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Reshaping Concrete: Inclusive Design for Low-Carbon Structures

Mohamed Ismail

Abstract

Less Economically Developed Countries (LEDCs) struggle to meet the demand for affordable housing in their growing cities. There are several reasons for this, but a major constraint is the high cost of construction materials. In LEDCs, material costs can constitute 60 to 80 percent of the total cost of residential construction. Nonetheless, their construction mimics the materially inefficient practices of the More Economically Developed Countries (MEDCs), which were developed to reduce labor over material costs. As a result, prismatic beams and flat slabs are often used despite their structural inefficiency. The mounting use of steel-reinforced concrete structures in LEDC cities also raises concern for the environmental costs of construction; construction accounts for 20-30 percent of LEDC carbon emissions.

This research addresses these challenges with a flexible and accessible methodology for the design and analysis of materially efficient concrete elements that may reduce the economic and environmental costs of urban construction. Designed for the constraints of LEDCs, structural elements are optimized to reduce the embodied carbon associated with the concrete and reinforcing steel while resisting the required loads of a standard building structure. The optimization method includes a novel approach to 3D-shape parameterization, as well as a decoupled analytical engineering analysis method that accounts for the key failure modes and constraints of reinforced concrete design. This method is then built into an open-source toolkit, combined with machine learning for real-time analysis and visualization, and tested using lab- and full-scale prototypes.

The goal of this research is to present several generalizable methods that are applicable and accessible to LEDC building designers. These methods can enable the design of concrete elements for multiple performance criteria such as structural behavior, acoustic transmission, and thermal mass. They can also enable an accessible design practice through machine learning, real-time iterative workflows, and visualization tools that include the end-user in the architectural design process. This paper provides a high-level overview of ongoing research that explores how materially efficient design methods might enable sustainable development through low-cost, low-carbon concrete structural systems for affordable housing in LEDCs.

Keywords: development, affordable housing, concrete, structural optimization, machine learning.

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Corresponding Author: Mohamed Ismail <ismail@mit.edu>

1. INTRODUCTION

Concrete is the most consumed synthetic product in the world; the production of cement alone accounts for 8 percent of global carbon emissions (Van Damme 2018). This is especially crucial to Less Economically Developed Countries (LEDCs) where over 90 percent of global urbanization by 2050 is expected to occur using largely concrete construction (UN DESA 2018). It is also important to note that residential construction accounts for over 40 percent of global concrete consumption, and this number is likely higher in urbanizing LEDCs (see Figure 1). Consequently, both the demand for concrete construction in developing countries and its environmental consequences will continue to rise.

Designers' response to concrete's environmental toll has traditionally involved revisiting low-carbon construction technologies and indigenous building materials. While this is a valid pathway toward sustainable construction, there are no existing materials that meet the performance criteria and availability of reinforced concrete in the Global South. Reinforced concrete is strong, stiff, durable, and able to resist fire and seismic damage. These properties and more have enabled dense vertical construction and infrastructure in More Economically Developed Countries (MEDCs) and continues to do so in LEDCs. In all likelihood, we will continue to use concrete for many more years, largely because it has played—and continues to play—a vital role in the sovereign development of countries worldwide. Therefore, rather than decrying construction in LEDCs, we have an opportunity to facilitate the thoughtful use of concrete in a manner that reflects their ambitions while reducing the environmental impact. This paper provides a high-level overview of research that explores how materially efficient design methods might enable sustainable development through low-cost, low-carbon concrete structural systems for affordable housing in LEDCs.

Figure 1: Construction of multi-story concrete housing outside of New Delhi, India.

1.1. Construction in LEDCs

LEDCs struggle to meet the demand for affordable housing in their growing cities. This is due to a number of factors, one of which is the high cost of construction materials. As shown in Figure 2, material expenses can account for the majority of the overall cost of residential building in LEDCs (CIDC 2012; McKinsey Global Institute 2014; Meikle 2011). Nonetheless, the construction practices of MEDCs, such as the use of beams and slabs with constant cross sections, are often adopted by LEDC builders. These structural systems are materially inefficient because they respond to a localized peak load with constant dimensions. This highlights an opportunity for structural components that are optimized for material efficiency while remaining relevant to LEDC construction contexts. The increased use of steel-reinforced concrete structures in LEDC cities also raises the environmental cost of construction; construction accounts for 20-30 percent of LEDC carbon emissions [4]. These numbers continue to rise as building-related CO_2 emissions grow by one percent each year. In order to enable sustainable development in LEDCs, we must reshape our most common building practices.

Looking at the mass distribution in multi-story buildings, most of the potential savings lie in horizontally-spanning elements such as structural floor slabs (Huberman et al. 2015; De Wolf et al. 2016). In high-rise buildings, between 60-80 percent of the mass and EE of the structure can be found in the floors (Foraboschi, Mercanzin, and Trabucco 2014). Consequently, this research aims to reduce the material impact of concrete construction in LEDCs, starting with the shape optimization of concrete floor systems.

1.2. Inclusive frameworks

New digital design and manufacturing techniques have improved the precision and predictability of material-efficient structural design (Barbosa et al.

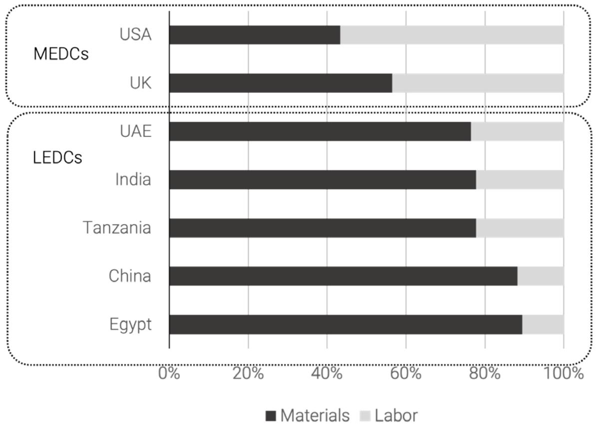


Figure 2: Residential construction costs broken down by materials and labor shows that material costs can make up 60-90 percent of construction costs in LEDCs (Meikle 2011).

2017). Unfortunately, early-stage structural design is a disjointed exercise in design and analysis that excludes the untrained stakeholder or future occupant. There is a clear divide between the methods designers employ to explore their options, and the information stakeholders receive before a structure is completed (Holgate 1992). The divide must be overcome if we are to disrupt common construction practices, allowing designers and stakeholders to move past barriers to change (Vennström and Eriksson 2010; Pham, Kim, and Luu 2020; Shafii, Ali, and Othman 2006). This research bridges the divide by providing tools for the design, analysis, and real-time visualization of complex structures early in the design process. These inclusive frameworks aim to empower LEDC designers and stakeholders through an appreciation of the performative and spatial effects of materially efficient design practices.

1.3. Research opportunity

This research addresses the challenges of construction in LEDCs with a flexible methodology for the design and analysis of materially efficient concrete elements that can reduce the economic and environmental costs of urban construction. Designed for the constraints of LEDCs, structural elements are optimized to reduce the embodied carbon (EC) associated with the concrete and reinforcing steel while resisting the same loads of a standard building structure. The optimization method uses a novel approach to 3D shape parameterization, as well as a decoupled analytical engineering analysis method that accounts for the key failure modes and constraints of reinforced concrete design. Due to the ubiquity of flat slab multi-story concrete construction, this research starts with the design and fabrication of shaped floor systems that can reduce the embodied carbon of a concrete frame by over 60 percent when compared to the most common typologies used in LEDC multi-story residential construction.

In order to broaden its potential impact, this research also involves the development of tools and methods for designers and stakeholders in LEDCs. The design of expressive and materially efficient structures is generally a slow process that does not allow for the simultaneous design of a building's architecture and structural system. Conversely, recent advances in surrogate modelling methods now allow for early-stage structural design and analysis while iterating through spatial forms. This suggests an opportunity for design methods that include expressive structural elements in early-stage building design. This research presents an opensource toolset for the design and analysis of complex concrete elements, machine learning (ML), and an intuitive design interface to communicate the potential performance and visual impact of materially efficient structures early in the design process. This is especially useful in designs with exposed structural systems, allowing structural performance to play a key role in the final architecture.

2. LITERATURE REVIEW

After World War II, materials constrained construction costs in many parts of the world while labor remained relatively abundant and inexpensive (Bechthold 2003). This led to many innovations in materially efficient structures by designers that relied upon an understanding of material, construction, and mechanics coupled with intuition. Architects and engineers such as Joseph Allen Stein (White 1994), Paulo Mendes da Rocha, Pierre Goudiaby Atepa, and Mahendra Raj (Raj et al. 2016) introduced efficient and long-spanning concrete systems such as thin shells, folded-plates, and space frames in many LEDCs. Today, research in LEDCs is largely focused on material substitution for low-energy construction or prefabricated systems that are easily assembled but rely upon imported materials (Koehn and Soni 2001). Research centers such as the Auroville Earth Research Institute in Pondicherry, India, utilize filler slabs, ferrocement channels, and local materials to reduce the cost and embodied energy (Frearson 2016; Davis, Varma, and Maïni 2019; Davis and Maïni 2016) of concrete construction. Research at the Indian Institute of Science (IISc) and Ethiopian Institute of Architecture, Building Construction, and City Development (EiABC) explores low-energy construction in rural regions, using local materials and low-energy substitutes for cement and hybrid structural elements such as filler slabs using construction waste and compressed soil tile construction (Venkatarama Reddy 2009; Cherenet, Sewnet, and Ethiopian Institute of Architecture, Building Construction and City Development 2012). Despite their promising results, these technologies have not been adapted to large-scale urban construction—where

Figure 3: The India International Center by J. A. Stein and Binoy Chatterjee, New Delhi, 1962; Municipal Stadium by Charles Correa and Mahendra Raj, Ahmedabad, 1966.

most LEDC demands lie—in part because they are not adaptable to the industrialized fabrication methods used in urban construction.

2.1. Efficient floor system research

In academic research, newly developed systems utilize digital fabrication and prefabricated elements that require little to no human labor and relatively complex methods of fabrication. Methods using adaptive and flexible robotic molds have been developed for the construction of doubly-curved concrete shells at Graz University of Technology (Amtsberg et al. 2016), ETH Zurich (Veenendaal and Block 2014), and Delft University of Technology (Schipper and Grünewald 2014). Researchers at the University of Manitoba, University of Bath, and University of Cambridge are exploring structural efficiency and lightweight construction through fabric formwork (West 2016) (Orr et al. 2014). The Block Research Group at ETH Zurich are developing compressive floor systems designed using thrust network analysis and built with high-strength materials like fiber-reinforced ultra-high performance concrete (López et al. 2014). The Digital Building Technology group at ETH Zurich is using topology optimization to design post-tensioned fiber-reinforced floor slabs like the Smart Slab (Dillenburger et al. 2018), built using particle-bed 3D printing for its complex form (Lowke et al. 2018). There is increasing work in additive fabrication methods like concrete 3D printing (Buswell et al. 2018) and dynamic casting (Lloret Fritschi 2016) to realize the complex results of design methods like topology optimization, but they often require non-normative concrete mixes and robotic fabrication facilities. It is difficult, but not impossible, to apply this research in LEDCs where access to such technologies is limited.

2.2. Shape optimization

This research uses shape optimization, the modification of a structure's geometric shape without changing its topology. Research in shape optimization has its roots in Galileo Galilei's analytical design of a cantilever beam of "uniform strength" (Galilei 1989; Timoshenko 1983), which uses analytical closed-form expressions of mechanics to derive optimal geometries. While these methods can be computed rapidly, they can only be applied to a narrow range of problem types. In contrast to these analytical methods, numerical shape optimization provides the freedom to design structures with innumerable geometries, load cases, and boundary conditions (Haftka and Grandhi 1986). Consequently, a number of researchers have developed iterative methods that couple finite element analysis (FEA) with numerical optimization algorithms for the design of efficient 2D and 3D structures (Imam 1982; Braibant and Fleury 1984). However, numerical shape optimization has a number of challenges that include: the definition of appropriate mesh densities, sensitivity to changing boundary conditions, and lengthy computation times when FEA is used to assess the performance of variable-shaped structures. In previous work, such methods exploited a direct analytical relationship between the element's geometric variables and the optimization's objective and constraint functions, allowing for rapid gradient-based solves. However, this approach cannot readily be applied to more geometrically complex and materially efficient shaped slabs defined by computational geometry operations, the focus of this research.

2.3. VR and ML in architecture

The connection between parametric design and CAD software has advanced our ability to visually evaluate structural design solutions over the primarily text-based interfaces of previous generations. However, understanding the spatial experience created by a structural concept is still indirect in CAD environments. In response, AEC firms are increasingly turning to VR as a tool for CAD and BIM visualization, 3D design, and coordination (Bouchlaghem et al. 2005). Modern advances largely coming from the phone industry have enabled the production of VR headsets with wide commercial adoption (Rubin 2014). Applications such as Mindesk (Ismail et al. 2021) have facilitated the digitization of prototyping and review operations, once bounded to physical operations, by enabling a bi-directional live link between CAD/BIM sources and VR devices. This live-link allows for the real-time interaction between stakeholders and the computational structural design tools discussed in this paper. Unfortunately, the time-consuming analysis of building performance prevents early-stage design workflows from including more efficient design options. This can be circumvented, however, by applying ML tools like predictive (surrogate) modelling for the real-time visualization and analysis of preliminary designs.

Predictive modelling methods like neural networks (NNs) have been used in early-stage structural design since the 1980s (Adeli 2001). Prior research utilized artificial NNs to predict the optimal design of reinforced concrete beams for a given set of load and boundary conditions (Mukherjee and Deshpande 1995; Sudarsana Rao and Ramesh Babu 2007), including the cost of formwork (Hadi 2003). Additional research has applied artificial NNs to the shear design of concrete beams, both without (Cladera and Marí 2004a) and with shear reinforcement (Cladera and Marí 2004b). While showing that the design process of concrete beams can be aided by the preliminary predictions of trained NNs, this work has been largely limited to the design of prismatic concrete elements. Beyond concrete, ML has been used to rapidly predict the results of structural optimization methods, e.g., for topology optimization of shells (Danhaive and Mueller 2018). This opens a new opportunity to link rapid ML with efficient geometry, and there is an unexplored potential for applying ML-supported predictive modeling to the geometry of efficient concrete structures.

2.4. Research opportunity

Some of the solutions for efficient concrete construction developed in LEDCs have the advantage of being designed and tested within their context, yet they are often reserved for boutique architectural applications rather than large-scale implementations. Little study and poor understanding of their behavior also leave their design to rules-of-thumb and additional factors of safety out of precaution. Alternatively, new academic precedents in floor system design rely on high-technology fabrication methods, complex procedures, and specialized materials largely unavailable to Indian builders, limiting their use to very few parts of the world.

There is an opportunity to inform shape optimization methods by analytical methods of reinforced concrete structural analysis and the fabrication methods available to LEDCs which may include CNC routing, injection molding, wood bending, and industrial laser cutting. This research links an understanding of concrete mechanics to novel methods of shape optimization and applies these principles to the development of accessible tools and workflows for LEDC concrete construction. Informed by the insights and experience of local partners, the method's flexibility allows for local fabrication and material constraints to inform the design space of the shape-optimized concrete geometries.

3. METHODOLOGY

New digital tools in analysis and fabrication enable designers to explore a greater variety of design options with an understanding of their structural performance early in the design process. This has renewed interest in expressive structures that both demonstrate and celebrate material efficiency (Block and Paulson 2019). Despite these new tools, there is little work done to connect efficient structural design to the architectural design workflow, limiting the expression of structural efficiency to specialized projects. The goal of this research is to present several generalizable methods that are applicable and accessible to LEDC building designers. These methods can enable the design of concrete elements for multiple performance criteria such as structural behavior, acoustic transmission, and thermal mass. They can also enable an accessible design practice through machine learning (ML), real-time iterative workflows, and visualization tools that include the end-user in the architectural design process. The following sections describe the three main components of this research aimed at advancing low-carbon design in LEDCs: an advanced method for the shape optimization of concrete elements, an accessible concrete analysis toolset, and predictive modelling for early-stage design.

3.1. Performance optimization of shaped concrete elements

This research begins with the design and analysis of a shape-optimized concrete beam. First, a shaped beam is defined using variable coordinates. The parametrization of and relationships between these coordinates can relate to an element's fabrication method. For example, the geometric relationship between variable coordinates can define curvature and complexity and delineate between doubly-curved geometry reliant on subtractive manufacturing, or singly-curved geometry that can be approximated with bent sheet materials. This enables viable optimized designs for LEDC construction by informing the initial geometric parametrization with existing fabrication constraints. The resultant beam is then cut into sections along its length and those sections' capacities are checked against the external loads at each location. Finally, the geometry is adjusted to minimize an objective score (embodied energy, weight, cost, etc.) while checking the discrepancy between the section's structural capacity and demand (see Figure 4).

This shape optimization method forms the foundation

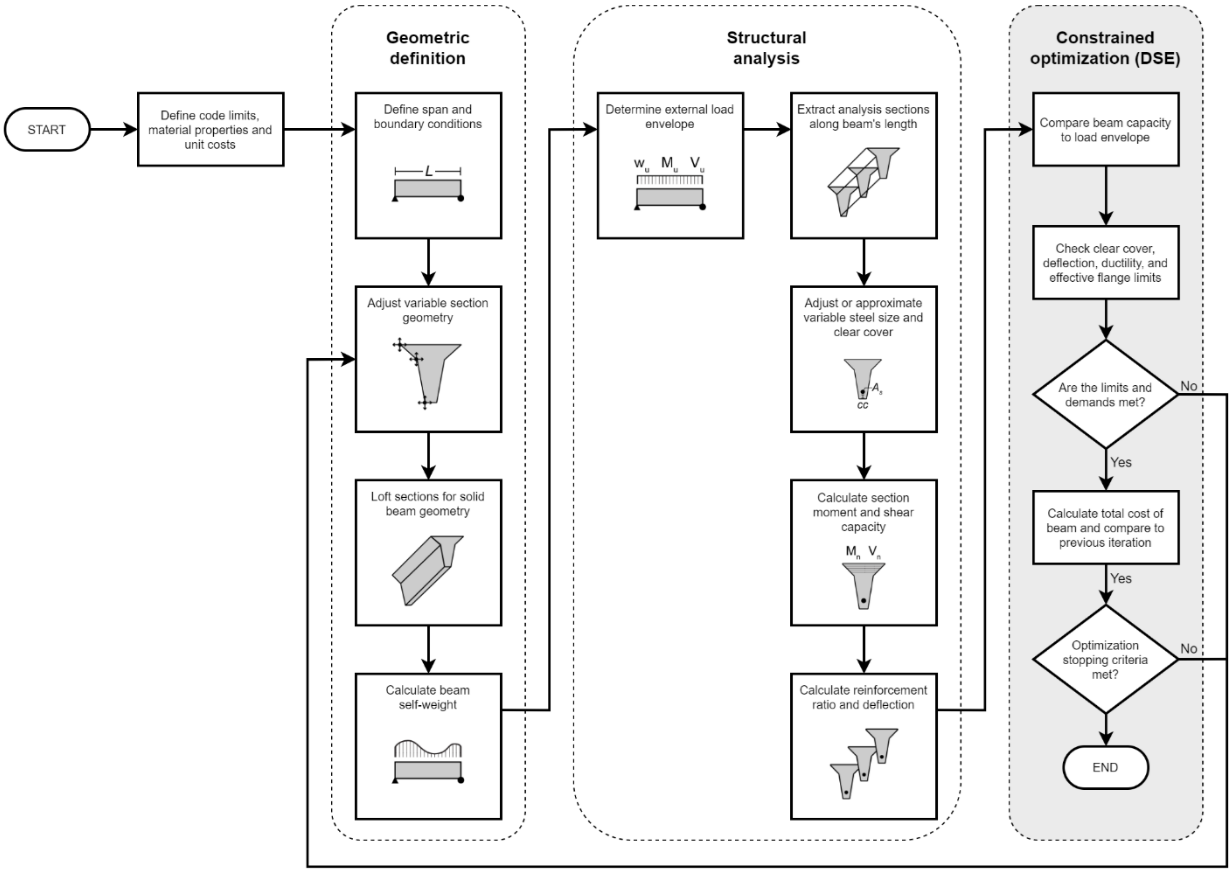


Figure 4: Overview of this shape-optimization methodology: the constrained optimization of one-way shaped beams.

of a research project that uses the method's flexibility and accessibility to generate analysis toolsets, design workflows, and physical experiments to prove its feasibility in producing safe and low-carbon structural elements. The following sections summarize how this shape optimization method is formalized through open-source toolsets and tested in various contexts through small- and full-scale prototyping, informing the original methodology in order to broaden its potential impact.

3.2. Digital toolset for accessible design

Many new tools allow designers to enhance their design workflow in CAD environments such as Rhino 3D (McNeel 2010) with numerical optimization, including toolkits like Galapagos, Goat (Flöry, Schmeidhofer, and Reis 2013), and Design Space Exploration, abbreviated DSE (Brown et al. 2020). These tools can help designers design shaped structures using constrained numerical optimization. What is missing, though, are tools that inform these designs by including the structural mechanics of complex material systems—like reinforced concrete—in order to optimize buildable shaped structures. This section describes one such toolset for the shape optimization of concrete elements, named Beam Shape Explorer (BSE)[1].

In order to make this method accessible to designers and engineers, an open-source Grasshopper (Baer et al. 2015) plugin called BSE is a toolset that uses analytical equations to evaluate the structural capacity of arbitrary beam sections. Through numerical optimization and analytical structural checks, this toolset can be integrated within the previously described method (Ismail and Mueller 2021) to design shaped concrete beams that fulfill structural and architectural requirements like clear spans, external load envelopes, architectural head heights, and fabrication complexity. Consequently, the previously described shaped beam design method is generalized and systematized as an open-source toolset that could be used in Rhino 3D, making it available to any designer with access to popular computational design tools (Figure 5).

In modern construction, floor systems are often required to not only resist structural loads, but also provide thermal energy storage, support thermal insulation, and

1 Available at https://github.com/mohismail/BeamShapeExplorer

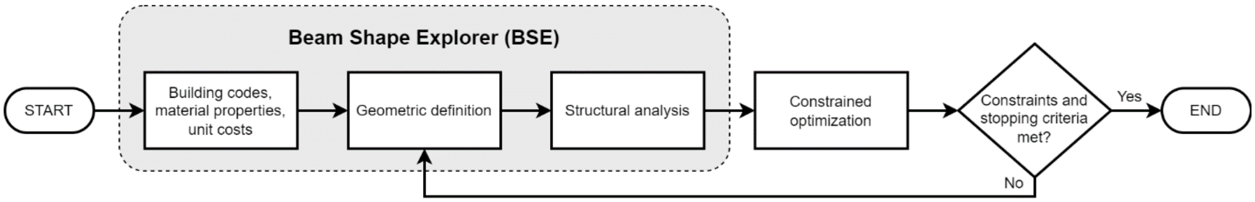


Figure 5: Revisited workflow for the shape optimization of concrete beams, highlighting how a tool like Beam Shape Explorer (BSE) provides access to this research's design methodology.

reduce acoustic transmission. While designing purely for structural efficiency presents a pathway towards low-carbon concrete construction, this can also diminish the secondary performance characteristics of concrete floor structures. This toolset can be used for the design and analysis of complex concrete elements, and enables the design of structures subject to secondary performance criteria such as thermal and acoustic energy transmission (Broyles et al. 2022) (see Figure 6). The flexibility of this toolset also allows for the sampling of a vast design space in order to use ML techniques like predictive modelling for the real-time prediction of complex solutions like shaped concrete beam designs.

While the details of this work fall outside the scope of this thesis, it is important to note that this research is at least partly enabled by the speed of the analytical structural method discussed in the prior section and the geometric precision enabled by the BSE toolset. Unlike historic approaches to shape optimization that center around finding the absolute minimal geometric solution, the speed and precision of BSE allows designers to characterize the structural behavior of an infinite number of geometries. By exploring designs beyond the structural "optimum", this opens up a limitless design space that can be analyzed across performance metrics and manufacturing constraints. Ultimately, an understanding of geometry and its implication on building performance ties all of these methods together through a shared design space.

3.3. Predictive modelling and visualization

The potential impact of this research depends on the insight and understanding of designers and stakeholders in LEDCs. They must be allowed to not only inform

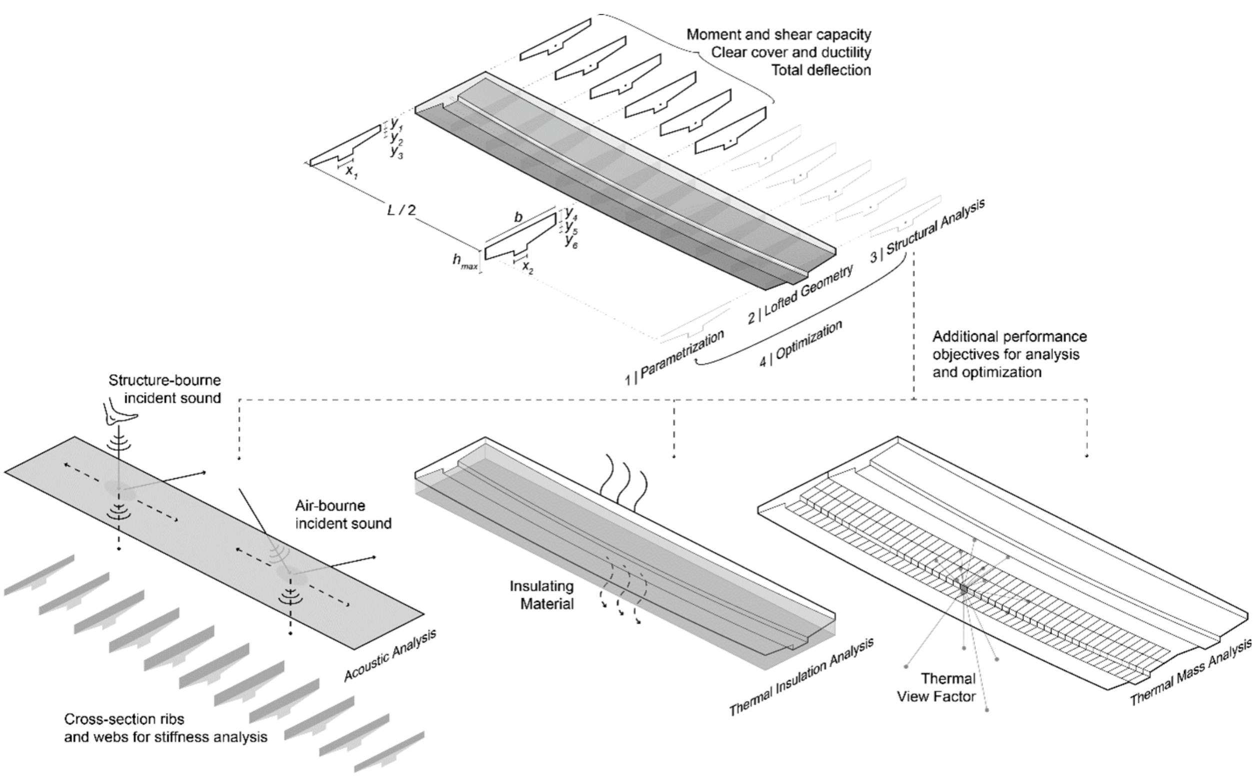


Figure 6: Design process for structural and secondary performance objectives.

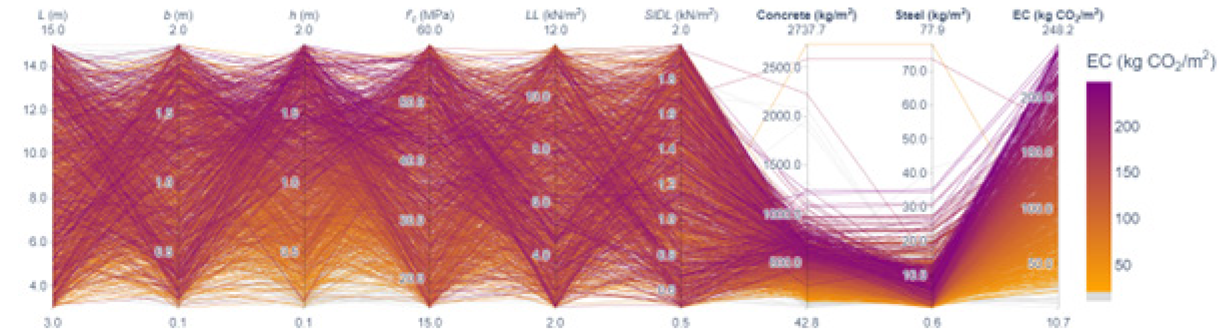


Figure 7: Parallel coordinate plots showing the results of sampling 2500 constrained optimization runs across the shaped beam design inputs. This plot shows results normalized by their supported floor area and is limited to designs with an EC below 250kgCO_2/m².

the design process but also be given the ability to explore vast design spaces of their own making. This is especially true in architecture that expresses, rather than conceals, the resolution of structural forces, allowing structure to play an integral part in the spatial experience. Unfortunately, many decisions must be made in early-stage design (building loads, bay spans, program distribution, etc.) before designers can even explore shape-optimized structural elements and the building's resultant performance. For example, Figure 7 shows a parallel coordinate plot that demonstrates the wide range of resultant EC (in kg CO_2/m²) of 2500 optimized shaped slab designs sampled across a range of values for clear span *L*, maximum depth *h* and width *b*, superimposed dead load *SDL* and live load *LL*, and concrete strengths f'_c. As can be seen, there is no immediately distinguishable relationship between the initial design decisions and the optimal beam geometry, making it difficult to predict the ideal geometry and building performance when these variables are still being explored. To that effect, recent advances in predictive modelling methods allow for early-stage structural design workflows like this while still exploring architectural forms (Danhaive and Mueller 2018). A predictive model can provide approximate results for complex problems, like shaped concrete slab designs, instantaneously. This suggests an opportunity for design methods that include expressive structural elements in early-stage building design. This research involves one such method, using predictive modeling for the real-time design of expressive concrete structures, coupled with a bi-directional VR interface in Rhino for visualization and user interaction.

The following section describes a predictive model built using an artificial neural network (NN) from the samples (shown in Figure 7) collected using this research's shape optimization method. This NN model is then added to the workflow described in Figure 8 to visualize the predicted optimal geometry, its performance, and demonstrates its spatial impact in real time.

4. RESULTS

The strategies presented in this research take advantage of emerging tools in architectural and structural design and fabrication and applies them to concrete construction in LEDCs, resulting in a novel approach to low-carbon concrete architecture for sustainable development. This section discusses how this work is advanced through structural prototyping to verify the design method's feasibility in the built environment, and interactive visualization that may further the method's accessibility to LEDC designers and stakeholders.

4.1. Structural prototyping

As discussed in the prior section, this research's methodology involves the design of shaped concrete slabs using variable coordinates informed by the fabrication method. This precludes the rationalization of a complex element's design for fabrication by including the fabrication logic at the onset of design. Consequently, this research has involved the design, fabrication, and testing of many lab- and full-scale shaped slab prototypes, and while a full discussion of these prototypes is beyond the scope of this paper, this section discusses the primary findings of those experiments. First, several small-scale prototypes have been built to test the viability of this design method subject to different formwork fabrication techniques. These include 3D-printed clay, wire-cut foam, singly-curved bent wood, and hand-curved bamboo formwork. These prototypes are designed by adjusting the parametrization to account for the fabrication constraints, and they are built to undergo structural load testing to verify that they resist the desired loads while achieving a ductile failure mode (proliferation of small evenly-distributed cracks) rather than a sudden brittle collapse.

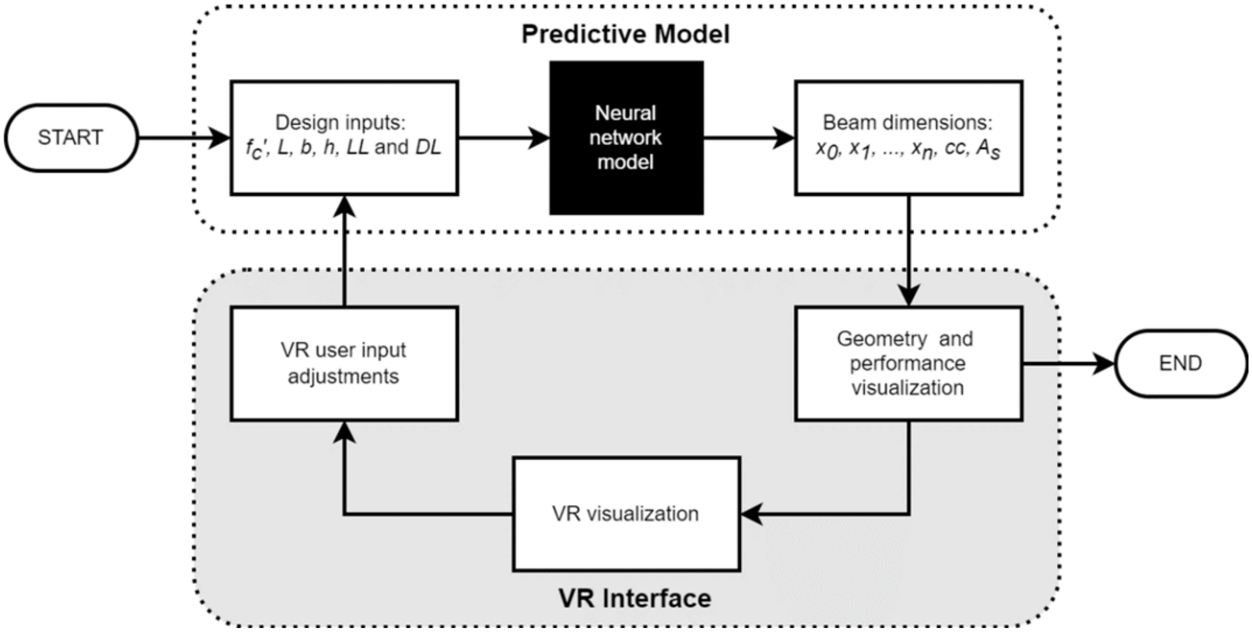


Figure 8: Diagram of predictive model and VR interface for the design of shaped concrete beams.

The results of one such prototype can be seen below in Figure 9. The beam was built using small bamboo elements, a widely-available material in many LEDCs, that were bent and attached to a wood frame, similar to traditional ship-building techniques. As can be seen in the adjoining plot, the beam exceeded the design strength of 10 kips applied as a central point load, and failed in a ductile manner with the proliferation of small cracks along the bottom face.

One example of this methodology's flexibility was also demonstrated by a prototype built in New Delhi with local research partners, TARA. The design was first presented to TARA with an expectation that the slab would be cast into CNC-milled extruded polystyrene foam, using subtractive manufacturing to machine the formwork and cast a doubly-curved geometry. However, TARA could not procure foam blocks in the required quantity so the slab parametrization was adjusted for single-curved surfaces that could be assembled from laser-cut sheet metal, a commonly used material for concrete formwork in India due to its availability and reusability (see Figure 10).

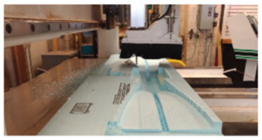
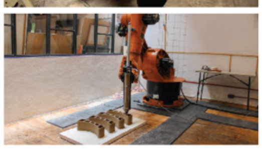
The updated design had an embodied energy reduction of 47 percent while using 30 percent less concrete and 68 percent less steel than an equivalent one-way flat slab. The slab was fabricated using a sheet metal mold, assembled from laser-cut 3 mm steel, and built for simple disassembly for future use. It was also load tested and met Indian building code requirements for residential floor structures. Mold fabrication was

Figure 9: Formwork and casting of a 1m beam built using bamboo formwork and the load test results demonstrating ductile failure beyond the design load of 10kN.

Figure 10: Steel plate formwork for a shaped concrete slab in New Delhi.

Figure 11: Sueños con tierra, a constructed pavilion with a close-up view of precast shaped beams supporting 3D-printed clay blocks that serve as lost formwork for a cast-in-place topping slab. Photo by Walter Shintani.

Table 1: Qualitative analysis of the different formwork methods.

Fabrication method		EC per casting	Labor intensity	Machine accessibility	Material availabliity	Relative feasibility
CNC-milled XPS		High	Low	Medium	Low	**Low**
Curved bamboo		Low	Low-medium	High	High	**High**
3D-printed clay		Low	High	Low	High	**Medium**
Bend and weld steel		Low	Medium	High	Low	**High**
Zip-formwork		Low	Low	High	High	**High**
Shaped Block-and-beam		Low	Medium-high	Medium	High	**Medium**

carried out by TARA and 70 percent of the cost was still due to materials. Similar full-scale prototypes have been built in the United States and Mexico, each with entirely different fabrication methods based on the availability of digital fabrication tools, expertise, and materials, but they were all designed using the same underlying design methodology. For example, Figure 11 shows a pavilion designed and built with local partners New Story and ÉCHALE in Mexico City to demonstrate how the long-existing practice of block-and-beam construction could be improved through shape optimization. This work resulted in a prototype that combines shaped precast beams, 3D-printed blocks made from local clays, and stabilized soil blocks built with local soil and small amounts of cement.

While further market analysis is necessary to test the scalability of each fabrication method in different contexts, some meaningful observations can already be made from the experiments carried out thus far. Table 1 summarizes a qualitative analysis of the viability of each tested fabrication method by describing the relative amount of time, fabrication difficulty, and material accessibility for a given context when compared to standard formwork construction methods. The table also compares the relative EC per use by approximating the total EC of each form and dividing it by the potential number of uses for each formwork material. Therefore, this analysis suggests that the most promising formwork methods explored so far are the curved bamboo form and both full-scale steel forms due to their widescale material availability, simple fabrication processes, and relatively low EC per use.

Importantly, this analysis evaluates the different formwork methods for their viability in modular residential construction where, ideally, the same formwork is used multiple times in a regular floorplan layout. However, if a design called for different shaped beams with various geometries, these formwork fabrication methods could be evaluated for specialization rather than modularity. For instance, in a design that called for shaped beams with various spans, a robotically-3D printed clay form would be the most appropriate as the material could easily be recycled after each use. The following chapter discusses the design of shaped beams for irregular floorplan layouts, potentially requiring recyclable low-carbon formwork rather than longer lasting steel or fiber-glass molds.

4.2. Interactive visualization

This research uses novel methods and tools for the design of structurally efficient concrete floor systems (Ismail and Mueller 2021). The method responds to designer inputs like span, applied loads, floor-to-floor heights, geometric complexity, and more, determining effective concrete slab designs for a given set of boundary conditions using numerical shape optimization and analytical equations. While the results are promising, the process can take over forty minutes to converge on a single design. A predictive model, on the other hand, can deliver approximate findings in real-time. In response to user inputs, a supervised learning model approximates the design of an efficient concrete structure that can be visualized and manipulated in VR.

Figure 12 shows an example NN model built using 2500 optimized concrete slab design samples generated with the shape optimization method described in this paper across a range of relevant user inputs. The design inputs are clear span *L*, maximum depth *h* and width *b*, superimposed dead load *SDL* and live load *LL*, and concrete strengths f'_c but they could also include aspects like steel strength f_y, material costs, and more. These samples are then used to build a NN predictive model

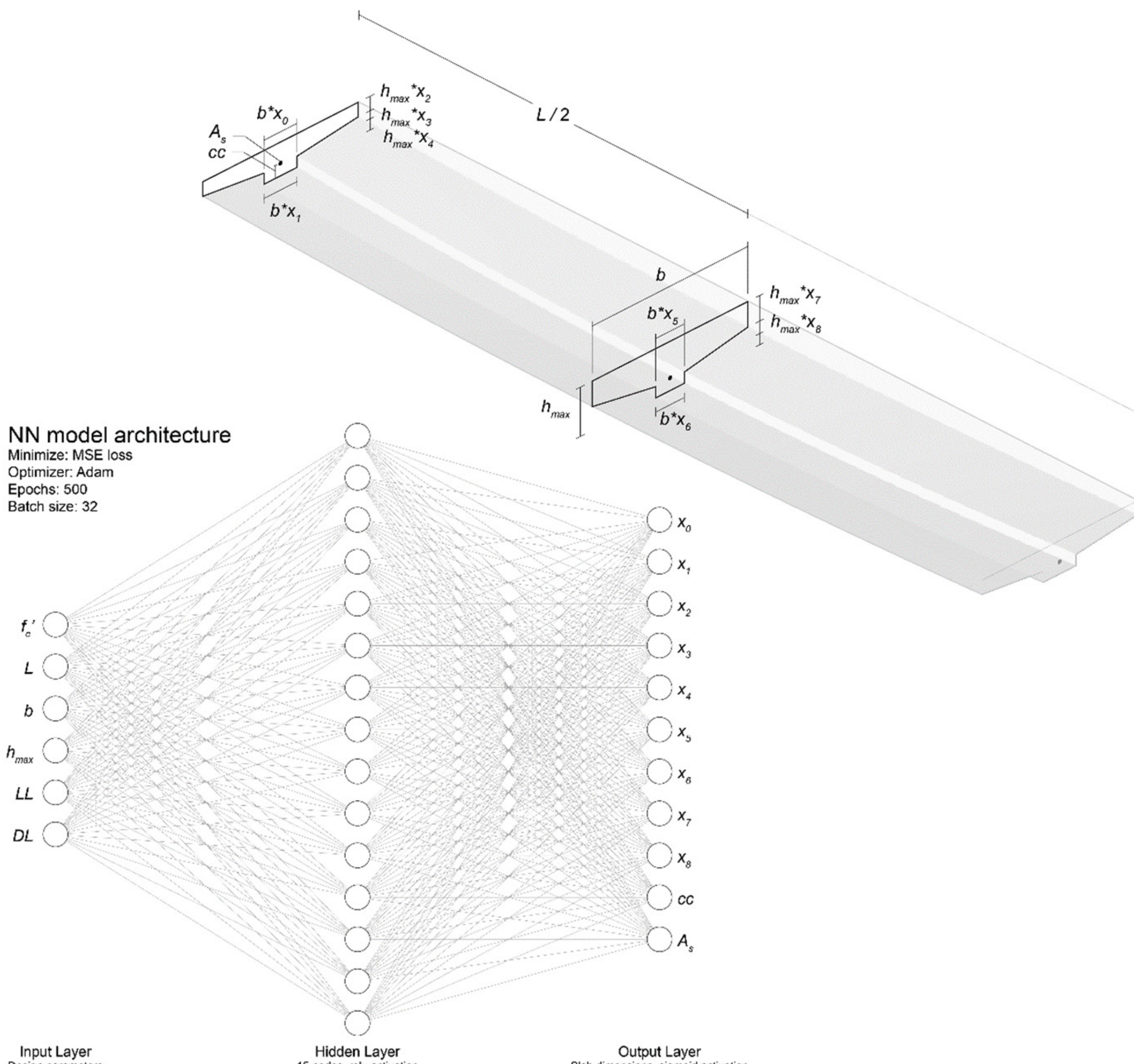


Figure 12: NN architecture (a fully connected multi-layer perceptron) for a predictive model that determines the design and performance of a shaped concrete beam subject to design inputs.

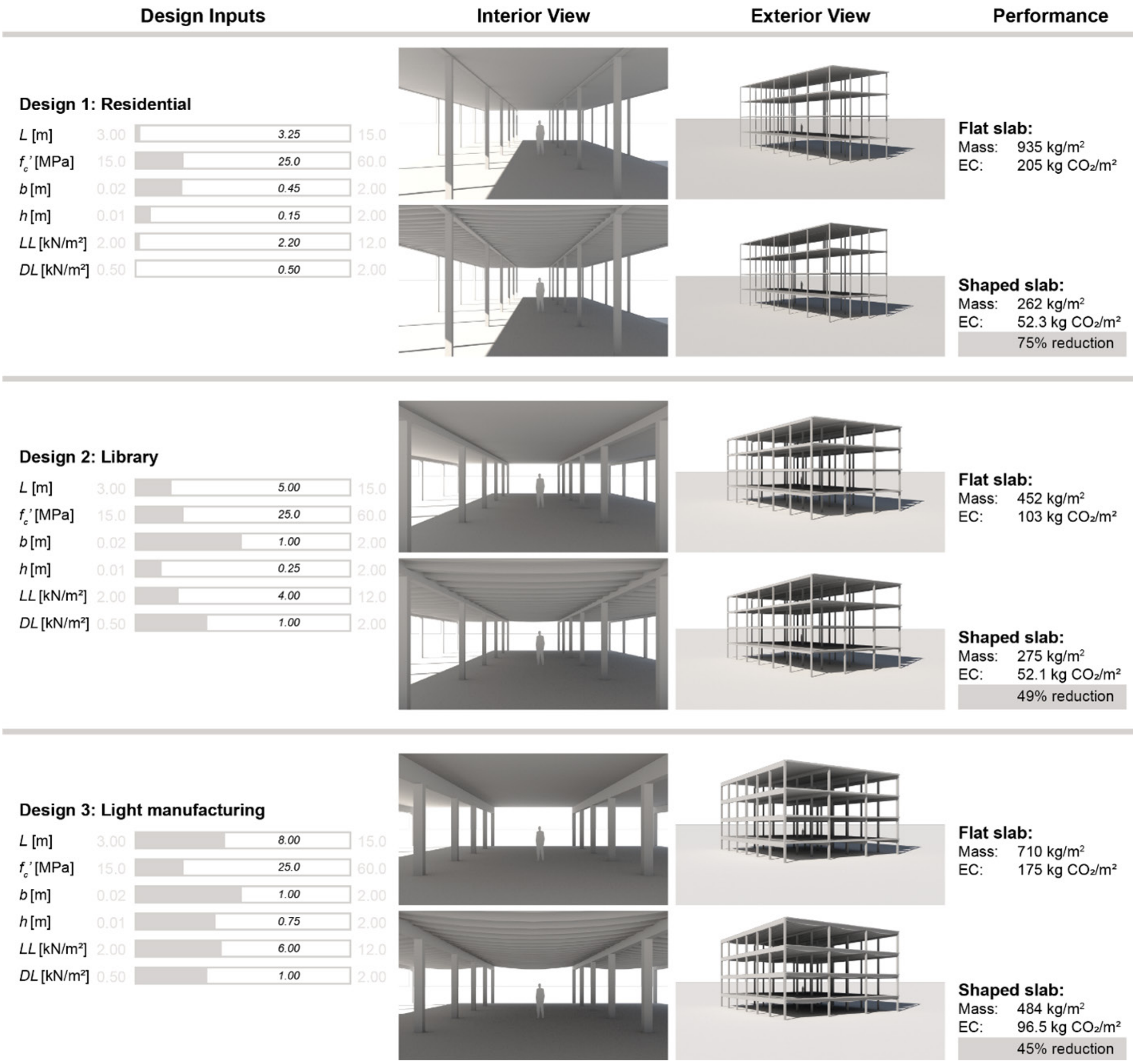


Figure 13: Three iterations of shaped concrete slab buildings generated using a neural network to predict their resultant mass and embodied carbon per unit floor area due to user inputs. The designs represent potential inputs for different architectural programs.

in Python, and streamed back into Grasshopper for real-time results in response to user inputs through the CAD or a VR interface (Ismail et al. 2021). This tool can also be used to assess the structural performance of a building model by providing metrics such as total mass or carbon per unit floor area, allowing designers and stakeholders in LEDCs to understand the performance ramifications of their early-stage design decisions. To illustrate one of the ways this might be used, a compilation of sample designs collected through the resulting ML tool is shown in Figure 13.

Another workflow enabled by the real-time design and analysis of concrete elements is AR and VR-aided structural design. New tools like Mindesk (Mindesk, Inc 2016) and Fologram (Jahn, Newnham, and Beanland 2018) offer a real-time platform that enables a live-link between CAD (in this case Rhinoceros 3D and Grasshopper) and VR, enabling visualization and intuitive parametric modelling by any user. A Virtual Reality User Interface (VRUI) allows the use of a pair of controllers or a mobile device, instead of a mouse and keyboard, to directly manipulate Rhino geometries and Grasshopper

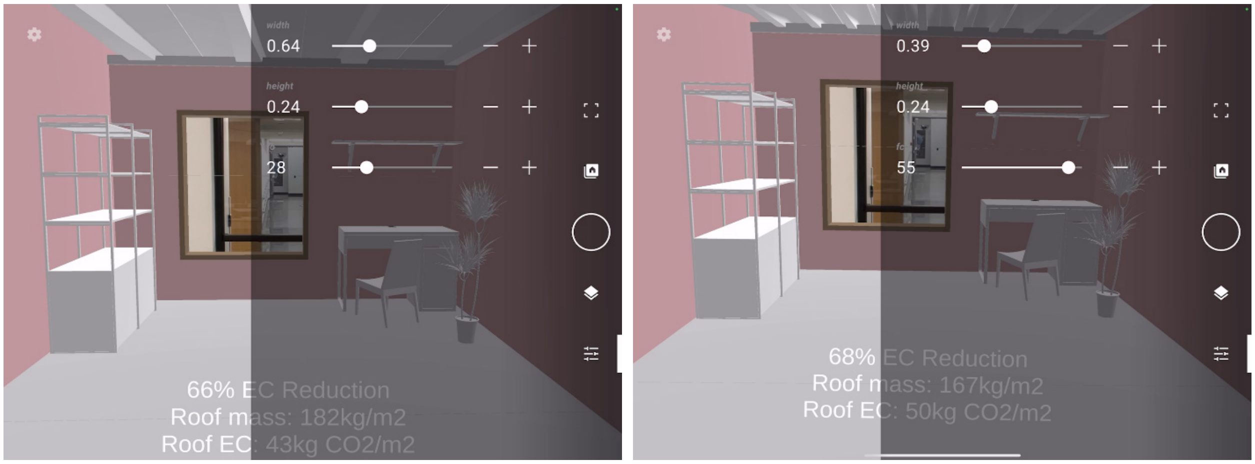


Figure 14: Shaped beam geometries for a residential structure with different widths and maximum heights generated using a NN model and visualized in real-time through Fologram and an iPad Pro 2021.

parameters while immersed in the virtual space. These interfaces enable designers to explore the complex design space of a shape optimized concrete structure in real-time by manipulating crucial architectural parameters, allowing designers and stakeholders to iterate rapidly with a preliminary understanding of the performative and architectural ramifications of their design choices (see Figure 14).

CONCLUSION

The construction industry is unsustainable and does not meet the needs of a rapidly urbanizing developing world. It is also undeniable that concrete is omnipresent and with projected demands for urban construction and new and restored infrastructure, concrete production shows no sign of slowing down. In response, this research presents design methods for structurally efficient floor systems that allow us to build far more with far less, reducing the environmental and economic costs of concrete construction while responding to the demands of LEDCs. Enabled by existing methods of structural optimization and emerging tools in digital fabrication, we can and should design structures that are both efficient and contextual. This method can enrich the design of the built environment by pairing emerging architectural visualization methods with early-stage structural optimization. The strategies presented in this chapter use new tools in VR and ML and applies them to existing methods of structural optimization, resulting in a novel workflow for the real-time visualization of expressive structures.

While further study is needed to understand the downstream impacts of materially efficient concrete beam designs, the initial results presented in this thesis are promising. For example, preliminary research by Feickert (2022) suggests that using shaped slabs could reduce the embodied carbon of a building's total structural system by at least 60 percent. If we expect to add 230 billion m² of new floor area to the global building stock by 2060, it is likely that at least half of that will be built from reinforced concrete (Architecture 2030 2021; Kuijpers 2020). Assuming an average building's structure requires 200 kgCO_2/m² (Kaethner and Burridge 2012; Simonen, Rodriguez, and De Wolf 2017), the design methods presented in this paper could prevent 345 million tons of CO_2 emissions annually, or 23 percent of the annual CO_2 captured by the Amazon Rainforest (The Economist 2022).

Today, most concrete construction in LEDCs mimics the materially inefficient practices of MEDCs, developed to reduce labor over material costs through modular elements and standardized dimensions. This must change. If urban construction is projected to double the existing floor area by 2050 (Detter 2018), we need immediate, scalable, and impactful innovations in concrete construction by and for designers in LEDCs. The regions facing rapid growth and development need to build fast and they must be allowed to do so on their own terms.

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