**Resilient Design: Climate Responsive Buildings**

**in Warm and Humid Terrain of India**

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**Abstract.** The increasing need for climate-resilient buildings in warm and humid regions is evident as climate change intensifies, causing more frequent floods, droughts, and heat waves. Rising greenhouse gas levels are worsening summer temperatures, while built environments face increased vulnerability to natural hazards like floods, landslides, and wildfires. This paper focuses on mitigating climate change impacts while providing thermal comfort and durability in residential construction. To tackle these challenges, a comprehensive approach to sustainable building design is crucial. Case studies in the paper highlight traditional Indian architecture, such as Kerala's “Naalukettu” and Stilt houses, demonstrating how local materials and techniques can be adapted to modern standards while remaining cost-effective. Bamboo structures in Assam illustrate how participatory design blends contemporary and traditional methods for low-cost resilience. The study underscores the need to integrate climate-resilient and climate-responsive strategies to create adaptable, durable buildings.

**Keywords:** Climate Responsive Architecture, Climate Resilient Structures, Sustainable Architecture, Warm and Humid climate, Building Technologies.

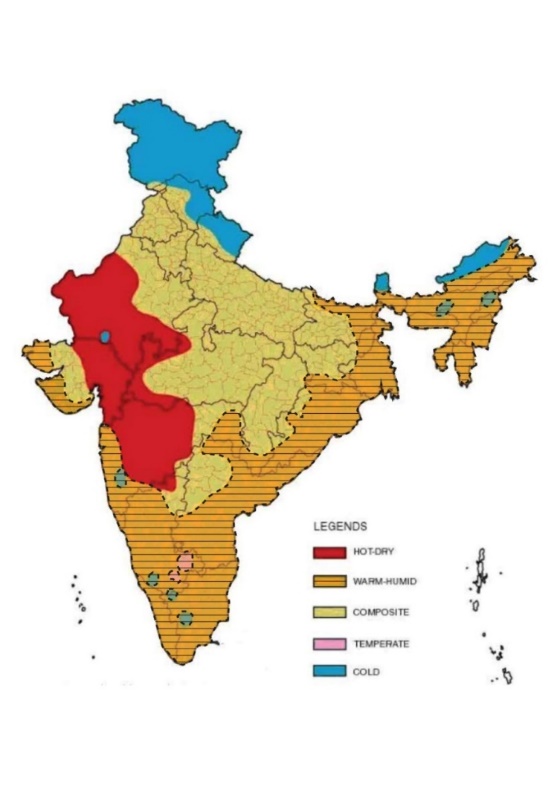
# Introduction

A climate-responsive built environment aims to enhance building performance and energy efficiency by employing design strategies that adapt to prevailing climatic conditions [1]. Techniques such as passive solar heating and natural ventilation are integrated to reduce reliance on mechanical cooling systems. In contrast, a climate-resilient built environment is fundamentally focused on the durability and recovery of structures in the face of extreme weather and long-term climatic shifts. This resilience is achieved through sustainable construction methods and materials that withstand environmental stresses [2]. While climate-responsive design maximizes immediate operational efficiency, climate-resilient design provides essential durability and the capacity for recovery, establishing a dual necessity for sustainable, adaptive architecture [2]. A key component of climate resilience is the reduction of greenhouse gas emissions, which can be achieved through the use of low-carbon materials and energy-efficient building designs [3]. Additionally, urban planning strategies aimed at minimizing the urban heat island effect—through the inclusion of green spaces, natural water bodies, and sustainable transport solutions—are critical [3]. To withstand environmental threats, climate-resilient architecture must incorporate earthquake-resistant structures, landslide mitigation measures, and fire-resistant materials [3].

Moreover, fostering community and ecosystem resilience is integral to a broader climate adaptation strategy. Disaster-ready infrastructure, the promotion of biodiversity, and the education of communities on sustainable practices are essential in creating environments that can recover quickly from climate-induced disturbances [3]. Strong regulatory frameworks and enforcement of stringent building codes are imperative to ensuring the long-term sustainability and resilience of built environments.

**1.1 Warm and Humid Climate**

India's geographical diversity gives rise to a complex array of climatic zones, spanning from extreme heat to severe cold. This variability, compounded by the escalating frequency and intensity of climate-induced extreme weather events, necessitates a transformative approach to building design and construction practices [4] . The country is distinctly classified into five major climatic regions; Figure 1 shows the Indian climate zonation map. This study specifically addresses building vulnerabilities experienced in warm and humid climates, particularly in light of vernacular constructions. Warm and humid climates, characteristic of India's tropical and subtropical regions, display consistently high summer temperatures ranging from 30°C to 40°C and humidity levels often exceeding 60%, potentially reaching 80% during the monsoon season[5]. The Indian monsoon significantly influences this climate, featuring two primary rainy periods: the southwest monsoon (June to September) and the northeast monsoon (October to December) [6]. These climatic conditions impact ecology while simultaneously creating challenges such as intense heat and waterlogging, particularly in coastal and inland regions. Notable states such as Kerala, Tamil Nadu, Assam and others exemplify the unique responses required for effective architectural solutions in these warm and humid settings.

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**Fig. 1.** Climate Zone Map of India (Source: NBC 2016, Vol. 2)

# Climate Responsiveness of Traditional Architecture

Traditional architectural techniques vernacular to warm and humid regions, are designed to respond effectively to the climate. The techniques focus on maximizing comfort, minimizing heat, and efficiently managing humidity [7]. Traditional houses often use mud or clay for walls, which have high thermal mass[7]. Houses are often built on elevated stone plinths to prevent moisture from the ground affecting the building and to facilitate airflow beneath the structure [7] Elevating the structure helps with ventilation, allowing air to circulate beneath and around the building, which helps to keep it cooler. Roofs are typically steeply pitched to allow rainwater to flow off easily and to provide shading for the walls[8]. This design helps to reduce heat absorption by the building. Suchtraditional architecture exemplifies principles of climate responsiveness and passive design in practice.

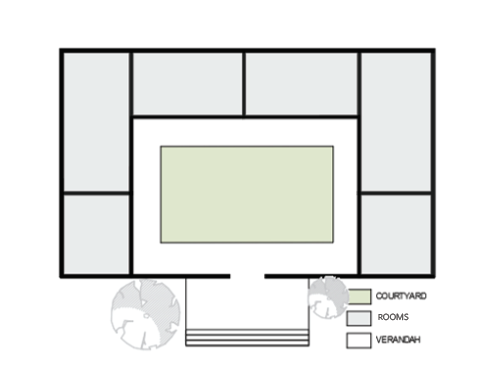
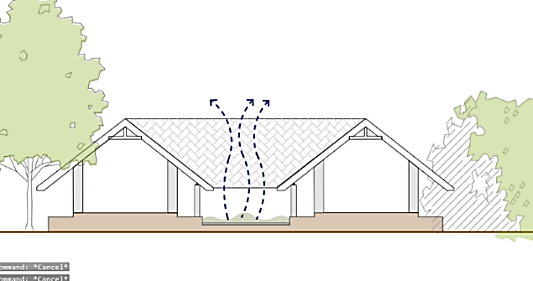
**Fig. 2.** Alampady Illam, Kozhikode

The study is conducted in an Alampady Illam, which is located in Kozhikode district of Kerala (Fig. 2). The building is 100 years old and climate-responsive due to its planning and material usage. Figure 3 shows the details of the courtyard, Verandahs and corridors present in the building. The materials used here are laterite bricks with lime mortar and clay tile for roofing and black oxide for flooring. The building has an optimum temperature at daytime due to the time lag of laterite; hence, it is porous. During the night, the building has a cool internal climate because of the use of clay tile for roofing. Here experiences proper air circulation due to the presence of a courtyard.

1. Courtyard and Verandahs (b) Corridors

**Fig. 3.** (a) Courtyard and verandahs, (b) Corridors supported by wooden colums, Alampady Illam, Kozhikode

**Fig. 4.** Typical arrangement of internal spaces and air circulation



**Fig. 5.** Present condition of building at Alampady Illam, Kozhikode

Figure 4 shows the Typical arrangements of the internal spaces and air circulation in the traditional building located in this area. Even though traditional construction techniques are climate responsive but it faces significant challenges from adverse climatic events, such as heavy rainfall and flooding, which can deteriorate materials like mud plaster and wooden roofing trusses due to moisture. Figure 5 shows Present condition of the traditional building. This deterioration negatively impacts the strength and overall performance of buildings. The construction methods also struggle with issues like dampness. This leads to an increase in the need of maintenance in Traditional buildings. To address these problems, CSIR-Central Building Research Institute (CBRI) developed hybrid construction technique featuring a brick pyramidal roof, designed to be suitable for both the rainy season and can be used in coastal regions in the warm, humid climate of India [10]. Additionally, as an alternative to traditional mud and cement plaster, non-erodible mud plaster cab be integrated. These technologies are not only climate-resilient and economical but also enhance overall building performance.

# Responsiveness to Resilience: A Hybrid Approach

The shift from traditional building materials to modern construction technologies has been driven by the scarcity of local materials and labour, leading to higher construction costs (Fig. 6). As a result, there has been a growing trend towards using more economical building techniques. However, sustainable materials have largely been replaced by alternatives like burnt bricks, cement mortar, and Reinforced Cement Concrete (RCC) slabs, which negatively impact the overall performance and sustainability of buildings. Additionally, modern building designs have become more compact, often lacking features like courtyards, which were once central to traditional architecture. This compact planning, combined with the use of materials that are not as energy-efficient, has increased the reliance on artificial cooling and lighting systems, further affecting the environmental and economic efficiency of contemporary buildings.

**Fig. 6.** Typical houses in Warm and Humid region of south India (Current Practices)

While climate-resilient buildings focus on durability and the ability to withstand and recover from extreme weather events, climate-responsive architecture emphasizes the optimization of energy efficiency through the adaptation of buildings to local climatic conditions. In warm and humid regions, climate-responsive strategies, such as passive cooling, natural ventilation, and shading, are employed to reduce energy consumption [8]. These two approaches—climate resilience and climate responsiveness—are not mutually exclusive; rather, they complement each other. By integrating resilience strategies that ensure long-term structural integrity with climate-responsive designs that maximize immediate energy efficiency, a hybrid approach can be developed. This combination of traditional climate-responsive techniques with modern climate-resilient strategies is crucial for addressing the pressing challenges of climate change, offering a sustainable and adaptable framework for building design in warm and humid regions.

This study examines the shift from climate-responsive to climate-resilient architecture in India's warm, humid regions, using case studies, observations, environmental assessments, and expert interviews to explore how traditional and modern building techniques can address climate challenges.

**3.1 Case Studies: Bamboo House of Assam**

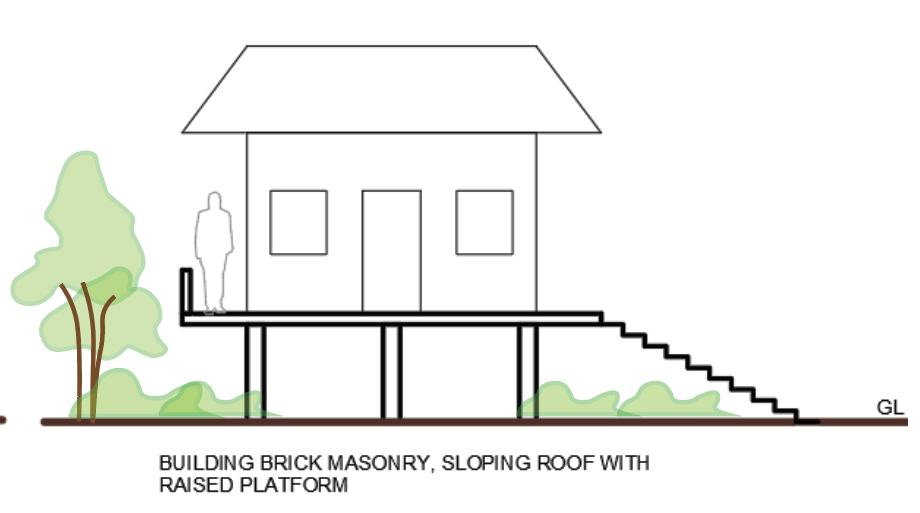
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1. Bamboo House (b) Playing areas (c) Semi-open space

**Fig. 7.** Bamboo House of Assam

In the recent past, 80 bamboo dwellings in Assam response to flash floods [3]. To prevent this, building were designed by considering modern vernacular architecture with a goal of fostering resilient and sustainable construction through connecting participatory design Fig. 7) . These houses are multifunctional rectangular houses that are hybrid typologies which combine contemporary technologies with local traditional architecture. Bamboo, lime and mud were used in construction. With the modifications like deeper bamboo foundations covered with cement -lime mixture for the purpose of withstanding floods. Raised platforms are created that allow daily activities like weaving, livestock raising, boat storage, and play areas for kids. Indigenous binding methods using rattan and bamboo dowels have been used to make the building resilient to lateral forces during floods. The study highlights the effectiveness of combining knowledge with modern building methods in disaster resilient community design. The integration of traditional techniques with post-disaster rehabilitation has resulted in a resilient built environment. The use of locally produced materials has also boosted the economy by creating employment opportunities and meeting essential needs. Architects, urban planners, and engineers must invest significant effort in post-disaster reconstruction efforts. They should focus on utilizing the best natural resources available to them to respond to flood-prone areas.

**3.2 Case Studies: Stilt Houses of Kerala**

**Fig. 8.** Stilt Houses in Alappuzha

The impact of land-use changes on urban flood disasters is a multifaceted issue shaped by various natural, social, and economic factors. The effects of different proportions of cultivated, forested, green, and developed land areas have shown varying results, highlighting the need for optimization to mitigate future urban flood risks. To address this challenge, it is crucial to identify sustainable, climate-resilient design modifications.

Stilted houses are the most adopted solution (Fig. 8), which are elevated structures with no living space on the ground floor, are designed to be resilient to flooding. Unlike traditional single-storey buildings that are more cost-effective but less flood-resistant, stilt buildings offer the significant advantage of avoiding damage during severe flooding due to their height above ground. With growing awareness of flood risks, this design has gained popularity for new constructions. To improve flood resistance in existing single-storey buildings, alternative strategies should emphasize retrofitting and revitalization efforts [9].

**3.3 Case Studies: Brick Pyramidal Roof**

CSIR-CBRI pyramid-shaped roofing system (Fig. 9) designed for coastal regions, utilizing locally sourced burnt clay bricks and cement mortar or M20 concrete, eliminating the risk of corrosion from salt-laden winds [10]. Unlike steel-reinforced concrete slabs or CGI sheets, which are susceptible to corrosion, this roof is supported by walls confined within a reinforced concrete (RCC) ring beam at the roof level, with no steel bars used. The pyramidal design features equal pitch on both sides, providing good aerodynamics to withstand high winds, making it suitable for areas prone to storms and cyclones. The roof slope is maintained at approximately 16 degrees to minimize wind forces, and it can be anchored to the ground using an under-reamed pile and anchor column to resist low air pressure during cyclones. The sloped sides facilitate quick rainwater drainage, reducing leakage risks. This roof design is ideal for houses with square or rectangular plans, with the RCC ring beam cast in dense M20 concrete and a 40 to 50 mm clear cover to prevent steel corrosion. In multi-storey buildings, only the top roof is constructed in the Brick Pyramidal Type, while the intermediate floors can be in normal RCC.

**Fig. 9.** Brick Pyramidal roof (CSIR- CBRI, Roorekee)

# Conclusions

The study emphasizes the need to transition from climate-responsive to climate-resilient architectural designs in India's warm and humid regions. By using local materials such as bamboo, lime, and mud, these methods provide valuable insights into adapting traditional techniques to meet modern sustainability standards, while ensuring long-term resilience against environmental stresses. The design of buildings should incorporate site conditions and address vulnerabilities for better performance. Proper orientation, openings, and shading devices can enhance efficiency. The study underscores the importance of integrating climate responsiveness, which focuses on energy optimization, with climate resilience, which ensures durability against extreme weather events like floods, heatwaves, and cyclones.

A hybrid approach, combining both strategies, allows buildings to respond to current climate conditions and withstand future uncertainties. This approach also promotes the use of traditional materials and techniques with a low carbon footprint, which are cost-effective and support local economies by creating employment opportunities. Additionally, incorporating disaster-preparedness features, such as elevated foundations, flood barriers, and green infrastructure, enhances the resilience of structures against climate-induced hazards. The study concludes by advocating for the integration of traditional knowledge into modern building codes to promote sustainability and resilience in residential construction. This integrated approach is essential for addressing climate change challenges and ensuring the long-term sustainability of the built environment in warm and humid regions of India.

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