Low-Carbon Concrete Construction: The Past, Present, and Future of Concrete Design in India

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The concrete frame gave freedom to the design of the interior and eliminated the need for external load-bearing walls. Today, due to rapid urbanization and constrained urban space, the concrete frame has become the ubiquitous system of construction in growing cities. As a result, steel-reinforced concrete frames dominate the skylines of Less Economically Developed Countries (LEDCs) like India. Consequently, the mounting use of concrete in India has garnered concern for the ecological impacts of construction. This suggests an opportunity to reduce the carbon emissions associated with concrete construction through efficient concrete construction, building more with less. Importantly, India has a rich history of efficient concrete architecture that utilized material efficiency when material costs constrained the cost of construction. These designers cultivated a spirit of structural expression and a command of physical forces that informed a new architectural idiom for Modern India. Today, the generally risk-averse nature of development has pushed concrete construction towards standardized typologies of monolithic construction and repeated modules for ease of construction. From a structural mechanics point of view, though, these modular systems of prismatic slabs, beams, and columns, are materially inefficient. In response to the demand for materially efficient concrete construction, this paper looks back at the work of novel designers in India and presents a potential application of their ideas to future urban construction in both India and beyond. The scope of this paper is the use of reinforced concrete as a structural material from the early 20th century up until today. Several key structures and designers will be highlighted for their contributions to concrete architecture's history before concluding with a proposal for the future of concrete design in LEDC cities. Applying an understanding of concrete mechanics and digital structural design, this research explores structural systems suited to the constraints of Indian construction.

CONSTRUCTION IN INDIA: CHALLENGES AND OPPORTUNITIES

Steel-reinforced concrete frames dominate the skylines of Less Economically Developed Countries (LEDCs) like India. With roots in the Hennebique system of the 1870s, the modern concrete frame gave freedom to the design of the interior and eliminated the need for external loadbearing walls (Hennebique Construction Company 1902). Today, due to an increasing need for low-cost urban construction, the concrete frame is the ubiquitous system of choice in LEDC cities. Notably, India needs to build 700 to 900 million square meters of urban space—the equivalent of a new Chicago—every year for an increasingly urbanized population (The Economic Times 2020). Therefore, motivated by the ecological and economic costs of concrete construction in India, this paper looks to the history and present practices of efficient concrete design in India to inspire research on future concrete architecture for LEDCs.

The mounting use of concrete in India has garnered concern for the economic and ecological costs of urban construction in LEDCs. Unlike in More Economically Developed Countries (MEDCs) like the United States, material costs, rather than labor, constrain affordable construction. For example, in the United States, material and labor account for half of residential construction costs each (Salama et al. 2005), while material costs can account for over 80% of residential construction costs in India (CIDC 2012). Additionally, the production of cement, a core ingredient in concrete, creates 8% of global carbon emissions, and that figure will only rise as concrete continues to be the most produced synthetic material in the world (Van Damme 2018). Concrete construction also makes up nearly one-tenth of global industrial water use, 75% of which is in drought and water-stressed regions (Miller, Horvath, and Monteiro 2018). The demand for fine aggregate in concrete has caused irreparable damage to natural ecosystems and to the criminalization of sand mining worldwide.

Today, the generally risk-averse nature of urban development has pushed concrete building towards standardized typologies of monolithic construction and repeated modules for ease of construction. From a structural mechanics point of view, though, the modular systems of prismatic slabs, beams,

Figure 1. Clockwise from top-left a) The India International Center by J. A. Stein and Binoy Chatterjee, New Delhi, 1962 b) Tagore Memorial Hall by BV Doshi and Mahendra Raj, Ahmedabad, 1965 c) Ferrocement panels, vaulted roof, and filler slab in Wall House by by Anupama Kundoo, Auroville, 2000 c) Long-spanning masonry and concrete vault at Auroville Earth Institute e) Filler slab; Development Alternatives Headquarters by Ashok B. Lall Architects, New Delhi, 2014.

and columns, are materially inefficient. In fact, most of the embodied energy and mass of multi-story concrete structures is in the horizontally-spanning floors and roofs. This suggests a valuable opportunity to reduce the carbon emissions of concrete construction through efficient concrete design, building more with less. The scope of this paper is the use of reinforced concrete as a structural material in India from the early 20th century up to today. Several key structures and designers are highlighted for their contributions to India's concrete architecture before concluding with a proposal for the future of concrete in urbanizing LEDCs.

PAST AND PRESENT INDIAN INNOVATIONS IN CONCRETE DESIGN AND CONSTRUCTION

Importantly, India already has a rich history of efficient concrete architecture that utilized material efficiency when material costs constrained the cost of construction and labor was relatively affordable. Examples range from the sophisticated tropical modernism of Joseph Allen Stein and Binoy Chatterjee (Chusid 2017) to the heroic public spaces by Mahendra Raj, B.V. Doshi, Charles Correa, and Raj Rewal (Raj et al. 2016). These designers cultivated a spirit of structural expression and a command of physical forces that informed a new architectural idiom for the newly independent India (Ismail and Mueller 2019). In the design and research of material efficient systems of concrete construction, a number of lessons could be learned by looking at the work of both past and current designers in India.

With an enthusiasm for modern technology, a humanist agenda, and an environmental mentality, Joseph Allen Stein moved from the US to India in 1952 to head the new architecture program at the Bengal Engineering College. Chief among his projects was the India International Centre (IIC) completed in 1962 at the Lodhi Estates, New Delhi (see Figure 1a). The IIC was designed in close coordination with Bengali engineer and partner, Binoy Chatterjee, and local building contractors, showcasing precise and thoroughly crafted concrete detailing. It is a powerful reminder that the brutalism of Le Corbusier's Chandigarh is not the only option for concrete architecture in South Asia. For the IIC, the designers used a material palette of handmade tiles to support local craftspeople, local quartzite for cladding, and concrete for the structural frames, domes, vaults, “jali” screens, and floors. Small-scale precast concrete elements were used in horizontal spanning systems of vaults and domes, allowing them to be held by hand by a few builders, reducing construction time and keeping the project within budget. Concrete panels were lined with pebbles or hand-rubbed, imbuing the material with humanity through texture and scale (White 1994).

Engineer Mahendra Raj is behind many of the structures that

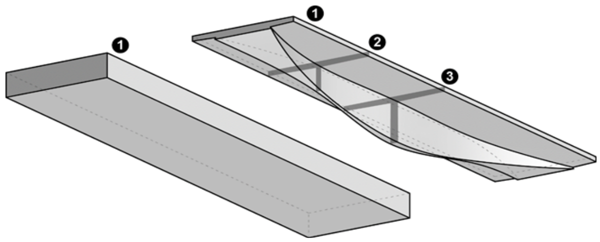

Figure 2. Overview of the design methodology: as opposed to the design of a prismatic slab where one section is designed for the maximum loading conditions, multiple sections are shaped according to the required capacity along the length of the slab.

defined Indian Modernism. Working with significant architects like Charles Correa and B.V. Doshi, Raj highlighted the resolution of forces while remaining true to the architect's intent and working within the material limitations of post-independence India. Two projects that demonstrate these efforts are Tagore Memorial Hall by B.V. Doshi (Figure 1b), and the Hall of Nations by Kuldip Singh and Raj Rewal. Completed in 1965, Tagore Hall was designed through an ongoing conversation between the architect and engineer. Raj and his team presented Doshi with a total of 12 different structural design options, each with clear dimensions and insight on their relative costs and constructability. Raj's office evaluated each iteration to demonstrate where and how material could be saved. The end result was the first folded-plate concrete structure in India with plates and columns that changed dimensions according to structural demand, reducing the need for material, and built in stages to accommodate workers pouring concrete by hand (Doshi, Tsuboi, and Raj 1967). Completed in 1972, the Hall of Nations was the world's first cast-in-situ reinforced concrete spaceframe. Designed and built within 13 months, Raj determined that cast-in-situ concrete would be substantially cheaper than a commercially-licensed and imported steel spaceframe, and no Indian contractor had the confidence to build precast elements with enough precision. Raj evaluated and designed the structure for not only its final loading conditions but also for the loads at each stage of its construction (Rewal and Raj 1972).

Presently, architects and researchers in India are continuing the legacy of these designers. Most of the ongoing research in India is focused on the material configuration of construction, using waste products or local resources as building materials, and prefabricated systems that are easily assembled yet reliant on imported materials and transportation costs (Koehn and Soni 2001). The construction of Development Alternative's headquarters (Figure 1e) in New Delhi (Lall 2015) and a number of buildings in Auroville, Pondicherry, utilize similar techniques to those of Stein (Frearson 2016; Davis, Varma, and Maïni 2019; Davis and Maïni 2016). Auroville-based architect, Anupama Kundoo, has designed a number of prefabricated housing prototypes to encourage the use of local materials and concrete composites for lightweight and low-energy construction (Figure 1c). For decades, designers and researchers at the Auroville Earth Institute (AVEI) have contributed to the field of earth-based construction methods, researching old and new technologies and passing them on to communities worldwide. Their research has explored the use of ferrocement channels, compressed stabilized earth blocks (CSEBs), vaulted structures, hybrid concrete-CSEB beams, and much more (Figure 1d). Research at the Indian Institute of Science shows the potential for low-energy construction materials in rural regions, using local materials, traditional building techniques, and low-energy supplements for cement in construction. This work includes the design of hybrid structural elements such as steel truss and concrete beams and filler slabs (Venkatarama Reddy 2009).

Past and present Indian designers demonstrate how efficient concrete architecture can emerge from their context and an understanding of concrete mechanics. Nonetheless, there has been a lack of knowledge transfer between the innovative and bespoke works of efficient concrete architecture discussed here and the scalable urban construction practices of LEDCs. Consequently, the next section of this paper discusses ongoing research by the authors, using the past to inspire the future of materially efficient concrete design in LEDCs.

NEXT STEPS: ADVANCING EFFICIENT CONCRETE CONSTRUCTION THROUGH COMPUTATION

This section presents a novel design method and structural slab prototype influenced by the work of India's structural innovators. Like Stein and Chatterjee, this research explores structural systems suited to the constraints of Indian construction that reduce the costs of concrete construction through an understanding of concrete mechanics, computational structural design, and emerging fabrication methods. As seen in Raj and Doshi's design of Tagore Hall, variable-section slabs that resist localized load demands along their length present an opportunity for material efficiency through increased geometric complexity. The resultant methodology for the shape optimization of one-way reinforced concrete slabs is demonstrated in Figure 2. It should be noted that for structural mechanics, this method references the National Building Code (NBC) of India, specifically the Indian Standard 456-2000: Plain and Reinforced Concrete Code of Practice (IS 456) (Bureau of Indian Standards 2000). The full method for the shape optimization of concrete slabs is explained in (Ismail and Mueller 2020).

The shape optimization and structural analysis are carried out using the RhinoCommon geometric library in Grasshopper ("What Is RhinoCommon?" n.d.) for shape parameterization, analytical expressions for structural and material behavior modelling, and a pre-packaged nonlinear constrained optimization algorithm. This work uses the derivative-free Constrained Optimization by Linear Approximation (Powell 2007) (COBYLA) algorithm in Radical, a tool in the Design Space Exploration Grasshopper plugin (Brown et al. 2019)

Figure 3. Rendering of multi-story construction built using shape-optimized concrete slabs.

that references the pre-existing NLOpt numerical optimization library for constrained optimization (Johnson n.d.). Through the use of a derivative-free algorithm, the optimization of a concrete element does not require an analytical relationship between geometric variables and objective and constraint functions, allowing designers to implement this method in common CAD software like Rhino 3D. An example shaped slab design is shown in Figure 3.

This methodology uses analytical structural analysis and numerical optimization to minimize a shaped slab's embodied energy (EE), a more comprehensive approach to material efficiency than minimizing material volume or mass. This can be modified to minimize economic costs with sufficient financial data. A shaped slab is assessed along its length by cutting a series of sections as shown in Figure 4, and the analysis is simplified by assuming symmetry and assessing only half of the element with each iteration. With reference to IS 456, the element is designed for a residential live load and a dead load of its self-weight, with the appropriate load factors for ultimate and service loads. The structural analysis involves several structural and geometric constraints for optimization so that the final design meets Indian concrete code requirements. Each of these constraints are checked during each iteration of the optimization and the geometry is adjusted accordingly. While similar to the structural analysis methods used by Raj and Chaterjee, the use of numerical optimization pushes past the prior limitations of materially efficient design. The result of this method is a variable section ribbed slab with a potential 55-70% reduction in EE, and a similar reduction in material and mass, when compared to a typical flat slab of 5m span. This span was chosen as an upper bound to multi-story residential construction in Indian cities, which are typically built with slabs spanning 3-5m.

A 1x5m span prototype was built with local partners in New Delhi to test the viability of this design method at full-scale. Working with the Society for Technology and Action for Rural Advancement (TARA), the fabrication and testing took place in New Delhi. The result is a 1x5m shaped slab designed with a 47% reduction in EE compared to a flat slab of similar span, loading, and support conditions. The slab was fabricated using a sheet metal mold, assembled from laser-cut 3mm steel, and built for simple disassembly for future use (Figure 5a). Mold fabrication was carried out by TARA using methods familiar to their builders and the slab was built with 40MPa concrete and reinforced with a 16mm bar for tensile reinforcement, 6mm

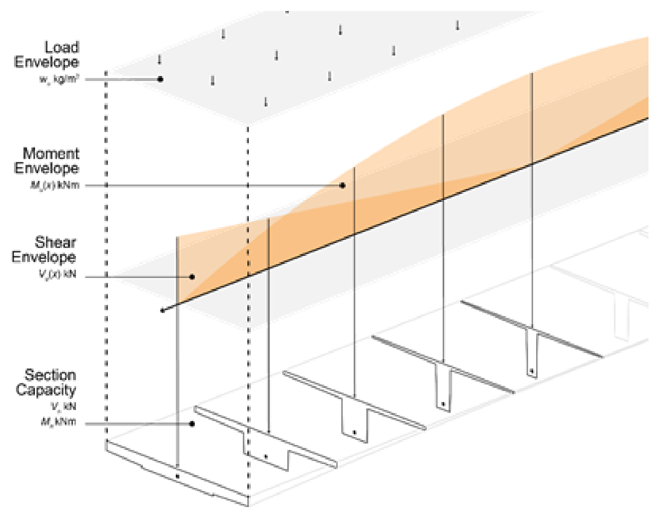

Figure 4. Structural analysis of a shaped slab.

Figure 5. a) Disassembled curved sheet metal formwork for full-scale prototype with rebar shown to the right b) Load test configuration at NCCB in Faridabad, India, after the prototype was tested.

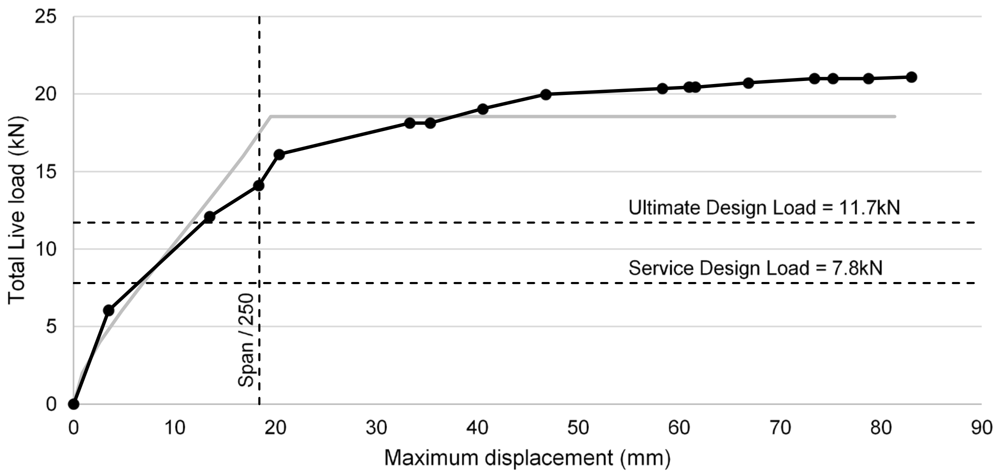

Figure 6. Load vs. displacement plot of prototype test, experimental results in black and predicted in grey.

steel bars for shear reinforcement, and a mesh of 6mm bars to reinforce the top flange. Importantly, all of these materials are available in standard Indian construction.

The full-scale prototype was load-tested at the facilities of the National Council for Cement and Building Materials (NCCBM) in Faridabad, India. The test setup (Figure 5b) consisted of simply-supported boundary conditions and two-point loads, located 1.6m from each support, with a central hydraulic jack. Test results were recorded manually at irregular load intervals, noting the maximum displacement at midspan. The results of this test are shown in Figure 6, along with the predicted behavior as discussed in (Ismail and Mueller 2020). The Indian code's deflection limit and factored design loads are also highlighted on the plot.

As shown above, the shaped slab behaved favorably, exhibiting a ductile failure mode rather than a sudden brittle failure. Additionally, the predicted performance aligned well with the experimental results, and the slab reached the desired service load without deflecting beyond the limit of L/250 and the slab exceeded the ultimate design load.

This methodology enables the design of materially efficient shaped slabs with a predictable structural performance. Although it does not include the cost of the formwork, the cost analysis of the slab showed that 70% of the prototypes cost was due to materials. This matches the assumption that material costs constitute the bulk of residential construction costs. While it is difficult to assess the feasibility of a new construction technology without long-term commitment and research beyond this paper's scope, further market analysis can determine the economic implications of complex formwork. The prototype's fabrication also demonstrates the flexibility of this method to account for fabrication limits and opportunities, such as the one-way curvature of bent-plate formwork. This mirrors the adjustments made to the Hall of Nations' construction methods in response to labor and economic considerations.

Similar to the methods of past and present Indian designers, this method allows for context-driven materially efficient concrete architecture. Yet, unlike the bespoke work of India's concrete innovators, this method has the potential for broader impact and scalability. At the building scale, structural elements typically account for 50% of the mass and EE. As a building exceeds 10 stories, the horizontal spanning elements can account for over 80% of the structure's mass and EE (Block and Paulson 2019). By removing 60% of the mass of horizontal spanning elements, as this research suggests, the structural weight can be reduced by nearly 50%. This does not include the secondary effects of reducing the dead load on vertical elements, which in turn decreases the demand on building foundations. Lateral loads like that of seismic events can also be reduced proportional to the reduction in a building's mass. In LEDCs like India, scalable methods like this are needed to meet the demands of a rapidly growing urban population.

CONCLUSION

India's need for urban housing is not unique; 90% of global urbanization by 2050 will occur in Africa and Asia ("2018 Revision of World Urbanization Prospects" 2018). This means that demand for concrete construction in LEDCs will only continue to rise, as will the environmental costs of concrete construction. If the Paris agreement on climate change is to be met, countries need to reduce their cement-related emissions by 16% in 2030 (Rodgers 2018). This paper proposes that efficient structural elements, appropriately designed for the context and local construction practices, could and should be used anywhere a flat concrete slab would be used.

Fortunately, there is a wealth of knowledge in the historic and present concrete architecture of India. Innovators like Mahendra Raj and Joseph Allen Stein recognized the importance of structural efficiency in a materially constrained environment, designing for the abilities of local craftsmen and laborers. Presently, the demand for urban space and the alarming environmental impact of construction has encouraged local research on indigenous materials and efficient building systems that draw from their predecessors. While this research is largely focused on the materials and systems of rural construction, like that of the AVEI and IISc, there is an opportunity to combine this work with the computational design and fabrication methods presented in this paper. This would allow designers to meet the needs of urban construction through novel methods of materially efficient design.

One such method is both explained and tested through physical prototyping and full-scale load testing in India to explore its viability to LEDC construction. This method results in an EE reduction of over 60% in residential floor systems without altering the standard material properties of Indian concrete construction. Historic practices in materially efficient concrete construction often relied upon rules-of-thumb, physical testing experience, or simplified models of concrete mechanics. Today, the widespread availability of computational optimization and digital fabrication allows designers to push those practices further with increased precision and fabrication potential. This paper applies this newfound design and fabrication freedom to the wide-spread issue of housing insecurity in LEDC cities.

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