Original Paper

Sustainable practices in Keylong's vernacular architecture.

A detailed study of construction and thermal efficiency in the Himalayas

Shiv Dayal Singh, Venu Shree, Harsimran Kaur

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Abstract. *This study meticulously investigates the resilience and sustainable attributes of vernacular architecture in Keylong, a paradigmatic region located in the Himalayan highlands. The research primarily concentrates on elucidating the indigenous construction techniques, materials, and their concomitant impact on thermal performance, underscoring the intersection between traditional wisdom and sustainable practices. The principal aim of this inquiry is to unravel the intricate relationship between vernacular architectural practices and their inherent sustainability, particularly in the context of the harsh climatic conditions prevalent in the Himalayan region. The objectives encompass a comprehensive analysis of the construction methodologies, material utilization, and the thermal efficiency inherent in these traditional dwellings, juxtaposed against contemporary building practices. Methodologically, the study employs a multifaceted approach, incorporating empirical data collection through state-of-the-art Tempnote TH32 dataloggers, coupled with qualitative assessments derived from local narratives and historical perspectives. This dual approach facilitates a holistic understanding of the vernacular architecture's performance and its adaptive strategies in the face of climatic adversities. The findings reveal a profound congruence between the vernacular architecture of Keylong and the principles of sustainability. The traditional constructions demonstrate remarkable thermal efficiency, primarily attributable to the judicious use of locally sourced materials and time-honored construction techniques. Moreover, these structures exhibit a remarkable resilience to the region's extreme weather conditions, embodying a sustainable architectural paradigm that harmonizes with the natural environment. The study's outcomes underscore the significance of reviving and integrating traditional architectural wisdom into contemporary sustainable building practices. It posits that such integration could offer viable solutions to the challenges posed by climate change, especially in ecologically sensitive and high-altitude regions. This research not only contributes to the academic discourse on sustainable architecture but also provides practical insights for architects,*

planners, and policymakers engaged in the development of resilient and sustainable habitats in the Himalayas and similar contexts.

1. Introduction

Vernacular architecture in Keylong, reflecting indigenous wisdom and environmental adaptability, is a sustainable design paradigm (Bothara et al., 2022; Mazraeh and Pazhouhanfar, 2018; Motealleh et al., 2018; Singh et al., 2010). These structures, dating back to 1960 and depicted in Figures 1 and 2, embody cultural and climatic responsiveness. Utilizing local materials like stone, wood, and mud soil, these buildings exemplify thermal insulation properties essential for the region's extreme winters (Chkeir et al., 2023; Rijal, 2021; Elert et al., 2021; Mendis et al., 2024). The varied spatial layouts address local needs and environmental nuances (Anna-Maria, 2009; Foruzanmehr, 2015; Zune et al., 2020). Additionally, the orientation of these structures, aligned with sunlight and topography, illustrates an effective use of solar energy. This introduction explores Keylong's vernacular architecture's multi-layered relationship with its environmental and cultural context, offering insights for modern sustainable design and cultural preservation amidst climate change challenges.

Figure 1. Vernacular architecture of Keylong Region (Source: Author)

Figure 2. Vernacular Architecture of Keylong Region (Source: Author)

2. Region: Lahaul and Spiti

The Lahaul and Spiti valleys, situated in the northern Indian state of Himachal Pradesh, encompass approximately 13,841 square kilometers and house a population of 31,564, as per the latest census data. These valleys, ensconced within the Himalayan Mountain range, exhibit a wide array of geographical and ecological diversities, contributing to their rich natural and cultural heritage. Distinct yet interconnected, Lahaul and Spiti present unique characteristics and challenges. Lahaul, positioned to the south, is distinguished by its verdant flora, fertile terrain, and clustered villages along the Chandra and Bhaga rivers. The primary economic activity in Lahaul revolves around agronomy, specifically the cultivation of barley and potatoes. This region also boasts of scenic monastic sites, notably the Key Monastery, and traditional wooden architecture with intricate carvings, symbolizing its rich cultural ethos.

Conversely, Spiti, the northern counterpart, is a high-altitude desert valley, characterized by its arid, barren landscape and mesmerizing vistas. It houses ancient monasteries, such as the renowned Tabo Monastery, colloquially referred to as the "Ajanta of the Himalayas." The inhabitants of Spiti have acclimatized to their rigorous environment through agro-pastoral practices, encompassing livestock herding and cultivation of hardy crops like barley and peas. The vernacular architecture across Lahaul and Spiti is a testament to the region's adaptation to the severe mountainous climate. Traditional dwellings, characterized by thick stone walls, flat roofs, and diminutive windows, epitomize the necessity to conserve thermal energy during prolonged winters. This architectural form illustrates the symbiotic relationship between the indigenous culture and environmental conditions. Tourism in Lahaul and Spiti has seen an upsurge, drawing visitors with its unspoiled landscapes, snow-capped peaks, and distinctive Buddhist monasteries. The region's allure lies in its untouched natural beauty and rich cultural tapestry, making it a destination of significant interest for a diverse array of tourists.

3. Study area - Keylong Region

Keylong, a picturesque township nestled in the Himalayas, serves as the administrative hub of the Lahaul and Spiti district in Himachal Pradesh. Accessible via the Manali-Leh Highway or the Atal Tunnel, Keylong's strategic geographic position is marked by a confluence of diverse climatic conditions and a rich cultural heritage. Flanked by the towering Great Himalayas and the Pir Panjal Range, it presents breathtaking vistas of snow-clad peaks and verdant valleys, as depicted in Figures 3 and 4. Perched at an elevation of approximately 3,080 meters (10,100 feet) above sea level and spanning an area of 1200 square kilometers, Keylong has a population of around 1,150, as indicated by the 2011 Census. This demographic data underscores the unique challenges and opportunities inherent in its remote and lofty location. Situated within the extensive Lahaul and Spiti district, Keylong exhibits distinct yet interconnected attributes. The local populace engages in a variety of livelihoods, including agriculture, animal husbandry, commerce, and tourism. Such diverse economic activities reflect the town’s multifaceted character. While the current study delves into Keylong's specific architectural and environmental dynamics, future research endeavors could amplify these findings through comparative analyses with similar high-altitude Himalayan regions. This broader perspective would enrich the understanding of vernacular architecture’s role across varying environmental and cultural landscapes. Keylong experiences a cold desert climate, characterized by prolonged, severe winters marked by frequent snowfalls and sub-zero temperatures. Conversely, the summers, albeit warmer, offer a brief window for agricultural activities. The cultivation of crops like barley and peas, integral to local farming practices, aligns with the brief growing season. Additionally, the region's robust livestock, including cows, yaks, and sheep, are well-adapted to these harsh conditions, bolstering the community's longstanding animal husbandry traditions.

Keylong, strategically positioned along the Himalayan trade routes, functions as a pivotal commercial hub, facilitating the exchange of goods with adjacent areas. Its geographical advantage has rendered it a critical nexus for commerce and the distribution of essential supplies. This aspect of Keylong underscores its significance in regional trade dynamics. Beyond its economic role, Keylong is a vibrant cultural epicenter, epitomizing the traditional lifestyle and heritage of its inhabitants. The town is home to several notable monasteries, including the Kardang and Shashur Monasteries. These establishments are not merely religious sanctuaries; they stand as architectural wonders, as illustrated in Figure 5. These monastic sites provide a window into the profound Buddhist culture and historical tapestry of the region, offering insights into the spiritual and aesthetic dimensions of Keylong's community life.

Figure 3. Location map - Keylong Region (Source- Author)

Figure 4. Keylong Village (Source- Author)

Figure 5. Local Buddhist monastery (Source- Author)

Keylong's bustling markets, adorned with vibrant Tibetan prayer flags and animated by local traders, present an authentic snapshot of the region's traditional lifestyle, as captured in Figure 6. These vibrant marketplaces not only offer a visual feast but also serve as cultural intersections where visitors can immerse themselves in the local ethos. Patrons have the opportunity to explore an array of indigenous handicrafts and savor regional cuisine, facilitating a deeper engagement with the community's customs and practices. This interaction between visitors and locals fosters a rich cultural exchange, allowing for a genuine experience of Keylong's unique cultural identity.

Figure 6. Keylong local market (Source- Author)

3.1 Climatic data

Keylong is a high-altitude town in the Himalayas, with diverse and extreme climatic conditions. The town has a unique geographic location in the western Himalayas of India, at an elevation of about 3,080 meters (10,100 feet). The town has a cold desert climate, which causes wide variations in temperature, humidity, precipitation, cloud cover, and wind speed throughout the year.

As per data from Metablue from Figure 7, Keylong witnesses temperature fluctuations ranging from approximately -20°C (-4°F) in January to around 30°C (86°F) in June and July. The coldest months with average minimum temperatures of -9.0°C (15.8°F) and -5.9°C (21.38°F) are January and February, while the July is the warmest month with average maximum temperatures of 18.2°C (64.76°F). Relative humidity spans from 40% to 80%, peaking in July and August.

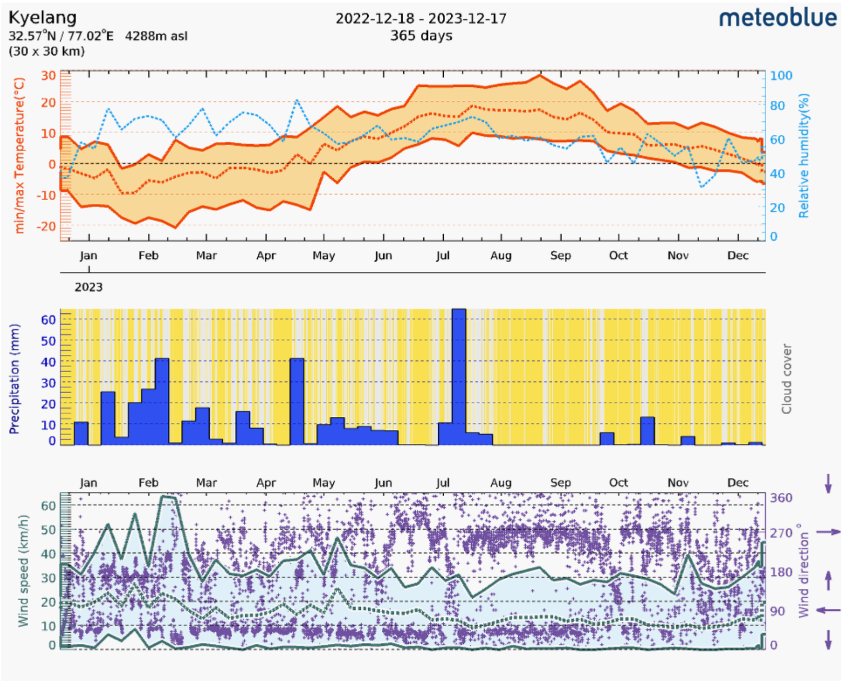

Figure 7. Climatic data of Keylong Region for year 2023 (Source: Metablue)

The precipitation pattern in Keylong is predominantly influenced by the monsoon season prevailing from June to September. July is the wettest month registering an average rainfall of 60 mm (2.4 in). Conversely November and December are the driest months experiencing an average rainfall of 6 mm (0.2 in) and 7 mm (0.3 in) respectively. The annual precipitation accumulates to 323 mm (12.7 in) while cloud cover ranges from 10% to 90%, reaching its highest in July and August.

Keylong encounters variable wind speeds throughout the year with peak speeds reaching up to 64 km/h (39.76 mph) between March and May. In contrast, the lowest wind speeds falling below 10 km/h (6 mph) are observed in July to

December. The prevailing wind direction is predominantly from the northeast, with slight variations corresponding to seasonal changes.

The climatic conditions in the Keylong region significantly impact the lifestyle, culture, and architectural practices of its residents. Navigating through extreme cold, low oxygen levels and scarce resources, the local populace predominantly engages in agriculture, animal husbandry, and trade. This pilot study sheds light on the intricate relationship between the climate and the multifaceted aspects of life in the Keylong region, emphasizing its far-reaching effects on various facets of the local community.

3.2 Climatic adaptive design

The vernacular architecture of Keylong exemplifies a profound understanding of the climatic challenges inherent to the region. Local builders and inhabitants have developed construction techniques that support local regionally available materials such as stone, mud and timber to create structures that withstand the extreme cold and limited resources. The Vernacular Architecture incorporates features like thick stone walls and insulated roofs to provide thermal mass, aiding in temperature regulation and offering protection against the harsh winter conditions (Aranguren et al., 2020; Hamard et al., 2013; Mangeli et al., 2023).

Furthermore, the design of vernacular buildings in Keylong showcases a keen awareness of the need for natural ventilation, passive cooling, and protection from intense sunlight. (Farouq et al., 2020; Mangeli et al., 2023; Zune et al., 2020). Traditional dwellings often feature small windows to minimize heat loss and maximize thermal efficiency. The spatial layout and orientation of these structures are intricately planned to capitalize on natural elements, promoting airflow for cooling during the warmer months (Zhao et al., 2020).

The climatic adaptive Vernacular Architecture of Keylong not only addresses the immediate challenges posed by its environment but also serves as a repository of local wisdom, cultural identity and sustainable living practices. In a research context an in-depth analysis of these architectural strategies would yield valuable insights applicable to contemporary design practices particularly in the face of evolving climate patterns and the imperative for sustainable construction in mountainous regions.

3.3 Pilot case study

In response to the challenging harsh climatic conditions of Keylong, the vernacular architecture style in the region has undergone a gradual evolution mirroring the demands of its environment. This architectural style bears resemblances to the Kath kuni architecture style. Our research methodology involved an extensive examination of various vernacular architecture types in Keylong with a specific focus on structures dating back to the 1960s. Through on-site visits to different locations, we meticulously selected a representative structure that was built in 1960 and owned by Mr. Soman for detailed analysis.

Figure 8. Local Vernacular Architecture Example (Source - Author)

Our comprehensive investigation delved into the construction techniques, methodologies, strategies, and the procurement and availability of building construction materials associated with the vernacular architecture of Keylong. To assess the relative performance of vernacular architecture compared to contemporary structures, we compared our findings with a modern building erected in the year 2000 by Mr. Jagan Nath. A critical aspect of our research involved conducting a month-long analysis of indoor temperature and humidity during the winter season, providing empirical data for a comparative evaluation.

This research design allows for a nuanced exploration of the effectiveness and adaptability of Keylong's vernacular architecture in the face of its harsh climate, offering valuable insights into construction practices and performance benchmarks for both traditional and contemporary structures.

3.4 Village settlement pattern

In the village settlement planning of Keylong, a distinctive amalgamation of linear and scattered planning principles is evident, reflecting a thoughtful adaptation to the unique topography and cultural dynamics of the region. The central framework of the village is structured around a linear plan, primarily manifested through the road network that serves as a vital artery for movement and commerce as shown in Figure 10. As shown in Figure 9 this linear arrangement strategically situates most shops along the main roads, fostering accessibility and facilitating daily transactions for both residents and passersby.

Figure 9. Keylong linear village settlement view (Source - Author)

However, woven within this linear fabric, elements of scattered planning come to the forefront, introducing a nuanced complexity to the overall settlement design. Notably, certain houses deviate from the linear alignment and find their place on elevated contours. This departure from the linear layout is indicative of a scattered planning approach, possibly influenced by factors such as land ownership patterns or a deliberate choice to reside at higher elevations as seen in Figure 10.

The scattered planning aspect gains prominence in the elevated houses, revealing a deliberate decision to occupy specific locations. This could stem from a desire for panoramic views, environmental considerations, or cultural preferences associated with certain elevations.

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Figure 10. Keylong linear village settlement view (Source - Author)

This hybrid approach to settlement planning underscores a pragmatic response to the challenging mountainous terrain of Keylong. By interweaving linear and scattered elements, the planning not only addresses the practicalities of transportation and daily life but also respects the diverse needs and preferences of the community.

4. Building Form and Orientation

4.1 Building Planning

In the Keylong area, building planning intricately aligns with the functional purpose of each room, a design approach intricately tied to the number of wooden columns (Kaaju) employed, ranging from one to six as detailed in Figure 11,12 and 13. This nuanced system of wooden column usage is historically rooted, with the vernacular architecture of Keylong evolving in response to the region's formidable climatic challenges.

Figure 11. Four Pillar (Kabzi) layout in planning (Source - Author)

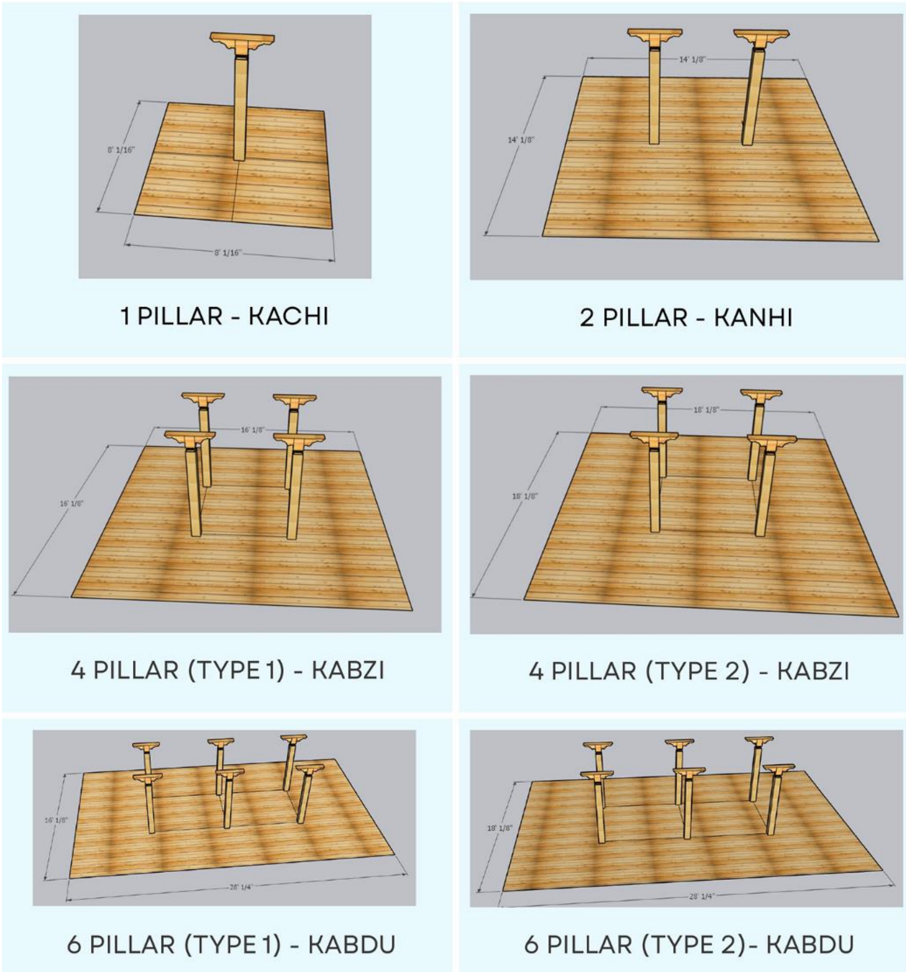

Figure 12. Types of Pillars used in indoor planning (Source - Author)

The architectural planning of structures in Keylong unfolds across three distinctive levels. The basement primarily accommodates cattle and also serves as a storage space for food and grains, a strategic response to the harsh winter climate that necessitates prolonged freshness of stored provisions as shown in Figure 14. The first floor is designated as the living area for occupants, segmented into various functional zones as shown in Figure 15. The second floor holds a pivotal role, dedicated to the deity area as shown in Figure 16. This space becomes a focal point for prayers, local gatherings, and various cultural activities.

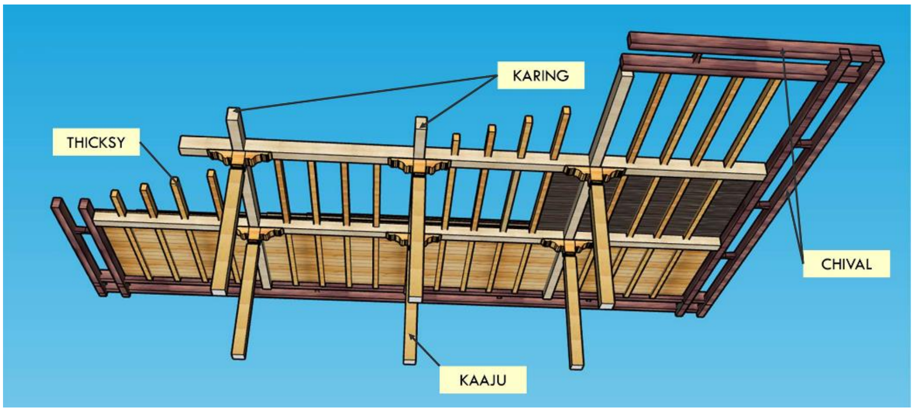

Figure 13. Structural details (Source - Author)

Figure 14. Building basement - For food storage (Source - Author)

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Figure 15. Building living space (Source - Author)

Figure 16. Deity area and space for local gathering (Source - Author)

The orientation of these buildings strategically considers the movement of sunlight, a response to the topography of the hills. Larger sides of the structures are deliberately exposed to sunlight, creating a thermal effect that warms the interiors during both winter and summer seasons.

4.2 Foundation

In response to the substantial structural requirements, the building's foundation in the Keylong area entails a meticulous process. The excavation involves digging a foundation that extends 4 feet in width and 5 feet in depth into the earth. Subsequently, solid blocks of stones are strategically placed at the base, forming a sturdy foundation. The construction process continues with the addition of layers: initially, a layer of mud is applied, followed by the placement of more stone blocks until reaching ground level height. This method employs large stones in conjunction with mud, which functions as a natural mortar, effectively binding the materials together. This amalgamation of large stones and mud not only ensures structural stability but also forms a robust foundation capable of withstanding the substantial load imposed by the building. This meticulous foundation construction process, rooted in the local vernacular architecture of Keylong, epitomizes an adaptation to the challenging terrain and the need for structural resilience. By employing locally sourced materials and leveraging traditional construction techniques, this approach exemplifies the integration of indigenous wisdom and practicality to address the specific structural demands imposed by the region's environmental and climatic conditions.

4.3 Walls

In response to the challenging climate conditions of the Keylong region, local masons have embraced a construction approach characterized by thick walls utilizing stone and wood as primary materials. Various research underscores the thermal insulation properties inherent in stone and wood, revealing their capacity to maintain favourable indoor temperatures as shown in Figure 17 (Alqadi et al., 2023; Farouq et al., 2023; Mangeli et al., 2023; Raju & Ravindhar, 2020). In Keylong's construction practices, walls typically range from 1 foot 6 inches to 2 feet in width with floor height lie between 6 feet to 8 feet, incorporating a combination of stone and mud as foundational materials as shown in Figure 17 and 18. The stacking of larger and smaller stones, interspersed with mud, enhances structural stability.

Figure 17. Outer Building wall facade (Source - Author)

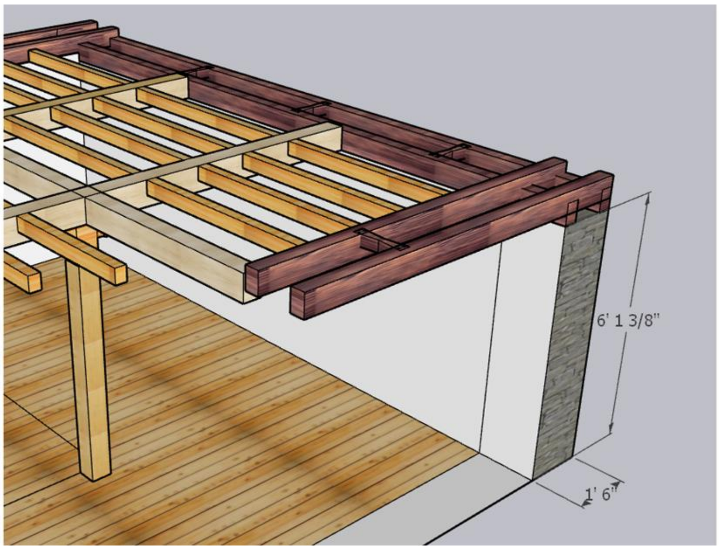

Figure 18. Wall detail (Source - Author)

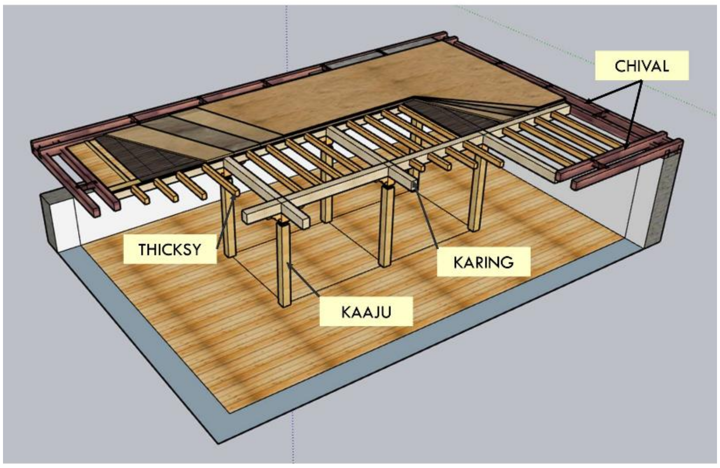

Figure 19. Structural details (Source - Author))

For both functional and aesthetic considerations, mud plaster is applied to the interior and exterior sides of the walls. This not only adds an extra layer of insulation but also contributes to the visual appeal of the structure. Interior partitions are crafted using the wattle and daub construction technique as shown in Figure 20 employing a wall width of 4 inches (Hema et al., 2021; Mendonca & Vieira, 2022). Over windows, wooden log members with a consistent width serve as lintel beams, providing additional structural support to the overall edifice. Crucially, all construction materials are locally sourced, a practice that not only aligns with sustainable principles but also ensures enhanced thermal comfort for occupants during winter months when temperatures plummet to negative degrees Celsius (Goodhew et al., 2021; Hema et al., 2021).

Figure 20. Wattle and daub detail (Source - Author)

4.4 Flooring

Flooring stands out as a pivotal element within vernacular building structures playing a crucial role in heat retention for occupants. The flooring system is stratified into several layers with the placement of columns at the base corresponding to different room spaces. The central beam (Karing) measuring 6 inches by 6 inches traverses horizontally and vertically between walls as shown in Figure 20 and 21. Situated between these central beams are secondary beams (Thicksy) measuring 4 inches by 3 inches, spaced at 1 foot 6 inches intervals. Atop these beams, a 2-inch layer of sun-dried branches from the Salix daphnoides plant as shown in Figure 22 locally abundant in the area is incorporated. Alternatively, wooden planks may be used in place of branches, dependent on the family's financial resources to enhance interior aesthetics as shown in Figure 13.

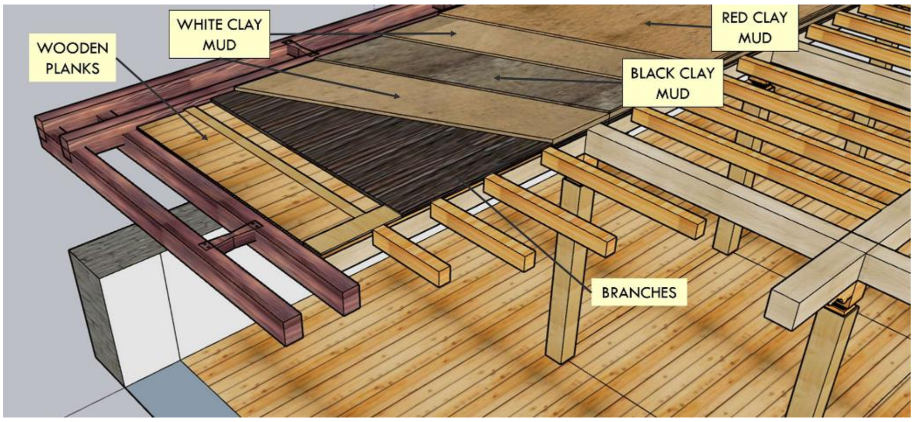

Figure 21. Flooring details (Source - Author)

Above this layer, three successive clay soil layers, each approx. 1 inch thick are employed which can be seen in Figure 21. This multi-layered soil composition acts as an effective insulator, preventing the loss of indoor heat. To complete the flooring structure a final layer is added offering a choice between a thin stone slab, Mud coating or wooden flooring. This topmost layer provides a refined surface for walking while contributing to the overall thermal efficiency of the building.

4.5 Roofing

The Keylong region experiences a formidable climate, marked by abundant snowfall, with snow layers reaching heights of 3 to 6 feet during peak conditions. Vernacular buildings in this area feature flat rooftops, employing a similar principle to the flooring structure. The construction involves layers of central and secondary beams, sun-dried branches or wooden planks, and multiple soil layers, with the addition of a final 1 to 2 inches of clay soil on the roof's surface as elaborated in Figure 23, 24 and 25. This design consideration, observed in response to the harsh winter conditions, enables the accumulation of snow layers on the rooftop (Zune et al., 2020).

Figure 22. Salix daphnoides tree (Source - Author)

Figure 23. Basement ceiling (Source - Author)

Figure 24. Roofing design (Source - Author)

Figure 25. Roofing details (Source - Author)

Research studies highlight the efficacy of snow as a natural insulator of heat. Comprising tiny ice crystals with entrapped air, snow forms a thermal barrier on the roof (Chandel et al., 2016; Singh et al., 2010; Zune et al., 2020. The air pockets within the snow layer act as effective barriers, preventing the escape of heat to the outdoor environment. This insulating effect contributes significantly to maintaining a warmer indoor environment during the severe winter months.

4.6 Building openings

The design of building openings stands as a critical element in vernacular building structures, profoundly influencing the creation of a conducive indoor environment for occupants. A strategic consideration in window placement aligns with the sun's direction, ensuring an optimal influx of sunlight into the building. Varied areas within the building are equipped with different numbers of windows, carefully calibrated to cater to the specific needs of each space. Each window is constructed with a standardized size of 4 feet by 3 feet, utilizing wood and glass, as depicted in Figure 25. Complementing this window configuration, a wooden beam is strategically positioned over each window, providing enhanced structural support, as illustrated in Figure 17.

This architectural approach exemplifies a refined integration of environmental considerations into building design, facilitating the creation of well-lit and appropriately ventilated interior spaces. (Vijayan et al., 2021). The deliberate alignment of window placement with solar orientation not only harnesses natural light effectively but also contributes to energy efficiency and the overall thermal performance of the structure.

Figure 26. Building openings (Source - Author)

5 Data collection

5.1 Indoor temperature and humidity

In Keylong, a Pilot case study was undertaken to explore the distinctive vernacular architecture prevalent in the region. The investigation revealed that vernacular buildings outperformed contemporary counterparts, attributed to the compatibility of building materials with the local environment. Various study emphasized that structures crafted from stone, wood, and soil contributed to a superior indoor environment for occupants. To ensure a comprehensive understanding of our methodology, we used Tempnote TH32 dataloggers with a systematic data collection process spanning different seasons. We conducted a statistical analysis using [specific software/method], allowing for a more robust interpretation of the thermal performance data.

The contemporary building incorporated materials such as baked red brick, cement, sand, aggregate, wood, and stone. The data collection spanned one month during the peak winter season in January 2023, offering a comprehensive snapshot of environmental conditions within both buildings. This research design facilitated a meticulous exploration of the thermal and humidity performance of vernacular and contemporary structures, providing empirical data to ascertain the effectiveness of traditional building practices in Keylong.

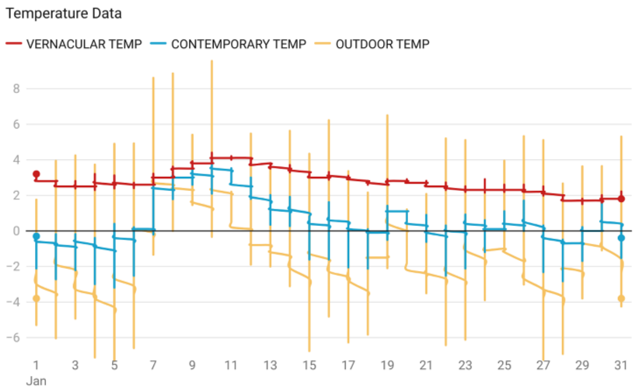

Figure 27. Temperature data (Source - Author)

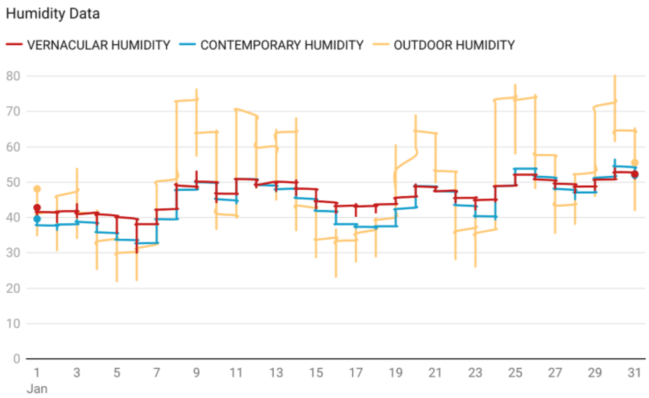

Figure 28. Humidity data (Source - Author)

6. Results and discussion

This investigation delves into the vernacular architecture of the Keylong region, with a primary focus on its construction patterns, materials and thermal performance in comparison to contemporary buildings. The vernacular buildings under study dating back to 1960, exemplify the utilization of locally sourced materials such as stone, wood and mud soil known for their commendable thermal insulative properties. The construction layout, based on various sizes, reflects a meticulous consideration of spatial needs within the local context. To assess the thermal performance of both vernacular and contemporary buildings, Tempnote TH32 dataloggers were employed during the peak winter season from January 1, 2023, to January 31, 2023.

As shown in Figure 27 and 28 the data revealed distinctive thermal profiles for vernacular and contemporary buildings. The contemporary building exhibited suboptimal performance, experiencing the lowest recorded temperature of -3.2 degrees Celsius and a high humidity level of 57 percent. Conversely, the vernacular architecture maintained a significantly more favourable temperature range from of 2.1 to 4.3 degrees Celsius, providing enhanced thermal comfort compared to its contemporary counterpart. A detailed analysis of the climatic data reveals significant patterns in temperature and humidity, correlating these with the architectural features unique to Keylong. This deeper analysis helps in understanding how traditional designs adapt to and mitigate climatic challenges.

The superior performance of vernacular buildings can be attributed to the inherent thermal properties of locally sourced materials namely stone, wood and mud which possess excellent insulation capabilities. This characteristic ensures better temperature regulation within the building mitigating the extremes of external climatic conditions. The vernacular architecture's reliance on various sizes for building areas reflects an intrinsic understanding of spatial requirements tailored to local needs. This flexibility in design caters to the functional demands of the occupants while aligning with the climatic nuances of the Keylong region. The empirical data collected underscores the thermal superiority of vernacular buildings and carries significant implications for contemporary architectural practices. Incorporating locally sourced materials and adopting construction strategies aligned with indigenous wisdom can enhance the energy efficiency and overall comfort of modern buildings, especially in regions with similar climate profiles.

7. Conclusion

In unravelling the intricacies of vernacular architecture in the Keylong region, our present study underscores the profound impact of indigenous design and construction practices on the thermal performance of buildings. The vernacular structures, dating back to 1960 and crafted from locally sourced materials such as stone, wood and mud showcase a remarkable synergy between traditional wisdom and environmental responsiveness. The spatial considerations, reflected in the various sizes of building areas, underscore a nuanced understanding of local needs and climatic nuances. As we conclude this exploration, the study not only reaffirms the thermal superiority of vernacular buildings in Keylong but also advocates for a re-evaluation of contemporary design approaches. The integration of locally sourced materials and construction strategies aligned with indigenous wisdom emerges as a crucial pathway toward creating resilient, energy-efficient and comfortable built environments in the face of evolving climate challenges. Looking ahead, future research endeavours can build upon these findings with a concentrated focus on the indoor environment. A crucial avenue for exploration involves conducting a yearly longitudinal study focused on the thermal comfort within vernacular buildings. This approach would offer a detailed understanding of how these structures perform across different seasons, allowing for an examination of temperature variations and occupant satisfaction over time. Another pivotal aspect for future investigation involves integrating advanced sensors to monitor indoor air quality parameters. This includes tracking humidity levels, air circulation, and particulate matter to gain a comprehensive understanding of the indoor environment's health. Such insights can be correlated with seasonal changes, and the data obtained can be instrumental in designing strategies to maintain optimal air quality within these vernacular spaces.

Furthermore, future research can delve into the energy efficiency of vernacular buildings by closely analysing the performance of traditional heating and cooling mechanisms. This exploration aims to understand how these structures naturally regulate indoor temperatures without excessive reliance on external energy sources, providing valuable insights for the development of sustainable design practices. By focusing on these key aspects, future research can contribute significantly to our understanding of the indoor environment in vernacular buildings, facilitating the development of sustainable and climate-responsive design principles tailored to the unique climatic conditions of Keylong.

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Authors

Shiv Dayal Singh (*corresponding author*) shiv_phdarch@nith.ac.in
Department of Architecture, National Institute of Technology Hamirpur, Hamirpur, India. (alternative e.mail: shivdayal1427@gmail.com)

Venu Shree venushree@nith.ac.in
Department of Architecture, National Institute of Technology Hamirpur, Hamirpur, India.

Harsimran Kaur harsimran.apd@iitbhu.ac.in
Department of Architecture, Planning and Design, Indian Institute of Technology (BHU) Varanasi, India.

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