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PASSIVE BUILDING DESIGN OF MASS HOUSING DEVELOPMENT IN THE WARM-HUMID REGIONS OF GHANA – A PATH TO SUSTAINABLE BUILDING DESIGN

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ABSTRACT

Traditionally, dwellings have been adapted to climate in the search of shelter with comfortable spaces. The evolution of the modern movement of architecture placed emphasis on the form-function concept at the expense of comfort issues with dependence on auxiliary space cooling devices to maintain thermal comfort in buildings. For Ghana as a country, recent attempts at addressing demand for housing have led to the development of architectural design solutions that have most invariably been based on approaches employed in the western countries despite climatic differences. The result is excessive energy use in buildings and destruction of the harmony between culture and nature. This paper discusses and presents the outcome of an effort to employ passive design concepts for warm-humid climates employed in a proposal for a contemporary mass housing project initiated by the Government of Ghana (GOG) to reduce the housing deficit in Ghana. A review of passive design concepts, strategies and techniques associated with layout planning and building form, building design and material selection for the natural environmental conditions of the warm-humid climatic regions was undertaken and applied in the design of the housing units. Computer aided simulations were used to achieve precise angles of orientation, effective natural air flow patterns, appropriate design and dimensions of shading devices for all year round performance. AutoCAD Architecture 2010 was used for the orthographic and three-dimensional drawings. The paper is expected to contribute to the identification of a genuine environmental responsive architecture, which is regional in context and provide a useful reference to the contemporary architectural design practice for regions under similar climatic and economic conditions.

Keywords: passive design, warm-humid climates, mass housing, sustainable building, Ghana

INTRODUCTION

The United Nation Commission on Environment and Development (UNCED) Earth Summit in Rio, June 1992 gave recognition to mankind's uncontrolled development activities having brought the world face to face with environmental crises of immense proportion. In Rio, a consensus was reached for governments of the world to adopt a sustainable approach to development that respects the ecological balance of the earth. Consumption of non-renewable energy for cooling, heating and lighting of buildings accounts for approximately 45% for total global energy (IEA, 1995). The developed world consumes the majority of the total global energy use in buildings. Moreover, the energy consumption of the developing world could reach same proportions as that of the developed world if sustainable design approaches are not adopted (La Roche, 2005). Current built environmental development approaches are not only seen to be unsustainable, but a major contributing factor to global environmental pollution and global warming.

In context to the call for sustainability, there has been a renewed interest in design of buildings in sympathy with prevailing climatic conditions both to create regional variations in architecture, reduce reliance on energy use. Garcia-Chavez (1995) asserts that amongst all the many functions and purposes, one of the most important roles of a building is to provide shelter from the natural elements of the weather; sun, wind and precipitation. The form, shape and material of the buildings in a particular region have been determined by the opportunities offered and constraints posed by climate, with the emergence of various architectural styles pertaining to various parts of the world (Lechner, 2001). The above have been buttressed by several discussions on a series of energy crises and environmental effects of ozone layer depletion and global warming on the built environment by both the national and international scientific communities.

Projections in the year 2009 by the Ghana statistical service put Ghana’s population at about 23,416578, with an urban population of about 43% of total population (GSS, 2010). The rapid growth in population has propelled housing requirements. Based on a 5-year population projection, it was estimated that 2.2million units will be needed within a 25 year period (KPMG, 2010). This translated into about 91,000 housing units per annum. An estimated housing supply of 45,000 per annum by the Ministry of Water Resources Works and Housing (MWRWH) leaves an annual shortfall in the region of about 45,000. Traditionally, communal living has dominated Ghana's housing as evidenced by the large proportion of enclosed housing units known as "compound houses" which constitutes 45% of the total housing stock of the country. Flats, however, have a lower share of 4%, which may be explained by the fact that the concept of vertical housing development has not been well grounded in the housing delivery process in Ghana. In the regional capitals where land has assumed high values, flats are becoming common in a bid to maximize space. In recent years, apartment development has become commonplace especially in the national capital and it appears this trend is likely to continue. However, the development of apartments does not employ passive design approaches to make their use and performance sustainable. At the building unit design level, dwellings exhibit limitations such as inefficiently sized dwelling units; poor levels of daylight within spaces; lack of visual connection to the external environment; and poor air distribution in habitable rooms.

Various governments over the years have made efforts to find a solution to the growing demand for housing in Ghana. In an attempt to reduce the housing deficit, the Government of Ghana (GOG) in 2010 entered into a public-private partnership agreement with the STX Engineering and Construction (STX E&C) firm to provide adequate housing units that are safe, descent, secure, healthy, and affordable to a wide range of the Ghanaian populace. The project was also to improve the housing delivery system to its citizenry to help the country to achieve its broad macro-economic development objective of reaching a middle income status. To ensure a successful delivery of the project, STX E & C engaged the services of the College of Architecture and Planning (CAP) of the Kwame Nkrumah University of Science and Technology (KNUST) as the main consultants for the project. The role of CAP as consultants involved developing architectural designs, including conceptual sketch designs, working (production) drawings, and project administration. The necessity of building quickly and inexpensively, combined with the local specific conditions, brought to bear the extreme importance of implementing sustainability strategies, by taking advantage, for instance, of passive design solutions in housing development on a large scale in an emerging economy as that of Ghana.

Passive building design techniques that were employed by the CAP team in the design of the GOG - STX E&C Mass Housing Project are presented in this paper. The aim of the paper is to evolve a sustainable building design approach for the warm-humid climate of Ghana to contribute as an emerging example for the Twenty-First Century.

PASSIVE DESIGN OF BUILDINGS IN WARM-HUMID CLIMATES

The concept of sustainability is gaining increased global, national, and local interest with respect to how it can be applied as a strategic planning tool to increase the viability, profitability, longevity, and ultimate success of human actions on a variety of scales (Pearce and Vanegas, 2002). Pearce and Vanegas (2002) further asserts that, besides the growing interest of the concept in the academic community, sustainability has been embraced as a decision criterion in both the public and private sectors.

Sustainability as applied in the development of the built environment is based on the understanding that resources are limited and their reckless usage may lead to environment and human catastrophe (Rahamimoff, 1995). It can be appreciated that the growing global concern for the use of energy and resources, sustainability places greater responsibility on building professionals to design buildings that are environmentally sustainable.

Passive building design approaches refer generally to the use of building design and choice of materials to provide cooling in an energy efficient manner to be able to avoid or minimize the use of conventional cooling systems that employ motorized mechanical components to move fluids and air (Huang, 2004). Zhou et al. (2006) defined passive building design techniques as utilization of natural resources to reduce the energy consumption of buildings and improve their thermal environment.

The designs of most contemporary buildings deny the inevitable interactions with the natural surroundings, and site characteristics such as orientation in the design process, and are subdued with expensive cooling and lighting equipment (Kumar, 2006). According to Schaefer (2006), sites and their locations for example are important factors in relation to environmental design strategies and impact on the indoor conditions of a building. This makes knowledge of the physical surroundings as well as micro-climates useful in formulating passive building design solutions. The design of buildings that do not take physical surroundings and micro-climates into consideration are highly dependent on mechanical and electrical systems to control the indoor environment (Garcia-Chavez, 1995). In an era where the international community is advocating for application of sustainability building principles, the use of conventional mechanical systems to obtain comfort is now questioned in energy poverty economies like that of Ghana. In this way, application of passive design techniques should not only be seen as an environmental issue but also from an economic point of view.

The characteristic little variations in the high temperature and high relative humidity of the warm humid climate call for specific responses in the utilization of passive building design techniques. The very slight seasonal climatic variations in the warm-humid regions make the physiological thermal requirements and the building characteristics necessary to achieve thermal comfort similar for the whole year. Due to the relatively narrow diurnal temperature fluctuation it is not possible to achieve much cooling by utilization of the thermodynamic properties of building components. The predominance of high humidity limits evaporative heat loss thus necessitates a corresponding high air velocity to increase the efficiency of sweat evaporation (Hyde, 2000).

As an exception, a certain heat storage capacity may be advantageous in buildings used in the daytime only. Depending on the diurnal temperature differences, a reduction of the daytime indoor temperature by 0.7-3.0°C may be possible, with a time lag of about 2 to 5 hours (Amos-Abanyie, 2012).

The construction of a building in the warm-humid climate should meet requirements such as: (i) storing as little heat as possible in the structure in order not to cause undesirable re-radiation of heat at night; (ii) promoting efficient ventilation in a continuous way; (iii) preventing radiant heat entering spaces during daytime by having the adequate systems to do so; and (iv) protecting people from rain (Gut and Ackerknecht, 1993).

Efficient air circulation is one of the few possibilities for natural climate control in warm-humid zones. However, cooling of occupants through the increased perspiration of the body can be felt only if the air is not fully saturated with humidity. Due to the high relative humidity, problems of condensation could also occur in the morning hours because the surfaces would be somewhat cooler than that of the air (Hyde, 2000). The prevalence of high relative humidity levels brings out the necessity of air speed adequate enough to promote an efficient evaporation of moisture from the skin, and also to avoid as much as possible, the discomfort caused by the humidity in clothes and on the skin. Continuous ventilation is therefore, the most important requirement regarding comfort, and it affects all building design aspects such as orientation, the size and location of windows, and layout of the buildings.

APPROACH AND SOURCES OF DATA

The basis of the paper are the results of passive building design techniques employed at the architectural design stage of the GOG - STX E&C Mass Housing Project. The entire project included different housing typologies, recreational areas, general car parking space, security booth(s), commercial centre, estate management office, a crèche and a central service zone. The passive design approaches employed in the design of the three bedroom block of flats are discussed in this paper.

The main approach adopted was a review of special building constitutions and features that have resulted from the traditional building design concepts, strategies and technologies that have been developed in response to the natural environmental conditions in warm and humid climatic regions. The identified traditional passive design concepts were applied in the design of the housing units.

According to de Schiller and Evans (2006), the ability to design passive buildings or environmentally responsive buildings depends on the skills and ability of the architect to identify varied climatic parameters within a site, develop awareness of possible future modifications produced by introduction of new built form and use this potential during the design process at different scales of application.

Computer aided simulations employing Autodesk Vasari, Autodesk Ecotect Analysis and Autodesk 3d Max Design were carried out to achieve precise angles of orientation, effective natural air flow patterns, appropriate design and dimensions of shading devices for all year round performance and effective illuminance (daylighting) levels. AutoCAD Architecture 2010 was used for the orthographic and three-dimensional drawings.

LOCATION AND CLIMATE CHARACTERISTICS OF GHANA

Ghana is located between latitudes 5^o to11^o E and longitudes 3^oW to 1^oE (Boateng, 1982). It is bounded on the west by the Cote I'Voire, on the east by the Republic of Togo and on the North by Burkina Faso, and on the south by the Atlantic Ocean (Figure 1).

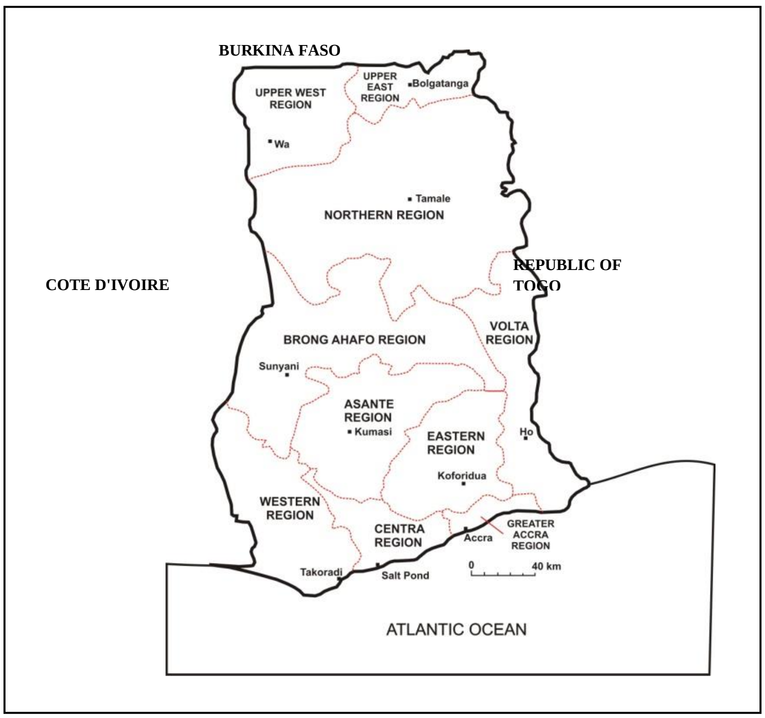

Figure 1: Administrative Regions of Ghana

The country lies in the tropics and exposed to the southwest winds, blowing from the south Atlantic towards the Guinea Coast, as well as the north-east trade winds blowing from the Sahara towards the Guinea Coast. Winds are lighter or even non-existent for longer periods due to minimal temperature differences. Along the narrow coastal areas, the constant heating and cooling patterns of land and sea create regular land and sea breezes. On the other hand, the inland regions may be completely calm and if, any, are very slight.

Solar radiation levels even though high come in diffuse. Temperatures follow a very constant diurnal pattern throughout the year. The haze may cause sky glare which can also be reduced by large shading devices. Temperatures in the warm-humid climate of Ghana are uniformly high and never falling below about 25^{o}C, but show variations over different parts of the country (Dickson and Benneh, 1988). Variations are due to the effect of altitude and, more importantly, to the effect of distance from the Atlantic Ocean. The highest mean monthly temperature of about 30^{o}C occurs between March and April and the lowest of about 26^{o}C in August. Along the coast, the mean diurnal range of temperature is 7 or 8^{o}C.

Humidity and rainfall are high for most part of the year. Relative humidity along the coastal belt in the south is generally between 95 and 100% during the night and early morning when the air over land is cooler than that over the sea. However, in the afternoons, relative humidity is about 75% in the South-west and about 65% in the South-east (Dickson and Benneh, 1988). Heavy precipitation and storms occur in the rainy seasons.

PASSIVE BUILDING DESIGN FEATURES OF THE MASS HOUSING UNITS

The project consists of many housing typologies: one bedroom apartment; one bedroom apartment with living room; two bedroom apartments; three bedroom apartments; three bedroom bungalows with a two-room outhouse; four bedroom bungalows with a two-room outhouse. All the flats comprised of a minimum of four storeys and of reinforced concrete post and beam construction. Each of the one bedroom apartment and one bedroom apartment with living room blocks has eight apartments on a floor. The two-bedroom and three-bedroom apartments have two apartments on each floor. The passive building design features of the three bedroom apartment block are discussed under three headings; (1) layout planning and building form; (ii) building design; and (iii) building material selection, in the following sections.

Layout Planning and Building Form

With the objective of achieving effective air circulation, buildings were arranged in line across the prevailing wind direction to have effective air movement pattern in the spaces. An open pattern with wide free spaces between buildings and of low density arrangement was adopted to provide sufficient air circulation (Figure 2). Adoption of multi-level structures, did not only provide higher densities, but provided a thermal advantage for design in a warm-humid region. The use of multi-level structures placed majority of the windows above the zone of likely maximum wind-damping effect by the surrounding vegetation to ensure better ventilation. The simulations of the various building design types allowed the adoption of options that can ensure an effective natural ventilation flow rate of a minimum of 2.0m/s within spaces as shown in Figure 3.

Vegetation in the warm-humid regions is rich as a result of high rainfall and provides an excellent means of improving the climatic conditions. Surface of vegetation does not heat up and it provides efficient shading at low cost (Silver and Guedes, 2006). Attention was paid to its use in this layout planning to ensure that their arrangement does not in any way impede air movement around buildings and circulation in the spaces. At the layout planning stage, an effort was also made to preserve much of the existing vegetation on various sites to help maintain a more stable microclimate, with lower air temperatures.

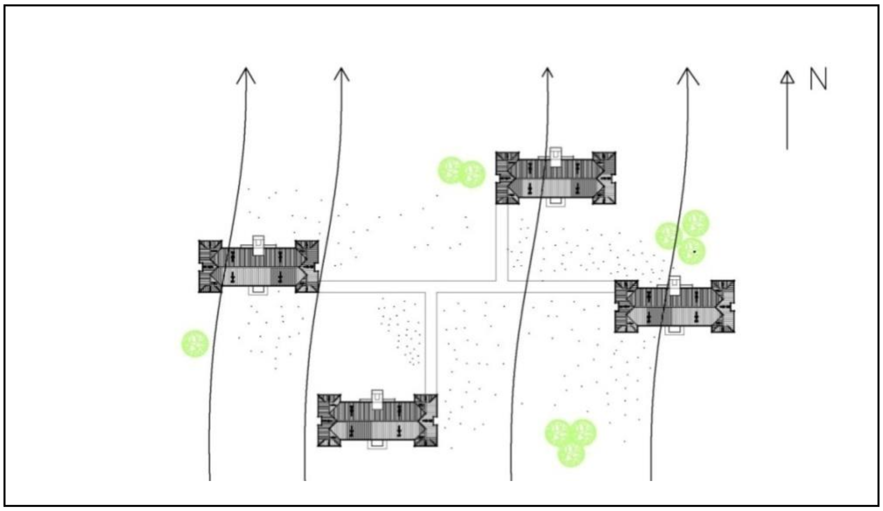

Figure 2: Open pattern layout of low building density

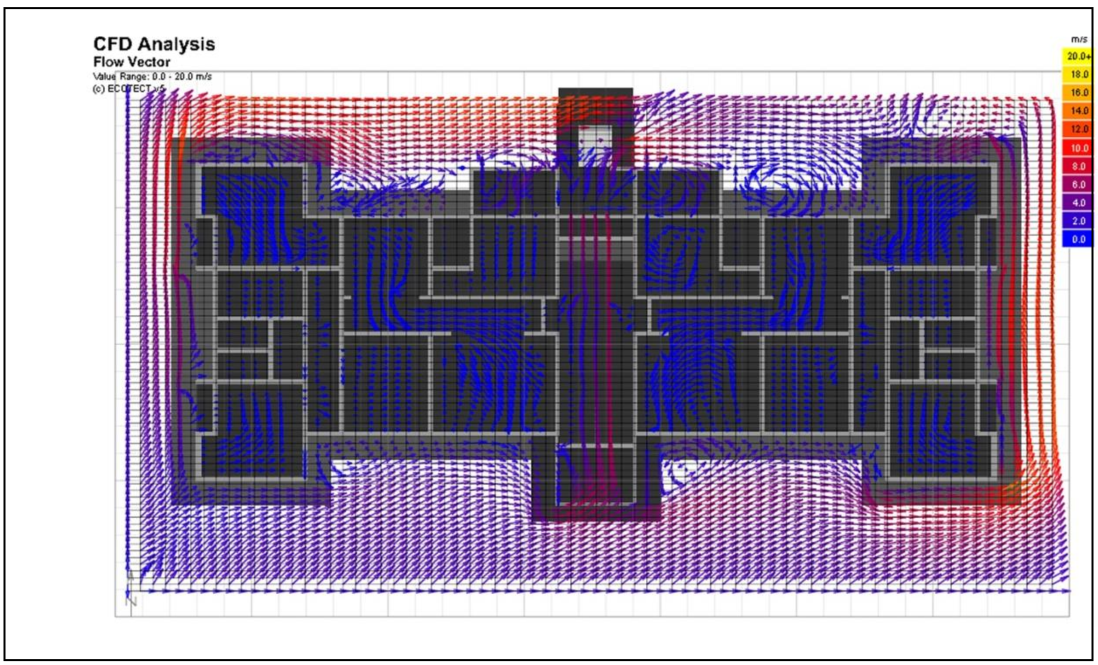

Figure 3: Natural ventilation flow rate pattern of three-bedroom block of flats

As a response to the high rainfall levels in the warm-humid climates, pitched roofs were adopted to make it easy to achieve a construction which is water-proof by allowing heavy rains to run off. Building forms with wide surface areas and for that matter high surface to volume ratios were adopted to favour ventilation and heat transmission at night-time. Concrete flat roofs were in some cases used over bathrooms and non-living spaces such as corridors and lobbies where water storage tanks were positioned.

Rectilinear building forms with long-shaped plans were adopted to avoid excessive building depth, in order to promote cross ventilation in all rooms. The long-shaped plan also enhances effective distribution of daylight in the spaces. An average indoor daylighting condition of not less than 150 lux was achieved based on wall, ceiling and floor reflectance of 60%, 80% and 20% respectively. In an attempt to achieve cost effective designs as a response to the client's requirements, compact spatial arrangement with double banking was adopted for some spaces within an apartment. This would have led to a situation where some spaces would not have had direct cross-ventilation. For this reason, functional arrangements were done to ensure that spaces were structured to have one of two opposite rooms not being fully enclosed by four walls. For example, the dining hall and the living rooms for a given apartment have semi-open three-walled enclosure (Figure 4). This avoided the situation where inner core corridors would have been denied adequate daylight or good ventilation as is the case in double-banking arrangement of spaces. Fanlights were also adopted to ensure effective daylighting of the core spaces with limited number of openings in an outer wall.

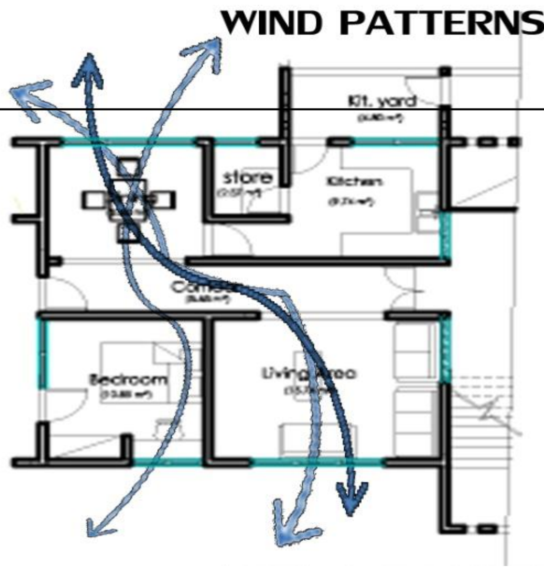

Figure 4: Air circulation in double banking arrangement

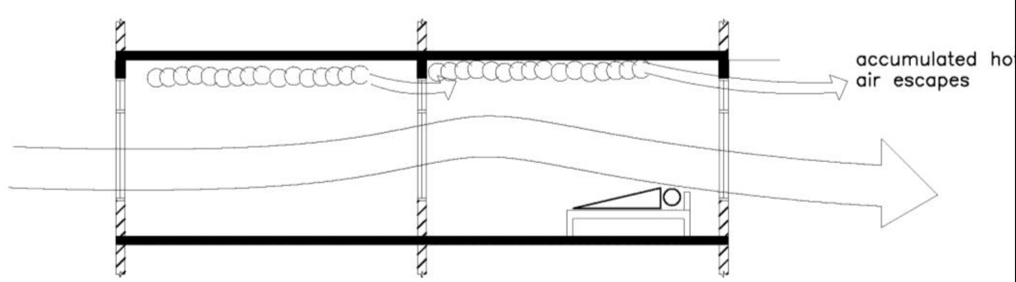

Figure 5: Typical cross-section showing indoor air pattern

Spaces were designed to have very high ceilings to allow hot air rise to the upper zone of the space and be kept away from the occupants. Low room heights and small volumes would not be efficient enough, as they could concentrate hot air closer to the occupants. Fanlights were adopted to allow accumulated hot air close to the ceiling to exit outdoors (Figure 5).

Building Design

The design of the buildings was done to satisfy the requirements of the warm-humid climate conditions: protection from internal temperature elevation during the day and, minimization during the evening and night (Lechner, 2001). Although the buildings designed were prototypes meant for various sites in the assigned regions, they were done to allow best possible orientation with respect to solar radiation to be achieved either by reflection or rotation of the building plans. The contradiction among orientation of the buildings with respect to solar radiation ingress and wind direction was resolved by making a reasonable compromise based on a detailed analysis of the situation of each site. The vegetation and structural elements, such as fins and recessions of windows were also explored to divert the direction of the wind as much as possible in the spaces.

Large openings were provided to as much as possible utilize the prevailing relatively low air movement associated with the warm-humid climates to provide cross ventilation for the achievement of evaporative cooling and avoidance of mould growth. Window to wall ratio of between 60 and 80%, was employed as suggested by Koranteng et al. (2011). The advantage of large openings is not only for better ventilation conditions, but also for the achievement of lower temperature during the night.

The provision of large window areas to ensure effective wind speeds necessitated adequate shading to effectively protect them from penetration of solar radiation, driving rain and intrusion of insects. Penetration of solar radiation could lead to a rise of indoor air temperature above the human thermal comfort band and subsequent discomfort. From a heat protection point of view, shading of windows, door and facades was carefully designed, in order to obtain a positive balance between the need of shading and the control of natural lighting. Shading elements in the form of overhanging eaves, hood and fins were provided not only against direct solar radiation, but also diffused radiation from the sky (Figure 6). Bearing in mind that upper floors receive much radiant heat, wide overhanging roofs were adopted to shade openings on the last floor of various blocks. With this in mind, hipped roofs as against gable roofs, were adopted for adequate protection all around including the critical eastern and western facades (Figure 7).

Figure 6: Protection of windows with hood, fins and overhangs

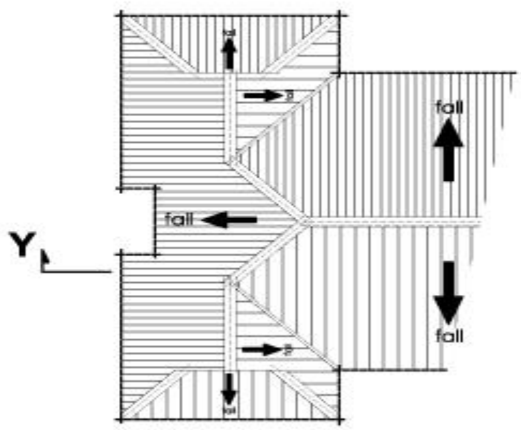

Figure 7: Hipped roofs protecting windows on all facades

Another technique to achieve effective airflow was the placement of windows to concentrate air movement at body level of occupants. To ensure adequate air flow around occupied zone of spaces, an effective height of window sills of between 0.5 and 0.9 meter above the floor was adopted. In bedrooms, window sills were brought as close as possible to the height of the beds to ensure adequate air flow around the occupants sleeping area and in living rooms (Figure 6). Louvre blades in adjustable frames were used for all the windows. Apart from allowing in the relatively large volumes of air, the adjustable louvers had a horizontal-pivot system which could be adjusted in a preferred direction, when open, to direct air flow toward desired sections in a space. Bearing in mind that the warm-humid climate foster breading of mosquitoes, fly- screens were specified for all the openings. Segments of the external walls were made of concrete perforated elements (Figure 8) to function like windows that cannot be closed and as such provided uninterrupted air flow to achieve a permanently ventilated space that constantly controlled heat gains and allowed cross ventilation.

Figure 8: Concrete perforated elements on external walls

Building Material Selection

Regarding choice of materials, this does not make utilization of heat capacity and resistance of the walls in warm-humid climates feasible as use of high thermal inertia may contribute to overheating and condensation (Givoni, 1976). Low heat capacity materials can prevent elevation of indoor temperature during the night when the external wind speed is usually at its lowest. Choice of materials for buildings in this project was guided by measures which avoid heat absorption and heat storage. In view of the above, the main criteria for the choice of materials for these designs were the prevention of daytime indoor temperature rise to above outdoor level and, the minimization of indoor level above that of outdoor during the evenings and at night hours.

Lightweight hydrafoam blocks were specified for the building envelope to provide a low heat capacity and prevent heat accumulation during daytime. Heavyweight material that are of high effusivity and low diffusivity can absorb part of the thermal energy of indoor air and improve indoor thermal conditions (Neves, 2006). Some internal wall surfaces in common areas such as the living room, dining room and the corridors in this project were cladded with flagstone to absorb part of the thermal energy of indoor air (Figure 9). This can improve indoor thermal conditions when combined with proper ventilation to help achieve comfortable conditions.

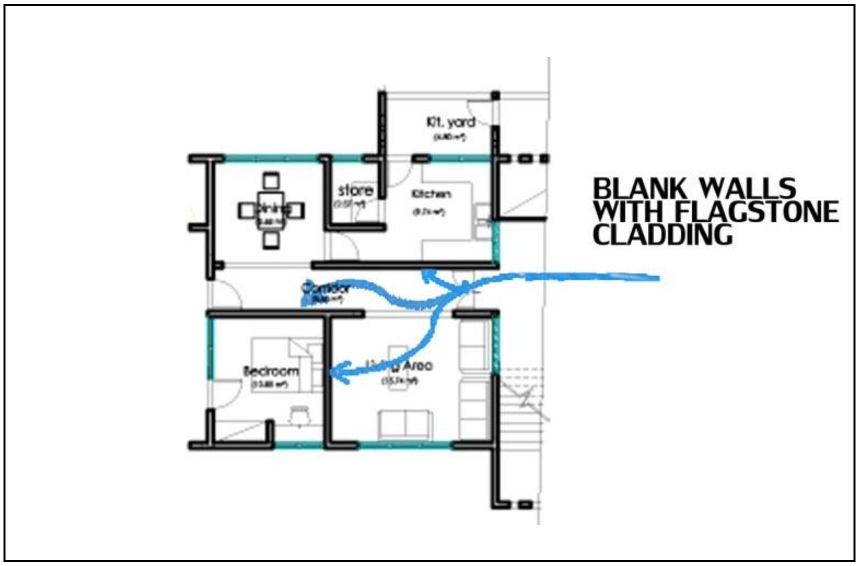

Figure 9: Internal wall surfaces with flagstone finish

The specification of materials for the roof was also guided by the use of materials of low heat capacity for a warm-humid climate. For this project, long span lightweight aluminum roofing sheets were specified owing to its low heat capacity. Plain colours were specified to be able to reflect back much of solar radiation in order not to cause heat stress during the daytime (Givoni, 1976).

Figure 11: Three-Dimensional view of the three-bedroom block of flats

CONCLUSION

The aim of the paper was to evolve a sustainable building design approach of mass housing for the warm-humid climate of Ghana to contribute as an emerging example for the Twenty-First Century. The case for this paper is the proposal of the public-private partnership agreement for a Mass Housing Project between the Government of Ghana and the STX Engineering and Construction firm.

The aim of the paper was to evolve a sustainable building design approach of mass housing for the warm-humid climate of Ghana to contribute as an emerging example for the Twenty-First Century. Adopting the approach of review, the features and strategies of traditional building responses to natural environmental conditions were identified and applied in the design of mass housing towards achieving energy efficient housing stock as a solution to minimize the housing deficit.

The paper brings to bare that effective utilization passive building design concepts as building layout and building form; building design; and building material selection can be integrated into contemporary architectural design practice to minimize or eliminate the contribution of buildings in global pollution and global warming. It also demonstrates that by proactively adopting sustainable building principles, it is possible to build comfortable sustainable buildings adapted to the warm-humid climate of Ghana and help to ensure that future generations can meet their needs even as the present generation meets its own needs.

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