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Comparison of Thermal Comfort Conditions in Multi-Storey Timber Frame and Cross-Laminated Residential Buildings

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Introduction

In recent years, timber construction systems have been increasingly used in multi-storey residential construction in Europe (Ceccotti 2008, Green 2012, Council e Investments 2014). In line with this international trend is the choice of the Trentino social housing company ITEA to build two five-storey multi-family apartment buildings in Trento (Italy) using two different timber wall systems. The two buildings are identical except for their structural system: timber frame (TF) and cross laminated timber (CLT). They also have a reinforced-concrete core located at the centre of one edge of the rectangular plan of each building. The design and the construction of these two buildings are the result of an international collaboration between ITEA and the Canadian social housing company Quebec Societè D'Habitation in order to evaluate and compare timber construction systems for social housing from the two countries. Since the two buildings have identical floor plans, layouts and finishes and differ only in their structural system, they present a unique opportunity for comparison of the two key forms of timber construction in terms of economic, engineering and indoor comfort issues. Their dynamic behaviour under lateral loads has already been examined (Reynolds, Casagrande e Tomasi 2016). This paper investigates the difference in indoor conditions and analyse the achieved thermal comfort by measuring physical parameters and surveying the occupants' perception.

The two structural systems used for the buildings represent two widely used but fundamentally different forms of timber construction. The sheathed stud-and-rail system of the first building, commonly referred to as light timber frame (TF), has been used for many years and can be used efficiently with prefabrication of elements, since fully sealed and insulated panels can be assembled in factory, lifted into place and connected to each other with hand tools on site. This form of construction is extremely lightweight, which gives the building low thermal mass and conse-

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quently low thermal inertia. This can lead to a lack of thermal comfort, particularly in summer, due to temperature fluctuations. Cross-laminated timber (CLT), used to form the timber shear walls in the second building, is a comparatively modern building component. Again, it can be highly prefabricated, and used with computer controlled cutting techniques to pre-cut openings for windows, doors and services to a high degree of accuracy. This system, known as 'massive timber', provides a higher thermal mass, if compared to the previous system. It is interesting, then, to investigate to what extent this difference of thermal properties affects the indoor conditions provided and the final users' satisfaction towards the thermal environment.

This experimental campaign falls into a broader policy adopted by ITEA to engage closely with the performance of the buildings they build and manage, in accordance with an increasing interest globally in building performance assessment and post-occupancy evaluation (POE). In the view of improving the quality and sustainability of buildings, POE has started to be more and more perceived as a natural part of project delivery but, in many cases, this procedure still proves difficult: POE has continued as a research activity, but for the most part designers, constructors and often their clients have not been very closely involved (Bordass e Leaman 2015).

The main purpose of POE techniques is to investigate occupants' reported levels of comfort and satisfaction and the degree to which they perceive their needs are being met by the building's indoor conditions, through structured questionnaires and interviews carried out after 3-18 months of occupancy (HEFCE 2006). The collected documentation provides information about habitability, functionality, indoor comfort and real energy consumption and allows to minimize the design-built performance gap (Chiu, et al. 2014). Post-occupancy evaluation is therefore a good opportunity to create a feedback loop for architects, planners, and building design and construction professionals in order to learn how different building design features and technologies influence occupant comfort, satisfaction and productivity (Gossauer und Wagner 2007). Moreover, building monitoring and surveys are meant to improve the cooperation between all the stakeholders involved in the design and building process and enhance their responsibility for the performance of the building. In the case here presented, with the POE it can be stressed that ITEA manages its building stock in an efficient and effective manner.

Methods

In the present paper, the analysis of the thermal comfort in two apartments was carried out. A traditional approach was used, by measuring the thermal-hygrometric environmental parameters together with the distribution of a dedicated questionnaire to the occupants. Measurements were carried out in accordance with UNI EN ISO 7730:2006 and UNI EN ISO 10551:2002.

Along with the monitoring campaign, in accordance with the Post Occupancy Evaluation Guidelines, users have been surveyed with questionnaires relating to the perceived thermal comfort and the satisfaction with the indoor environment. Moreover, questions related to user behaviour, heating and cooling system management, and doors and windows opening are asked.

Finally, a dynamic simulation model of the apartments has been developed by modelling with the use of DesignBuilder software the geometry, the structure, the envelope and the mechanical systems. After having set the real outdoor temperature profile during the two periods of monitoring, the evolution of the physical thermal-hygrometric parameters and the comfort indexes has been simulated.

Characteristics of the selected apartments

The apartments dispose of one, two or three rooms and have a net floor area varying from 40 m^2 to a maximum of 88 m^2. They are occupied by 13 young families with 2 or 3 children, 7 single person households and 8 two-people-households of one elderly person or single parent with a child (the apartments selected for the research project belong to the latter category). Moreover, all the apartments have been evaluated and certified in the energetic classes A+ and

B+ and they have reached the “Silver” level of the ARCA certification system (ARCA 2014). Both the buildings present the same underfloor radiant heating system and controlled mechanical ventilation system that guarantees air renewal and purification in buildings. The heating system is based on a centralized condensing boiler, with an outdoor reset control of eater supply temperature. The boiler produces the hot water that feeds the radiant floor system. During the heating period, the mechanical ventilation system provides fresh air to the dwellings (with a lower threshold of 18°C for the supply air temperature). However, the occupants can freely interact with the envelope by opening and closing the windows. The ambient temperature controllers are set to the constant value of 20°C during occupied time, with a setback temperature of 16°C.

An external view of the two buildings is shown in **Fig. 1**.

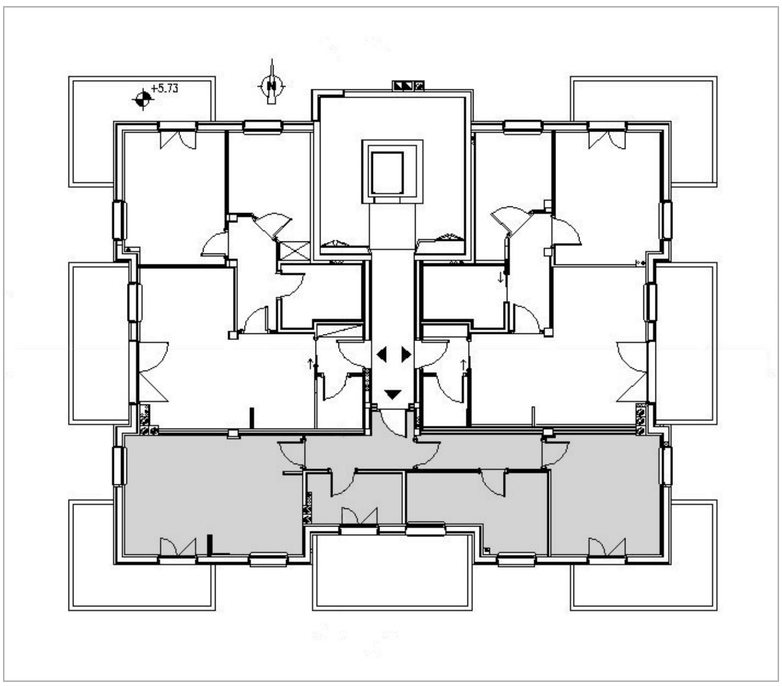
The tested apartments are one per building, on the second floor, having same shape, dimension, number of occupants and exposure (south), as shown in **Fig. 2** and **Fig. 3**. In the north (TF) building, the walls are made with 120 mm x 180 mm solid timber studs with OSB sheathing panels, 18 mm thick, on both sides of the wall. A timber-concrete composite structure is used for the floors, connecting 100 mm x 200 mm glulam beams to a 50 mm thick concrete slab. In the south (CLT) building, the walls are made with 5-layer CLT panels with a thickness of 153 mm for the ground and the first floor and of 133 mm for the upper floors. Floors are made with 5-layer CLT panel with a height of 153 mm.

Fig. 1

The north five-storey timber building

Fig. 2

The second floor plan and the apartment selected for the campaign (grey). The layout is the same for the two buildings



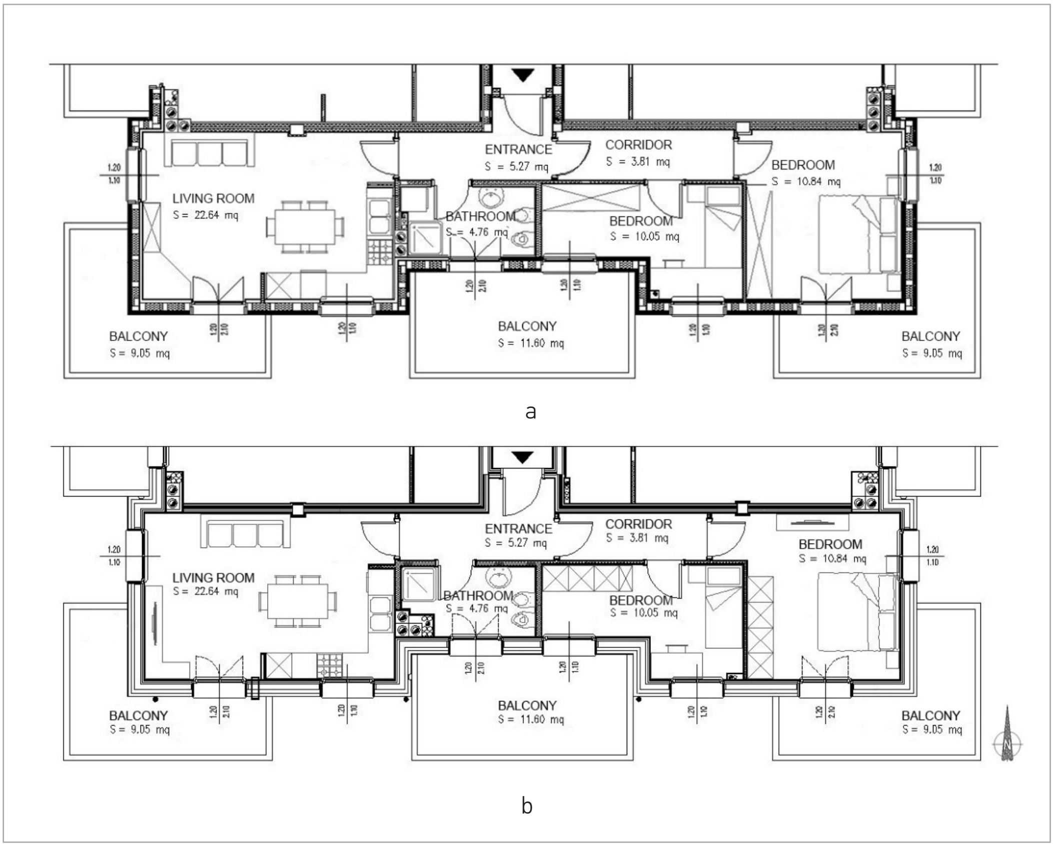


Fig. 3

The apartment floor plan in the north TF building (a) and in the south CLT building (b)

Experimental campaign

The experimental campaign was carried out in two different periods, two weeks during late winter (February-March 2016) and two weeks during early summer (May-June 2016). In each campaign, a microclimatic measurement system has been set the first week in the living room and the second one in a bedroom. Together with the microclimatic station, thermal-hygrometric probes have been put in each room of the apartments.

The following parameters were measured:

- Air dry bulb temperature T_a [°C];
- Globothermometer temperature T_g, used to calculate the mean radiant temperature T_{mr} [°C];
- Air Relative Humidity *RH* [%];
- Mean air velocity v_a [m/s].

The acquisition rate for each of the measured parameter has been set to 10 min. By means of these parameters, the Predicted Mean Vote *PMV* and the Predicted Percentage of Dissatisfied *PPD* were calculated.

The following instruments by LSI-Lastem form Milan (Italy) have been used:

- air temperature and RH% sensor with Pt100 output for temperature (resolution 0.01°C, uncertainty of 0.1°C) and 0-1 Vdc output for RH% (resolution 1%, uncertainty of ±3.5%);
- radiant termperature sensor with Pt100 output (resolution 0.01°C, uncertainty 0.15°C);
- hot wire anemometer using one sample every 100 ms and update output every one sec, with a resolution of 0.01 m/s (uncertainty ÷0,5 m/s = NA, 0,5÷1 m/s = ± (0,05+0,05 Va) m/s, >1 m/s= ± (0,1+0,05 Va) m/s)

Questionnaire survey

During the experimental campaign, the questionnaire has been distributed to the occupants, two persons for each apartment considered. The questionnaires were based on the one proposed by UNI EN ISO 10551 with some modifications. Three different questionnaires (A, B and C) have been developed to be submitted to the occupants. Particular attention has been paid to the formulation of the questions, the choice of the evaluation scales and the general structure of the questionnaire, since these are the most significant factors affecting the response rate and the reliability of the answers. In particular, the A type has been filled out twice a day (in the morning and in the evening), while the B and C types only once a day, in the evening.

The occupants were asked to analyse their indoor environment from different point of view:

_ Thermal sensation,
_ Thermal comfort,
_ Thermal preference,
_ Acceptability,
_ Tolerability,
_ Possibility of individual control of microclimate,
_ Satisfaction for individual control.

The questionnaire is divided into four parts:

_ first part: personal data (age, sex, ...);
_ second part: thermal survey (activity performed in the last 15 minutes; clothing; judgment about tolerability of thermal environment, eventual preference for different conditions) (Questionnaire A);
_ third part: personal habits and environment control (occupancy schedule; windows openings; thermostat temperature settings) (Questionnaire B);
_ fourth part: judgment about air movement, eventual preference for different conditions (Questionnaire C).

Modelling

A dynamic building simulation has been carried out in order to calculate the energy performance and the trend of the indoor main physical quantities, by using the software DesignBuilder.

As weather file, an EPW file (EnergyPlus Weather file) has been obtained from local forecasting data, in order to run a simulation as close as possible to real conditions. The apartment model has been subdivided in five thermal zones: living room/kitchen, corridor, bathroom, double bedroom and single bedroom.

Trends of air dry bulb temperature, mean radiant temperature, operative temperature and relative humidity have been extrapolated and the results have been generated at weekly, daily and hourly rate. As number of steps per hour for the simulation, it was decided to set a data acquisition every 10 minutes that is consistent with the acquisition rate of the sensors.

Expexted results

The experimental campaign is of great importance because the real trend of the considered physical quantities in real condition of use are recorded and analysed. So, it is possible to compare the performance of the two apartments considering actual weather conditions and the behaviour of the occupants. Furthermore, the questionnaire survey is necessary in order to define the indoor comfort perception of the users (that can be very different from what expected) and to correlate it with the data coming from the instrumental survey, originating the comfort indexes. The data recorded can also be used to calibrate the model of the building. In fact, dynamic energy models often suffer from output uncertainties due to the high level and precision of input required, and simulation results can be quite different from realities. Once the model is calibrated, it is also possible to verify the coherence of the PMV and PPD indexes coming from instrumental survey, from questionnaires and from the dynamic model. After that, the model can be considered as a "virtual exact copy" of the real building and some parameters can be properly changed (materials, shape, exposure, geometry and so on) in order to evaluate new solutions that could improve the users' comfort conditions. This last part of the research is not presented here.

Results and discussion

Winter analysis

By comparing the temperatures measured by the temperature probes, it can be noticed that temperatures are higher in the CLT apartment with an average gap of 0.8 °C (see Graph 1, on the top).

Set the clothing value to 0.8 and the metabolic activity to 1.3, PMV and PPD have been evaluated. Due to a technical malfunction of the microclimatic station, some data are lacking, on days 20th, 21nd and after 23rd of February. For what concerns the CLT apartment, PMV values lie mostly within the limits of the comfort zone for the category B, while in the TF apartment PMV values exceed the lower comfort limit, with a general slightly cold/cold thermal sensation (see **Fig. 4**, on the bottom). The PPD trend is consistent with the PMV trend, with higher values (up to 18%) in concurrence of the days where comfort limits are exceeded.

What emerges from the data analysis is that temperatures decrease faster in the TF apartment: this is evident in **Fig. 5**, where the segments connecting the maximum and minimum daily temperatures are steeper for the TF apartment. The TF building cools more rapidly if compared to the CLT building, due to its lower thermal mass.

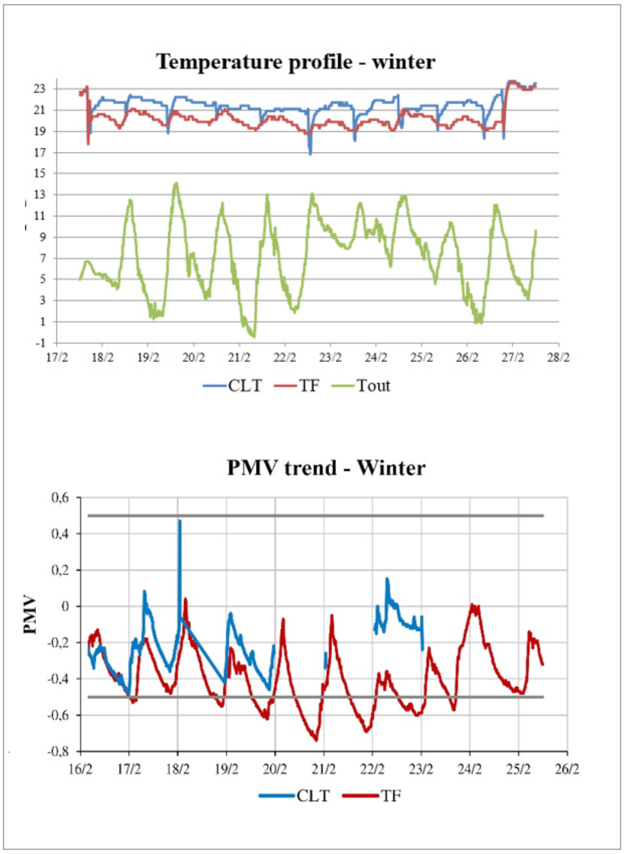


Fig. 4

Temperature and PMV profiles during a week of the winter experimental campaign (17th-26th February)

Summer analysis

For what concerns the summer period, an analysis of the different temperature profiles has been conducted, in relation also with the external temperatures. It has been observed that during the first week of the experimental campaign, in May, the CLT building presents higher indoor temperatures while the TF building cools off during night temperatures. On the contrary, in June, when the minimum temperature values increase of an average of 4.5°C, the CLT massive building shows lower temperature thanks to its higher thermal time lag and lower decrement factor (0.023 for the CLT wall in front of 0.388 of the TF wall), thermal transmittance being equal (see **Fig. 6** and **Table 1**).

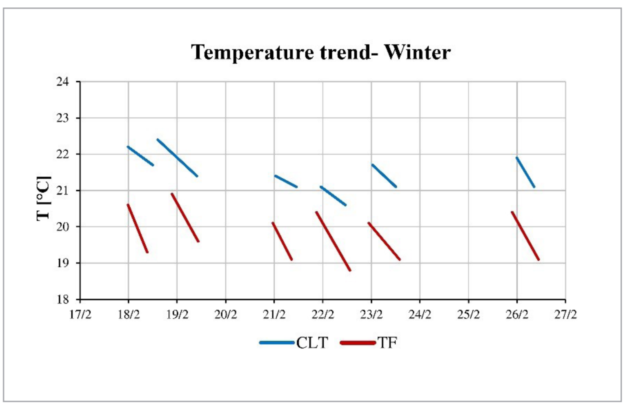


Fig. 5

Temperature trend during a week of the winter experimental campaign (17th-26th February)

Fig. 6

Temperature and PMV profiles during a week of the summer experimental campaign (13^{th}-20^{th} June)

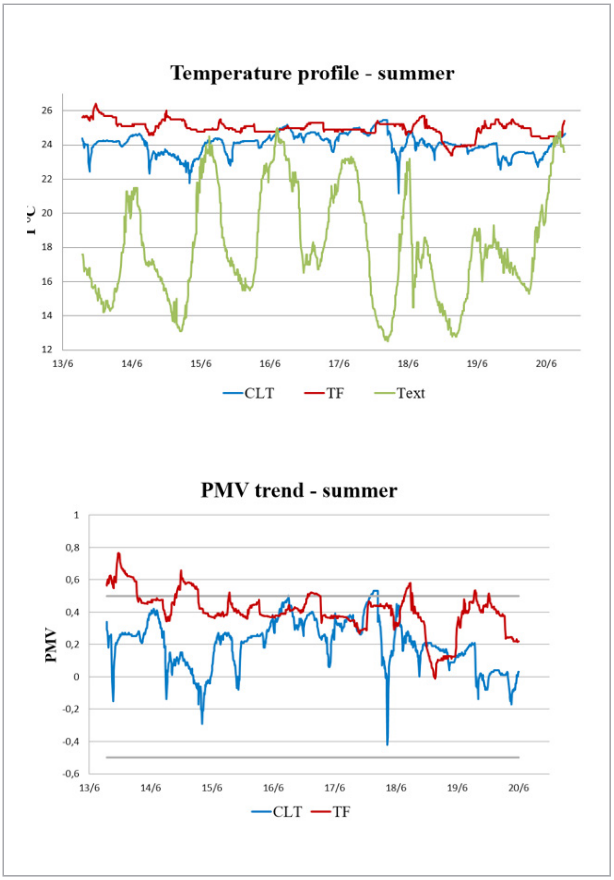


Table 1

Thermal properties of the external wall in the CLT and TF buildings

	CLT wall	TF wall
thickness [cm]	42,4	35,6
U [W/m²K]	0,156	0,157
f[h]	20,19	9,42
d	0,023	0,388

Survey results

In **Table 2**, the average results from the qualitative survey during winter period are reported. The response about acceptability is not present since the environment has always been reported by the occupants as acceptable rather than unacceptable. A 7-degree two-pole judgement scale is used for the thermal perception, from very cold (-3) to very hot (+3) comprising a central neutral point, whose value is zero, and for thermal preference, from much colder (-3) to much warmer (+3) with a central point of absence of change (0). A 5-degree scale is used for thermal comfort, from 'comfortable'(0) to 'uncomfortable'(5), and for tolerability, from 'perfectly tolerable' to 'intolerable'. Finally, the form for the acceptability statement is a binary structure 'generally acceptable'/'generally unacceptable'.

What emerge from the questionnaires is that the thermal perception, which is linked to the PMV, ranges within the comfort limits, except for the CLT apartment during the second week, in which a value equal to 1 is registered. However, this sensation of warmth is

Table 2

Qualitative survey results for the winter period

	16^{th}-25^{th} February				27^{th} February-7^{th} March			
	CLT apartment		TF apartment		CLT apartment		TF apartment	
	Morning	Evening	Morning	Evening	Morning	Evening	Morning	Evening
Clothing value [Clo]	0,75	0,75	0,79	0,73	0,7	0,7	0,77	0,8
Metabolic activity [Met]	1,17	1,62	0,69	1,23	1,2	1,4	0,74	1,07
Thermal perception	0,28	0,1	0,11	-0,25	1	1,12	-0,14	-0,17
Thermal comfort	0,28	0	0,33	0,12	0	0,12	0,14	0,15
Thermal preference	0,28	0	0,22	0,37	0,2	0,125	0,14	0,17
Tolerability	0	0	0	0	0	0	0	0,17

not perceived by the occupants as a discomfort. This can be seen by the value of thermal comfort and of tolerability, which are pretty much equal to zero. Moreover, this warmth does not provoke any preference for cooler conditions, as it can be seen by the all positive values of the thermal preference. It can be assumed in consequence that the condition of ‘slightly cold’ (as in the TF apartment) generates a more irritating sensation than the condition of ‘slightly warm’.

The results from the qualitative survey during summer period, shown in Table 3, show a thermal perception that present always positive values in a range of [0.33,1.25]. However, in correspondence of the maximum value of thermal perception, thermal comfort is equal to zero and thermal preference is positive. This means that the occupants perceive a slightly warm sensation, which nevertheless does not have an influence on well-being.

Table 3

Qualitative survey results for the summer period

	20th-27th Mai				13rd Mai-20th June			
	CLT apartment		TF apartment		CLT apartment		TF apartment	
	Morning	Evening	Morning	Evening	Morning	Evening	Morning	Evening
Clothing value [Clo]	0,58	0,61	0,68	0,58	0,6	0,55	0,49	0,5
Metabolic activity [Met]	1,05	1,07	0,73	1,4	0,86	1,7	0,67	1,07
Thermal perception	0,75	0,67	0,33	0,67	0,67	1,25	0,33	0,33
Thermal comfort	0	0,33	0	0,33	0,33	0	0	0
Thermal preference	0,25	0,33	0	-0,33	0,33	0,75	-0,33	-0,33
Tolerability	0	0	0	0	0	0	0	0

Conclusions

Despite the fact that both the buildings have proven to be comfortable, some differences were identified in the comparison of the indoor conditions in the two apartments. During the winter period, it has been observed that, when the outdoor temperature drops, the value of the indoor temperature decreases faster in the TF apartment than in the CLT apartment, on average of 1.2°C against 0.6°C. Thus, the building that cools down more rapidly is the one with lower mass, which can hardly reduce heat loss from the flat.

By analysing the external temperature evolution during the summer period, it has been noticed that the maximum values are similar in the two weeks of campaign while the minimum are rather different: in May, the average temperatures are 4.5°C lower than in June. This has caused that in the first week of campaign the temperature is higher in the CLT building while, on the contrary, in the second week, when minimum temperatures outdoor significantly increase, this trend reversed and temperatures are higher in the TF building. This is due to the significance of thermal parameters such as the thermal lag and the decrement factor in summer period. In fact, the thermal lag value is equal to 20 hours in the CLT building and 9 hours in the TF building, and the decrement factor is higher in the TF building since this structural system is less able to store heat compared with the CLT alternative.

Furthermore, it is important to draw the attention to the fact that, thanks to the questionnaires to the occupants, it was possible to know the different behaviour towards the heating system management and windows. This has helped to analyse the obtained results particularly with respect to the subjective users’ experience.

The buildings’ occupants have reported a state of overall comfort with a perceived slightly warm sensation in both seasons, but this does not provoke a desire for lower temperatures. It means that both the TF and CLT building systems can provide a suitable inner thermal comfort with very little difference regarding temperature trend in winter and summertime. The users do not seem to notice the differences, always expressing satisfaction and high tolerance also in periods with a limited small discomfort. It can be said that TF and CLT different thermal properties, although influencing the inner trend of thermal quantities, do not seem to affect the indoor comfort conditions and the final users' satisfaction towards the thermal environment.

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