Fabrication and Construction Methods for Low-Cost, Low-Carbon Structural Components for Housing in India

by
Abigail M. Anderson

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Abstract

In Less Economically Developed Countries (LEDCs), material costs often constrain construction projects. There is research interest in reducing materials usage, and thus cost and carbon footprint, by redesigning reinforced concrete elements. Research at MIT aims to redesign reinforced concrete slabs to reduce concrete usage, specifically with the Indian construction context in mind, and some groups have arrived at an algorithm for creating optimized slab forms. In this thesis, I transition optimized forms from laboratory-level, idealized slabs which require subtractive milling digital fabrication to realistic slabs that are practical to produce on a larger scale on construction sites in India. I examine trade-offs between cost of fabrication and materials reduction achieved, while ensuring that structural integrity is maintained. Of the three formwork fabrication methods examined, bent wood provides the most promising solution because of the consistency and complex shapes that are achievable, but it has drawbacks when other dimensions of analysis are considered. I demonstrate that structural optimization of reinforced concrete can have positive, practical implications for housing in India.

Thesis Supervisor: Caitlin Mueller

Title: Associate Professor of Civil and Environmental Engineering and Architecture

Acknowledgments

This thesis would not have been possible without the advice and support of several important people. I thank my advisor, Professor Caitlin Mueller, for helping me combine my interests in civil engineering, architecture, and development into a unique thesis that lies at the intersection of these passions. I have enjoyed each step of this process, and have learned from her sage advice and been inspired by her genuine intelligence along the way.

Without graduate student Mohamed Ismail, none of this work would have been possible. I thank him for allowing me to be a part of the bigger work that he is doing as an MIT Tata Fellow and student in the SM in Architecture Studies program. I have learned so much about architecture, design, and fabrication from him. He helped me prepare for and conduct interviews in India, and was a wonderful travel companion along the way. Without him, such extensive fabrication and load testing would not have been possible in the timeframe of this project. I also had the opportunity, through Moh, to get introduced to the MIT Tata Center. I thank the Tata Center for sending me to India and supporting the lab fabrication for my experiments.

In a fabrication-intensive thesis such as this one, many hours are spent in various shops. I thank Chris Dewart in the Architecture shop for sharing his expertise in fabrication and woodworking with me, and for spending time brainstorming with me to design practical formworks. I thank Steve Rudolph in the Civil & Environmental Engineering shop for helping me with concrete casting and testing, and for being available to help when I encountered issues in the final stages of formwork fabrication.

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Lastly, I am thankful to those who have emotionally supported me throughout this process, and without whose support I would not be at MIT in the first place, let alone having the opportunity to explore my passions in such relevant research. I thank my parents and sister, as well as my extended family, for their love and consistent care for my whole life. I thank my friends, who have rejoiced with me over triumphs and wept with me over failures. And, finally, I thank God, without whom I would not have had the strength, mental capacity, or stamina to graduate from MIT and accomplish all that I have.

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Chapter 1: Introduction and Literature Review

1.1 Introduction

Reinforced concrete (RC) construction techniques were designed by the West, for the West. These techniques aim to reduce labor, often compromising material usage; common forms are straightforward to build and easy to replicate, but material is often wasted. Many Less Economically Developed Countries (LEDCs) have imported these techniques and applied them in their own construction sectors, replicating the materially-inefficient processes. However, in LEDCs, there is often a surplus of labor, so labor costs are low relative to the costs of materials (see Figure 1). Reducing labor intensity of processes in these countries is counterproductive, and the labor surplus in countries like India should be leveraged. In this thesis, I examine the ways that the labor surplus in India provides an opportunity to transform the materially-inefficient RC construction process, thus reducing carbon emissions and building costs.

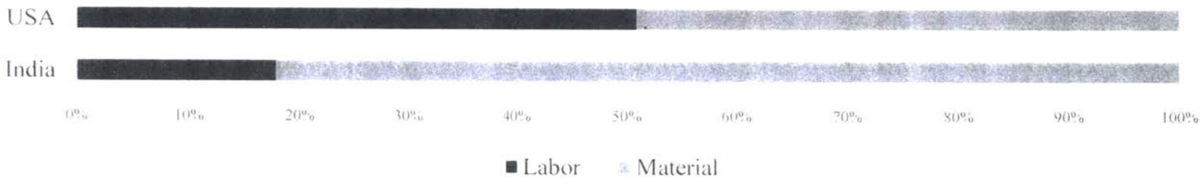


Figure 1: Comparative costs of material and labor for construction (Credit: Ismail and Mueller 2018)

Research in this field has focused on computational optimization for the redesign of RC building elements, as well as the current negative impacts of the prevalence of inefficient concrete construction. Professor Caitlin Mueller and Mohamed Ismail in MIT's Digital Structures research group have been working to design a beam and floor slab system that leverages computational tools to minimize the amount of concrete, and, by correlation, steel, that is required. The slabs in Figure 2 have been computationally optimized to reduce the amount of concrete used while maintaining the load capacity of a typical prismatic slab. Such forms are simple to construct using digital fabrication technology, but would be challenging and time-consuming to build on a typical construction site. In a country like the United States, the cost of labor for building such a beam on a construction site would outweigh its material benefits, but in India, contractors may be more eager to implement this construction method because of the high percentage that materials cost contributes to overall cost of a project. This thesis presents and analyzes ways that the optimized beams could be constructed on-site in India.

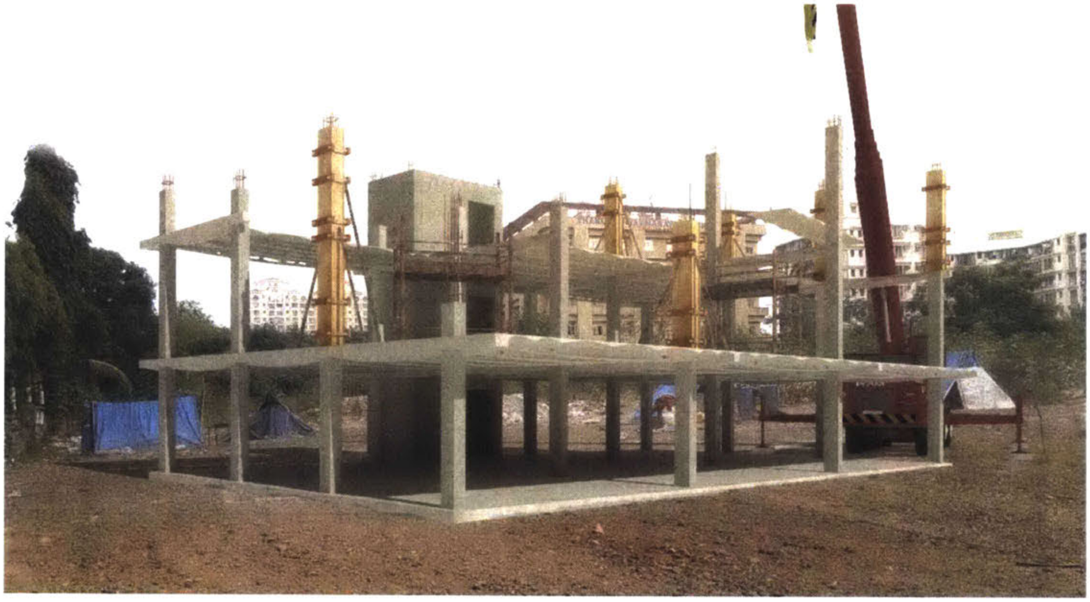


Figure 2: Computationally optimized slabs in Indian construction context (Credit: Ismail)

Concrete is one of the most common and trusted building materials in India (Bhasin and Singh 2019), and new concrete structures are being constructed around the country (see Figure 3). Concrete is also one of the largest contributors to the 12.4% of energy-related greenhouse gas emissions that come from the manufacturing and construction sector, as of 2013 ("Global Emissions" 2017). According to work by Catherine De Wolf (2017), 0.18-0.22 kilograms of carbon dioxide are emitted for each kilogram of high-strength concrete in a building, in the "cradle-to-gate" part of its lifespan alone, from excavation, through processing and transportation, to building completion (De Wolf 2017). In 2012, India produced 6.0% of the world's greenhouse gas emissions ("Global Emissions" 2017). Sand, an important ingredient in concrete, is becoming rare and thus very expensive in India, so manufacturers are shifting to manually producing sand from coarser aggregate (Sreenivasa 2012). Due to these and other factors, it is important, especially in India, to focus on reducing the amount of concrete used in the construction sector.

Figure 3: Massive concrete structures are emerging in open fields. (Credit: Ismail)

Reinforced concrete (RC) is a composite construction material which takes advantage of the high compressive strength of concrete and the high tensile strength of steel. This thesis focuses on RC floor slab design because of the ubiquity of reinforced concrete floor slabs in India and worldwide. RC beam and slab systems are widely replicated and highly trusted as a reliable construction technique. This research specifically presents improvement techniques for one-way slabs. One-way slabs are ideal for early-stage research because of their relative simplicity from a structural mechanics perspective. Ribbed slabs made up of T beams, essentially carving away unnecessary concrete, are already well-documented as a way to save material, and this research builds on and improves this common concrete reduction strategy.

The research in this thesis is composed of exploration and experimentation. I interviewed stakeholders in the Indian construction industry to better understand the RC construction process there. From review of relevant literature and these interviews, I designed and built two T beams, sections of a concrete slab, without the use of digital fabrication techniques. These formworks created T beams which approximate the optimized T beam geometry. I then physically load tested these beams and two control beams. I used Abaqus to computationally model these tests and support my results. I present the results of each fabrication method and highlight which best maintain the structural benefits of modified beam forms, but can practically be fabricated and used in construction in the Indian context.

1.2 Literature Review

Reinforced concrete dominates the Indian construction industry, and related literature abounds. Scholars experiment with using digital methods to improve the concrete construction process and reduce its negative effects. Others study building and building codes in India. Additionally, some researchers combine these two areas of research, aiming to optimize different concrete-related factors in Indian construction specifically. In this section, I present existing research on reinforced concrete optimization; the constructability of digitally-designed structures; fabric formwork; the Indian construction context; and traditional fabrication technologies and materials.

1.2.1 Reinforced Concrete Optimization

Much scholarly research is being conducted to optimize reinforced concrete building systems, from maximizing mix strength to reducing the amount of material used to maintain structural integrity. Researchers are using computational tools to reimagine RC forms. Physical tests of unique forms are also crucial in these explorations of materials reduction strategies.

For example, several research groups have been exploring lightweight concrete floor systems. Liew et al. (2017) provide an overview of the process of building and load testing an efficient concrete floor system, from concept design, through form finding, to fabrication and testing. In the work presented in "Design, Fabrication and Testing of a Prototype, Thin-Vaulted, Unreinforced Concrete Floor," the structural system supporting floor slabs is composed of funicular arches arranged in a unique pattern so as to support floor slabs in optimally-shaped rooms. The layout of supporting arches was determined using shape optimization in RhinoVAULT. The paper details the material properties of the concrete used for testing in laboratory facilities in Zurich, before constructing the actual structure in Addis Ababa. Next, it describes the experimental testing process for the floor prototype, which included serviceability loading tests (see Figure 4) and an ultimate loading test. The floor system tested performed well under the tested loads, and because of the layout of the support arches, it is much lighter than a traditional floor slab. Although the authors do not study reinforced concrete forms, the fabrication and experimental testing methods used in Liew et al. influenced the lab testing process in this thesis (Liew et al. 2017).

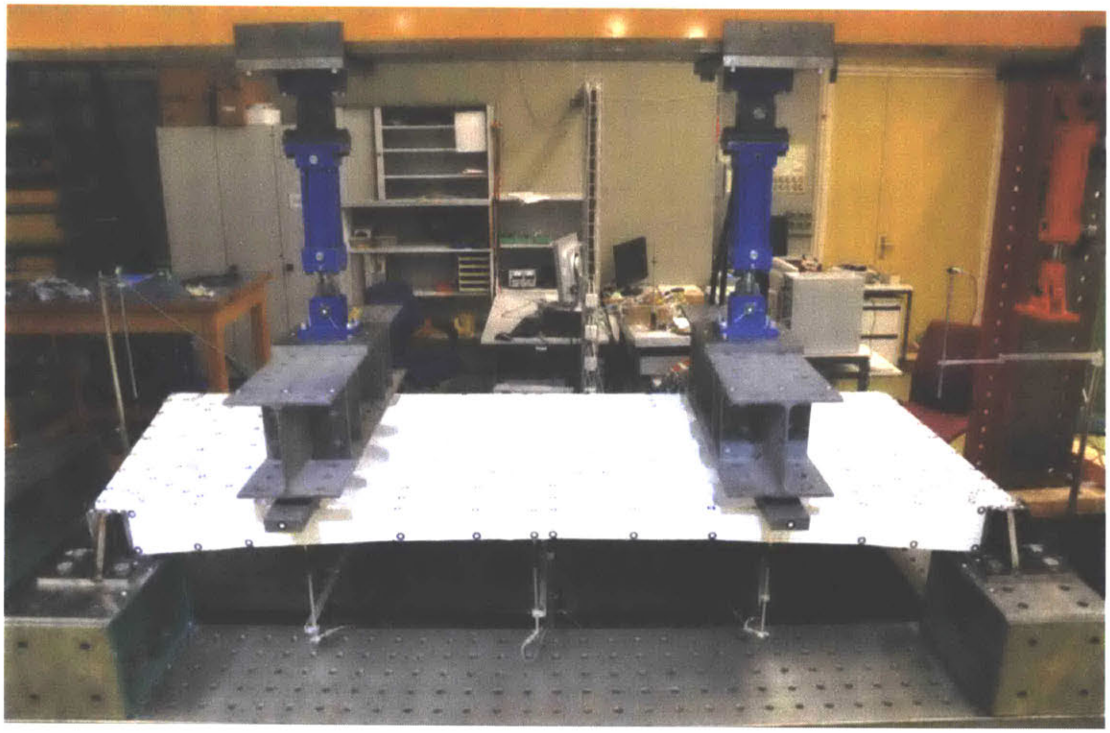


Figure 4: Complete four-point-bending experimental setup for service loading of a thin-vaulted, unreinforced concrete floor (Credit: Liew et al. 2017)

Hawkins et al. (2017) address the issue of excessive concrete and steel waste in prismatic RC slabs through computational optimization. They use a variety of methods to arrive at thin shell geometries (Figure 5) with a foamed concrete fill, comparing the bending and tensile strain energy for each. They measure the utilization of different regions of each shell under live and dead loading conditions. Through this process, they achieve an approximately 62% reduction in embodied energy, compared with a traditional flat slab (Hawkins et al. 2017). However, they do not investigate the implications of their work for low-cost housing projects or the feasibility of replicating their work on a larger scale.

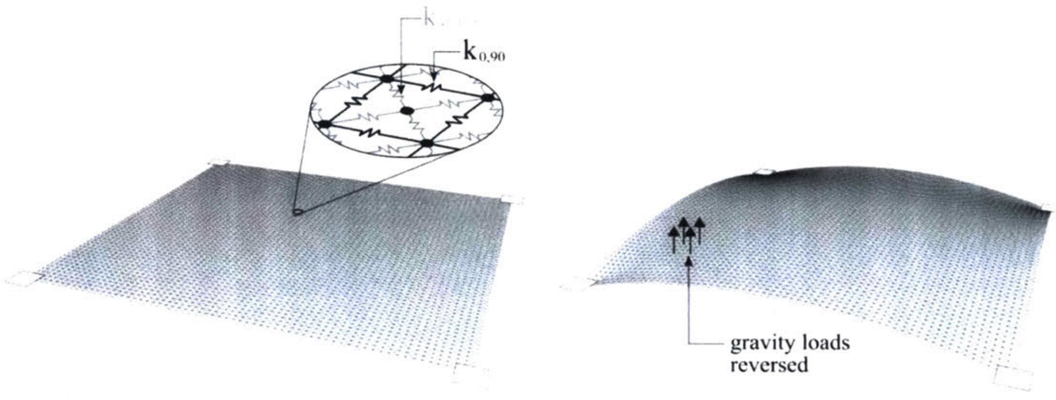
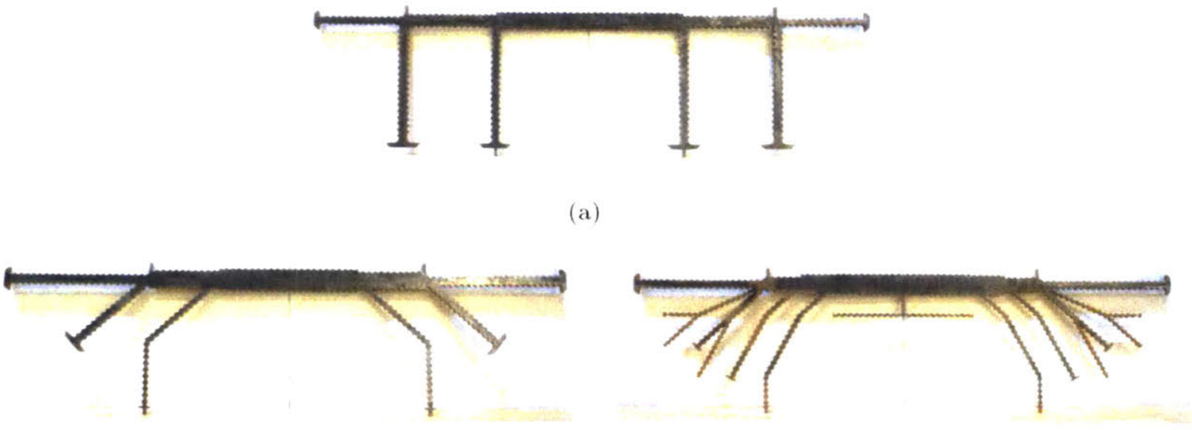


Figure 5: Form-finding with an initially flat cable-net (Credit: Hawkins et al. 2017)

More generally, some researchers have developed applications of topology optimization for RC design. Topology optimization is a design tool which uses various algorithms to create solutions that outperform traditionally-designed elements. In the case of RC, topology optimization can focus on the optimization of the geometry of the concrete and/or the steel. Jewett and Carstensen (2019) study the performance of strut-and-tie designed RC beams. They redesign traditional reinforcement using varying degrees of topological complexity; see Figure 6 for the three tested reinforcement layouts. Through fabrication and testing of beams with identical concrete volumes but varying waterjet-cut steel reinforcement, they discover that any topology optimization of steel reinforcement significantly improves the stiffness and strength of a beam, regardless of topological complexity. This implies that improvements can be made on traditional reinforcement using topology optimization without introducing the high fabrication complexity involved in the most optimized forms (Jewett and Carstensen 2019).



(a)

(b)

(c)

Figure 6: Steel reinforcement cut by waterjet in (a) standard, (b) TopOpt 2x8, and (c) TopOpt 4x16 reinforcement layouts (Credit: Jewett and Carstensen 2019)

In *Formworks for Concrete: Subsidies to Optimizing the Design* (2017), Magalhães Maranhão et al. explore the specifics of formwork assembly. They focus on plywood formwork, since that is most common in their Brazilian construction context. They estimate that 60% of the time required for RC construction is dedicated to formwork assembly, 25% is dedicated to steel positioning, and 15% is dedicated to the actual pouring of the concrete. Formwork removal strategies and concrete pouring pressures are also examined (Magalhaes Maranhao, Christoforo, and Rocco Lahr 2017).

1.2.2 Constructability of Digitally-Designed Structures

As computational algorithms and parametric design advance, it is important to assess the practicality of these advances; a digitally-designed bridge may be beautiful and may reduce building materials, but if it is impossible to construct with current fabrication methods, it will remain in the computer workspace. Górczyński and Rabiej (2011) examine the paradigms that shape architects' relationship with fabrication and production. They emphasize that, today, architects are closer to their final products due to advances in CAD-CAM integration. Designers today must remember the real-world fabrication constraints when working in the nearly-unconstrained digital design workspace (Górczyński and Rabiej 2011). However, Górczyński and Rabiej do not discuss the reality that traditional construction practices are often so ingrained in the construction sector that unconventional designs are impractical.

Although it may not yet be widespread, digital design techniques have been translated to reality in a number of famous buildings. Two examples are Zaha Hadid's *Morpheus* in Macau (Figure 7(a)), and Zaha Hadid's *Galaxy Soho* in Beijing (Figure 7(b)). However, these buildings are exceptional, and digitally designed structures are still the exception, rather than the rule.

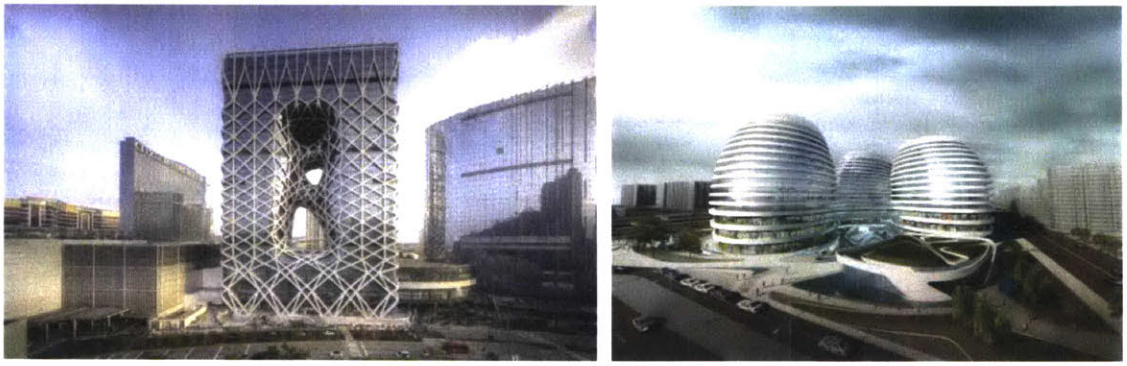


Figure 7: Existing digitally designed structures, including (a) Morpheus (Credit: "Morpheus Hotel / Zaha Hadid Architects | ArchDaily" 2019) and (b) Galaxy Soho (Credit: Khim 2012)

The topologically optimized Unikabeton Prototype at the Aarhus School of Architecture, shown in Figure 8, is an example of a computationally-designed, topologically-optimized full-scale structure. Søndergaard and Dombernowsky (2011) explore the connection between computational design and precise robotic fabrication of concrete. They use a large-scale industrial mill to construct polystyrene molds, which are then assembled on-site using traditional reinforcement assembly techniques. The authors argue that topology optimization and computational design techniques necessitate an entirely new design methodology (Søndergaard and Dombernowsky 2011).

Figure 8: Unikabeton Prototype at the Aarhus School of Architecture (Credit: Søndergaard and Dombernowsky 2011)

3D printing has the potential to create formworks for concrete with complex, optimized geometries. Jipa et al. (2016) utilize binder-jet 3D-printing to create a formwork for an optimized slab. This method of additive manufacturing produces sandstone formwork for concrete. Instead of traditional steel reinforcement, the authors use small steel fibers that are six to ten millimeters long. This process enables them to produce the complex slab shown in Figure 9, which, through topology optimization, was designed to have only 18% of the volume of a traditional prismatic slab (Jipa et al. 2016).

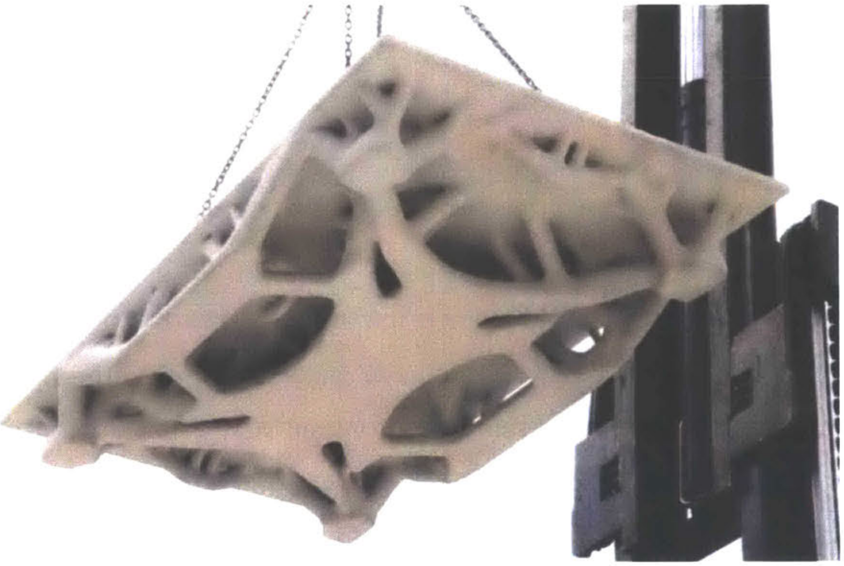


Figure 9: Topology optimized slab built with a 3D-printed formwork (Credit: Jipa et al. 2016)

Digital fabrication technologies enable new construction methods. Companies like ICON are working to 3D print tiny houses, in partnership with nonprofits like New Story, to build more affordable homes. In March 2019, this collaboration led to 600- to 800-square-foot homes like the one in Figure 10 being printed in just 24 hours for only $4,000 each. ICON advertises that 3D printing building materials like concrete costs less than traditional building methods and uses a smaller volume of material. Only a few workers are required for the entire construction process, because the 3D printer is operated by tablet. New Story is seeking funding to print these houses in El Salvador for current residents of the slums (Bendix 2019).

Figure 10: A 3D-printed home that costs only $4,000 (Credit: Bendix 2019)

1.2.3 Fabric Formwork

Fabric formwork for concrete has several advantages, including that its flexibility allows it to form a wide variety of shapes. Several researchers are using fabric to create unusual shapes and non-prismatic beams. Orr et al. (2014) design an optimized RC beam using flexible fabric formwork. Using an iterative method, they achieve materials savings of up to 40%. They design for two states: the ultimate state and a serviceability limit state. They demonstrate that the use of fabric formwork can significantly reduce the amount of material used, while at the same time creating architecturally interesting forms (see Figure 11) (Orr et al. 2014). According to Garbett et al. (2016), "fabric formwork provides the means of easily forming more complex optimised components and therefore creating significant material savings" (Garbett, Darby, and Ibell 2016, page 850).

Figure 11: Fabric formwork creates architecturally interesting forms and can shape optimized beams (Credit: "Bespoke Reinforcement for New Concrete Structures" 2019)

Mark West is a pioneer in the use of fabric formwork and the founder of the Centre for Architectural Structures and Technology at the University of Manitoba. He has explored the use of fabric formwork in foundation construction, where the fabric stays a part of the structure and acts as a barrier between the concrete and the ground. He provides recommendations for fabric type and assembly technique for fabric formwork. West focuses on the architectural and design applications of creatively-applied fabric formwork, in addition to the structural potential of fabric-created funicular forms (West 2017).

The type of fabric used in fabric formwork has evolved. Historically, the construction industry often used burlap because of its low cost. However, burlap and other "hessian" fabrics are not ideal for formwork, as they propagate tears easily, stick to the concrete, and are weak. Today, woven polyethylene and polypropylene fabrics are commonly used in fabric formwork (West 2017). In Orr (2012), the author uses a woven polyester material as a flexible fabric formwork (Orr 2012). West (2017) presents a variety of geotextiles used for casting, including uncoated woven polypropylene geotextiles and translucent polyethylene woven fabrics. These fabrics are cheap, strong, do not propagate tears, and detach easily from concrete, so a formwork release agent is unnecessary (West 2017).

Orr (2012) emphasizes the accessibility of using flexible formwork on-site as a replacement for traditional orthogonal forms, and suggests that fabric forms be cast on the ground on-site and then lifted into place (Orr 2012). The process of casting on-site, however, has a variety of disadvantages. Consistent quality is hard to maintain. Laborers must be skilled and able to repeat a process exactly to form identical RC units; there is a risk that wide variability could exist among different slabs.

One major issue with using fabric formwork is the difficulty of exactly recreating computationally-determined optimized shapes. Garbett et al. (2016) show that, by using iterative optimization methods, it is possible to precisely control and predict the structural capacity of beam sections using fabric formwork. They use an algorithm to optimize geometry given several constraints, including a constant breadth or depth, and to predict the hydrostatic shape formed by hanging fabric. However, "the hydrostatic shape [of the concrete in the fabric]...limited the amount of optimisation that could be achieved" (page 852); the hydrostatic properties of concrete in fabric constrain the shape of the final beam, and beam geometries optimized for certain constraints may be unattainable with fabric formwork (Garbett, Darby, and Ibell 2016). Orr (2012) optimizes sections along the beam with this constraint in mind to create a non-prismatic beam that can be shaped with fabric formwork (Orr 2012).

1.2.4 Indian Construction Context

Each region's construction industry is unique, with specific nuances and complications that must be understood if interventions and improvements are to be achieved. According to Niraula and Kusayanagi (2006), the construction industries in Nepal and Cambodia often do not deliver major infrastructure projects on schedule. The authors investigate technological and human resource factors that contribute to this issue. They report on the disconnect between research and industry, citing complaints by leaders in industry that university graduates are not equipped with practical skills for industry. Their article outlines a strategy which integrates human resources and technology development in order to better complete infrastructure projects in developing countries. Overseas development assistance (ODA), specifically from Japan, often focuses on training a few technical experts from a country, rather than developing educational systems that will disseminate knowledge across the entire construction industry. The paper claims that ten times more personnel will be trained if the same amount of ODA that is currently spent on training technical experts is instead diverted to local trainings of civil engineers in-country (Niraula and Kusayanagi 2006).

In a 2012 newspaper article, Simha provides a brief overview of building codes in India, including those governing lighting, ventilation, HVAC, MEP, acoustics, and escalators. The author highlights certain issues that are particularly applicable in the Indian context, such as the effects that high altitudes and sub-zero temperatures can have on drainage and sanitation systems.

Reducing fire hazards is important in Indian construction. Safety and durability are key in India's National Building Code (Simha 2012).

Several sources focus on specific elements of concrete construction in India. Precast is becoming more popular because it can provide faster construction; Akhtar (2017) claims that it can reduce construction time by 40-50%. Suppliers for precast concrete construction in India are mostly European; for example, a British firm makes steel plates for beds, and an Italian firm makes tilting molds for walls, columns, and beams. According to Akhtar's article, precast concrete is much more commonplace in Europe today, but India is moving towards it (Akhtar 2017).

In a 2014 MIT Technology & Public Policy thesis, Schuchman investigates the impacts of different building types and materials in India. There has been a shift from fired-clay bricks, which produce black smoke in production, to stabilized brick, which are composed of traditional earthen materials and chemical binders. Schuchman argues that both types of brick should be considered for construction, depending on location; each has variable environmental and economic impacts in different regions. The thesis focuses mostly on cement as an additive to blocks, such as concrete stabilized earth blocks (CSEBs). This work provides a helpful analysis of the full life cycle of bricks, including CSEBs, in India (Schuchman 2014).

Indian cities are rapidly expanding as labor migrants transition from rural to urban areas in search of economic opportunity. Cities do not have enough affordable housing for these migrants, so many live in slums or informal settlements. Overcrowding is common in large cities in India, and traffic and smog problems result (see Figure 12). In 2012, the government estimated an 18.98 million-home shortage nationwide. The gap between supply of affordable housing and demand for it is widening: there are projected to be 30 million families without homes by 2022. About 95% of the people without homes are in the two lowest income brackets, so affordable housing by the government or through public-private partnerships is crucial. The government aims to have affordable housing for all by 2022—several million new units in the next three years. A number of government initiatives and programs incentivize affordable housing construction ("Mainstreaming Affordable Housing in India: Moving towards Housing for All by 2022" 2016).

Figure 12: Overcrowding in Mumbai (Credit: Anderson)

1.2.5 Traditional Fabrication Technologies and Materials

India is a country rich with tradition, including within the construction sector. Various wood-bending techniques in India date back for hundreds of years. Particularly in the shipbuilding industry, local craftsmen can achieve complicated curves similar to those required by digitally optimized geometries. In the Orissa state, on Chilika Lake, communities of boat-builders curve wood using heat. They heat the wood, being careful to prevent it from burning, and, after a few minutes of heat application, bend it to the desired shape using metal and wooden bars (Raut and Tripati 1993). In Beypore, Kerala, shipbuilding is a tradition that has been passed down from generation to generation for hundreds of years (Skupniewicz and Gami 2019). Boats like the one in Figure 13 exhibit two-dimensionally curved surfaces created without the use of high-tech fabrication methods. According to Rao (2015), boats in the Kerala region are built using a stitched plank system: workmen cut wood to the appropriate size, drill holes through the planks, and stitch them together using grass and a silk thread (nylon rope). Then, they fill any holes with coconut fiber to ensure the boat will be watertight. Caulking aids in sealing joints throughout the process. Finally, coal-tar is applied for better sealing (Rao, Sudheer, and Kumar 2015).

Figure 13: The shipbuilding industry in India boasts expertise in wood-bending (Credit: Rao, Sudheer, and Kumar 2015)

Red sandstone is widely available in northern India. It plays a prominent role in the structural systems of some historic buildings. In the Fatehpur Sikri palace complex in Agra, for example, flat domes are common (see Figure 14(a)). Another widespread use of red sandstone in traditional and modern buildings is in waterproofing. As shown in Figure 14(b), red sandstone's porosity makes it a good barrier between the earth and the poured concrete foundations.

Figure 14: Red sandstone is widely available in northern India and has been used for both (a) flat domes (Credit: Anderson) and (b) waterproofing (Credit: Ismail)

Architect Anupama Kundoo brings many traditional Indian materials and techniques into her unique designs. Wall House in Auroville (Figure 15) uses thin concrete screens, brick walls, nested ceramic pots to form a vault, and inverted ceramic pots to create voids in concrete floor slabs. The building is designed to maintain a comfortable airflow and blur the division between interior and exterior (Callejas 2019). However, such artistic, ecofriendly techniques are difficult to replicate at a larger scale, and today, such designs are mostly applied to individual projects.

Figure 15: Wall House by Anupama Kundoo, Auroville, India (Credit: Callejas 2019)

1.2.6 Open Research Questions

As shown in this chapter, research has been done on reinforced concrete optimization, fabrication of digital designs, fabric formwork, and traditional fabrication methods. If the Indian government would like to apply this research to efficient residential construction to address the affordable housing shortage, however, optimization and digital fabrication methods must be combined to leverage the advantages of each in a less-technology-intensive setting.

In this thesis, I explore the potential of current fabrication methods to construct digitally-optimized slabs. I apply two fabrication techniques described in this chapter to the construction of digitally optimized slabs: wood bending and fabric. Ancient boatbuilding and wood bending techniques from India reveal an expertise in creating curved wood shapes. How can we take advantage of this existing expertise to approximate the complex curves of the optimized slab geometry?

Fabric formwork also has the potential for application in our specific case. Instead of exploring how to create an optimized beam with fabric formwork using an iterative process accounting for fabric and hydrostatic properties, I explore the potential of fabric to approximate the previously-determined optimized slab shape. I fabricate and test T beams created with bent plywood, fabric, and milled foam formworks.

1.3 Structure of Thesis

The following chapters present the methodology and results from the author's work to answer these questions. Chapters 2, 3, and 4 describe three diverse research approaches. Chapter 2 presents field work in India, including interviews and site visits, and findings of this work relating to common construction practices and trends in India and the constructability of an optimized ribbed slab. Chapter 3 details the fabrication process of the optimized T beam and two approximate variations, and the lessons learned through lab fabrication. Chapter 4 focuses on the testing of these beams, in both lab and computational settings. Finally, Chapter 5 connects and discusses the findings of the three chapters, and presents overall conclusions and areas for future work.

This work was largely aided by graduate student Mohamed Ismail and my advisor, Professor Caitlin Mueller. All photos and graphics have been appropriately credited. All images not credited are the author's.

Chapter 2: Field Work

Before fabricating the three beam formworks, I travelled to India for two weeks in January 2019 to get a better understanding of the construction context there. I used site visits and interviews to corroborate the findings of my literature review and decide which fabrication techniques to pursue. In this chapter, I describe the methodology and findings of my trip. Field work was completed in collaboration with a graduate student in the Department of Architecture, Mohamed Ismail.

2.1 Methodology: Field Research

Context is important in any engineering or construction project. To verify that our overarching project is feasible in the Indian construction context, and to better understand the unique constraints on construction projects in India, I travelled to India to conduct a series of interviews and visit construction sites. I interviewed a number of developers, architects, engineers, and academics in India who have experience with the construction sector there. I also went on three official site visits, and observed many large-scale construction projects in and around Delhi, Mumbai, and Ahmedabad.

To create a balanced view of the Indian construction sector, I reached out to many contacts who are fully or tangentially involved in the sector. Then, a few of those contacts met us personally or connected us with experts in the field. While in India, I met with construction managers and engineers from two major developers; product developers from a major company; several academics and engineering alumni from a university in Ahmedabad; and businessmen in the precast concrete industry. Before travel, the research was approved by MIT's Institutional Review Board, and consent forms were signed by participants at the interviews.

I carefully developed a series of questions to glean the information needed from the interview subjects. These questions are displayed in Table 1. At each interview, these questions led to discussions of formwork, industrial trends, and labor. In the next section, I present the major takeaways from these interviews and their implications for the project.

Table 1: Interview Questions and Explanations

Question	Explanation
What types of projects does your company work on?	To learn some background of each company, specifically focusing on common materials
Describe your experience with concrete casting.	To understand the expertise areas of everyone in the room, as well as the casting processes that were familiar to them
What type of formwork do you use? How many times do you usually reuse it? (And other formwork-related questions)	To understand the current formwork practices common in large-scale and small-scale construction in India
After seeing this 3D print of an optimized T beam, do you think an insert for a traditional slab of similar geometry could be used on your sites? What materials would you suggest we use for this insert? What issues do you see arising? (I brought a small 3D print of a slab section that we have optimized, and a print of the corresponding negative volume that could be placed in a conventional slab formwork to remove unnecessary material and create the optimized shape. Both are pictured at right.)	To gauge the interest of developers and engineers in using a formwork insert To glean feedback on the modification to the formwork construction process we were suggesting: does this technique make sense, or would another be more practical? 
What is the current state of the precast concrete industry? How do you predict it will grow or change in the near future?	To learn whether there is potential for our optimized slabs to be precast off-site, and whether this practice would be accepted by the construction industry
How does the surplus of labor in India affect your construction projects?	To better understand how the price and skill level of labor affect aspects of construction projects such as equipment used, timeline, and building quality

Site visits usually occurred in a more organic manner. Through connections of Ismail's and our interviewees', we were able to visit three very different active construction sites. The first was a small office building whose foundation was nearly finished; the second was a single-family home whose basement was nearly complete; and the third was an EMAAR-India residential community, where we saw condominiums at all stages of the construction process. In the next section, I discuss the findings from interviews and site visits during the trip to India.

2.2 Results: Construction Feasibility

Through interviews and emails with a number of individuals working in the construction sector, I investigated the potential for using a formwork insert on construction sites in India to create the precise geometry of our optimized slab, as well as the receptivity of industry professionals to modifying their processes to reduce materials usage. The idea of a formwork insert for reducing the volumes of concrete and steel required in slabs met with positive reception on a theoretical level by interviewees, and several well-grounded concerns emerged. In this section, I summarize each interview and site visit, and then present the overarching themes that emerged from the research in India. For full notes from the interviews, see Appendix A.

2.2.1 Interview & Site Visit Summaries

EMAAR is a property developer with offices around the world. While in Delhi, we met with two members of their Gurgaon office: Mr. Yogesh Bhasin, General Manager of Design & Development for EMAAR India, and Mr. Lalan Prasad Singh, Project Head. We learned about the construction methods that EMAAR India uses. All of their concrete buildings are cast in-situ; they expressed hesitance about using precast elements because regions in northern India are in seismic zones 4 or 5. Precast is not ideal for earthquake zones because of the weak joints it produces, and it is difficult to find skilled structural consultants in this region to design methods to strengthen these weak joints. They sometimes use hollow-core slabs, cast near-site. They were confident that ribbed slabs with prestressed concrete are being used in India, but EMAAR does not use this technique on its sites. They use plywood formwork with reusable aluminum structuring. According to these interviewees, about 30% of the cost of their buildings is labor. After presenting them with a 3D print of a T beam component of our optimized ribbed slab, both stated that they thought our design would be feasible to construct on-site in India with a simple formwork insert. However, they emphasized that projects and spans are always different; Bhasin stated that "in our cities, no building is typical." This could reduce the practicability of a formwork insert to shape the optimized slabs we are designing because each project would require a unique insert. Both interviewees were skeptical that the flanges of the optimized T beam were only about four centimeters thick; they cited the Indian National Building Code's fire requirements[1], and sound and vibration transfer reduction goals, and maintained that the slab should be no less than ten centimeters thick at any point (Bhasin and Singh 2019).

Indiabulls Housing Finance, a major financial conglomerate in India, has a real estate group which develops property throughout the country. At their Gurgaon office, we met with Mr. Shalabh

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[1] NBC 2016: Fire and Life Safety, Tables 20 and 21

Raizada, the Head of Operations; Mr. CM Batwara, the Senior Vice President of Planning and Design; Mr. Sachin Sharma, the Vice President of Projects and Construction; and Mr. Deepak Bansal, the Assistant Vice President of Planning and Design. These interviewees provided valuable insight into the construction sector in India. They discussed their own projects, as well as technological advances they are aware of in the construction industry. Some were well-acquainted with the properties of concrete, and they described on-site challenges, such as high setting time and weather changes. They do not use pre-stressed or post-tensioned concrete because Delhi is in a seismic zone; while these technologies can be deployed in seismic regions, they are still uncommon in India and expertise in this area is still growing. Indiabulls uses plywood and steel formwork, but they recognize the limitations of plywood. Upon seeing our model, they recognized that constructing such a shape would require more labor, but they admitted that labor is cheap so the slab would not cost much more. And they highlighted that economy is key in the success of construction-related innovations (Bansal et al. 2019).

In Mumbai, we met with two employees of the Godrej Group who specifically focus on innovation and design: Henry Skupniewicz, the Head of Fabrication Futures, and Hriday Gami, who works on the outreach programs of Godrej's Innovation and Design Centre. We discussed the construction industry in India. Mr. Skupniewicz and Mr. Gami highlighted that, in India, buildings must be designed with a high safety factor because of the potential for error by unskilled laborers. They mentioned some Mumbai affordable housing projects which use steel columns with precast concrete walls; precast is making some progress as an industry in Mumbai. They pointed out that CNC and other digital fabrication machines are definitely available in India, but on a more informal basis—you just have to "have a guy." Because of this, Mr. Skupniewicz asserted that nearly anything can be fabricated in India. Mr. Skupniewicz and Mr. Gami suggested that I look into boat-making communities to learn about their advanced wood bending techniques. In addition, we toured the Godrej Group's Mumbai campus and learned about the history of the company. Godrej began as a lock designer and manufacturer during colonization, and today has branches in appliances, furniture design, aerospace, construction, and more (Skupniewicz and Gami 2019).

CEPT University, formerly the Centre for Environmental Planning and Technology, is an architecture, technology, and design university in Ahmedabad, India. We met with five people at CEPT, all of whom are either faculty, staff, or alumni of the university. The participants were experienced with industrial and experimental concrete construction, and they were all optimistic that our optimized T-slabs are feasible. The Dean of the Faculty of Design, Anand Belhe, was enthusiastic about innovations on RC: he has a company which uses fiber reinforcing within the formwork, which then becomes permanently attached to the bottom of the beam (where tensile support is required); they are exploring the potential of fiberglass reinforced plastic (FRP) for shaping and reinforcing concrete simultaneously. The two alumni present, Mr. Nikunj Dave and Mr. Keyur Sarda, currently work at or own precast concrete companies in India. They were both optimistic that our project could be precast, but they did not mention much about whether the industry would accept it on a larger scale. Chirayu Bhatt, the Director of the Teaching and Learning Center at CEPT, was enthusiastic about the potential for MIT and CEPT to work together in the future, perhaps in the form of a 2-week design studio in Ahmedabad exploring the optimized ribbed slabs we've designed from an architectural perspective (Belhe et al. 2019). Table 2 summarizes the findings of these four interviews, specifically relating to the current research.

Table 2: Interview Results

Interview	Formwork insert possible?	Formwork insert-related concerns	Future of labor in India	Future of precast in India
EMAAR	Yes	Projects are unique and always changing; flanges are too thin	Currently 30% of building cost, and getting more expensive	Not practical in the highly seismic region of northern India
Indiabulls	Yes	Would require more labor	Cheap; did not speculate on future	Hesitant due to high seismicity
Godrej	Yes	Potential for error by unskilled laborers	N/a	Potential for fabricating anything, but not always practical
CEPT	Yes	Scaling of the manufacturing process for inserts	Focus on higher-tech and research-related jobs	Everything is possible with precast

The first two sites visited were projects of Harsh Vardhan Jain Architects. Harsh Vardhan Jain, the lead architect, gave us site tours. On the first site, a small office building, there were about fifteen laborers, both men and women, taking part in a bucket brigade to transport concrete from the driveway, down to the basement level of the building, and up a ladder to the people manually pouring the concrete (see Figure 16). Instead of using a pump, workers carried wet concrete in baskets on their heads or in wheelbarrows along this route. Mr. Jain explained that labor is so cheap that a pump is not always efficient, and also, for the basement walls that were currently being poured, it is better to pour small amounts by hand because less hydrostatic pressure is exerted on the formwork. On the second site, a single-family residential project, the foundation had also been cast and columns were being built and poured. The two sites used differing formwork: the first used high-density polyethylene (HDPE), a plastic material made of layered sheets with perpendicular ribs sandwiched between them to create corrugation. Although this material is more expensive than traditional plywood, much of the concrete will be exposed, so the owner was willing to spend extra money on the formwork to ensure a clean finish. The second site used plywood, because it is cheaper, and most of the concrete will be covered by other building materials so the finishing is not as important. Both forms were supported by aluminum structuring.

Figure 16: Many workers take part in a bucket brigade for pouring concrete (Credit: Ismail)

We had the opportunity to visit an EMAAR-India site. Mr. Amit Rana, a project manager on that site, gave us a thorough tour, discussed the construction processes, and answered our questions. EMAAR's Emerald Hills residential complex will be a neighborhood of several hundred three-story residential units. Some are sold and nearly complete, others have complete structures and are undergoing interior and exterior finishing, and others have concrete that is still being poured. We observed different stages of the various processes, and several are documented in Appendix B. Figures 17-19 show an image from each site.

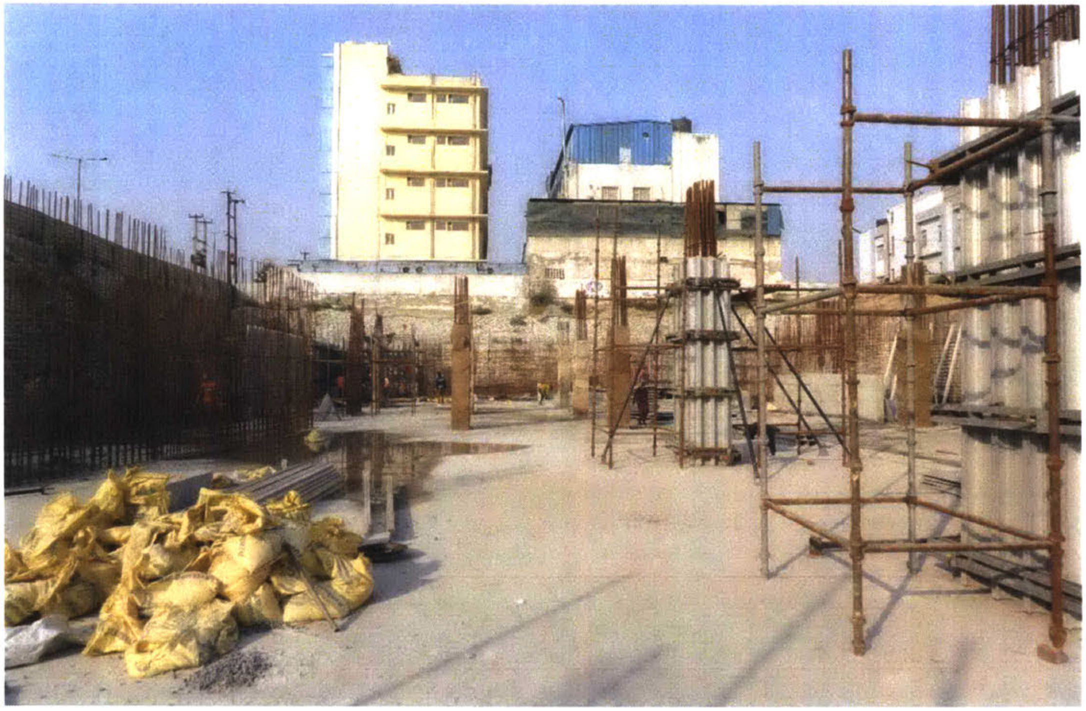


Figure 17: Site 1: Harsh Vardhan Jain Architects' small office building (Credit: Ismail)

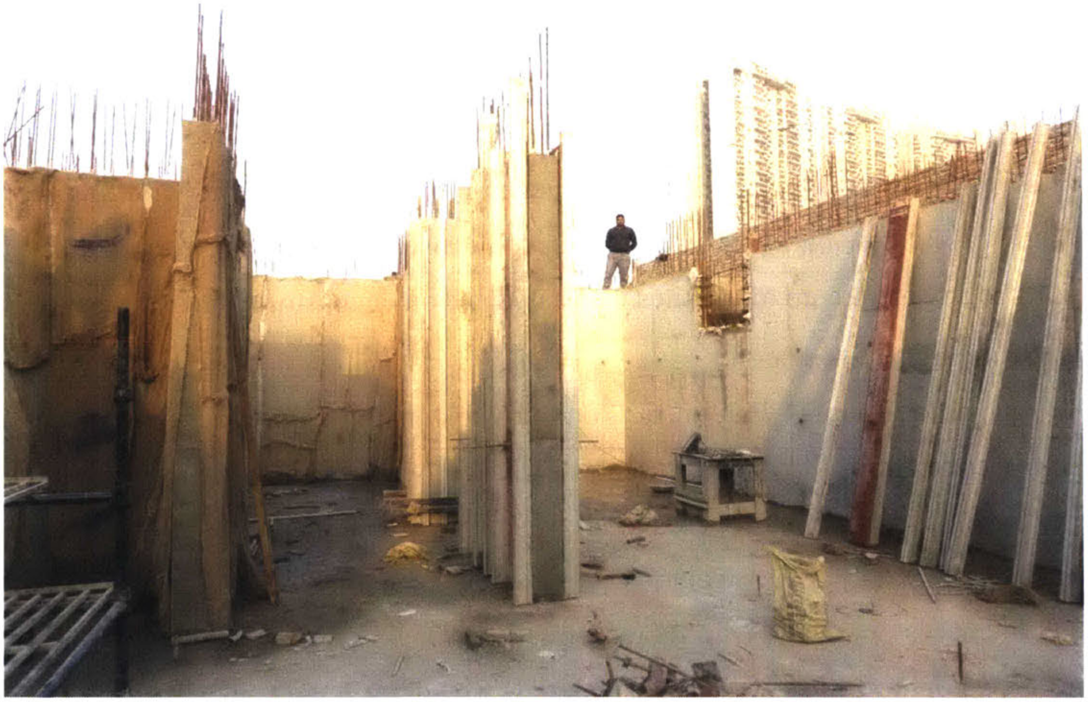


Figure 18: Site 2: Harsh Vardhan Jain Architects' residential building (Credit: Ismail)

Figure 19: Site 3: EMAAR-India's Emerald Hills residential complex (Credit: Ismail)

Outside of interviews and site visits, travelling to Delhi, Mumbai, and Ahmedabad revealed the current plethora of concrete development in India. Residential and commercial skyscrapers are blooming around each city, and previously-undeveloped fields now house enormous half-built communities. Partially-finished concrete construction projects are common, with formwork often visible. Many of the new buildings are skyscrapers, densely packed in a repetitive pattern. See Appendix B for a photo record of the sites we visited and other construction projects we observed.

2.2.2 Major Findings

Several major findings with impacts on our work emerged from these interviews and site visits. Firstly, concrete in Indian construction will likely continue to dominate the industry for many years to come. Reinforced concrete is arguably the most common and most trusted material, and the Indian market only accepts concrete and steel (Bansal et al. 2019). Thus, our project's goal of reducing the necessary concrete in RC construction is highly salient in the Indian construction sector, more than optimization of alternate materials would be.

At each interview we asked about the effects of labor cost and availability on construction processes. On each site we observed many more workers than would be present on a comparable site in the U.S., and, although we saw several machines like cement mixers on site, few were being used. It is evident that, currently, many jobs that could be performed by machines are filled by workers because of the low cost of labor. However, several of our interviewees projected that labor will get more expensive in coming years (Bhasin and Singh 2019). This could precipitate a shift to the use of machinery that is less human-intensive, and a reduction in labor. We need to keep this shift in mind when designing formwork for optimized slabs, because although labor may be cheap now, it may become more expensive than machines in the near future; our formwork should be easily adaptable to require more or less labor as is economically required.

While there is a surplus of labor today, much of this labor is untrained for construction work. The result of unskilled labor is a high number of errors and often low-quality construction (Skupniewicz and Gami 2019), (Bhasin and Singh 2019). We witnessed some issues, including cracking at the column-foundation connections. Any formwork that we design must not require a high level of expertise or assume anything about the training of the workers who will be building it. From this perspective, the simpler the better, and less variability in outcomes of a type of formwork is preferable.

We asked about the future of precast concrete in India at each interview, and received a variety of answers. Some interviewees were hesitant and pessimistic about the future of precast, especially because of the fact that projects are always changing; precast elements may become obsolete in a new iteration of the design (Bansal et al. 2019). Each project is different so it would be difficult to standardize precast elements. Also, precast buildings have weaker joints, so they are less safe in earthquake zones like Delhi (Bhasin and Singh 2019). However, in Mumbai, affordable housing is being constructed with steel columns and precast concrete walls (Skupniewicz and Gami 2019). In the Gujarat region, precast is mostly used for posts or spanning members. Much research is happening in Ahmedabad regarding advanced precast methods and uses (Belhe et al. 2019). We were assured that any shape we need could be precast, but the efficiency of this method at a smaller scale is questionable. Precast may be useful for tests or small projects with optimized slabs, but it may not make sense economically unless the project is large enough that it has a high number of repeated elements. Some of these issues with precast would pertain to a standard formwork insert as well; each project would require a different insert to shape an optimized slab, so this may not be an efficient way to fabricate optimized slabs.

In summary:

- Reinforced concrete will likely continue to dominate the construction industry in India.

- Increases in cost of labor may precipitate changes in construction practices.
- The prevalence of unskilled laborers on construction sites necessitates straightforward practices with low variability in results.
- Projections on the future of precast are mixed, and highly dependent on region.
- Digital fabrication methods are likely to become more available and cheaper than human labor in India in the near future.

Chapter 3: Structural Form Development

Upon finishing my research in India, I began to design formwork fabrication methods that may be feasible and replicable at a large scale in India. In this section, I present two of these fabrication methods, as well as the control method of digital fabrication with a CNC mill. I explain how I constructed each formwork, and then I present the results of each process. I discuss the feasibility of each in India, incorporating lessons learned from the field work presented in Chapter 2.

3.1 Methodology: Lab Fabrication

This thesis builds off of previous work by Mohamed Ismail, a graduate student in Professor Mueller's Digital Structures group at MIT (Ismail 2019). He has been working to design an algorithm in Grasshopper for Rhino that produces optimized concrete geometries. He began by focusing on simply supported beams: he reduced their volumes by adding inserts of plastic water bottles, and by shaving away unnecessary material from the sides of the beams. This algorithm developed into a reduction method for one-way slabs. As of early 2019, the algorithm produces an optimized slab geometry given certain design parameters such as span, width, and service load. The optimization process and Grasshopper optimization algorithm are in Figures 20 and 21.

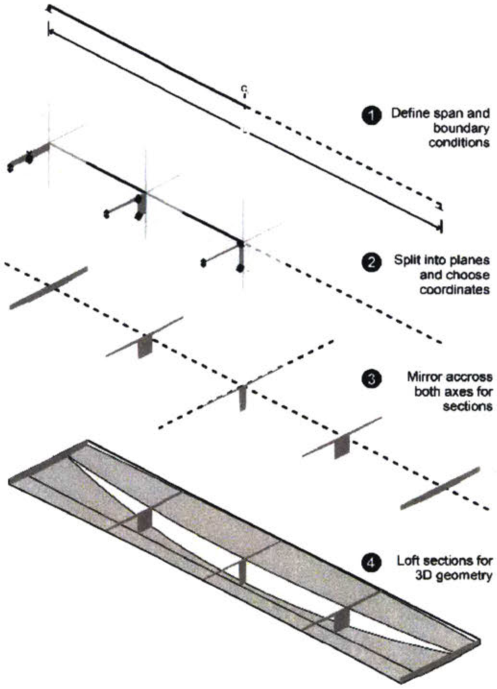


Figure 20: Optimization process (Credit: Ismail)

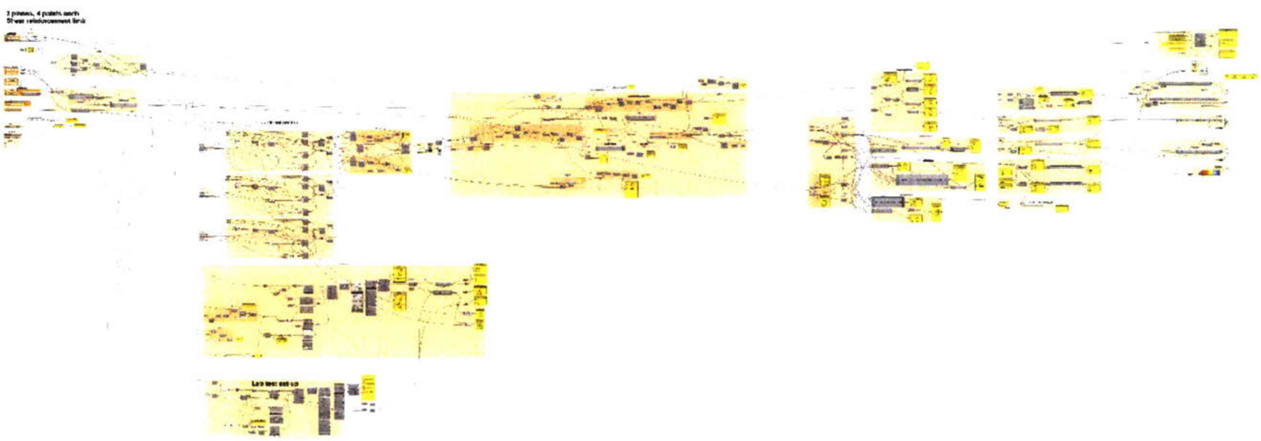


Figure 21: Grasshopper optimization algorithm (Credit: Ismail)

The T beam that I focus on in this work was produced by Ismail's algorithm for a span of 1.25 meters and a service load of 19.77 kN/m distributed across the center line of the beam, as pictured in Figure 22. 10 centimeters of material were added to each end of the beam to provide a space for attachment of the supports. This version of a ribbed slab, without the extended ends, provides a 58.1% reduction in materials usage, including a 69.6% reduction in concrete and a 1.0% reduction in steel. Shear and moment diagrams for this beam are shown in Figure 23.

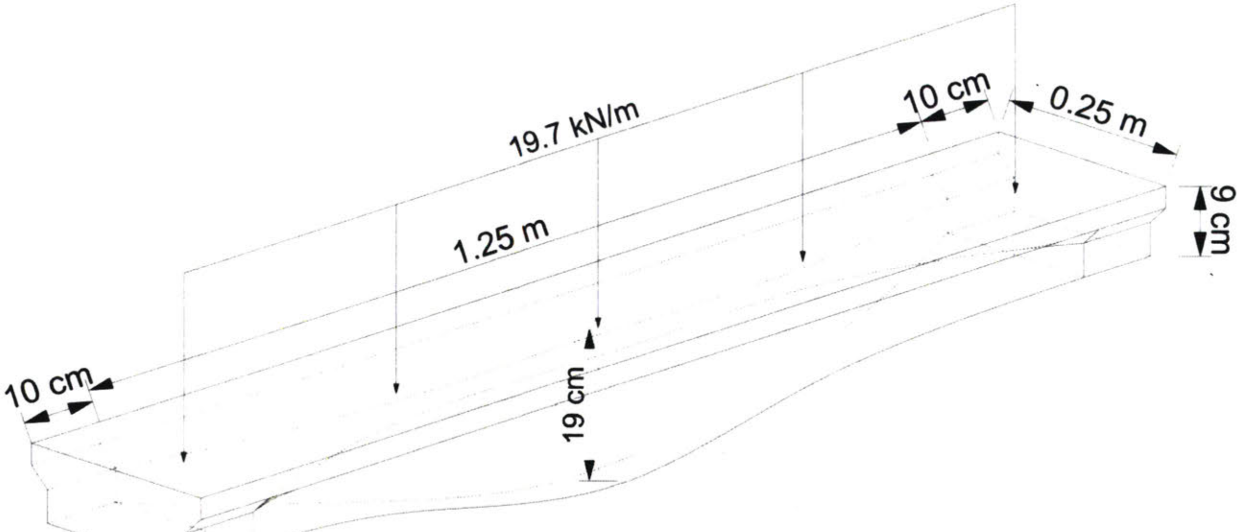


Figure 22: Optimized T beam form with dimensions and loading

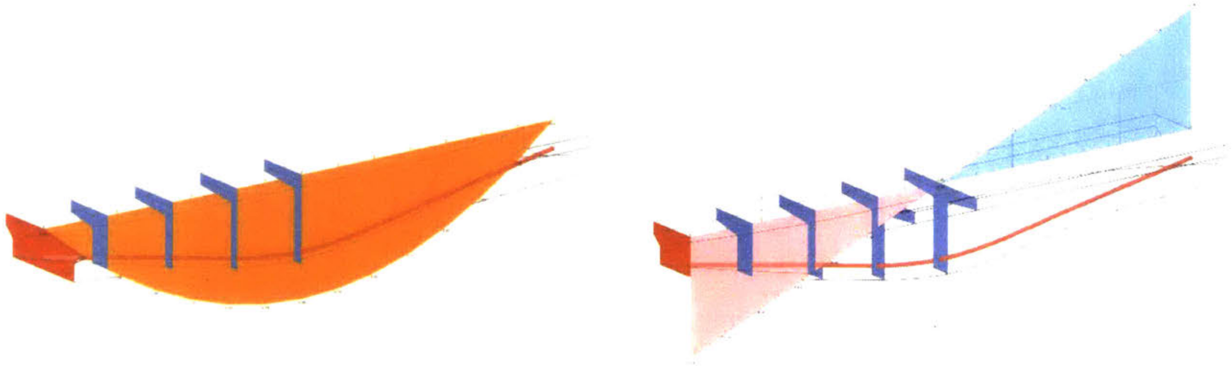


Figure 23: Moment and shear diagrams for the optimized T beam (Credit: Ismail)

I test three methods for fabricating this optimized T beam either precisely or approximately. The formwork assembly for each method is pictured in Figure 24. The first method, milling, requires the use of digital fabrication technology, while the other two do not. The following sub-sections describe each method and the reasoning and assembly involved. Additional photos of the fabrication processes can be found in Appendix C.

3.1.1 Milled Foam

To create a precise physical model of the optimized T beam, I use a CNC machine to mill extruded polystyrene (XPS) into the exact geometry. For this research, I layer three sheets of XPS, commonly known as blue foam, and adhere them with gorilla glue. Because of constraints on drill bit size, I mill the foam in several pieces. I assemble the foam inside plywood boxes that can be easily disassembled. I mill and assemble two identical formworks, in order to increase the robustness of our results. While this technique is highly dependent on digital fabrication methods that may not be available in parts of India, it is important to fabricate and test a control beam that is as close as possible to the computationally-optimized geometry.

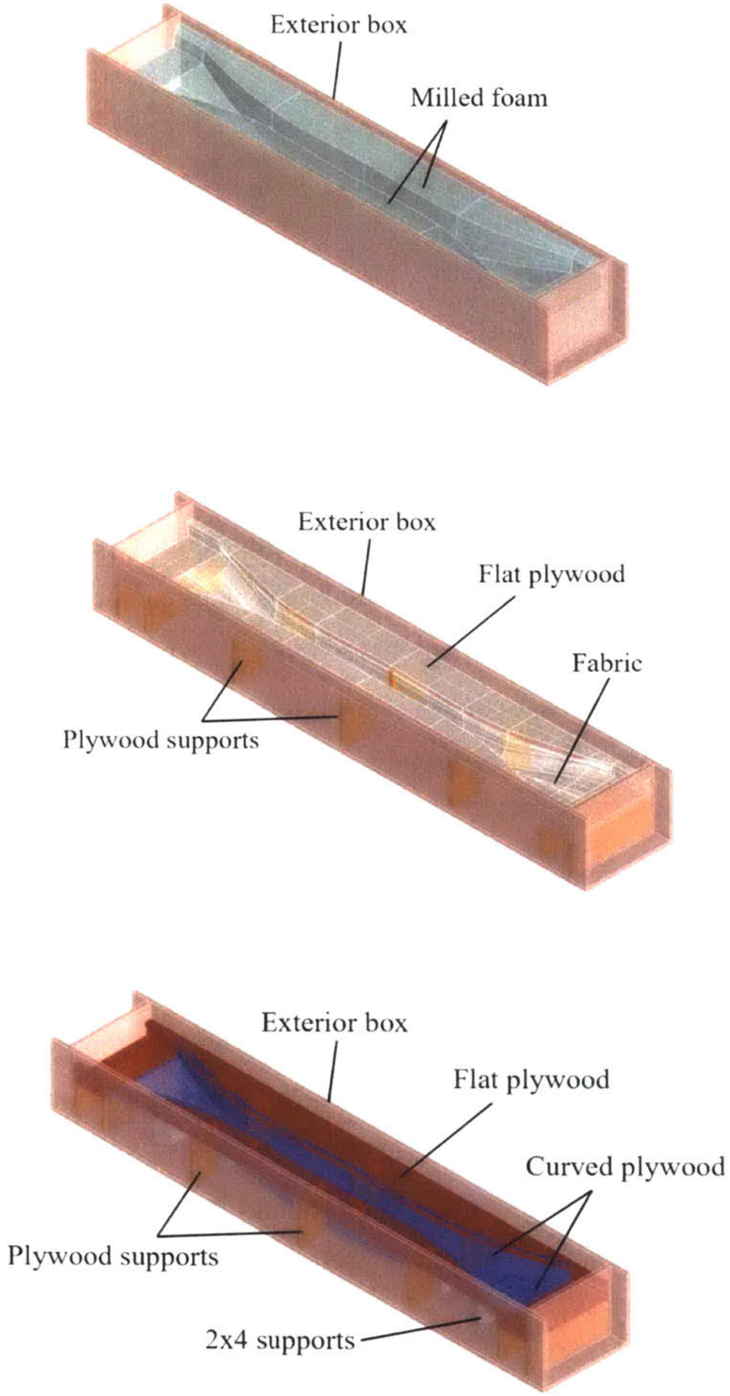


Figure 24: Formwork assemblies for milled foam, fabric, and bent wood formworks

CNC mills are powerful tools because of their ability to cut material in precise shapes and to different heights or contours. CNC stands for Computer Numerical Control, and in this thesis, CNC milling is carried out by an ONSRUD 3-axis mill using several different drill bits. In the process of CNC milling, the user imports a geometry to a load path setup software like Mastercam. Then, drill bits and tool paths are assigned to different parts of the geometry. Finally, the software exports G-code, which is then read by the CNC mill to direct it to execute the dictated cuts. A CNC mill is displayed in Figure 25.

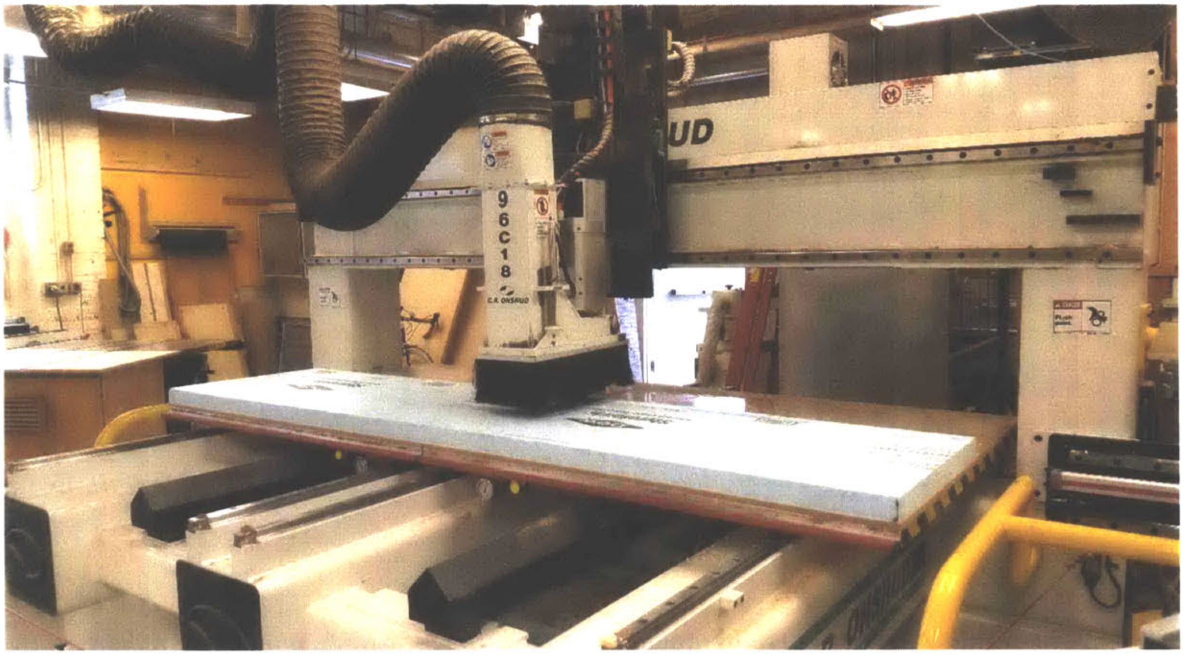


Figure 25: A common CNC mill machine milling extruded polystyrene

3.1.2 Fabric

Fabric has the potential to approximate the unusual shape of our T beam in a simple, replicable fabrication method. I use a combination of plywood and fabric to approximate the optimized, non-prismatic T beam shape. A similar methodology was used by Orr (2012) to create non-prismatic T beams that were specifically designed for fabric formwork (Orr 2012).

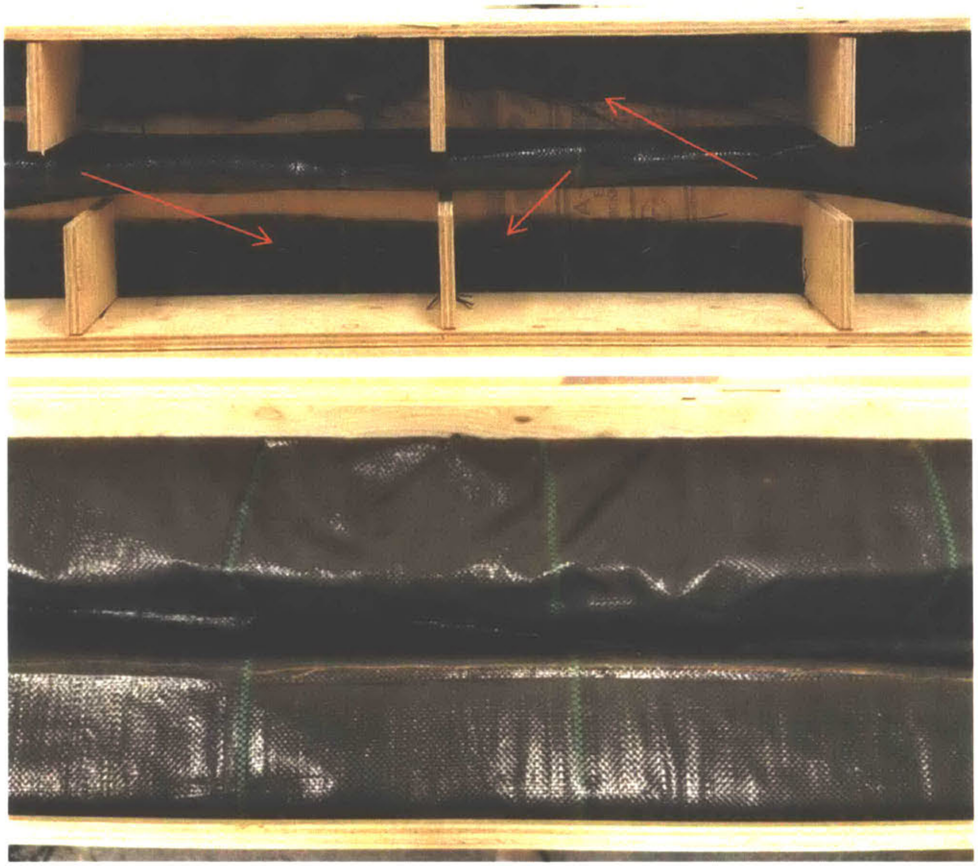


Figure 26: Fabric fabrication: (a) staples, visible from underside; (b) wrinkles in half, as seen from top

Using a similar process, I cut plywood sheets and assemble them to form flat flange undersides, supports, and an exterior box. I then attach the fabric to the flange supports using a technique described in West (2017): I wrap the fabric around the top of the plywood frame, and staple it along the underside, so the fabric is wrapped around the two flat flange undersides (see Figure 26(a)). To approximate the changing depth of the web of the T beam, I measure the width of the fabric at different points in the beam in Rhino and in reality, as shown in Figure 27.

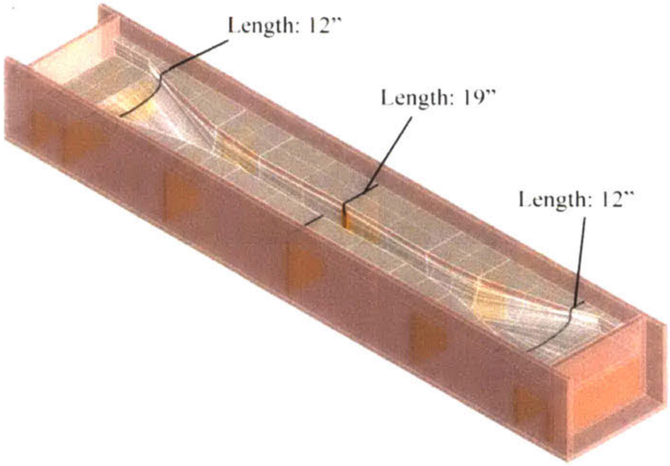


Figure 27: Fabric widths at different points

Fabric type is important. Based on research described in section 1.2.3, I decided to use a heavy woven polypropylene geotextile that is marketed as a weed barrier and soil erosion control. This fabric should not bind with the concrete, and will even eliminate the need for the application of a release agent. Ideally, this fabric-plywood composite formwork should be reusable many times, more than plywood alone or foam, because of the durability of this PPE fabric. However, the stiffness of this fabric made it difficult to lay out in the precise geometry required; some wrinkling is shown in Figure 26(b). Because of the small scale of the beam, it is likely that fabric stiffness issues were greater than they would be at full building scale, but they are nevertheless important to consider.

3.1.3 Wood Bending

As described in Chapter 1, wood bending is common in parts of India. One-dimensionally bending wood requires much less expertise than the boatbuilding described, and can be learned and performed relatively quickly. Thus, the third formwork I build is an approximation of the optimized geometry which contains no two-dimensionally curved surfaces. The process I describe below was largely informed by Chris Dewart at the MIT Architecture Shop, who has expertise in wood bending and assembly.

I use three layers of thin (⅛") plywood to create curves approximating the sides of the web of the T beam. I glue and then clamp them to an MDF (medium-density fiberboard) form that was milled on the CNC machine, as shown in Figure 28. Because the form was a simple curve, however, it could be cut with a jigsaw; I use a CNC machine to speed up the process and ensure that the curves are precise. This MDF form can be reused many times. For the bottom face, instead of creating another MDF form, I build a series of supports from a 2x4. Next, I attach two layers of ⅛" plywood that have been milled into a precise symmetrical curved shape to these supports using a nail gun, applying glue in between for lamination. After this, I assemble cut flat plywood parts and supports; the exterior plywood box; and the three curved pieces to assemble the formwork shown in Figure 24.

Figure 28: Three layers of ⅛" plywood clamped to curved MDF form

3.1.4 Rebar Layout and Casting

3/8" diameter rebar is bent and inserted along the bottom of each beam, with small 3D-printed rebar chairs supporting it to ensure 15 mm of concrete cover. A steel mesh of ⅛" diameter rods lies across the top of the T beam (beneath approximately 15 mm of concrete cover), also supported by rebar chairs. Stirrups connect the steel mesh and the rebar every 6 cm. The ideal beam created from each formwork, including the rebar, stirrups, and steel mesh, is shown in the top row of Table 4.

All four beams were cast over a period of two days. A mix of cement, sand, water, and placticizer was used for all beams. The precise ratios are displayed in Table 3. We designed for a concrete strength of 30 MPa. According to cylinder tests, the strength of each mix varied from 17.54 MPa to 36.27 MPa. This strength is the average of three cylinder tests for each mix. Harris Super X VOC general purpose reactive form release agent was applied generously to facilitate formwork removal. The beams cured for 21 days, and were load tested on Day 21. Although this does not represent the full 28-day strength of the concrete, we can safely compare our results to one another and scale them up to predict the beams' behaviors at 28 days. Chapter 4 presents the load testing setup and results, while the rest of this chapter is devoted to evaluation of the formwork fabrication methods.

Table 3: Concrete Mix Design and Strength

	Foam 1	Bent Wood	Foam 2	Fabric	Units
Cement	26.62	25.22	30.94	30.94	lbs
Sand	102.74	104.14	96.09	96.09	lbs
Water	14.37	14.37	16.71	16.71	lbs
Plasticizer	30.00	21.50	21.50	21.50	oz
1.5% sand	1.54	1.56	1.44	1.44	lbs
Total	145.27	145.29	145.18	145.18	lbs
Design Strength	30	30	30	30	MPa
Mix Strength	**21.55**	**17.54**	**36.27**	**30.13**	**MPa**

3.2 Results: Lab Fabrication

This section presents the findings from each fabrication process and compares and contrasts them, especially remarking on the reusability of each formwork after its removal two days following casting. Figure 29 displays the three types of formworks produced from this work, and Figure 30 shows the four T beams fabricated from these formworks. Several important lessons emerged from the fabrication of formworks and casting and demolding of beams, which are summarized in Table 4.

Figure 29: Milled foam, fabric, and bent wood final formworks

Figure 30: Final beams produced by, from left, milled foam formwork (2), fabric formwork, and bent wood formwork

3.2.1 Milled Foam

The milled foam formwork was intended to create the precise optimized geometry for testing, rather than to explore feasible fabrication methods for construction in India. However, in the future, CNC milling and other digital fabrication methods may become more standard in India, so this fabrication method should not be fully disregarded as infeasible. CNC machines are already becoming more common in India (Skupniewicz and Gami 2019), and this fabrication methodology could become simple there in the near future.

This formwork was removed from the concrete remarkably easily. The foam came apart from the concrete with little force, and without breaking. We expect that this formwork, although disassembled into the constituent foam pieces in the process of removal, could be reassembled relatively easily and re-used several more times, provided that a release agent is applied generously each time. The beam itself has remnants of the shape of the CNC mill's bit imprinted from the patterning of the foam, leaving a nice texturing on the surface that could make for an interesting architectural finish (see Figure 31).

Figure 31: Texturing on the surface of the milled foam beams (Credit: Yan Liu)

3.2.2 Fabric

Removing the fabric formwork was simple, and could have been simpler with an improved assembly. The fabric form peeled off from the concrete easily, as was expected. The assembly of the plywood supports on either side, pictured in Figure 32, was complicated, and disassembly was made more difficult than necessary because of screw placement. However, the assembly of these end supports could be improved with iteration and at a larger scale.

Figure 32: Complicated plywood supports made the end of each non-milled beam flat for load testing

As is visible in Figure 30, the maximum depth of the web of the fabric beam is less than the depths of the other three beams. The width of the web at the center is greater than that width in the other beams. The hydrostatic pressure of the concrete on the fabric created a wider, flatter shape than was expected. This altered shape translated into bulging around the vertical plywood supports, which force a reduction in the width of the web to the optimized width at three points. However, the bulging around these three points creates a geometry that is highly altered from the optimized geometry, and this discrepancy will likely reduce the load capacity of the beam.

As discussed in section 3.1.2, the PPE fabric had low elasticity and thus resulted in high folding. Figure 33 highlights the evidence of these wrinkles in the concrete beam. This is one limitation of using a type of fabric with such low elasticity. These wrinkles could have negative or unpredictable implications on the structural capacity of this beam. Wrinkles could be worse if less time or precision were dedicated to assembly. However, at a larger scale, wrinkles would be less of an issue because of their small size in proportion to the whole beam.

Figure 33: Evidence of wrinkles from fabric formwork

Fabric formwork assembly also required a high degree of precision, including careful cutting, measurements, and stapling. Each time such a formwork is assembled, it will be different. This variability is compounded by the fact that many different workers may contribute to formwork assembly on a single project, some of whom are unskilled in construction and/or fabric working. This variability could lead to variability in slab geometry and thus structural strength, which would be dangerous for any building.

3.2.3 Wood bending

Wood bending took the longest amount of time, but produced clean, predictable results. As is evident in Figure 29, the bent wood formwork left a hole that was covered by duct tape. These corners were complicated, but could be reworked in a later iteration to avoid the necessity for duct tape. However, this solution worked sufficiently for our purposes.

As described in section 3.1.3, I used a CNC mill to precisely cut the MDF form for the sides of the web and for the bottom plywood pieces. This made my process simpler, but the CNC machine was not required. However, the lack of a CNC machine could introduce higher variability into the curvature of the bent wood pieces. If workers are well-trained in the use of a jigsaw or handsaw, the curves are achievable without the use of digital fabrication. After assembly, the plywood formwork can be reused many times. Due to the generous application of a formwork release agent, our formwork was simple to remove, apart from the complications caused by screw placement in the flat sections at either end of the beam described in section 3.2.2.

The process of cutting and bending flat sheets of material is feasible at a larger scale, as has been proven by the work of our partner organization in India. The organization Development Alternatives in India has a branch called Technology and Action for Rural Advancement (TARA), which incubates micro-enterprises and encourages rural technologies and businesses centering around development innovations. While in Delhi, we worked with TARA to organize the fabrication of a full-scale (5 meter span) optimized T beam, pictured in Figure 34. After much discussion, the formwork of choice was rolled steel plates welded together. This introduced the constraint of one-dimensional curvature to our model, similar to the constraint imposed by the bent wood. The final beam produced by the bent wood method in this thesis has the same geometry as a beam produced by bent steel would have; one-dimensional curvature is a practical constraint to introduce, and building formwork to produce that geometry is feasible.

Figure 34: Full-scale T beam, constructed in Delhi by TARA, using rolled steel formwork (visible in photo). (Credit: Biswajit Swain)

3.2.4 Comparison and Analysis

Table 4 presents the findings from the fabrication process for the three types of beams. I analyze each formwork along different quantitative and qualitative dimensions of analysis. Appendix D further explains the cost calculations. To calculate the actual volume of each beam, I use its measured weight and assume its density to be 2400 kg/m^3. The volume reduction percentage is the percentage of material that is removed in this beam as compared with a prismatic beam of the same dimensions, whose volume is 0.069 m^3. For example, for the milled foam beam, I calculate the predicted reduction factor using the beam's volume in Rhino:

$$Volume\ reduction = 1 - \frac{0.023}{0.069} = 1 - 0.333 = 0.667$$

Beams were weighed after testing when they had cured for a full 28 days.

Table 4: Fabrication Results

	Milled Foam 	*Fabric* 	*Bent wood* 
Section			
Material(s)	Extruded polystyrene, 1/2" plywood, screws, Gorilla glue, silicone sealant	PPE fabric, 1/2" plywood, staples, screws	1/8" plywood, 1/2" plywood, wood glue, screws, MDF form, silicone sealant
Tool(s)	Clamps, bandsaw, table saw, CNC mill, driver drill	Clamps, bandsaw, table saw, staple gun, driver drill	Clamps, bandsaw, table saw, nail gun, driver drill
Time	Short	Medium	Long
Formwork weight	9.3 kg	11.5 kg	14.4 kg
Assembly difficulty	Easy	Hard	Hard
Skill required	Low	High	Medium
Disassembly difficulty	Easy	Easy	Medium
Reusable?	Yes	Yes	Yes
Formwork cost	$87	$75	$135
Beam weight	43.8 kg	56.5 kg	60.0 kg
Volume (Rhino/actual)	0.023 m^3 / 0.018 m^3	0.027 m^3 / 0.024 m^3	0.028 m^3 / 0.025 m^3
Volume reduction (Rhino/actual)	66.7% / 73.7%	60.9% / 65.2%	59.4% / 63.8%

Several findings emerge from the comparison of the tested formwork methods. The bent wood formwork was by far the heaviest of the three types, because of the high density of plywood. This could have negative implications at a larger scale on construction sites, and could complicate the construction process; if formwork is heavier, temporary shoring must be stronger. It could also be more difficult for workers to carry and assemble the formwork in-situ.

Apart from the varying costs of concrete among the three beams, the monetary cost of formwork materials varies as well. Milled foam and bent plywood have similar costs, while fabric costs about half of either. Included in these calculations is the cost of waste materials, such as the milled out portion of foam and the excess plywood that remains after cutting. On site in India, I expect the cost comparison among the three formworks to be similar: foam and plywood may be most expensive, and fabric the least expensive. However, the availability of each material varies by region in India, and thus cost will vary as well. Formwork cost should also be compared with the materials reduction achieved: bent wood costs the most and achieves the least materials reduction, so on the basis of cost alone, it appears the least desirable of the three formwork types.

Apart from digital fabrication tool requirements, skill requirements place an important limitation on the feasibility of different types of formwork. As discussed in section 3.2.2, fabric formwork requires precision and expertise to avoid wrinkling in the fabric. In section 3.2.3, I highlighted that the cutting of curves in wood and MDF could require expertise in wood cutting techniques. Even if a CNC mill is available for foam, CAD skills and the ability to apply the optimization algorithm to a specific case are required.

As discussed in Chapter 2, labor is becoming more expensive in India. This implies that it is important for fabrication methods to be easily adaptable from human to machine labor. Fabric formwork would be difficult to adapt to machine assembly. Wood, however, could feasibly be bent into precise shapes and assembled into larger formworks by machines in the near future.

3D scans of the three beams were made using a Sense 3D Scanner. With perfect technology and more time, these scans would give a better idea of the correlation between the Rhino models and the beams. This could provide a better estimate of the actual geometry, which would be helpful in later Abaqus analysis. However, due to imperfections in the meshes produced by the 3D scanner, the model geometries are incomplete.

The fabric and bent wood formworks require a slightly greater amount of concrete than the optimized beam: they provide a 65.2% and a 63.8% reduction in concrete respectively, as compared to a prismatic beam, while the optimized beam provides a 73.7% reduction. This is mostly due to the flat, and thus thicker, flanges; the optimized beam has variable depth flanges, which are difficult to achieve with either fabric or bent wood. In all cases, the actual volume was less that the Rhino volume, which translates to a greater reduction factor; this may have negative implications on the load capacity of the physical models of the beams.

The fabric beam's actual geometry was different from the predicted approximated geometry in Rhino, as discussed in section 3.2.2. However, the volumes of the two beams were similar: although the shape of the web was different, it deformed in such a way as to contain nearly the predicted amount of concrete, but be about 3 cm less deep. Clearly, this reduction in depth was compensated by a corresponding increase in width.

There are other types of formworks that are not explored in this thesis, including vacuum forming and injection molding for a reusable insert that would have the same shape as the milled foam used here. However, the two methods explored here are adaptable to different design parameters, which is important for construction in India (Bhasin and Singh 2019). Chapter 4 will present the methodology and results of load testing the four beams whose fabrication was described in this chapter.

Chapter 4: Analysis and Testing of Structural Forms

In this chapter, I present the setups and results for physical and computational load testing of variations of the optimized beam. Physical load testing is important to discover whether predicted load capacities are accurate and to validate the findings of my computational analysis. In turn, my computational testing can show how beams spanning longer systems than we are able to test at the MIT lab facilities will perform, which allows for extrapolation of the physical load testing results to a scale that is practical for construction.

This chapter is broken into three sections. First, I describe the methodology for the physical load tests. Next, I outline the process by which I used the finite element analysis software Abaqus to build and test a digital model of the optimized T beam. Finally, I present the results of testing in both the lab and the computational environments.

4.1 Methodology: Testing Setup

I test physical models of these four beams in the lab at 21-day strength and record the failure load and deflections at the center for each. We approximate a distributed load using the apparatus pictured below (Figure 35). We use a 60,000 lb. Baldwin test frame with an ADMET controller and a testing rig partially assembled by Jackson Jewett (Jewett 2018). A Linear Variable Differential Transformer, or LVDT, labelled in Figure 35, precisely measures displacement of the bottom center point of the beam. This setup is slightly different than the designed-for 19.7 kN/m distributed along the center line because of lab machine constraints. Due to the maximum shear and moment constraints displayed in Figure 23, we expect that each beam will support at least 24 kN total, or 6 kN at each evenly-spaced point. The mix designs and concrete strengths are slightly different for each beam, as presented in Table 3: they vary from 17.54 MPa to 36.27 MPa.

Several complications arose in the setup of the physical load tests. The testing for the milled foam beams went smoothly, but the other two beams required slight adjustment of the supports. The plywood supports at each end, pictured in Figure 32, deformed the support platforms slightly, especially in the fabric beam: the supports needed to be moved about 4 cm away from the center on both sides for the fabric beam, resulting in an overall span increase of 8 cm, and about 1 cm away from the center for the bent wood beam, resulting in an overall span increase of 2 cm. However, because the span of the beam is 1.25 m, this small difference is unlikely to significantly affect the behavior or load capacity of these beams.

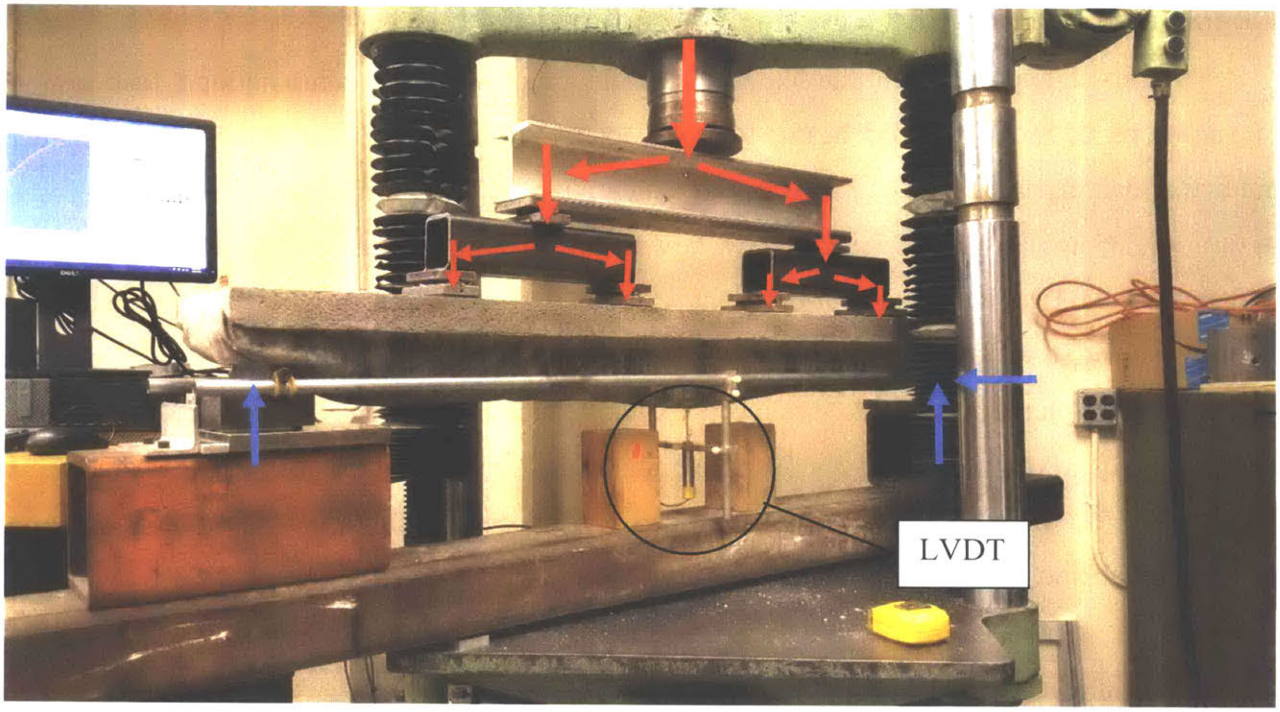


Figure 35: Load testing setup, with load path shown in red and supports in blue

4.2 Methodology: Computational Analysis

I attempt to provide a computational setup that will match the behavior of the physically-tested beams, so that future researchers can be comfortable using this computational tool to predict behavior at a scale that is infeasible for lab testing. I use Simula Abaqus/CAE 2017. Firstly, I perform tests that match exactly our testing setup: four point loads distributed evenly along the beam. I run a series of tests at different loads and measure the displacement at the center for each. I run multiple tests to confirm elastic behavior at lower loads; behavior in the linear elastic range may be more predictable than behavior at or near failure load. I predict that this load setup will most accurately match the measured displacements from physical load testing.

Secondly, I run tests with a fully distributed load across the top surface of the beam (not including the extensions for support placement). Because the beam was designed for a load of 19.7 kN along the center line, I need to calculate the pressure this represents applied over the entire tributary width:

$$19.7\frac{kN}{m} \div 0.25m = 78.8\frac{kN}{m^2} = 0.0788\frac{N}{mm^2}$$

Therefore, I apply a pressure of 0.0788 N/mm^2 to the beam, as well as various fractions of that to examine the beam's behavior in different regions. Again, I measure the deflection at the center of the beam for each load. The supports (orange) and loading conditions (yellow/purple) for both setups are shown in Figure 36.

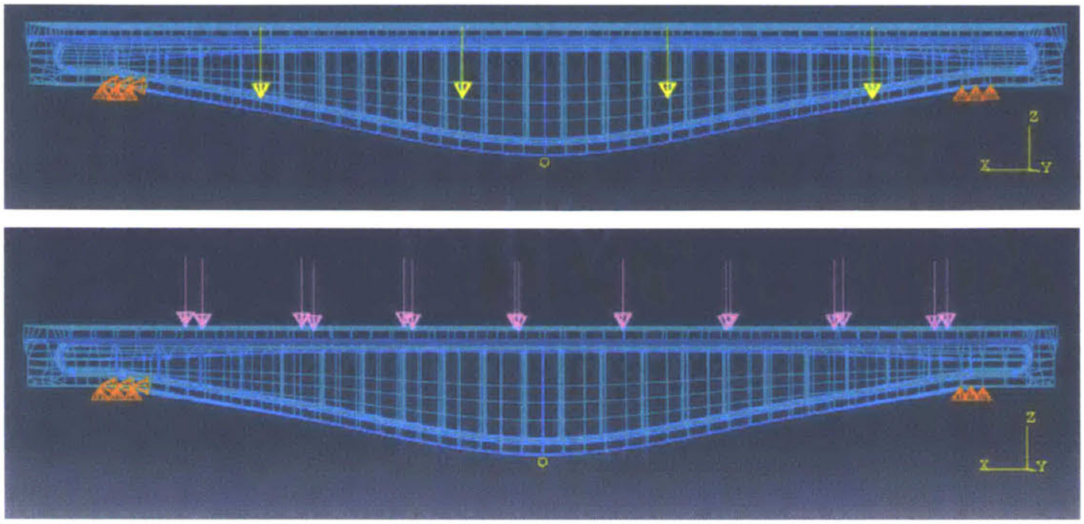


Figure 36: Support and loading conditions for (a) four point loads and (b) a distributed load

In Abaqus, I use the following parameters:

- Units:
    - Model is in millimeters
    - Loads are in Newton
- Materials:
    - Concrete
        - Elastic: Young's modulus: 25,000 MPa (N/mm^2); Poisson's ratio: 0.2
        - Concrete Damaged Plasticity:
            - Plasticity: Dilation angle: 31; Eccentricity: 0.1; fb0/fc0: 1.16; K: 0.667; Viscosity parameter: 0
            - Compressive Behavior: Yield stress: 30 MPa; Inelastic strain: 0
            - Tensile Behavior: Yield stress: 3 MPa; Cracking strain: 0
    - Steel
        - Elastic: Young's modulus: 200,000 MPa; Poisson's ratio 0.2
- Mesh: 1519 nodes; 1008 elements

- Supports: pin-roller (simply supported)
- Reinforcement: embed the three parts representing the steel rebar, steel mesh, and stirrups into the part representing the concrete

4.3 Results: Physical and Computational Testing

4.3.1 Load Testing

The results of the physical load testing of the four beams are shown in Figure 38 and summarized in Table 5. Photos of the cracked beams are in Figure 37. All load-displacement curves follow a similar shape, with evident steel yield points where the slopes change. However, the Beam 1 curve, shown in blue, sharply drops off before reaching the designed-for 24 kN load. This is likely because the mix strength is less than the designed-for 30 MPa. The four beams are made of concrete mixes with different strengths, ranging from 17.54-36.27 MPa (as stipulated in Table 3), so a difference in load capacity should be expected. The weakness in Beam 1 manifested in the immediate shear failure upon reaching the steel yield at 23.39 kN. However, Beam 2 also had a similarly weak concrete mix, and yet reached and surpassed its design capacity; perhaps it would have outperformed Beam 3 had its mix design been stronger.

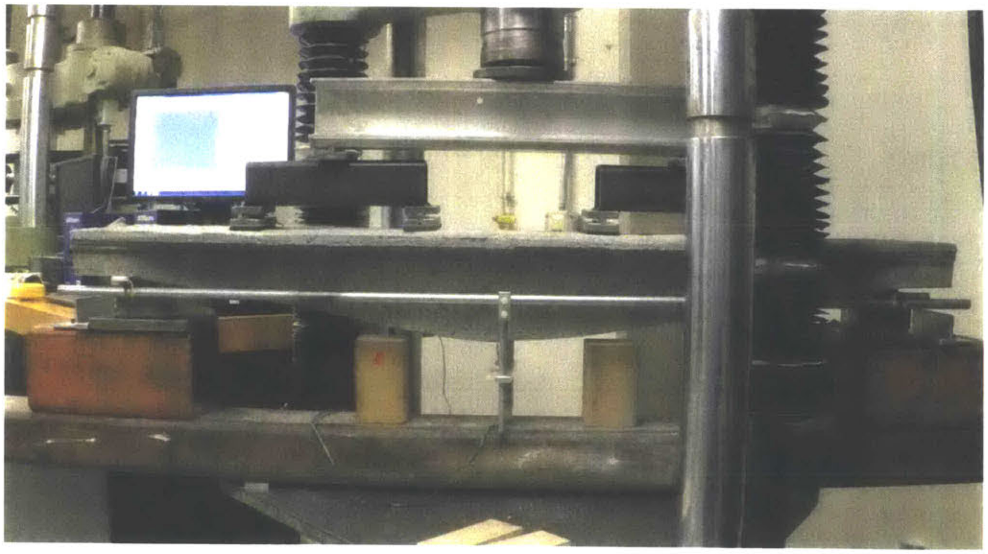


Figure 37: Deformed beams (from top: foam 1, bent wood, foam 2, fabric)

Table 5: Physical Test Results

Beam	Displacement at 24 kN (mm)	Displacement at Failure (mm)	Steel Yield (kN)
1. Foam 1	4.65*	4.65	23.39
2. Bent Wood	4.69	4.92	24.62
3. Foam 2	4.29	5.14	27.79
4. Fabric	6.43*	6.43	21.18

*Shows displacement at plastic failure, as beam did not reach 24 kN of loading

From Figure 38(a), it appears that beams 1, 2, and 3 have similar stiffnesses:

$$K_{1,2,3} \approx 5.0 \frac{kN}{mm}$$

This is logical because these three beams have a similar shape and maximum depth at the center point (19 cm). The fabric beam, while designed to have a similar depth, bulged in the center, as discussed in section 3.2.2. This translated to a web depth about 3 cm less than the web depth of the other beams, which significantly reduced the stiffness of the beam to:

$$K_4 \approx 3.3 \frac{kN}{mm}$$

In Beams 2, 3, and 4, the steel failure appears ductile: the load remains constant as deflection increases after steel yield has been reached. In Beam 3 especially, this ductile action occurs for a long time after the steel has yielded. Fluctuations along this section of the load-displacement curve are likely caused by inconsistent slippage between the steel and the concrete.

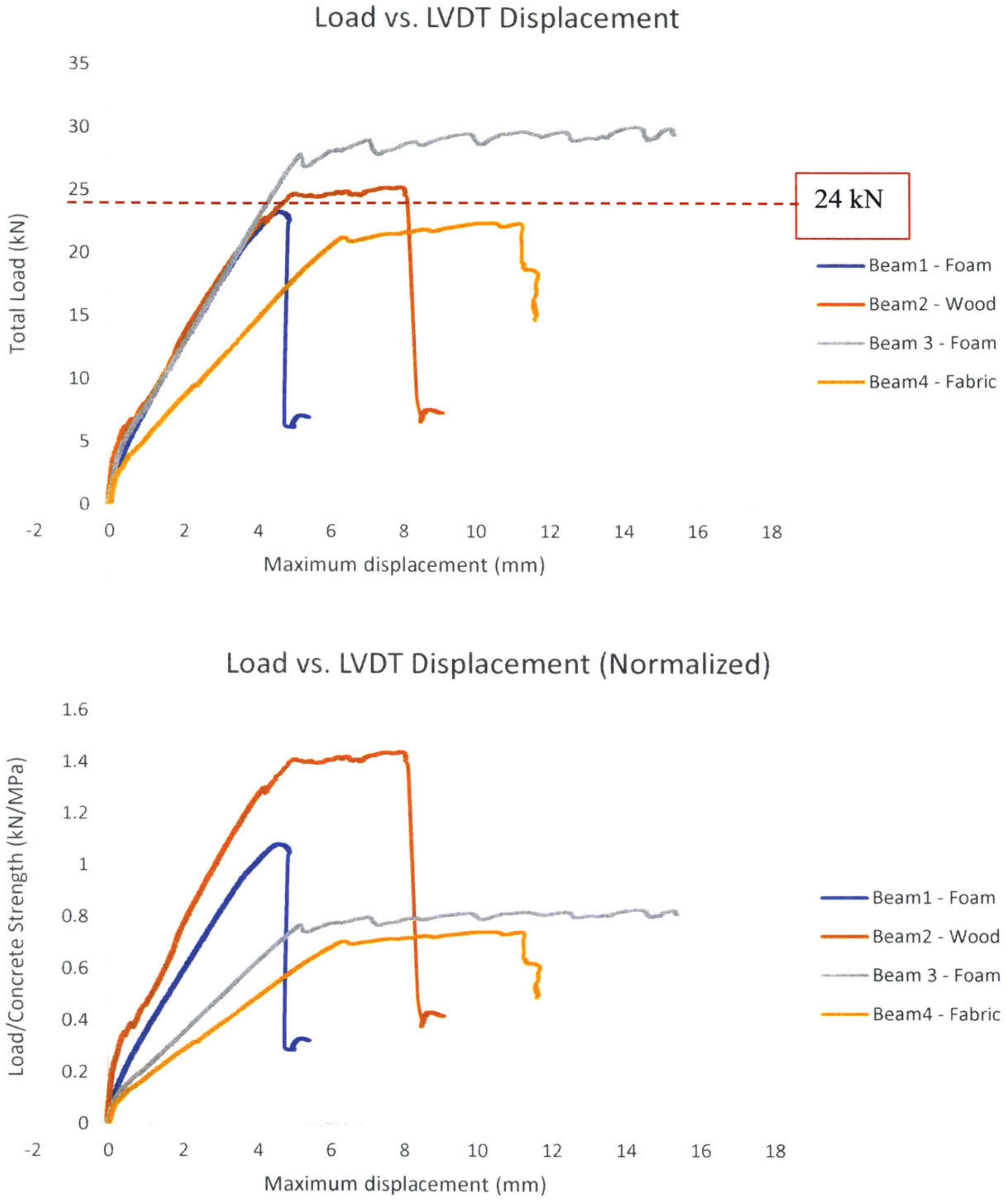


Figure 38: Physical load testing results including (a) raw data and (b) normalized

Figure 38(b) normalizes the load-displacement curves by dividing the load values for each beam by the actual concrete strength. We would expect this normalization to reduce the variation among the curves, but instead, it does the opposite: each beam performs distinctly and has a different stiffness. Normalization by concrete strength alone does not provide for an entirely accurate comparison among the beams; other factors, such as steel layout and volume, will affect performance.

Nevertheless, there are some conclusions we can draw from the normalized plot displayed in Figure 38(b). Stiffness and strength seem to correlate: the stiffest beam is also the strongest (Beam 2), while the least stiff is also the least strong (Beam 4). According to the normalized plot, Beam 2 is by far the strongest; it was both strong before normalization, and also it had a weak mix strength, thus increasing its performance in the normalized plot; the normalized plot reveals its impressive performance, despite its material strength. The two foam-formed beams perform with intermediate stiffness and strength, and in both plots, fabric is the weakest.

4.3.2 Computational Analysis

Table 6 presents the findings of the two groups of computational tests run in Abaqus, and Figure 39 summarizes the results in a chart. Highlighted in bold in Table 6 are the displacements at a load comparable to the service load examined in section 4.3.1. For both load cases, non-linear elastic behavior is exhibited: as the total applied load increases, the deflection increases in a non-linear manner which reflects the expected failure behavior of reinforced concrete. The similar behavior of the two tests suggests that our approximation of four point loads evenly distributed along the center line accurately represents a service load distributed across the entire face of the T beam.

Table 6: Computational Test Results

Load Setup	**Pressure (MPa)**	**Total Load (N)**	**Displacement at center (mm)**
4 points	-	4000	0.114
4 points	-	10000	0.337
4 points	-	16000	0.908
4 points	-	**24000**	**2.035**
Distributed over area	0.0197	6156.25	0.163
Distributed over area	0.0394	12312.5	0.447
Distributed over area	0.0591	18468.75	1.063
Distributed over area	**0.0788**	**24625**	**1.864**

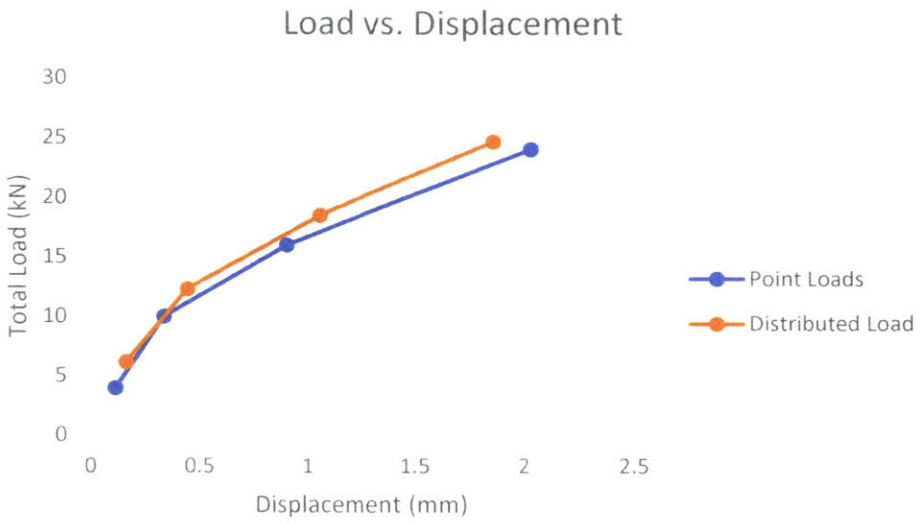
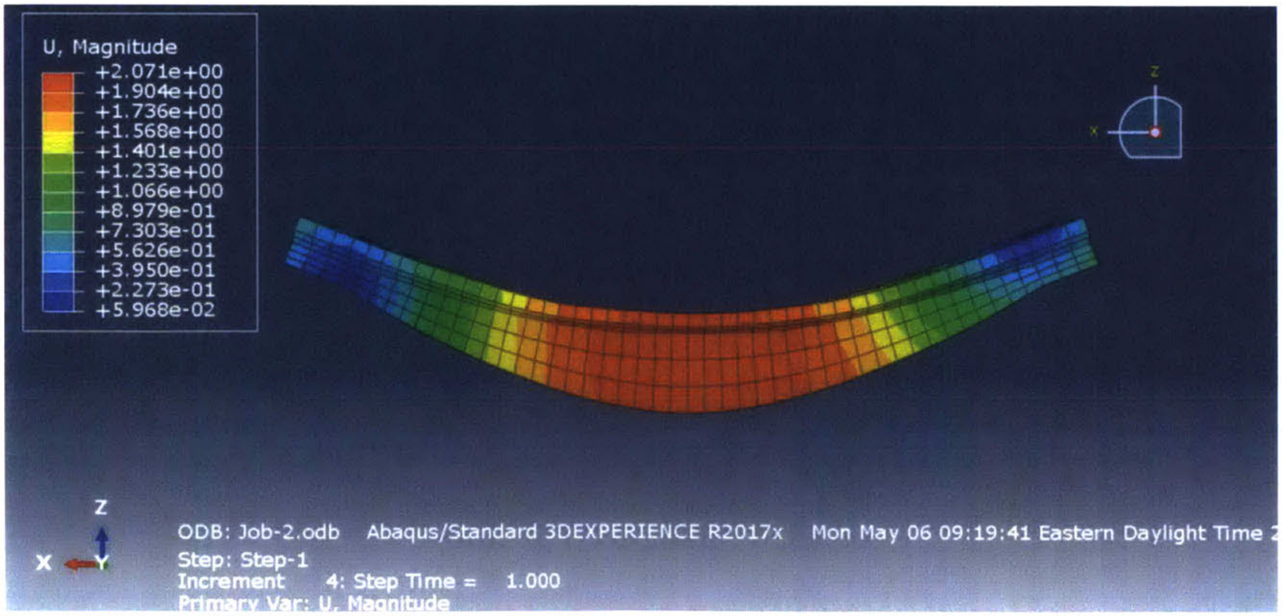


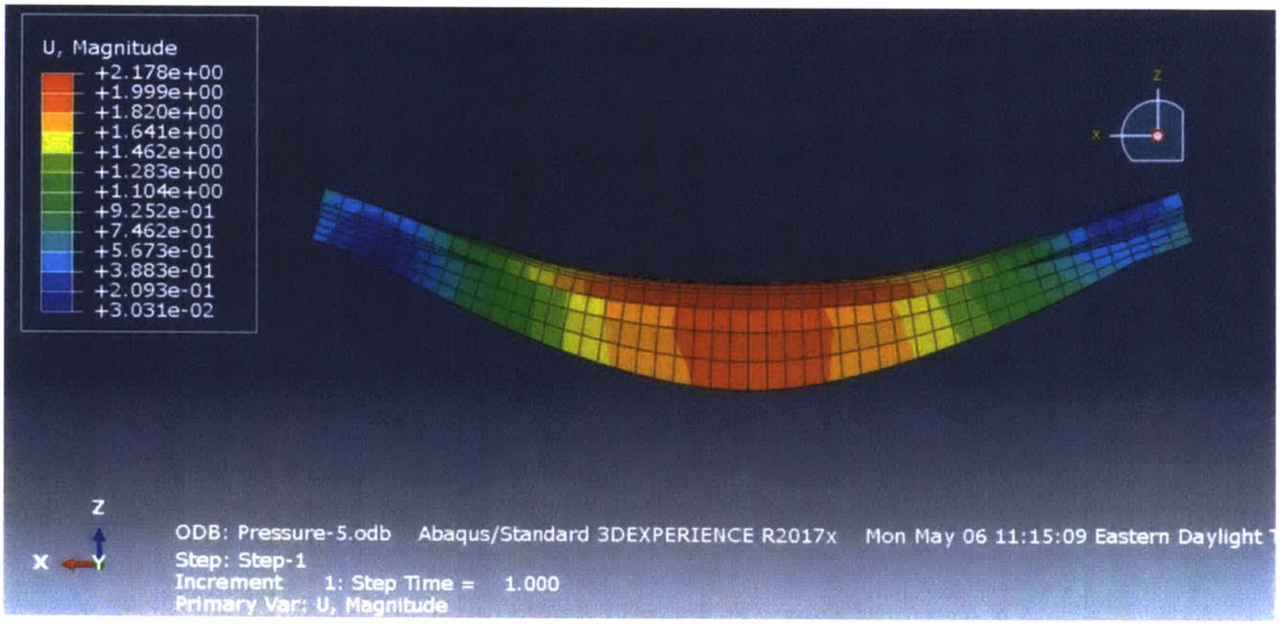
Figure 39: Abaqus loading results

Figures 40 and 41 show the deflection at different points along the beam. In both cases, we see similar behavior at the pin and roller supports. Highest deflections occur at the center of the span. There are high deflections along the flanges for the distributed load; this is the highest displacement of any point on the beam, higher than the center bottom point which has been compared thus far. However, in a real-world setting with a full-scale ribbed slab, these flanges would be supported from the sides by adjacent T beams.



```
ODB: Job-2.odb    Abaqus/Standard 3DEXPERIENCE R2017x    Mon May 06 09:19:41 Eastern Daylight Time
Step: Step-1
Increment     4: Step Time =    1.000
Primary Var: U, Magnitude
```

Figure 40: Deflection of the control beam under four point loads of 6 kN each



ODB: Pressure-5.odb Abaqus/Standard 3DEXPERIENCE R2017x Mon May 06 11:15:09 Eastern Daylight
Step: Step-1
Increment 1: Step Time = 1.000
Primary Var: U, Magnitude

Figure 41: Deflection of the control beam under a distributed load of 0.0788 MPa

4.3.3 Overlap and Differences

The magnitudes of the deflections, displayed in the fourth column of Table 6, differ from the deflection magnitudes found in physical load testing. Abaqus-predicted deflections are about one-third to one-half of the physically-tested deflections, as presented in Figure 42. However, in Abaqus, I only study the behavior of the optimized beam, whose physical model was created by milling foam. Correlation between the physical and computational models for the other beam geometries could differ. There could also be discrepancies in the material model used in Abaqus and the actual reinforced concrete used in the physical tests.

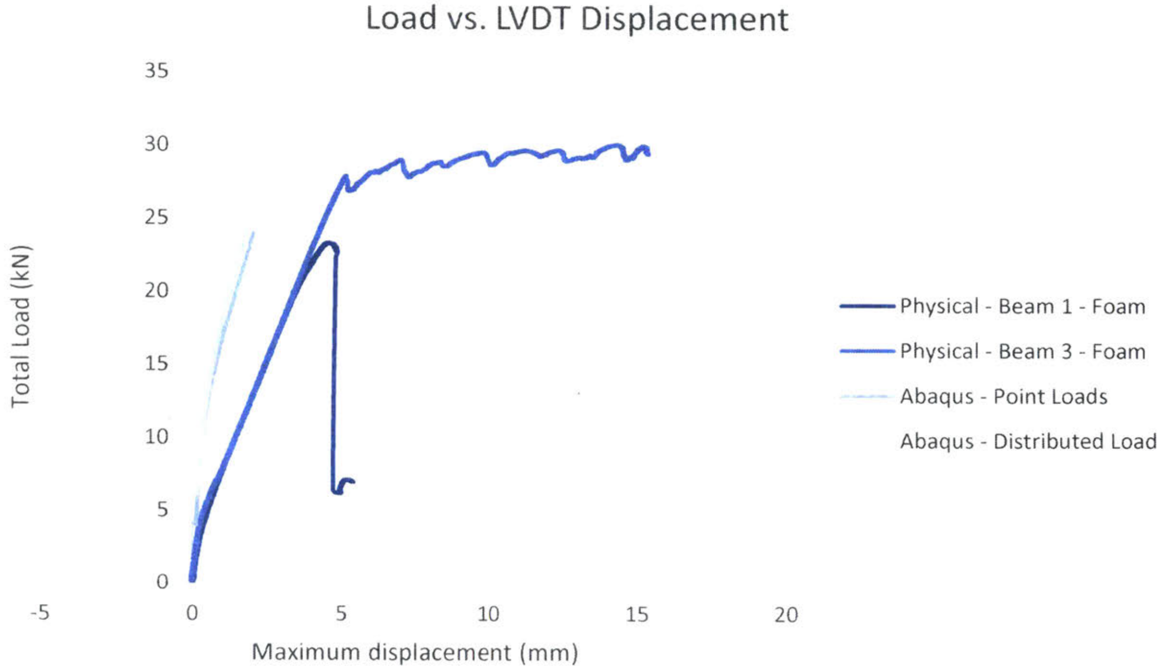


Figure 42: Deflections from both physical and computational models of the optimized beams

Apart from this disparity between the physical and computational models, an important caveat to this work must be made: due to the constraints of our testing facility, the largest T beam tested spanned only 1.25 m. Beams at a larger scale may perform differently, and the correlation between the two models may change at different scales. Additionally, the presence of adjacent T beams, forming a slab, may change their behavior in both models.

This work has shown an imperfect match between the tested Abaqus model and the physically-tested beams. A variety of factors could contribute to this disparity, including material property specifications within Abaqus, Abaqus meshing imperfections, and casting imperfections (both in the concrete and in the steel mesh, stirrups, and rebar assembly and placement). Because both are highly simplified models of real-world conditions with unidirectional loading, further work is needed to accurately confirm the safety of a similar optimized ribbed RC floor slab system. In Chapter 5, I summarize the conclusions of this thesis and offer several specific paths for future work.

Chapter 5: Discussion and Conclusions

5.1 Summary of Contributions

This thesis has examined the potential for constructing an optimized reinforced concrete slab in the Indian construction context. Chapter 2 presented country-specific work, including interviews and site visits, which led to the assembly of a list of relevant factors that must be accounted for when designing for the construction industry in India. Chapter 3 described the process of building formworks using three different methods, including milled foam, bent wood, and fabric. Chapter 4 outlined the process and results of load testing these beams, as well as attempting to confirm the measured deflections for the milled foam beam using Abaqus.

I discover that, although assembling a formwork out of bent wood that approximates the optimized form may be challenging, such a formwork produces a strong, predictable beam that supports loads as well as the optimized beam. Although the volume reduction factor for this beam is less than that for the optimized beam, a 63.8% reduction is still significant. Additionally, the bending of a flat material is feasible on the ground in India: our partners at TARA suggested this technique with rolled steel to make the full-scale model (see section 3.2.3). Although this formwork method is expensive and heavy, it provides a feasible, digital-fabrication-free method for constructing beams that incorporates most of the elements and materials savings of the optimized beam.

Fabric formwork provides a cheaper and lighter but less accurate method for approximating the optimized beam. An important caveat to the fabric formwork approach is that, while materially efficient, the technical complexities of its assembly may not be suited to India's unskilled labor force. Orr (2012) suggests that fabric-formed elements are cast on-site at ground level and then lifted into place (Orr 2012). This, however, requires skilled labor on-site, a reality which may be absent on Indian construction sites. However, with practice and repetition, fabric may provide a cheap alternative to milled foam or a similarly-shaped plastic insert.

5.2 Potential Impact

I have shown that nearly-optimized beams created without the use of digital fabrication technology can support loads similar to those supported by traditional prismatic beams while reducing the volume of material used by up to 65%. This could have a powerful impact on the affordable housing industry in India, and, more broadly, on the reinforced concrete industry across the developing world. Because labor and materials costs are so drastically different in LEDCs as compared with MEDCs, there is room for labor-intensive material reduction techniques like those presented in this thesis. This market shift could increase the number of affordable homes that are constructed by reducing the cost of each, thus providing more families with safe homes.

The materials reduction provided by this work will not only affect the monetary cost of construction, but will also reduce the carbon footprint of each home. Less concrete and steel will be required, which means that materials transportation costs will be lower. Along all steps of the supply chain, lower carbon emissions will be produced.

5.3 Limitations and Future Work

The small scale of the beams tested in this project limits the applicability of our results to full-scale construction scenarios. We, in partnership with TARA, are building and testing a full-scale model of an optimized T beam created with one-dimensionally curved steel (see section 3.2.3), which may support the findings of this thesis regarding failure mode and load. However, more testing at this scale is necessary to confirm our findings and ensure safety and predictability when applied to full-scale construction projects.

As described in section 4.3.3, in this thesis, computational analysis was limited to the optimized beam geometry. This was due to time constraints and modelling discrepancies between Rhino models and physical models. In future work, more Abaqus models should be constructed to more thoroughly examine the correlation between these models and physical beams of different geometries. This could provide a means of predicting deflections of beams of larger spans without having to construct each one, although as emphasized in the previous paragraph, physical testing at a larger scale is irreplaceable to a certain extent.

It was expressed by several interviewees that seismicity is a major concern for construction, especially in northern India. In this work, I focused on unidirectional loading conditions; I did not study the performance of the optimized T beams under seismic loads. If these beam geometries are to be applied in northern India, vigorous testing under simulated seismic conditions is crucial to ensure safety. If they are precast, especially, their connections with other elements must be able to withstand seismic loads.

5.4 Concluding Remarks

There is potential for the reimagining of the concrete construction process in India without major changes to a well-established industry. This thesis has shown that optimized T beams can be approximated without the use of digital fabrication technology; methods using common materials in formwork can produce T beams with high materials reduction factors and strengths comparable to those of a fully-optimized beam. Bent wood provides the most promising formwork method of the three studied in this thesis for application in India, but it is an imperfect solution. With further research and testing, optimized slabs incorporating these fabrication methods could transform construction methods for the ubiquitous RC elements across India.

Appendix A: Interview Notes

EMAAR-India, Gurgaon - 9 January 2019
Yogesh Bhasin, GM - Design & Development
Lalan Prasad Singh, Project Head
Connection provided by: Anand Bishnoi and his contact Balmukund Singh (Head—Business HR, EMAAR-India)

Notes:

- Using =< 25% fly ash -- lots of concrete structures
- EMAAR has architects, engineers (decide type of structure [material]), designers
- Share details with CMP dept
  - They hire different types of contractors (A/BC)
  - Then: G+2 (low-rise buildings) give drawings and build up (sequencing)
- 3 agencies:
  - structural/civil
  - MP (mechanical/plumbing)
  - Electrical
- Usually column/slab systems
- Cast in situ + blocks (fly ash)/brick(banned in India)
  - Prefer AC blocks (assuming they meant autoclaved aerated concrete, AAC)
- Zone 4/5 seismic--precast not good for earthquake zones because of weak joints → shorter structures (max 50/60 stories)
- Detailing critical (rebar) → high cost in joints
- BuroHappold
- Use hollow-core slabs -- cast near-site
- Min 75 mm topping slab (Indian code)
- Not much precast in Delhi
- Ribbed slabs with prestressed concrete already exist (unsure if they're popular in India)
- Using plywood formwork with aluminum structuring -- cost a little higher, but faster
- Need high quality--have lots of quality checks
- Consume more here--go more vertical
- Labor is more costly here in Delhi -- about 30% of cost of building
  - Getting more expensive
- Don't do "typical" buildings
- Yes they build affordable housing--13-14 stories to save on structural costs; repetition of same design
  - Apartments a bit smaller, cheaper
  - Mumbai--very small, 350 ft^2, b/c land so costly
  - Land cost depends on locality
- This research has happened already, but not common here
- Formwork design
- Temperature variation (hot)
- Easily reusable
- Need to sustain 2-hr fire requirement (1-hr is minimum by law)
- Also sound barrier and excitation (vibration not transfer between floors)
  - At least 100 mm thick to avoid vibration transfer

- Here, more manpower and less technical expertise
- Precast -- only better for repeated buildings
  - Also, hard for seismic zoning
- Call to do site visit
- 40-50 MPa (min 25-30) for floor slab concrete

Indiabulls, Gurgaon - 11 January 2019
Deepak Bansal, Assistant Vice President - Construction
CM Batwara, Senior Vice President - Planning & Design
Shalabh Raizada, Head - Operations
Sachin Sharma, Vice President - Projects & Construction
Connection provided by: Anand Bishnoi and his contact Ashok Kumar Bishnoi (Senior Vice President, Indiabulls)

Notes:

- Deepak—mostly manages the concrete; workability and strength
  - Major challenges: slump; setting time; weather changes
- 2-way slabs become one-way; more rebar needed
  - 2-way preferred in India
  - We should try 2-way ribbed slabs
- Waffle slabs—not much expertise here
- Don't use pre-stressed or post-tensioned conc. because it (Delhi) is a seismic zone
- Variance in construction
- We should use polystyrene—cheap material—for formwork inserts—very feasible
- Precast hasn't taken off
  - Because projects change as they are built (so precast pieces wouldn't make sense)
- Homex—company from Mexico, affordable housing
- They use plywood and steel formwork
  - Plywood has its limitations
- 2 problems:
  - Hollows within slab—how to insert hollows? Air?
  - Think beyond linear behavior of steel—can it be distributed in other directions?
    - Small space frames
  - Durability of concrete—less than expected
    - Low-density/porous
    - Designed only for 50 years
- Ours would take more labor, but labor is cheap so not much more cost (that was their reasoning, before we pointed that out)
- Reinforcement is bent on-site
- Here (where land isn't so expensive) (Gurgaon, outside of Delhi), have enough space on-site to work
- *Must be economical*
- Concrete is seen as strongest material
- 3d woven fabric—of polystyrene (experiments using this to replace steel mesh)(he showed us this outside, on the seat of his motorcycle—it's just the mesh that the seat cover is made out of)

- Market only accepts concrete and steel
- No maintenance

Godrej Properties, Mumbai - 14 January 2019
Henry Skupniewicz, Head of Fabrication Futures, Innovation and Design Centre
Hriday Gami, Innovation and Design Centre
Connection provided by: MIT Professor Caitlin Mueller

Notes:

- Sometimes use coconut or mango wood for formwork—very hard, but also have sap
- Dome: outer shell of dry material (removable), triangle of mango wood, and bamboo struts
- Need high safety factor because of potential for error by unskilled laborers
- Hriday: only ½ cost of building is construction—other half is interiors and fittings
- Mumbai affordable housing steel columns with precast conc. walls
- CNC machines are definitely available, but just in back alleys (have to "have a guy")
- Can fabricate pretty much anything—just don't specify methods. It will get done – Henry
- Beypore and other boat-making communities
    - Should look into them—can achieve 2-dim curves
    - https://en.wikipedia.org/wiki/Uru_(boat) – "secrecy that shrouds the technology"
- Joseph Allenstein – architect of buildings here
- Jaggery (sugar) + sand casting (making molds)

CEPT University, Ahmedabad - 16 January 2019
Anand Belhe, CEPT, Dean, Faculty of Design
Chirayu Bhatt, CEPT, Director, Teaching and Learning Center
Nikunj Dave, Managing Director, Aarya Precast
Keyur Sarda, Kesarjan Building Centre Pvt. Ltd. Precast
Paresh Shah, CEPT, Dean & Professor, Faculty of Technology

Notes:

- Kesarjan: recycling of material: product of the concrete (not mass production)
- Nikunj: precast; focus on reinforcing
- Anand: Polymer concrete (not cement); dust on roads that causes pollution-->use as a filler; fiberglass waste
    - Polymer concrete channel (in roads)
    - Forms: how to not need thousands of steel forms; designed new fiberglass mold for polymer concrete channel-->very low-tech to cast--fiber form not reusable; acts like reinforcement (tensile) FRP
        - Formwork from pultrusion
- Construction professor: rammed earth, bamboo
    - Field work: independent construction variable
    - Precast in Gujarat: usually for posts or spanning members--sp. for rural areas
    - Joint
- Precast is feasible-->use permanent formwork (like FRP) or high-strength concrete

    - Shape is feasible in small companies
    - Sell permanent molds for customers to cast on-site
        - Curvature 2d--need FRP (created by making a permanent mold)
    - Lost formwork (Nikunj)
    - Small scale
    - Reducing raw material necessary (raised cost of lost formwork is countered by less concrete necessary)
- Utilizing sag of concrete (flexible formwork)
- Lighter, so lower seismic effects
    - Modular slabs on beams here survived earthquake (because of expansion/contraction)
        - Boys + Girls Hostel block (GU@NIT)
- CEPT offers 1-2 week summer/winter school--possible collaboration for teaching about this formwork and digital design process
- CEPT-MIT Teaching and Learning Lab connection
- Scaling of our project? Need to pick a scale for our beams--then experiment, and then find a size and replicate
- Possibly using this in architecture classes
- Nikunj:
    - Not using hollow-core slabs because of India's contracts system
        - Not exploring because it's a long process
    - Future work: explore improving materials themselves

Appendix B: Site Visits Photo Journal

This section presents several photos from each site visited, as well as miscellaneous photos of construction in and around Delhi, Mumbai, and Ahmedabad.

Site 1

The first site we visited, a small office building being constructed by Harsh Vardhan's firm Harsh Vardhan Jain Architects, is in the process of having its foundation poured. *Photo: Mohamed Ismail*

These photos show the aluminum structuring and HDPE formwork that replaced plywood, to create smooth exposed-concrete surfaces. Although HDPE is more expensive, it also produces much cleaner surfaces, something that the owner of this building chose to invest in. *Photo: Mohamed Ismail*

Concrete is mixed at the top of this hill, near the site entrance, and then shoveled into this chute. At the bottom, a wheelbarrow collects the concrete and then a worker wheels it to the part of the site where it is needed. *Photo: Mohamed Ismail*

The end of the concrete-pouring bucket brigade: workers carry concrete on their heads and then lift it up to the person at the top of the ladder, who slowly and carefully pours it into the formwork. *Photo: Mohamed Ismail*

The people at the top of the scaffolding are pouring concrete into the formwork. Two hard hats are visible, but note that the majority of workers are not wearing them. *Photo: Abigail Anderson*

Site 2

The second site, again by Harsh Vardhan Jain Architects, is a smaller residential project. Plywood formwork (red) and aluminum formwork structuring (silver) are visible. Workers on this site were resting (top). *Photo: Mohamed Ismail*

Burlap covers the concrete walls as they cure to reduce moisture loss and cracking. *Photo: Mohamed Ismail*

Harsh Vardhan Jain, pictured here, is the lead architect on these two projects. *Photo credit: Mohamed Ismail*

This site uses aluminum structuring that is similar to Site 1's, but the material touching the concrete itself is plywood instead of HDPE. Red sandstone, colored gray here from the concrete, is used along the outside of the foundation as waterproofing. This material would be expensive elsewhere in the world, but in this area, it is more common. Its porosity makes it a good waterproofing material. *Photo: Mohamed Ismail*

Site 3

At EMAAR's Emerald Hills site, we saw large-scale residential construction at several stages of the construction process. In this part of the site, still in the early stages of construction, columns are being cast. Rebar and stirrups are visible on the right, and a completed ground-level column is visible on the left. In the background on the left is a row of nearly-completed homes that are part of the same site. *Photo: Mohamed Ismail*

Concrete slab construction with shoring supporting second-level floor slab formwork. *Photo: Mohamed Ismail*

The formwork patterns used for pouring the first-level floor slabs are visible on their undersides. Plywood of various sizes is evident. *Photo: Abigail Anderson*

Staircases are cast concrete diagonal slabs with plastered-over bricks making up the stairs. *Photo: Mohamed Ismail*

On the left of the photo is a row of houses with nearly-complete facades. The type of bricks that lie under the plastered and painted facades are shown on the right of the photo. *Photo: Mohamed Ismail*

The exterior facade in the process of drying, with scaffolding for workers still attached. *Photo: Mohamed Ismail*


This street is nearly complete. *Photo: Abigail Anderson*


These luxury apartments are nearly ready for move-in, and many are already sold to eager clients. *Photo: Mohamed Ismail*

Construction Around India

Tower blocks under construction in Delhi. Bricks, likely fly ash, compose the exterior walls on lower stories. *Photo: Abigail Anderson*

Smaller-scale construction projects are also common. This building uses a different type of brick for its exterior facades between concrete slabs and columns. *Photo: Mohamed Ismail*

Massive tower cranes and thirty-story scaffolding support the construction of these reinforced concrete buildings. Note the several bridges between towers, and the thick smog present in many major Indian cities. *Photo: Mohamed Ismail*

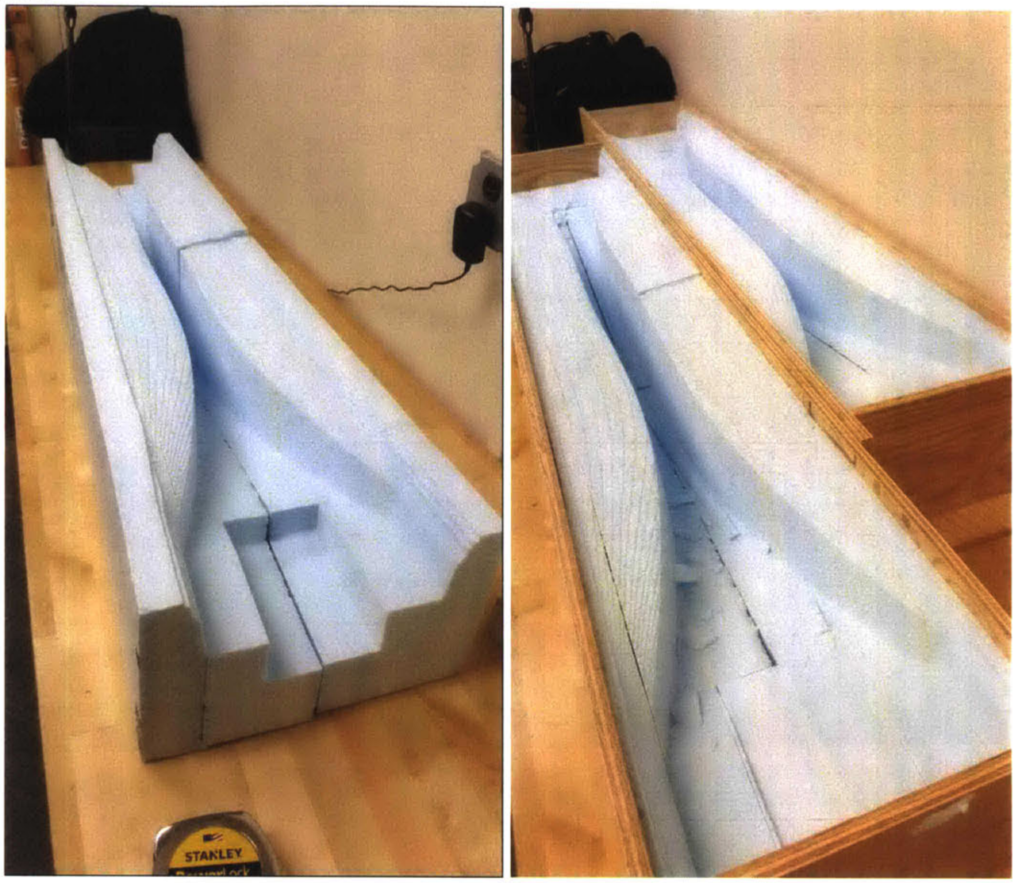
New mixed-use complexes are springing up all over Delhi and Gurgaon. *Photo: Mohamed Ismail*

Many of the major construction projects relate to public transit. *Photo: Mohamed Ismail*

Appendix C: Fabrication Process Photos

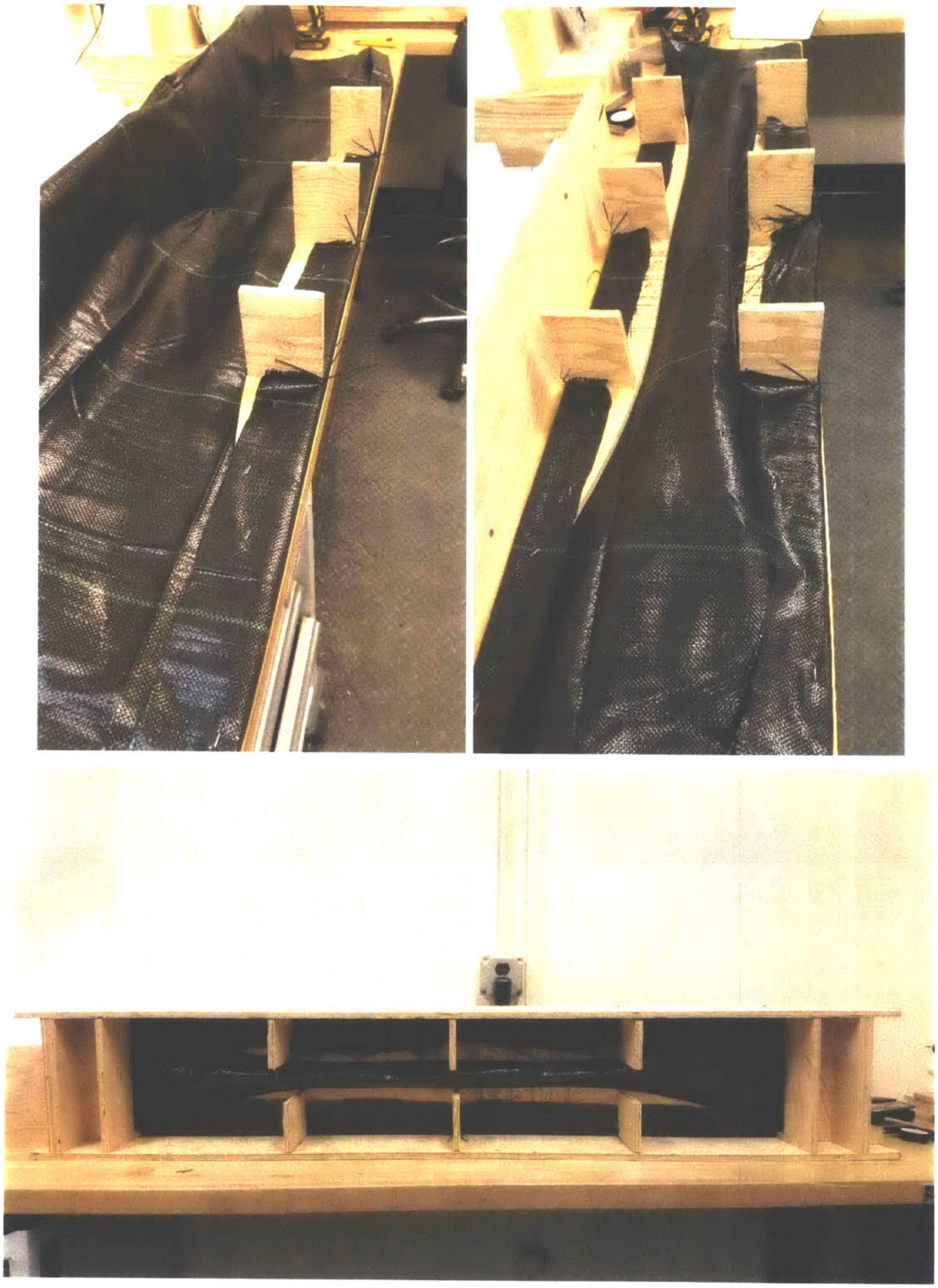
This appendix includes photos of each step in the process of fabricating the different formworks, including milled foam, fabric, and bent wood.

Milled Foam

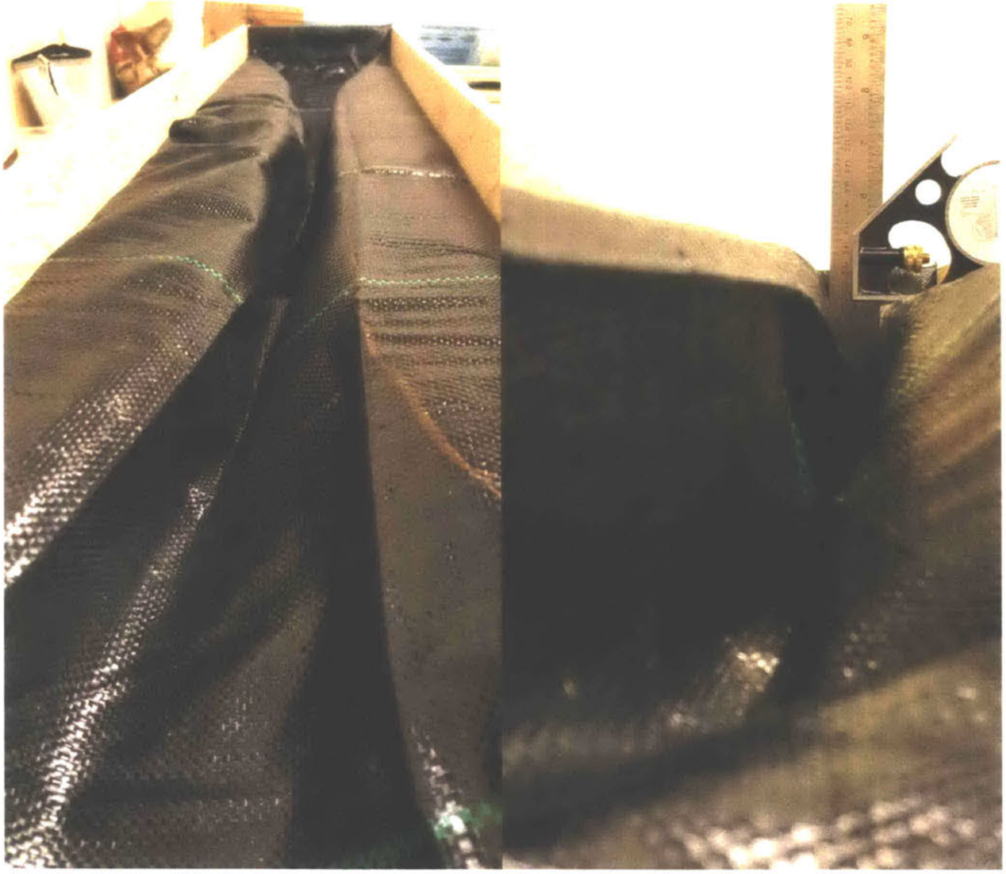


Foam was milled in blocks and then screwed into exterior plywood boxes.

Fabric

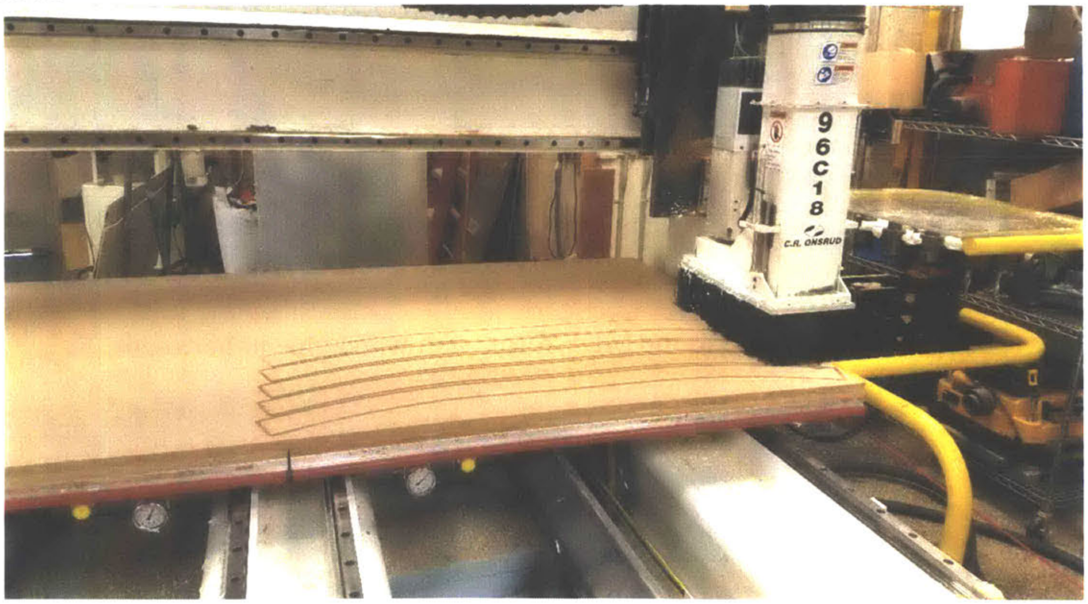


First, plywood supports were screwed to the flat plywood flange supports. Then, fabric was stapled on the underside of one section, and then the other.



Final curvature of the fabric, with a combo square to confirm correct depth of the web at different points.

Bent Wood

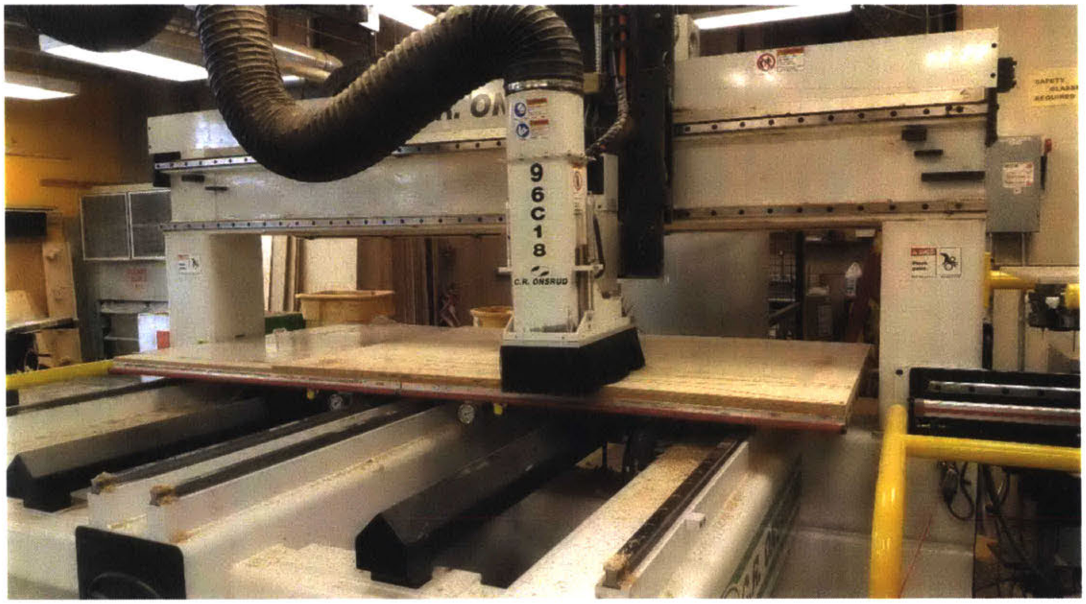


Milling of the MDF form for shaping the sides of the web.

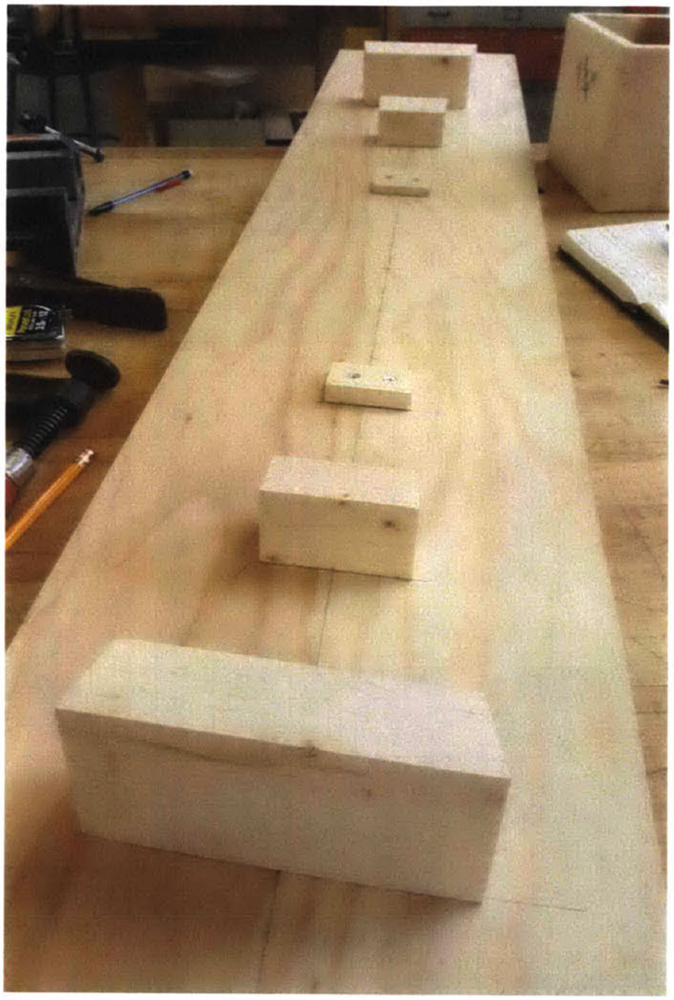
Gluing MDF form.

Clamping 3 layers of 1/8" plywood to the MDF form, with wood glue in between.

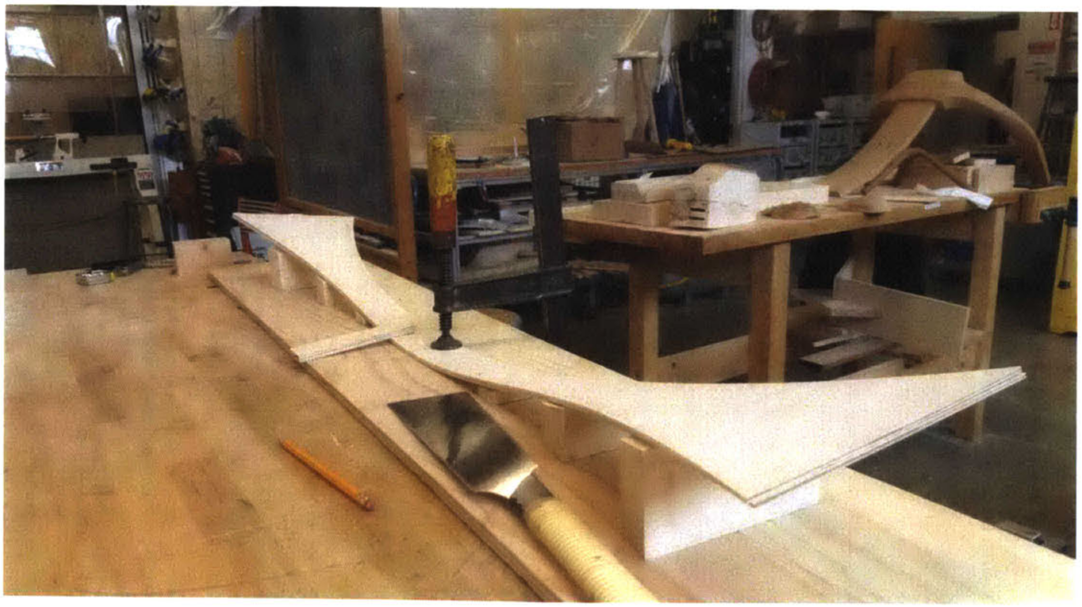
Final web geometry.



Milling flange supports and bottom of web.

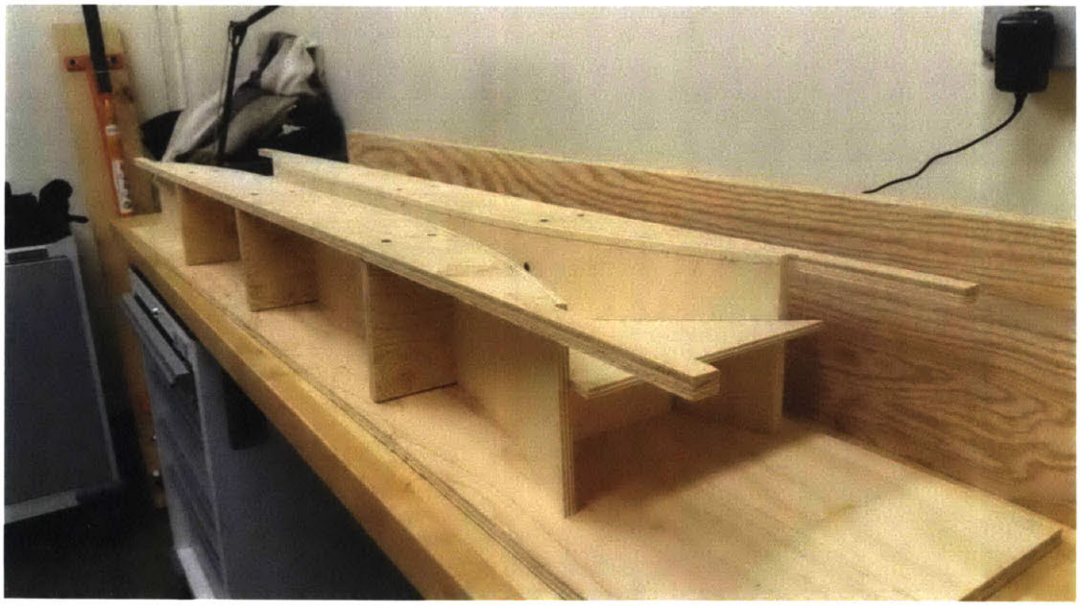


Screwing supports for bottom of web to the base of the formwork.



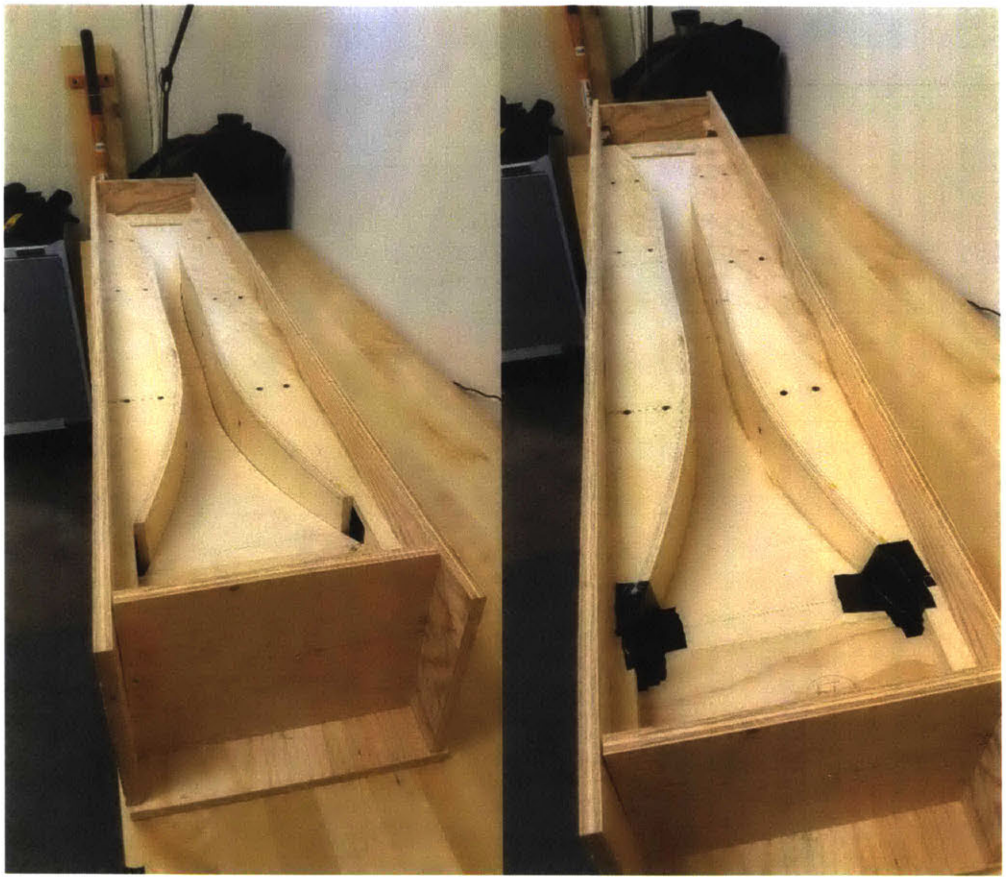
Attaching two layers of 1/8" plywood to the web supports to form the bottom of the web.

Attaching the flange supports to the curved pieces and the base



Assembling the various curved and flat parts. Plywood supports for the flanges are visible.

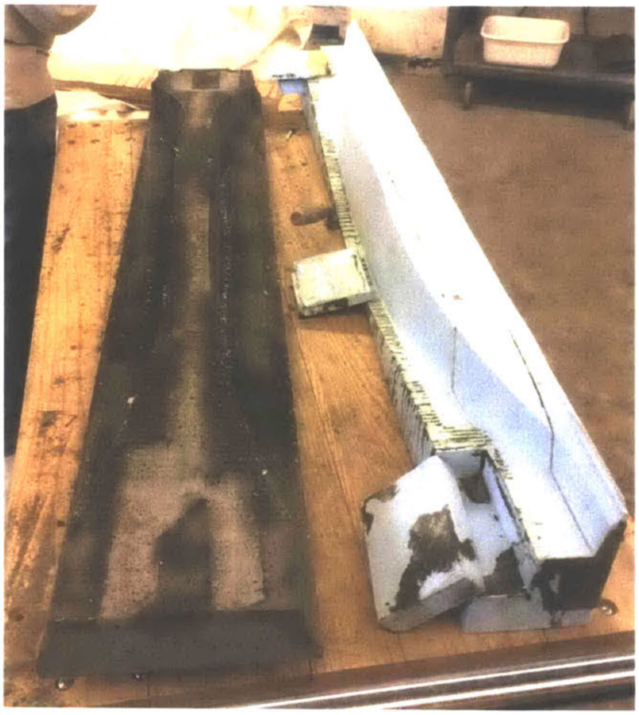
Assembling the bounding box.



Mold with holes, and then final mold with silicone and duct tape covering the holes.

Demolding

Removal of the plywood box from the foam inserts. *Photo: Yan Liu.*



The foam was removed fairly cleanly. *Photo: Yan Liu.*

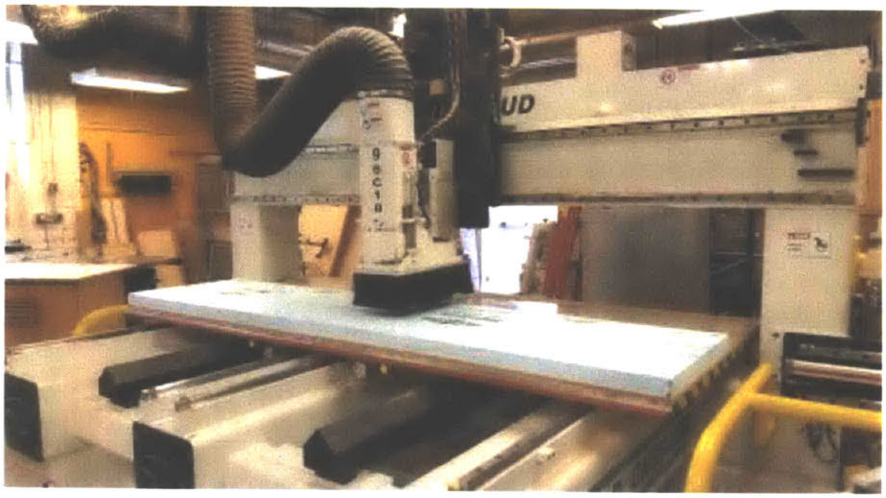
Removal of the fabric formwork. *Photo: Yan Liu.*

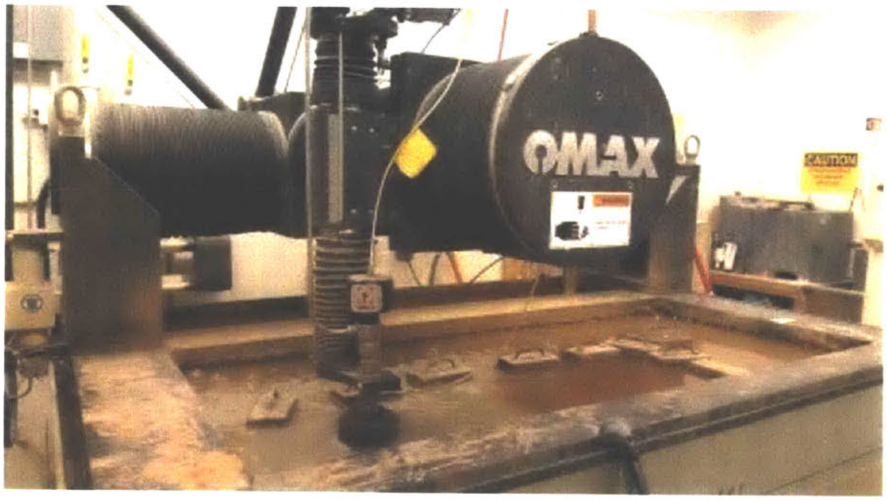
Bulging of the fabric formwork. *Photo: Yan Liu.*

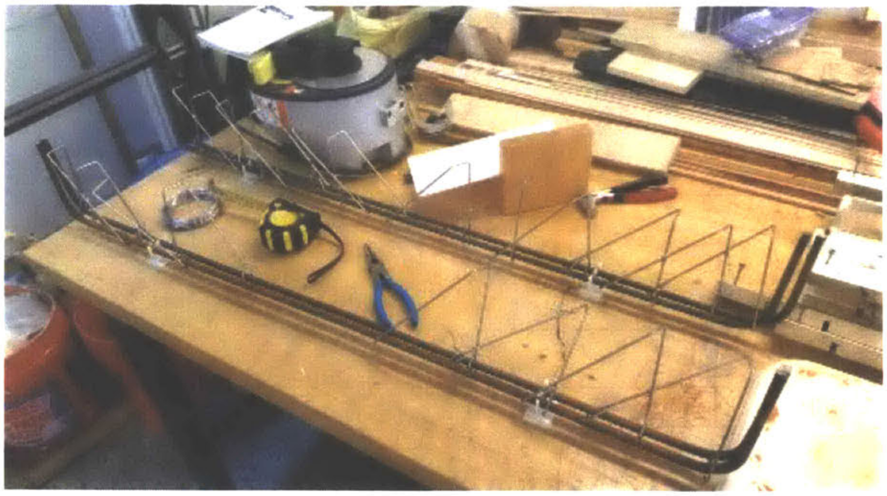
Demolding of the bent wood beam. *Photo: Yan Liu.*

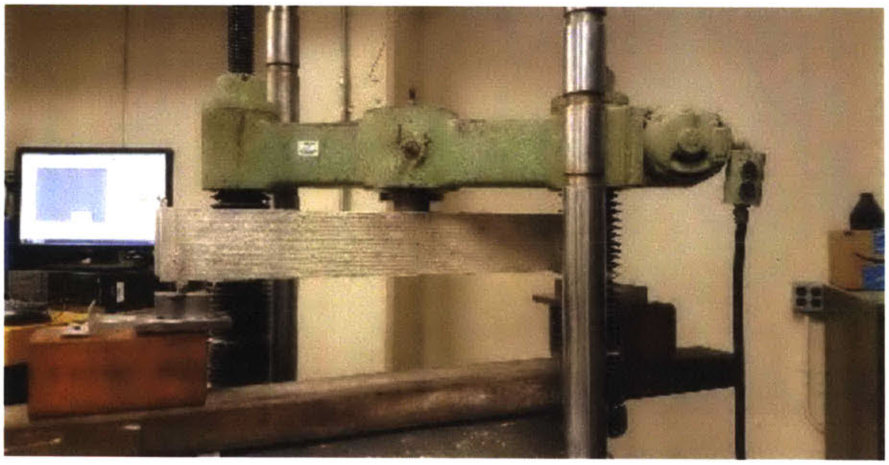
Initial Tests

Initial formwork tests were performed in Fall 2018 on a simpler optimized beam form to test different methods and rebar setups. The following photos document the fabrication and testing process for these beams.









Appendix D: Cost Calculations

Bounding box for all: $32
1/2" ply, 1/2 sheet - $30
Screws - $2

Milled foam: $100 + $32 = **$87**
1/2 sheet of 3-layered foam - $45
1/2 bottle gorilla glue - $10

Bent wood: $103 + $32 = **$135**
2x4 - $8
1/2" ply, 1 sheet - $60
Stapes - $1
1/8" ply, 1/2 sheet - $30
1/2 bottle of silicone glue - $4

Fabric: $43 + $32 = **$75**
1/8 of a 6'x16' roll - $3
1/2" ply, 2/3 sheet - $40

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