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ASSESSING THE EFFECTS OF BOUNDARY CONDITIONS ON THE VIBRATIONAL COMFORT OF ON-SITE TIMBER-CONCRETE COMPOSITE FLOORS

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ABSTRACT: The design of timber-concrete composite structures (TCC) is usually governed by the serviceability rather than the strength, particularly for medium to long span floors. In terms of users' comfort, issues can come from vibrations of TCC floors. Indeed, discrepancies are usually observed between the calculations at the design stage and the on-site measurements, due to the gap between design assumptions and in service conditions (boundary conditions, partition walls, floor finishing…). This paper focuses on the comparison between analytical, experimental (on-site and laboratory) and numerical approaches in the assessment of vibration performance of a TCC floor to obtain the frequencies corresponding to different boundary conditions. Results show unexpected differences between analytical models and laboratory experimental measurements for simple boundary conditions. A new equation is being developed to adapt the design of the TCC floors of the full-scale building under study, which presents the specificity of a TCC floor with overhang. A FEM model is developed to assess the validity of the proposed analytical equation.

KEYWORDS: timber-concrete floor, overhang, vibration assessment, multi-approach analysis

1 INTRODUCTION

TCC is known for improving the vibrational comfort for users compared to a timber floor. Nevertheless SLS (vibration) is still a dimensional criterion. The next version of EC5 should include a new design method, modifying both the assessment of the fundamental frequency (proposing an equation for semi-rigid support for example) and the limit criteria ($4 \cdot f_w$, 7 or 8Hz depending on the required performance level) [1]. Yet literature suggests that while analytical models and laboratory experiments fit well together (on dynamical properties), they are too conservative compared to the dynamic properties observed in real buildings [2, 3], and therefore force oversized designs to meet the SLS criteria.

The objective of this work is to assess the influence of boundary conditions (support conditions, overhang, partition walls and floor finishing), by combining modelling (analytical and numerical) and experimentation (laboratory and on-site) on a case study presenting particularities about overhangs. Indeed, TCC floors in the building under study (ESB) have one overhang, and they are supported by a truss structure with an overhang portion itself. The laboratory tests are conducted on two TCC specimens that are as identical as possible as those in the full-scale building (where on-site measurements were conducted in the past [4]). Yet, as dimensions and materials could not be exactly the same, direct comparisons between on-site and laboratory results are not possible. Moreover, due to current limitation in the numerical model (only rigid timber/concrete interface), it cannot be directly compared to laboratory and on-site measurements. For these reasons, and because an evolution of an analytical equation is proposed in this paper, analytical calculations serve as the reference to which numerical, laboratory and on-site are successively compared. In the following, once the case study is described (§2), analytical state of the art and proposed evolution necessary for the case study (overhang combined with 2D behaviour) are detailed in §3. Experimental (§4) and numerical (§5) works are then explained.

2 DESCRIPTION OF STUDIED TCC FLOORS

The case study introduced in this paper is the large-span TCC floor of the ESB building, built in 2011 and presenting some interesting features for the aim of this work. Several experimental campaigns have been performed on the on-site building and parallel laboratory tests have been conducted to better understand the structural response of the floor and propose an analytical and numerical approach to better design such a TCC floor. Two TCC specimens have been built at a smaller scale but as identical as possible as the floors of the full-scale building. The characteristics of both building and specimens are detailed in the following.

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2.1 ON-SITE BUILDING

The expansion of the ESB building is constituted by three floors, realized with two parallel trusses in glue-laminated timber (Figure 1). The trusses are around 45m long and 13m height with a one-side overhang of about 9 to 10m. The architectural design of both trusses is the same, but timber cross-sections are different because of the slightly different supported loads.
Figure 2 shows that each truss is simply supported in three points (one is V-shaped): the part between the two vertical columns (Section C) is linked to the existing concrete building, the part with the overhang (Sections A and B) is more flexible because of the lack of a closed ground floor. Some partition walls have a structural function to assure the wind bracing resistance.

Figure 1: *3D representation of the ESB expansion building (overhang on the right)*

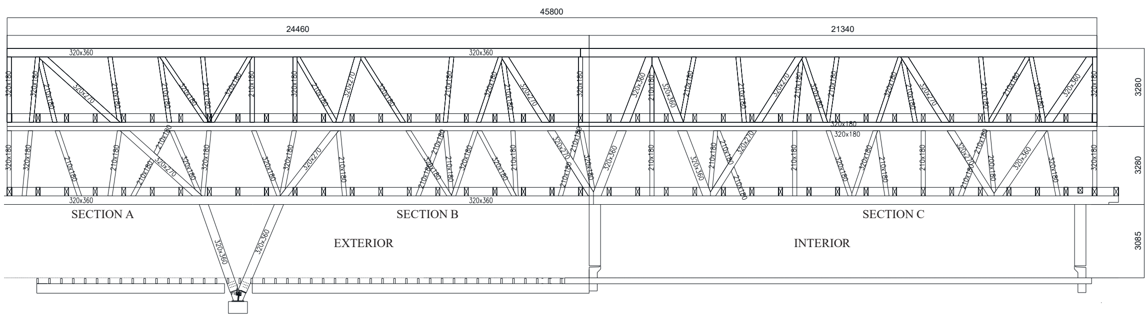

Figure 2: *Geometry of the South truss (overhang on the left side), with the biggest cross-sections and loads*

The South and North trusses are linked together through TCC floors object of the study. The total span of the floor is 9.6m, including a walkway of 2.0m, forming an overhang (Figure 3), also visible in Figure 1.

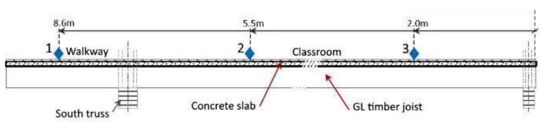

Figure 3: *Geometry of the TCC floor. The two supporting trusses with different cross-sections are visible. 1, 2 and 3 are the sensors positions (§4.2)*

The cross section of the TCC floor is represented in Figure 4 and the main characteristics are detailed in Table 1.

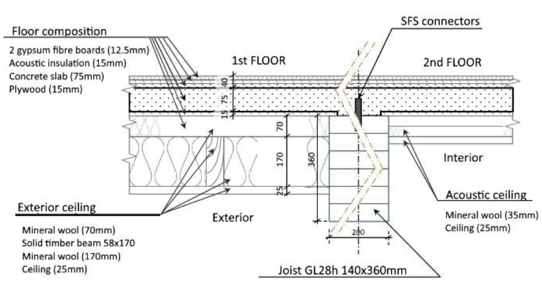

Figure 4: *Cross-section of the TCC floor for the first floor (left) and the second floor (right)*

Table 1: *Geometric and mechanical properties of materials used for the TCC floors (from design papers and Eurocodes)*

Element	Material property	Symbol	Value
GL28h timber joists	Width	b_2	140mm
	Height	h_2	360mm
	Effective width	b_{eff}	1.2m
	Total span	L_{tot}	9.6m
	Overhang span	L_f	2.0m
	Joists spacing	e	1.2m
	Mean density	ρ_{m2}	460kg/m³
	Young's modulus	E_{m2}	12600N/mm²
Plywood	Thickness	h_3	15mm
	Mean density	ρ_{m3}	580kg/m³
Concrete slab C20/25	Thickness	h_1	75mm
	Mean density	ρ_{m1}	2200kg/m³
	Young's modulus	E_{m1}	29962N/mm²
Connector	Diameter	d	7.5mm
	Length	l	165mm
	Mean distance between connectors	s_p	344mm
Non-structural elements	Ceiling and floor finishing	m	514kg

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2.2 LABORATORY SPECIMENS

The laboratory tests have been performed on two specimens as similar as possible as the on-site TCC (§2.1). The dimensions of the TCC specimens are represented in Figure 5.
Before assembly, the mass, density, moisture content and longitudinal Young modulus (through vibration method) of each glulam beams have been measured. A 20μm polyethylene protective film between the concrete slab and the timber (beam and plywood) was used to avoid excessive humidification.

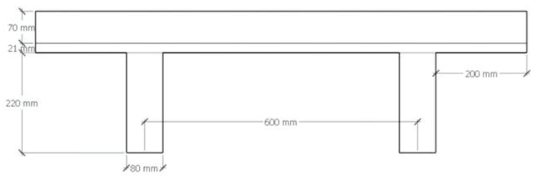

Figure 5: *Geometry of the two laboratory TCC specimens*

The mechanical characteristics of the specimens are detailed in Table 2. For the Young's modulus of timber and its density, the mean values from the four timber joists are given.

Table 2: *Geometric and mechanical properties of materials used for the laboratory specimens*

Element	Material properties	Symbol	Value
GL24h timber joists	Width	b_2	80mm
	Height	h_2	220mm
	Effective width	b_{eff}	540mm
	Total span	L_{tot}	6.0m
	Overhang span	L_f	1.0m and 2.0m
	Joists spacing	e	0.6m
	Mean density	ρ_{m2}	473kg/m^3
	Young's modulus	E_{m2}	11224N/mm²
Plywood	Thickness	h_3	21mm
	Mean density	ρ_{m3}	580kg/m^3
Concrete slab C25/30	Thickness	h_1	70mm
	Mean density	ρ_{m1}	2157kg/m^3
	Young's modulus	E_{m1}	31476N/mm²
Connector	Diameter	d	7.5mm
	Length	l	100mm
	Mean distance between connectors	s_p	231mm
Non-structural elements	Floor finishing and partition wall	m	30kg

3 ANALYTICAL APPROACH

3.1 EQUATIONS STATE-OF-THE-ART

The current version of EC5-1-1 [5] suggests to assess the vibrational comfort of a floor following three steps:

1. Calculation of the fundamental frequency f_1 (Hz);
2. Calculation of the maximum deflection w_{1kN} (mm) due to a vertical static point-load F=1kN;
3. Calculation of the velocity v (m/N s²) as a structural response due to a unit impact force

The paper will be only focused on the calculation of the fundamental frequency. The proposed calculation of this parameter is given from Equation (1):

$$f_1 = \frac{\pi}{2L^2}\sqrt{\frac{(EI)_L}{m}} \tag{1}$$

where L is the floor span, in m, $(EI)_L$ is the bending stiffness along the floor span par meter width, in Nm²/m, and m is the floor mass per unit area, in kg/m².
The velocity criterion is used for single span floors having a fundamental frequency exceeding 8Hz, that are approximatively rectangular in plan and are supported by rigid supports [6]. Equation (1) is a simplified version of the flexural behaviour of a rectangular orthotropic plate (LxB) on supported edges, whose equation takes into account the elastic constant D in both directions, along and transverse to the floor span (Equation (2)) [7].

$$f_{m,n} = \frac{\pi}{2L^2\sqrt{\rho}}\sqrt{D_x m^4 + 2D_{xy}m^2n^2\left(\frac{L}{B}\right)^2 + D_y n^4\left(\frac{L}{B}\right)^4} \tag{2}$$

Even if EC5-1-1 does not specify this, Equation (1) can only be used when the transversal bending stiffness $(EI)_B$ is not exceeding 1% of the longitudinal bending stiffness $(EI)_L$. This means that the approximated value of the fundamental frequency from Equation (1) is given for a one-way spanning floor (1D behaviour), having a negligible effect of transversal bending stiffness (low $(EI)_B$ and/or large floor width B). The EC5 National Annex of Finland [8] suggests using the complete equation to better assess the fundamental frequency of a two-way spanning floor (2D behaviour) on supported edges (Equation (3)).

$$f_1 = \frac{\pi}{2L^2}\sqrt{\frac{(EI)_L}{m}}\sqrt{1+\left[2\left(\frac{L}{B}\right)^2+\left(\frac{L}{B}\right)^4\right]\frac{(EI)_B}{(EI)_L}} \tag{3}$$

As Equation (1) is based on some strict assumptions and validated on floors having a span not exceeding 4.5m, the calculation of fundamental frequency is usually quite far from the real measured one from experimental results [2, 3]. The provisional version of the future EC5 [1] includes lots of improvements to adapt and generalize Equation (1), as indicated in Equation (4).

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$$f_1 = k_{e,1} k_{e,2} \frac{\pi}{2L^2} \sqrt{\frac{(EI)_L}{m}} \quad (4)$$

First of all, the consideration of the two-way spanning (2D) behaviour of a floor to consider the effect of the transverse floor stiffness has been added, through the factor $k_{e,2}$, given in Equation (5).

$$k_{e,2} = \sqrt{1 + \left(\frac{L}{B}\right)^4 \frac{(EI)_B}{(EI)_L}} \quad (5)$$

The equation given for $k_{e,2}$ is a simplification of Equation (3), neglecting the $(L/B)^2$ term. This is similar to the current approach used into the National Annex of Austria [9], to be used when the ratio between transversal and longitudinal bending stiffnesses is higher than 5%. Nevertheless, no specification concerning this ratio is given in the future version of EC5. The presence of a double span floor is also considered in prEN EC5-1-1 [1] through the factor $k_{e,1}$. The Annex K has to be considered if the floor configuration is more complex. Finally, the stiffness of the supports has been introduced to include floors supported by elastic beams. The suggested equation in prEN EC5-1-1 (Equation (6)) is adapted from [10].

$$\frac{1}{{f_1}^2} = \frac{1}{f_{1,rigid}^2} + \frac{1}{f_{1,beam1}^2} + \frac{1}{f_{1,beam2}^2} \quad (6)$$

Considering the boundary conditions, neither the current version of EC5 [5] nor the provisional version of the future EC5 [1], mention the possibility to have other supports than the isostatic ones (pin/roller). In the literature, some coefficients have been proposed to consider the fixed/pinned, the fixed/fixed, the fixed/free (cantilever) conditions [11, 12, 9]. In Equation (1) the coefficient $\pi/2$ is substituted by $\lambda^2/2\pi$, also called C_B. The same approach is suggested into the National Annex of Austria, by multiplying Equation (1) by a coefficient $k_{e,1}$, different from the $k_{e,1}$ of the future EC5.

Table 3: *Comparison between coefficients proposed to adapt Eq. (1) to different ends conditions*

Ends conditions	λ [11]	C_B [12]	$k_{e,1}$ [9]
Pin-roller	π	1.57	1
Fix-pin	3.927	2.45	1.562
Fix-fix	4.730	3.56	2.268
Fix-free	1.875	0.56	0.356

However, the studied boundary conditions do not cover the case of overhangs, as in the case of ESB building. To adapt the fundamental frequency equations to the full-scale ESB floor, an approximated equation proposed by [13] and adapted by [14] from a FEM analysis has been used. Equation (7) is defined for a simply supported beam with one-side overhang of an arbitrary length. The coefficient K_1 is given graphically as a function of the ratio between the span without overhang and the total length of the beam (Figure 6).

$$f_1 = \sqrt{K_1 \frac{(EI)_L}{\rho A L^2}} \quad (7)$$

The calculation of the equivalent bending stiffness $(EI)_{ef}$ for a composite floor is unchanged (EC5 Annex B).

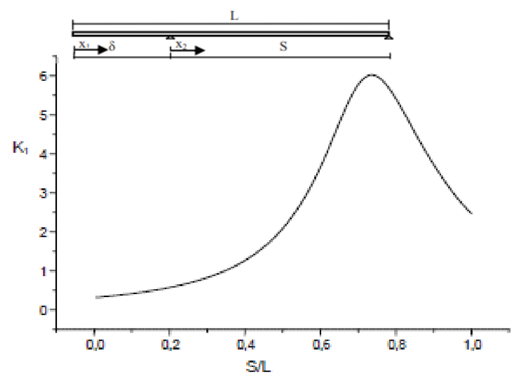

Figure 6: *Representation of the variation of K_1 as a function of the S/L ratio [14]*

3.2 ANALYTICAL RESULTS FOR ON-SITE BUILDING

To assess the fundamental frequency of the ESB floor, Equation (7) has firstly been applied to catch the overhang behaviour. A coefficient K_1 equal to 5.55 has been assessed from Figure 6 entering with the ratio $(L_{tot}-L_f)/L_{tot} = 0.79$. The longitudinal bending stiffness $(EI)_L$ has been computed from the Annex B of EC5. The value for the ESB floor is 2.34×10^7Nm²/m. The floor mass has been computed as the sum of self-weight loads, including supported and suspended layers, but not partition walls. The numerical value of m for the ESB floor is 238kg/m². L is the total length of the joists L_{tot} (Table 1). A fundamental frequency of 8.09Hz has been determined from Equation (7).

Equation (7) has also been studied with pinned-clamped ends restraints [14]. These conditions approach much more the on-site conditions because of the stiffness of the supporting walls. The fundamental frequency increases to 11.97Hz in this case. However, it seems difficult to justify such a configuration for the ESB floors, as the two supports conditions are very similar.

The current version of EC5 (Equation (1)) has been used for the original design computation of the floor, without considering the overhang and using a span of 9.6m (L_{tot}). A fundamental frequency of 5.39Hz is computed with these assumptions. When the overhang if fully neglected, considering a span of 7.6m, a frequency of 8.62Hz is retrieved (Table 4). It seems therefore very important to consider the presence of the overhang for a better assessment of the fundamental frequency.

In all cases, the 2D behaviour of the floor is not considered yet. The ratio between transversal and longitudinal bending stiffnesses for the ESB floor has been assessed to check if the 2D behaviour is really negligible. The obtained ratio is around 5%, showing the important 2D behaviour of this TCC floor, mainly due to the connected concrete slab. With this assumption, Equation (3) and its simplified version from the National Annex of Austria seems to be more precise in assessing the fundamental frequency of the floor. The results give 5.47Hz and 5.76Hz respectively. A floor width *B* of 12m (10x1.2m) has been considered for the computation, according to the slab discontinuity joints at each partition wall with wind bracing functions. Indeed, no specification is given in EC5 to clarify the definition of the floor width to consider. Finally, it has to be underlined that the future EC5 approach (Equation (4)) is the same as the Austrian equation, with $k_{e,1} = 1$ for the ESB case. Table 4 summarizes the results when applying the explained equations.

Table 4: *Results of fundamental frequencies f_1 for ESB floor from current available equations*

Configuration	2D floor	f_1 (Hz)	Source
	-	8.09	Eq. (7)
	-	11.97	Eq. (7)
	-	5.39	Eq. (1)
	-	8.62	Eq. (1)
	yes	5.44	Eq. (4)(5)
	yes	5.59	Eq. (3)

The last parameter to consider is the elastic supports. As a matter of fact, the ESB floor is supported by two timber trusses, that cannot be considered as rigid supports. Equation (6) has thus to be used and the natural frequencies of supporting trusses (beams) assessed. For this purpose, a numerical model has been realized for both trusses. The models are slightly different due to the cross-sections and loads, but the truss design is the same. As the stiffness of the truss itself is affected by the overhang, the modal shapes have been observed to retrieve the fundamental frequency for the overhang and the one for the part between the V-shaped column and the first vertical column (Section A and Section B respectively, Figure 2). It has to be underlined that the analysis only focuses on the less stiff part of the trusses (the exterior part, Sections A and B). The results for the fundamental frequencies of the trusses are summarized in Table 5. The difference between South and North trusses can be considered as negligible.

Table 5: *Fundamental frequencies f_1 of the supporting trusses*

Truss	f_1 (Hz) Section A	f_1 (Hz) Section B
South	5.82	8.40
North	5.84	8.42

Equation (6) has been applied to the results of Table 4 (except for the clamped case), giving a frequency value for Section A and another one for Section B (Table 6).

Table 6: *Results for the ESB floor on elastic supports*

Configuration	f_1 (Hz) Section A	f_1 (Hz) Section B
	3.67	4.79
	3.27	4.00
	3.72	4.90
	3.29	4.01
	3.32	4.07

Taking into account the elastic supporting beams have a very strong impact on fundamental frequency, especially for the overhang part, as it will be demonstrated in §4.2.
Existing equations are not fully adapted to such a complex configuration. The authors have decided to combine the different equations to better catch the real structural dynamic response of the ESB floor. The suggested equations from the future version of EC5 (Equations (4), (5) and (6)) have been adapted considering the coefficient K_1 taking into account the overhang configuration. The 2D behaviour is considered too, giving finally Equation (8).

$$f_1 = \sqrt{K_1 \frac{(EI)_L}{m}} \sqrt{1 + \left[2\left(\frac{L}{B}\right)^2 + \left(\frac{L}{B}\right)^4\right] \frac{(EI)_B}{(EI)_L}} \qquad (8)$$

A different width *B* has been considered for Section A and Section B to take into account the discontinuity joints cutting the concrete slab where the partition walls are (across the V-shaped column). For the overhang (Section A) it has been assumed *B* = 8.4m (7x1.2m) and for Section B the floor width is assumed as 12m. The results are summarized in Table 7. The results from Equation (3) have also been added for comparison purposes (in italic).

Table 7: *Results of f_1 for the ESB floor with two-way spanning and elastic supports (values from complete equation in italic)*

f_1 (Hz) rigid	f_1 (Hz) Section A	f_1 (Hz) Section B
8.39 (*8.83*) (*B* = 8.4m)	3.70 (*3.74*)	-
8.16 (*8.61*) (*B* = 12m)	-	4.81 (*4.89*)

3.3 ANALYTICAL RESULTS FOR LABORATORY SPECIMENS

The analytical equations described in §3 are used to estimate the fundamental frequency of some of the configurations tested in laboratory. The TCC tested are

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described in §2.2, calculations are based on the geometry and the material properties given in Table 2. Additional information about these tests (configurations, protocol) can be found in §4.3. Table 8 presents the equation used for each configuration, the value of the coefficient (either λ from Table 3 or K_1) and the fundamental frequency f_1. As the specimens are only 1080mm wide and not supported on their sides, 1D equations (only based on $(EI)_L$) are used. It should be noted that the results for configurations including a fixed support are expected to be quite far from experimental results, as laboratory means were not adapted to generate such a perfect mechanical linkage.

Table 8: *Fundamental frequencies f_1 according to analytical equations for the TCC tested in laboratory*

Configuration	Equation	f_1 (Hz)
	Eq. (1) $\lambda = \pi$	10.04
	Eq. (1) $\lambda = 3.927$	15.68
	Eq. (1) $\lambda = 4.730$	22.75
 1m	Eq. (7) $K_1 = 5.0$	14.29
 2m	Eq. (7) $K_1 = 4.8$	14.00

4 EXPERIMENTAL APPROACH

4.1 EXPERIMENTAL SET-UP

Measurement protocol has been defined according EN 16929 [15], which specifies test methods for the determination of natural frequencies, damping, unit point load deflection and acceleration of floors composed of sawn timber, engineered wood products, mass timber beams or slabs, with or without concrete screeds, as well as for timber-concrete composite floors. Data acquisition was performed with a NI measurement device and a LabVIEW interface, with a packager for accelerometers (8μg resolution, sensitivity 10V/g (± 5%) and a frequency range of 0.15 to 1000Hz (± 5%)). A total of 9 accelerometers was available for the experimental set-up. Double face tape (on-site measurements) and metal plates (laboratory tests) were used to fix the accelerometers to the floor (Figure 7).

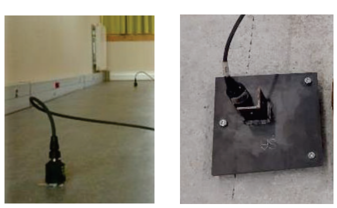

Figure 7: *Accelerometers floors fixation for on-site (left) and laboratory (right) measurements*

The approach used for all performed tests was to have an output-only signal, without measuring force. Different excitation sources have been used: weight drop, walking, running, ambient vibrations. The registered signals are accelerations at the measurement points.

Different acquisition frequencies have been tested, assuming finally that 100-150Hz is enough to capture the relevant frequencies of these systems. The acquisition length for each measurement was between 10 to 90 seconds, depending on the time necessary to reach the static equilibrium.

The modal analysis technique used to get the structural response in terms of natural frequencies and modal shapes is the Frequency Domain Decomposition [16].

4.2 EXPERIMENTAL MEASUREMENTS FOR ON-SITE BUILDING

Measurements took place at first and second floor, focusing on the external part only (Sections A and B). Two positions have been tested, one in Section A and the other in Section B. For each position 3 accelerometers have been installed parallel to the joists, at half distance between joists (points 1, 2 and 3 in Figure 3). The building was empty during measurements.

Different types of loading were tested: 5kg weight drop (sandbag) from 80cm height (using a small crane or manually), normal and fast walk, and ambient vibrations. Impact tests and walking are performed in different locations of the floors. For each position, at least 3 measurements have been performed to manage repeatability.

Table 9 presents the results of the fundamental frequency at different measurements points and floor positions. Only the results at 2nd floor are presented, the 1st floor gives globally the same frequencies. The results show that the elastic supports have a strong impact. The fundamental frequency of Section A decreases of about 40% compared to Section B because of the overhang flexibility. Compared to the analytic results based on Equation (8), which is the most complete available (overhang, 2D and elastic supports), experimental measurements show quite different and greater values of f_1. The differences between analytical and on-site frequencies observed by [2, 3] on single span floors are therefore observed again in the case of overhang floors on elastic supports.

Table 9: *Analytical and on-site experimental results for the ESB floor (2nd floor)*

Section	Pos.	Analytic	Exp.	Δ^* (%)
	1		4.33	
A	2	3.70	4.40	18.1
	3		4.37	
	1		7.03	
B	2	4.81	7.00	46.1
	3		7.05	

**Δ is the difference (in %) of the experimental result relatively to the analytical one*

4.3 EXPERIMENTAL MEASUREMENTS ON LABORATORY SPECIMENS

The aim of the laboratory experiments was to measure the dynamic properties for different ends conditions and finishing: roller, pinned or fixed supports, with or without overhang, with or without floor finishing and with partition walls at different locations on the floor. Different preliminary tests have been performed to verify the reliability of the measurements protocol:

- The calibration of the load drop height to assure that accelerometers are not overloaded. A drop height of 50mm has been chosen.
- Checking that the energy given to the floor is enough to induce vibration on the whole specimen: two accelerometers were fixed on the concrete slab and under the joist to ensure having the same response in terms of frequency and damping ratio.
- The fixation of accelerometers to the rough concrete slab: a three-point metal plate has shown to be more adapted to the irregular surface than double face tape, to avoid surface sanding.
- The number of measurements repetitions to have a coefficient of variation lower than 0.5%: 4 measurements prove to get the purpose.
- The definition of measurement positions to catch as much as possible the modal shapes for all boundary conditions: all configurations have been numerically modelled to define the maximum displacement for each modal shape. A set-up of 6 accelerometers has shown to be the better configuration to get all the modal shapes with a good accuracy.
- The specimens were put on small pieces of wood directly on the ground: by applying Equation (6) it has been shown that such supports can be considered as rigid supports.

A sandbag (mass 4636g) was dropped at different locations to excite the TCC. The impact force was applied for all boundary conditions on the top of TCC at mid and third span to excite the first three flexural modes.

Firstly, the geometrical ends conditions presented in Table 8 were tested for both specimens: Pin-roller, Fix-pin, Fix-fix and Pin-roller with one-side overhang of 1 and 2 m (Figure 8, right). The pinned configuration resists both vertical and horizontal movements but not bending moment; as specimens have a huge masse (1076kg), there was no need to put anything to restrain the horizontal and vertical movements. The roller configuration, allowing the horizontal movement, was realized by putting a steel rod under the specimens (Figure 8, left). Finally, the fixed configuration was achieved by putting a concrete block (600 kg) on edges, applying its weight on the slab trough a surface of approximately 30x80cm (Figure 8, middle).

Figure 8: *Tested boundary conditions (roller, fixed, overhang)*

Results are summarized in Table 10 for both specimens. Second and third frequencies and damping ratios have also been assessed through laboratory measurements, but not presented in this paper. The differences between the two specimens are negligible.

Table 10: *Experimental fundamental frequency f_1 (Hz) for laboratory specimens under different ends conditions*

Ends condition	Specimen 1	Specimen 2
	8.33	8.37
	9.05	9.10
	9.24	9.29
 1m	11.26	11.28
 2m	11.46	11.40

Table 11 presents a comparison between these experimental results and the analytical prediction. The biggest differences appear for fixed configurations, which can be explained by the fact that the experimental means of realizing a fixed support do not increase the rigidity enough. Nevertheless, better fit was expected for isostatic supports, as differences are high (between 9.0 and 13.7%). The assumed values of some material properties might be the cause: compression tests on concrete could not be performed to assess its Young's modulus, data for moisture content of wood were lost for some stages of the whole study, timber properties are the mean values from the two specimens, even if experimentally values from both specimens are very close (Table 10).

Table 11: *Analytical and experimental results for laboratory specimens*

Ends condition	Ana.	Exp.	Δ^* (%)
	9.18	8.35	-9.0
	14.34	9.08	-36.7
	20.80	9.27	-55.4
 1m	13.06	11.27	-13.7
 2m	12.80	11.43	-10.7

**Δ is the difference (in %) of the experimental result relatively to the analytical one*

Other tests have been realized to consider the effect of finishing and partition walls. The ends conditions are the isostatic ones for all these tests. Only the specimen 2 has been selected for the further measurements. The configuration without any finishing has been tested

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again, to have a reference value. Previous tests have been performed during summertime, this second measurement campaign was performed during winter, in a heated building, leading to dryer moisture content of wood. A parquet floor has been put in place over a fibrewood undercoat 5mm thin (Figure 9, left). Frequencies decrease compared to the floor without finishing (Table 12). Finally, the presence of partition walls has been investigated. The wall provides an additional mass of 27kg to the floor. Six configurations have been tested: two positions of the wall perpendicular to the joists (at 2/5 and 3/5 of the span), two positions of the wall parallel to the joists (at 2/5 of the span and at mid-span), one position with two partition walls parallel to the joists and one position with a T-section wall approximatively at mid-span (Figure 9, middle and right).

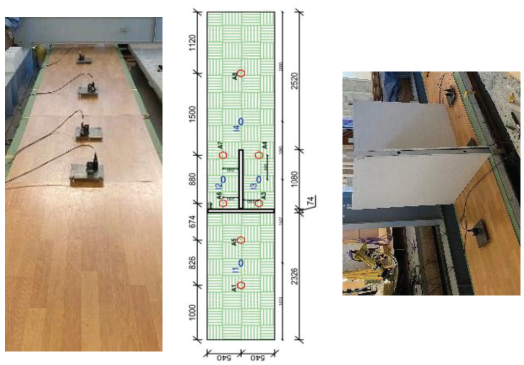

Figure 9: *Tested specimen with finishes (left) and partition walls (T-section)*

Results for this second measurement campaign are summarized in Table 12. Adding a partition wall at mid-span has a negative impact on fundamental frequency, as expected, because in this situation the wall is not connected to other elements of the building, therefore its weight is obviously added to the floor, while the possible increasing floor stiffness is not adequately represented with this setup. The orientation of the wall has a relatively small impact on the structural response. Adding twice the partition wall mass, the frequency decreases, mainly when the wall is positioned near to the mid-span.

Table 12: *Experimental results for laboratory specimen under various finishing (floor and partition walls) conditions*

Finishing condition	f_1 *(Hz)*
Without finishing	9.63
Parquet floor	9.47
Perpendicular wall at 2/5 span	9.22
Perpendicular wall at 3/5 span	9.25
Parallel wall at 2/5 span	9.33
Parallel wall at mid-span	9.22
Two parallel walls	9.15
T-section wall	9.03

5 NUMERICAL MODEL

The long-term objective of the finite elements model is to predict the rigidity and the modal parameters of TCC for different boundary conditions. In this paper, the focus is to corroborate the analytical equations used in §3, especially the one combining the 2D behaviour with an overhang (Equation (8)). The rest of the numerical study being too extensive and not totally finalized yet, it will be the focus of a future publication.

5.1 COMPARISON TO AVAILABLE ANALYTICAL EQUATIONS

The case study for analytical and numerical comparisons is the geometry and materials described in §2.2. The 6m long floor (L_{tot}) includes two joists and one concrete slab. For the sake of comparing the different analytical equations to FEM results, the aim is not the determination of the equivalent stiffness of the composite section $(EI)_{ef}$, but the effect of boundary conditions on the fundamental frequency. Therefore, the model introduced in this paper uses a perfectly rigid interface between timber and concrete.

Concrete is modelled as an isotropic material and timber as an orthotropic one. The values for modules of rigidity and densities are given in Table 2, except for the timber shear modulus. Indeed, the low G values for timber induce deflections that are significant compared to bending deflections. As this shear deflection is not modelled analytically, it was artificially removed from the model by implementing values ten times greater than normal (G = 6GPa).

The different modelled boundary conditions are: single span floor on isostatic supports, with an embedded support on one and on both ends, a one-side overhang floor on isostatic supports with 1 and 2m overhang, and finally a one-side overhang floor embedded at one end with a 1 and 2m overhang (Table 13). Supports are modelled by defining a surface of 75mm x b_2 (joists width) beneath the joists, where either the 3 translations or just the vertical one are fixed. For embedded supports, the surfaces of the section on the end are fixed.

The meshing is generated using Hex20 50mm length side volumetric meshes. A modal analysis is performed on the aforementioned models, modal shapes are observed (*e.g.* Figure 10) and the fundamental frequencies are extracted (Table 13). These models and calculations are achieved using the software Ansys Mechanical 2023 Release 1.

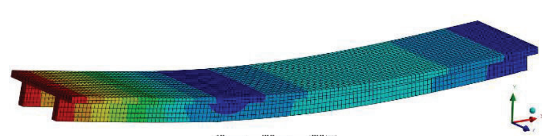

Figure 10: *Modal shape (f_1 = 15.81 Hz) for an isostatic floor with 2m overhang*

Table 13 includes also the analytical fundamental frequencies corresponding to each numerical model.

The difference (Δ) is calculated as a percentage of the analytical value. It can be observed a relatively good accordance between analytical and numerical values with a difference up to 7.3%.

Table 13: *Analytical and numerical comparison of the fundamental frequency (Hz) for different boundary conditions*

Configuration	Analytical	Numerical	Δ^* (%)
	11.84	11.65	-1.6
	18.50	17.97	-2.9
	26.84	25.51	-5.0
 1m	16.42	16.08	-2.1
 2m	16.59	15.82	-4.6
 1m	25.73	24.71	-4.0
 2m	19.53	18.11	-7.3

**Δ is the difference (in %) of the numerical result relatively to the analytical one.*

5.2 COMPARISON TO PROPOSED ANALYTICAL EQUATION

As previously showed (§5.1), the numerical model predicts quite well the analytical results of available equations (Equations (1) and (7)). The numerical model can now be used to assess the validity of the proposed Equation (8), the one combining the K_1 factor for overhang configurations and $(EI)_B$ on $(EI)_L$ ratio to include the 2D behaviour. The modelling approach is similar for materials, meshing and boundary conditions. In the longitudinal direction, three configurations are used: single span floor on isostatic supports, 1 and 2m overhang on isostatic supports. In the transversal direction, widths of 1.2, 2.4, 4.8 and 9.6m (Figure 11) are modelled, and a blocked vertical displacement is imposed to the ends of the concrete slabs, therefore modelling the 2D effect on the floor.

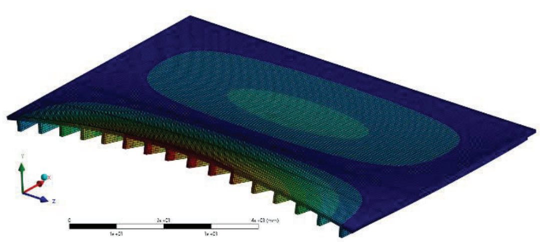

Figure 11: *Modal shape (f_1 = 16.43 Hz) for an isostatic floor with 2m overhang (width B = 9.6m) supported on its longitudinal sides*

Table 14 shows that the numerical model predicts accurately the results of Equation (3) for a single span floor on isostatic supports (Δ_{max} is 5.7%). It should be noted that analytical calculations using the proposed equations of the future EC5 (Equations (4) and (5)), without the $(L/B)^2$ term, provide less satisfactory results, with Δ values between 8 and 19.5%. The equation proposed in this paper (Equation (8)) fits relatively well (Δ_{max} = 4.2%) for lower values of the ratio *L/B* (*B* equal to 4.8 and 9.6m), but is much less precise for bigger values of *L/B* (Δ_{max} = 23.9%) for 1.2 and 2.4m. Additional calculations should be performed to assess more precisely the *L/B* ratio over which the analytical equation fits. As bigger values of *L/B* are not very representative of real floors, it is hoped that Equation (8) could be validated for realistic *L/B* ratios.

Table 14: *Analytical and numerical comparison of the fundamental frequency (Hz) for different widths of floor supported on their longitudinal sides (2D effect)*

Model		1.2m	2.4m	4.8m	9.6m
	Ana	86.80	28.05	14.78	12.10
	Num	86.99	26.46	14.80	12.57
	Δ^* %	0.2	-5.7	0.1	3.9
	Ana	119.20	36.47	19.41	16.73
 1m	Num	90.68	30.65	19.55	17.09
	Δ^* %	-23.9	-16.0	0.7	2.2
	Ana	116.79	35.74	19.02	16.40
 2m	Num	97.51	35.27	19.82	16.44
	Δ^* %	-16.5	-1.3	4.2	0.2

**Δ is the difference (in %) of the numerical result relatively to the analytical one.*

6 CONCLUSIONS

The first main conclusion of the work presented in this paper is that analytical calculation of the fundamental frequency of a floor is possible via several equations, yet none was strictly adapted to the specific case of TCC floors with overhang. Equations exist to take into account its longitudinal and transversal stiffness and the elasticity of its supports, other ones to take into account an overhang. In this study these equations have been combined to compare the analytical results to on-site measurements. It is observed that same conclusions as in [2, 3] (made for single span floors) can be drown also in the presented case study with overhang. Nevertheless, the validity of the proposed equation is still to be fully justified, a FEM model tends to show that for realistic *L/B* ratios (when *B* is greater than 1 or 2m) the proposed equations fits well.

The analytical approach has been used as a reference to compare experimental and numerical results, because experimental on-site and laboratory measurements cannot be directly compared (scaled specimens).

The important differences between analytical and experimental laboratory results are quite surprising, especially for simple boundary conditions. More detailed investigations will be necessary, nevertheless some variations can be already explained by the possibly different moisture content of the specimens during the experimental campaigns. Materials properties (timber and concrete) are also assumed as mean values from both specimens, the analytical approach should add a sensitivity analysis based on varying materials properties. Expected analytical results have to show a

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confidence interval to catch the variability from experimental results.

The experimental on-site analyses present a higher stiffness of the ESB floor, even considering the overhang and the elastic supports. The analytical calculations are more conservative because they do not consider the stiffness contribution of secondary elements and partition walls. This means that current equations, including the ones proposed into the future EC5, tend to underassess the fundamental frequency of TCC floors.

The numerical approach has to be fully validated for a rigid connection between timber and concrete. Nevertheless, it allows some interesting comparisons with analytical equations, showing that the two-way spanning behavior cannot be neglected into design.

Further steps of the work should allow the development of a more reliable numerical model, taking into account the real stiffness of the interface. A comparison between on-site and laboratory experiments will finally be possible through the numerical model.

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