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BUILDING ENVELOPE VIS-A-VIS INDOOR THERMAL DISCOMFORT IN TROPICAL DESIGN: HOW VULNERABLE ARE THE CONSTITUENT ELEMENTS?

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Abstract: Tropical climate is characterised with high temperature consequent upon high solar gains which in effect impacts negatively on the interior spaces thereby creating thermal discomfort for healthy living environment. This has resulted into adoption of various active and passive design techniques/approaches to ameliorate the indoor living condition. This article focuses on computer modelling of the heat transfer mechanisms into the building with a view to identifying which element(s) of the building envelope is/are most vulnerable. In doing this, a virtual model of a predominant residential building typology in the study area of Ogbomoso, Nigeria, is subjected to thermal analyses via DesignBuilder, a computer simulation package using Ogbomoso climatic data as obtained from a global climatic database, Meteonorm. Results of the analysis indicate Exterior Glazing, Ceiling (Roof), Walls, Floor among others, are vulnerable in that descending order with the most notable ones, Exterior Glazing and Ceiling, calling for special attention. The paper therefore concludes by offering useful suggestions to address issues related to the most vulnerable elements so identified, with a view to improving the interior living spaces in the study area.
Keywords: Building Envelope, Thermal Comfort, Solar Gains, Tropical, Virtual Model, Simulation, Indoor, Residential Building Typology, Thermal Analyses.

Introduction

Thermal comfort is defined by the *American Society of Heating, Refrigerating and Air-Conditioning Engineers* (ASHRAE), as the state of mind in humans that expresses satisfaction with the surrounding environment (ASHRAE Standard 55, 2004). This is corroborated by the World Health Organization (WHO, 2012) as satisfaction with room temperature, humidity and indoor air circulation and an adequate balance between the perception of warm and cold, as well as dry and damp indoor air. Anything contrary to this, results into thermal discomfort.

Thermal comfort is an index of good indoor climate and a key component for quality of indoor environments as humans need to maintain individual internal body temperature of around 37°C. We function best at this temperature and variations on each side are detrimental

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(Bill and Randall, 2000; Appah and Koranteng, 2012). It is maintained when the heat generated by human metabolism is allowed to dissipate, thus maintaining thermal equilibrium with the surroundings. It is affected by heat conduction, convection, radiation, and evaporative heat loss.

Comfort is a subjective matter which varies with individuals (Bill and Randall, 2000) as no two people would perceive and describe it equally (Phil, 2012). It involves a large number of variables, categorized into Environmental Variables (i.e. Indoor Air Temperature, Mean Radiant Temperature, Relative Humidity and Air Velocity) as well as Physiological Variables (i.e. Metabolic Heat Production Rate and Clothing Insulation). In addition to these variables, culture, time of the year, health status, percentage of fat in an individual, among others, have contributory impacts on people's comfort perceptions (Thi, 2011). As such, a comfort range accepted by most people in the society should be considered for design purpose. Research in this field has identified the climatic conditions under which man is most comfortable, both at work and while resting as a temperature range of 22ºC ± 2ºC (i.e. operational comfort level) in the ambient air (Torben and Peter, 2010). This may however be extended over a wider range when considering adaptive comfort approach especially for free-running buildings in the tropics (Thi, 2011). As such, frequency distribution of air temperatures and comfort votes research carried out by Kayode and Folorunso (2003) in Lagos, Nigeria shows a comfortable temperature range of 26ºC to 28ºC, comfortably cool between 24ºC and 26ºC, and comfortably warm between 28ºC and 30ºC. Anything outside this range brings about discomfort.

Tropical region includes all the areas on earth where the sun reaches a point directly overhead at least once during the solar year. It is predominantly characterised with high solar gains with its attendant high temperature, leaving all the twelve months having mean temperatures above 18°C (64°F) (Wikipedia, 2012). As such, tropical cities like Ogbomoso, Western Nigeria within this context, are characterised with high exterior temperature as much as 34°C (93.2°F) in some instances (Ayinla, 2011). This no doubt, would impact on the living conditions of the people particularly the design approach, with a view to shielding the interior spaces from the prevailing harsh outdoor climatic conditions for thermally comfortable living environment.

Human considers an environment as thermally comfortable if no thermal discomfort is present (i.e. thermal neutrality exists), else he either feels too warm or too cold. His perception of indoor (i.e. interior) thermal comfort is largely influenced by the fabric of the building envelope (particularly the floor, wall, window and roof) as well as his current thermodynamic processes at the time of comfort evaluation (Ward, 2004).

As human thermodynamic processes are affected by a number of factors inclusive of the body metabolic rate, clothing level, air velocity, air temperature, mean radiant temperature, among others, so also the overall indoor energy balance is influenced by the fabric of the building envelope, as determined by its insulation level which either enhances or inhibits transfer of thermal energy across its membrane (Givoni, 1998; Ajibola, 2001; Randall, 2007; Barrios et al, 2012).

The building envelope constitutes the physical separator between the interior and the exterior environments of a building. It is a dynamic system which responds to the permanent variability in external radiation, climate conditions and internal requirements for overall users' comfort (Mary, 2010). It is a specialised area of architectural and engineering practice that draws from all areas of building science and indoor climate control (Wikipedia, 2012). Its physical components include the foundation, roof, walls, doors and windows as its functions can be separated into three categories of Support (to resist and transfer mechanical loads), Control (to control the flow of matter and energy of all types with a view to providing comfort) and Finishing (to meet human desires on the inside and outside).

In the face of diminishing raw materials and growing CO_2 emissions today, common measures of the effectiveness of a building envelope include physical protection from weather and climate (comfort), indoor air quality (hygiene and public health), durability and energy efficiency, achieved by direct response to the environment through its design, rather than controlling the environment through over-reliance on technology (Mary, 2010; Sue et al, 2004). As such, the developments of recent decades with the enormous increase in the requirements placed on the building envelope have resulted in multiple-layer constructions in which every single layer has to perform specific functions for overall users' comfort. Each of these needs therefore, informs the design decisions (such as the choice of interior and exterior materials, layers as well as their detailing) on the specific elements of the envelope to be selected. Elements selection in this context is largely dependent upon their capacities to reduce heat transmission outwards – or inwards – through the enclosure. Where there is a temperature difference between two places, heat tend to flow from the higher temperature to the lower one as nature always hate imbalance. On a daily basis, the Sun rises, the air temperature increases and heat is transferred directly via windows and indirectly via the building structure (Randall, 2007). This transmission occurs generally through *conduction, convection* and *radiation* (Esmond, 1984).

Essentially, the thermal performance of a building is the degree at which the building modifies the prevailing outdoor climate to create a unique indoor environment. Building shape, orientation, window to wall ratio, and more importantly, 'fabrics of its envelope', among others, contribute to the way buildings are able to respond to their external environments (Appah and Koranteng, 2012).

The Study Area: Its Climate, the Design Implications and Choice of the Sample

Ogbomoso, a typical city in the South Western Nigeria, lies on latitude 8º08´ North of the equator and longitude 4º15´ East of the Greenwich Meridian within a derived Savannah region. Temperatures throughout Nigeria are generally high as diurnal variations are more pronounced than seasonal ones. Ogbomoso in particular has a climate largely independent of the topographical features but varies by the interactions between two principal wind currents; *The Harmattan* (often appears as a dense fog and covers everything with a layer of fine particles) and *South-West Wind.* While the former is hot and dry and carries a reddish dust from the desert (North-East), causing high temperatures during the day and cools at nights, the latter which is moist, blows off the Atlantic Ocean, thereby facilitating cloudy and rainy weather. The interactions between these two air masses play a distinct role in the country's seasons and temperatures (Nationsencyclopedia, 2012; Traveltips, 2012). As such, two major seasons of Rainy and Dry are experienced on an annual basis.

From a five-year, monthly study (2004-2008) conducted by Ayinla (2011), Ogbomoso has an average air temperature range of between 25.13 and 28.51ºC with highest maximum and least minimum values of 34.73 and 18.9ºC respectively. This is accompanied with high solar radiation (i.e. radiation value of above 10KJ/m^2/day for some months), high humidity (usually above 60%) and low air velocity (usually between 1.5 and 2.0m/s) which usually result in thermal discomfort of the interior spaces in most part of the year. This implies a high propensity of the building occupants in the area to experience thermal discomfort during most part of the year. (Countrystudies, 2012; Nationsencyclopedia, 2012; Traveltips, 2012). Hence, the need for appropriate design interventions, through thermal analyses of the prevalent fabrics of the building envelope in the area without (or with least) recourse to mechanical installations. This is to mitigate the effects of the harsh outdoor climatic elements (particularly high temperature and solar gains) on the interior living conditions of the building occupants.

In doing this, numerical dominance of 'single storey, three-bedroom apartment, single unit' residential building typology (i.e. bungalows) in the study area facilitates its selection for the study with a view to generalising the research output for similar structures in the area.

Figure 1 below illustrates a typical photograph of an existing representative unit of the typology. The choice of this unpainted reference sample is to avoid the beneficial impact of the paint on the indoor thermal condition, which may otherwise affect overall result of the study (through computer simulation).

Computer Modelling, Simulation Strategy and Assumptions

Computer simulation has been proven to be a reliable tool for investigating thermal performance of buildings as it provides dynamic analyses with accurate results (Aditi, 2010).

Of the available numerous indoor comfort simulation softwares inclusive of DesignBuilder, Ecotect, e-QUEST, TRNSYS, IES, Anthermc, TAS, among others, DesignBuilder was chosen for the purpose of this analysis in view of its advanced graphical user interface, which has been specially developed to run EnergyPlus simulations with virtual building models as it readily provides tools for energy efficiency and sustainability analyses of buildings (such as solar and weather tools), which are very important for this study. It is a user friendly modelling environment which provides a range of relevant environmental performance data.

As such, a virtual model of a three-bedroom apartment, representative of the predominant residential building typology in the study area (Author's field work, 2012) was generated to determine which of the elements of a building envelope is most vulnerable to heat transfer from the exterior to the interior in the area. The model was a one storey building covering a land area of 13.5 by 10.5 square metres. It consisted of three Bedrooms, Living Area, Kitchen, Dining, combined Bath/Toilets, Store and Sit-out. The floor to floor height was maintained at 3.0m. The core walling material remained hollow sandcrete block-walls of 225mm and 150mm thicknesses for external walls and partitions respectively. The surface finish on the core walling material remained 20mm thick cement plaster for both surfaces (exterior and interior) as Asbestos roofing sheets and Asbestos ceiling sheets with timber roof carcass formed the roof elements. Timbre frames with 6mm clear glass louvers infill formed the components of the windows as all doors were of wooden material. The general outlook for the virtual model of the building is as illustrated in figure 2 of the Appendix.

Climatic data for the study area, Ogbomoso, was obtained from *Meteonom*, a global climatic database and integrated into the software database for the analyses purpose. With the exceptions of the material specifications, occupancy periods (as peculiar to the study area) and natural ventilation (all through), other DesignBuilder's default settings in respect of residential/domestic apartments as defined in the *ASHRAE* handbook and the *EnergyPlus* user manual, were maintained for the simulations.

Simulation Proper and Outputs

The simulation output variable considered relevant for the purpose of this analysis was essentially the Solar Gains due to the Wall Fabrics, Partitions, Ceiling, Ground Floor Materials and Exterior Glazing, obtained through a twenty-four hour Cooling Design Simulation on the day with highest recorded temperature (in the hottest month of March i.e. 23rd of March) in the study area, as obtained in the previous climatic study of the area by Ayinla (Ayinla, 2011). Effects of varying thermal behavioural patterns of the elements (in terms of individual heat gains) are then established by comparing the numerical values obtained (at two hours interval) in each case as indicated in figure 3**.** Through these comparisons, significant roles played by each element of the envelope on the overall indoor thermal condition in the virtual model of the residential building in the study area are established. Hence, the aim of the investigation accomplished.

Results of the investigation reveal highest solar gains into the interior through the Exterior Glazing (i.e. 7.04KW). This was closely followed by the Ceiling fabric (i.e. 2.8KW), then Wall Fabric (External walls i.e. -0.89KW) followed by the Partitions i.e. -2.32KW), among others, in that descending order. As such, special attention needs to be paid to the Exterior Glazing as it constitutes a major source of huge heat gain into the interior spaces in the study area.

Discussion of Results: Windows, Roof and Thermal Comfort

Human comfort in buildings can be adversely affected by the presence of large hot or cold surfaces—notably windows and skylights, and this can be strongly influenced by a number of mechanisms inclusive of; exchange of long-wave, electromagnetic radiation between building occupants and their surroundings; convective effects from cooling or warming air currents and; absorption of solar radiation by the body as graphically illustrated in figure 4. Even when the room air is maintained at a comfortable temperature, occupants may experience significant discomfort as a result of radiant heat exchange with window surfaces.

Realizing this shortcoming, existing standards for thermal comfort and recent specialized tools are being evaluated for possible adaptation and enhancement to help address the window comfort issue as a parametric approach to study windows and their effects on indoor comfort vis-a-vis relative importance of long and short-wave (solar) radiation and the feasibility of defining simplified measures of thermal comfort for windows is ongoing at Berkeley Research Centre, California (Peter et al, 2009).

However, designing well-shaded walls and insulated/high performance windows with suitably low e-glass with minimal placement on the east and west elevations would go a long way in addressing the problem. Windows facing east or west should be protected by a sufficiently wide horizontal-shading device (such as wide eaves, verandah or pergola), a vertical shading device or the window should be placed high on the wall under the eave. External sun-shading devices are preferred to internal and interstitial shading devices. Aligning windows and doors should assist in maximising natural ventilation to allow for the capture of prevailing breezes and to allow cross-flow breezes.

Similarly, a near vertical sun during the hottest hours of the day causes the roof to bear the greatest intensity of heat as pitched or sloping roofs with big eaves that can create plenty of shade around the building and protect the outer walls from getting soaked are recommended. High-level ventilation through roof cavity space via roof vents should be provided with window types that offer the best ventilation performance. Metal roofs can be avoided, unless absolutely difficult, as they have the disadvantage of being very effective heat conductors and can possibly suffer from corrosion caused by contact with sulphur dioxide in the atmosphere. Flat roofs are not advisable because of the risk of leaking during heavy rains. Flat roofs made of concrete with or without a false ceiling are often subject to cracking due to contraction and expansion (Plumbe, 1987 in Peter, 2009). The construction of secondary roofs and facades, with a gap of several millimetres between the primary and secondary surfaces, to allow for ample airflow around the primary building, is very important. This prevents sunlight from shining on and directly heating its outside surfaces. Thermal insulation or the construction of a false ceiling will have a similar positive effect. A light roof colour to reflect unwanted heat may reduce the heat transmission into the building as reflectance of a surface is a measure of the energy that is neither absorbed nor transmitted and is expressed as a ratio of the reflected energy to the total incident radiation energy (Peter et al, 2009). These measures shall go a long way to address the identified indoor discomfort issues at this level of human habitation.

Conclusion

Thermal discomfort in buildings can create unsatisfactory conditions for the occupants as this can be unhealthy, distracting, and likely to reduce performance and overall productivity. Through computer modelling and analyses, this paper has identified in their descending order, two major elements of the building envelope, Windows and Ceiling (i.e. roof) respectively, of a residential building typology in the tropical city of Ogbomoso, Nigeria, as the most vulnerable sources (via the characteristic high solar gains in the region) for indoor thermal discomfort. The challenge was to come up with useful suggestions for achieving self-sustaining buildings which will adequately address the discomfort and facilitate healthy living, with minimum energy utilization as demonstrated in this submission. It should be noted that this study was carried out on a predominant single storey building. It is hereby suggested that the future studies could be conducted on a multi-storey building for overall generalization of the results for the entire study area.

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APPENDIX

Figure 1: An existing representative unit of the dominant Residential Building Typology in the study area (Source: Author's field work, 2012)

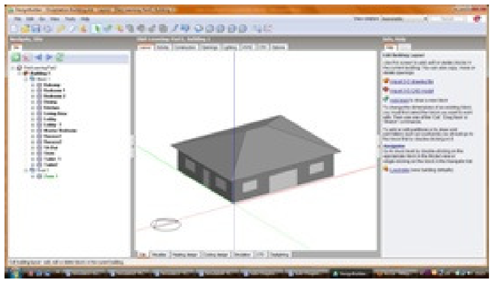

Figure 2: General outlook of the building model as appeared on DesignBuilder Interface (source: DesignBuilder Simulation output, 2012)

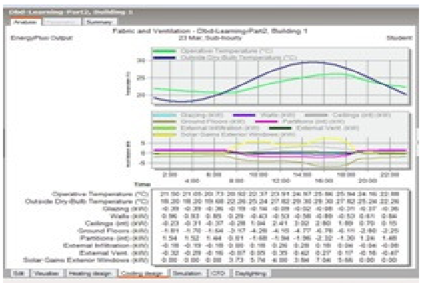

Figure3: Simulation results indicating different heat gain sources at the building level (source: DesignBuilder Simulation output, 2012)

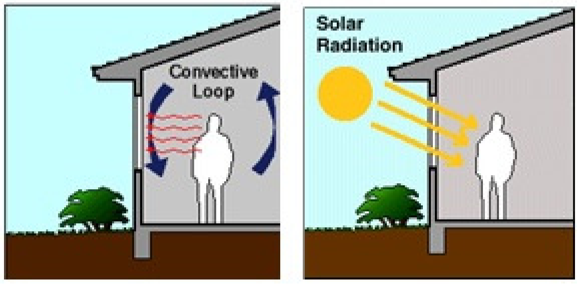

Figure 4. Convective, long-wave radiative and short-wave solar effects on thermal comfort (source: Wikipedia, 2012)