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Exploring the relationship between structurally defined geometrical parameters of reinforced concrete beams and the thermal comfort on indoor environment

Daniel Sang-Hoon Lee [a] *, Emanuele Naboni [a]

[a] *Royal Danish Academy of Fine Arts, School of Architecture, Design and Conservation, Institute of Architecture and Technology*

Abstract

The paper presents a research exploring the thermal mass effect of reinforced concrete beams with structurally optimised geometrical forms. Fully exposed concrete soffits in architectural contexts create more than just visual impacts on the indoor climate through their possible interferences with light, sound and thermal conditions. It is considered that the characteristics of interferences would have close relationship with material and geometrical properties of the soffits; especially when the soffits are other than flat form. In the current investigation the relationship between the thermal mass effect (and the implication on thermal comfort) and the given geometrical parameters of exposed soffit reinforced concrete beams are explored.

The geometrical parameters of the beams are initially defined in means of structural optimisation. The beams consist of flange and web in likeness of T-sectioned beams. However, both flange and web are curved vertically for the required bending and shear capacity of the sections. At the same time, the web is also curved horizontally for increased shear capacities. In the research, both the vertical and horizontal geometrical parameters are varied to observe the resultant heat exchange behaviour, and the implication on thermal comfort indoor environment. However, the current paper presents the thermal mass characteristics of one geometrical type.

The study is based on results derived from computational fluid dynamics (CFD) analysis, where Rhino 3D is used for geometrical modelling of the beams and office space.

Keywords: Indoor Thermal Comfort, CFD, Geometrical Optimisation, Integrated Design Solutions, Exposed Concrete Soffit

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* Corresponding author. Tel.: +45-41701646
E-mail address: Daniel.lee@kadk.dk

1. Introduction

Research and developments for more innovative applications of thermal mass has its fundamental aim in the utilisation of initial embodied energy for minimising the total operational energy consumed from heating, cooling, and for other powering appliances. The accurate applications of thermal mass for indoor comfort requires more complex insights to how materials respond in dynamic environments based on numerous correlated variables. Throughout the decades global researchers have developed numerous analytical methods, and explored to identify significant factors that govern thermal mass effects. In contexts of forced convection, the explanation of heat transfer mechanism for thermal mass effects becomes more complex as it involves dynamic airflow, which is rapidly influenced by both material and geometrical configurations of the given three-dimensional space.

In both cases of natural and forced convection, the heat transfer between air and thermal mass is closely affected by geometrical configurations of the given space; dimensions of the space, furniture layouts, window locations and sizes, air inlet and outlet locations and the capacities, locations of heat sources etc. For such complexity, there is limit to develop further insights using only two-dimensional based analytical methods, and full-scale experiment based research methods often have restrictions with resources.

It is one of the main intentions of the current research to examine and explore the known thermal mass effects on indoor climate through application of computational fluid dynamic (CFD) method. Depending on the nature of the analysis and size of the built models, CFD analysis can demand high-performance computation specifications. However, with increasing efficiencies of computational analysis methods; in conjunction with growing possibilities of cloud-based computing methods, CFD seems to be one of the most economical and practical methods for current investigation purposes.

Nomenclature

A	surface area of mass
a	thermal diffusivity
c	specific heat capacity
h_c	convective heat transfer coefficient
k	thermal conductivity
q	rate of energy transfer
T_{air}	air temperature
$T_{surface}$	surface temperature of building element
v	velocity
ρ	density

2. Literature Review

2.1. Thermal Mass and Building Components

Thermal mass characteristics and adequate design application of concrete for reducing mechanical cooling as well as heating energy for indoor comfort have been widely discussed as part of academic discourses. In warmer climates, indoor temperatures often increase above thermal comfort level of the occupants. Thus, the excess heat is directly controlled by mechanical air-conditioning systems. The amount of energy used for the air-conditioning can be reduced through active use of building's thermal mass; the excess heat in an indoor space is absorbed by building elements such as walls and floors. The rate at which the heat in the air is transferred/absorbed into the building elements can be described as below:

$$q = h_c A(T_{air} - T_{surface}) \tag{1}$$

Thus for a given surface point of a building component, the rate of energy transfer, q, increases with the temperature difference ($T_{air} - T_{surface}$). As long as there is a difference in ($T_{air} - T_{surface}$) there will be a heat flow; when the difference value is positive there is heat transfer from the air to the building component, and for the difference value is negative heat will transfer from the building component to the air. In between the positive and negative difference is zero difference; where no heat transfer occurs, yet such condition exists only shortly in real dynamic environments.

Thus in case of an office building during the warm season, the indoor air will first be heated from the heat sources such as human bodies or electrical components (computers or coffee makers); which then transfers the energy to exposed building components such as walls, floors and ceilings by convection. Therefore, as the building components absorb the heat energy from the air, the increment rate of the indoor temperature reduces accordingly. It is important that the absorbed heat be released back to the atmosphere during the non-occupancy hours, leaving the thermal mass ready again to take on the heat from the next day. There are three physical properties, which are often mentioned related to thermal mass characteristics; $\boldsymbol{k}$ = thermal conductivity, $\boldsymbol{\rho}$ = density and $\boldsymbol{c}$ = specific heat capacity. Often, thermal diffusivity, $\boldsymbol{\alpha = k/ \rho c}$, is mentioned related to the speed at which thermal profile develops through a mass. However, thermal diffusivity may not be the most suited for thermal mass discussion, as it does not reflect the actual energy storage. Thus for the actual indication of how fast energy penetrates through a mass can be given by the thermal penetration property, $\boldsymbol{k\rho c}$ [1].

2.2. Concrete Thermal Mass and Energy Efficiency

As it was discussed for Eq. 1, more heat from the air will be absorbed to the building components when the temperature difference ($T_{air} - T_{surface}$) is larger. One of the methods to increase the temperature difference is to drop the $T_{surface}$ of the building components through night ventilation. Night ventilation is an important strategy as it increase the amount of heat released back from the building components, and preparing them again for the next day's heat absorption. Natural night ventilation concept has been investigated as an energy efficient method to enhance the thermal mass property of concrete elements. As the indoor heat has been taken away by the thermal mass of exposed building components, resultantly less mechanical cooling energy is required. Such concept has been actively developed under load shifting control strategies.

Based on numerical simulations studies predicting cooling load over 10-day sequence, office buildings in La Rochelle, a city located southwest of France, pre-cooled by night ventilation with airflow rate of 4500 m^3h^{-1} could save 177 kWh, which is approximately half of the required mechanical cooling energy, 320 kWh [2]. The effects of night ventilation on the daytime indoor comfort are summarised below by Kolokotroni & Aronis [3]:

a. Reducing peak air-temperatures
b. Reducing air temperature throughout the day, and in particular during the morning hours
c. Reducing slab temperatures
d. Creating a time lag between the occurrence of external and internal maximum temperatures.

According to the research for an average 5000 m^2 office, there could be 1050 – 2230 GBP/annum (equivalent to 1550 – 3300 USD/ annum) saving [3].

The article by Braun [4] indicates that with more optimal precooling control strategy with night ventilation adopted, there could be total energy cost saving of 41.4% in commercial building. A comprehensive review on load shifting control strategies was published by Sun *et al* [5]. The review, including different thermal storage facilities; building thermal mass (BTM), thermal energy storage system (TES) and phase change material (PCM), addresses that current investigations show 'the load shifting control using building thermal mass can achieve more than 30% daily peak load reduction and a significant overall cost saving from 8.5% to 29%'

2.2.1. Exposed Soffit Concrete Floor as Thermally Active Element

Concrete floor elements have seen active developments as the main thermal storage unit. The core mechanism for such systems is at enhancing convective heat transfer between the floor and the adjacent air by initiating increased air flow either i) on the surface of the floor [6] [7] or, ii) through hollow core within floor slabs [8] [9] [10]. A combined system may use both the airflow system through hollow core with exposed soffit. The direct thermal storage system with exposed soffit can be used in conjunction with natural night-time ventilation, whereas indirect hollow core airflow system is main applied in connection with mechanical ventilation system. The direct system with exposed soffit had advantage as it has higher total surface heat transfer value (radiative and convective) at 7-8 W/m^{2}K, whereas the indirect system with hollow core slabs has sole convective heat transfer value of the voids at 2-3 W/m^{2}K [7]. However, in a climate where the external temperature is above 35 °C, it could be beneficial to use the thermal mass in conjunction with mechanical cooling system. For such cases, it could be more justifiable to use exposed soffit concrete floor as thermal mass, in conjunction with more energy efficient convection HVAC systems, such as Chilled Beam system [11].

2.2.2. Design Parameters for Enhanced Heat Exchange Characteristic

Based on Eq. 1, the rate of heat energy transfer is governed by three main parameters:

- Convective heat transfer coefficient
- Surface area
- Temperature difference

For an indoor space, the magnitude of convective heat transfer coefficient mainly depend on the orientation of the thermal mass element in relation to the direction of heat flow. The following values can be used as initial reference for still air conditions, where the air speed at the surface is not greater than 0.1 m/s [12]:

- For vertical surfaces (horizontal or parallel heat flow) $h_c = 2.5$ W/m^{2}K
- For horizontal surfaces
  - Heat flow up (air to ceiling, floor to room air) $h_c = 5.0$ W/m^{2}K
  - Heat flow down (air to floor, ceiling to room air) $h_c = 0.7$ W/m^{2}K
  - As hot air rises, the upward heat transfer is stronger.

When the surface is exposed to wind or mechanically ventilated airflow, and thus the air velocity, $\boldsymbol{v}$ is greater than the above, and then the convective heat transfer coefficient can be estimated from the following empirical equation [12]:

$$h_c = 4 + 4v \tag{2}$$

The above values are to be used for steady-state analysis of heat transfer. For transient analysis the convective heat transfer coefficient is calculated and updated at given time-steps; in respect of surface temperature difference, velocity and air flow characteristic (laminar or turbulent) on the point of calculations, and as the parameters also vary depending on the points of calculations over the given surface area of the thermal mass. Over a number of decades many research have been carried out to develop more simplified correlation-based empirical formulae. However, there can be large differences between the calculated coefficients based on different formulae; as the formulae are developed for specific enclosed space's geometry [13]. The discrepancy will be greater as the geometrical forms of the buildings elements become more complex. The possible representation method of translating complex geometrical surfaces into more analytically friendly flat slab with equivalent volume and increased convective coefficient has been discussed [14]; but such model seems insufficient as calculating the corresponding convective coefficient is already problematic.

Research that is more comprehensive was carried out to develop adaptive algorithm for surface convection in cooperation with computational fluid dynamics techniques [15]. Yet the study still indicates high discrepancy for predicted energy consumption with forced convections.

3. Scope of Current Investigations

The effects of thermal mass on saving mechanical energy have been discussed by numerous research as above demonstrated; and yet there exists discrepancies between theoretical calculations and actual measure energy consumptions. The main cause of discrepancy may due to the complex nature of convective heat transfer based on different airflow characteristics in an indoor space. During the literature review it has been pointed out that, the indoor airflow is affected not only by material characteristics of the thermal mass, but also due to geometrical parameters.

The current investigation is proposed to explore the thermal mass effect of form-active reinforced concrete beam with exposed soffit. The term, ‘form-active’ refers to geometrically optimised structural form, which was developed with the aim to increase the level of material-utilisation; in other words, the materials in most part of the structures are used close to their yield capacity. Thus there are reduced amount of in-active mass of materials, thus it is more sustainable in terms of material consumption.

The research specifically explores thermal mass effects of ‘form-active’ beams developed by Lee [16]. The research states that the beams required 27% less embodied energy in construction, when compared with T-section beams with the equivalent structural capacity. Such reduction in embodied energy is from the beams’ efficient geometrical forms, which can provide the same load carrying capacity with less material. Thus, it is the interest of the current investigation to explore the possible thermal mass effect of such geometrically optimised reinforced concrete beams, with the interest in finding additional environmental impacts of the beams with reduced embodied energy on indoor comfort. The investigation commenced by identifying geometrical parameters of the form-active beam that would affect air movement, and eventually the convective heat transfer characteristics in the indoor space. The geometrical parameters are varied for comparison of resultant indoor temperature fluctuation with the case of flat ceiling. Again, the main objective of the currently presented investigation is to explore the possible thermal mass effect of the beams in specific structurally optimised forms. Therefore, it is not within the scope of current investigation to study within the context or model size of, for example, an entire office space. Such investigations should follow at later stage of the research, and it will require model developments into more realistic building indoor parameters including the plan layouts, locations of the windows, orientation of the building and arrangements of furniture. At the current stage, such additional parameters will only hinder the understanding of fundamental thermal mass behaviour of the specific beams under observation, and thus the current investigation observe the thermal mass behaviour of the beams within the context of confined spatial definitions.

Due to the complex three dimensional investigation context, which involves dynamic energy flows, the current investigation explores the application of computational fluid dynamics (CFD) method to understand heat transfer within the context of a) Natural Convection in a closed environment and, b) Forced Convection with inlets of external wind through opened windows, and outlets of ventilation opening. In either cases, the main observation point is how effectively the ambient heat is transferred to exposed soffit through surface air movement; characterised by specifically defined surface geometry.

4. Geometry of Form-active Beams (FABs)

The construction of reinforced concrete elements in complex geometrical forms is difficult to justify with conventional rigid formwork, which uses plywood, steel or aluminium as the main formwork material. It often comes with greatly increased costs of materials and labour, as the rigid and prismatic materials must be processed to create doubly curved forms. However, such forms can be built with increased practicality and reduced cost when constructed using flexible fabric formwork. Fabric formwork for more sustainable concrete construction have been explored by a number of researchers and practitioners throughout the history; which in result provided design opportunities to explore cross-objective based building components for concrete [16] [17].

The physical profile of form-active beams (FABs) [16] is defined by the following geometrical parameters:

a. Web depth: the varying web depth to suit the required bending moment capacity of the beams are one of the most distinct feature of the beams, which was considered to have the most significant influence on the surround air flow and thus the overall heat exchange mechanism.

Fig. 1. Side view of a FAB – Web Depth

b. Flange arch: the thickness of flange varies in respect of the induced principal stresses in flange that follows so called, the ‘compression force path’. The gradually increased flange thickness towards the ends was designed to increase the strength with respect to diagonal tension failure.

Fig. 2. Side view of a FAB - Flange Arch

c. Web width: the lateral profile of the web was designed to increase material utilisation as well as effective shear stress distribution between flange and web at sections closer to the ends.

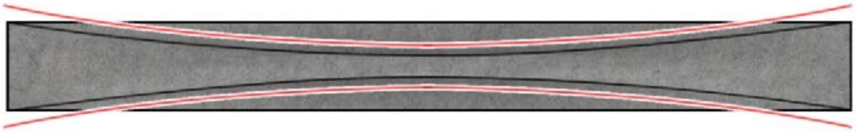

Fig. 3. Reflected ceiling view of a FAB - Web Width

Fig. 4. (Left) perspective view of FAB, (Right) mid-span cross-section

5. Study Models

5.1. General Scheme

The purpose of the experiment is to study thermal mass characteristics of FABs (with structural defined geometry) in comparison with conventional flat ceiling with equal volume. For the studies, a three dimensional computational model has been created in reference to the current office space of the author at the Royal Danish Academy. In fact, only the half of the two-person shared space has been created for single person study as well as relevant simplification for computational analysis. The model space has floor area of 7.08 m^2 (3.16m x 2.24m) with the effective heights of the air space below the ceiling vary between 0.582 to 0.47m; depending on the type of the ceiling and measured location. Please note in normal office environment, the height of air space between the ceiling and the floor is around 2.4m. However, such height is not modelled in the current studies as the interest of the investigations lies within the heat exchange characteristics between the ceiling and the adjacent air volume. More detail descriptions of the studies are as follow;

5.2.1. Study for Heat Absorption Behaviour

The study assumes that the indoor environment has starting temperature of 19 °C. Then total heat flux of 100W

[12] entered the air volume through the bottom surface; over the course of eight hours, which is based on the duration of a normal 9:00 to 17:00 office hours. Then the heat is removed and the room is left in the condition for seven hours.

5.2.2. Study for *Heat Dissipation Behaviour*

At 17:00 time, the heat is removed from the model, and left in the condition for seven hours; reflecting until mid-night. Thus, the study is investigating heat dissipation behaviour of the ceilings in adiabatic condition, where there is no addition/extraction of energy from the environment after the initial 100W boundary condition was removed. The intention for carrying the study firstly based on adiabatic condition is mainly for other ventilated conditions the development of understanding around heat dissipation behaviour would become more complex as there would be additional factors affecting the behaviour, and these factors must be studied in more significant manner.

5. 2. Ceiling Profile

The ceiling profile with FABs is created based on the beams dimensions given in Lee [16]. There are total seven beams in the model with 3.16m span. Each beam has the mid-span depth of 285mm, and the flange thickness varying from 80mm at supports to 40mm at the mid-span. Each beam has volume of 0.095 m^3, which for seven beams equals to 0.665 m^3.

Fig. 5. Flat Ceiling and Air Volume for CFD analysis

Fig. 6. FAB Ceiling and Air Volume for CFD analysis

5.2. Model Boundary Conditions

There are two parts in the current study. The first part is to observe heat absorption behaviour of the two ceiling types, and the second part is to see how they lose heat, firstly in adiabatic condition and secondly in a ventilated condition.

6. Results and Discussions

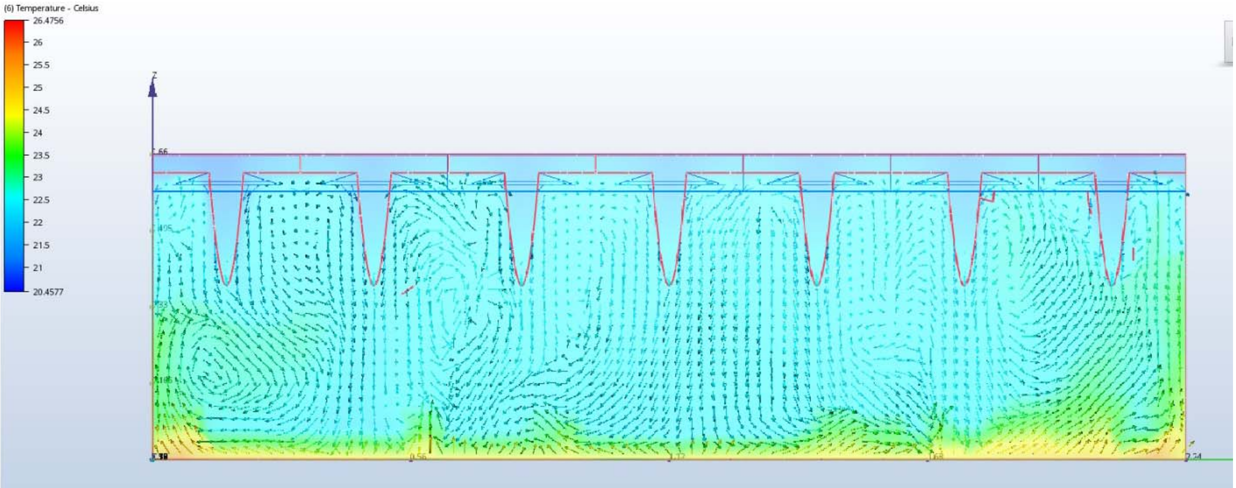

Fig. 7. An image of a CFD result for FAB ceiling

6.1. Heat Absorption Study

After eight hours exposure to 100W energy, the indoor air temperature rose to around 23 °C from the initial 19 °C. The CFD analysis results showed that the indoor air temperature at a fixed point was approximately 0.4 °C lower in the model with FAB ceiling than with flat ceiling. Initially the temperature was lower by 0.6 °C, which then reduced to about 0.2°C around 17:00. Thus, the result shows that the temperature difference in the indoor air between FAB and Flat ceiling decreases with time (Fig. 8.). It can be also seen from the graph of temperature variation at ceiling surface point (Fig. 9.) that FAB ceiling's temperature increased at higher rate than flat ceiling.

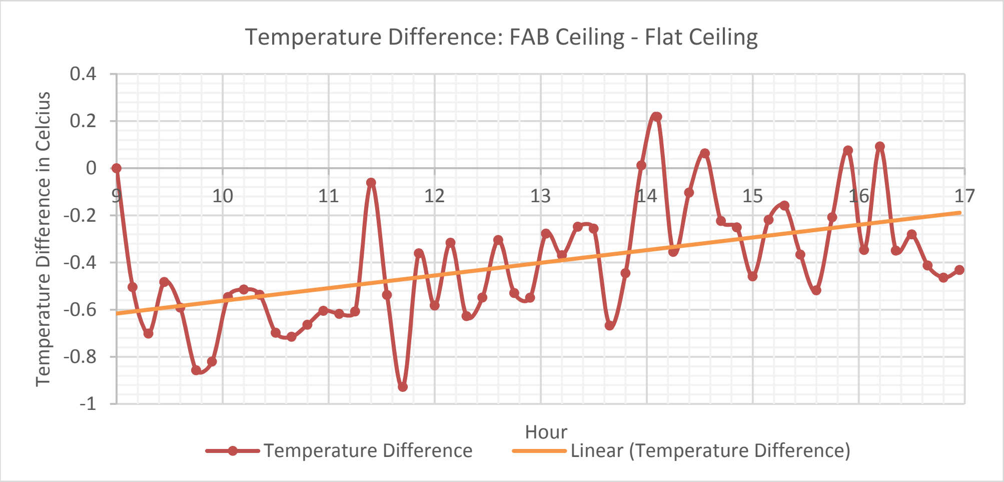

Fig. 8. Graph of Temperature difference between the FAB and the flat ceilings.

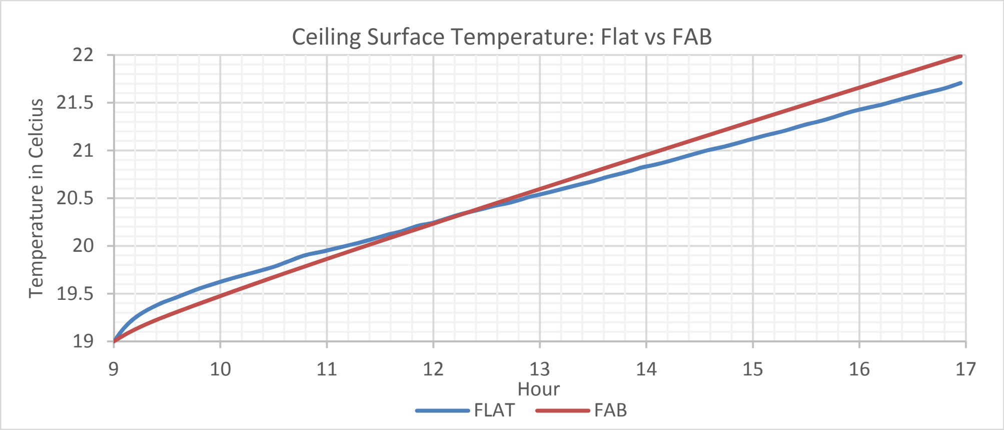

Fig. 9. Graph of Ceiling surface temperature comparison

6.2. Heat Dissipation Study

At 17:00 hr, the 100W heat source was removed from the model. The results showed that in case of the flat ceiling, the temperature of both air and concrete ceiling drops to reach a balance temperature point. The air temperature drops significantly more than the concrete ceilings to reach the balance point. However, in case of FAB ceilings, the balance point takes much longer to reach. While the temperature of air and concrete dropped concurrently in case of flat ceiling, the temperatures of FAB ceilings dropped at a very slow pace even after the air temperature dropped below the ceiling temperature.

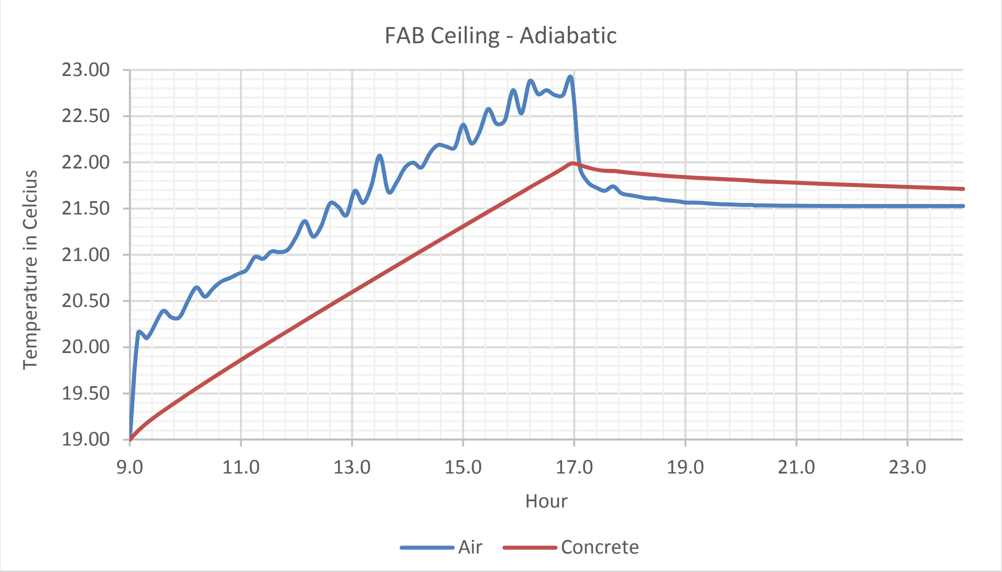

Fig. 10. Graph comparing temperature variations of ambient air and FAB ceiling

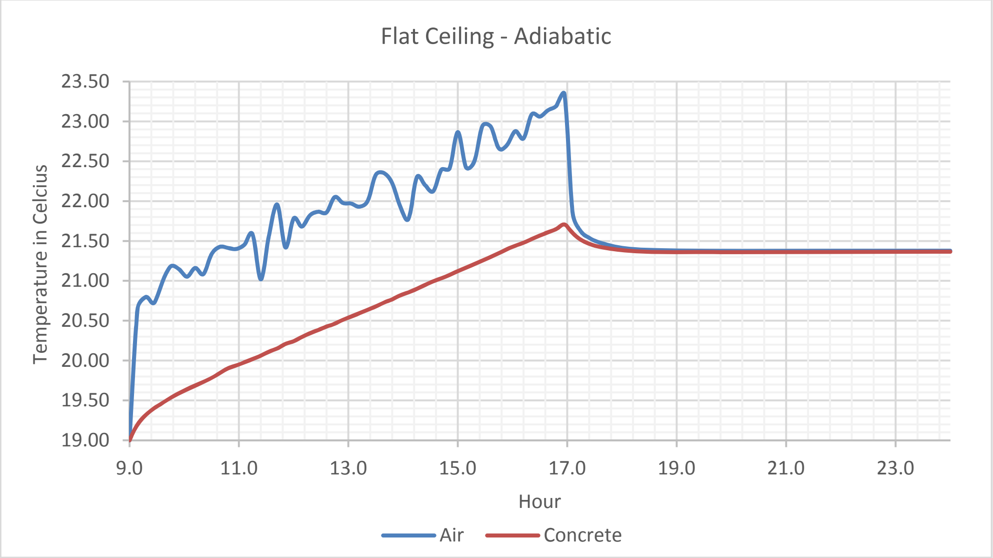

Fig. 11. Comparison graph of temperature variation between indoor air and the flat ceiling

7. Summary and Conclusions

The paper presented investigations carried out as part of a research exploring the effects of geometrical parameters of FABs ceiling on indoor thermal climate. The results based on CFD analysis showed that an indoor space with FABs ceiling could lower the indoor air temperature by 0.4 °C. A possibly explanation could be due to the faster heat absorption rate of FABs; owing to their increased surface geometrical profile in comparison with flat ceiling. However, over a longer period, the difference of indoor air temperature between FABs and flat ceilings would decrease. The analysis of heat dissipation in adiabatic condition showed that the temperature drop in FABs is significantly slower than flat ceiling, and this may indicate that night ventilation strategy would be essential for FABs ceiling.

From the CFD analysis, it was possible to map different heat flux values over the ceilings' surface area. This would allow calculating convective heat transfer coefficients at specific locations; which could be further studied with the adjacent airflow characteristics to modify the geometry of FABs accordingly.

However, it is to state also that accuracy of such analysis results is heavily depending on a number of factors including the mesh size, and further work for increasing the accuracy of results are currently in process.

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