An analytical method to evaluate effects of screw connectors on effective bending stiffness of Timber-Concrete Composite slabs

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Summary
One of the most widespread hybridisation techniques for structural elements is combined use of timber and concrete, giving rise to Timber-Concrete Composite (TCC) members, particularly slabs. Thus, optimisation of such elements is performed, since their thickness is significantly reduced with respect to timber slabs, while mass and environmental impact is far less than traditional reinforced concrete ones. One of the main required characteristics for slabs is an adequate effective bending stiffness, since it guarantees fulfillmnet of serviceability requirements (e.g., vibrations and deflections); this parameter is affected by efficiency of connectors themselves, factor γ according to γ-method presented in EN 1995-1-1 Annex B, so that analytical investigation is hereby presented. Moreover, the research preliminarily examines, in qualitative terms, reusability and recyclability opportunities according to studied connectors.

1 INTRODUCTION

The concept of connections in modern timber structures generally relies on steel connectors, which are used either with full timber or with timber-hybrid, as e.g., timber-concrete and timber steel composites. The theoretical background is built according to Johansen theory [1], which dates back to 1949, but it is still the common basis for EN1995-1-1 [2]. Diffusion of timber structures is experiencing a renewed interest, due to wood material intrinsic sustainability [3], crossing the boundaries of regions where it is traditionally widespread; this fact necessarily asks for innovative solutions in order to make this strategy applicable potentially everywhere, such as high seismicity areas. In this context, hybridisation of timber with concrete – Timber–Concrete Composites (TCC) – gives rise to appealing solutions, both at the level of the entire structure and at the level of the member itself.

Focusing on the latter, TCC slabs are of particular importance due to their competitiveness in terms of mechanical properties, load capacity, stiffness, deformations, and vibrations; these characteristics are achieved thanks to exploitation of composite action between concrete topping and timber element, which depends on the characteristics of shear connectors [4]. Composite action is achieved in case shear forces can be transmitted between the two layers, so in case no shear connectors are present, no composite action can be accounted for (Figure 1a). On the other hand, the opposite situation is called "full composite action" where no slip between two layers is observed, such that the section's neutral axis is located exactly at the interface between concrete and timber layers. In this way the potential of both the two materials is exploited, given that concrete and timber are respectively subjected to compressive and tensile stresses. This last situation is generally considered a theoretical benchmark, since an intermediate condition is achieved in real cases, where relative slip between two layers is observed (Figure 1b); the significance of abovementioned relative slip, and consequently of the level of composite action, depends on the slip modulus of the connector K_s, which may vary in a very wide range [5].

The level of the composite action is analytically considered in EN1995-1-1 [2] with factor γ in the equation of effective bending stiffness $(EI)_{ef}$, but information on slip modulus is provided just in case of a connection between two timber members, with fastener inserted perpendicularly to the shear plane; in this case the connection stiffness is considered equivalent to the embedment stiffness K_h, and it depends on connector diameter d and timber density ρ. The equation provided by Eurocode 5 is suggested to be multiplied by 2 in case concrete-timber connection is studied [2], assuming no deformation in the concrete portion, even though the weakness of this formulation is highlighted in case inclined fasteners are used. Focusing on screwed connections, some investigations that consider also the influence of the angle α between the screw and the shear plane and the withdrawal stiffness K_w are available [6, 7, 8, 9], so that a more comprehensive consideration of relevant parameters is provided. However, a comprehensive analytical procedure to evaluate level of composite action starting from a wide dataset characterised by the presence of different screw lengths and diameters, insertion angle, embedment length in timber portion, wood species is not available. This paper first aims at collecting experimental data on screw connections stiffness, in order to use them to develop an innovative analytical procedure that considers comprehensively abovementioned characteristics.

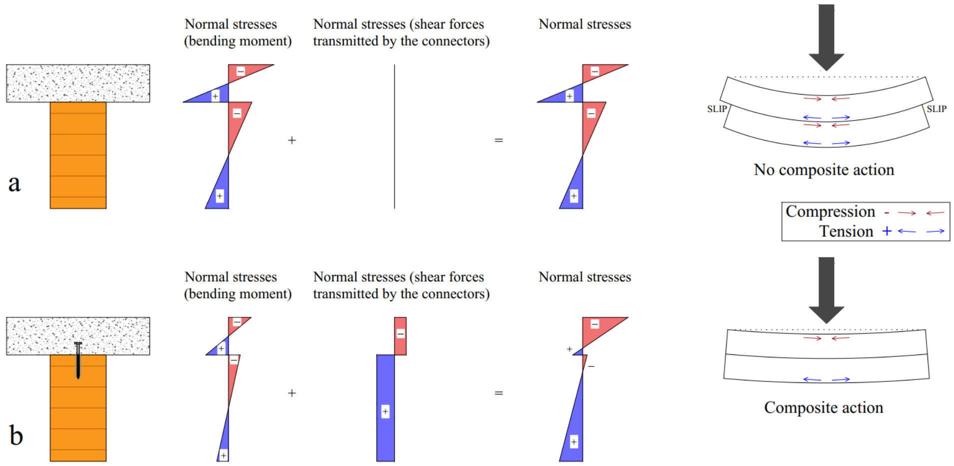

Figure 1. Timber-concrete composite sections. a) no composite action; b) intermediate (almost full) composite action, adapted from [5].

Finally, considering the built-up database, information on failure modes and timber damage, where available, are retrieved, in order to preliminarily assess relevant parameters to establish a relationship between experimental observations and reusability rates. According to cradle-to-grave (A-C) Life Cycle Assessment (LCA) analysis [10], sustainability of timber material is ensured primarily by lower Global Warming Potential (GWP) impact with respect to concrete; moreover, accounting for stage D (Benefits and Loads Beyond the System Boundary) and biogenic carbon content, the environmental advantage derived from timber use becomes evident [11]. A few efforts are traced back in literature where the environmental issue is faced from the perspective of deconstructability easiness [12, 13]: for sure the simplicity in demountability is governed by deformations entity, which in static service loading conditions is expected to be small. However, disassembling simplicity should be foreseen during design phase, as it cannot be improvised during End-of-Life stage of a structure, and this was generally not planned for existing structures, such that it is a quite novel topic. Moreover, no investigation was retrieved considering demountability simplicity in case of extreme loads, given that e.g., seismic loading conditions are expected to lead to greater deformations with higher damage level. So, reusability rate should be intended as a function of structural observations because planning a fixed value without considering a set of deformations, damages, failures modes, etc. is suspected to result into estimations far from reality.

2 METHOD

Starting from EN1995-1-1 [2] equation for effective bending stiffness $(EI)_{ef}$ (1), the factor for efficiency of the mechanical connections γ is calculated (2), considering a composite section made by two layers, respectively timber (i=1) and concrete (i=2).

$$(EI)_{ef} = \sum_{i=1}^{2} \left(E_i I_i + \gamma_i E_i A_i a_i^2 \right) \tag{1}$$

$$\gamma_i = \begin{cases} 1 & \text{for i} = 1 \\ \dfrac{1}{1 + \dfrac{\pi^2 E_i A_i s_i}{K_s L^2}} & \text{for i} = 2 \end{cases} \quad (2)$$

Where:

- E_i is modulus of elasticity of cross-section i;
- I_i is second moment of inertia of cross-section i;
- A_i is area of cross-section i;
- a_i is the distance between centroid of the composite cross-section and the centroid of cross-section i;
- s_i is spacing between connectors;
- K_s is stiffness of connectors;
- L is span of the member.

In order to evaluate stiffness of the connectors, some equations from literature are considered in Table 1, listed with increasing complexity in terms of considered parameters. References [2, 4] considers slip modulus K_s equivalent to embedment stiffness K_h. On the other hand, references [6, 8] suggest a more comprehensive evaluation of K_s, as a combination of embedment (K_h) and withdrawal stiffnesses (K_w).

Table 1. Analytical formulation for slip modulus Ks of single shear screw connectors in timber and TCC members.

Reference	Equation
[2]	$K_s = K_h = \frac{\rho^{1.5} \cdot d}{23}$ (3) for dowel-type fastener in timber-timber connections, where: - ρ is timber density - d is screw diameter $K_s = K_h = \frac{\rho^{1.5} \cdot d}{11.5}$ (4) for dowel-type fastener in timber-concrete connections
[4]	$K_s = K_h = \Psi \cdot E_{timber} \cdot d$ (5) for dowel-type fastener in timber-concrete connections (Ψ depends on the ratio between the timber-concrete gap and the screw diameter), where: - E_{timber} is elastic modulus of timber (parallel to grain direction)
[6]	$K_s = K_w \cdot \sin\alpha \cdot (\sin\alpha - \mu \cdot \cos\alpha) + K_h \cdot \cos\alpha \cdot (\cos\alpha + \mu \cdot \sin\alpha)$ (6) for screw-type fastener in timber-concrete connections, where: - $K_w = 780 \cdot d^{0.2} \cdot L^{0.4}$ (7) is withdrawal stiffness [14] (or alternatively it is experimentally evaluated) - L is screw embedment length in timber portion - $K_h = \frac{\rho^{1.5} \cdot d}{11.5}$ is embedment stiffness [2]
[8]	$K_s = \frac{3 \cdot E \cdot I \cdot d \cdot n \cdot \left[2 \cdot \left(3 \frac{t_{gap}}{\sin\alpha} + 2 \cdot L\right) \cdot K_w \cdot \pi \cdot \varphi \cdot L \cdot (\cos^2\alpha + 0.5\mu \cdot \sin 2\alpha) + 0.9 \cdot K_h \cdot L^2 \cdot (\sin^2\alpha - 0.5\mu \cdot \sin 2\alpha)\right]}{3 \cdot E \cdot I \cdot \left(3 \frac{t_{gap}}{\sin\alpha} + 2 \cdot L\right) + 0.9 \cdot K_h \cdot d \cdot L^2 \cdot \left(\frac{t_{gap}}{\sin\alpha}\right)^3 \cdot \sin^2\alpha}$ (8) for screw-type fastener in timber-concrete connections, where: - E, I are respectively elastic modulus and second moment of inertia of the screw - t_{gap} is the gap thickness - α is screw insertion angle - φ is the ratio between K_h and K_w - μ is friction coefficient between concrete and timber - $K_w = \frac{0.173 \cdot l^{0.414} \cdot \rho^{0.715} \cdot d^{-0.512}}{5.092 \cdot \cos^2\alpha + 6.351 \cdot \sin^2\alpha}$ (9) [9] - $K_h = \frac{0.00011 \cdot \rho^{2.443} \cdot d^{-0.956}}{7.663 \cdot \cos^2\alpha + 2.645 \cdot \sin^2\alpha}$ (10) [9]

The new analytical methodology is built up according to collected data presented in Table 2, such that a wide range of parameters with respect to screw diameter, screw insertion angle, and timber density are considered.

Table 2. Collected data to create a database for the analytical approach. d=screw diameter; ρ=timber density; α=screw insertion angle; L=screw embedment length into timber portion; t_{gap}=gap timber-concrete thickness; K_s=connector slip modulus; L_t=screw threaded length.

#	Reference	d (mm)	ρ (kg/m^3)	α (°)	L (mm)	t_{gap} (mm)	K_s (kN/mm)	L_t (mm)
1	[15]	6	408	35	50	0	6.14	80
2	[15]	6	408	35	60	0	7.52	100
3	[15]	6	408	55	50	0	2.75	80
4	[15]	6	408	55	60	0	4.48	100
5	[15]	6	544	35	50	0	7.52	80
6	[15]	6	544	35	60	0	6.67	100
7	[15]	6	544	55	50	0	1.77	80
8	[15]	6	544	55	60	0	4.10	100
9	[7]	9	560	90	85	3	3.50	160
10	[7]	9	430	90	85	3	2.20	160
11	[16]	11	440	45	80	0	13.94	150
12	[16]	11	440	45	80	5	8.59	150
13	[16]	11	440	45	80	15	5.17	150
14	[16]	11	440	30	80	0	26.85	150
15	[16]	11	440	30	80	5	13.34	150
16	[16]	11	440	30	80	15	10.94	150
17	[16]	11	440	45	100	0	17.92	200
18	[16]	11	440	45	100	5	9.10	200
19	[16]	11	440	45	100	15	6.09	200
20	[16]	11	440	30	100	0	31.21	200
21	[16]	11	440	30	100	5	17.78	200
22	[16]	11	440	30	100	15	11.58	200
23	[16]	11	504.4	45	80	0	12.35	150
24	[16]	11	504.4	45	80	5	7.35	150
25	[16]	11	504.4	45	80	15	5.52	150
26	[16]	11	504.4	30	80	0	22.88	150
27	[16]	11	504.4	30	80	5	12.94	150
28	[16]	11	504.4	30	80	15	9.01	150
29	[16]	11	504.4	45	100	0	18.29	200
30	[16]	11	504.4	45	100	5	8.61	200
31	[16]	11	504.4	30	100	0	23.69	200
32	[16]	11	504.4	30	100	5	13.66	200
33	[17]	10	450	90	110	0	2.04	100

34	[13]	13	422	30	130	0	32.40	200
35	[13]	13	422	45	130	0	26.50	200
36	[13]	13	422	60	130	0	16.00	200
37	[13]	13	422	90	130	0	2.80	200
38	[13]	13	422	45	130	0	32.10	200
39	[6]	8	385	45	100	0	8.70	80
40	[6]	10	385	45	100	0	9.50	80
41	[6]	12	385	45	100	0	10.20	80
42	[18]	12	578	45	100	15	22.72	N/A
43	[18]	10	578	45	100	15	18.02	N/A
44	[18]	8	578	45	100	15	13.13	N/A
45	[18]	12	578	45	80	15	17.09	N/A
46	[18]	12	578	45	120	15	24.79	N/A
47	[18]	12	578	45	100	15	21.48	N/A
48	[18]	12	578	45	100	15	23.04	N/A

3 RESULTS AND DISCUSSION

Considering references from Table 1 and existing equations [6, 8, 9], an innovative analytical approach is suggested, according to collected data presented in Table 2. Starting from equation (8), the focus is on K_h equation, so considering equation (9), it is rewritten with general coefficients, as shown in equation (10). Finally, after a simplified regression analysis, coefficients ω_2, ω_3, and ω_4 are fixed according to their average values that fit the calculated K_s with experimental ones (11); moreover, ω_2 is considered linearly dependent from screw diameter *d*, according to equation (12). Coefficient ω_2 is firstly calculated with regression analysis in order to fit each analytical value with its experimental equivalent one, then fitting curve is designed maximizing the correlation coefficient R^2. So, equation of slip modulus is not directly modified, but one of the main driving parameter – K_h – is redesigned in a more accurate way, as shown in Figure 2, where the results of the suggested approach fit the experimental values collected in Table 2; finally, equation (8) is still considered valid for K_s.

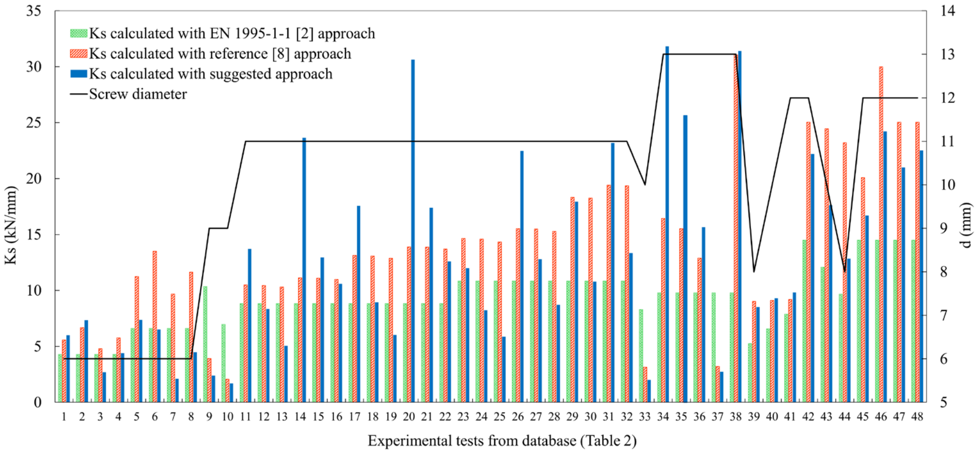

Figure 2. K_s values from three different analytical formulae.

$$K_h = \frac{\rho^{\omega_1} \cdot d^{-\omega_2}}{\omega_3 \cdot cos^2 \alpha + \omega_4 \cdot sin^2 \alpha} \quad (10)$$

$$K_h = \frac{\rho^{1.034} \cdot d^{-\omega_2}}{4.692 \cdot cos^2 \alpha + 1.966 \cdot sin^2 \alpha} \quad (11)$$

$$\omega_2 = 2.31 e^{-4.58 \cdot 10^{-2} \cdot d} \; (R^2 = 0.556) \quad (12)$$

The effects of a more accurate evaluation of connectors stiffness are directly observable both in the values of level of composite action γ_2 and effective bending stiffness $(EI)_{ef}$. In case K_s is evaluated according to equation (4), the screw insertion angle is not accounted for, such that the most evident differences are observable, mostly, for α values much lower than 90° (Figure 3). The greater accuracy in accounting for the slip modulus directly affects positively effective bending stiffness: in most of the cases K_s evaluated with equation (4) is lower with respect to equation (8), with embedment stiffness according to equations (11, 12), such that in case this last analytical approach is adopted, $(EI)_{ef}$ increases. In this way more accurate evaluations of vibrational and deflection performances are obtained, such that savings of materials are achieved.

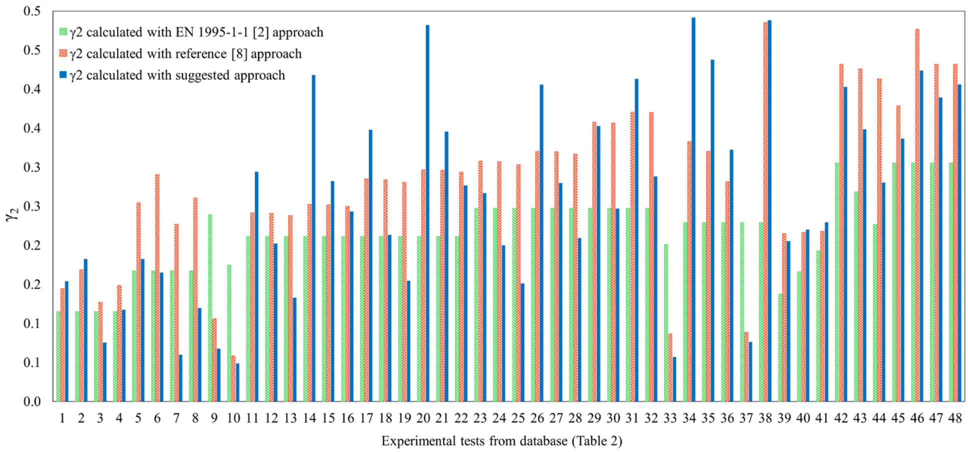

Figure 3. Comparison of γ_2 parameter computed with slip moduli calculated respectively with EN1995-1-1 approach according to equation (4), reference [8] approach according to equation (8) and analytical approach suggested in this investigation.

To provide values for real case studies, some examples of TCC slabs with different screw diameters and insertion angles was investigated and results in terms of γ_2 parameter are presented in Table 3.

Table 3. Examples of γ_2 parameter considering K_s computed with the method discussed in this paper. L=100 mm, L_t=60 mm, μ=0.3, E_{timber}=12000 MPa, A=150000 mm^2, s=50 mm, *slab span*=6 m.

d (mm)	α (°)	K_w (N/mm^3)	K_h (N/mm^3)	K_s (kN/mm)	γ_2 (-)
6	90	5.00	5.72	0.93	0.04
6	30	5.87	5.72	11.49	0.32
8	90	4.31	4.75	1.03	0.04
8	30	5.07	4.75	12.72	0.34
12	90	3.51	4.83	1.56	0.06
12	30	4.12	4.83	19.41	0.44

The observation on material savings brings to the last result, which sheds a light on sustainability of structural members: the focus is on the End-of-Life stage, which is suggested to be studied according to deformations and damages that are generally observed after the service life (for real cases) and after the test is performed (for experimental tests). Nowadays a strong effort is devoted to reuse practices, since they characterise an interesting alternative to recycling, which is however a sustainable solution; the difference between reusing and recycling lies in the fact that in the first case the product is not considered a waste, while in the other one it is a waste, even though reprocessing will deliver a new product. Considering the selected database, in some cases evidences of the specimens' failure modes and damages are present, so they are considered as references [7, 13, 16]. In this way a set of parameters is selected, relying on the fact that they are considered the most influencing ones to facilitate or hinder reusability for timber beam:

- Fastener type. This parameter encloses a set of different mechanical connectors (e.g., screws, bolts, nails, dowels, etc.), but it should be considered that also grooved connections or metal plates may be used. Moreover, in some cases notches are cut in the timber beam, which is an additional parameter that affects reusability easiness.
- Timber characteristics. Density of timber drives some parameters, as withdrawal and embedment strengths, and consequently damage. Moreover, timber strengths affect delamination, crushing, splitting, etc. In this context, a more precise classification of timber damages would lead to more accurate reuse rate estimation, considering that the severity of different damages is not the same.
- Failure mode and plastic hinge(s) position. This cluster of parameters is the result of previous ones, given that the failure mode depends on connectors and timber characteristics; moreover, damage and crushing in the surrounding area of plastic hinge is generally highlighted, so that also their position and number should be considered.

According to this set of parameters, a preliminary qualitative equation to estimate reusability rate of timber members ($R_{\%}$) is suggested (13). Considering that this is an absolutely novel topic no information about quantitative values is provided, given also that more in-depth investigations may lead to modifications of the selected set of parameters.

$$R_{\%} = \text{f(fastener type; timber characteristics; failure mode, plastic hinge(s) position)} \qquad (13)$$

4 CONCLUSIONS

The presented analytical approach takes into account a more precise consideration of parameters which influence is sometimes neglected or underestimated. In particular, considering a weighted coefficient for screw diameter allows for more accurate estimation of the embedment strength, which directly affects slip modulus and consequently effective bending stiffness of the Timber-Concrete Composite slab. This procedure should be read also an optimization process, where the accuracy in parameters estimation leads to materials waste minimization. Effective bending stiffness drives e.g., deflection and vibration verification, which in case they are not satisfied, modifications in the design procedure are needed; inaccuracies in slip modulus estimation, disregarding e.g., connector insertion angle, commonly results into underestimation of this parameter, which directly leads to values of effective bending stiffness lower than real ones, with useless design modifications.

One of the aim of this paper is the preliminary assessment of a relationship between environmental and structural parameters, since it is not possible to think about one of these without considering the other one. The environmental performance is hereby suggested as the reuse rate of timber portion; this choice is driven by the fact that reusing a structural member (or a portion of it) avoids that it becomes – even just for a small period – a waste, with significant environmental and economical advantages. Considering the suggested qualitative relationship, it should be considered just an initial assessment, which needs to be developed according to other data retrievable in literature, but also in accordance with laboratory experiments and numerical modelling. Moreover, other future developments are oriented towards a more comprehensive consideration of connectors, enlarging the focus from screws to bolts, nails, screws with springs, etc.; in this way the suggested procedure will be firstly tested and then eventually adapted to other connectors.

Apart from the assessment of an accurate analytical procedure, the paper aims at suggesting the close interdepency between structural and environmental design, where for sure the dependence of the second from the first one is evident and increasingly more accepted, while the opposite relationship is often ignored. In this context, the relationship between these two apparently far fields should be built from scratch, in order to establish a truly sustainable structural design methodology for the next future.

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