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Wall elements made of timber and wood-cement compounds – building-physical properties and structural performance

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ABSTRACT: Cement-bonded wood-based materials (wood-cement compounds, WCCs) are used in construction since more than 100 years. Until today, they are chiefly used non-structurally where their good fire resistance, thermal and acoustic insulation and thermal mass are combined with a relatively low density. Main application forms of WCCs are prefabricated panels but pourable mixes are also available. WCCs allow creating light-weight structural elements if applied, for example, in composite timber-WCC elements. Such multi-functional elements cannot only fulfill a structural task but provide also building-physical performances. This paper reports on test results for thermal insulation and specific heat capacity of WCCs and timber-WCC walls, also comparing them to performance features of other construction materials and code requirements. The paper also presents results from full-scale buckling tests, and evaluates the suitability of structural design approaches. This contribution is complemented by companion papers on mechanical properties of WCCs and performance features of timber-WCC slab elements.

1 INTRODUCTION

Wood-cement compounds (WCCs) have a high potential for their application in building construction as very light-weight, economically and ecologically performing concrete-like structural material (Fadai & Winter 2015a). WCCs should principally be applied in structural elements with composite action, e.g. together with timber or other light-weight materials (Macchi & Zwicky 2014a,b, Zwicky 2015a), to not unnecessarily increase overall weight.

WCCs should definitely not be regarded as substitution for regular concrete, as their stiffness and strength are rather low (Zwicky 2015a, Macchi & Zwicky 2016).

WCCs are particularly suited for creating multifunctional structural elements, i.e. construction elements which not only fulfill a load-bearing task but also provide building-physical performance features, such as fire resistance, thermal and acoustic insulation, and thermal mass. The consideration of WCCs in construction elements of any kind should also have a positive effect on the eco-balance of buildings (Plüss & Zwicky 2014).

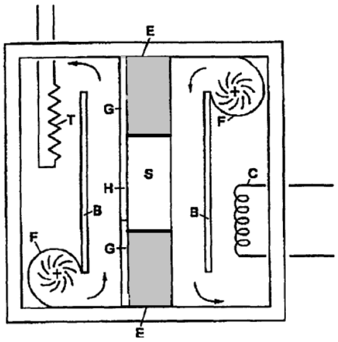
This paper looks into the potential performance features of WCC-based wall elements. It provides detailed information from laboratory testing for thermal resistance and specific heat properties of WCCs and timber-WCC wall elements. Furthermore, the paper reports and evaluates results of full-scale buckling tests on wall elements conceived for three- and six-story buildings. Suitability of associated structural design approaches is also discussed in detail. The contribution is concluded by generally assessing the potential of this new construction material. This contribution on timber-WCC wall elements is complemented by companion papers on recipe development and fresh mix properties of WCCs as well as associated short- and long-term mechanical properties (Macchi & Zwicky 2016), and on structural, acoustic insulation and ecological performance features of timber-WCC slab elements (Eymard & Zwicky 2016).

2 BUILDING-PHYSICAL PROPERTIES OF WCC-BASED CONSTRUCTION ELEMENTS

2.1 *Thermal insulation*

2.1.1 *Test procedure and specimens*

Thermal insulation (or thermal conductivity, respectively) of wall elements containing WCC only or timber and WCC, respectively, was determined in analogy to EN 1934 (1998). In such tests, the total heat flow per surface and time unit is determined for a given temperature between two faces of a test specimen allocated between a hot and a cold chamber, Figure 1.



B air guide plate
C cooling coil
E lateral face insulation
F ventilator
G protective plate
H heat flow meter
S specimen
T electrical heater

Figure 1. Thermal resistance measurement by hot box method (EN 1934 1998).

The test series covered two different WCC recipes with two different target densities, and two different types of timber grid reinforcements. Every test series consisted of three specimens, resulting in a total of twelve specimens to be tested.

Table 1 shows nominal dimensions, mass, density and illustrative images of the test specimens. Figure 2 shows the two different timber grids applied in the two wall types. The 24 cm thick walls had two layers of 60x60 mm^2 vertical battens, spaced at 126 mm, while the 20 cm thick walls had two layers of 40x40 mm^2 vertical battens, spaced at 100 mm. Both wall types had one central layer with three horizontal battens of 24x48 mm^2.

The test specimens were stored in the laboratory prior to the tests in June/July 2015, at a temperature of 23°C to 29°C and a relative humidity of 50% to 60%. The hot box tests were performed until a stationary heat flow was obtained and took at least 24 hours.

2.1.2 *Results and evaluation*

Measurement accuracy for thermal resistance depends on homogeneity and humidity of the specimen (EN 1934 1998), usually attaining ±5%. The higher the inhomogeneity in the specimen, the more complex is the prediction of measurement accuracy. If all measurement inaccuracies for moderately inhomogeneous walls acc. to EN 1934 (1998) are added, the measurements should still show an accuracy of approx. 12.5%. Table 2 shows results for average specimen temperature, thermal resistance R_t and global thermal conductivity $\lambda_t = t/R_t$ where t is the wall thickness.

Table 1. Test results from thermal resistance measurements acc. to EN 1934 (1998).

Specimen	Length	Width	Thickness	Mass	Density	AVG (COV)	Appearance
	cm	cm	cm	kg	kg/m^3	kg/m^3	
M1 WCC1-1	50	50	24	38.45	641	634 (1.2%)	
M1 WCC1-2				38.05	634		
M1 WCC1-3				37.55	626		
M2 WCC1-1			20	31.55	631	631 (1.4%)	
M2 WCC1-2				32.00	640		
M2 WCC1-3				31.10	622		
WCC1-1	30	30	6	3.35	619	662 (5.6%)	
WCC1-2				3.67	680		
WCC1-3				3.71	686		
WCC5-1				6.49	1’201	1'223 (2.4%)	
WCC5-2				6.54	1’212		
WCC5-3				6.79	1’256		

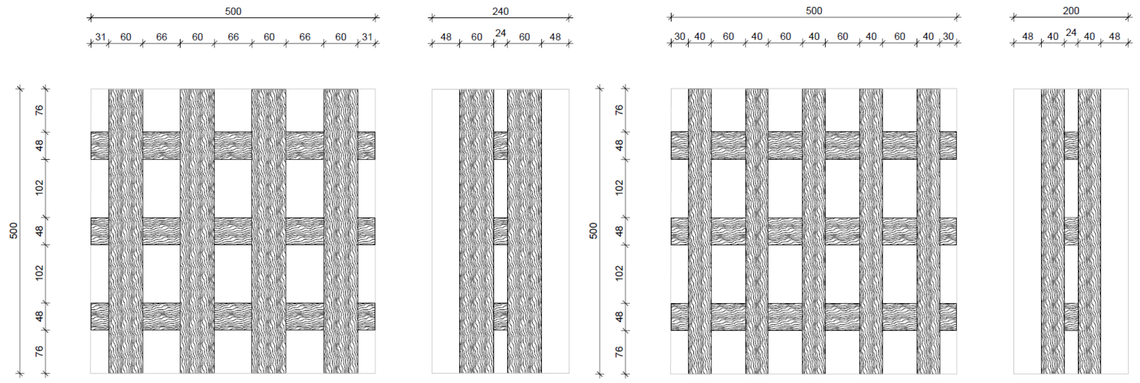


Figure 2. Timber grids in wall of 24 cm thickness (left) and 20 cm thickness (right).

It becomes evident from the results in Table 2 that their variation is acceptable. It can further be noted that the thermal resistance of the two different wall types are essentially the same, considering the attainable measurement accuracy (see above). As it can be seen from Figure 2, the only difference between the two wall types is the thickness of the layers with vertical battens. The small difference in thermal resistance between the two test series M1 and M2 therefore can be attributed to the differences in geometry and material distribution in this layer, i.e. the larger volume of timber available in the 24 cm wall M1 slightly increases the thermal resistance. However, as the thermal resistance increase remains very limited but the timber thickness increase is much more significant, it must be concluded that the timber battens essentially act as thermal bridges. This is also reflected by the increase of the average overall thermal conductivity.

This can also be deduced if the results of test series WCC1 are applied to series M1 and M2. Considering a linear extrapolation, it can be shown that the exterior layers in pure WCC1 (covering between 40% (M1) and 48% (M2) of the total thickness, respectively) provide ca. 58% of the thermal resistance. The central layer (occupying between 10% (M1) and 12% (M2) of the total thickness, respectively) with a mix of WCC1 and horizontal timber battens offers approx. 35% of the thermal resistance. The layers with a mix of WCC1 and vertical timber battens (corresponding to 50% (M1) and 40% (M2) of the wall thickness, respectively) only deliver 5% to 8% of the thermal resistance. Essentially, it is the layers with a considerable ratio of WCC, i.e. the outermost and the central layer, that provide the thermal resistance of the wall element.

Table 2. Results from hot box tests on mixed timber-WCC and pure WCC wall elements.

Specimen	Thickness *t*	T_{spec}	R_t	AVG (COV)	λ_t	AVG (COV)
	cm	°C	m^{2}K/W	m^{2}K/W	W/mK	W/mK
M1 WCC1-1	24	24.31	0.81	0.81 (3.7%)	0.30	0.30 (3.7%)
M1 WCC1-2		23.74	0.78		0.31	
M1 WCC1-3		23.87	0.84		0.29	
M2 WCC1-1	20	26.01	0.83	0.79 (8.8%)	0.24	0.25 (9.2%)
M2 WCC1-2		25.77	0.83		0.24	
M2 WCC1-3		24.93	0.71		0.28	
WCC1-1	6	25.89	0.3	0.29 (3.4%)	0.20	0.21 (3.5%)
WCC1-2		24.27	0.29		0.21	
WCC1-3		24.70	0.28		0.21	
WCC5-1	6	25.88	0.15	0.13 (11.5%)	0.40	0.45 (11.1%)
WCC5-2		25.48	0.13		0.46	
WCC5-3		22.65	0.12		0.50	

2.1.3 *Comparison to other construction materials and to building code requirements*

The thermal conductivities for pure wood-cement compounds (series WCC1 and WCC5 in Table 2) correspond well with values for other types of light-weight concrete (Sengul et al. 2011).

A regular expanded clay aggregate concrete, with a density between 600 kg/m^3 and 700 kg/m^3, usually provides λ_t-values between 0.20 W/mK and 0.23 W/mK, while 0.46 W/mK may usually be assumed for a density of 1’200 kg/m^3. Note that the thermal resistance of WCCs is provided by its porosity, being created by the resin contained in the spruce sawdust that works as an air-entraining agent (Macchi & Zwicky 2014a).

Thermal resistance requirements for wall elements may differ considerably from country to country. The UK and Switzerland have among the most severe requirements and demand a thermal resistance between approx. 5.5 m^2K/W and 6 m^2K/W for an external wall. Using the lighter-weight WCC1 (Table 2) only to provide this thermal resistance would require wall thicknesses between 1.14 m and 1.22 m. As these dimensions are rather unrealistic, the application of suitable insulation material in the construction of WCC-based wall elements is still necessary.

2.2 *Heat storage capacity*

Heat storage capacity or specific heat capacity, respectively, of construction materials may be exploited in dynamic verifications of thermal performance of buildings and is also needed to assess the hygric behavior of construction elements (Fadai & Nackler 2015). The specific heat capacity corresponds to the thermal energy required to heat 1 kg of a material by 1 K.

Specific heat capacity tests were performed on the same WCC mixes as analyzed before w.r.t. thermal resistance. The test setup is based on the consideration that mixing two different materials with two different temperatures launches a heat exchange. It is assumed that the warmer material emits the same heat quantity as is absorbed by the cooler material. The result of this heat exchange is a mixing temperature lying between the two initial temperatures. The mixing temperature thereby depends on the difference of the two specific heat capacities involved.

Cubic samples of WCCs with dimensions of 4x4x16 cm^3 were submerged in heated water contained in an isolated box. The WCC samples were cooled to 5°C prior to the test, and their mass was measured shortly before the test. Mass and temperature of the water were also measured prior to the test. After submerging the samples in the heated water, continuous measurements of the temperature of water and WCC were performed until compensation temperature was reached.

The specific heat storage capacity can then be determined by considering that the increase or decrease, respectively, of material temperature is proportional to the specific heat capacity:

$$m_{water} \cdot \Delta T_{water} \cdot c_{water} = m_{WCC} \cdot \Delta T_{WCC} \cdot c_{WCC} \tag{1}$$

where m = mass, ΔT = difference to mixing temperature, and c = specific heat capacity. Table 3 summarizes the test results on WCCs and provides comparison values of other materials.

Table 3. Densities and specific heat capacities of tested WCCs and other materials.

Material	Density	c
	kg/m^3	kJ/(kgK)
WCC1	795	1.87
WCC5	1’468	1.35
WCC chip board (Fadai & Winter 2015b)	560-750	1.74-1.64
Spruce (Fadai & Winter 2015b)	430	1.6
Wood fiber board	110	2.1
Plywood panel	800	2.7
Concrete	2’400	0.9-1.1
Expanded clay concrete	1’000	0.9-1.1
Rock wool	90-150	1.0
Foam glass	125-150	0.8
Expanded polystyrene	15-30	1.4
Steel	7’850	0.5
Air	1.2	1.0
Water (at 10°C)	1’000	4.19

WCC1 shows a surprisingly high specific heat capacity while a value between concrete and spruce should be expected. This can probably be attributed to a relatively high humidity content, as also reflected by the rather high density. The heat capacity of WCC5 seems plausible. Both provide more specific heat capacity than regular light-weight concrete of comparable density.

The measured specific heat capacities of the WCCs analyzed here are comparable to other experimental results for WCC insulation and noise protection chipboards (Fadai & Winter 2015b), tested in the same manner. As shown elsewhere (Fadai & Nackler 2015), WCC-based wall construction allows to attain thermal performances comparable to concrete or honeycomb masonry w.r.t. operation temperatures, annual heating energy demand and annual overheating hours.

2.3 *Acoustic insulation*

Tests on acoustic insulation properties of composite slab elements made of timber and pourable WCC are currently performed (December 2015). Acoustic insulation tests on wall elements are reserved for future developments. Test results for acoustic insulation properties of timber-WCC composite slab elements are reported and discussed by Eymard & Zwicky (2016).

3 LOAD-BEARING CAPACITY OF TIMBER-WCC WALL ELEMENTS

3.1 *Conceptual considerations*

3.1.1 *Fire protection requirements*

Escape routes in buildings shall be constructed with non-combustible materials. If wooden elements shall be used in such a context, they have to be totally encapsulated by non-combustible material and the structure in itself has to contain no voids. Prefabricated WCC panels are already widely used as fire cladding, as they are usually classified as limited combustibility material (Fadai & Winter 2015a), i.e. class A2 according to EN 13501-1 (2002).

This property could also be confirmed in combustibility tests on pourable WCCs (Zwicky 2015b). It could be shown that, even though WCCs ignite at approx. 210°C (i.e. at wood gasification temperature), the combustion stops if the specimen is removed from the furnace. Hence, the material can be considered difficultly inflammable. Exhaust fumes produced during combustion do not contain particular pollutants, and the calorific values provided by WCCs of 2.8 MJ/kg (WCC5) to 5.9 MJ/kg (WCC1) are high enough to be interesting for thermal recycling. The high ash content of 56% (WCC1) to 69% (WCC5) requires mixing WCCs with other combustibles.

3.1.2 *Economic considerations*

By using pourable WCCs in the production process, the problem of filling the voids between timber elements can be alienated. As timber members with larger dimensions – as usually needed in structural elements with stability problems – are normally more expensive in terms of price per volume, the requirement of filling the voids in the element can be exploited to brace cheaper timber elements with smaller cross-sections with regard to buckling.

3.2 *Buckling tests*

To determine the load-bearing capacity of slender structural wall elements, 2nd order effects (i.e. buckling) have to be considered for developing a structural design approach. As the buckling load is a non-linear function of the element length and of structural boundary conditions, experimental verification should be performed on full-scale elements.

3.2.1 *Test specimens and test setup for buckling tests*

The buckling test specimens had a width of 500 mm, contained the same timber grids and had the same thicknesses as in the thermal resistance tests, Figure 2. Two different timber grids combined with WCCs 1 and 5 resulted in four test series of full-scale buckling tests, with three specimens each, for pure normal force loading. The buckling length was chosen at 3 m, representative for residential buildings. Combined normal and shear force loading will be tested in the future.

This conceptual design provides the advantage of timber components being completely encapsulated. It also offers increased flexural inertia, as the vertical battens of standard C24 timber quality (SIA 265 2013) are stabilized by the WCC matrix and form a composite section with them. Average compressive strength from three specimens amounted to 1.5 MPa (WCC1) and 5.6 MPa (WCC2). The design values of elastic moduli of 530 MPa (WCC1) and 1’580 MPa (WCC5) – assuming 10% COV and being 58% of the average – are very low (Zwicky 2015a) but provide sufficient stabilization. Still, the timber battens have to provide considerable inertia.

The preliminary structural design of the specimens targeted wall elements of 3- and 6-story buildings with estimated wall loads of 260 kN/m and 600 kN/m, respectively. The preliminary design of the timber sections was based on the directives of SIA 265 (2013) and assumed a rigid connection between the layers with vertical timber battens. Upper and lower bounds were established by considering or neglecting the WCC contribution to normal force resistance.

3.2.2 *Test results and evaluation*

Table 4 shows maximum compression loads $R_{exp,i}$ and associated deflections $w(R_{exp})$. The deflections have been corrected by the Southwell Plot method to include initial deformation.

The results show that the variability of buckling loads is very low but associated horizontal deflections (and thus, bending moments) vary very much, except for series WCC5fin. Figure 3 illustrates this point with the experimental behavior of test series WCC1-fin as an example.

Table 4. Results of full-scale buckling tests on timber-WCC wall elements.

Specimen	Thickness	$R_{exp,i}$	AVG (COV)	$w(R_{exp})$	AVG (COV)	R_k	r_d	n_d
	cm	kN	kN	mm	mm	kN	kN/m	kN/m
WCC1fin-1	20	-261.3	-266 (6.5%)	13.8	22.8 (45%)	-232	-309	-260
WCC1fin-2		-251.4		20.7				
WCC1fin-3		-284.9		34.0				
WCC5fin-1		-457.2	-441 (13.1%)	36.9	38.5 (6%)	-349	-465	
WCC5fin-2		-489.3		37.3				
WCC5fin-3		-376.9		41.4				
WCC1gros-1	24	-438.5	-497 (10.9%)	30.0	27.4 (28%)	-421	-561	-600
WCC1gros-2		-546.0		18.8				
WCC1gros-3		-507.0		33.4				
WCC5gros-1		-695.4	-689 (1.7%)	3.6	9.4 (58%)	-603	-804	
WCC5gros-2		-676.3		10.1				
WCC5gros-3		-696.7		14.4				

3.3 *Structural design approach*

3.3.1 *Statistical evaluation of test results*

SIA 265/1 (2009) provides a statistical approach to determine a characteristic value of a structural resistance R_k, i.e. a 5% percentile. The characteristic value R_k (as a basis for determining a design value R_d) is expressed as a fraction of the average resistance and considers the number and the variability of test results. A minimum coefficient of variation of 10% has to be considered, being obviously governing for the first and last test series. The fraction parameter between characteristic and average resistance assumes a log-normal distribution of strength.

Table 4 shows buckling loads R_k determined according to this approach. Fuzziness in the resistance model and transposing experimental results to practical conditions requires considering a total partial safety factor of 1.5 (SIA 265 2013) when determining a design value R_d. Considering specimen width (section 3.2.1), Table 4 displays available resistances r_d for wall loads. Comparing these to the initially assumed wall loads (section 3.2.1, Table 4) shows that only the thicker WCC1 wall is slightly too weak and would require a somewhat higher timber content or a decrease of applicable load of approx. 10%. Note that long-term loading or a more severe moisture exposure (class 2, i.e. partly protected or directly weathered) require a considerable reduction of the available resistance (SIA 265 2013) which was not investigated in the present tests.

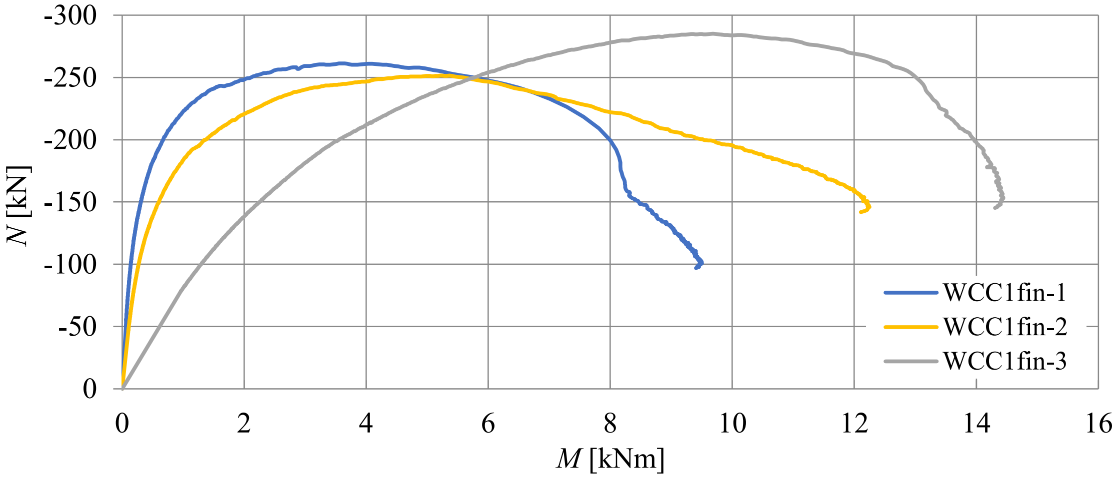


Figure 3. Typical moment-normal force behavior of timber-WCC walls in buckling tests.

3.3.2 *Analytical determination of buckling resistance*

For the re-calculation of buckling resistances, the applicability of structural design methods of timber and concrete codes was investigated. By applying the SIA 265 (2013) approach for determining the buckling resistance of a compressed timber element, it could be deduced that cracking of WCC and flexibility of the connection between vertical timber battens should principally be considered to find correspondence between analytical and experimental results. Yet, having test results available for one buckling length only was not sufficient to determine all parameters (i.e. influences of connection stiffness and straightness of timber components).

The buckling verification of compressed reinforced concrete members according to SIA 262 (2013) is performed with M-N interaction diagrams. As the structural behavior is non-linear (2nd order effects), all calculations are performed on design value level. Assuming different strain planes, considering rigid reinforcement bond, and integrating stress distributions return the specific points of an interaction diagram. A linear elastic perfectly plastic constitutive law in compression was assumed for WCCs, with elastic moduli acc. to section 3.2.1, and design compressive strengths of 0.7 MPa (WCC1) and 2.8 MPa (WCC5), respectively, while tensile strength was neglected. For timber, a linear elastic behavior until brittle failure was assumed, with an elastic modulus of 11 GPa and design strengths of 12 MPa in compression and 8 MPa in tension (SIA 265 2013). The lines in Figure 4 show associated results.

Bending moments, $M_d = -N_d \cdot e_d$, are considered through normal force eccentricities, subdivided into initial eccentricity e_{0d} (i.e. imperfections), 1st order eccentricity e_{1d} at column ends, and eccentricity e_{2d} due to flexural deformations. SIA 262 (2013) determines e_{0d} as a function of the buckling length or the effective reinforcement depth. Flexural deformations are determined by integrating the curvatures χ_d over the column length. In a first step, $\chi_{d,max}$ is determined by assuming that yield strain is reached in both reinforcement layers. Here, this means assuming that yield strains in tension and compression are attained at the outermost fibers of the battens. The resulting point M_d-N_d is compared to the available resistance (symbols • in Figure 4). Secondly, $\chi_{d,max}$ is refined by considering the value associated to N_{Rd} from the first step (symbols ■ in Figure 4). The comparison between experimental and analytical results in Figure 4 shows that the adaptation of the relatively simple approach of SIA 262 (2013) produces excellent agreement between analytical and experimental results. Differences can be attributed to underestimating timber strengths.

4 CONCLUSIONS

Wood-cement compounds are well suited for industrial production and transportation as they are light-weight, pourable, self-compacting and relatively cheap (Macchi & Zwicky 2016). WCCs

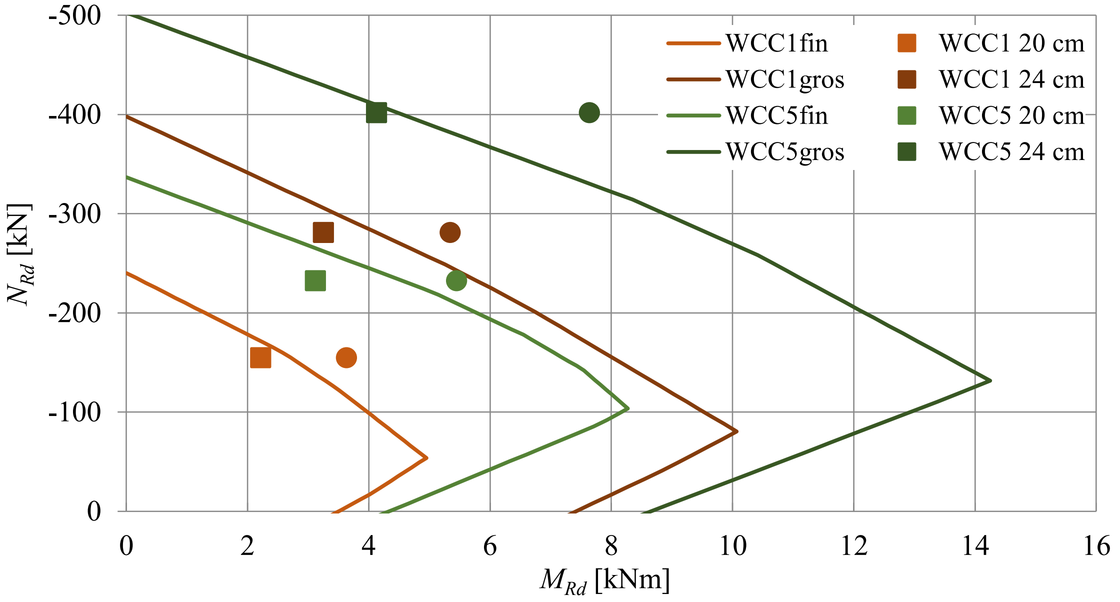


Figure 4. Analytical M-N interaction diagrams and comparison to experimental results.

provide thermal insulation comparable to regular light-weight concrete, and contribute to acoustic insulation. They offer reasonable specific heat capacity and can serve as fire protection cladding.

These non-structural features of WCCs come at the prize of reduced mechanical properties. In compressed wall elements, WCCs can be used to stabilize cheap timber elements with smaller cross-sections, and they also contribute to the overall buckling resistance (20% and 13% for WCC1 elements and 43% and 31% for WCC5 elements, respectively, in the present tests).

Current concrete design approaches (SIA 262 2013), based on sound mechanics, seem best suited for the structural design of such multi-functional (or hybrid) timber-WCC wall elements. Influences of long-term loading and moisture exposure should be considered.

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