An Overview of Seismic-Resistant Design in Ancient Indian Temples

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Abstract

Ancient Indian temples, famous for their architectural marvels, also exhibit advanced seismic-resistant design principles that have enabled them to withstand earthquakes for centuries. This paper explores the innovative techniques used by ancient builders to enhance the seismic resilience of these structures. Key features include massive stone foundations, sand-box technology, interlocking stone blocks, mortise and tenon joints, proper geometrical planning, and accuracy in execution, which allowed for stability, flexibility, and energy dissipation during seismic events. The article also highlights the relevance of these ancient techniques in modern seismic-resistant design, drawing parallels with contemporary practices such as base isolation and energy dissipation mechanisms. Additionally, it discusses the challenges and strategies to ensure the seismic safety of these heritage structures.

Keywords: Ancient Indian temples, seismic-resistant design, ancient aseismic techniques, seismic safety of heritage structures.

1. Introduction

The architectural heritage of India is a testament to the advanced engineering skills and aesthetic sensibilities of its ancient civilizations. Among the most iconic symbols of this rich heritage are the numerous temples scattered across the subcontinent. These temples serve not only as places of worship but also as remarkable examples of structural engineering marvels, especially considering the limited technological resources available at the time. These temples, many of which have stood for centuries, have weathered the ravages of time and natural disasters, such as earthquakes.

Temples, dating back to 1000 BCE, were outdoor shrines situated under consecrated trees or near water sources [1]. However, a significant shift occurred during the Mahajan padas period (600 BCE-345 BCE), marking the emergence of the temple as a closed structure [2]. At Besnagar, Madhya Pradesh, the remains of an oval-shaped temple, resembling thatched huts, dated to around 400 BCE have been unearthed [3,4]. Gradually, people began to construct larger and more permanent structures for temples. With the advent of a wealthy elite class who financed the construction, the trend got pace. Temple No. 40 at Sanchi, a Mauryan 3rd-century BCE apsidal temple, features a stone-raised plinth and a wood-constructed superstructure [5]. During the period from 200 BCE to 300 CE, people began constructing temples with multi-story structures, high ceilings, and detailed carvings and decorations [2]. During the Gupta era, which lasted until 550 CE, significant advancements in temple construction technology occurred. The Bhitargaon Temple, Uttar Pradesh, is among the surviving temples built during this period. Over time, advancements in temple construction technology have resulted in the development of more complex and versatile temples. Here it is pertinent to mention that, from its early days, the temple building in India has been significantly influenced by Śilpa Śāstra and Vāstuśāstra. Śilpa Śāstra provides detailed guidelines for sculpture, ornamentation, and the artistic aspects of temple construction. On the other hand, Vāstuśāstra chiefly focuses on the alignment, proportions, and energy flow within the temple, ensuring harmony with cosmic principles.

India is located in a seismically active region, where the collision of the Indian and Eurasian tectonic plates has resulted in many devastating earthquakes [6]. This geophysical reality compelled ancient Indian scientists to observe and study earthquakes in great detail. There are numerous allusions to earthquakes in early Indian texts [7]. To protect themselves from the devastating effects of earthquakes, they developed several indigenous seismic-resistant techniques that mitigate the impact of seismic forces on structures. As one of the most important structures in their social lives, temples were understandably equipped with the best available seismic-resistant features. The seismic-resistant design of ancient Indian temples is a subject of immense interest and study. This article delves into this topic, highlighting various aspects such as the choice of forms and geometry, selection of construction materials, innovative foundation designs, and the creative design of superstructures, all of which were employed to ensure the durability and stability of these temples against earthquakes.

2. Choice of form and geometry

The structural form and geometry of ancient Indian temples significantly contributed to their seismic resistance capability. Key features in this regard are discussed below.

a. Plan Symmetry

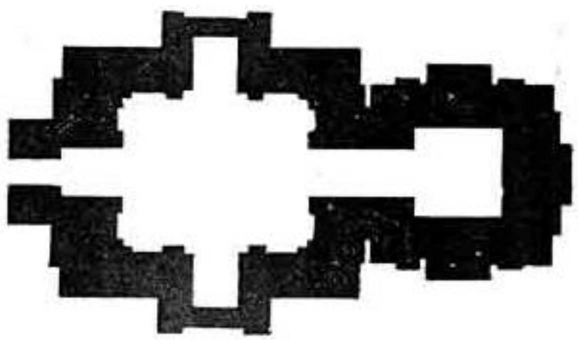
Plan symmetry is a fundamental aspect of the seismic-resistant design of ancient Indian temples. The symmetrical plans resulted in simple yet effective structural systems that evenly distribute seismic forces during an earthquake, reducing the likelihood of torsional movements and excessive stress concentration. Indian temple architects employed geometric principles, such as the use of squares and triangles, to achieve symmetry. For example, the layout plan of the Mukteshvara Temple, Bhubaneswar, built around 950 CE, is shown in Figure 1(a).

b. Conical Shape or Pyramidal Shape

Many Indian temples featured a conical or pyramidal shape, characterized by a broad base and a tapering top. This distinctive architectural feature significantly lowered the center of gravity of the entire structure. Since the moment at the base due to seismic load is approximately proportional to the height of the center of gravity of the structure, the conical or pyramidal shape of the temple greatly reduces the earthquake-induced base moment, thereby enhancing seismic resilience. Figure 1(b) shows a photograph of the Mukteshvara Temple, which has a conical-shaped shikhara (the tower above the garbha griha) and a pyramidal-shaped mandapa.

c. Structural Plan Density

Structural plan density refers to the distribution and concentration of structural elements within the footprint of a building. It is defined as the total cross-sectional area of all vertical structural members at the plinth level divided by the gross floor area. Ancient Indian temples were designed with thick walls and compact layouts, which contributed to the overall structural plan density. For example, the plan shown in Figure 1(a) has a structural plan density of about 45%. High structural plan density reduces stress on the structural elements and improves stability during earthquakes.



(a)

(b)

Figure 1: *Mukteshvara Temple, Bhubaneswar (a) Plan [8], (b) Photograph showing side view (Photograph by Author)*

3. Selection of Construction Materials

The selection of construction materials in ancient Indian temples was a critical aspect of their design, contributing to their longevity, durability, and seismic resilience. The choice of materials was influenced by availability, workability, climate of the region, and cultural significance. Stone, brick, and wood were the primary construction materials.

a. Stone

Stone was chosen for its durability and strength. It can safely withstand the additional stress generated during an earthquake. Sometimes stone with mortarless joints used that enhances the structure's ductility. Granite, sandstone, and laterite were the most commonly used. The choice of stone was chiefly based on availability and workability. Granite, one of the hardest stones available, was commonly used in South India. Sandstone was widely used in North India. It was favoured for its ease of carving and aesthetic appeal. Laterite was used for temple building mainly in parts of eastern India, where it was readily available. It is lightweight, and easy to cut, but has sufficient strength. The photograph of an arch over the entrance gate of Kalachand Temple, Bishnupur, which is made of Laterite is shown in Figure 2(a).

b. Wood

In the early phases of temple construction, wood was the primary material due to its availability. While stone eventually became the dominant material due to its durability and resistance to weathering, wood continued to be used for various structural elements, such as beams and rafters, and decorative elements. However, in the Himalayan region, which is more earthquake-prone than other parts of India, the use of wood as the primary construction material for temples continued for two main reasons. First, wood is relatively lightweight, which results in less lateral force during earthquakes. Second, due to their elasticity and strength, wooden structures have the natural ability to flex and return to their original shape during earthquakes. For better seismic resilience, many ancient temples made of wood in the Himalayan region are still surviving. The Lakshana Devi Temple, Bharmour, shown in Figure 2(b), is one of them.

c. Brick

Bricks were employed in the construction of many temples. They offer several advantages, including ease of handling, good thermal insulation properties, and ease of carving when wet. However, compared to wood and stone, bricks are more susceptible to damage during earthquakes due to their rigidity and lower tensile strength. Consequently, bricks were primarily used in temple construction in less earthquake-prone regions and areas where stone was scarce. For example, the Rarh region of West Bengal has several ancient temples made of a special variety of bricks known as terracotta bricks. A photograph of the terracotta brickwork on the Radhabinod Temple in Kenduli is shown in Figure 2(c).

(a) (b) (c)

Figure 2: *Temples built with different materials (a) Laterite stone in Kalachand Temple, Bishnupur (Photograph by Author), (b) Wood in Lakshana Devi Temple, Bharmour [9], (c) Terracotta bricks in Radhabinod Temple, Kenduli (Photograph by Author)*

4. Foundations

The foundation of a structure is critical to its stability, especially in earthquake-prone areas. Ancient Indian temples often featured massive foundations designed to distribute the weight of the structure evenly and anchor it firmly to the ground. Here are some key features of these foundations:

a. Deep Foundations

To ensure stability, especially for large temples, deep foundations were used. Excavations were done to reach stable soil or rock layers, providing a solid base for the structure. Figure 3(a) shows a photograph of the deep foundation of a about 1000-year-old temple excavated in Dinajpur, Bangladesh.

b. Stepped Foundations

Many temples feature stepped foundations, which disperse the load and provide better stability against lateral forces, such as those from earthquakes. The temple foundation shown in Figure 3(a) also features steps.

c. Stone Blocks

Large, interlocking stone blocks were often used in the foundation to provide strength and durability. These blocks were precisely cut and fitted together, normally without the use of mortar, allowing for some movement and flexibility during seismic activity. A photograph of the foundation of a Pandya dynasty temple unearthed near Tirunelveli, Tamil Nadu, as shown in Figure 3(b), exemplifies this technique.

(a) (b)

Figure 3: *(a) Foundation of a about 1000-yr-old temple excavated in Dinajpur, Bangladesh [10], (b)Foundation of a Pandya dynasty temple unearthed near Tirunelveli, Tamil Nadu [11]*

d. Sandbox

This technique may be considered the forerunner of the modern-day base isolator. Some temples were constructed on layers of sand or other pliable materials, which is termed sandbox by modern researchers [12,13]. The sandbox acted as a cushion, absorbing seismic waves and reducing the transmission of vibrations to the superstructure. This significantly enhances the seismic resilience of the superstructure. Ramappa Temple, Telangana, and Brihadisvara Temple, Tamil Nadu, are two prominent temples where this technology was implemented. A schematic of the foundation of Thanjavur Brihadisvara Temple showing the sandbox is given in Figure 4 [13].

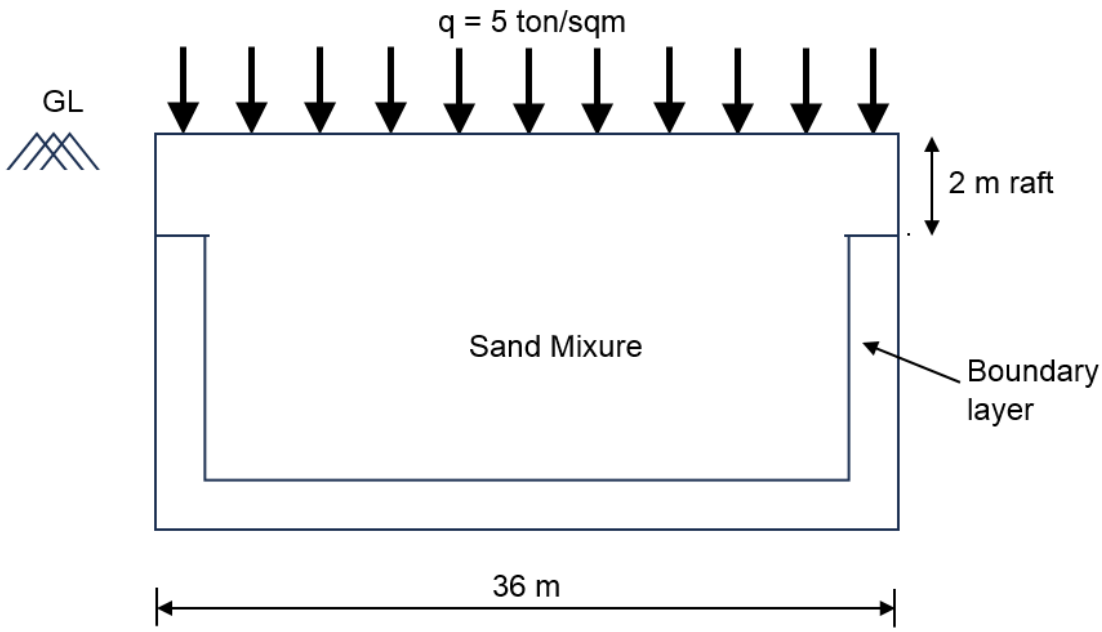


Figure 4: *Schematic of the foundation of Thanjavur Brihadisvara Temple showing sandbox (Redrawn from Ref. [13])*

5. Superstructure

The builders of ancient Indian temples incorporated numerous special features into the construction of the superstructure, significantly enhancing their seismic resilience. Here are some of the key elements:

5.1 Vertical Alignment

The vertical alignment of structural components, such as pillars, columns, and walls, is another critical aspect of the structural design of Indian temples, contributing significantly to their seismic resistance and overall stability. Proper vertical alignment helps distribute loads evenly and provides a clear path for the transfer of the lateral seismic force from the superstructure to the foundation. Figure 5(a) depicts the West Tower of the Meenakshi Temple in Tamil Nadu, a remarkable example of the meticulous vertical alignment practised by ancient temple builders.

5.2 Multi-Tiered Construction

Many ancient Indian temples were built with multiple tiers, each acting as an independent structural unit. This multi-tiered construction allowed for energy dissipation at each level, reducing the overall seismic demand on the lower level of the structure, which, in general, experiences greater stress during earthquakes. The stepped design also provided additional stability and reduced the risk of a complete structural collapse. This type of construction technique can be observed in "Ratna" temples in Bengal (see Figure 5(b)).

5.3 Flexible Roofs

The roofs of some of the ancient temples were designed to be flexible, with overlapping stone slabs or wooden beams. This flexibility allowed the roof to move independently of the walls during an earthquake, reducing the risk of roof collapse and protecting the integrity of the overall structure. One example of this kind of roof is shown in Figure 5(c), which is a photograph of the Gaudargudi Temple at Aihole.

5.4 Interlocking Stones and Mortise and Ttenon Joints

One of the most remarkable features of ancient Indian temples is the use of interlocking stones and mortise and tenon joints. This technique involved cutting stones with precise indentations that allowed them to fit together tightly. The interlocking mechanism provided stability and allowed the structure to flex slightly during an earthquake, dissipating seismic energy and preventing collapse. A stone block with an upward projection for interlocking arrangement from the ruins of a temple at Ratnagiri, Odisha is shown in Figure 5(d).

5.5 Metal Nails to Join Stone Blocks

In some temples, U-shaped metal nails are employed to secure the stone blocks together, as illustrated in Figure 5(e). The use of metal nails, instead of traditional mortar, enhances the ductility of the structure. This increased ductility allows the building to better absorb and dissipate seismic energy. Consequently, the temple's resilience to earthquakes has significantly improved.

5.6 Short Columns

Shorter columns were less likely to buckle and had a greater load-carrying capacity. These columns were often connected through strong architraves or arches, which helped distribute the load more evenly. This interconnected design enhanced the overall stability and earthquake resilience of the structure. The short columns used in Sri Bishnu temple, Bhatra, West Bengal, are shown in Figure 5(f).

6. Modern Scope of Research

The seismic-resistant design of ancient Indian temples has attracted modern-day researchers from several fields, including structural engineering, architecture, archaeology, and materials science. The study on this topic provides an advanced understanding of ancient techniques and offers valuable lessons for contemporary seismic engineering. This expanding field of research includes several key directions, as listed below.

- Employing modern tools like 3D laser scanning and finite element modelling to study the structural integrity and seismic resilience of ancient temples.

- Investigating the composition and properties of building materials used, such as stone and mortar, to understand their role in seismic resistance.
- Analyzing ancient construction methods, including the use of sandbox, interlocking stones, and flexible joints, to learn how these techniques mitigated seismic forces.
- Studying epigraphic evidence and historical records to gain insights into the knowledge and practices of ancient builders.
- Developing methods to preserve and retrofit these historical structures using a blend of ancient and modern techniques, ensuring their integrity against future seismic events.

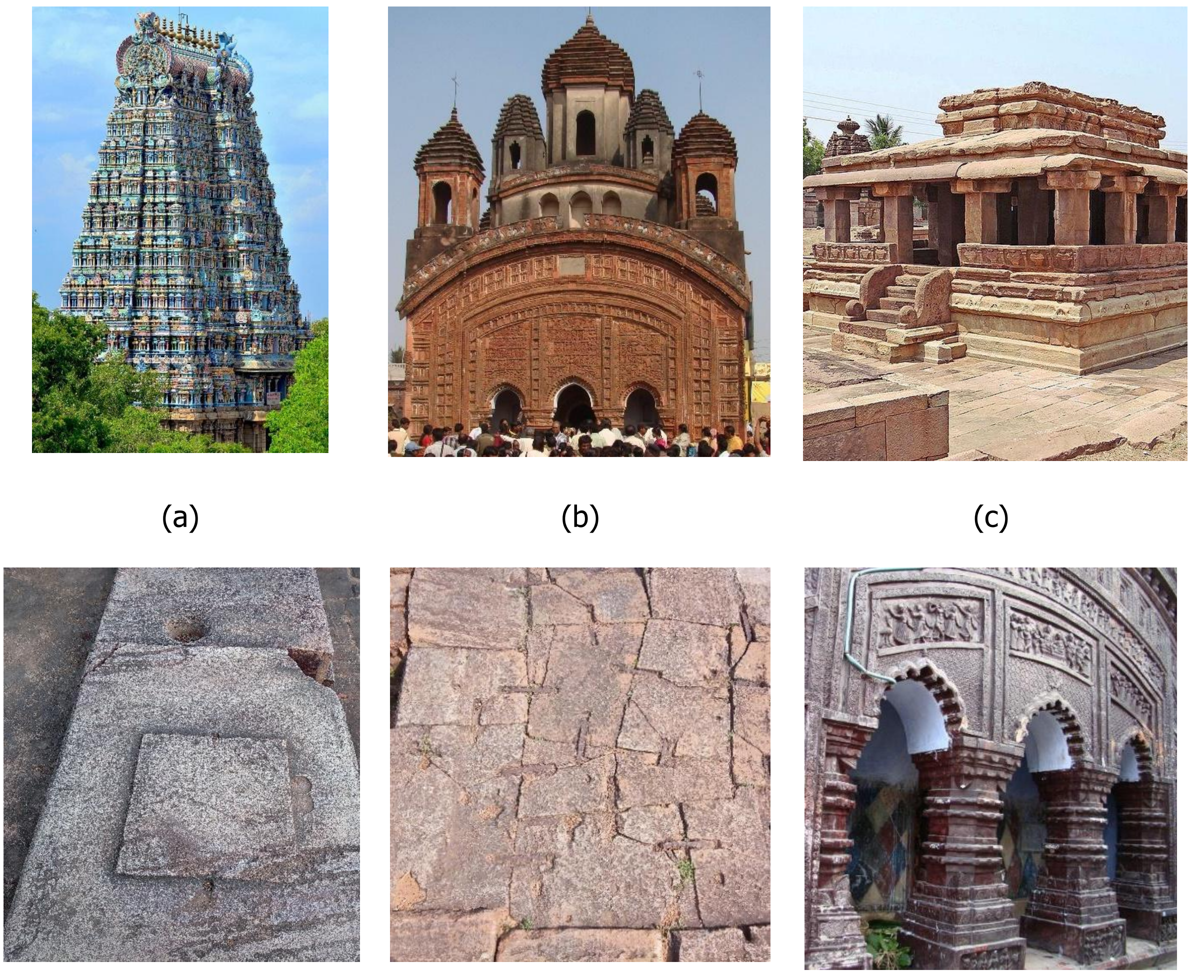


Figure 5: *(a) West Tower of Meenakshi Temple, Tamil Nadu [14]; (b) Radhabinod Temple, Kenduli, West Bengal (Photograph by Author); (c) Gaudargudi Temple, Aihole, Karnataka [15]; (d) A stone block with upward projection for interlocking arrangement from the ruins of a temple at Ratnagiri, Odisha (Photograph by Author); (e) Stone blocks joined with U-shaped nails at Udayagiri, Odisha (Photograph by Author); (f) Short columns in Sri Bishnu temple, Bhatra, West Bengal (Photograph by Author)*

7. Conclusion

The seismic-resistant design of ancient Indian temples is a testament to the advanced engineering skills and deep understanding of natural forces possessed by ancient builders, long before the advent of modern engineering. Ancient builders employed a combination of meticulously chosen materials, strategic architectural designs, and innovative construction techniques to construct temples that have withstood the test of time and numerous seismic events. The principles of Vāstuśāstra, emphasizing symmetry and proportion, ensured balanced force distribution during earthquakes, while the tapered designs of vimanas and shikharas lowered the center of gravity, enhancing stability. The temples had high structural plan density, which reduced stress on the structural elements. Wood, brick, and stone were the primary construction materials. The materials were selected based on availability, longevity, durability, and seismic resilience. Early forms of base isolation, achieved by laying foundations on sand or gravel, further cushioned these structures against ground motions. Other improvised foundation designs include the use of deep foundations, stepped foundations, and interlocking stone blocks. The incorporation of techniques such as flexible joints, flexible roofs, and multi-tiered construction allowed different parts of the temples to move independently during earthquakes, preventing catastrophic failures. Proper vertical alignment and the use of short columns significantly enhance the seismic resistance capacity and overall stability of ancient temples. The study of these ancient structures not only provides insights into historical engineering practices but also offers valuable lessons for modern seismic design. By combining traditional knowledge with contemporary technology, we can enhance the resilience of modern buildings and preserve the rich cultural heritage of ancient temples for future generations.

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