Assessing external double skin envelopes coupled with night ventilation and thermal mass for passive cooling in the tropics

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Abstract: The paper conceptualizes and investigates the potential of utilizing double skin envelopes consist of thermal mass coupled with night ventilation for passive cooling in warm humid climates. On-site thermal performance investigations resulted in redefining thermal mass effect in double skin envelopes. The work demonstrates that thermal mass in the double skin envelope contributed to work as a heat sink thus promoting passive cooling although the tropics are characterized with slight diurnal ranges as compared to hot dry climates. Results provide evidence of passive cooling with internal air temperatures moving 2-3.5 degrees C below the ambient levels due to envelope dependency with heat removal, stack force and night ventilation primarily created due to double skin envelopes. Findings show empirical evidence of passive cooling suggesting that the double skin envelopes can play a positive role in addressing extreme climatic conditions.

Keywords: Passive cooling, External double skin envelopes, Thermal mass, Night ventilation.

1. Introduction

Validity of energy sustainability of buildings lies in the optimization of climate, building and occupant interplay. This is known as bioclimatic design (Olgay, 1953). This interplay when manipulated properly using passive strategies can reduce energy demand in buildings (Syzkolay, 1987). In the context of the tropics, where climate plays a major role in making buildings overheated much energy is consumed for cooling purposes. Thus, passive cooling becomes vital. However, with the complexities involved with climate interaction, the components of building design can play a dual role in climate response. For example, envelopes can promote daylight and ventilation, but heat gain through daylight and ventilation can be a problem in making buildings truly climate responsive and sustainable in terms of operational energy. A previous study (Rajapaksha et al, 2015) conceptualized a set of interventions involving a double skin envelope for passive cooling in tropics. The specific focus of this research is worked out in further justifying this concept and presenting the significance of design interventions at the building envelop level for building – climate interplay with a filed investigation.
2. Buildings in the tropics and indoor overheating

Climate responsive design is based on the way a building form and structure, moderate climate for human good and well-being (Hyde, 2000). Environmental load dominancy is a common behavior in tropical warm humid climates if the building design does not behave as a selective mode (Hawks, 1996). However, buildings located in warm humid climates face more challenges when perform as selective mode of operation due to the penetration of irradiation through openings or glazed areas and the heat flow through the external wall surfaces and roof into indoor spaces. This results in an indoor heat gain, role of natural ventilation being in conflict and seen as an unresolved duality associated with thermal performance functions of the building components, in particular building envelope.

2.1. Passive cooling, ventilation and thermal mass.

Passive cooling has the potential to cover almost all the processes and measures which support to minimize the cooling requirements of buildings in warm climates. It consists of each and every preventive method to avoid overheating of building interior, strategies that reject the heat entering through the building envelop and remove heat generated within the interiors of the building. The modification of climate variables is possible by the effects of basic passive strategies. As shown by the bioclimatic charts, the comfort zone can be extended within the given outdoor temperature ranges by using following effects with the use of building design; Airflow effect and Thermal mass effect with night ventilation

2.1.1 Limitations in ventilative cooling

However, ventilation can create a heat gain in buildings in warm climates and seasons. This results in the interests of controlling overheating and the role of natural ventilation being in conflict (Rajapaksha, 2004). The prevention of overheating is a useful pre-condition for passive cooling of buildings and natural ventilation is desirable when the outdoor air is at a lower temperature than the indoor air or when it can prevent the elevation of the indoor temperature above the outdoor level, caused by direct or indirect solar gain (Givoni, 1998).

2.1.2 Thermal mass for climate modification in tropics

The thermal mass of a building absorbs heat during the day and regulates the magnitude of indoor temperature swings, reduces peak cooling load and transfers a part of the absorbed heat into the night hours (Antinucci, 1990). The most important features of thermal mass are the moderation of internal temperatures by averaging diurnal (day/night) extremes (stabilising internal temperatures) and delaying the time at which peak temperatures occur inside. This is more effective in maintaining indoor air temperatures within comfort limits if the mean outdoor temperature of the day does not exceed the comfort limits and the nocturnal ventilation is coupled with the thermal mass. Thermal mass can act as a heat sink. When interact with climate, some of heat is stored, and released later to the environment or indoor spaces when the outdoor temperature reaches its peak and starts decreasing. This is a repetitive cycle over a 24-hour period, referred to as periodic heat flow (Koenigsberger et al, 1974:83). This behaviour of thermal mass can influence the thermal behaviour and thermal landscape of a building and thus the indoor air temperature. Two previous studies (Rajapaksha, 2014,2015) suggest that high mass envelop coupled with night ventilation has the potential to lower the indoor air temperature than the
ambient during daytime and restore indoor thermal comfort even in February, March, April and May, the warmest period of the year in Sri Lanka.

3. Thermal performance of External Double Skin Envelopes (EDSEs)

External double skin envelop offers an opportunity in softening the transition and dialogue between inside and outside. It is a manipulation of mutual connectivity between the indoor environment of the shelter and the natural environment. Thermal performance of external double skin envelops (EDSE) depends greatly on the architecture of the EDSE and chosen means of “building + climate + occupant” interplay. Daylight and ventilation can be two of the main concerns for a selective mode building where building design plays a major role in modifying indoor climate in maintaining indoor comfort. Authors have attempted to classify EDSE in respect to thermal performance expectations of climate types (Beldinelli, 2009). The work highlights that approach to EDSE has to take the climatic factors into account to improve climate response and thus energy efficiency.

Indoor air temperature behavior in and around a double skin envelop and thus inside a building are results from many concurrent thermal, optical and fluid flow processes which interact in a dynamic way (Haase et al, 2009). These mechanisms greatly depend on the geometric, thermo physical, optical and aerodynamic characteristics of the EDSE and building design itself. The complexity of this concept and technology requires an appropriate composition of all design variables involved namely “microclimate, plan form, sectional form and envelop”. Heat transfer due to conduction and convection are complex depending on the air temperature distribution within the cavity or the buffer space inside the EDSE, air flow behavior and velocity, type of ventilation receive and pressure levels inside the EDSE and main indoor volume inside the building.

The effect of EDSEs for reducing indoor overheating potential has been discussed in the context of natural and hybrid ventilation (Gratia. Et al, 2007). The shading inside the cavity of EDSEs, amount of thermal mass and its location have a greater impact on the behavior of heat gain control due to environmental and internal loads as well. However, the potential of EDSEs in severe year-around warm humid climates such as in tropics are known to be less understood. Literature suggest that thermal mass in the EDSEs can play a greater role in manipulating outdoor-indoor climate modification thus enhancing bioclimatic influence of buildings which act as climatic filters. To optimize climatic performance, thermal mass in the EDSE must be allowed to interact thermally with the interior or exterior, known as thermal coupling, by all forms of heat transfer. It is aimed to conceptualize the characteristics of EDSEs for increasing the time constant and heat storage capacity of the building form and envelope. The best way to promote this is to ventilate the building and its structure in the night through EDSE.

4. Developing a design matrix for EDSEs – a conceptual stage

An integrated building-climate performance model (Figure 1–right) is proposed for EDSEs based on a design matrix which is a conceptualization of the built environment as a bioclimatic system. Within the design matrix an EDSE can be seen as a complex system which interacts with the microclimate, plan form, sectional form, main envelope and even mechanical systems efficiency. For the optimum interactive performance, a hierarchical order (Hyde, 2000) can be identified in respect to increase the passive influence of the building design and grouped in four orderly interventions.
4.1. EDSEs for office buildings in the tropics

Opportunities for bioclimatic influence of EDSEs in the tropics may be attributed to thermal mass effect with shading and night ventilation. Since the diurnal temperature variation is relatively smaller in tropics, the potential of thermal coupling during daytime become more challenging. The specific challenge of this paper is to show how this challenge can be met by manipulating architecture of EDSEs in association with the plan form, sectional form and the complete envelope. The work presents and justify a conceptual form consisting of “supply air types” EDSEs with shading and night ventilation to the windward facades and “exhaust air type” EDSEs to the wind shadow orientations in buildings (Figure 9).

5. Methodology of the research

Method of research employed two case studies associated with filed investigations in two stages, a multi storey office building and an office cum residential building. The stage one aimed at exploring the efficiency of thermal mass and night ventilation for indoor climate modification and the stage two explores the potential of double skin for cooling spaces in real case buildings. The base building for stage one onsite investigation was selected through a desk evaluation of the seven locally certified green office buildings. The Energy Utility Index (EUI) was used as the basis of the sampling and the building with the lowest EUI (Figure 2) was selected as the first stage case study representing most general characteristics of the heat gain problems. The office cum residential building was selected as the 2nd stage case study due to its cooling indoor environment. One space of this building is designed with a masonry double skin (Figure 4).

5.1. Instrumentation

Hobo UX 100 temperature/RH 3.5% data loggers used for measuring hourly climatic data. Surface temperature using K-alloy thermocouples and Wind velocity data using VelociCalc- model TSI 9565 were
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also taken in hourly intervals. Ambient climatic data were downloaded from Met, Department which is located just 100 meters away from the case study building in Colombo.

5.2 Research plan

Initial on site field investigations were carried out for at least 24 hours with the selected building sample during February 2015, for indoor air and wall surface temperatures. New seven storey office building of Central Engineering Consultancy Bureau, which is the first case study building with EUI of 190 KWh/m²/a was observed as a potential base case due to it’s a) free running mode in weekends including Fridays, b) external accessible buffer zones which seems to offer an opportunity to integrate an EDSE for simulation and c) simple rectangular form.

![Diagram of building envelope and 5th floor plate/office](image)

Figure 2: External envelope and 5th floor plate/office of the selected building, CECB

5.2.1 Case study 1 - Detail field investigation on seven storey office

First, a detailed hourly thermal performance investigation was carried out for 48 hours during the weekend under free running mode for external and internal air temperatures, wall surface temperatures, wind climate and daylight levels (Rajapaksha et al, 2015). The objective of the field investigation was to identify the “level of indoor climate modification” and “heat sink capacity” of the building envelope. Thermal performance measurements were recorded from 13th–16th Feb, 2015 across the sectional volume involving external outside microclimates on both northeast and southwest orientations, external and internal surfaces of the wall on both these orientations and internal space at the 5th floor, a typical floor. Behavior was monitored during 13th, 14th and 15th for “free running mode”. Nocturnal ventilation was provided by keeping the windows open through the night on the 14th February.

5.2.1.1 Results and Discussion on case study 1

A. Naturally ventilated mode without night ventilation on 14th of February:

Internal air temperature behavior between 9 am to 5 pm moved around 29.5 degrees C which is around 0.5 degree lower than the ambient level (Figure 4). Aulliciem’s comfort formula ($Tn = 11.9 + 0.534 To$) suggests that 24-28 can be a comfortable range with high RH levels for Colombo. “$Tn$” is the predicted neutral temperature and “To” is the mean outdoor temperature for the months in question. The
behavior shows a mild passive cooling potential but not fully realized during the daytime because indoor air is moving above the comfort range suggesting bioclimatic influence of the building form needs to be revisited. Since, the internal air temperature and climate modification is just 0.5 degree C lower than the ambient, the inside situation can be critical when outside air reaches 30-33 degrees on a typical common day for most part of the year in Colombo. The ambient of the investigation period was not high as usual. In addition, night time indoor air temperatures moved higher than the cooler ambient and diurnal range was observed as 7 degrees C suggesting a climatic opportunity for heat sink effect of thermal mass (Figure 3).

B. Naturally ventilated mode with night ventilation on 15\textsuperscript{th} of February:

As reported in the previous paper (Rajapaksha et al, 2015) the effect of night ventilation was seen on the 15\textsuperscript{th} of February, 2015 (Figure.4-Right). Internal air temperature at 10 am was 4 degrees C lower than the ambient and 6 degrees C lower than the ambient around 2 pm. The elevation of indoor air during this day was just 4 degrees when the elevation of ambient moved up to 6 degrees C at 2 pm. A time lag of indoor and ambient was not observed due to availability of ventilation. However, indoor air remained just above comfort zone suggesting full potential of bioclimatic influence is not visible.

Further readings showed a comparison of surface temperatures, indoor and outdoor air temperatures. Results showed a “mild heat sink effect” and “weaker insulating capacity” of the thermal mass on the external envelope.

5.2.2 Case study 2- detailed field investigation on office cum residential building

The case study 2 was used to investigate the effects of a west facing EDSE on indoor air temperature adjoining the double skin. The cavity inside this EDSE is about 600mm wide with masonry brick wall construction. The cavity can be ventilated in the night. A comparison of thermal performance was carried out with another adjoining space which is enclosed with a single skin envelope in the same building. A detailed hourly thermal performance was carried out for both indoor spaces during the same period for 48 hours in naturally ventilated mode. HOBO readings were taken for external and internal air temperatures.
temperatures, all wall surface temperatures, external outside microclimate and ambient air temperatures from the 16th -18th March, 2015 in 15 minute intervals and later averaged for hourly values. Thermal performance of the internal and external surfaces of the external wall of the double skin and the internal surface of the internal wall of the double skin too were recorded accordingly. The objective was to identify the level of indoor climate modification and heat sink capacity of the building envelop. Similarly, the thermal performance investigation was repeated from the 19th-21st March 2015 for 48 hours with the provision of nocturnal ventilation by keeping the windows open throughout the night.

5.2.2.1 Results and discussion on case study 2

A). Naturally ventilated mode without night ventilation on 17th of March:

Indoor air temperature inside the occupied space of the building was observed to be lower than the ambient through the daytime from 10 am to 3 pm, in the indoor space with Single skin thermal mass whereas in the indoor space enclosed with a EDSE integrated with thermal mass, the lowering of indoor air temperature was visible from 6 am to 9pm, a longer time than the other space. A significant reduction of indoor air temperature was seen in the space enclosed with an EDSE which consists of high thermal mass than the indoor space surrounded by a single skin thermal mass (Figures 5 and 6).

Figure 5: Indoor place close to single skin wall thermal mass

Figure 6: Space close to double skin wall thermal mass
For example, indoor air temperature at 4 pm moved around 30.7 Degrees C in the space enclosed with Single skin thermal mass walls, which is a reduction of about 1.3 degrees C than its ambient counterpart of 32 degrees C whereas in the space enclosed with an EDSE consists of high thermal mass moved around 29.1 which is a reduction of about 2.9 degrees C than the ambient. The evidence illustrates a passive cooling status throughout the day time. Internal surface temperature of the internal skin of the EDSE moved significantly lower than the indoor air temperature compared to the internal surface temperature of the single skin wall illustrating its higher heat sink capacity.

Higher Insulative capacity of the EDSE was seen with surface temperature behavior of double skin wall (Figure 6). For example, surface temperatures from most external surface to most internal surface at 4 pm are as follows which shows a gradual lowering of values.

- External surface of the west facade 42.6 degrees C
- Internal surface of single skin 30.4 degrees C
- Internal surface of internal skin of EDSE 28.5 degrees C

Monitoring was conducted for three days involving 17thMarch2105. Similar behaviors were observed during the total investigation period.

B.) Naturally ventilated mode with night ventilation on 20th of March:

The effect of night ventilation was seen on the 20th of March, 2015. Internal air temperature moved much lower than ambient during the day due to the effects of night ventilation on the 19th March in both the spaces. The reduction was much significant in the space enclosed with the EDSE than the single skin wall on the same orientation. For example, indoor air temperature at 10 am was 3.8 degrees C lower than the ambient and 3.7 degrees C lower than the ambient around 2 pm in the space enclosed with the EDSE while indoor air temperature at 10 am was 1.8 degrees C lower than the ambient and 1.6 degrees C lower than the ambient around 2 pm in the space enclosed with the single skin wall

With the introduction of night ventilation on the previous day, internal wall surface temperature moved lower than the indoor air temperature in both the spaces where the reduction was higher in the space in which EDSE integrated as thermal mass. The results suggest some promising thermal behavior indicating the potential of night ventilation and EDSEs for passive cooling on the following day.
Research findings:

The on-site thermal performance investigation used to justify thermal mass effect in double skin envelopes. The work demonstrates that thermal mass in the double skin envelope contributed to work as a heat sink and thus passive cooling although the tropics are characterized with slight diurnal ranges as compared to hot dry climates. Results provide evidence of passive cooling with internal air temperatures moving below the ambient levels due to envelope dependency with heat sink effect and night ventilation primarily created due to double skin envelopes. Findings show empirical evidence of passive cooling suggesting that the concept developed for double skin envelopes with thermal mass and night ventilation can play a positive role in addressing extreme climatic conditions.

6. Conceptualizing a generic sectional form for EDSE for tropics

According to the theoretical evidence and based on research findings a building should have two different types of DSEFs, namely exhaust air and controlled supply air in tropical situations. Exhaust air type envelope promotes a stack force within the indoor volume and thus heat sink effect of the total building envelop by removing hot air. As a result of this, a vacuum of air is created at the lower zone of the building’s indoor volume. If the vacuum is filled with air without heat, and facing windward orientation the lower air zone gets relatively higher pressure levels. In addition, if this vacuum zone is provided with shading, darkness and protected from solar radiation, the air pressure in this area can be maintained continuously at a very much higher level than the zone closer to upper level of the exhaust air envelope on the leeward orientation.

Figure 9: Conceptual section showing integration of double skin external envelop. The exhaust air type on the leeward side promotes heat removal and supply air type envelop on windward side encourage selected airflow through a shaded air gap.

This thermal landscape can be an ideal situation which generates buoyancy driven air flow within the building volume. The total scenario helps to remove heat from interior in both day and night and
even flush the entire envelope mass with cold air in the night. This conceptual model needs a detailed investigation for its thermal performance.

6. Conclusion and future research

Thermal performance of a double skin high thermal mass envelope was seen applicable to a certain degree with night ventilation in tropics. The effect of lowering air temperature inside a building by more than 1.5 degree C was evident with this assessment of case study. Future research has been focused on more real life building practices to explore the maximum potential of EDSE in tropical situations. The work is being carried out with more field investigations to find out evidence and then justify this conceptual characterization for future practice and application in non-domestic buildings.

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