Review of Long-Term Performance of Timber-Concrete Composite Beams

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Timber-concrete composite (TCC) beams are formed by integrating timber beams and concrete slabs into a cohesive structural unit using shear connectors. This integration capitalizes on the tensile strength of timber and the compressive strength of concrete, resulting in excellent load-bearing capacity, bending stiffness, vibration comfort, sound insulation, and fire resistance. The long-term behavior of TCC beams must be emphasized, considering the significant time-dependent behaviors of timber, concrete, and the connection system. This work analyzed the long-term mechanical behavior of TCC beams and systematically reviewed the current research on the long-term performance. The primary focus was on the experimental studies of the shear performance of the shear connectors and the mechanical performance of TCC beams under long-term loads. Furthermore, theoretical methods and numerical simulation analyses for evaluating the long-term performance of TCC beams were analyzed. Strengths and weaknesses of existing theoretical methods are identified, and further research and development in the calculation method of TCC beams under long-term loads is proposed.

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INTRODUCTION

The green and environmentally friendly characteristics of timber structures align with the contemporary focus on ecological balance and sustainable development. In addition, using eco-friendly timber as a building material can reduce construction waste and chemical pollution (Huber *et al*. 2019; Himes and Busby 2020; Duan *et al*. 2022). With the advancement of modern timber construction technologies, timber structures are now widely applied in public buildings such as apartments, office buildings, and conference centers (Pastori *et al*. 2022; Svatoš-Ražnjević *et al*. 2022; Li *et al*. 2023). The timber-concrete composite (TCC) beam is a structural component developed from timber beams, combining the timber beam with a concrete slab through shear connectors to form a cohesive unit, as shown in Fig. 1. Compared to traditional timber beams, TCC beams significantly enhance the strength and stiffness of structural components, as well as improve vibration performance, sound insulation, and fire resistance. This makes them particularly suitable for multi-story and large-span timber structures (Xie *et al*. 2020; Zhang *et al*. 2020; Du *et al*. 2021; Li *et al*. 2023).

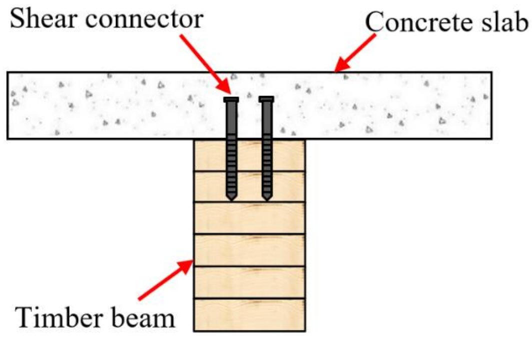

Fig. 1. Timber-concrete composite beam

The creep behavior of wood and the shrinkage and creep of concrete contribute to the long-term deformations in TCC beams, which cannot be overlooked. The redistribution of internal forces further complicates the theoretical analysis of the long-term mechanical performance of the composite beams. Therefore, evaluating the long-term mechanical behavior of TCC beams is crucial in the design and application. This paper reviews the research findings on the long-term mechanical performance of timber-concrete composite beams, analyzing the long-term stress mechanisms, with a focus on experimental studies on the long-term behavior. This includes shear tests of shear connectors under long-term loads and bending tests of composite beams. Furthermore, the theoretical methods and numerical simulation analyses for evaluating the long-term performance of TCC beams are analyzed.

LONG-TERM PERFORMANCE OF SHEAR CONNECTORS

Long-term tests on shear connection specimens aim to analyze the deformation growth patterns of shear connectors under sustained loads. Different types of shear connectors vary in shear stiffness and load-bearing capacity. To compare the long-term deformation variations among different shear connector types, the sustained load is generally set at 30% of the ultimate strength under short-term loading. Fragiacomo *et al*. (2007) used the creep coefficient to measure the relative deformation of structural components or joints under long-term loads compared to their initial deformation, which is calculated as follows,

$$\varphi(t)=\frac{\varepsilon(t)-\varepsilon_0}{\varepsilon_0} \tag{1}$$

where $\varphi(t)$ is creep coefficient of the shear connectors, $\varepsilon(t)$ is total deformation of the structural component at time t, and ε_0 is initial deformation of the structural component.

Table 1 presents the long-term loading test data for several timber-concrete connection specimens. The long-term deformation of the shear connection specimens shows a characteristic pattern of rapid growth in the early stages, followed by a slowdown in the later stages (Jorge *et al*. 2010). The tests varied in terms of environmental conditions, loading duration, specimen size, and material types. From these variations, some key parameters significantly impacting the creep coefficient can be identified.

Table 1. Long-Term Tests of Timber-Concrete Composite Connection Specimens

Authors	Connector type	K_s (kN/mm)	Wood type	Concrete grade	Environmental condition	*t* (Day)	Load (kN)	*φ*(*t*)
Jorge *et al*. 2010)	SFS screw	/	Glulam	LC20/22	Constant	600	/	0.91
				LC12/13		600		0.79
				LC16/18		600		0.695
Fragiacomo *et al*. (2012)	SFS screw	11.9	Redwood	LC25	Constant	421	/	0.85
Van Der *et al*. (1999)	16 mm screw	21.5	Glulam	LC9	Constant	343	19.2	0.32
	12 mm screw	8.7				426	10.6	0.69
Dias (2005)	8 mm rebar	14.6	Glued spruce	C20	Constant	426	4.50	0.66
	10 mm rebar	16.3	Spruce	C20		573	6.90	0.49
	10 mm rebar	14.0	Spruce	C50		573	7.10	0.63
	10 mm rebar	27.0	Pine	C20		573	7.40	0.75
	10 mm rebar	34.5	Chestnut	C20		573	8.10	1.45
	10 mm rebar	16.0	Spruce	LC16		426	5.80	1.01
Jiang *et al*. (2021)	12 mm screw	6.63	Glulam	C30	Indoor variation	365	32.71	0.59
		6.58		LC30	Indoor variation		31.94	0.72
		6.58		LC30	Outdoor variation		31.94	1.80
Jorge *et al*. (2005)	SFS screw	31.8	Glulam	LC20	Constant	606	10.94	0.91
		31.1		LC16		606	9.82	0.51
		29.2		LC12		606	10.29	0.65
Shi *et al*. (2020)	Notch connector	/	Glulam	C30	Constant	342	25.2	1.38
							50.5	1.30

Note: K_s is shear stiffness of shear connectors; *t* is holding time of long-term load; *φ*(*t*) is creep coefficient of the shear connectors; C is normal concrete; LC is lightweight concrete.

Effect of Timber and Concrete Types

Due to the differing creep characteristics of timber and concrete, the long-term performance of timber-concrete composite beam is more complex than that of pure timber and concrete beams. Timber shrinks or expands with changes in relative humidity and temperature. In the current long-term experiments of shear connections, the concrete used mainly falls into two types: lightweight aggregate concrete and ordinary concrete. Jorge *et al*. (2010) investigated the creep behavior of shear connectors with lightweight concrete. As the concrete strength increased from 21.0 to 30.7 MPa, the creep coefficient increased from 0.79 to 0.91. Fragiacomo *et al*. (2007) found that the type of concrete had no significant impact on the long-term performance of connectors. However, Dias (2005) discovered that the creep coefficient of shear connectors using lightweight aggregate concrete was approximately twice that of those using ordinary concrete through experiments. Additionally, Jiang *et al*. (2021) found that the one-year creep coefficient of screw connections using lightweight concrete was about 1.2 times that of screw connections using ordinary concrete. Van de Kuilen *et al*. (2011) analyzed the impact of concrete grade on the long-term behavior of shear connections, finding that reducing the concrete grade can lower the creep coefficient. Furthermore, the type of timber also affects the long-term load-bearing behavior of shear connections. Dias (2005) performed long-term loading tests on TCC specimens using pine, chestnut, and glued spruce, and found that the creep coefficients of the specimens using logs were relatively large.

Effect of Environmental Condition Variations

Fragiacomo *et al*. (2007) conducted experimental tests on the long-term behavior of the 'Tecnaria' connector. The test results demonstrated that creep deformation increased due to the hygroscopic behavior of the timber surrounding the connectors under fluctuating humidity in a dynamic and ever-changing environment. A notable increase in delayed slips was found when the loaded specimens were subjected to relative humidity cycles with a period exceeding seven days and an amplitude of at least 40%. Fragiacomo *et al*. (2007) found that in the absence of a plywood interlayer between the timber and concrete components, high environmental humidity can cause wet concrete to seep and potentially lead to timber decay. Furthermore, Jiang *et al*. (2021) employed lightweight concrete in place of normal concrete to investigate the effect of environmental conditions on the long-term behavior of shear connectors. The creep coefficient of screw connections under outdoor environments was approximately 2.5 times that of those tested in indoor environments. The variation in ambient temperature and humidity significantly affected the creep coefficient of lightweight aggregate concrete specimens. The significant swelling of timber in outdoor environments led to a substantial increase in deflection. Additionally, mechano-sorptive creep in timber, induced by fluctuations in humidity, was more pronounced in such environments, further contributing to a greater increase in deflection.

Effect of Shear Connectors Types and Load Levels

The types of shear connections and the load levels had impacts on the creep coefficients. Comparing existing research findings revealed that the creep coefficient of notched connections was greater than that of screw connections. Jorge *et al*. (2010) studied the effects of concrete type and screw diameter on the shear capacity and stiffness of connectors. The results demonstrated that the creep coefficients of the various shear connectors generally ranged from 0.5 to 2.0, falling between the intrinsic creep coefficients of timber and concrete. Shi *et al*. (2020) conducted long-term tests on notched connectors, and found that after approximately one year of loading, the long-term slip for notched connections with load levels of 0.30 and 0.15 were 0.221 mm and 0.338 mm, respectively. According to predictions from an improved creep model, the creep coefficient of slotted connectors at the end of a 50-year service life was 3.0, and long-term loading had a minimal impact on the creep coefficient of shear connections. Van de Kuilen *et al*. (2011) examined the impact of dowel fastener types on the long-term behavior of shear connections, discovering that an increase in screw diameter reduced the creep coefficient.

LONG-TERM PERFORMANCE OF COMPOSITE BEAMS

The long-term beam tests are usually adopted to study the variation patterns of beam deflection deformation under long-term loading conditions. Table 2 summarizes the long-term loading test data of several timber-concrete composite beams.

Effect of Construction Methods and Load Levels

Fragiacomo *et al*. (2007; 2012) conducted two long-term experiments of TCC beams, which were constructed using two methods: unsupported and supported. In the unsupported method, the timber beams bore the construction load, while in the supported method, supports were placed under the timber beams during construction and removed after the concrete hardened. The test results indicated that using the supported construction method could reduce the initial deformation of the composite beams, and the final long-term deformation value could be reduced by approximately 15%. Shi *et al*. (2021) conducted a long-term experimental study on prefabricated TCC beams, revealing that when the long-term load was doubled, the deflection increase of the composite beams rose by about 60%, but the creep coefficient decreased by about 20%. Tao *et al*. (2022) found that the stiffness and load-bearing capacity of composite beams with prefabricated glued steel plate connections were increased by approximately 14.8% and 35.4%, respectively, compared to those using glued steel plate connectors. Augeard *et al*. (2020) examined the creep performance of TCC structures under sustained cyclic loads. The average creep coefficients for the three groups of specimens were found to be 0.25, 0.11, and 0.15, respectively. The specimens incorporating ultra-high-performance fiber-reinforced concrete demonstrated the lowest creep coefficient of 0.11, compared to those using ordinary concrete.

Effect of Concrete Types

Using lightweight concrete instead of ordinary concrete can have two opposing effects on long-term mechanical performance (Jorge *et al*. 2010). Lightweight concrete reduces the self-weight of structures, which is beneficial for reducing deformation. On the other hand, lightweight concrete has a lower elasticity modulus and a higher shrinkage compared to ordinary concrete. Fragiacomo *et al*. (2012, 2013) conducted full-scale tests on a six-story TCC building and long-term experiments on composite beams and found that specimens with lightweight concrete exhibited significant shrinkage and cracking during loading. Three months post-loading, the creep coefficient reached 1.0. The cracking compromised the protective function of the outer concrete layer, adversely affecting the long-term durability of the composite beams. Yeoh (2010) found through experiments that using low-shrinkage concrete reduced the long-term deformation of composite beams by 15% compared to using ordinary concrete.

Table 2. Long-Term Tests of Timber-Concrete Composite Beams

Authors	Connector Type	Wood Type	Concrete Type	Concrete Grade	Environmental Condition	φ(t)
Yeoh. (2010)	Notch	LVL	Normal	C35	Variable	0.99
			Low shrinkage			1.06
	Steel plate		Low shrinkage			1.12
Fragiacomo *et al*. (2007)	Notch	Log	Normal	C30	Variable	0.53
						0.58
Ceccotti *et al*. (2007)	Dowel	Glulam	Normal	C30	Variable	1.38
Kanócz *et al*. (2012)	Screw	Log	Steel fiber reinforced	C25	Variable	2.32
Fragiacomo *et al*. (2013)	Steel plate	Glulam	Self-compacting	C20	Variable	0.61
	Screw					0.51
Hailui *et al*. (2015)	Notch	LVL	Normal	C30	Constant temperature	7.7
	SFS screw				Variable moisture	7.9
Fragiacomo *et al*. (2012)	SFS screw	Mahogany	Lightweight	LC25	Variable	1.48
						1.16
Van Der *et al*. (1999)	Screw	LVL	Normal	C25	Variable	2.4
	Steel plate					1.8
	Notch+Screw					1.6
	Concrete notch					1.4
Jiang *et al*. (2021)	Screw	Glulam	Normal	C30	Indoor variation	1.26
			Lightweight	LC30	Indoor variation	1.20
			Lightweight	LC30	Indoor variation	1.65
			Lightweight	LC30	Outdoor variation	2.47
Shi *et al*. (2020)	Notch+Screw	Glulam	Normal	C35	Variable	0.88
Shi *et al*. (2021)	Screw	Glulam	Prefabricated	C30	Variable	0.98
						0.89
						0.96
Eisenhut *et al*. (2016)	Epoxy	Glulam	High performance concrete	/	Outdoor variation	1.75-2.24

Note: C is normal concrete; LC is lightweight concrete.

In long-term experiments on TCC beams by Kanócz *et al*. (2012), the concrete slab was poured with steel fiber-reinforced concrete. Theoretically, the inclusion of fibers can reduce concrete shrinkage and long-term deformation of composite beams. However, the absence of a control group in the experiment leaves the application of fiber-reinforced concrete in TCC beams open for further research. Jiang *et al*. (2021) observed that the overall trend in long-term deflection growth for composite beams using lightweight concrete was similar to those using ordinary concrete. Interestingly, the one-year creep coefficient of composite beams with lightweight concrete was slightly smaller than that of beams with ordinary concrete. Fu *et al*. (2020) investigated the bond performance between wood chip concrete and timber, glued using four different adhesives. Wood chip concrete was made by substituting 15% of the coarse aggregate volume with beech wood chips, aiming to reduce the weight and enhance the thermal insulation properties of the concrete, while maintaining a majority of its compressive strength.

Effect of Environmental Condition Variations

Fragiacomo *et al*. (2013) studied the time-dependent characteristics of TCC floors and precast concrete slabs. Throughout the experiment, continuous monitoring was performed on mid-span deflection, relative slip at connection points, and the relative humidity and temperature of the environment. The experimental results were validated using finite element models, predicting the total deflection of the specimens after a 50-year service life. Hailu (2015) conducted long-term tests on four TCC beams, focusing on the impact of cyclic variations in environmental humidity on the deformation and stiffness of the composite beams. The tests were conducted under a controlled environment with a constant temperature and relative humidity fluctuating periodically between 50% and 95%. The results showed that changes in relative humidity led to significant increases in structural deformation. After the long-term load was removed, the stiffness of composite beams degraded by approximately 20% to 50%. Jiang *et al.* (2021) observed that the long-term deformation of composite beams subjected to outdoor variations increased at a much faster rate than that of beams exposed to indoor conditions. The one-year creep coefficient of the outdoor-tested beam specimens was roughly twice that of the indoor-tested specimens. Eisenhut *et al*. (2016a,b) investigated the long-term behavior of adhesive-bonded timber-concrete composite beams and found that the deflection of these beams exhibited similar changes in response to seasonal temperature and humidity variations. Fu *et al*. (2024) discovered that increasing relative humidity levels (55%, 75%, 95%) during testing of wood-concrete composites led to a corresponding increase in wood moisture content. This increase significantly reduced the shear strength of timber-concrete composite (TCC) joints. The swelling of the wood under these conditions induced internal stresses and caused damage to the concrete at the interface, ultimately decreasing shear bond strength. It was also noted that the grade of concrete (ranging from C30 to C50) had minimal impact on the effects of moisture-induced stresses. Bathon *et al*. (2006) investigated the shear behavior of timber-concrete joints bonded with brittle epoxy and ductile polyurethane. The results showed that the wet spruce timber-concrete joint retained comparable shear capacity after 12 months when compared to the reference joint. In contrast, dry spruce wood-concrete joints exhibited a decline in both shear strength and stiffness. Hwang *et al*. (2023) examined the moisture content of nail-laminated timber (NLT)-concrete composite floors under outdoor environments. It was found that the moisture content of NLT increased with higher ambient relative humidity and the pouring of wet concrete.

Effect of Shear Connector Types

Fragiacomo *et al*. (2013) investigated two different types of connectors (steel plates and screws). In the long-term tests, both composite beam specimens exhibited similar time-dependent trends in mid-span deflection. The long-term loading resulted in increases in the mid-span deflection after 339 days by 48% and 77%, respectively. Van Der Linden (1999) found that the differences between the creep coefficient of the composite beams used steel plate connectors and notch connectors were relatively small, and the creep coefficient of the composite beams used screw connectors was significantly larger. Kuhlmann *et al*. (2004) investigated the long-term behavior of notched connections and found that the creep coefficient of notched connections reinforced with screws was lower compared to those without screws. Auclair *et al*. (2016) introduced a novel shear connector for TCC beam, comprising an elongated cylinder of ultra-high-performance fiber-reinforced concrete and a steel core. This design prioritized sustainability by aiming to minimize the use of structural adhesives and steel elements, while also considering constructability and ease of assembly. Daňková *et al*. (2019) developed a non-metallic connector made from beech plywood, which improved adhesion to the glulam rib and incorporated holes in the upper portion to facilitate rebar placement and concrete penetration. Additionally, adhesives can serve as connecting components. However, wood, concrete, and epoxy adhesives exhibit distinct hygrothermal properties, leading to internal stresses during bonding under varying temperature and moisture conditions. Tannert *et al*. (2017) conducted long-term studies under indoor climatic conditions and found that adhesive bonding was a more rigid method for achieving composite action between timber and concrete, with a calculated connection efficiency of over 95% for both beams after 4.5 years of loading. Furthermore, long-term loads of approximately 30% of beam capacity did not cause any degradation of the adhesive bond.

THEORETICAL ANALYSIS OF LONG-TERM PERFORMANCE OF TIMBER-CONCRETE COMPOSITE BEAMS

Theoretical Research

Currently, the long-term theoretical analyses for TCC beams can be categorized into numerical simulation methods and calculation methods. Numerical methods for simulating long-term loading tests offer advantages such as low cost and flexible parameter selection. Finite element models can be divided into one-dimensional (1D) finite element models and three-dimensional (3D) finite element models. One-dimensional finite element models are computationally inexpensive but require experimental data to obtain relevant parameters for connectors. Amadio *et al*. (2001) proposed a 1D finite element model assuming equal vertical displacements between the timber beam and the concrete slab, with no slip between the concrete slab and the connectors, and using spring elements to simulate shear connectors, showing good simulation results. Fragiacomo (2005) developed a finite element model of TCC beams under long-term loads, fully considering the deformation capacity of the connectors and the rheological properties of concrete, timber, and connections. The model accurately simulated the creep of component materials and the effects of moisture content on the creep of timber and connectors using precise linear models. This model applies an effective step-by-step procedure without the need to store the entire stress history at certain points to illustrate creep behavior. Three-dimensional finite element models do not require the mechanical and rheological characterization of the connection but involve extensive contact calculations, leading to high computational costs. Dias (2005) proposed a 3D finite element model that aligns well with long-term experimental data of composite beams in stable environments. Fragiacomo *et al*. (2014) developed a 3D numerical model to capture the time-dependent behavior of TCC beams with notched connectors, subjected to long-term loads and simultaneous exposure to varying temperature and humidity conditions.

Kavaliauskas *et al*. (2005) analyzed the applicability of the method in Eurocode 5 for the design of timber-concrete composite beams and suggested that this method is only suitable for the design under short-term ultimate loads. However, in practical engineering, timber-concrete composite beams often bear long-term loads, and their design is frequently controlled by long-term deformation limits. For the calculation of long-term deformations, Ceccotti (2002) recommended using reduction factors for the short-term elastic modulus of concrete, the short-term elastic modulus of the timber beam, and the short-term stiffness of the shear connectors to derive the modulus and stiffness for long-term design calculations, as follows,

$$E_{\mathrm{c,eff}} = \frac{E_{\mathrm{c}}}{1+\varphi_{\mathrm{c}}} \tag{1}$$

$$E_{\mathrm{t,eff}} = \frac{E_{\mathrm{t}}}{1+\varphi_{\mathrm{t}}} \tag{2}$$

$$K_{\mathrm{eff}} = \frac{K}{1+2\varphi_{\mathrm{t}}} \tag{3}$$

where φ_{c} is creep coefficient of concrete, and φ_{t} is creep coefficient of timber.

For the sake of computational convenience, this method assumes that timber and concrete behave as ideal elastic bodies, assuming that the load-slip curve of shear connectors follows a linear relationship. Under relatively small external loads (such as normal service loads), shear connectors also exhibit nonlinear force characteristics (Van de Kuilen *et al*. 2011). However, for engineering design purposes, this method can satisfy the design requirements of timber-concrete composite beams for relatively stable environmental conditions. It holds certain physical significance, it is straightforward in form, and it is convenient for practical calculations, making it suitable for application in actual engineering projects. Nevertheless, considering the following two scenarios, this method requires further refinement: (1) Given the current lack of an accurate model for predicting the long-term deformation of shear connectors, it is recommended to conduct long-term tests on shear connection specimens to obtain the long-term deformation characteristics of shear connectors; (2) The current method cannot accurately account for the effects of the environmental changes. Since the long-term mechanical properties of timber and concrete differ, environmental variations can generate secondary internal forces within the structure. These secondary forces need to be considered when evaluating the long-term mechanical performance. Schänzlin *et al*. (2003; 2007) proposed an approach where strains induced by environmental changes in composite beams are equivalent to external loads and are superimposed on the design loads. Additionally, they categorized the environmental conditions surrounding the structure and used corresponding correction factors to adjust the creep of the materials. Fragiacomo *et al*. (2006a, b) utilized the "γ-method" to calculate the deformation of composite beams under short-term loads and applied differential equations to compute long-term deformations, ultimately summing the deformation values. For engineering design purposes, it is feasible to approximate the deformation caused by environmental humidity changes on a weekly basis and extrapolate the approximate deformation corresponding to the design life span (Fragiacomo *et al*. 2013).

Design Method – Eurocode 5

Eurocode 5 (EN 1995-1-1: 2004), currently the most widely used standard, offers the comprehensive provisions for the long-term deformation of timber structure. It includes detailed guidelines on calculation methods and requirements, specifically addressing the time-dependent modulus and stiffness of component materials and shear connections.

(1) Provisions of materials and connections

In Eurocode 5, the evaluation of the final deformation of timber members under the serviceability limit state incorporates a correction coefficient k_{def}, which adjusts the elastic modulus, shear modulus, and joint stiffness, as follows,

$$E_{w,\,fin} = \frac{E_w}{1+k_{def,\,w}} \tag{4}$$

$$E_{c,\,fin} = \frac{E_c}{1+k_{def,\,c}} \tag{5}$$

$$K_{ser,\,fin} = \frac{K_{ser}}{1+k_{def,\,S}} \tag{6}$$

where $k_{def,\,w}$ is dependent on different categories of wooden products and environmental conditions; the values of k_{def} are 0.6, 0.8, and 2.0 for structures in environmental conditions class 1, class 2, and class 3, respectively, according to the conventional wood products; $k_{def,\,c}$ is the creep coefficients of the concrete; and $k_{def,\,S}$ is the creep coefficient of the shear connector.

The aforementioned formula effectively meets the design requirements for timber-concrete composite beams under short-term ultimate limit states (Yeoh *et al*. 2011; Du *et al*. 2021; Wei *et al*. 2021). It should be noted that Eurocode 5 considers the impact of connectors between timber and concrete on time-dependent deflection to be minimal, treating the creep properties of connectors as a modified combination of timber and concrete. However, Eurocode 5(EN 1995-1-1: 2004) provides only a simplified calculation method for reduced wood stiffness in Section 3.2.3, without offering detailed guidance on timber creep behaviors.

(2) γ-Method

Eurocode 5 (EN 1995-1-1: 2004) provides a method for calculating the effective bending stiffness of timber-timber composite beams using flexible connectors. This method involves using an equivalent cross-section to account for the interface slip effect, thereby determining the effective stiffness of the composite beam. Subsequently, the deformation is calculated based on the principles of material mechanics. The effective stiffness can be calculated using the following formula,

$$EI_{eff} = E_1 I_1 + E_2 I_2 + \gamma_1 E_1 A_1 a_1^2 + \gamma_2 E_2 A_2 a_2^2 \tag{7}$$

where EI_{eff} is effective flexural stiffness of composite beam with partial shear connection, a_1 is distance from the concrete neutral axis to the composite section neutral axis, a_2 is distance from the wood neutral axis to the composite section neutral axis, γ_1 is connection efficiency factor for the concrete slab; and γ_2 is connection efficiency factor for the wood beam.

Design Guide for Timber-Concrete Composite Floors in Canada

The design guide for timber-concrete composite floors in Canada (Auclair 2020) presents a simplified approach for evaluating long-term deflections by considering the creep adjustment factor of each component of the TCC floor. However, it does not directly account for the effect of concrete shrinkage on deflection. Instead, conservative assumptions are made regarding the creep adjustment factor to ensure a realistic prediction of long-term deflection.

(1) Concrete creep coefficient

The guide provides a mathematical formula for predicting long-term deflection over time, which involves multiplying the instantaneous deflection caused by sustained load by a specific factor,

$$K_{\text{creep, c}} = \left(1 + \frac{S}{1 + 50\rho'}\right) \tag{8}$$

where ρ' is the proportion of steel reinforcement under compression, and S is a time-varying coefficient.

It is important to note that Eq. 8 is only valid when the concrete has reached an age of 28 days. If the concrete is subjected to loading before 28 days, the creep factor must be adjusted in accordance with the guidelines specified in CSA A23.3-14. (CSA A23.3-14. 2014).

(2) Timber creep coefficient

The CSA O86-14 (CSA O86-14. 2014) does not provide a method for calculating long-term deflection over time. However, its appendix provides formulas applicable to laminated veneer lumber for estimating its long-term deflection at the end of its service life (50 years).

$$\Delta_{\text{max}} = \Delta_{\text{ST}} + \Delta_{\text{LT}} \tag{9}$$

where Δ_{ST} is elastic deflection due to short-term loads, Δ_{LT} is long-term deflection due to long-term loads, Δ_{LT} is $K_{creep,t} \times \Delta_{inst,LT}$), $\Delta_{inst,LT}$ is instantaneous deflection due to long-term loads, and $K_{creep,t}$ is creep modification factor for timber. $K_{creep,t}$ is 2.0 for dry service conditions (moisture content<19%).

The CSA O86-14 (CSA O86-14. 2014) provides calculation methods only for cross-laminated timber (CLT) and does not specify creep adjustment factors for other types of wood products. Therefore, when using other wood types, a conservative approach can be taken by applying the same creep adjustment factors as those for CLT, in accordance with the requirements of the National Design Specification (NDS) (American Wood Council. 2015). The creep adjustment factor is 1.5 for glued laminated timber and structural composite lumber under dry conditions, while it is 2.0 for wood structural panels and CLT.

(3) Connection creep coefficient

The long-term shear stiffness (K_{LT}) of the connectors is typically obtained through push-out experiments. In the absence of specific data, the serviceability shear stiffness of the connectors can be estimated by dividing it by twice the creep adjustment factor of the wood (Schmidt *et al*. 2004). This approach assumes that twice the timber creep adjustment factor provides a conservative estimate for the shear connector, as its creep is generally between 1 and 2 times that of the timber (Li *et al*. 2023).

(4) Deflection Calculation

According to the effective modulus method (Ceccotti *et al*. 2002), the Young modulus of concrete, timber, and the shear stiffness of the connections are reduced based on their respective creep adjustment factors. The total long-term deformation of TCC floor is determined using Eq. 9. In cases where specific data are unavailable, it is a conservative approach to estimate the serviceability shear stiffness of the connections by dividing it by twice the creep adjustment factor of wood (Fragiacomo *et al*. 2004). This assumption is based on the observation that twice the creep adjustment factor of timber generally falls between 1 and 2 times that of timber creep (Du *et al*. 2021), making it a reasonable estimate for shear connector performance. The effective modulus of each component is calculated using the following equations.

$$E_{\mathrm{c,LT}} = \frac{E_{\mathrm{c}}}{K_{\mathrm{creep,c}}} \tag{10}$$

$$E_{\mathrm{t,LT}} = \frac{E_{\mathrm{t}}}{K_{\mathrm{creep,t}}} \tag{11}$$

$$K_{\mathrm{LT}} = \frac{K}{2K_{\mathrm{creep,t}}} \tag{12}$$

where E_{c} is Young modulus of concrete, E_{t} is Young modulus of timber, K is shear stiffness of the connector, $K_{\mathrm{creep,c}}$ is creep modification factor for concrete, and $K_{\mathrm{creep,t}}$ is creep modification factor for timber.

Further research could focus on developing more precise models and calculation methods to address a variety of scenarios. Accurate models are crucial for predicting the long-term deformation of shear connectors. Calculation techniques must be improved to account for environmental variations and the nonlinear behavior of materials. Furthermore, numerical simulation and analytical methods should be further advanced to provide a more comprehensive theoretical framework for the design and analysis of TCC beams under long-term loading.

CONCLUSIONS

This paper analyzed the long-term mechanical behavior of timber-concrete composite (TCC) beams and systematically reviewed the current research on the long-term performance. The conclusions can be summarized as follows:

1. The mechanical properties of timber change with environmental conditions, particularly humidity and moisture content. Under prolonged loading, timber undergoes plastic deformation, leading to a decrease in strength and stiffness over time. The cyclical changes in moisture content cause noticeable creep in timber, contributing to the long-term deformation growth of structural components.

2. Shear connectors play a crucial role in maintaining the integrity of timber-concrete composite beams by transferring shear forces between the timber and concrete components. Long-term tests have indicated that the creep coefficient of shear connectors is affected by the type of connectors, loading conditions, and environmental factors. Different shear connectors exhibit varying degrees of long-term slip and deformation, which must be considered in the design of TCC beams.
3. The differing long-term mechanical behaviors of concrete, timber, and shear connectors lead to complex internal force redistributions within composite beams under prolonged loading. The timber typically undergoes significant creep, particularly under environmental effects. This results in a dynamic stress distribution across the cross-section of the composite beam, necessitating careful consideration of these effects in the design and analysis of TCC beams to ensure structural integrity and longevity.
4. To enhance the practical application of TCC beams in engineering, more accurate models for predicting the long-term deformation of shear connectors are required. Additionally, refining calculation methods to include environmental variations and the nonlinear behavior of materials will improve the reliability of long-term performance predictions. Continued development in both numerical simulation and analytical methods will provide a more comprehensive theoretical framework for the design and analysis of TCC beams under long-term loads.

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