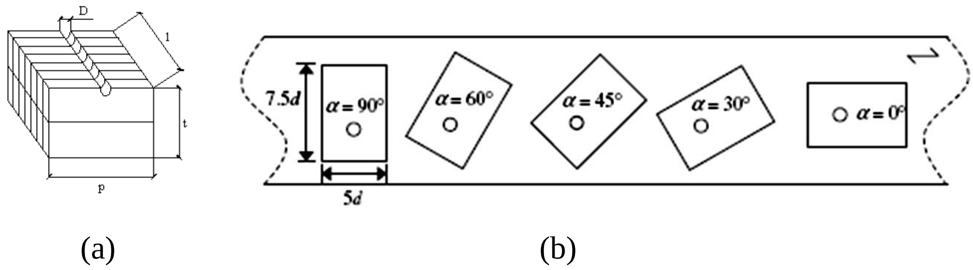


Figure 1. Embedding strength specimen: (a) specimen fabrication half-hole, (b) specimen fabrication full-hole [5]

Embedding strength of wood was determined based on loading value (P or $P_{5\%}$) by dividing load obtained by area sectional of press it was multiplied by diameter of dowel and thickness wood. It can determined by offset method in slip 0.05D (D is diameter of dowel) as Figure 2. Embedding strength, F_e, calculated using the equation:

$$F_e = \frac{P_{max}}{D.t} \quad (1)$$

where P_{max} is maximum compressive loading, D is diameter of dowel, and t is thickness of glulam bamboo as is showed in Figure 1 (a).

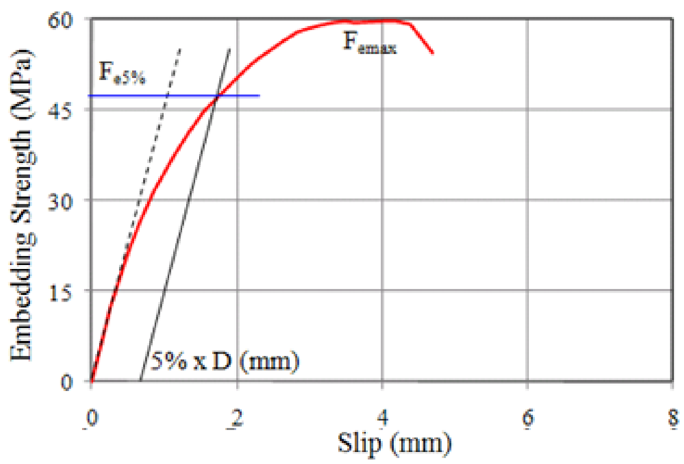


Figure 2. Embedding strength-slip curve [4]

The equation for embedding strength of wood is:

$$F_{e\theta} = \frac{F_{e\parallel}F_{e\perp}}{F_{e\parallel}sin^2\theta + F_{e\perp}cos^2\theta} \quad (2)$$

$$F_{e\perp} = 77.25\ G \text{ (MPa)} \quad (3)$$

$$F_{e\parallel} = 212\ G^{1.45}\ D^{-0.5} \text{ (MPa)} \quad (4)$$

where F_e, G and D are embedding strength of wood, specific gravity of wood and diameter dowels, respectively.

Contact Problem Modeling

Non-conform contact problem without friction is such kind of contact problem where introducing of load increment is not necessary, but iteration procedure must be introduced because contact area is not known as *a priory*. The problem is solved when continued distribution of normal stresses across the whole contact area is obtained. At the end of contact area the stress must be zero or very close to zero. *Non-conform contact problem with friction* - because of friction presence iteration procedure must be carried out. The increments of loading must be introduced as well [10]:

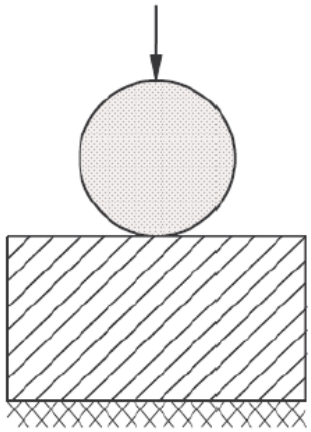


Figure 3. Non-conform contact

A general equation for total potential of *N* bodies in contact in time *t* , according to virtual work principle is:

$$\sum_{L=1}^{N} \int_{{}^{t}V} {}^{t}\tau_{ij}\, \delta_t e_{ij}\, d^{t}V \;=\; \sum_{L=1}^{N} \left\{ \int_{{}^{t}V} \delta u_i \;{}^{t}f^{B} d^{t}V + \int_{{}^{t}S_f} \delta u_i^{S}\;{}^{t}f_i^{\,S} d^{t}S \right\} + \sum_{L=1}^{N} \int_{{}^{t}S_c} \delta u_i^{c}\;{}^{t}f_i^{\,c} d \quad (5)$$

where δ=slip, τ= shear stresses, V=volume, displacement of nodes *U* and *e*. The part of brace on the right side of equation represents usual members in virtual displacement method, while the third member represents the contribution of contact stresses. A fundamental relation in non-linear FEM analysis that must be solved is:

$$\int_{{}^{t+\Delta t}V} {}^{t+\Delta t}\tau_{ij}\, \delta_{t+\Delta t} e_{ij}\; d^{t+\Delta t}V = {}^{t+\Delta t}\Re \quad (6)$$

where on the left side of (9) is internal virtual work and:

$${}^{t+\Delta t}\Re = \int_{{}^{t+\Delta t}V} {}^{t+\Delta t}f_i^{B}\; \delta u_i\; d^{t+\Delta t}\, V + \int_{{}^{t+\Delta t}S_f} {}^{t+\Delta t}f_i^{\,S}\; \delta u_i^{S}\; d^{t+\Delta t}\, S \quad (7)$$

is exterior virtual work (R).

The fundamental problem in general non-linear analysis is to solve equilibrium state of bodies, which corresponds to real load. If we suppose that load is a function of time, the condition of equilibrium can be represented with:

$${}^{t}R - {}^{t}F = 0 \quad (8)$$

Exterior load is:

$$ {}^{t}R = {}^{t}R_B + {}^{t}R_S + {}^{t}R_C \tag{9} $$

with volume, surface and concentrated forces. If momentary stress is concerned like initial stress, than the node forces obtained from stress satisfy the condition:

$$ R_t = {}^{t}F \tag{10} $$

that is:

$$ {}^{t}F = \sum_m \int_{{}^{t}V^{(m)}}^{t} B^{(m)^T} \tau^{(m)t} dV^{(m)} \tag{11} $$

for all of that, the stresses and volumes of bodies in time *t* are unknown. When non-linear response is supposed, then equation (8) must be satisfied through whole load history, i.e. in time *t* from zero to any time in which problem is concerned. In statically analysis, that contact problem is, the time is a convenient variable. The time describes various intensity of load, and also a various configurations. That is the essence of incremental method.

Materials and Methods

Experimental Testing Method

Embedding strength tests carried out on glulam bamboo using bamboo petung (*Dendrocalamus asper*) and deformed bolt of 12.2 mm in diameter. The difference of water content in the test specimen bamboo should be minimized because it can affect distribution of test data. Therefore, before testing the test specimen are conditioned in an oven at a temperature of 38°C to 40°C in a few days until their water content reaches and relative humadity constantly about 12% and 65%.

Testing method of embedding strength of bamboo was adopted from ASTMD 5764 “Standard Test Method For Evaluating Dowel-Bearing Strength Of Wood And Wood-Based Products” as shown in Figure 3. The load was applied at a constant rate of 5 mm/minute and embedment of steel dowel into glulam member was continuously with two LVDTs. Testing load performed using UTM which is integrated data logger in a computer unit with a constant speed of 5 mm / minute [5] and slip (depth of penetration of dowel to test piece glulam bamboo) dowel was measured continuously using an LVDT (linear variable displacement transducer). The testing was stopped when a decline in compressive load after maximum load is reached. There are three groups of specimen: group A - parallel loading to grain in radial direction, group B - parallel loading to grain in tangential direction, and group C - Perpendicular loading to grain (see Figure 4). In each group, there were ten replicates, and testing with ten replicates each group (see Figure 4).

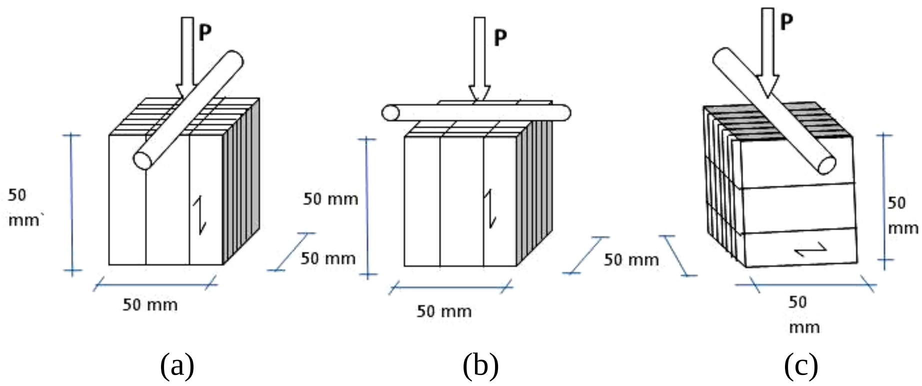


Figure 4. Embedding strength testing model of glulam bamboo, specimen test in:
(a) group A, (b) group B, and (c) group C

Numerical Model

Glulam bamboo has nonlinear properties, the ADINA (Automatic Dynamic Incremental Nonlinear Analysis) 8.7 finite element software was selected to model two-dimensional plain stress. Glulam bamboo material parameters and foundation material parameters was determined through ASTM D 143-Compression test. It was used lamina multilayer linear elastic orthotropic having constitutive as follows: Young's Modulus (E) E_L = 11,840 MPa ; E_R = 511.14 MPa; E_T = 814.39 Mpa, Poisson's ratio ν_{LR} = 0.179; ν_{LT} = 0.229; ν_{RT} = 0.231, and Shear Modulus (G, MPa) G_{LR} = 412.031; G_{LT} = 627.001; G_{RT} = 238.776. two-dimensional eight-noded, quadrilateral isoparametric brick element having two degrees of freedom at each node was employed to embody the model. Contact area between glulam bamboo and bolt were modelled using surface-to-surface contact elements (Lagrange multiplier algorithm) with a frictional coefficient of 0.7.

Results and Discussion

Test photos of embedding strength of glulam specimen are shown in Figure 5 where the specimens were cracked after formation of plastic embedment of glulam member beneath the steel dowel. The specimens had broken pre-failure preceded by plastic deformation bamboo grain under dowels (see Figure 6).

Figure 5. Embedding strength testing of glulam bamboo

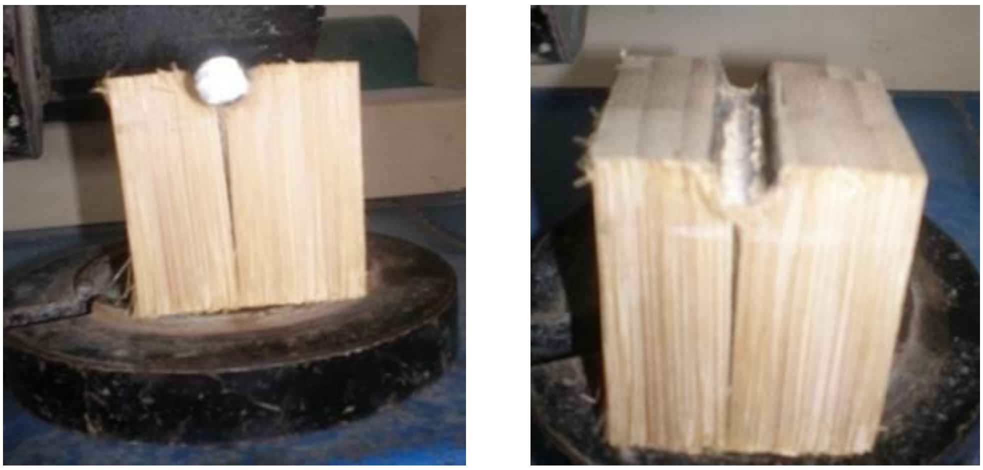
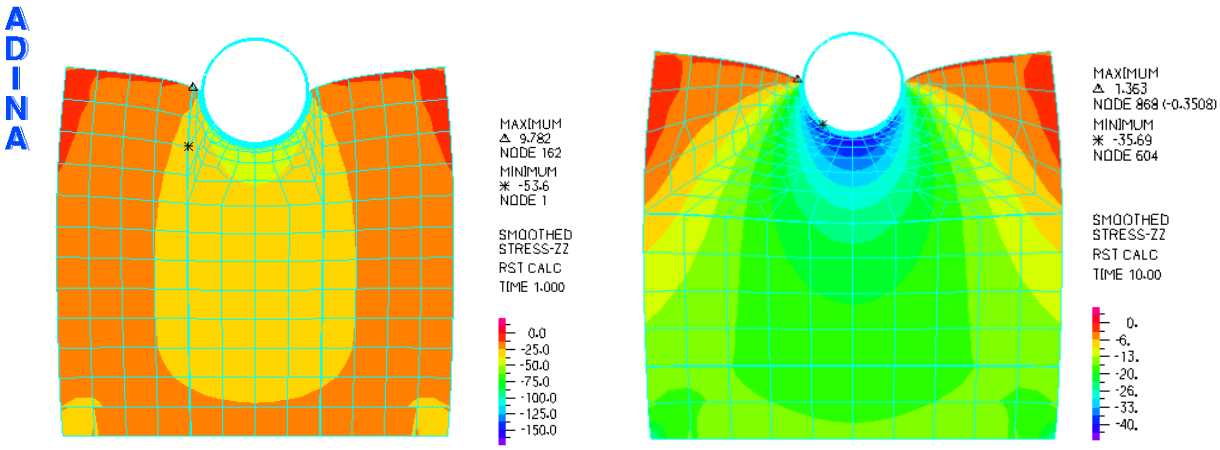


Figure 6. The failure form of embedding strength test

The glulam specimens were tested had a moisture content of 11.14% to 12.45% and specific gravity from 0.575 to 0.7951. Embedding strength ($F_{e\ max}$) of glulam bamboo with loading to grain parallel in radial direction almost equal with the embedding strength of the specimen with loading to grain parallel in tangential direction. However, the slip modulus, which is the slope of the load-embedment curve at initial load, of the specimen with loading to grain parallel in tangential direction is around 15% higher than that of the specimen with loading to grain parallel in radial direction as indicated in Figure 8. rigid value to a greater rigidity held parallel to radial grains. While load direction perpendicular grains testing had a lower stiffness and $F_{e\ max}$ and maximum load reached in large slip value. Numerical analysis result using ADINA^{TM} with a stresses diagram embedding strength had maximum stresses 53.6 MPa and 35.69 MPa of parallel and perpendicular to grain, respectively are shown in figure 7 below. Diagram embedding strength-slip of specimen to experimental results are shown in Figure 8.



(a) (b)

Figure 7. The numerical analysis results of embedding strength on glulam bamboo: a. parallel to grain, and b. perpendicular to grain

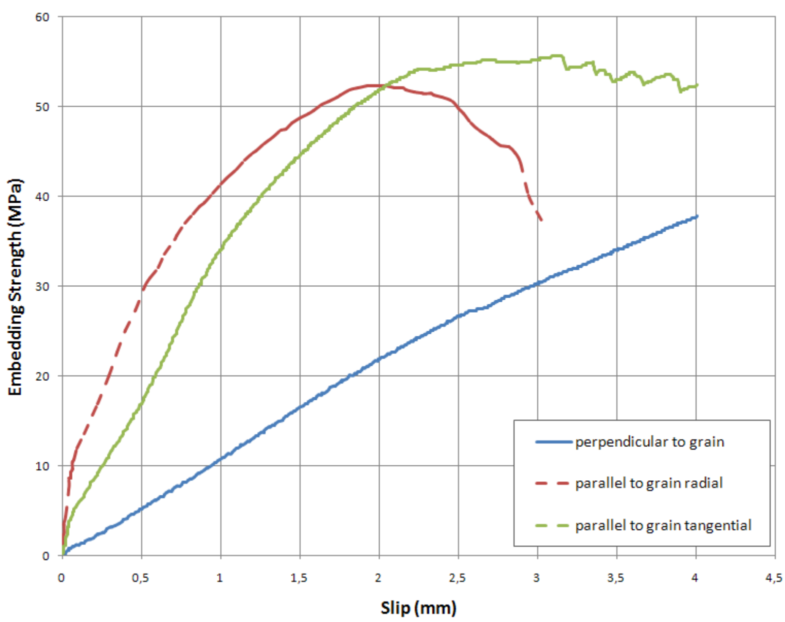


Figure 8. Correlation between embedding strength and slip of specimen

Figure 9 and 10 show, correlation between embedding strength and slip of specimen graph experiment and numerical results were relative similar. It was indicated, numerical analysis can be used to estimate properties and embedding strength value of glulam bamboo.

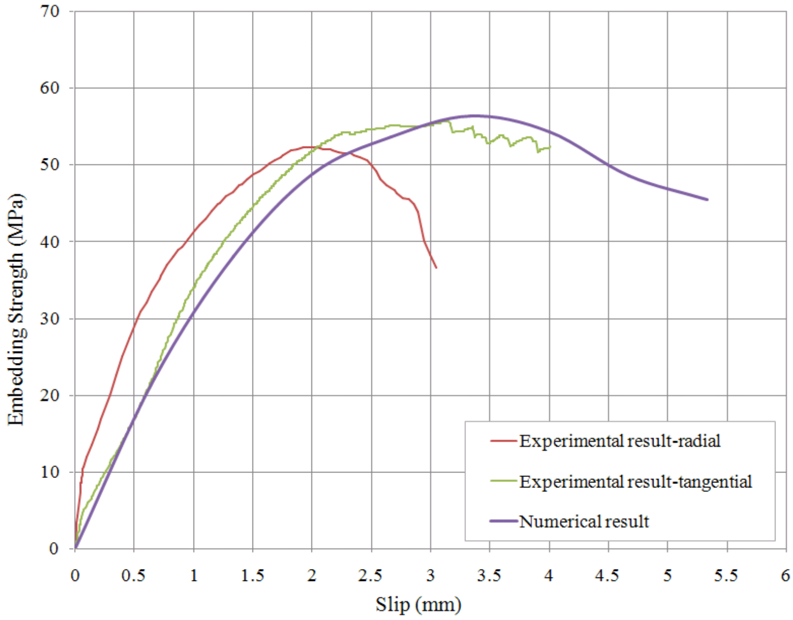


Figure 9. Correlation between embedding strength and slip of specimen parallel to grain (radial and tangential), experimental and numerical results

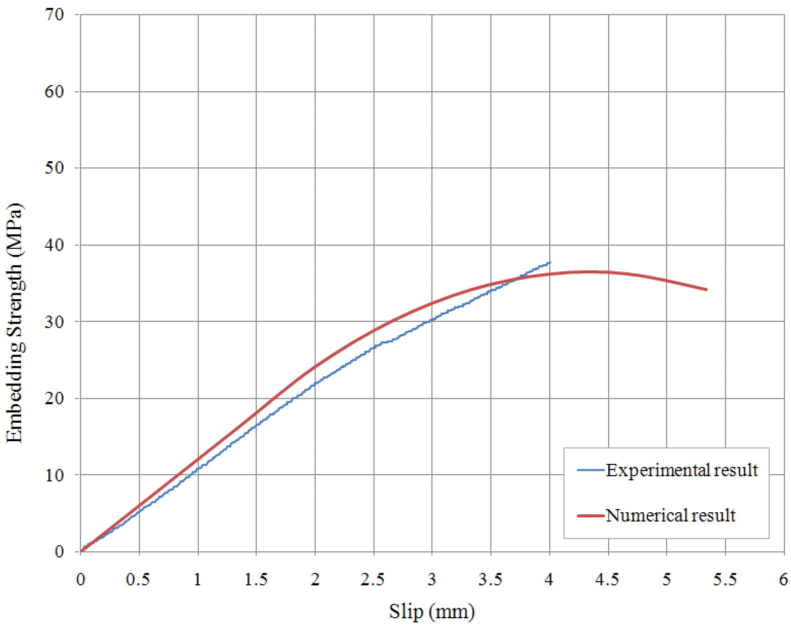


Figure 10. Correlation between embedding strength and slip of specimen perpendicular to grain experimental and numerical results

Embedding strength is determined based on Equation 1, P_{max} is maximum compressive load during testing. a. parallel loading to grain radial, embedding strength test results glulam bamboo with grain direction parallel to a radial load according to Figure 11. Embedding strength value of glulam bamboo with grain direction parallel to a radial load to get higher than NDS and Eurocode5 formula; b. parallel loading to grain tangential, embedding strength test results glulam bamboo with grain direction parallel to tangential load according to Figure 12. The embedding strength of glulam bamboo to a radial parallel load grain to get formula whose value is below than NDS and Eurocode5; c. Load perpendicular test to direction grains, an embedding strength test results glulam bamboo with grain direction perpendicular to load according to Figure 13. Embedding strength of glulam bamboo on load direction perpendicular grains get formula whose value is below than NDS and Eurocode5.

Embedding strength of radial parallel grains (F_e and $F_{e5\%}$), was from 39.37 to 65.06 MPa and 33.12 to 58.8 MPa at specific gravity ranging from 0.58 to 0.76, embedding strength aligned tangential grains (F_e and $F_{e5\%}$), respectively from 29.34 to 62.99 MPa and 23.12 to 57.8 MPa at specific gravity ranging from 0.57 to 0.79, and embedding strength of perpendicular to grain (F_e and $F_{e5\%}$) on specific gravity ranged from 0.59 to 0.77, respectively, from 23.13 to 59.14 MPa and 22.4 to 53.10 MPa.

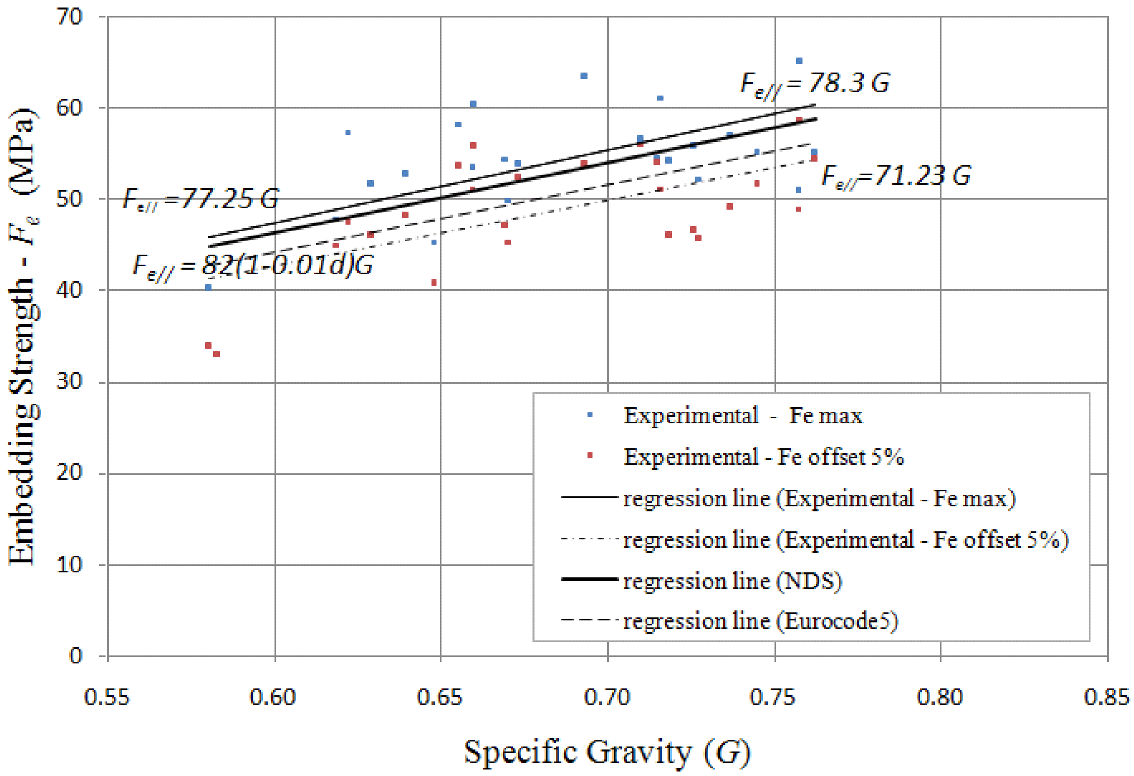


Figure 11. Correlation between embedding strength (F_e) and specific gravity (G) group A

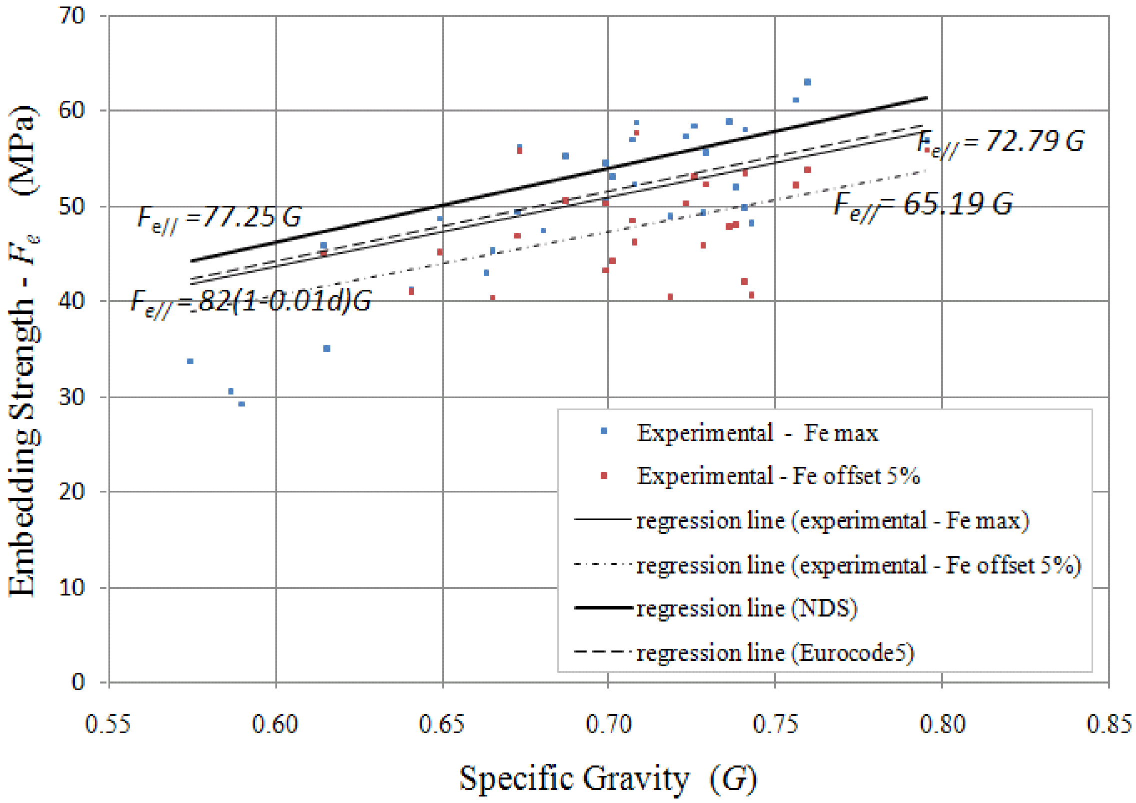


Figure 12. Correlation between embedding strength (F_e) and specific gravity (G) group B

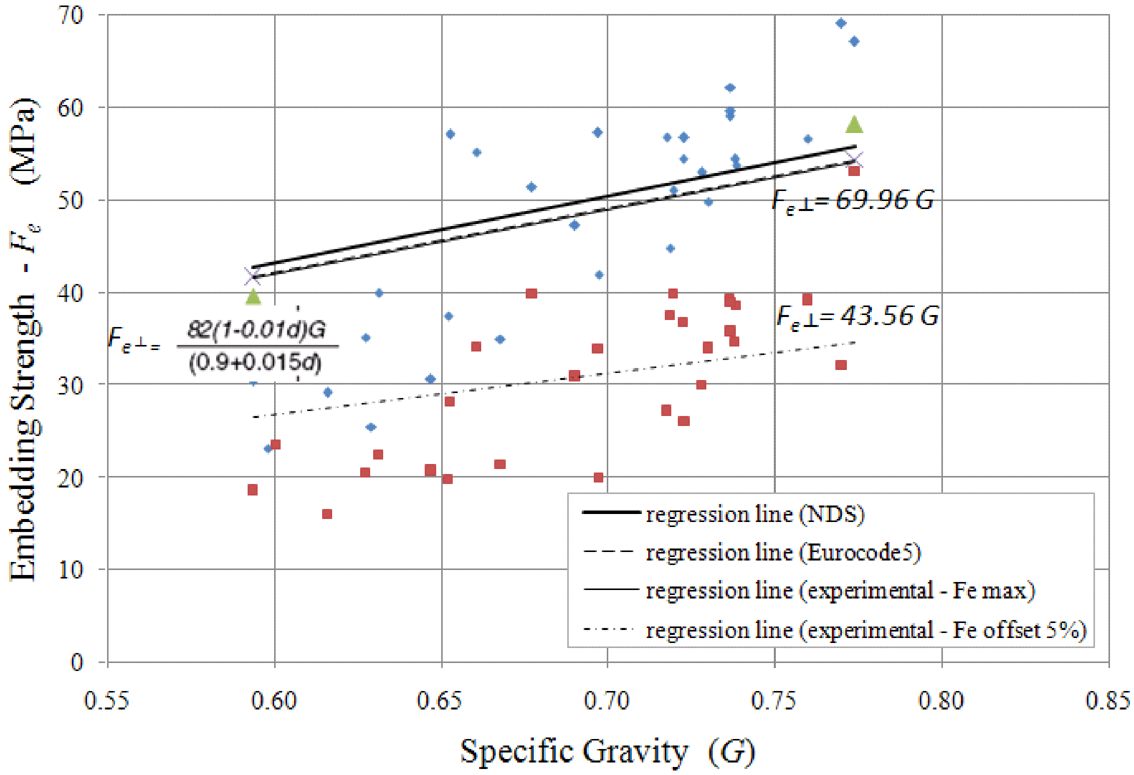


Figure 13. Correlation between embedding strength (F_e) and specific gravity (G) group C

Conclusions

The following conclusions can be drawn from this study.

- The average embedding strength of group A, group B and group C which was evaluated by the 5% off-set method were found to be 54.13, 48.14 and 30.27 MPa, respectively.
- The experimental results indicated that embedding strength parallel to grain (group A and B) was significantly higher than that of group C. This phenomenon was also well observed in the numerical results.
- The embedding strength of glulam bamboo could be well predicted using 78.4G for parallel to grain radial, 72.79G for parallel to grain tangential; and 69.96G for perpendicular to grain radial, where G is the specific gravity of the glulam bamboo.

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