

Computational Fluid Dynamics Modelling of Passive Cooling in Earthquake-Resistant Low-Income Housing Using Sustainable Materials

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Abstract. This study develops a Computational Fluid Dynamics (CFD) model to evaluate passive cooling and seismic resilience in low-income housing using sustainable materials: compressed stabilized earth blocks (CSEB, ~ 0.75 W/m \cdot K), bamboo (~ 0.12 W/m \cdot K), and recycled insulation. Simulations analyze airflow, temperature, and heat transfer under tropical conditions (30–40°C, 1.5–3.5 m/s wind) with cross-ventilation, shading, and roof vents, plus structural assessment. Results show peak indoor temperatures 5–7°C above outdoor levels (38°C outdoor \rightarrow 43–45°C baseline; 33–36°C with strategies), 4.2°C average reduction from combined ventilation vs. sealed baseline, and CSEB/bamboo walls 2–3°C cooler than concrete (1.4 W/m \cdot K) due to lower conductivity/higher thermal mass. Cooling Effectiveness Index (CEI) ranged 0.55–0.72, demonstrating enhanced thermal comfort and earthquake resistance without mechanical cooling.

1 Introduction

Passive cooling refers to an environmentally sustainable design approach to the provision of acceptable indoor comfort as it minimizes the need for mechanical cooling, which consumes electricity. For low-income housing, this is crucial because residents often lack adequate electrical connections, and air conditioning can be prohibitively expensive in many developing country contexts [9]. The primary passive cooling strategies include natural ventilation, thermal mass, solar shading, and orientation, all of which aim to mitigate heat gain within buildings. Passive cooling strategies result in an improved quality of life for occupants by providing thermally comfortable conditions while reducing energy costs. There has been increased awareness and liking of ecofriendly materials like compressed stabilized earth blocks (CSEB), bamboo and recycled insulation. Moreover, the materials are thermal insulating and have useful environmental properties, which render them applicable as passive cooling materials in low-income projects [4][7][14]. CFD enables architects and engineers to predict the relationships between architectural elements, such as window location and orientation, wall thickness and materials, and roof ventilation strategies, in indoor thermal environments, compared to other

traditional methods [3]. The CFD arena provides the possibility of architect and engineers to consider it as a tool of trial-and-error based passive cooling in low-cost housing scenarios where the building construction is not realistic and the trial-and-error process is prohibitive [5]. It can help architects and engineers implement thermal performance, design strategies on the areas that are susceptible to earthquakes, taking into consideration both the settlement and the safety of the design [10]. The rest of this paper is displayed in the following way. In section II, the literature review is also crucial, as it covers the previous works done regarding passive cooling methods, earthquake-resilient design, and the use of CFD to study the performance of buildings.

2 Literature Review

Passive cooling techniques have become widely used in sustainably designed buildings, particularly in hot regions with limited energy resources. Careful architectural features, such as cross and stack ventilation, thermal mass, and shading devices, along with appropriate building orientation, contribute to a substantial reduction in indoor temperatures and enhance comfort levels without the need for mechanical aids. For affordable housing, passive strategies reduce costs and help enhance the overall quality of life among residents.

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The study documented natural ventilation combined with thermal mass elements provided to buildings for overheating mitigation in most developing countries' crucial regions. Additionally, construction materials such as adobe, bamboo, and compressed stabilized earth blocks (CSEB) have also demonstrated good insulation and thermal regulation properties. They demonstrated that these materials can offer superior overall thermal performance compared to conventional concrete when combined with optimized building designs. All evidences in favor of these strategies however useful they can be, regionally specific strategies formed on the basis of climate data and occupant conduct advance the interdependence on simulation tools [8]. The problem of informal settlements in the case of earthquakes has attracted the focus on the design of low-income houses [6]. During earthquakes, traditional houses in these areas are likely to collapse when exposed to even moderate shaking, which causes widespread destruction and casualties. [11] reports that many basic techniques significantly enhance the structural resilience of these houses while remaining affordable within construction budgets. Cheap earthquake-resistant housing is possible with modular bamboo frames, ferrocement panels, or reinforced stone masonry composites [2]. They laid out the framework for assessing seismic vulnerabilities and advanced appropriate retrofitting strategies targeted at low-income regions [12]. It enables the time- and resource-efficient evaluation of passive cooling techniques prior to construction [13]. This tropical housing study revealed that building form and roof design have a great impact on the airflow in the interiors which confirms the hypothesis of shape adaptation that enhances ventilation. The paper on cross-ventilation has shown that, room geometry and positioning of windows can be optimized through CFD simulations, even in low-income urban areas. Although simulation tools have improved over time, aiding in complex design cost-efficiency for such houses, additional research incorporating structural modeling focused on earthquake-resilient design using CFD is still needed.

3 Methodology

This research uses CFD, or Computational Fluid Dynamics, to model airflow and heat transfer for a proposed low-cost housing unit [15]. CFD modeling is performed based on the finite volume method (FVM), which partitions the domain into numerous small control volumes. This approach enables the numerical solution of the governing equations governing fluid motion and thermal energy transport. The basic equations used in the CFD model are the Navier-Stokes equations, which govern fluid flow, and the energy equation, which relates

to heat transfer. As expressed, The Navier-Stokes equation for incompressible, steady-state flow is given by:

$$\rho(\vec{u} \cdot \nabla)\vec{u} = -\nabla p + \mu\nabla^2\vec{u} \quad (1)$$

Where in (1)

ρ denotes the density of air,

\vec{u} represents the velocity vector,

p refers to pressure and

μ is the dynamic viscosity of air.

Windows, vents, and roofs are often part of structures where air flows through. The airflow patterns reveal the effectiveness of passive ventilation, which helps evaluate passive cooling techniques. In order to describe the distribution of heat, an energy conservation equation, can be used:

$$\rho c_p (\vec{u} \cdot \nabla T) = k\nabla^2 T \quad (2)$$

Where in (2)

c_p is the specific heat of air,

T is temperature,

k is thermal conductivity.

The equation takes into consideration the natural convection or conduction heating and cooling, material properties and solar energy. For the outdoor environment, temperatures are provided with gradients, along with wind speeds for areas that are tropical or sub-tropical. In three-dimensional simulations, we are using discrete software packages, e.g. ANSYS Fluent, or Open FOAM, to simulate the three-dimensional spatial simulations. The house geometry model includes wall thickness in full scale, as well as the thermal conductivities of materials and openings, allowing for a reasonable level of accuracy to be achieved. The construction methods demonstrate structural robustness with associated low-cost housing design models. The less-than-robust lightweight roofing features flexible bamboo or steel frame elements, and critical wall junctions incorporate some bent framing. The base pads can isolate seismic basal ground shock from the horizontal movement shock of layering, making these structures more resilient during an earthquake event. Part of our design includes important key ventilating openings with placements for vertical load transfer.

Figure 1 (workflow diagram) describes the design approach and process of low-income housing, in particular, the evaluation of the efficiency of passive cooling methods (CFD simulation). It begins with the temperature and wind measurements of climate data clinics, thermal conductivity, density and structural dimensions of materials, such as wall thickness and reinforcement patterns fetched out of the CFD configuration. This consists of geometry modelling, grid generation, boundary condition allocation, simulation of energy equations and structural safety analysis under the potential seismic events.

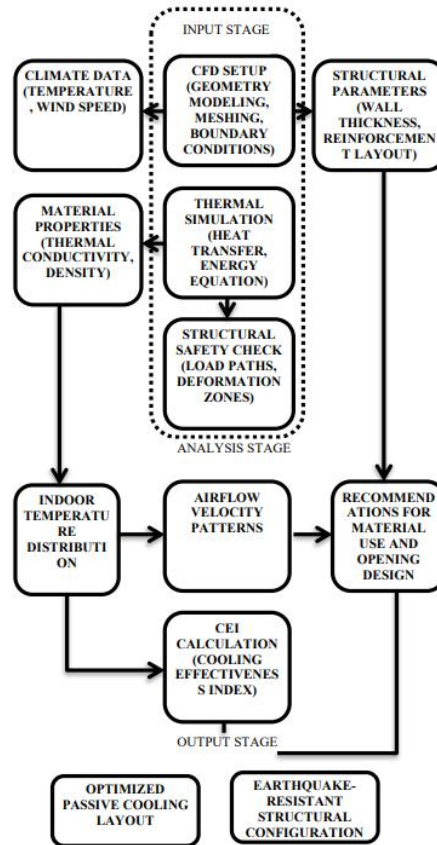


Fig. 1. Integrated CFD-Based Workflow for Passive Cooling and Earthquake-Resistant Housing Design

4 Results

CFD modelling simulation for the temperature range of 30 - 40 °C and external wind speed range of 1.5 - 3.5 m/s was conducted, comparing CSEB (thermal conductivity ~0.75 W/m·K, density ~1800 kg/m³), bamboo (~0.12 W/m·K), and recycled insulation to concrete (1.4 W/m·K, 2400 kg/m³). The opening design of the building model allowed for natural ventilation, permitting self-maintained air circulation within the building's interior spaces. Airflow streamlines visuals showed that windows with cross-ventilation provided improved overall air supply through all occupied spaces when aligned with the site's prevailing winds. Indoor air velocity ranged from 0.3 - 0.9 m/s, maximum at vents and minimum towards room corners. Peak indoor temperatures recorded during the hottest part of the day were only 5-7°C hotter than outside conditions (e.g., 38°C outdoor → 43-45°C baseline; CSEB/bamboo model → 36-40°C peak, 33-36°C daytime average with shading/ventilation). Shading elements like overhangs and louvers reduced solar heat gain by blocking direct sunlight on southern and western facades. Cross and stack ventilation in combination reduced average indoor temperatures by an additional 4.2°C compared to a sealed structure (baseline avg. 39.5°C → 35.3°C). CSEB/bamboo configurations showed 2-3°C lower steady-state temperatures vs. concrete due to superior thermal inertia/insulation. A quantitative analysis used the Cooling Effectiveness Index (CEI):

$$CEI = \frac{T_{out} - T_{in}}{T_{out} - T_{ref}} \quad (3)$$

Where in (3) T_{out} is outdoor temperature, T_{in} indoor temperature, T_{ref} reference (no cooling) temperature. Simulations yielded CEI 0.55-0.72, indicating enhanced comfort relative to baseline buildings [10].

Figure 2 shows a bar chart illustrating how different passive cooling methods help reduce an indoor space's temperature compared to the outdoor temperature of 38 degrees Celsius. Each group compares the baseline indoor temperature (without any cooling methods) to the indoor temperature achieved using each specific technique.

5 Discussion

This research indicates that passive cooling methods may greatly improve low-income housing. While there have been different ways to reduce dwelling temperatures, shaded cross ventilation and thermal mass stack ventilation are clearer cool choices. Moreover, this is important for lower socioeconomic groups as they often cannot afford mechanical equipment (air conditioning) which often will not even work because of inconsistent power supply services. These options would improve overall living conditions by reducing heat-related illness. Furthermore, these groups are more likely to experience climate change vulnerability which may require more accessible resilient permanent housing solutions. Besides, materials like CSEB and bamboo reduce the

carbon footprint and improve thermal performance of buildings so better for energy efficiency.

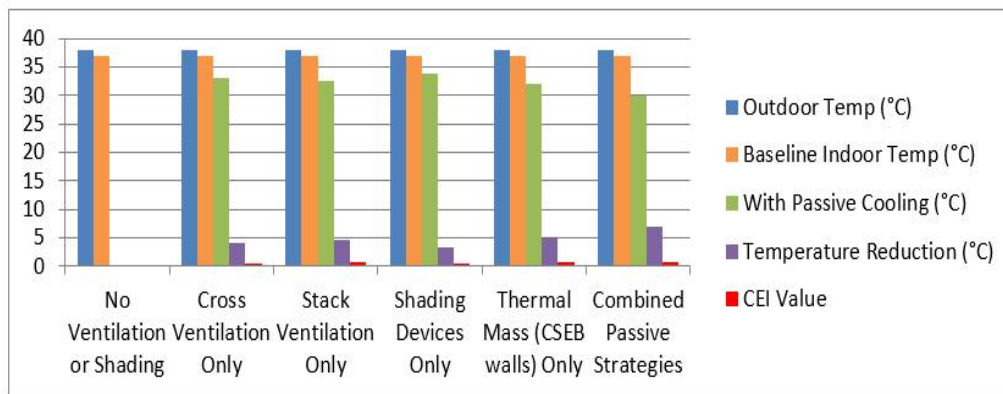


Fig. 2. Indoor Temperature Reduction Achieved by Passive Cooling Techniques

6 Conclusion

This research looked at passive cooling strategies and earthquake safe features in affordable housing, built from sustainable materials, using CFD modeling. The simulation showed that the comfort level in terms of indoor climate control due to ventilation, thermal mass, and shade devices-maintained focus cross and stack passive ventilation improvement, was comfortable by approximately 7 Degrees Celsius in comparison to non-ventilated buildings, more than acceptable. In addition, build detail reinforcement at joints with lightweight construction materials and wider windows for resisting lateral seismic forces and adequate, or preventing residual mechanical control free earthquake sheltering safety of occupants. These strategies provide significant support for developing low-income residents in earthquake and extreme heat-prone countries [1]. CFD modeling does not just support local relevance, guiding the design journey, coupled with verified steering context that strengthens reasoning improving assurance toward making decisions of this nature which increases the value added to community infrastructure project, and environmental sustainability by way of energy reduction and waste reduction in material transportation that impact climate change for future generations.

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