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Slab elements made of timber and wood-cement compounds – structural and other performances

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ABSTRACT: Cement-bonded wood-based materials (Wood-Cement Compound: WCC) are used in construction since the beginning of the 20th century already. Until today, however, they are chiefly used as non-structural finishing layers where their good fire resistance, thermal and acoustic insulation properties are combined with a relatively low and thus, structurally beneficial density. WCCs should not be seen as an alternative to regular structural concrete – as stiffness and strength of WCCs usually are rather low – but should rather be applied in structural elements with composite action, e.g. together with timber or other light-weight structural elements (to not unnecessarily increase the overall weight). This article reports on results from full-scale tests up to failure on timber-WCC composite slab elements and compares their structural performance to more traditional timber-concrete composite slabs. Test results for determining acoustic insulation properties of timber-WCC slab elements are also presented as well as an eco-balance analysis.

1 INTRODUCTION

Concrete is nowadays the most widely used construction material. Its main drawbacks are a significant self-weight and the use of non-renewable resources. Moreover, it provides rather low thermal insulation properties, thermal storage capacity and acoustic insulation.

Wood-Cement Compound (WCC) materials mix a hydraulic binder with wood aggregates (e.g. sawdust). They have been used since the beginning of the 20th century and they are currently used as non-structural finishing layers for their good properties in thermal, acoustic and fire resistance. Different pourable mixtures have been developed and tested (Macchi and Zwicky 2016). The most promising recipes have been used to develop structural elements (here, slabs) where WCC has been placed in the compressive layer of a timber-WCC composite section in order to increase stiffness but also provide further building-physical and ecological performances.

The main application potential of WCCs lies in prefabricated elements for dry, modular building construction. Due to its composition, mechanical strength is significantly lower than for regular concrete, for example. However, other advantages are expected, such as acoustic and fire insulation. The goal here is to verify if this material can be used as a multi-functional solution for slab elements. Thus, an eco-balance investigation is also presented to compare WCC slabs to more classical solutions in terms of energy consumption.

2 FULL-SCALE TESTS ON TIMBER-WCC SLABS

2.1 *Test specimens*

The test campaign regroups six different single-span slabs. All specimens have an 8 m span and 0.76 m width. Different configurations have been tested, Figure 1 shows their geometry. The first specimen (called Ref) was used as a reference. A continuous shear connector in form of a vertical steel mesh has been used between SCC and timber (Bathon & Graf, 2000). Furthermore, two main geometries were tested: specimens with timber beams embedded in WCC (Types 1 and 2), and a "+/-" connection (Types 3 to 5). The overall geometries have been chosen to be theoretically close in terms of flexural stiffness, assuming a rigid connection between timber and WCC.

Due to production difficulties, some defects could be identified prior to the tests. The most important defects where noticed in Type 3 and Type 4 with cracks in the WCC along the slab close to the timber-WCC interface. Type 1 also showed a small crack pattern in the WCC. Concerning WCC5, a too dry mix seems to be responsible of significant visual defects in its external surface, however, no cracks have been spotted in this material.

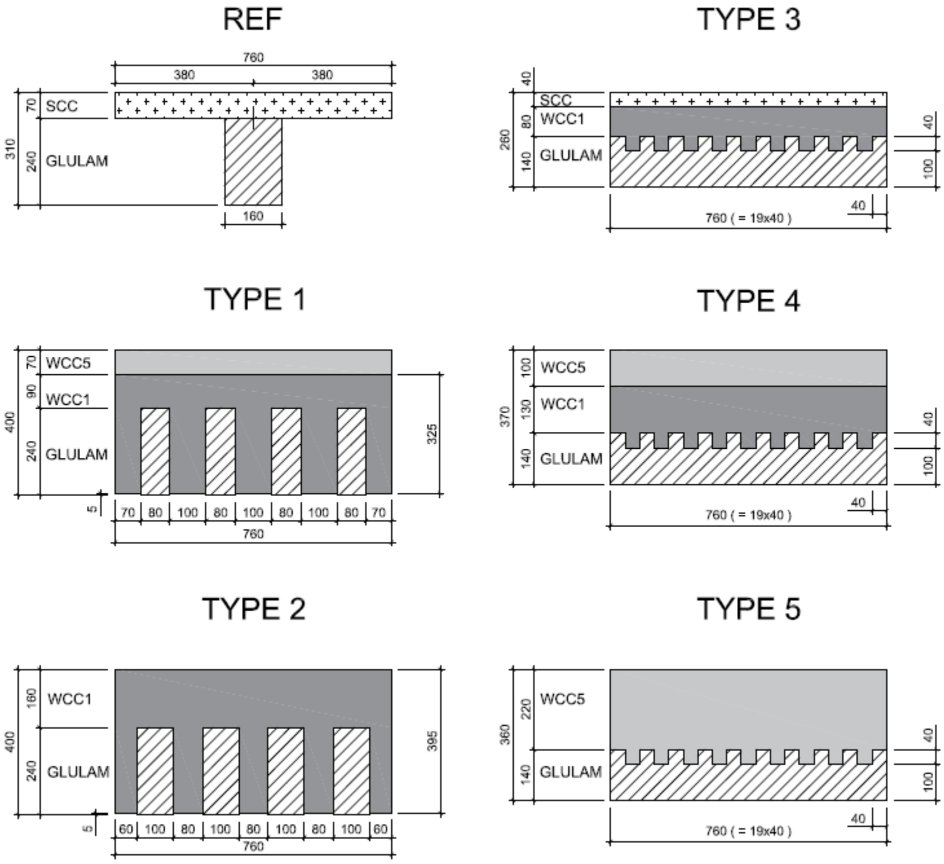

Figure 1. Cross-sections of the tested specimens. Dimensions in mm.

2.2 *Materials properties*

Four different materials have been used. Glued laminated timber (glulam) beams, a self-compacting concrete (SCC) and two different WCCs (WCC1 and WCC5). The main difference between the two WCCs is the sawdust/cement ratio (0.58 and 0.40 for WCC1 and WCC5, respectively). Cement-based materials have been tested using cylinders with 15 cm diameter and 30 cm height. Compression tests according to standard SIA 262/1 (2013) gave the compressive strength and Young's modulus. SCC specimens where also tested in tension using the double-punch test (Chen & Trumbauer 1972). Table 1 shows the results. WCCs could not be tested in tension due to their low strength. Its tensile strength has been estimated from previous. It should be noted that the observed mechanical parameters are significantly lower than for previous samples made in the laboratory. Indeed, for WCC1, a Young's modulus around 900 MPa was expected; and, for WCC5, compressive strength and Young's modulus where expected to be around 5 MPa and 2700 MPa, respectively. Therefore, more tests must be conducted to industrially reproduce the laboratory results in terms of mechanical properties.

Table 1. Average and coefficients of variation of mechanical properties of cement-based test materials.

	f_c	COV	f_t	COV	E_c	COV	Density
	MPa	%	MPa	%	MPa	%	kg/m^3
SCC	44.4	1.8	3.0	19.2	32,300	2.4	2265
WCC1	2.1	5.7	0.3	-	650	15.0	850
WCC5	3.5	13.3	0.4	-	960	4.3	1100

2.3 *Connection between WCC and timber*

Connection between materials in a composite slab is a key parameter to ensure an effective distribution of loads between the different materials. A large number of studies on timber-concrete connectors has already been performed (e.g. Ceccotti 2002, Deam et al. 2008, Kuhlmann & Michelfelder 2006). Considering the weak mechanical behavior of WCC's, a surface connection called "+/-" has been tested. Indeed, punctual connections could cause significant stress concentrations in the WCC material leading to premature failure.

2.4 *Test procedure*

Six-point bending tests have been performed on each specimen until failure, by applying a load at each 1/5 of the span (1.60 m) to simulate a uniformly distributed load. Moreover, two series of load cycles were performed between the three serviceability load levels calculated according to SIA 261 (2003), with the goal to observe a potential stiffness drop in the range of serviceability loads.

2.5 *Tests results*

2.5.1 *Global behavior*

Figure 2 shows the load-deflection curves obtained for the six tested specimens. It should be noted that these results have been modified for the load corresponding to self-weight and testing rig (between 19 kN and 23 kN, depending on the specimen). Due to differences between tested specimens, several failure modes have been experienced.

The reference slab (Ref) experienced a hardening behavior linked to a significant slip between SCC and timber, i.e. associated to decreasing connector stiffness. Indeed, the load-deflection relationship shows two local peaks (around 65 mm and 105 mm of deflection, respectively). After each local peak, significant slip between SCC and timber has been measured.

Specimens with timber beams (Type 1 and 2) experienced, generally, the highest load and deflection up to failure. For example, the Type 2 specimen gave the most promising results. Furthermore, no debonding of the WCC material occurred until failure. Type 1, by comparison, shows a similar initial stiffness. However, the slope of the curve changed for a rather low load-level (around 32 mm of deflection) and, during the first series of load-cycles (between 45 and 50 mm of deflection, approximately), significant debonding occurred which can explain the difference between Type 1 and Type 2 specimens.

For specimens with "+/-" connection, two different behaviors were observed: Type 3 and Type 4 experienced early failure in the WCC material (along the crack pattern seen prior to the tests). This failure occurred for the same load level (approximately 40 kN). This leads to unexploitable slip measures between WCC1 and timber due to the position of displacement sensors. After this load peak, tests have been continued but the corresponding load-deflection curve is essentially the one of the timber structure with a WCC layer acting as an extra load. Indeed, the post-peak stiffness is quite the same for the two specimens. Type 5, however, experienced a noticeable slip between WCC5 and timber during the test, until failure of the first timber lamellae (Figure 3). The load-deflection relationship shows a significant hardening behavior.

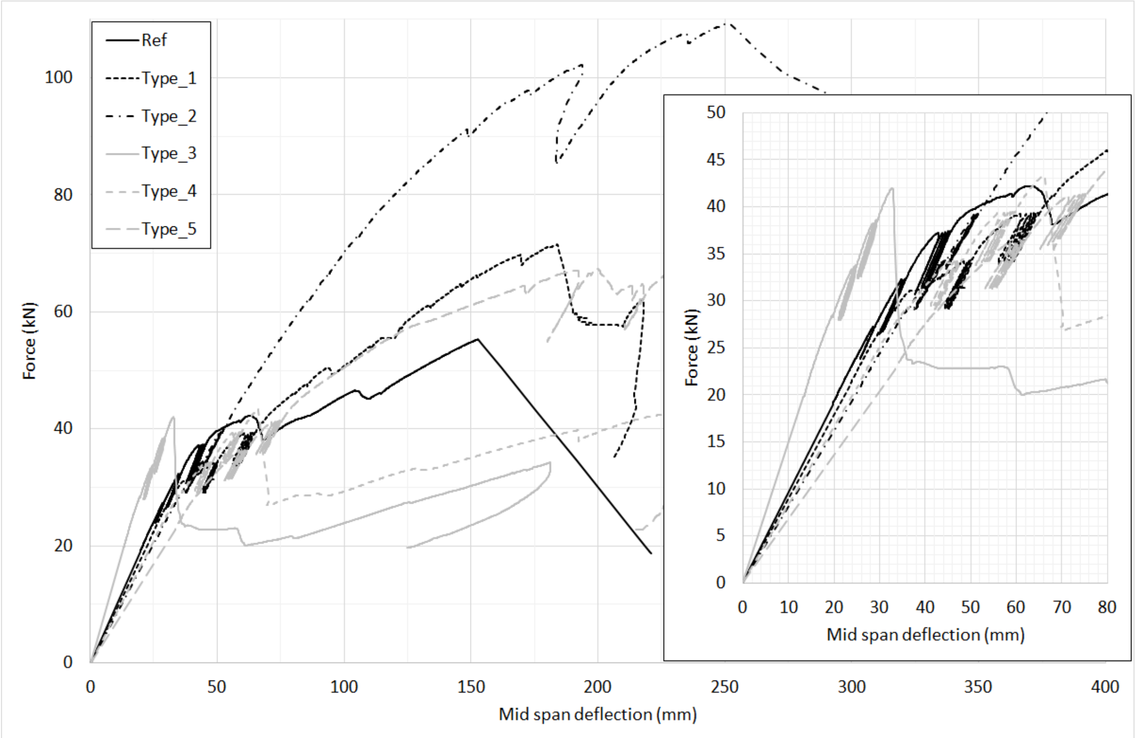

Figure 2. Load-deflection relationships for all the tested specimens.


Figure 3. Type 5 specimen during test

2.5.2 *Comparison to building code requirements*

For the verification of Serviceability Limit State (SLS), deflection can, in some cases, be compensated by a camber. However, the variable actions should not provoke a deflection higher than L/350 = 23 mm (SIA 261 2003). Table 2 shows the equivalent uniformly distributed load corresponding to an experimental mid-span deflection of L/350. A comparison can be made regarding the standard requirements for different types of useable areas in buildings. The results show a satisfying behavior regarding the requirements for several types of useable areas. The reference specimen can be used for any kind of useable area, up to the category for shopping (cat. D). Type 1 is apt for residential and office buildings, while Types 2, 4 and 5 additionally cover meeting areas. Type 3 shows an insufficient performance. Note, however, that deflection due to permanent loads, and also at long-term, must be compensated by camber.

Considering the Ultimate Limit State (ULS), the equivalent uniform load (in terms of bending moment) at failure q_{Rm} are shown in Table 3. The values presented have been calculated according to standard SIA 261 (2003). q_{Rk} has been found by dividing q_{Rm} by 1.5, assuming a coefficient of variation of 20% (SIA 265/1 2009). This value has been used to take into account that only one test has been performed for each configuration. q_{Rd} has then been calculated by dividing q_{Rk} by 1.5 (partial safety factor γ_R for glulam timber and concrete). The comparison to a factored dimensioning load, assuming variable load of q_k = 5 kPa and self-weight shows that ULS performance is insufficient. To satisfy ULS requirements, smaller spans should be used. Table 3 shows corresponding results. It becomes evident from the results in Tables 2 and 3 that ULS performance of all tested specimens is governing for structural design.

Table 2. Equivalent load for variable actions at SLS.

Specimens	q_{exp} (L/350)	Type of useable area	ψ_1	$q_{k,req}$	$\psi_1 \cdot q_{k,req}$
	kPa			kPa	kPa
Ref	3.70	A - Residential	0.5	2.00	1.00
Type 1	2.00	B - Office	0.5	3.00	1.50
Type 2	3.29	C - Meetings	0.7	3.00	2.10
Type 3	0.27	D - Shopping	0.7	5.00	3.50
Type 4	2.59				
Type 5	2.14				

Table 3. Test results at ULS.

	q_{Rm}	q_{Rk}	q_{Rd}	q_d	L_{eq}
	kPa	kPa	kPa	kPa	m
Ref	10.96	7.31	4.87	12.23	5.05
Type 1	14.17	9.45	6.30	12.69	5.60
Type 2	21.67	14.45	9.63	12.39	7.05
Type 3	8.32	5.55	3.70	12.43	4.35
Type 4	8.58	5.72	3.81	12.60	4.40
Type 5	15.42	10.28	6.85	13.08	5.79

3 ACOUSTIC INSULATION

Tests on acoustic insulation properties of composite slab elements made of timber and pourable WCC are currently performed (December 2015). To give the reader an idea on the acoustic insulation potential of such construction elements, results from earlier investigations (Fadai & Winter 2015) on slab elements made of cross-laminated timber slabs in composite action with glued-on prefabricated cement-bonded woodchip boards (Velox® WS50) are reported here.

3.1 *Sound insulation tests and results*

Acoustic insulation properties for impact and airborne sound were determined and assessed according to governing standards (EN ISO 140-4 1999, EN ISO 140-7/A 2005, EN ISO 717-1 2013, and EN ISO 717-2 2013). The first three test series focused on impact sound insulation – often governing and thus particularly important for wood-based construction – while a fourth test series looked at airborne sound insulation.

The first test investigated a cross-laminated timber (CLT) panel of 6 cm thickness or a surface-related mass of 32 kg/m^2, respectively, and showed a normalized impact noise level reduction of 87 dB. The second series analyzed a CLT panel in composite action with 5 cm Velox® WS50 woodchip panel and a 5 cm self-compacting concrete (SCC) layer on top, with a distributed mass of 180 kg/m^2, and resulted in a normalized impact noise level reduction of 75 dB. In the third test, the construction of the second was complemented with 2 mm fiber board and 7 mm laminate (i.e. also with a minor surface mass increase of approx. 4 kg/m^2) as often encountered in building construction, and resulted in a normalized impact noise reduction of 63 dB.

The fourth test looked at airborne sound insulation of the third test setup. The associated normalized sound level difference amounts to 33 dB.

3.2 *Comparison to building code requirements*

Acoustic insulation requirements differ again from country to country. Most building codes consider different noise protection classes where the noise 'load' is considered, on the one hand, and the noise sensitivity, on the other. For example, the noise protection requirements for the exterior wall of a hospital next to an industrial zone differ from those for a residential building in a calm neighborhood.

For external airborne sound levels up to 64 dB at day and 56 dB at night, respectively, the Swiss code SIA 181 (2006) requires an airborne sound insulation level of 26 dB for low noise sensitivity, 31 dB for average noise sensitivity and 36 dB for high noise sensitivity, respectively. For higher external airborne sound levels, the acoustic insulation demand increases linearly with the external sound level. Comparing these requirements to the result of the fourth test shows that the investigated slab type may be sufficient for sound levels up to 67 dB at day and 59 dB at night, respectively, assuming average noise sensitivity to exterior airborne sound.

For internal airborne sound, SIA 181 (2006) requires insulation levels above values between 42 dB and 67 dB, depending on sound load (i.e. utilization) and noise sensitivity. Moderate sound loads (e.g. from a living room) and average noise sensitivity require a sound insulation level of 52 dB. Considering the result from the fourth test shows that the investigated slab system requires further acoustic insulation improvements for its application as internal floor slab.

For impact sound insulation, SIA 181 (2006) requires sound insulation levels below values between 63 dB and 38 dB, depending on sound load and noise sensitivity. Moderate sound levels (e.g. from a living room) and average noise sensitivity require a sound insulation level of 53 dB. This limit cannot be achieved with the investigated composite slab system which is only just sufficient for low impact sound levels at the source and low noise sensitivity.

3.3 *Measures to improve sound insulation properties*

The sound insulation of massive one-layer structural elements is principally determined by their surface-related mass and their deflection stiffness. For multi-layer structural elements (as investigated here), better sound insulation can be achieved with equivalent mass.

In such mass-spring systems, the sound insulation increases at a rate of 6 dB per octave below the resonance frequency. Above this frequency, sound insulation increases by 18 dB per octave. To achieve suitable sound insulation, the resonance frequency must thus be as low as possible (< 80 Hz). Resonance frequency can be reduced by increasing voids between layers, increasing vibrating mass and decreasing connection stiffness. To avoid cavity resonance, voids have to be correctly insulated acoustically.

The sound insulation of multi-layer slab elements can thus be improved either by increasing their mass or by improving the decoupling of layers. In practice, this is usually attained by pouring relatively heavy screed layers (5-7 cm cement screed) on a soft impact sound insulation board, as often encountered in pure timber construction. Note that, for WCC-based timber construction, the thickness of the cement screed can be reduced.

It becomes evident from the test results that, for airborne sound insulation, interior sound insulation requirements are governing. Also note that the difference between experimental impact sound insulation to the code requirement is smaller than that for internal airborne sound insulation, i.e. acoustic optimization of the slab system for airborne sound insulation is governing.

4 ECO-BALANCE

The results presented here complement a previous eco-balance analysis performed on concrete, timber and timber-concrete composite slabs (Plüss & Zwicky 2014). Design of traditional 9 m span elements was performed using Swiss standards for timber and concrete structures (SIA 262 2003, SIA 265 2003), meeting all requirements at SLS and ULS. Secondary layers (non-structural) have been designed to meet fire resistance, acoustic and thermal insulation requirements. Eco-balance calculations are based on the public eco-impact database of the Coordination of the Federal Services of Building and Real Estate (CFSC 2014). Two replacements of the secondary structure have been considered during the assumed 90 years of service life of the building. Transportation has not been taken into account as its impact is very low and small differences were observed for the different construction methods.

The goal here is to compare these solutions with the timber-WCC slabs, considering the ecological impact per surface unit. In order to guarantee compatibility between the two analyses, calculations consider timber-WCC slabs meeting the dimensioning requirements for a 9 m span. The energy consumption of each timber-WCC slab has been multiplied by the square of the spans' ratio, considering L_{eq} (Table 3). Only Type 2 and Type 5 are presented here, as they are considered to be the most representative solutions for each configuration (embedded and "+/-", respectively). First, focus has been set on the non-renewable primary energy for fabrication and evacuation.

Considering the load-bearing structure only, timber-WCC slabs appear to be a significantly more energy-consuming solution (Figure 4, left). This is due to the considerably more important volume of WCC compared to a regular concrete solution, for example, and its relatively high content in cement. Looking at WCC solutions, Type 5 is significantly more energy-consuming than Type 2 due to its weaker bending strength at ULS, according to experimental results. Emission of greenhouse gases (EGG) are not presented as they gave qualitatively similar results.

However, for wood and WCC materials, combustion allows to recover energy at the end of life of the construction material. A former study (Zwicky 2015) shows the calorific value that can be recovered from the combustion of WCC1 (6 MJ/kg) and WCC5 (3 MJ/kg). A calorific value of 9 MJ/kg has been used for timber (Winter & Fadai 2015). If the recovered energy is deduced from the primary non-renewable energy for fabrication and evacuation, WCC solutions appear less energy-consuming, even allowing a negative energy balance (Figure 4, right).

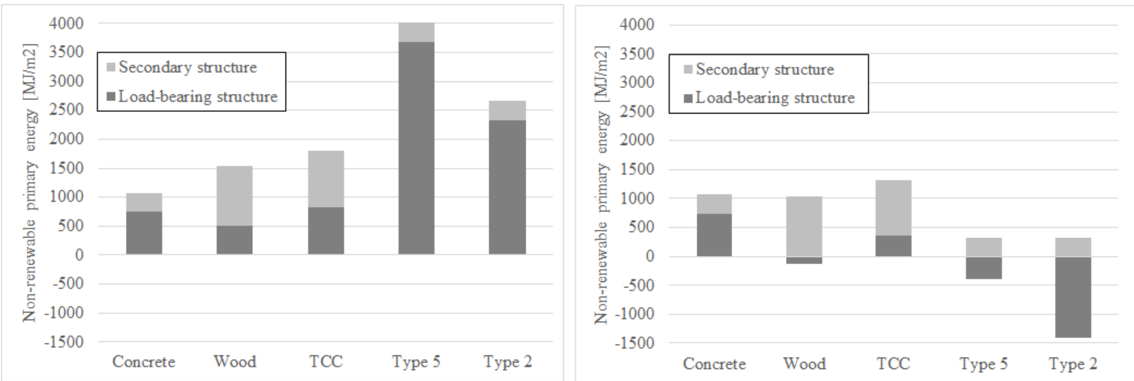

Figure 4. Non-renewable primary energy: fabrication and evacuation (left). Taking into account recovered energy by combustion (right).

CONCLUSION AND PERSPECTIVES

Even though efforts still need to be made to improve the industrial processing of WCCs, experimental results on slabs show an interesting behavior. The tested configurations satisfy SLS requirements for variable actions for several types of useable areas. ULS requirements seem more difficult to be satisfied. For the tested sections, a span reduction is needed. Though, a section with WCC poured around timber beams seems more promising than the "+/-" surface connector. However, more experimental tests must be conducted to give a proper conclusion. Furthermore, more experimental configurations are to be tested such as continuous slabs. A numerical model is also being investigated to reproduce the experimental data and help for future design.

In terms of acoustic insulation, building codes demand to satisfy three different noise protection requirements. Results show an acceptable protection for external airborne sound level. However, for internal airborne sound and impact sounds, further acoustic insulation improvements have to be implemented, such as adding a relatively heavy screed layer on top of the WCC slabs. Internal airborne sound insulation is governing the acoustic optimization of the slab.

Studying the necessary non-renewable primary energy of different floor solutions, WCC solutions appear significantly more energy-consuming to produce. However, once the potential energy recovering is taken into account, the energy balance is more interesting for WCC solution than for concrete slabs, regarding this ecological criteria.

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