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Thermal properties of Timber and Indoor thermal comfort

Rahman Yusuf[1] Shanghai Jiao Tong University

[1] *School of Design, Shanghai Jiao Tong University, Jiangsu, China*

Abstract- *Timber is used in construction more frequently for its green credentials and its healthy property but overheating in wooden house is becoming a serious problem as climate change increases which affects the thermal comfort of the occupants. This paper tries to find out the relationship between timber and thermal comfort, focusing on the properties of timber, perceived thermal comfort and provides a comparison between Cross laminated timber and Timber Frame buildings.*

***Key words**:* Timber properties, Thermal comfort, Perceived thermal comfort, Indoor environment, Cross laminated timber, Timber frame

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1. INTRODUCTION

Humans have evolved in natural environment surrounded by trees and nature, psychologically humans are still adapted to the natural environment due to which materials like concrete feel really cold whereas wood is considered a warm material and we feel comfortable in that environment. For thousands of years the human habitat was built using natural materials such as wood and stone which had no environmental impact.

From 1950 onwards the concrete started being more preferred as compared to other materials, few demerits of concrete are the high thermal conductivity and high carbon footprint. So, in the current society, which is concerning the environmental problems, timber has come into people's sight once again as a good construction material. "The renewed interest in efficient energy buildings, where it is possible to live healthy with reduced costs, is demonstrated by the increase of timber structure buildings in the real estate building sector"(Tonelli & Grimaudo, 2014).

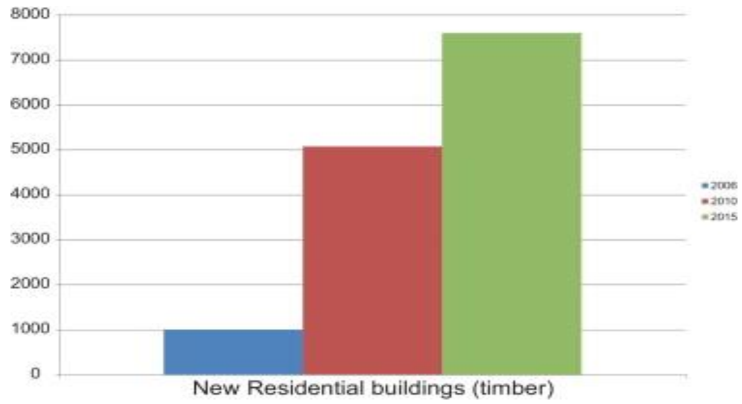

Chart-1: Trend of new timber residential buildings 2006–2015

As a natural construction material, timber is beneficial to human health. Researches have shown that patients who had a view of nature in the hospital had higher chances of recovering early. Wood has a soothing effect on humans, a study conducted showed that secondary school students had lower stress levels and decreased heart rate when exposed to wood (Kelz et al., 2011)

"The wood is a porous, permeable, hygroscopic, orthotropic, biological composite material of extreme chemical diversity and physical intricacy. Low thermal conductivity of wood is touted as one of its stellar properties"(Adekunle & Nikolopoulou, 2016).

However, although timber is used in construction more frequently for its green credentials and its healthy property, "the lack of thermal mass along with the low U-values can be a risk factor in increasing overheating"(Barbosa et al., 2010).

Keeping people feel comfortable in indoor environment is necessary for construction, even as the climate is becoming warmer.

Comfort is defined as 'a state of physical ease' (*Oxford Dictionary*). The feeling of comfort—or, more accurately, discomfort— is based on a network of sense organs: the eyes, ears, nose, tactile sensors, heat sensors, and brain. Comfort can be felt in the following aspects: thermal comfort, hygienic comfort, visual comfort, auditory comfort and olfactory comfort. And thermal comfort is an important aspect because the body of human being works at a specific temperature 37℃ is the body temperature and the skin temperature is 32℃.

This paper tries to find out what factors influence the thermal comfort in a wooden environment, does timber perform better in thermal comfort than other materials and how we can improve the thermal performance of timber buildings. Thermal comfort is calculated as a product of six parameters: air temperature, mean radiant temperature, air speed, humidity, metabolic rate, and clothing level (ASHRAE 55). In between these six factors, air temperature is the most possible one that can be affected by timber properties. Besides, there is a perceived thermal comfort which affect how people feel the thermal environment.
So, our focus on the question how do wood properties affect people's thermal comfort and this paper explore the relationship between temperature and timber properties, comparation of timber and other materials in thermal performance, timber and perceived comfort.

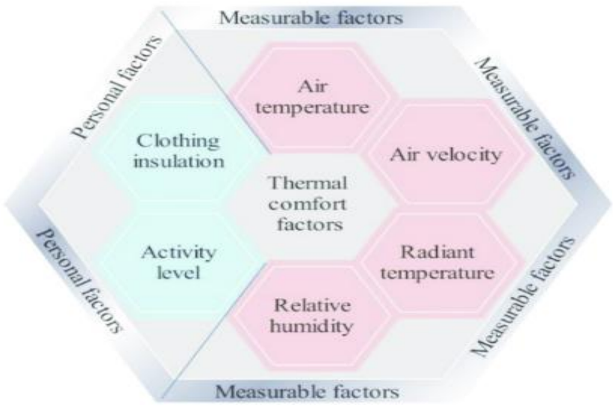

Fig-1: factors of thermal comfort

2. PROPERTIES OF WOOD
2.1 Thermal conductivity

Thermal conductivity k is a measure of the rate of heat flow (W/mk) through a material subjected to unit temperature difference (K) across unit thickness (m).

The thermal conductivity of wood is significantly lower than most metal and other materials like concrete which makes it a good insulating material.

There are a lot of factors that into play in terms of thermal conductivity of wood such as density, moisture content, grain directions, knots (Simpson & TenWolde, 1999). In dry state the thermal conductivity of spruce wood is 0.08 W/mK as compared to the red bricks and concrete whose thermal conductivity is 0.5 W/mK and 1.75 W/mK respectively (Vololonirina et al., 2014). The thermal conductivity strongly depends, on moisture content and density of the wood material considered with a linear relation(Tenwolde et al., 1988):

$$\lambda = d\,(a_0 + a_1 M) + k_0$$

where d is the dry density, a0 and a1 are two constants, M is the moisture content (percent of dry weight) and k0 is a constant.

Conductivity differs also in the direction for example radial direction or tangential direction or transversal direction. "Wood has an anisotropic behavior in thermal field: in the direction of the grain, for example, the wood thermal conductivity is about twice compared to the perpendicular one while similar values can be obtained for tangential and radial directions" (Peron et al., 2020).

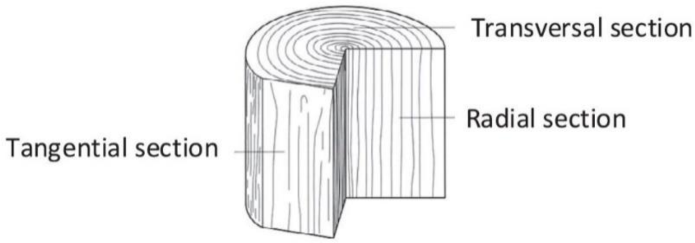

Fig-2: section of a log of wood

2.2 Thermal mass

Heat capacity is defined as the amount of energy needed to increase one unit of mass (kg or lb) one unit in temperature (K or °F). higher the heat capacity higher is the thermal mass. The heat capacity of timber and its products is significantly lower than brick (1360kJm3/K) and earth wall (1800kJm3/K)(Adekunle & Nikolopoulou, 2016).

There are three factors as followed that determine thermal mass.:

(1) Specific heat capacity

Specific heat capacity refers to a material's capacity to store heat for every kilogram of mass. A material of 'high' thermal mass has a high specific heat capacity. Specific heat capacity is measured in J/kg.K.

(2) Density

The density refers to the mass (or 'weight') per unit volume of a material and is measured in kg/m3. A high density material maximises the overall weight and is an aspect of 'high' thermal mass.

(3) Thermal conductivity

Thermal conductivity measures the ease with which heat can travel through a material. For 'high' thermal mass, thermal conductivity usually needs to be moderate so that the absorption and release of heat synchronises with the building's heating and cooling cycle. Thermal conductivity is measured in units of W/m.K.

2.3 Hygroscopic

Wood is hygroscopic in nature which means that it has the ability to absorb moisture from air. Thermal conductivity directly proportional with an increase in humidity and temperature(Vololonirina et al., 2014)

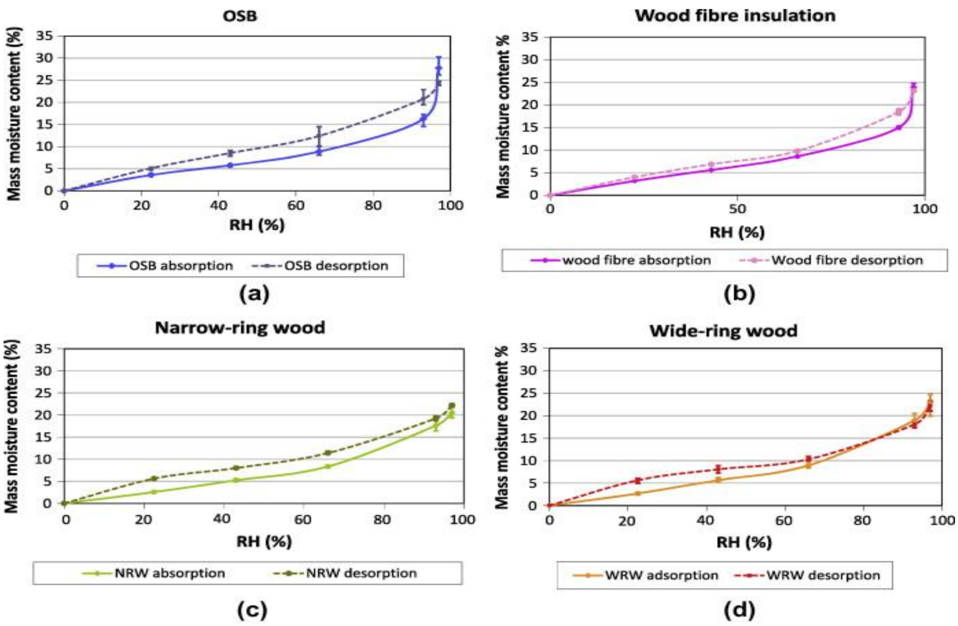

Chart-2: Sorption and desorption isotherms: evolution of mass moisture content with relative humidity at 20 °C of OSB (a), wood fibre insulation (b), narrow-ring wood (c) and wide-ring wood (d).

The four materials show a sigmoidal profile that represents the typical shape of the sorption and desorption isotherm for wood as for other hygroscopic natural materials including wool, cotton, etc. Wood-based materials are very hygroscopic compared to other building materials, such as terracotta or concrete.

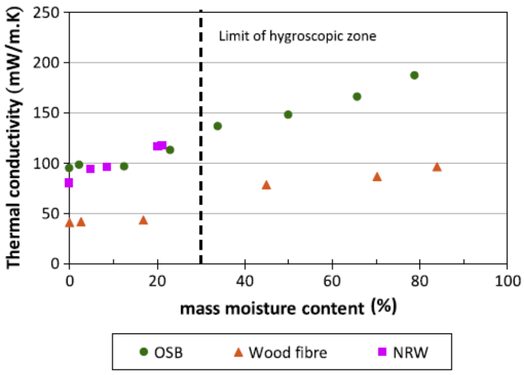

Chart-3: Thermal conductivity at 20 _C versus mass moisture content of OSB, Woodbfibre, Narrow-ring wood (NRW). Conductivity was generally not linear over the entire field of moisture content but had a visible linear trend when a small range of moisture content beyond the hygroscopic zone was considered.

2.4 Thermal expansion coefficient

Dry wood expands in when heating and contracts upon cooling which means that the coefficient is positive. A study conducted showed that the expansion and contraction was independent of the type of species of the wood rather it contracted and expanded parallel to the grains of the wood.

"In tests of both hardwoods and softwoods, the parallel-to-grain values have ranged from about 3.1 to 4.5 × 10-6 K–1 (1.7 to 2.5 × 10-6 °F–1)" (Glass & Zelinka, 2010).

3. DISCUSSION

3.1 Perceived thermal comfort

Perceptions means how we interpret information and in the case of thermal comfort different colours can alter our how we perceive temperature, this is referred as Hue-heat hypothesis (HHH)(Mogensen & English, 1926) This means the different colors have different effect on the perception. A study conducted showed that participants reported lower temperature when exposed to red light whereas higher temperature was perceived when shades of blue were shown (Chinazzo et al., 2018)

3.1.1 Setting

A study (Blankenberger et al., 2019) done in university of Oregon aimed to explore the impact of wood on perceived thermal comfort, subjective qualities of wood and the physiological responses. A total of 56 participants were chosen out of which 28 were males and 28 were females who were then subjected to different environment and the responses were noted down. The room was 12x8x9 feet in size and radiant temperature, room temperature, humidity and airflow are controllable. The walls were equipped with reversable panels which had wood on one side and gypsum board on the other side.

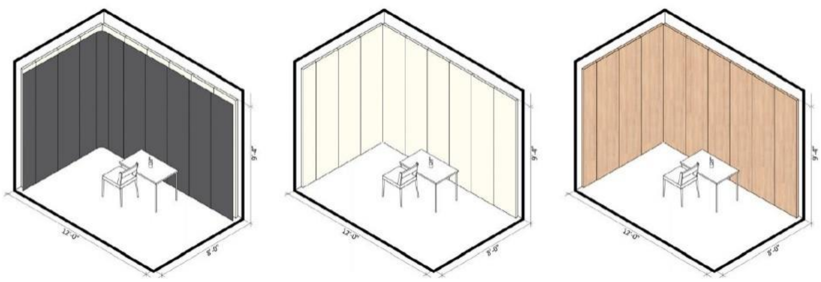

Fig-3: Types of wall treatment 1.1 black curtain (left) 1.2 gypsum wall (center) 1.3 wood (right)

3.1.2 Survey

After the first 20 minutes when the participants get adjusted to the environment survey is done at every 5 minutes where they have to describe the following. At the end of the survey participants were asked to the temperature.

Thermal sensation (TS)	At this precise moment, how are you feeling? (7-point scale)						
	Cold (-3)	Cool (-2)	Slightly cool (-1)	Neutral (0)	Slightly warm (+1)	Warm (+2)	Hot (+3)
Thermal acceptability (TA)	How acceptable is your thermal environment? (5-point scale)						
	Clearly unacceptable (1)	(2)	(3)	(4)	Clearly acceptable (5)		
Thermal preference (TP)	How would you prefer to feel now? (3-point scale)						
	Cooler (-1)	No change (0)	Warmer (+1)				
Temperature estimation (TE)	Open-ended (°F or °C)						

Fig-4: Thermal comfort survey

3.1.3 Procedure

Fig-5: Timeline of experiment

The acclimation period is the time during which a black curtain covered the wall treatment. At the 40-minute mark, the curtain was pulled away and participants then experienced either wood or white-painted walls for the treatment period.

3.1.4 Result

The responses of the two groups were noted down.

Wood		
	Q5|Q6	Q5|Q9
Thermal Sensation	0.39*	0.39*
Thermal Acceptability	0.21*	0.14*
Thermal Perception	0.11*	0.18
Temperature Estimate (°F)	-0.36	0.79

Table 1: Mean perceived thermal comfort results of wood

White		
	Q5|Q6	Q5|Q9
Thermal Sensation	-0.03*	-0.36*
Thermal Acceptability	-0.12*	-0.12*
Thermal Perception	-0.08*	0.10
Temperature Estimate (°F)	-0.04	0.50

Table-1: Mean perceived thermal comfort results of gypsum wall

More people preferred wood over white gypsum wall and related wood with positive qualities.

3.2 Heat transfer properties of Timber Framed Wall

A study (Liu et al., 2018)was conducted, heat transfer was measured of 12 different types of timber walls. The walls differed in different types of insulation, size of studs and sheathings. The heat transfer was measured by hot box heat flow meter test method. The hot box is divided in 3 parts hot box, specimen to be tested and cold box.

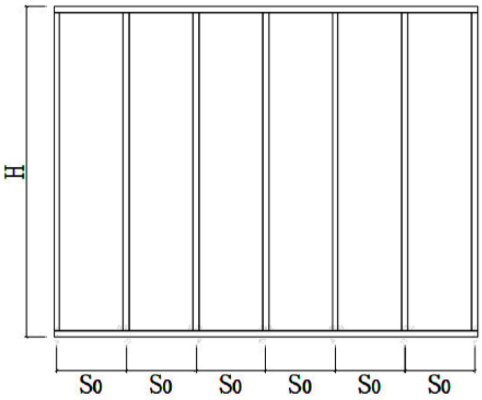

Fig-6: the wall frame

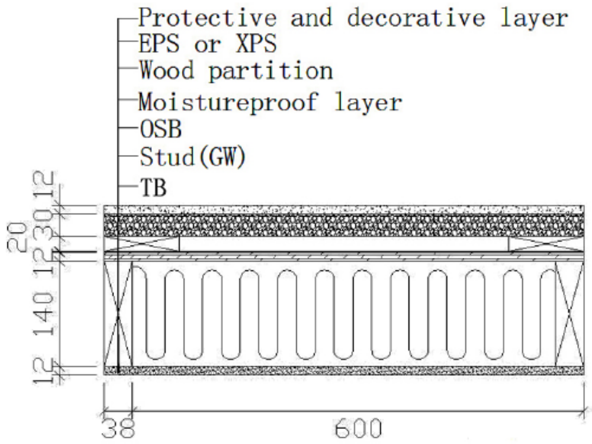

Fig-7: section of wall

Wall materials and frame structure design

Spruce pine fir (SPF) was used as the studs of wood frame walls. Oriented Strand Board (OSB) and Thistle Board Finish (TB) were used as sheathings.

Glass wool (GW) was used as insulation in the wall; for external insulation material either Expanded Polystyrene Sheet or Extruded Polystyrene Foam Sheet was used.

These are the details of the 12 different types of walls; the materials used, stud spacing, type of insulation used etc.

Samples	Stud spacing (mm)	Wall materials	Stud thickness (mm)
1	400	TB+GW+Stud+OSB	89
2	400	TB+GW+Stud+OSB+EPS	89
3	400	TB+GW+Stud+OSB+XPS	89
4	600	TB+GW+Stud+OSB	89
5	600	TB+GW+Stud+OSB+EPS	89
6	600	TB+GW+Stud+OSB+XPS	89
7	400	TB+GW+Stud+OSB	140
8	400	TB+GW+Stud+OSB+EPS	140
9	400	TB+GW+Stud+OSB+XPS	140
10	600	TB+GW+Stud+OSB	140
11	600	TB+GW+Stud+OSB+EPS	140
12	600	TB+GW+Stud+OSB+XPS	140

Table-2: Details of walls

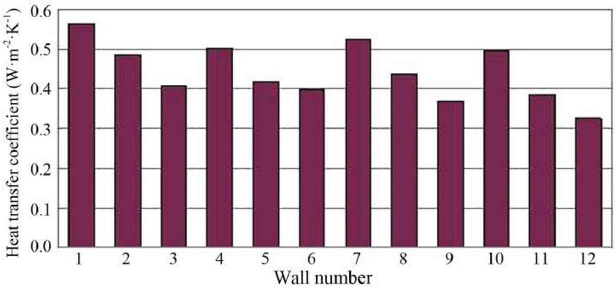

Chart-4: heat transfer coefficient of walls

Two types of stud thickness were 89 mm and 140 mm. heat transfer coefficient of 140 mm was less 0.006 as compared to 89 mm 0.073 W/m K thus thermal resistance of 140 mm stud was higher 0.59 m2K/W, the thermal resistance of 89 mm stud was 0.11.

Thermal resistance can be enhanced to improve thermal insulation performance of wall by increasing stud thickness.

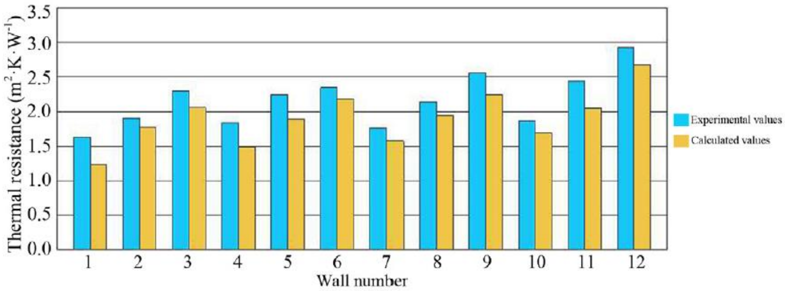

Chart-5: thermal resistance of walls

3.2.1 The thermal mass of timber

The thermal mass is determined by conductivity, specific heat capacity and density. Generally, timber is regarded as light-weight construction material, and considering its low conductivity and medium heat capacity at the same time, timber has poor performance as thermal masses comparing to heavy-weight materials like concrete. "In a climate that features warm winters and hot summers, the houses that perform better are heavy houses. Heavy stone or masonry walls work as thermal masses that guarantee winter comfort and absorb thermal loads in summer" (Tonelli & Grimaudo 2014).

A research (Martin & Miloš 2015) in the Czech Republic proves that "Wooden houses without thermal storage mass overheat more than typical brick houses" and "It is appropriate to increase the amount of thermal storage mass in these wooden buildings".

	Material	Specific heat capacity	Thermal conductivity	Density	Effectiveness
	water	4200	0.60	1000	high
	stone	1000	1.8	2300	high
	brick	800	0.73	1700	high
	concrete	1000	1.13	2000	high
	unfired clay bricks	1000	0.21	700	high
	dense concrete block	1000	1.63	2300	high
	gypsum plaster	1000	0.5	1300	high
	aircrete block	1000	0.15	600	medium
	steel	480	45	7800	low
	timber	1200	0.14	650	low
	mineral fibre insulation	1000	0.035	25	low
	carpet	-	0.05	-	low

Table-3: list of common material's thermal mass effectiveness

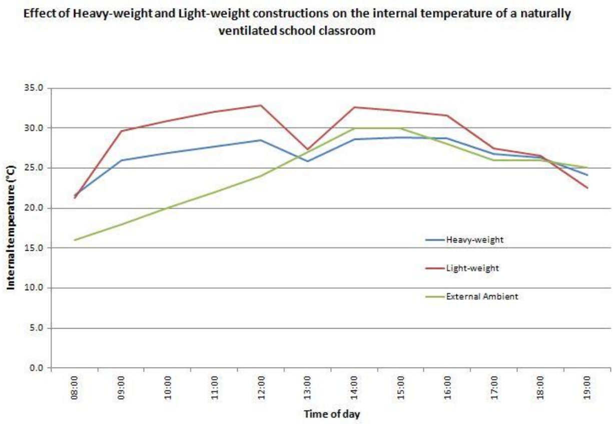

Chart-6: effect of heavy-weight and light-weight construction on the internal temperature of a naturally ventilated room

3.2.2 Improve the thermal mass of timber construction

For the poor performance of timber in thermal mass, people usually use the double-wall strategy to improve this performance during timber construction, with suitable ventilation. For example, in the Solar Decathlon International competition, the case "MED in Italy" conceived the envelop as a climate damper to optimize energy losses and gains and organized the envelop into two layers. "An inside layer, supplied with inertial mass in direct contact with the inside room, which allows heat accumulation at any time: the mass works as thermal fly-wheel both in winter and in summer. An outer layer, characterized by an insulating coat, allows the insulation of the building from winter cold and from summer irradiation. A cross ventilation during hot weather nights cools the mass carrying out the heat of house functioning accumulated during the day and so preventing that this is released inside during nocturnal time, as it happens in winter." (Tonelli & Grimaudo, 2014)

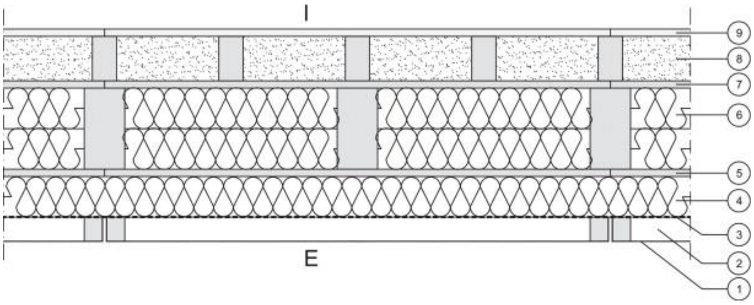

Fig-8: Wall stratigraphy with mass filled in a wall cavity

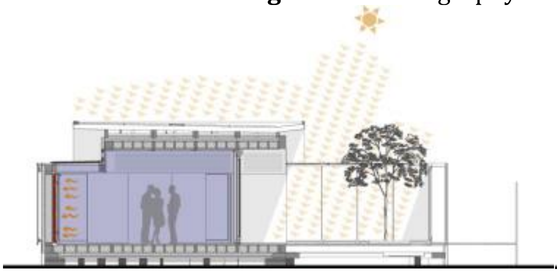

Fig-9: Bioclimatic scheme: summer behaviour (day)

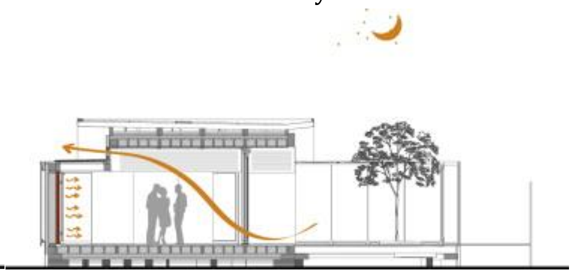

Fig-10: Bioclimatic scheme: summer behaviour (night)

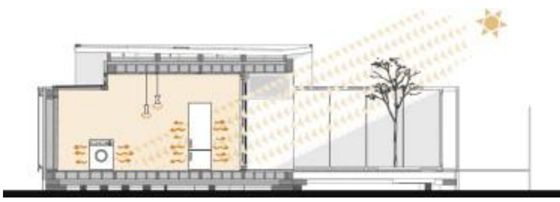

Fig-11: Bioclimatic scheme: winter behaviour (day)

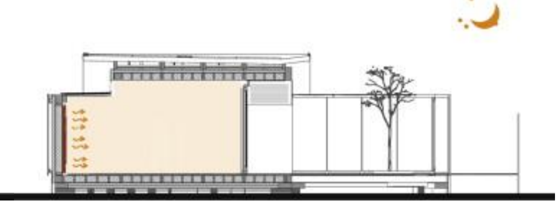

Fig-12: Bioclimatic scheme: winter behaviour (night)

3.2.3 Effective of thermal mass

(1) Thickness

Considering thermal mass on a daily cycle basis, the most effective depth of the material is the first 50 mm. Between 50 and 100 mm, efficiency further diminishes and beyond 100 mm the mass effect is largely inconsequential.

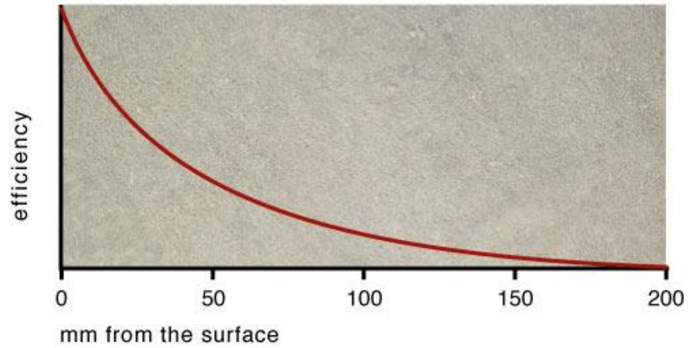

Chart-7: thickness of materials affects the thermal mass effect

The importance of thickness and thermal mass is a key in developing opportunities for including significant thermal mass in lightweight construction. A number of systems have been recently developed that demonstrate that although external walls can be of super-insulated timber frame type, internal finishes including floors, ceilings and partition walls can provide sufficiently high thermal mass without resort to masonry construction.

Fig-13: Exposed terracotta ceiling blocks providing thermal mass to timber frame construction

(2) Thermal storage mass

A research (Němeček & Kalousek, 2015)on thermal storage mass in the Czech Republic shows that “Heat storage capacity above 500 kJ m−2 is not effective in preventing overheating.” It defines a curve of the effectiveness of thermal mass in preventing overheating.

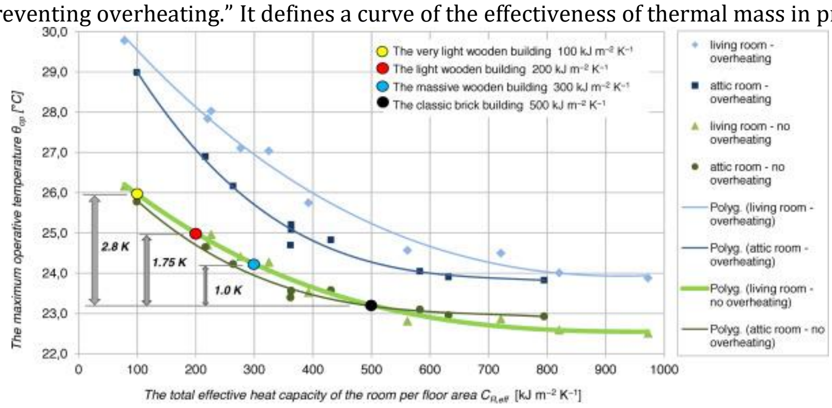

Chart-8: Curves describing the dependence between the maximum operative temperature reached in the interior and the total effective heat capacity of the room per floor area

3.3 Comparison of Cross Laminated Timber and Timber Frame

A study(Albatici et al., 2017) was conducted on two identical buildings whose only difference was the structural system. One building had Timber Frame structure (TF) and other was a Cross Laminated Timber (CLT) building. The buildings had identical floor plans and are located in Italy. Timber Frame buildings have been used for many years now, factory made components can be brought to site and installed but it is extremely light due to which the thermal mass is low. Cross Laminated Timber is made by sticking sheets of timber perpendicularly to each other. CLT shear walls are made and opening of windows and doors have to be precut; as compared to TF, CLT has a higher thermal mass. Microclimate stations were placed in the rooms to record the temperature.

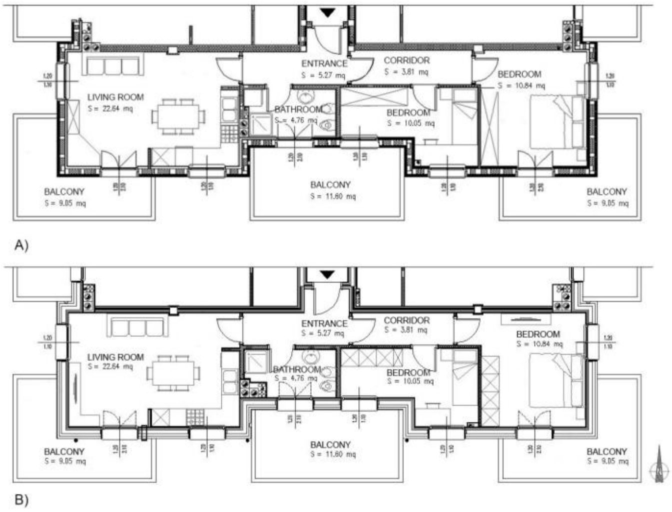

Fig-14: house plan (A) TF building and (B) CLT building

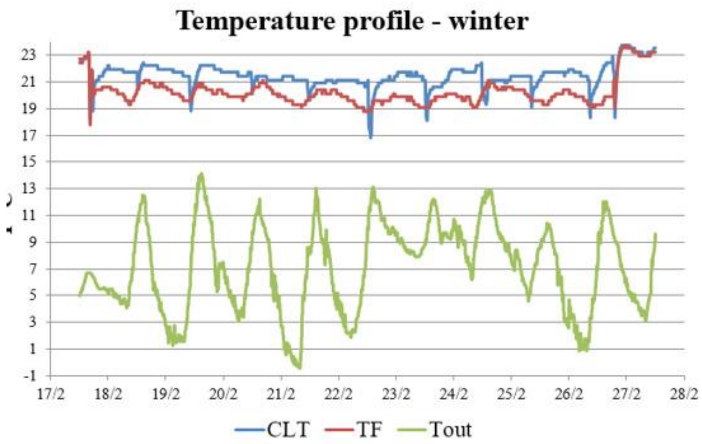

Fig-15: temperature profile in winter

During winter the average temperature recorded in CLT was 0.8°C lower than the TF.

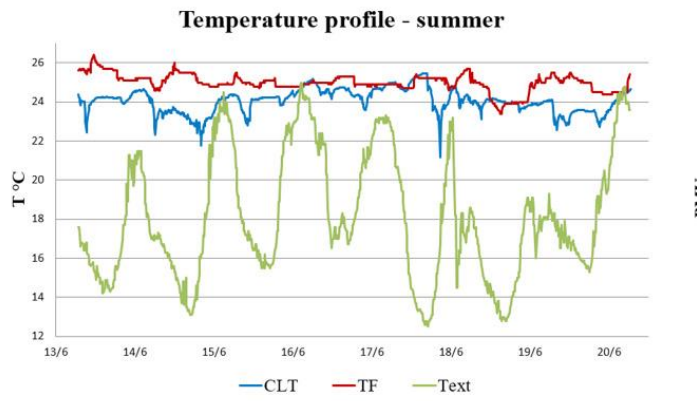

Fig-16: temperature profile in summer

During the first week of May when the minimum temperature was low then higher indoor temperature was recorded in CLT building. Whereas in June, when the minimum temperatures increased CLT building showed lower temperature than TF buildings.

3.3.1 Result

During the winter period the CLT is better at keeping the temperature stable because the thermal mass is high so the heat loss is less. May is less hot than June, TF buildings perform better in May because when temperature is lower at the night time then the TF is better at losing the heat and cooling the indoor environment. When the temperature increases then CLT buildings are more efficient. In most of the conditions CLT is better than TF.

4. CONCLUSION

4.1 General conclusion

- Factors influencing thermal comfort in a wooden environment are perceived thermal comfort conductivity thermal mass, hygroscopic.
- Timber has good performance in thermal comfort because of perceived thermal comfort and high conductivity, and has poor performance because of low thermal mass.

4.2 Perceived Thermal Comfort

- Participants who were exposed to wood were more comfortable and gave more positive responses.
- Participants exposed to gypsum white wall felt the environment could be a little cooler which means they were uncomfortable.

4.3 Timber Framed Wall

- The heat transfer in walls which had 600 mm spacing was less because less studs meant more space for glass wool which is good at insulating.
- Insulation performance of XPS was superior to those of EPS.
- Sample wall 12 which had glass wool insulation, OSB, XPS, TB, 140mm stud at a spacing of 600mm showed the best thermal insulation properties.

4.4 Thermal mass and thermal comfort

- Wooden houses without thermal storage mass overheat more than typical brick houses, and it can be improved by adding thermal mass through some strategies.
- The efficiency of thermal mass and local climate environment should be noticed when adding thermal mass.

4.5 Comparison of TF and CLT

- TF will be a better option for places who have a huge variation in temperature in a single day.
- In most scenarios CLT would be better because of high thermal mass and heat transfer coefficient is 0.15 W/m2K.

4.6 Hygroscopic

- If the relative humidity is low then it is favourable because the moisture content of wood is also low which leads to low thermal conductivity.
- For wood and wood products, the optimum range of moisture content was from 0 to 30 %. 30% is the limit of hygroscopic zone. Thermal conductivity increases significantly if moisture content is more than 30%.

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