APPLICATION OF THE COMPONENT METHOD TO STRUCTURAL JOINTS WITH DOWEL FASTENERS IN TIMBER CONSTRUCTION

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ABSTRACT

A general procedure for the evaluation of the mechanical properties of structural joints, named “component method” [01], is now available from intensive research works at the European level. This procedure allows the analytical prediction of the resistance, but also of the stiffness and the deformation capacity, of structural joints under external forces (axial or shear forces, bending moments, …). In the present paper, timber joints with dowel fasteners are considered. Two components may be identified: the “dowel fastener in bending and shear” and the “timber member in embedding”.

1 INTRODUCTION

Glued laminated timber (glulam) is a very useful material in timber construction. Almost any shape and size can be produced. The main advantages of this kind of material are that it reduces the effects of imperfections in individual solid timber pieces and allows large structural components to be produced economically.

However, the crucial areas in many glulam structures are the joints that have to be studied more in order to physically predict their behaviour on the basis of their mechanic material and geometrical characteristics.

Research works on steel joints have led to the development and acceptance of a general concept for the characterization of the behaviour of structural joints applicable to all kinds of material. This procedure is known as the "component method". This one is nowadays integrated as a reference procedure in two European design codes, respectively for “Steel Structures” (Eurocode 3) [03] and "Composite Structures" (Eurocode 4) [04]. The use of the component method allows the modelling of a joint as a set of individual components. Once the behaviour of all the constitutive components is known, it is possible to predict the behaviour of the whole joint by assembling them according to physical principles (equilibrium of internal forces, compatibility of the displacements, respect of the resistance, ductility criteria, etc).

More recently, a research project has been set up in Belgium, with the objective to apply the component method to joints in timber construction.

In the present paper, timber joints with dowel fasteners are considered. Two components may be identified in these joints:

- The “dowel fastener in bending and shear”;
- The “timber member in embedding”;

The “dowel fastener in bending and shear” component is known from past researches, whereas little information is available for the “timber member in embedding” component. EC5 [05] proposes a formula to predict the behaviour of the latter; but it only depends on two factors: the dowel diameter and the timber density. The significant influence of the grain direction (material anisotropy) and of the thickness of the connected members are for instance neglected: For joints made with dowel type fasteners, the slip modulus K_{emb} per shear plane and per fastener under service load should be taken, according to EC5, from the formula (1) with ρ_m, the density of the jointed wood, in kg/m³ and d in mm:

$$K_{emb} = \rho_m^{1.5} d / 25 \tag{1}$$

Experimental, numerical and analytical investigations have so been carried out at Liège University in collaboration with CTIB-TCHN (Belgian Institute for Wood Technology). Experimental tests have been used as references for numerical and analytical developments.

This article presents the laboratory tests performed on specimens with different fibre directions. A numerical model has been developed and used to conduct a parametrical study in which the main geometrical properties of the joints vary. Finally an analytical model for the embedding stiffness has been proposed and used to derive the rotational stiffness of full timber joints. These models will be applied in further research steps to joints and comparisons with experimental tests will be achieved.

2 EMBEDDING TESTS

The procedure EN 383 [07] provides instructions for the design of embedding test specimens with 0° and 90° of grain directions (Figure 1a and 1b). However the response of timber for other grain directions is also required as far as the embedding component behaviour is concerned. So in order to fulfil, with the same test specimen, the recommendations of EN 383 on the limitation of the boundary effects, but for any grain direction, a square specimen is used, as see in Figure 1c.

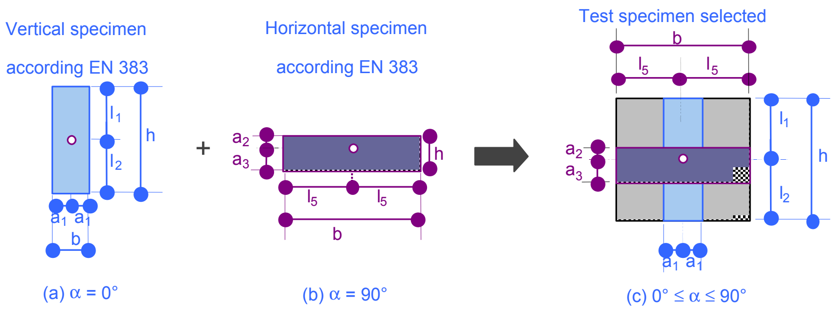

Figure 1: Specimens for embedding tests.

The objective of these tests are to study the influence of the grain direction, the dowel diameter, the thickness of the sample and finally to determine experimental values of embedding stiffness. So a set of specimens have been fabricated according to the grain direction α (0°, 10°, 20°, 30°, 45°, 60°, 70°, 80°, 90°), the dowel diameter D (10mm, 16mm, 20mm) and the thickness t of the sample (1,5 D, 2D) [13], Figure 2a. Besides, several embedding tests on the rectangular model recommended by EN 383 is also proposed to verify and to complete test results on square specimens, Figure 2b and Figure 2c. Coniferous timber with the class GL28h is used in these tests.

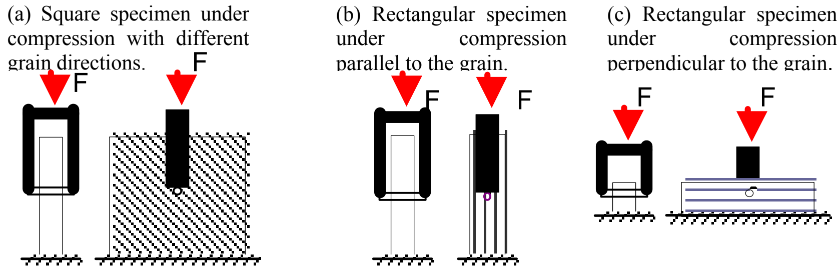

Figure 2: Scheme of embedding tests.

3 REPROCESSING OF THE EMBEDDING TEST RESULTS

The embedding component just covers local deformation effect of the hole under dowel pressure. But the measured displacement of the dowel at point B (Figure 3) includes more than that: the displacement due to the embedding effect but also the shortening of the inferior part of the sample in compression. The second contribution may be obtained by simply measuring the displacement at point A (Figure 3). The embedding deformation is therefore obtained as the relative displacement between A and B. With the applied force on the dowel, being known, the embedding behavioural curve may be therefore drawn.

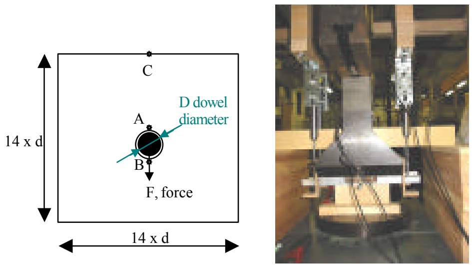

Figure 3: General view of the test device.

In the present paper, only the linear behaviour of the embedding component is studied, K_{emb} (Figure 4). Should the dowel be rigid, the embedding modulus (k_{emb}) could be defined as the stiffness (K_{emb}) per unit of sample thickness. But as the dowel, with its considerable length, deforms in bending and the contact pressure with the sample is not constant over the sample thickness, then a correction is required to get a "true" embedding modulus [13]. This correction may amount 5 to 10%.

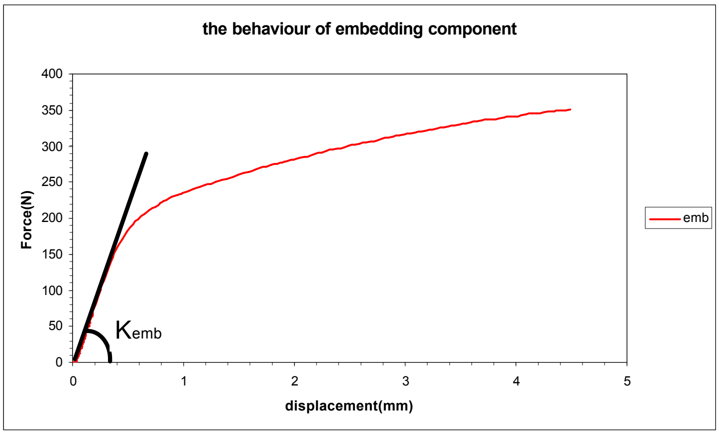

Figure 4: Embedding “Load-slip” curve.

4 PRESENTATION AND DISCUSSION OF THE EMBEDDING TEST RESULTS

The embedding moduli got from the embedding tests will be reported in Table 1 to 6 according to the dowel diameter, the sample thickness and the grain direction.

4.1 Samples of diameter D10

alpha / N/mm²	0	0	10	20	30	45	60	70	80	90	90
Sample 1	351.79	387.55	323.79	380.33	332.48	348.73	246.22	no.	no.	264.20	143.57
Sample 2	341.27	388.28	366.36	388.12	330.79	279.03	322.66	no.	no.	257.73	224.35
Sample 3	338.16	375.85	334.86	404.44	393.87	280.08	292.84	no.	no.	247.86	224.35
Sample 4	no.	410.78	no.	376.80	326.52	304.64	251.76	no.	no.	292.13	no.
Sample 5	no.	401.22	no.	353.58	309.11	301.89	no.	no.	no.	212.19	no.
Note:	**(b=6D)**										**(h=6D)**

Table 1: Experimental values of embedding moduli of samples according to different grain directions, dowel of diameter D10 and sample thickness 4D (*no.: non available*).

alpha		0	10	20	30	45	60	70	80	90	
Sample 1		509.83		272.10		686.60				595.29	
Sample 2		439.19		392.01		355.87				446.19	
Sample 3		489.24		403.61		315.95				261.50	

Table 2: Experimental values of embedding moduli of samples according to different grain directions, dowel of diameter D10 and sample thickness 1,5D.

4.2 Samples of diameter D16

alpha / N/mm²	0	0	10	20	30	45	60	70	80	90	90
Sample 1	308.50	378.73	334.33	380.62	307.13	258.69	252.57	no.	234.11	198.67	233.26
Sample 2	339.83	370.33	347.16	306.77	307.04	268.54	270.21	no.	251.82	266.35	225.54
Sample 3	378.44	378.00	436.55	407.49	304.13	272.63	252.70	no.	139.96	188.81	249.43
Sample 4	330.70	360.40	no.	no.	308.19	283.14	256.95	no.	152.45	no.	229.84
Sample 5	295.94	379.72	no.	no.	330.03	311.86	no.	no.	152.43	no.	214.45
Note:	**(b=6D)**										**(h=6D)**

Table 3: Experimental values of embedding moduli of samples according to different grain directions, dowel of diameter D16 and sample thickness 4D.

alpha		0	10	20	30	45	60	70	80	90	
				418.72		327.26				347.34	
				514.17		251.54				306.88	
				400.69		305.30				342.53	

Table 4: Experimental values of embedding moduli of samples according to different grain directions, dowel of diameter D16 and sample thickness 1.5D.

4.3 Samples of diameter D20

alpha / N/mm²	0	0	10	20	30	45	60	70	80	90	90
eprou.1	410.11	378.88	365.92	326.52	293.56	381.97	286.01	310.34	265.55	251.70	281.30
eprou.2	382.24	396.29	281.73	331.93	388.82	308.85	294.93	349.59	246.28	253.22	226.98
eprou.3	403.21	420.11	388.09	375.15	416.16	371.79	292.30	305.20	275.78	254.69	292.08
eprou.4	412.06	431.51	no.	no.	no.	323.74	no.	307.38	166.28	324.91	no.
eprou.5	404.35	390.55	no.	no.	no.	316.93	no.	242.04	334.64	282.63	no.
Note:	**(b=6D)**										**(h=6D)**

Table 5: Experimental values of embedding moduli of samples according to different grain directions, dowel of diameter D20 and sample thickness 4D.

alpha		0	10	20	30	45	60	70	80	90	
		623.59		506.30		388.51				338.53	
		613.93		565.30		400.85				344.34	
		537.17		590.72		384.81				290.85	

Table 6: Experimental values of embedding moduli of samples according to different grain directions, dowel of diameter D20 and sample thickness 1.5D.

4.4 Discussion of the results

Analysis on all experimental results proves that there is almost no influence of the dowel diameter on the embedding modulus. All the values of embedding modulus with the different grain directions, dowel diameter and the sample thickness are reported in Figure 5. Then, the continuous (red) curve represents the theoretical evolution of embedding modulus according to the formula (2) where $k_{0°}$ and $k_{90°}$ are the two key values. The graph allows:

- To justify a small influence of the factor of dowel diameter for the calculation of embedding modulus in numerical and analytical model.
- To validate experimentally the formula (2), that has been demonstrated in a previous study of relationship between embedding stiffness and grain direction [13]. An embedding modulus of any grain direction can be assessed by the two components, $k_{0°}$ and $k_{90°}$,.

$$k_a = k_0 \cos^2 a + k_{90} \sin^2 a \qquad (2)$$

- Because of the non-homogeneity of the timber, the embedding modulus of one fibre direction differs from different samples. In the Figure 5, the continuous (red) curve represents the mean values through the scatter plot and two discontinuous curves, the areas where find almost all embedding modulus values. Some experimental values will be used in the next numerical and analytical investigation: $k_{0°}$ = 450-500 N/mm² and $k_{90°}$ = 150-300 N/mm².

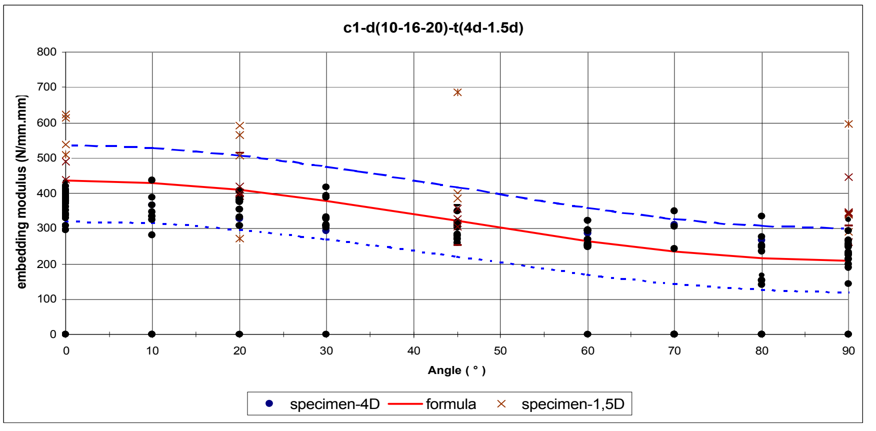

Figure 5: Graph of experimental and theoretical values performed on embedding tests, diameter (D10, D16 and D20) and thickness (4D and 1,5D).

5 NUMERICAL SIMULATION OF EMBEDDING TESTS

The numerical model is a “plane stress” one, it is composed of a layer of volume elements representing the timber and of a rigid foundation simulating the action of the dowel, Figure 6. The contact between the dowel and the timber is also considered. The actual geometrical dimensions of the specimen are respected.

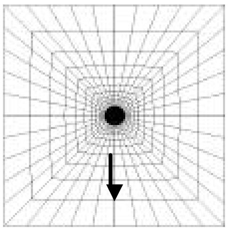

Figure 6: Numerical model used to simulate the experimental tests.

As the actual of mechanical properties of the timber material were initially not available, related assumptions have been made on the basis of the indications provided by the European code, EN338 [12]. For resinous material classified GL28h according to the manufacturer, the following values have so been adopted:

- E_0 = 12000 N/mm²; E_{90} = 400 N/mm²; G = 750 N/mm²;ν = 0.3;
- $f_{t,0}$ = 16 N/mm²; $f_{c,0}$ = 22N/mm²; $f_{t,90}$ = 0.4 N/mm²; $f_{c,90}$ = 5,6 N/mm²;

Furthermore, wood is supposed to possess an elastic-perfectly plastic behaviour in the longitudinal and transversal directions, Figure 7.

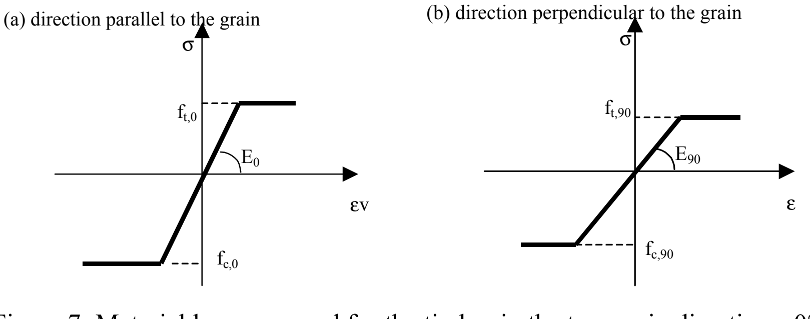

Figure 7: Material laws assumed for the timber in the two grain directions, 0° and 90°.

Some of the results of these simulations are referred to in section 7.

6 ANALYTICAL MODEL TO PREDICT EMBEDDING MODULI

The in plane dimensions of the timber element are assumed to be much longer than the dowel diameter. Some other assumptions are also made:

- elastic state;
- small deformations;
- dowel in perfect contact with the timber hole;
- absence of friction between the dowel and the timber hole;

The force P applied on the dowel leads a stress field in the timber element, along the hole (diametrical pressure). This stress field exhibits a maximum value at point B and decreases progressively until zero at D' (D''), Figure 8.

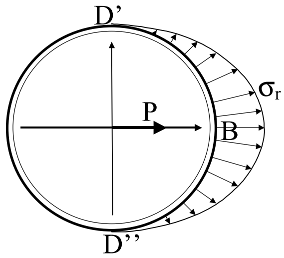

Figure 8: Stress field along the timber hole.

A function is proposed to express this field of stress:

$$\sigma_r = \frac{2}{\sqrt{1+3\sin^2\theta}} - 1, 0 \le \theta \le 2\pi, \tag{3}$$

This function is already normalized, ($\sigma_{max} = 1$). The force P that corresponds to this distribution is:

$$P_x = Dt\left(\frac{2}{\sqrt{3}}\operatorname{arctanh}\left(\frac{\sqrt{3}}{2}\right) - 1\right), P_y = 0, \tag{4}$$

If the mechanical characteristics of the material are known, the value of the embedding modulus may be derived [13].

7 COMPARATIVE STUDY OF NUMERICAL AND ANALYTICAL MODELS TO EXPERIMENTAL RESULTS

As it has been shown that the embedding modulus for any grain direction depends on the two embedding moduli $k_{0°}$ and $k_{90°}$, the comparative study of the numerical and analytical approaches to the experimental one may be achieved through these two key values.

Table 7 shows a comparison of embedding moduli obtained from numerical, analytical and experimental investigations:

(N,mm)	k_0			k_{90}		
	D10	D16	D20	D10	D16	D20
Numerical	4370.74	5214.31	5574.33	786.61	938.27	1018.79
Analytical	4776.35			615.65		
Experimental	400-500			150-300		

Table 7: Comparison of numerical and analytical embedding modulus values with experimental ones.

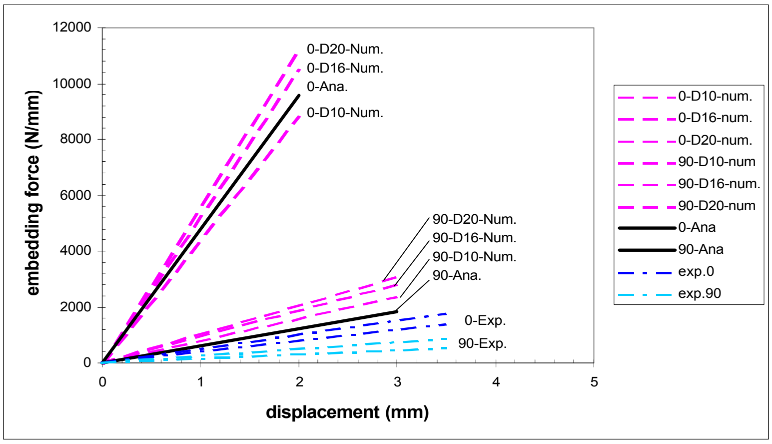

Figure 9: Graphical representation of Table 7.

The analytical values are independent of the dowel diameter, whereas the numerical results are slightly influenced by this parameter. The explanation of this difference is to be found in the assumption of "infinite plate dimensions" made in the analytical model; while the limited dimensions of numerical simulation cause boundary effects. Anyway, the numerical and analytical results are in rather good agreement.

On other hand both, numerical and analytical, results differ significantly from the experimental ones. For specimen "parallel to the grain", the ratio between the calculated and experimental value amounts 10, and 2 for specimen "perpendicular to the grain". Possible reasons for such a high divergence will be expressed in section 8.

8 CONCLUSION

The ovalisation of the timber hole due to the embedment of the dowel is one of the most important components in the timber joint.

So the development of an analytical formula to predict embedding stiffness moduli is of main importance. An analytical model is proposed and is shown to be in good agreement with results of the numerical simulations. Nevertheless, its similarity with the experimental results is less optimal. Two possible reasons may be contemplated:

- The mechanical properties of the timber material considered in the analytical and numerical investigations are those recommended by prEN 338 [12], according to the class of wood used. These properties are probably different from the actual ones. It has therefore been decided to proceed to material testing.
- Timber is modelled in the numerical and analytical as an anisotropic and continuous material without damage. The behaviour of the actual timber is much more complex. That will be taken into account in further investigations.

On the basis of this, new numerical simulations will be performed and the analytical model will be further developed.

REFERENCES

[01] Jaspart J.P. (1991). "Study of the semi-rigidity of beam-to-column joints and its influence on the resistance and stability of steel buildings.", PhD thesis, M&S Department, Liège University, Belgium (in French).

[02] CTIB, Projet de recherche K_ser : Modélisation de la déformation dans les modules de calcul des assemblages en bois. Programme 2001-2003, novembre 2002

[03] ENV 1993 Eurocode 3 – Design of steel structures.

[04] ENV 1994 Eurocode 4 – Design of composite steel and concrete structures.

[05] prEN 1995-1-1 Eurocode 5 – Design of timber structures - General Rules and rules for buildings- Final Draft (Stage 34)

[06] CTIB, Projet de recherche K_ser : Modélisation de la déformation dans les modules de calcul des assemblages en bois. Programme 2001-2003. Rapport opérationnel, juin 2002

[07] prEN 383 Timber structures – Test methods - Dertermination of embedding strength and foundation values for dowel type fasteners.

[08] CTIB, Projet de recherche K_ser : Modélisation de la déformation dans les modules de calcul des assemblages en bois. Programme 2001-2003. Rapport scientifique, décembre 2002.

[09] S.G. LEKHNITSKII, Anisotropic Plates, Gordon and Breach science publishers, 1968.

[10] prEN 1194, Timber structures- Glued laminated timber – Strength classes and determination of characteristic values.

[11] prEn 408, Timber structures – Structural timber and glued laminated timber – Determination of some physical and mechanical properties.

[12] prEN 338, Structural timber – Strength classes.

[13] CTIB, Projet de recherche K_ser : Modélisation de la déformation dans les modules de calcul des assemblages en bois. Programme 2001-2003. Rapport scientifique, Mars 2004.