Innovative Masonry Shell Construction
in India’s Evolving Building Crafts
A Case for Tile Vaulting

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This dissertation is submitted for the degree of
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DECLARATION

This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration except as specified in the acknowledgements and text.

This work is not substantially the same as any that I have submitted, or, is being concurrently submitted for a degree or diploma or other qualification at the University of Cambridge or any other University or similar institution.

I further state that no substantial part of my dissertation has already been submitted, or, is being concurrently submitted for any such degree, diploma or other qualification at the University of Cambridge or any other University or similar institution.

This work does not exceed the prescribed 80,000 word limit by the Architecture Degree Committee.
GRATITUDE

“With a little help from my friends…”

Reaching out to people over the course of my PhD has been akin to sending messages in bottles into the vast ocean. You wait until someone picks it up, finds it worthwhile and sends one back. And in the midst of such uncertainty, I have always had help from my family and friends who, true to the Beatles song, lent me their hands. Getting by without them would have been painstakingly difficult for me let alone accomplishing this study.

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Aftab Amirali Jalia
“Why should pillars supporting a dome converge towards the common apex of their separated being, which apex is in fact their ‘key’?”
Ananda K. Coomaraswamy, 1938

“An arch never sleeps. Its thrust always are active; but a dome, once its rings are firmly built, is at rest.”
Sir Hebert Baker, 1944

“Progress imposes not only new possibilities for the future but new restrictions.”
Norbert Wiener, 1954

“Pot is the man; no deceit is necessary, no deceit is possible.”
Nari Gandhi, 1978

“Can’t we be ‘modern’ with other materials besides concrete, glass and aluminium trimmings? Can’t we go back to the year 1 B.C. (Before Concrete) and carry on with that wonderful history of research and development?”
Laurie Baker, 1986

“If you do not know where you come from, then you don’t know where you are, and if you don’t know where you are, then you don’t know where you’re going.”
Terry Pratchett, 2010

“No future is possible without a past.”
Olafur Eliasson, 2017
CONTENTS

Summary 3
Methodology 5
Literature Review 7

PART ONE - Tile Vaulting and Relevance Today

Chapter 1
Tile Vaulting and Its Relevance Today 21
Map of Vaulting Techniques in India 28

Chapter 2
A Brief History of Masonry Shells in India 29

PART TWO - Modules, Methods and Motivations

Chapter 3
Evaluating ‘Catalan’ Vaulting at Villa Sarabhai 55

Chapter 4
Ceramic Fuses 97
Case study 1: Sangam, Pune 121
Case study 3: Public Toilet, Surat 124
Case study 2: Sangath, Ahmedabad 126

Burnt Clay Tubes 129
Case study 1: Gramin Takniki Kendra 142
Case study 2: Ratanpar School 145

Chapter 5
National Institute of Design, Ahmedabad 153
Muzaffarnagar Technique 163

PART THREE - Prototypes | Comparatives | Conclusion

Chapter 6
Prototypes 1 to 5: Frog to Phoenix 177
Art born out of Architecture 215

Chapter 7
Conclusion: Tile vaulting for India in the 21st century 222

Chapter 8
Limitations and Extension of Research 241

Bibliography 245
Image credits 255
“The light afforded by Theory will ever appear dim before the Torch of Experience; and well is she represented without hands, and useless, unless guided by Practice.”

- Edward Cresy, 1839

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1 Edward Cresy, A practical treatise on bridge-building, and on the equilibrium of vaults and arches : with the professional life and selections from the works of Rennie (London: J. Williams, 1839).
SUMMARY

This thesis uses the lens of building technology to examine cultural exchange and its relationship to the building crafts. By focusing on masonry vaulting in India, my research brings together two worlds – one that shines light on the variety of innovative masonry shell construction techniques and the other that seeks to evaluate the scope of tile vaulting, an over 600-year old Mediterranean building technique, within India’s evolving building crafts culture. This thesis is organized in three parts:

PART ONE
Tile Vaulting and Relevance Today | A Brief History of Masonry Shells in India
Part one introduces tile vaulting’s unique principles compared to other vaulting traditions while contextualizing its relevance to present day India. A survey of varied masonry vaulting techniques and modules, endemic and imported, practiced across India is presented against the backdrop of what is a predominantly reinforced concrete-based construction industry.

PART TWO
Modules, Methods and Motivations
The second part of this research comprises case studies that include some of India’s most iconic buildings such as the Villa Sarabhai by Le Corbusier, the National Institute of Design by Gautam Sarabhai and Sangath by B.V. Doshi, each of which employed innovative construction techniques for its vaults. The production and use of the enigmatic ceramic fuses in India is examined for the first time alongside their indigenous cousins: burnt clay tubes. Together with Muzaffarnagar vaulting, the case studies reveal cultural motivations for architectural expression and production in postcolonial India.

PART THREE
Prototypes | Comparatives | Limitations & Extension of Research
Part three presents five tile vaulting prototypes in India constructed with local artisans to gain understanding of its cultural reception, assess effective transfer of skills and potential internalization. Recommendations for tile vaulting’s potential uptake into mainstream architectural production is evaluated by comparing findings against prevalent building methods, contextualizing architectural trends and social policy. Limitations and scope for extension of research are also discussed.
METHODOLOGY

David Turnbull describes our ways of producing knowledge as messy, spatial and local. Every culture assembles knowledge in peculiar ways, through the linking of people, practices and places. As a result, the spaces we inhabit and assemblages we work with are not as homogenous and coherent as our modernist perspectives have led us to believe. They are rather complex and heterogeneous motleys.²

Despite India’s sophisticated building crafts tradition, studies that examine construction techniques in socio-political contexts are largely absent in its academic discourse. This study brings forth the hand-dominant craft of innovative masonry vaulting practiced in the country and argues for its sustenance by challenging misplaced cultural perceptions of building with modest materials. It is important to highlight that this research did not follow a linear progression but instead a permutation of research methodologies, the unanticipated discovery and critical review of building modules and techniques charted the course of its iterative evolution.

**Historiography: Synthesizing primary and secondary sources**

Relevant literature on postcolonial and modern architecture in India and the world was historiographically compared for understanding the acceptance and rejection of specific building technologies across cultures. By further focusing on vaulting, I cross-examined secondary and primary data sources and, in the process, was able to unearth previously overlooked manuscripts, photographs and drawings notably in the archives at the RIBA in London, South Asian Studies Department at the University of Cambridge, Fondation Le Corbusier and Cité Archives in Paris, Sangath and the National Institute of Design in Ahmedabad (NID), India.³

As several sources were in French and Spanish, such as the correspondence between Le Corbusier and his staff in India or instructive literature on tile vaulting, these had to be translated using online tools or with external help. With the passing of key people associated with the construction of some case study buildings completed over 50 years ago, unexpected

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³ During the period of this research, the Royal Institute of British Architects (RIBA) in London had their archives at a temporary facility in Parsons Green and the Victoria and Albert Museum depending on collections sought. While the Fondation Le Corbusier is a popular and well-organized archive, Cité houses the collection donated by Jean-Louis Veret and has documents from his time in India which proved extremely useful to piece together missing links of information never published before.
photos and drawings uncovered at the Vastu Shilpa Foundation, Cité archives and NID in particular proved highly beneficial in recreating the missing narrative of their time.

**Onsite investigations: Interviews, photography and measured drawings**

Findings from archival research were further corroborated through interviews with those involved with the occupancy, design and construction of masonry vaulting or the manufacture of building materials (as in the case of ceramic fuses and burnt clay tubes). This was done over 7 trips to India made between June 2014 and April 2017. Where interviews in person were not granted or simply not possible, they were conducted over email or phone.

Fieldtrips across 10 Indian cities and villages viz. Pune, Bhuj, Ahmedabad, New Delhi, Bilimora, Surat, Chandigarh, Wardha, Auroville and Ratanpar allowed me to examine, photograph, measure and 3D lasercan (as in the case of the Villa Sarabhai) remarkable structures and prevalent masonry vaulting methods and synthesize them as case studies which have served as primary sources of data while writing.

**Prototyping: Studying prevalent vaulting methods, training artisans and gauging potential uptake**

The proposition of introducing tile vaulting in India would have been incomplete without actually building test tile vaults in the country and assessing its potential uptake. For this, I partnered with Hunnarshala, an NGO based in Bhuj, the Kutch region of Gujarat and with the Aga Khan Trust for Culture in New Delhi. With the technique unknown to craftsmen in India, I had to first teach it to them through small-scaled prototypes (1.8 m x 1.8m) before building full-scale structures (3.5 m x 3.5 m) in both locations.

Further, in order to gauge the retention of the lessons two years later, the full-scale structures were constructed through autonomous building exercises before being tested for load bearing capacity. A total of five tile-vaulted structures were built in Bhuj and New Delhi between March 2015 and April 2017.

Observations on working methods recorded during prototyping serve as primary sources of data which were subsequently synthesized to compare tile vaulting alongside other prevalent vaulting methods in India against modules, costs, rise to span ratio and thickness of vault with potential for labour engagement.
LITERATURE REVIEW

PART ONE

Tile Vaulting and Relevance Today
The reason we know about tile vaulting today is largely due to the Guastavino Company in New York and its thorough documentation initiated by renowned historian George R. Collins. A father-son collaborative, the Guastavino Company built over a thousand buildings in the U.S. During his lifetime, Guastavino himself made most of the business opportunity given to him by the Society of the Arts to publish an essay on his patented system of an age-old construction technique native to Spain. The scale and prominence of Guastavino built works prompted Collins to tell their story in his seminal paper "The Transfer of Thin Masonry Vaulting from Spain to America" in the Journal of the Society of Architectural Historians. In the same journal issue, Turpin Bannister presented Roussillon Vaulting, the French version of tile vaulting. The apparent dearth of publications on the subject in the English language was peculiar for the next several years only to be overcome by researchers such as Janet Parks in 1996 at Columbia University, Neumann in 1999, Ochsendorf in 2010 at MIT. Research on the actual building technique was also extended further with findings published by Ramage in 2007, 2009 and 2012 as well as with De Jong in 2011 at the University of Cambridge. Around the same period, the Block Research Group at ETH, Zurich has also explored novel form finding and construction methods based upon the tile vaulting principles.

4 George R. Collins was a professor of art and architecture history at the Columbia University, New York. He was the first to shine light on the work of Guastavino Company and his seminal paper Masonry Vaulting from Spain to America, JSAH, 1968 continues to form the basis of many extended research projects such as those by Santiago Huerta, John Ochsendorf and Dietrich Neumann.
Owing to the Spanish origins of tile vaulting, it is obvious for a sizable body of non-English publications to exist on the subject. Spanish publications lead the charge in their consistency often serving as vital sources of technical information on tile vaulting for their English counterparts when looking beyond the works of the Guastavino Company. The scope of these publications ranges from historical overview to regional expression such as in the works of Gaudi, Muncunill and other Catalan architects. In 1997, La Bóveda Catalana\(^{13}\) collected essays specifically on the structural mechanics of tile vaulting while compiling publications dating from 1946 and referencing those dating back to the 15\(^{th}\) century. More recent writing on tile vaulting has been championed largely by Huerta and Truno between 2002 and 2012.\(^{14}\)

Tile vaulting has also received attention due to its deployment by leading modernists such as Le Corbusier and Mies van der Rohe as has been studied in Italian by Gulli in 1994, in Catalan by Marza (ed. 1988) and Spanish by Nonell.\(^{15}\)

To understand the relevance of tile vaulting today, we must not only compare it with other prevalent masonry vaulting methods but also take into account the handful of buildings that have been built in the method in the past decade by contemporary architects and builders. Allen and Zalewski’s (2010) diagrams comparing Roman, Nubian and Tile Vaulting form and lucid studies on Graphic Statics have made tile vaulting more accessible today.\(^{16}\) Robert Willis (1845) and John Fitchen (1961) have presented the principles of Gothic vaulting before mechanized construction through highly illustrative texts as has Leedy in his study of Fan Vaulting (1980).\(^{17}\) These texts serve as parallel studies for the tile vaulting, highlighting the use of geometry and stereotomy in the design and construction of remarkable structures made using vaulting principles.

Pfammatter (2009), Margolius (2002) and Loomis (1999)\(^{18}\) are among the very few that specifically investigate the direct relationship between architectural technology and cultural

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\(^{13}\) Juan Bassegoda Nonell, La Boveda Catalana (Zaragoza: Insitutucion Fernando el Catolico, 1997)


\(^{15}\) Riccardo Gulli, ‘La huella de la construccion tabicada en la arquitectura de Le Corbusier’, in Las bóvedas de guastavino en América, ed. by Varios autores ([n.p]: Instituto Juan De Herrera, 2002) and Fundació Caixa de Catalunya, Le Corbusier i Barcelona, ed. by Fernando Marza (Barcelona: Fundació Caixa de Catalunya, 1992).

\(^{16}\) Edward Allen and Waclaw Zalewski, Form and Forces: Designing Efficient, Expressive Structures (Hoboken, New Jersey: John Wiley & Sons, 2010).


\(^{18}\) Ulrich Pfammatter, Building the future : building technology and cultural history from the Industrial Revolution until today (Munich, New York: Prestel, 2008); Ivan Margolius, Architects+engineers=structures...
aspiration related to vaulting. Through their architecture, the National Art Schools of Cuba, despite their dereliction today, continue to remind us of the virtues of a society’s desire to improve its own conditions. Fry and Drew (1956) explore a host of architectural strategies for environmental comfort in the tropics and these provide engaging lessons on tectonics, configurations and materials and attest Joseph Allen Stein’s ideal: “India offers the great possibility of beauty with simplicity.”

Tile vaulting’s lightweight building principles and low carbon footprint potential are aligned with Adriaan Beukers’s study on ‘Lightness’ in order to cope with the prevailing environmental crisis.

As tile vaulting is novel to India, no literature on the technique exists and we must therefore synthesize various lessons offered from attempts around the world to contextualize its application for India. To this effect, my efforts in tile vaulting alongside artisans are the first of its kind.

### Brief History of Shell Structures in India, 1786 – present

Writers on traditional shell construction in Hindustan, the geographical region comprising today’s India, development of forms and social context are Brown (1942), Juneja (ed. 2001) and Koch (1991, 2006, 2014). Thomas Metcalf’s (1989) interest in modern India and his writings offer perspectives from the British point of view towards Imperialism especially in the post-colonial age. His cultural readings are filled with observations on issues that inform architecture: patronage, tradition and reform, civil society and politics. The making of New Delhi, the Empire’s new capital for India, and its architectural statement are well reviewed and documented by Robert Byron (1931) and retrospectively by Irving (1983). Mainstone’s ‘Developments in Structural Form’ (1975, 1998) offers an excellent overview of vaulting structures although it only loosely connects it with building practices in India. Mainstone (ed. 2000) collects an article by Giles Tillotson that talks about the ‘Dome in India’ from a political representation point of view but does not discuss any construction...
techniques. The only paper to reveal India’s connection with the Guastavino Company and by extension to tile vaulting is by Vegas and Mileto (2012).

Miki and Madhavi Desai’s research (2000) on the search for identity in Indian architecture is by far the most critical look at the birth of the Indian architectural voice. It traces the origins to the pedagogy introduced in Indian art and architectural schools in colonial times while Jon Lang (2002) sets his attention on the emergence of modern architecture in India. The discussion of prevalent construction ideologies in India first touched upon by Scriver and Bhatt (1990) notes the changing attitudes of Indian architects towards novel ways to build in the country while seeking inspiration from the West. Stephen White’s monograph on Joseph Allen Stein (1993) is among the few that consider ‘how’ an architect chose to engage with construction processes unique to a particular country and participated in synthesizing it with modern sensibilities. Stein’s work in India has remarkable shell structures but as with the studies above, the consideration of how they were constructed is beyond the scope of set research and therefore offers an incredible opportunity to build upon.

Moreover, it is Jeffrey Chusid’s (2010) astute observation of Stein’s ability for ‘embracing the flawed’ that extends to practices such as Nari Gandhi’s and Laurie Baker’s who worked in India and consciously articulated Gandhian ideas for why mechanized systems must play supporting roles to a chiefly handmade building culture. It must be noted that none of these studies discuss vaulted construction systems in detail even though they feature extensively in the work of abovementioned architects. The themes initiated by the above publications are updated by Scriver and Srivastava (2017) to include, more comprehensively, cultural drivers and behind-the-scenes struggles in the production of modern Indian architecture.

Architects and building experts associated with Auroville have also written about novel ideas in vaulting such as Kundoo (2008), which documents the experiments of ceramicist Ray Meeker in firing an entire clay building to create an unprecedented monolithic structure.

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Other works by the Auroville Earth Institute (AVEI) are widely available through their web portals and training manuals. Reports by a handful of award committees are also vital sources of information as they often discuss noteworthy construction principles that qualify merit. To this effect, the Aga Khan Award for Architecture’s reports on projects that did not win the award such as Rewal’s Parliament Library (built 2007), Sangath (built 1983) and the Volontariat Home for Homeless Children (built 2011) to the Holcim Foundation’s report on Lall’s Development Alternatives Building (2008). Films by Manu Rewal on Le Corbusier in India (2001) and Rewal’s Parliament Library (2004) also provide good insight on the nuances of building in India by those directly involved in the projects.31

Building Materials & Technology Promotion Council’s (BMTPC, 1998) compendium of building materials in India and K.S. Jagadish’s Building with Stabilized Mud (2013) serve not only as important technical references but also as an indicator of the country’s changing interests in building materials and the very clear shift to natural and energy-efficient materials that are being encouraged by the states and national government. Similarly, Kazi Ashraf’s Made in India (2007), The State of Indian Architecture (2016) and Edward Leland Rothfarb’s brilliant study of the historic city Orchha’s art and architecture in 2012,32 though not connected to vaulting, are excellent pieces of writing on visual culture, where architecture and allied arts complement each other to facilitate cultural production. It also brings to light the changing sensibilities towards heritage conservation in India and the scope for reviving traditional building crafts and techniques for the future.

PART TWO: Modules, Methods and Motivations

Villa Sarabhai

As one of only two residences completed by Le Corbusier in India, the Villa Sarabhai has received a lot of attention in academia and industry with numerous publications featuring the house in different capacities. While its photogenic appeal has been the subject of features by GA and Taschen, Peter Serenyi (1976), Curtis (1986) and Jencks (2000) are among leading academics to have written about the Villa Sarabhai in context of Corbusier’s work in India and abroad.33 More recently, Ubbelohde (2003) has studied the thermal performance of the

31 Le Corbusier in India, dir. by Manu Rewal (2001) & The Architecture of Raj Rewal, dir. by Manu Rewal
house over the period of a year while Sendai (2012) has written about the villa’s design evolution based primarily on having to deal with the harsh Indian climate.\textsuperscript{34} Caroline Maniaque-Benton’s monograph in 2009 on the Maisons Jaoul\textsuperscript{35} is an excellent resource for comparative study between the Villa Sarabhai and its Parisian cousin for the multitude of sources, research methodology and scope. Luis Guillermo Hernández Vásquez’s unpublished doctoral thesis (2015) is an evocative study of the visual imagery that the Villa Sarabhai and other Corbusier buildings in Ahmedabad share with traditional Indian buildings.\textsuperscript{36}

Gargiani and Rosellini’s (2011) encyclopaedic presentation of Corbusier’s work from the period of 1940 to 1965 examines the architect’s fascination with \textit{Beton Brut} and its resulting architectural expression across projects around the world.\textsuperscript{37} With the exception of Serenyi, all above publications faithfully assume and base their research on Corbusier’s construction details presented to them through the drawings and photographs through the \textit{Oeuvre Complete} (published from 1935 onwards), an eight volume retrospective on his work worded in parts by Corbusier himself. This misleading presumption is what led to my discovery that the vaults at the Villa Sarabhai were in fact not constructed as Catalan tile vaults. However, the primary sources of archival data for me have been the Fondation Le Corbusier and the Cite Archives in Paris.

\textbf{Ceramic Fuses and Burnt Clay Tubes}

Ceramic fuses were bottomless terracotta bottles invented by Jaques Couelle in 1941 that worked on an interlocking principle for self-support making them useful for vaulting. Today, they remain largely unknown in the architectural world with only a handful scholars having written on the subject. Although unaware of ceramic fuses, Lancaster (2009) presents a coherent study of similar interlocking terracotta tubes and their construction techniques traced back to Roman North Africa from an interdisciplinary perspective across art, architecture and archaeology while postulating that they served primarily as storage containers.


\textsuperscript{37} Roberto Gargiani, Anna Rosellini and Stephen Piccolo, \textit{Le Corbusier: Beton Brut and Ineffable Space} (Lausanne : EPFL Press, 2011).}
of olive oil in trade routes around the Mediterranean.\textsuperscript{38} She also cites the archaeological findings of Oxford professor Mensun Bound whose work in turn reveals remarkable details on hollow terracotta tubes used for vaulting in Roman times (tubi fittili). Similarly, R.J.A. Wilson (1992) writes about the same tubes in the Journal of Roman Archaeology but does not mention ceramic fuses.

The fuses remain largely unknown beyond mainland Europe even today. Cursory gestures at linking the development of hollow bricks with ceramic fuses are made in the Transactions of the Ceramic Society journals (1959) while Robert Mark (1993) also mentions the use of hollow terracotta tubes in the construction of domes in Rome.\textsuperscript{39} There is also no mention of ceramic fuses in Campbell’s extensive study of the history of brick.\textsuperscript{40}

Couelle’s French and U.S. Patent papers confirm his ‘invention’ of ceramic fuses. Fernand Pouillon’s autobiography \textit{Memoires d’un architecte} is a first hand account of an active, prominent French architect who learnt about ceramic fuses and employed them for rapid construction.\textsuperscript{41} Ilana Ortar’s \textit{Camp of the Jews} probes Pouillon’s work from an anthropological – artistic perspective to explore the meanings in collective memories of survivors of the refugee camps constructed by Pouillon.\textsuperscript{42} In a book by Bonillo (2001) featuring Pouillon’s work, details on ceramic fuses are curiously absent as they are from other publications by Picon (1997) and Voorde et. al (2016) that specifically look at post-war building materials developed for rapid construction in continental Europe.\textsuperscript{43}

In a more recent publication by a Delft structural engineer, Wim Kamerling (2016), explores some aspects of ceramic fuses as a lost building technique, presenting structural tests on newly manufactured fuses.\textsuperscript{44} But the history of the fuses is not a subject of interest to his research, which is confined largely to structural analysis. None of the above available literature on ceramic fuses talks discusses cultural exchanges nor touches upon why they simply vanished from the building industry.

\textsuperscript{40} James W. P. Campbell, \textit{Brick: A World History} (London: Thames and Hudson, 2003).
\textsuperscript{44} Wim Kamerling, Composite Hollow Core Vaults (Netherlands: TU Delft Open, 2016).
Further, the literature on ceramic fuses is largely relegated to the Western world and no studies have been undertaken from a cultural or structural point of view for their use in the Indian subcontinent despite several remarkable structures built there. One such case study examined in this thesis is Sangath, B.V. Doshi’s studio that is featured in numerous publications most notably Curtis (1986) and Steele (1998) but both fail to mention about Doshi’s innovative use of the unique and important building module.  

On the subject of Wardha tumblers, also called Guna tiles or the scientifically correct term: Burnt Clay Tubes, the Centre of Science for Villages (CSV) has issued manuals (1998) that are meant to serve a non-technical audience interested in building using the module. Sharma and Chetty’s paper on Guna tiles is the first academic paper found that proposes a refined application of the Guna tile. To this effect, the thorough onsite research work of the architect-engineer team of Rupal and Rajendra Desai is crucial and grossly overlooked over the years. Two of their many publications are important for the further development of the research that this thesis hopes to have laid the foundation for: Burnt Clay Tubes: Structural and Thermal Performance Study (1995) and The Gramin Takniki Kendra (1998) which was the result of their extensive research on the Wardha Tumblers at the Centre of Science for Villages. The tiles have received little recognition in India with a handful of articles published in Indian journals such as by Ramchandani (1998) and the Indian Department of Science and Technology (2001).

As the publications are all focused on presenting research that either teaches to build or builds upon lab tests on structural loading and thermal performance, they ignore the question of the origin and possible metamorphosis of the tiles from ceramic fuses which would tell us more about the underlying attitude of frugal engineering and improvisation that lies inherent to the Indian building industry.

Regarding the Muzaffarnagar technique, the only documented source of information is Samuel Wilson’s thesis at MIT (2016) which was written shortly after the prototypes were

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49 Samuel Wilson, ‘Structural Design of Shallow Masonry Domes’ (Master’s Thesis, Massachusetts Institute of Technology, Department of Civil and Environmental Engineering, 2016).
constructed at Hunnarshala – a time when I had the opportunity to study the prototypes and interview the masons who built them. Other masons in North India execute similar vaulting techniques, but I was not able to find any reliable technical documentation on the methods.

PART THREE

Prototypes | Comparatives | Limitations & Extension of Research

My inspiration for form finding and prototyping funicular tile vaults in India came from Robert Hooke’s simple yet powerful thesis on the inverted chain principle in 1675 and from Karl Culmann’s graphic statics. Although used traditionally for form finding, graphic statics goes hand in hand today with the preservation of shell structures. Paulo B. Lourenço’s paper on Preservation Engineering brings to light the fundamental issue concerning analysis and form finding of masonry structures. We can argue that the most important aspect of graphic statics is its ability to be understood not in abstract numerical terms but by superimposing the ‘calculations’ over the structure form itself.

Extending their earlier book Shaping Structures (1998), Edward Allen and Waclaw Zalewski’s Form and Forces (2010) makes for an engaging introduction for engineering and architecture students for structures that can be ‘found’ through the iterative process of graphic statics. Its simplification of Karl Culmann’s original treatise (1864) makes the method palpable and has promoted form finding for compressive and axial forces in structures in contemporary architecture. The ideas of Rankine (1864) and Maxwell (1870) on graphic statics have been ruminated over by Eddy (1878) and Robert Bow (1873) who contributed to the ‘Bow’s Notation’ now widely used. George Sydenham Clarke (1890) perhaps deserves mention for being among the first to introduce Culmann’s technique to Britain having seen ‘its advantages’ in other parts of Europe. Refined upon further by Luigi Cremona (1890), British naval architecture professors Cathcart and Chaffee (1910) explored higher functions of Graphic Statics for calculating index powers, moments and measurements of friction which require and deserve thorough understanding while Hess (1913) solved a great variety of truss configurations. Wolfe (1921) is among the earliest writers on the technique in the U.S. and presents an excellent overview of the fundamentals.

51 Karl Culmann, Die Graphische Statik, 8 vols (Zurich: Meyer & Zeller (A. Reiman), 1875).
already mastered in Europe, particularly offering an analysis of Gothic vaulting and masonry structures.\textsuperscript{52}

Contemporary writings on Graphic Statics are chiefly those that promote its uses and touch upon overdue advancements for a technique that has largely remained ignored since the 1950s. Serious revisiting of it has most likely been encouraged by the surge in scholarship on timbrel vaulting and structural art, especially by Mainstone\textsuperscript{53} in 1998, Remo Pedreschi (2000), Stanford Anderson (2005) and David Billington (1997, 2008) and Ochsendorf (2010).\textsuperscript{54} An important development in contemporary use of Graphic Statics is Block’s doctoral thesis (2009) and his Thrust Network Analysis that offers a complicated application of graphic statics as it views the structure all at once, as a single problem, unlike Frezier or Poleni (Huerta, 2006) who preferred to ‘slice’ a funicular structure to resolve compressive forces spread over a catenary ‘arch’. However, Block’s explorations (2014) are specific and focused on the construction process of complex unreinforced masonry geometries and the TNA’s interactive computer model allows new explorations with universal applications. Similarly, Skidmore Owning and Merrill’s foremost structural engineer, Bill Baker has not only authored a paper informally titled ‘things I wish I knew when I started designing structures’ (2011) urging young students – architects and engineers to learn Graphic Statics but he has also co-authored (2013) a paper with and guided the doctoral thesis of Lauren Beghini (2013) that looks at material and topological optimization using Maxwell’s principles of vector reciprocity.\textsuperscript{55}

In a more traditional approach, but equally revolutionary, are Jacques Heyman’s research on structural history (1995, 1996, 1998) that reaffirm the solace of the ‘Plasticity Theory’, calling upon builders for finding eloquent structural forms by reminding that geometry always took precedence over mechanics throughout building history.\textsuperscript{56} Heyman’s research into Coulomb’s work (1997) reveals the latter’s analogous understanding of soil mechanics and structural masonry establishing a creative interdisciplinary approach to equilibrium in

\textsuperscript{53} Rowland J. Mainstone, Developments in Structural Form (London: Allen Lane, 1975).
\textsuperscript{55} William Baker, ‘Structural Innovation: Combining Classic Theories with New Technologies’, Structural Innovation Lecture at Northeastern University, 2014
structures. Santiago Huerta (2006) remains a leading voice in explaining Gaudi’s relentless faith in Graphic Statics, attesting alternatives to number-crunching engineering approach while Josep Duran (2013) offers an alternative view of Gaudi’s protégé, Cesar Martinell’s ‘wine cathedrals’ that continue to command an atavistic adaptation by contemporary architects such as Calatrava’s Ysios Winery, 2000 and Richard Rogers’s Protos Bodegas, 2010. Kurrer’s colossal compendium (2008) on the genealogy of theory of structures aptly collects and emerges as a singlemost comprehensive reference for understanding the changing attitude of engineers towards structural calculations in the western world while Addis (2007) provides a brilliant overview of the history of building, erasing boundaries between design, architecture and engineering.

Form finding has been and continues to be a highly personal endeavour for architects and few books document this more vividly than Frei Otto and Bodo Rasch’s (1995) that presents the German architect’s most basic experiments in finding forms through soap bubbles to the excessively indulgent photogrammetric calculations using scaled models at the Institute of Lightweight Structures. At the other end of the spectrum, Ramage (2013) explores Alfonso Ramirez Ponce’s inspiration for Ladrillo Recargado (leaning brick) while Juan Antonio Ramirez (2000) draws a complex tapestry of the subliminal presence of the beehive form in catenary structures as well as colour selection in architecture.

While the bulk of literature speaks of vaulting and masonry as a skill that offers the technological achievement of an industrially advanced nature though still put together by hand, the works of Gramazio and Kohler offer the other extreme of fully digitized construction and argue its merits in a world that is increasingly ‘online’. However, most papers seek exclusively to either emphasize one approach or another, but not instead to find middle ground in combining building crafts traditions with computation tools from a production perspective. The chief architect of the Sagrada Familia, Mark Burry and Michael Ramage stand out to this end. Andrew Saint (2008) and Pfammatter (2000) present resonant studies on the changing roles of the architecture and engineering professions: from being conjoined in early building times to the evolution of their distinctive identities propelled by modernism to their re-converging paths in contemporary times.

57 Llorens Duran, ‘Wine Cathedrals: Making the most of Masonry’, in Institution of Civil Engineers (ICE Publishing, 2013), CLXVI, 329 - 342.
PART I

Tile Vaulting and Its Relevance Today |
A Brief History of Masonry Shells in India
Chapter 1

Tile Vaulting: Techniques and Distinctions

Builders around the world deploy an incredible number of methods for the construction of masonry shells. In order to understand what makes tile vaulting distinctive, we must briefly look at other predominant vaulting techniques. The most commonly used ones are of the north European tradition (or Roman) that use heavy formwork to support the shells until fully set. Though not always, Roman shells are often semicircular in shape and therefore not structurally optimal. The Nubian method or the African / Middle-Eastern tradition use a leaning brick technique which eliminates formwork completely and follows catenary geometric profiles in order to contain thrust lines efficiently. The Mexican architect Alfonso Ramirez Ponce has created numerous beautiful roofs based on the leaning brick (ladrillo recargado) method that are cost appropriate and durable.

Above:
Comparing the most widely used vaulting techniques – left to right:

i. Roman (semicircular section built using formwork).
ii. Nubian (catenary section, no formwork)
iii. Tile vaulting (catenary section, can also be shallow, no formwork

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The origins of tile vaulting or Catalan vaulting, as it is popularly known today, have been traced to the 14th century in Valencia, Spain. As the building technique received recognition, tile vaulting gradually spread through Spain and the Mediterranean region before being taken to different parts of the world such as Italy, France, Portugal, Algeria and Colombia. Owing to its subsequent geographic dispersion, tile vaulting has also come to be known by different names: timbrel vault or cohesive construction as called by Rafael Guastavino, volta in folio in Italian, voûte à la roussillon or voûte plate in French, bóveda tabicada in Spanish, voltes de barandat in Valencian, maó de pla in Catalan, abóbada de tijolo in Portuguese and rhorfas in Arabic. But for the sake of consistency and contemporary reference, I have referred to the technique as ‘tile vaulting’ throughout this thesis except for where it was deployed specifically as Catalan vaulting as in the case of the Villa Sarabhai by Le Corbusier (see Part II, Chapter 3).

Research on tile vaulting was prompted by the works of the Guastavino Company founded by Rafael Guastavino in 1882 when he immigrated to the U.S.A from Spain. The company collaborated with leading architects of the time and patented several innovations related to tile vaulting. A resounding commercial success, through their numerous commissions and dedication to tile vaulting, the Guastavino Company played a vital role in refining the technique further, preparing detailed drawings and disseminating information on it. Their most famous projects in the U.S.A. include the Boston Public Library and the remarkable Grand Central Station, New York.

Unlike traditional vaulting that requires heavy scaffolding, formwork, a full size brick and cement mortar, tile vaulting is constructed in layers with minimal guidework that is required only to maintain the curve of the shell. The first layer of the shell comprises of brick tiles stuck to each other in plaster of Paris. This fast-setting gypsum mortar is key to being able to build quickly and without formwork. Once the first layer of the desired single or double curved shell is completed, a second layer of tiles is placed on a bed of cement mortar at preferably 45 or 90 degrees to the previous layer. This is done to break the mortar joints with the previous layer and create a masonry bond. The second layer can also be laid almost immediately upon completing the first layer. Depending on the desired thickness of the shell, subsequent layers are added in cement mortar. As a final finish, the Guastavino Company clad the soffit layer of the vaults and domes with a glazed ceramic tile with raised pointing to accentuate the coursing of the tiles.

63 Ibid, p. 20
Working purely on geometry and flaunting their laminated construction system, tile vaulting epitomizes the credo of structural honesty and resisting through form. Due to their resulting lightweight section, almost complete elimination of formwork, reduction of materials and speed of construction, tile vaulting offers economy of construction. Perhaps the most astounding comparative example offered by Ochsendorf is the Brunelleschi’s dome for the Basilica di Santa Maria del Fiore in Florence (43 m diameter) which weighs over ten times more than Guastavino’s dome for St. John the Divine (40 m diameter) and required fourteen years to build compared to the fifteen weeks by Guastavino in 1909.  

For the execution of a high standard of tile vaulting, the Guastavino Company manufactured its own brick tiles, relied heavily on skilled labour to synchronize its many aspects of preparing different mortar mixes in gypsum plaster and cement and maintaining geometries in case of complex to attain a high standard of sound and durable construction that was possible to replicate across the geographies. During this time tile vaulting continued to be

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64 John Ochsendorf, Guastavino Vaulting: The Art of Structural Tile. 1st edn (New York: Princeton Architectural Press, 2010), p. 126. St John the Divine’s dome has features a tapering section that is thinnest at the crown and the building received a lot of attention in the journals of its time.
practiced in other parts of the world, such as Spain and Colombia, but the sheer number of projects completed by the Guastavino Company overshadowed its foreign counterparts.

Under the Guastavino Company, the technique reached its zenith in sophistication and beauty and yet pressured by decades of changing labour conditions, preferences in building materials and techniques, the Guastavino Company folded operations in 1962. Their work in tile vaulting barely received the recognition it deserved in coming decades. Tile vaulting, on the other hand, has inspired a generation of architects and engineers familiar with its construction principles.

Contemporaneous to Guastavino, many architects in Catalonia such as Lluis Domenech I Montaner, Lluis Muncunill and Antoni Gaudi deployed tile vaulting in their works to create distinctive architecture in the region. Spanish engineer Eduardo Torroja (1899 – 1961) has been noted to marvel at the Catalonian vault’s technical capabilities and structural prowess. Madrid born engineer Felix Candela’s (1910 – 1997) interests in structural theory and shells led him to experiment extensively with shells in Mexico due to the country’s less confining codes and he retained his interest in optimizing materials and structural form. Similarly, Uruguayan engineer Eladio Dieste sought to distill the essence of efficiency in his reinforced vaults that are today renowned for their unprecedented structural expression. It is the collection of these intrinsic qualities of structural efficiency and ease of building attributed to tile vaulting that has caused the revival of the technique and recent surge in research on its many aspects.

Relevance of tile vaulting today

"Finally, the disinterested assistance which I have received from the most distinguished architects, due principally to their ready comprehension of the fact that the new construction is the renaissance of an old and noble system, for several centuries unused, but applied now owing to the necessities of the age, has encouraged me to publish in book form the lectures referred to, in the hope that it will have the approval of all interested in the constructive arts."67

- Rafael Guastavino, 1893

65 Ibid. p. 194
The relevance of tile vaulting today is multi-faceted. At a time when building life cycle, durability, preservation and sustainability are themes central to the design of built environments, tile vaulting offers a robust, holistic solution for construction.

Not tethered to typology or tectonics, tile vaulting’s possible applications range from architecture of an industrial scale to adaptive reuse, from the construction of foundations to billowing light sail-like roofs. In his exposition on ‘Lightness: The Inevitable Renaissance of Minimum Energy Structures’, Adriaan Beukers has extrapolated upon the inevitable credo of building lean for a sustainable future. Lightness here refers to not building flimsy or even temporary but being ‘smart by nature’ and of internalizing complex natural phenomena which necessitate structural and material optimization to minimize redundancy while their durability renders them cost-appropriate.

Recognizing its potential for quick, safe and durable construction, UN Habitat has been preparing a manual for disseminating technical information on the safe application of tile vaulting. In academia, John Ochsendorf at MIT has played a vital role in consolidating the research on Guastavino and expanding it to include Graphic Statics, the pioneering work of Swiss engineer Karl Culmann. The Block Research Group, based at ETH Zurich, has been developing computational tools for form finding based on Thrust Network Analysis, which in turn has been developed from Graphic Statics. Having been instrumental in reviving the technique, Michael Ramage of the University of Cambridge has worked on a number of tile vaulted structures in the past decade: Pines Calyx (2004) and Crossway House (2009) in England and the Mapungubwe Interpretation Centre in South Africa (2010) through Light Earth Designs. Notably, the domes of Pines Calyx span 12 m and are only 120 mm thick making them proportional to an eggshell while giving a sense of its optimal use of material.\textsuperscript{68}

Tile vaulting is steadily finding mainstream commercial appeal with Fosters + Partners having built a prototype vault at the Venice Biennale 2016 in precedence to their full scale production for the Droneport Project in Rwanda.\textsuperscript{69} The prototype was created in

conjunction with engineering consultancy offered by ODB and Spanish mason Carlos Martin Jimenez, skilled in tile vaulting.

It is in this context that the adaptability of tile vaulting can be confidently established for its advantages of lightweight, durable structural form and moisture-proofing that extend to infrastructural contraptions such as underground drainage, water tanks, etc. for integrated solutions.70

In times when we are forewarned by those71 who have witnessed the decline of innovative clay vaulting techniques due to plaguing issues of slow speed of construction, increasing labour costs and material acceptance, my study seeks to assess the scope for tile vaulting in India – where favourable conditions offer opportunities to explore its potential in a systematic approach.

70 UN Habitat released a building manual at their recent conference in Colombia in April 2014 highlighting these abovementioned possibilities of tile vaulting.
India

Geographical Distribution of Masonry Vaulting Case Studies

- Traditional Masonry Shells
- Modified Traditional Masonry Shells
- Tile Vaulting Prototypes
- Failed Tile Vaulting Attempts
- Ceramic Fuses
- Burnt Clay Tubes
- Reinforced brick vault
- Production of Ceramic Fuses
“Its history can no more be separated from that of the lands surrounding it than the clay can be separated from the hands of the potter who shapes it.”

Fernand Braudel

Chapter 2

A Brief History of Masonry Shells in India, 1786 to present

India’s long history of compression structures dates back several centuries. Made predominantly of bricks, the structural feat of some of these structures continues to draw technical and aesthetic interests even today. Through centuries, building craftsmen in India, while retaining systems of knowledge of their own traditions, were exposed to a variety of construction and building-related techniques which have over the course of time also been absorbed and indigenized to be viewed today as local or traditional. Invariably, a multitude of construction techniques also influenced vaulting in India. As a result vaulting in India, from traditional to contemporary times, features a remarkable range of indigenous and imported building techniques. These include the three widespread techniques of Roman, Nubian and attempted tile vaulting but also a host of other innovative structures made of ceramic fuses which trace their origins to Roman North Africa as early as 5 B.C.

It is arguable that the earliest and most recurrent image of the dome in India is that of the Buddhist Stupas. These Buddhist-era creations began as earth mounds shaped as domes

73 Some of these are: wattle-and-daub walls, the Rat-trap bond and other brick masonry bonds, lime and grit-finished plaster finishes for surfaces, mosaic, terrazzo flooring and the production of Athangudi tiles.
later evolving into complex vaulted forms as seen in the subtractive caves of the Chaitya period at Karla, Maharashtra 5 A.D. Today, vaulting is largely an additive form of construction perceived to be introduced in India by the Islamic rulers who came from Central Asian provinces in 1192 A.D. Rudimentary in expression and lacking in technical skill, the first structural attempts for arcuate forms, largely inspired by the rich building traditions of Iran, Uzbekistan and Afghanistan, failed to produce more than clumsy shallow conical domes as seen first in the Quwwat ul-Islam complex in Delhi.

However, it was under the Mughals and the Deccan Sultanates that vaults and domes in India achieved remarkable structural and aesthetic accomplishment. Notable examples of brick domes from this period are: Humayun’s Tomb, Delhi (diameter 22.5m) completed in 1572 which became the blueprint for the magnificent Taj Mahal, Agra (1653). Gol Gumbaz in Bijapur (diameter of 44m) built in 1656 claims to be the largest corbelled dome in India. The influence of Mughal building styles and techniques largely had pan-Indian appeal. A modest-scale parallel to this achievement was the profusely decorative brick temple architecture of Bishnupur, West Bengal in the 15th and 17th centuries.

Also, while building superstructures in brick were abundant, the module was deployed in landscape architecture as well for highly expressive results. One such example is the exquisitely patterned floorscape at Bibi ka Maqbara (1661) in Aurangabad made in fired brick that continues to enthrall visitors today.

 Nonetheless, shell structures remained the most visible features of Mughal architecture. True to their origins in Uzbekistan and Central Asia, vaulting techniques of the Mughals incorporated corbelling or squinches, often hidden by decorative muqarnas. Architects of foreign lands were employed to design and oversee the construction of these buildings of unprecedented scale. Further, builders of these monuments built the neck of the dome in stone with higher layers made of brick, as in the dome of the Humayun’s Tomb, in an effort to build lighter as one went higher. Sophisticated structural concepts of the double and triple dome also existed as much as a functional element as an aesthetic one such as the bulbous triple dome of Safdarjung’s Tomb, Delhi built in 1753.

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76 Ibid. p. 44. For example, the architect of the Humayun’s Tomb Mirak Mirza Ghiyath was originally from Herat and designed the Humayun’s tomb in Delhi.
Domes were also great compositional elements in an architecture that was wide and tall and sought high visibility from great distances. They were bold statements of wielding power. Ebba Koch has theorized that through the use of red and white colours of building materials, the Mughals wanted to convey the message to the common people that they associated themselves with the highest of the castes in Hindustan: with red sandstone of the Kshatriyas (soldiers) and white belonging to Brahmins (priests) – two of the highest castes of the Hindus.77

Thus, through their use of building materials and techniques, the Mughals asserted a certain status to their architecture, setting the tone for how they wished to be perceived by their subjects. For the Mughals, as for the Deccan Sultanates, monumental structures declared their ambitions and domed structures allowed them to achieve the scale for these appropriately bold statements. This sophistication and diversity in brick use across typologies and cultures further testifies the symbolic status that the material enjoyed in the culture of the land.

Top:
Buddhist Karla Caves, Chaitya Period

Middle: (l-r)
Trabeated attempts for base of dome at Quwwat ul-Islam Complex, 1192

Subsequent development of corbelled dome and decorations at Quwwat ul-Islam Complex

Brick Paving at Bibi ka Maqbara, Aurangabad
British Occupation of India, 1757 – 1947 A.D.

Undoubtedly, the grandeur of buildings built by the Mughals, Qutb Shahi and other dynasties in India appealed to the British as they gained control over Hindustan. Buildings commissioned by them continued to feature traditional elements built in techniques familiar to them. Subsequent years of British buildings in India would see a spur of Indo-Saracenic architecture combining Gothic and Neo-Classical architectural elements with Indo-Islamic ones – most striking of which are the pointed arch and the dome.78

In 1786, Survey of India’s Major General John Garstin designed and built the rather quirky Golghar in Bankipur near Patna. Built as a granary, Golghar is a large dome measuring 38m in diameter at base and 28m in height having two symmetrically mirrored spiraling staircases for workers to ascend and descend from respectively. Its proportions and free-standing form resemble the Stupa more than the bulbous Islamic domes which were roofing elements above a plinth superstructure.

Although functionally driven, the reference of traditional imagery here is no coincidence and had been a longstanding debate among the British Empire in order to determine an appropriate language for representation. The new architectural ‘language’ needed to be more articulate and well-documented but not different in essence from that of the Mughals. This preference for Indo-Saracenic architecture, which was politically driven and indulgently orientalist,79 was seriously reassessed when Edwin Lutyens and Herbert Baker were

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78 The works of George Wittet, Robert Chisholm and William Emerson among others continue to date the country and are still in use, most protected by the Archaeological Survey of India – the chief conservation body of the government of India.
appointed to design a new capital for the British Raj in Delhi. In no time, both architects dismissed the idea of imbuing traditional imagery from India, choosing instead to retain the time tested surface finishes for buildings having a brick skeleton clad with stone. They did however, deploy the iconic impact of domes in their own work, albeit to different geometries that were akin to the neo-classical architecture than Islamic.

Making New Delhi: Edwin Lutyens and Herbert Baker (1912 - 1930)

After touring India in order to familiarize themselves with the extent of the kingdom and its wide variety of visual culture, Baker and Lutyens both expressed their disdain for having a purely ‘Indian’ architectural language for Delhi. They strongly associated their role in India with developing an architectural language that was not only lasting but also derived from classical building styles – particularly Roman. In a letter that Lutyens wrote to Baker to “On no account have parabolic vaults or domes! It would take us 2000 years to get the drift of it. The Greeks might have done it – but we all (in Western tradition) got switched off to the other lines.” Baker agreed but as the older and more seasoned architect to the Empire suggested that they ought to pitch this notion to their patrons as: “Ungyometrical arches and vaults in conjunction do not express a scientific logical government which the Government of India is or should be.”

Governmental buildings in New Delhi by Lutyens and Baker both extensively feature load-bearing vaults as well as domes made of bricks. For instance, the dome of the Durbar Hall in Rashtrapati Bhavan is a triple dome of 22 m diameter and 22.8 m high. The dome’s configuration is somewhat a reference to St. Paul’s Cathedral by Christopher Wren – an architect greatly admired by Baker and Lutyens both. The Rashtrapati Bhavan’s bottom-most shallow dome is made of brick, a second brick dome having a conical section with the topmost dome made of reinforced concrete. Robert Irving provides a very lively anecdote which he attributes to Robert Byron, on how the brick dome was constructed through concentric rings of brick laid to the beat of drums.

82 Robert Grant Irving, Indian Summer: Lutyens, Baker and Imperial Delhi (New Haven and London: Yale University Press, 1981), page 270. Robert Byron was a travel writer and one tends to take his colourful account with a pinch of salt although the description of the construction and pomp with which it is described to have been executed sound plausible – as long as they had sturdy enough scaffolding that high for such drama!
Arthur Gordon Shoosmith, architectural assistant to Edwin Lutyens in India was commissioned to build the Garrison St. Martin’s Church, Delhi in 1928 – 30. At this juncture, it is important to consider Lutyens’s advice to Shoosmith: “A building of one material is for some strange reason much more noble than one of many. It may be the accent it gives of sincerity, the persistence of texture, and definite unity.”

Shoosmith heeded to this advice and created what was perhaps the first exposed brick building of this scale in India. Almost windowless, its massive exterior is 22m wide and 48m long with the height of the belfry tower reaching 40m. The barrel vaulted roof was made with heavy formwork as a proper Roman vault. The vault’s external surface was later layered with concrete and glazed tiles added for waterproofing and reducing heat gain. The vault is hidden on the outside by a high parapet to blend with the overall form. However, unlike its English-bond articulated exterior, the vaulted interior has always been rendered.

Years after its construction, St. Martin’s Church continued to receive great attention from being reported first by Country Life in 1931 for its ‘masculine’ qualities and costing £17,000 to being celebrated by historians such as Philip Davies in 1986 who described it as: “A great lumbering dinosaur of a building... made out of 3.5 million bricks.”

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84 This conclusion is drawn upon by comparing archival photos of the building and the author’s visit to the building in June 2014.
Clockwise: (from top)

Durbar Hall dome interior and exterior, 1931

Construction of the Secretariat buildings by Baker showing Roman arch and supportwork, 1921

Garrison St. Martin’s church: barrel vault under construction and perspective rendering, 1929
Herbert Baker and the almost coming of tile vaulting to India

Spanish researchers Camilla Mileto and Fernando Vegas Lopez-Manzanares uncovered revealing correspondences between Herbert Baker and the Guastavino Company among other consultants that considered building the domes of the Parliament Building in tile vaulting.

Additionally charged with designing the Parliament Building on Raisina Hill, Herbert Baker developed a plan that featured a grand central hall surrounded by three houses of Parliament. Each of these structures would be capped by shell structures with the central hall having a large dome over it. Originally interested in cladding the soffit of the dome with Akoustolith, the revered acoustic tiles produced by the Guastavino Company, Baker initiated correspondence to discuss its details.

Upon seeing the drawings and prestige associated with the overseas project, the Guastavino Company offered to build the domes of the Parliament buildings using tile vaulting. The solution would include cladding the soffit layer with Akoustolith but following much deliberation, Baker remained unconvinced of the idea of constructing the Parliament’s domes in ‘two or three layers of tiles no thicker than English roofing tiles’.

Through archival drawings we can determine that all the domes of the Indian Parliament building were most likely constructed in two distinct layers: an outer concrete shell propped by trusses and the interior being a plastered metal lath suspended from the trusses. The role of the Guastavino Company was ultimately limited to supplying Akoustolith tiles for cladding the three chambers and the central hall. (See photos)

Baker further modified some construction details provided by the Guastavino Company in order to achieve a smoother looking surface devoid of raised pointing. Combined with changes to the cladding mortar by local workmen, Baker’s adjustment to the application of Akoustolith tiles turned out to have disastrous effects. Tiles started to fall off the ceiling within three months of the building’s inauguration in January 1927 for which Baker and his team were criticized for in the press.

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86 The ceramic tile developed in house and patented by Guastavino Company possessed remarkable acoustical qualities and was aesthetically very pleasing and came with the express endorsement of leading acoustician of the time Hope Bagenal


88 Ibid. See the illustration in the first chapter of the thesis for the surface finishes offered by the Guastavino company that show a preference for raised pointing to accentuate the coursing patterns.
As a result all four halls within the Indian Parliament building that are lined with Akoustolith tiles had a fine wire mesh applied all over them. The exact period when the meshes were applied remains unclear but they were found to still be in place at the time of writing this thesis.\footnote{I visited the site on 12 June 2014 and was able to see the central hall and the Lok Sabha and Rajya Sabha (Lower and Upper Houses of Parliament respectively.) Some tiles could be seen coming loose and suspended on the wire mesh. It was not possible to take any photos due to the government’s strict rules against it.} Clearly visible even to the naked eye, it is a pity that no permanent solution has been found for the repair and preservation of an otherwise magnificent design. What could have been a showcase of technology at the highest architectural scale was reduced to a pathological case study of ignorance and lack of trust in collaboration.

The rather unfortunate results from working with Guastavino’s acoustic tiles in India must certainly have led to the lack of confidence in the material and in general the building.
technique itself with Baker passing on his soured experience onto those involved with the building process locally.

Baker’s vision for the Parliament’s central dome was rather grand evoking images of the Pantheon which he had visited before starting work in India. This and his admiration for Roman architecture may have further dissuaded him from exploring Guastavino’s ‘new’ construction system. Baker’s reticence to a building technique he was not familiar with would resurface in coming years with his demolition of the Bank of England’s which featured domes made with hollow brick cones championed by Sir John Soane.90

The Akoustolith episode in India qualifies as an interesting case study in speculating how Baker’s decision may have introduced tile vaulting of the highest standards in India through the Guastavino Company.91 No doubt the Indian contractors on the Legislative Assembly project would have learnt the system and tried to build other buildings in the same method – perhaps even making it easier for Le Corbusier to build Catalan vaults in Ahmedabad and Chandigarh three decades later and perhaps more importantly, have inspired a structurally superior version of Raj Rewal’s rendition of the many domes in Parliament Library completed in 2002.

Baker and Lutyens had to their advantage years of tested brick building from England. Baker’s insistence at times on materials being produced in Britain and shipped to India conveys the sense of assurance in homemade production and not risking a compromise on quality.92 However, turning a blind eye to the possibilities of architectural technology and local craftsmanship evidently did not serve the architects any better.

90 See chapter 4 on Ceramic fuses, Soane’s Brick Cones and Burnt clay tubes for more information.
Post-Colonial Practices, 1947 to date

“India is on the move and the old order passes.” 93

Jawaharlal Nehru

The evolution of modern architecture in India has been riddled with contradictions. With an impetus on redefining its identity after Independence in 1947, the vast architectural landscape of the country also faced the question of representation. The tension induced by this postcolonial condition personified itself through two prominent voices which although never publicly collided, were diametric opposites. The first was that of Mahatma Gandhi whose ideas on leading a modest life of frugality, self-reliance and empowering rural areas over urban can be extended to the kind of architectural expression it espoused.

His contemporary, political ally and close friend, Jawaharlal Nehru’s views on progress and governance were different and as India’s first prime minister, Nehru’s capacity to impress them was far greater. As someone who admired modern civilization, for Nehru the decolonization of India was not just a political event but also one that deserved the necessary social, economic and technical changes without delay.4

Jawaharlal Nehru led a surge in the adoption of already established idioms representing progress and this is perhaps best embodied in the creation of Chandigarh. As a new city designed to be unfettered by tradition, Chandigarh became a metaphor for the barrage of modernist visuals, construction techniques and planning ideas being introduced to India. And even though India was no stranger to massive building efforts; the creation of New Delhi and its governmental buildings had been completed less than two decades ago, Chandigarh’s inception sanctioned the full arrival of modernity in India. Through its heavy use of concrete, steel and brick the expressive new architecture had an overriding effect on the existing hand-dominant building culture of India.

Mostly western and technologically advanced, new building materials and associated building techniques gradually elbowed a formidable range of indigenous choices to the peripheries. Reinforced concrete’s total dominance in delivering quick ‘modern’ results in not only buildings but also infrastructure adversely affected the choice of building techniques that architects, engineers, contractors and builders began to make. Indigenous craftsmanship in

93 N.N. Chatterjee, Nehru’s Thoughts on National Topics: India Discovers Herself Again (New Delhi: Publications Division, Ministry of Information and Broadcasting, 2002). Quote from Nehru’s speech from September 7th, 1946.
stone, wood, a wide range of terracotta products as well as a host of building techniques that had been internalized and developed for over centuries under various influences of cultural exchange such as trade, religious evangelism and colonization suffered during this period.

Cultural exchanges with the western world only widened in postcolonial times, as did the influx of not just foreign architects but also the return of foreign-trained Indian architects that saw themselves in prominent advisory positions. Further, the influence that leading modernist architects such as Le Corbusier, Louis Kahn and others brought to India through their direct engagement accelerated the process of cement concrete’s incursion into the urban, modern India.

This perspective turned inwards only around the mid-70s when discourse on bridging tradition with modernism began to emerge led by Indian architects who articulated the problem of banality created by blind emulation of modernist aesthetics in the vibrant and diverse culture of India. Worldwide, architects, postcolonial theorists and academics rigorously questioned the benefits of globalisation against the resistance to resulting homogenization.\(^95\) Culture is not immune to change and must after all remain questionable for its evolution with time is in essence healthy. With the emerging review of the postcolonial condition, there was a growing discourse on evaluating the merits and demerits of regional architectural as a product of cultural thought.

Steps towards expressing this ideology were perhaps best represented in the travelling exhibition: Vistara: Architecture of India in 1986 curated by Charles Correa. Another catalyst agent was the Aga Khan Award for Architecture that recognized outstanding architectural projects in the developing world with emphasis on the Middle East and South Asian regions. This contrasted starkly with the Pritzker Prize that predominantly celebrated architects and architecture in the western world. But what made the AKAA more important was the discourse that it was able to generate alongside the award through participating architects from around the world that supplemented its objectives of promoting regional sensitivities.\(^96\)

Therefore, while the surge in reinforced concrete as a building material was in tandem with that all over the world, the modest brick emerged as a dissenting voice and enjoyed a particularly important phase of employment and appreciation in India. Masonry vaulting in brick and specialized terracotta products began to appear at more modest scales and vaulting

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\(^95\) See writings by Edward Said (Orientalism, 1978) and Homi Bhabha (The location of culture, 2004) that articulate nuances in postcolonial and orientalist legacies. in the developing world. \(^96\) Books, conference proceedings and awarded projects are copiously published, archived and digitally made available through the Aga Khan Trust for Culture’s digital outreach arm: ArchNet at MIT (www.archnet.org).
in India witnessed a plethora of independent voices and renditions through both module and method. These included ceramic fuses and burnt clay tubes (also known as Wardha or Guna tiles) which have been explored in detail in Part II of this thesis.

**Outliers of modern Indian architecture**

Frank Lloyd Wright’s student at Taliesin, Nari Gandhi (1934 – 1993) returned to India to become the country’s foremost voice in organic architecture. Extending Wright’s style with an Indian flavour, Gandhi’s approach to architectural production was that of the anti-machine aesthetic laying emphasis on labour intensive, craft-based construction practice.

True to this ideology, Nari Gandhi’s emancipated approach to building arches and vaulted structures was both precarious and inventive. For instance, the stone arches and fibre-reinforced plastic roof of the Malik House at Lonavla in Maharashtra state were determined to function as an interdependent structure with the weight of the trusses and roof laterally stabilizing the arches.\(^7\) Gandhi further explored a highly individualized triangular arch made through excessive formwork which became a regular tectonic element in his work. Towards the end of his career, Gandhi was exploring more complex methods of designing and building arches – some of which resemble works by Cesar Martinell of Spain but these were unfortunately never realised.

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\(^7\) Rahul Gore, ‘A Documentation of Four Houses of Nari Gandhi and Analysis based on the Principles and Philosophies of the Architect.’ (Undergraduate Thesis, Centre for Environmental Planning and Technology, Department of Architecture, 1996).
A more rational counterpart of Nari Gandhi was Joseph Allen Stein (1912 – 2001). An American who worked in India for 40 years, Stein actively sought to blend India’s rich crafts building tradition with modern construction techniques. And although much of Stein’s work is derived from the Bay Area architecture of California, his understanding that prefabricated concrete building components ought to be sized to suit the human hand proved highly beneficial in the construction of several remarkable structures by making prudent use of Indian artisans. Stein also worked with brick but did not produce any brick vaulted structures. Instead his numerous lightweight shell structures in concrete and steel such as the Escorts Factory (1964), recall the long-span reinforced brick roofs by Eladio Dieste and offer lessons for a possible adaptation for vaulting with terracotta in India.98

The architect, Laurie Baker’s (1917 – 2007) contribution to building with brick in India is of a different order. Even in his Experimental Houses, Delhi (1980) Baker expressed concerns about the ‘very highly intensive energy consumption of steel and concrete’ and created two all brick prototypes with parabolic and inverted parabolic roofs using minimal steel.99 Baker noted that although the formwork for creating the vaults was slightly expensive, having multiple units of the same kind would have greatly reduced the price of formwork and resulted in a better cost-benefit model.

Left:
Escorts II Motorscooter Assembly Plant, Faridabad
Joseph Allen Stein, 1964

Below:
Joseph Allen Stein’s experiments with prefabricating modules sized to the human hand offer great insight into adapting to contextual nuances in construction.
Directly influenced by Mahatma Gandhi who convinced him to remain in India and work for the poor, Baker maintained an unparalleled voice of reason in his architecture. From the brick jāali to curved filler slabs made of Mangalore roofing tiles, Baker constantly sought to improve upon building methods and reduce costs all while keeping the materials and processes as simple as possible. Demonstrating the social disparity in architectural expression, Baker famously said: “What I’ve got left of a working life, I’d like to concentrate on mud. Not something rural and folkly, but a proper decent mud building. Its very difficult to get clients for mud building. When it comes to the poor who’ve already been living on mud, they know it only for its disadvantages. Their dream is a brick-and-cement building.” His legacy is sustained through his Thissur-based COSTFORD (Centre for Science and Technology for Rural Development) and continues to build on his philosophy and train masons from across India in a variety of building skills.

Above:
Brick jāali wall of the Centre for Development Studies in Thiruvananthapuram

Above right:
SEWA Campus, Vilapillsala

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100 Ibid, page 71.
In the spirit of Lutyens’ and Laurie Baker’s ‘one material building’, the Aga Khan Award winning Lepers’ Hospital by Per Christian Brynildsen and Jan Olav Jensen built in a remote village of Lasur in 1983 – 85 is of particular note.\footnote{Brynildsen and Jensen were then students at the Oslo School of Architecture during the construction of the hospital and were credited with two semesters worth of credits for the work.} Designed by Norwegian architects and engineers and built using locally available stone and brick by local masons, the hospital is a hallmark of responsibly executed non-iconic architecture that meets the urgency of need. Built with walls also in brick but predominantly random rubble masonry, brick vaults sit on reinforced concrete beams secured by tie rods. The segmental vaults spring from reinforced concrete beams, span about 4 metres and are secured by tie rods at regular intervals. The vaults are topped with cement and china mosaic made with discarded blue and white glazed tiles sourced from a factory nearby.\footnote{Cynthia Davidson, ‘Lepers’ Hospital’, in Legacies for the Future: Contemporary Architecture in Islamic Societies: Thames and Hudson, 1998), p. 71.}

The project demonstrates the possibility of creating built environments that empower people of a region. Being realistic to what was possible to achieve in a region devoid of high technology with the dearth of a variety of materials or honed skills, the creation of a durable ‘one material’ building has created a sense of security and dignity among its users.
Auroville Earth Institute — Changing the rules of vaulting in India

Auroville is a community near Pondicherry, largely made up of expatriates and devotees of the spiritual gurus Sri Aurobindo and the Mother. Thriving on concepts that seek harmony with nature, Auroville’s Earth Institute is today the most prominent voice of building with earth in India. Its director, Satprem Maini has been heading the institute since its founding in 1989 by HUDCO\(^\text{103}\) and has introduced concepts of funicular form finding and optimization of vaults to the Indian audience.

Regularly attended by architects, engineers and environmentalists, Satprem’s extensive workshops discuss and demonstrate the theory and building of vaults in India through primarily two methods: Roman and Nubian. Of these, the Nubian one is favoured and promoted for its omission of formwork, superior catenary form and cost-saving construction.

Over the years, the Earth Institute has created numerous vaults and domes using its principles of which a noteworthy example is the Dhyanalinga Dome near Coimbatore (1999) built in an astonishing 9 weeks by 200 workers without any formwork. The project report states that the dome used fired bricks instead of the preferred compressed stabilized mud blocks (CSEB) due to a tight deadline. Measuring 22.16m in diameter, the dome rises 7.9m and uses no concrete or steel reinforcement by behaving purely in compression. This was attained by using granite stones as haunches to allow force lines to be accommodated within the middle third of the dome’s tapering section is 530mm thick at the springers and 210mm thick at the oculus.\(^\text{104}\)

It is vital to note that Satprem relies heavily on a variety of graphic statics methods for form finding, improvising upon each to arrive at a desirable result. For instance, in the case of the Dhyanalinga dome, he started the graphic analysis with Gernot Minke’s Line of Thrust method (L.T) and identified its shortcomings for not accounting concentric forces at the base when building without support work. To resolve this, Satprem chose to analyze the dome as an arch – essentially by using the slicing principle\(^\text{105}\) - and modified the section at

\(103\) HUDCO - Housing and Urban Development Corporation is Government of India enterprise established in 1970 to assist in the uniform development of urban centres chiefly through better access to housing, finance and adoption of suitable construction technologies.


\(105\) Santiago Huerta, ‘Structural Design in the Work of Gaudi’, Architecture Science Review, 49.4 (2006), 324-39. Huerta mentions that Frezier proposed the principle of slicing first in 1737 while it was implemented by Poleni in 1748 in his analysis for St. Peter’s dome. Today, the concept is very widely used as part of the Graphic Statics tradition.
the base to optimize the line of thrust to lie within the middle third of the dome’s tapering section, thus resolving the structural calculations purely graphically.

From top to bottom: Nubian vault under construction using minimal guidework

The Dhyanalinga dome under construction with graphical analysis of its structure.
Outcroppings of Auroville’s training school are also independently creating some remarkable structures such as the vaulted exposed brick structure for the Coonan Cross Church in Mattancherry, Kerala by Wallmakers completed in 2015.\footnote{Email correspondence with Shobhita Jacob, Wallmakers on 11th May 2014 regarding the Mattancherry church.}

Auroville-based architect Anupama Kundoo has also successfully created vaulted structures such as her own residence in 2006 using burnt clay tubes and given the module fresh expression by showcasing them alongside other cost-saving terracotta-enhanced reinforced concrete structures. The origins of burnt clay tubes and their more proliferated use is examined in greater details in Part II, Chapter 4 of this thesis.

Kundoo’s doctoral research on fired in-situ structures by Auroville-based potter Ray Meeker, documents the latter’s extensive efforts in creating monolithic vaulted houses. Meeker pursued the idea of eliminating cement mortar in masonry and instead created brick masonry vaults with clay-rich mortar joints which upon firing would transform into ceramic.\footnote{Anupama Kundoo, ‘Building with Fire: Baked-in-situ Mud Houses of India: Evolution and Analysis of Ray Meeker’s Experiments’ (PhD Thesis, Technischen Universität Berlin, 2008), p. 22.} These lessons were finally put to use in the construction of Anupama Kundoo’s Volontariat Home for Homeless Children, Pondicherry 2011 (photos below).
Resonating with the construction technique of fired earth shelters by Nader Khalili, Kundoo quotes him: “Here, instead of taking the materials to the fire, we were bringing the fire to the material, And thus a new horizon had opened up to us”. Although extremely energy intensive, the beauty of the construction system was multifold – it eliminated any joints making it truly a ‘one material building.’

The approach to architectural production and India’s economic and demographics are also intimately linked. As the Indian population burgeoned post independence, heavy migration to cities further exacerbated not only the housing shortfall in urban and rural areas but also the rural-urban divide manifested itself in new socio-political conditions. Building techniques available in the city’s capitalist economy capable of rapid delivery, best incarnated by cement concrete, contrasted with hand-hewn construction methods of the village.

Reflecting upon their experience from working in rural areas, the Desais stated: “Buying power has replaced manpower, that resources are not available to people to build their own buildings without the intervention of the marketplace or the governments and yet the predominant expert technical assistance available is one that promotes energy intensive and modern technologies that alienate the rural builders from the building process. And to not have that palpable association with your own buildings creates the kind of dissociation and looking down upon rural / crafts-based building methods that have just been shunned inducing a discontinuity in trust and pride.”

Brick Production in India and Cultural Associations

Brick and its most basic constituent, clay, continue to suffer from being stigmatized as a telluric material when compared to cement concrete, which in contrast remains the benchmark of a modern, progressive lifestyle conferring its masters a social status of affluence and sense of permanence. The disparity in this understanding is accentuated with the economic boom of India and the developing world that seeks to compare itself with western models of achievement.

On the other hand exposed brickwork finishes may be seen to possess a cryptic aesthetic quality appreciated only by the educated urban elite familiar or perhaps those sensitized to the Brutalist ideals of architecture with Le Corbusier and Louis Kahn having directly influenced future generations of architects in India. Their work sanctioned the use of

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exposed brick and adversely reserved its appeal to a limited set of people rarely trickling down to the bourgeois.

As the production and use of fired clay products is intimately linked with the promising architecture of shell structures, it is necessary to understand the underlying motivations for their use and place today. India accounts for over 10% of the world’s fired clay brick production making it the second largest producer of bricks having more than 100,000 brick kilns that produce in excess of 200 million bricks annually.\(^\text{110}\) The construction industry itself in the country is set to grow at 6.6% per year between 2005 through 2030 owing to an increasing infrastructure and affordable housing market.\(^\text{111}\) The late but definite foray of international brick manufacturers in India such as Wienerberger as well as dedicated investments by major domestic business houses such as Tata and Mahindra into affordable housing further testifies the growing construction market.\(^\text{112}\)

Concerns within the brick industry revolve around the competition that alternative materials such as concrete blocks, Aircrete and Fly Ash-Lime Gypsum (FaL-G) blocks provide.\(^\text{113}\) However, several factors reinforce the continuation of brick production and sustain the involvement of labour such as:

i) Changes in production methods such as energy efficient kilns, improved onsite presses and the scientifically attested production of cement stabilized soil blocks.

ii) Government of India rural housing and employment schemes such as the National Rural Employment Guarantee Act (NREGA) and the Pradhan Mantri Gram Awas Yojana (PMAY-G)\(^\text{114}\) for assisting the rural and peri-urban populations to build capacities and ensure safe, affordable housing.


\(^{112}\) Wienerberger’s brick manufacturing plant in Bangalore was operational in 2009 and has a 200 million annual brick production capacity.

\(^{113}\) Sameer Maithel and Ashwin Sabapathy, ‘Strategies for Ceaner Walling Materials in India’, Shakti Sustainable Energy Foundation Initiative, 2011

\(^{114}\) Mahatma Gandhi National Rural Employment Guarantee Act (NREGA) was introduced in 2005 to enhance the livelihood of the rural population by guaranteeing a 100 days / financial year of wage-employment to families that has adult members volunteering to do unskilled manual work.
iii) The permeating sense in the Indian architectural community of environmental sustainability and expressive structural form fuelled by domestic organizations such as Auroville’s Earth Institute, COSTFORD and others.

The manner in which we choose to build conveys much about our social values and prevalent concerns. Coomaraswamy’s passionate essay: Symbolism of the Dome\textsuperscript{115} concerns itself with ‘why’ the dome (and vault) symbolizes its deeper connection with the human psyche, while my exploration of ‘how’ seeks out a variety of methods that artisans and builders in India choose to build shell structures. My study thus weaves a tapestry of India’s cultural reflections through its taste for architectural experimentation by using vaulting as not merely a recurring roofing technique but an age-old ontological practice that has persisted and adapted to times contemporary.

\textsuperscript{115} Architecture in Medieval India: Forms, Contexts, Histories, ed. by Monica Juneja (Delhi: Permanent Black, 2001). p 244
PART II

Modules, Methods and Motivations
Chapter 3
Evaluating Catalan Vaulting at Villa Sarabhai
(1951 – 1955)

Summary

“For the structure, Catalan vaults: cradle-vaults of flat tiles set in plaster without formwork, coupled with a row of bricks cast roughly in cement. These half-cylinders are carried to the walls by the intermediary of a rough concrete lintel. The composition serves to create openings in these walls, all parallel, playing solids against voids – but playing intensely the architectural game…Much research has gone into this house. One of the most brilliant solutions is that of the roof.” — Le Corbusier on Villa Sarabhai

I undertook the study of the Villa Sarabhai primarily because it claimed to have Catalan vaults and therefore would have been the first and only known example in India to date. Even without this distinction, the Villa Sarabhai House is an iconic modern house as its architectural language embodies Corbusier’s pursuit of Beton Brut, best reflected in his works in Chandigarh and Ahmedabad, that has had lasting influence in India.

This chapter explores Le Corbusier’s attempts at tile vaulting in Chandigarh and Ahmedabad. While tile vaults were successfully built at the Maisons Jaoul, a similar project built simultaneously under the close scrutiny of his atelier in Paris, through onsite investigations, archival research and interviews with the owners and maintenance crew, I show that the vaults at the Villa Sarabhai are indeed not constructed as claimed in the Catalan method.

Above and following page:
The Villa Sarabhai remains a highly influential work of architecture in India and the house itself has accumulated a rich patina of life since its completion in 1955.
Le Corbusier in India

“India is a country not yet molested by the machine age or inhumane theories. To me India seems supremely human.”

Le Corbusier was invited to design the city of Chandigarh due to unforeseen circumstances but his contribution to India extended beyond the city. For Corbusier, India offered a great opportunity to apply his ideas for city planning and refresh the palette of his architectural vocabulary for a broader canvas.

His first ever time in India, Corbusier was famously fascinated by the myriad visual culture of the country. Just like the British Empire sent off the Baker-Lutyens team across India to take in the visual culture of the place, Le Corbusier was accompanied on a similar orientation tour by his new patrons around Chandigarh, Delhi, Jaipur and parts of Gujarat. The peculiarities and diversity in landscape, architecture and lifestyles all copiously filled Corbusier’s sketchbooks on each of his trips and he continued to convey his excitement in his letters to his mother and wife.

In March 1951, while on an official visit to Chandigarh, Le Corbusier was invited to visit Ahmedabad by the Municipal Corporation to discuss an offer to design a 30,000 sq. ft Museum for Painting, Sculpture and Archaeology. Although the letter was sent by the Chairman of the Recreational and Cultural Committee of the Municipal Corporation of Ahmedabad, the invitation was campaigned by a coterie of the city’s elite business families with the intention of commissioning Corbusier for their own projects. Corbusier was contractually bound to visit Chandigarh twice a year and he could fit in his trips to Ahmedabad easily when enroute to Bombay before flying onward to Paris. Le Corbusier obliged to the Ahmedabadis’ requests and bagged five commissions upon arrival: a house for Ahmedabad’s Mayor Chinubhai Chimanlal, an office building for the Ahmedabad Mill Owners Association (AMOA) – which Chinubhai was Chairman of, a house for Surottam Hutheesing (later called Shodan House), Sanskar Kendra (City Museum) and a house for Mrs. Manorama Sarabhai.

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118 Much has been written about Chandigarh falling into Corbusier’s hands after the untimely death of Matthew Nowicki and Albert Mayer’s reluctance to continue. Jane Drew and Maxwell Fry, both already consultants to the project are said to have been instrumental in ensuring Corbusier’s candidature for the position. For more information on the genesis of Chandigarh read Vikramaditya Prakash’s: Chandigarh’s Le Corbusier: The Struggle for Modernity in Post-colonial India.
119 Letter P3-4-15, Fondation Le Corbusier, Paris. The letter was addressed to Le Corbusier, C/O East Punjab Capital Project, Simla.
Mrs. Sarabhai was the sister of the Mayor of Ahmedabad and while the above-mentioned patrons were related to each other through familial or business ties their respective commissions and requirements remained distinct and disconnected. Renowned for their wealth, contribution to the freedom movement and patronage of the arts and education, the Sarabhaïs have also been compared to the Medicis of Florence for their stature and influence on contemporary culture. Two other important personalities of the Sarabhai family were the siblings – Gira and Gautam Sarabhai. Gira Sarabhai had studied architecture under Frank Lloyd Wright at Taliesin around 1948, while Gautam studied at the University of Cambridge and subsequently developed a keen interest in architecture.

In the following months and years, Corbusier’s interactions with Gira and Gautam Sarabhai were particularly vital to him in attaining overall understanding of the Ahmedabads’ tastes and aspirations. Although they had not directly commissioned Corbusier’s services, they remained in contact with him over the years regarding the various projects and even served as interlocutors on occasion. Gira had accompanied Le Corbusier on one of his orientation tours around Ahmedabad and having developed a bond with her, Corbusier, upon returning to Paris to work on the designs for Ahmedabad, wrote to Gira asking for dimensions of the Hutheesing temple and the Sarkhej Roza which the two had visited along with Chinubhai, the Mayor of Ahmedabad.

At this point, it was almost serendipitous for a young 24 year old Indian architect, Balkrishna Doshi, to arrive at Corbusier’s studio at Rue de Sevres. Corbusier’s office had attracted young apprentices from around the world but Doshi would be the first from India. Doshi had travelled to London to prepare for the RIBA exams and learnt about Corbusier’s work through his publications. He attended a CIAM meeting in London before making up his mind to work for Corbusier in Paris. Having left his architectural training incomplete in Bombay and later London, Doshi thus arrived in Paris with sufficient skills and knowledge to serve in Corbusier’s studio and would go on to spend the next four years assisting in the design and preparation of drawings in Paris before eventually returning to India in 1955 to supervise the completion of Corbusier’s India projects.

Vaulted Form and Corbusier’s Discovery of Catalan Vaulting  

120 First by William Curtis in Ideas and Forms (1994) and then in Taschen’s Indian Interiors publication. Traditionally textile merchants and mill owners, the Sarabhaïs were an influential family in Ahmedabad. The eldest scion Vikram Sarabhai was a renowned Atomic physicist – founder of the Indian Space Research Organisation, IIM’s first director and a driving force in putting Ahmedabad at the forefront of a modern post-independence India. His siblings – Gautam and Gira Sarabhai were leaders in the cultural realm.  
121 P3-5-155, LC letter to Gira Sarabhai dated 3rd May 1951, FLC Archives  
When I am given a task, I am in the habit of tucking it away in my memory, that is, of not allowing any sketch to be done for several months. The human head is so made that it maintains a certain independence: it’s a box into which you can pour helter-skelter the elements of a problem…then one day, a spontaneous initiative of the inner being takes place, everything falls into place; one takes a pencil, a bit of charcoal, some coloured pencils (colour is the key to the process) and one gives birth right there on the paper: the idea comes forth, the child comes forth, it has come into the world, it is born.123

The above quote justifies Corbusier’s recurring fascination with the vaulted form and perhaps a long harboured desire to create a remarkable vaulted structure of his own. This fascination is captured in Corbusier’s sketch of Gaudi’s school at Sagrada Familia made during his visit in 1928.124

Corbusier’s first famous design of a vaulted structure was the Monol House in 1920. Characterized by similar attributes, his subsequent creations were often referenced retrospectively as ‘Monol-type’ with each featuring internal divisions of rooms through bays capped with vaulted ceilings reflected in the elevation and rooftop gardens.

While the visual references made by scholars are justified in comparing Corbusier’s various buildings, most of the subsequent literature seems to plainly assume that the previous one is correct.125 Of his vaulted creations, two buildings have received most attention: the Maisons Jaoul in Paris and the Villa Sarabhai in Ahmedabad. And some even go further to associate the building technique with a cultural phenomenon: Kenneth Frampton notes that the Villa Sarabhai’s vaulting technique (and that of Maisons Jaoul - both dated around the same time)

124 Riccardo Gullí, 'La huella de la construccions tabicada en la arquitectura de Le Corbusier', in Las bóvedas de guastavino en América, ed. by Varios autores ([n.p]: Instituto Juan De Herrera, 2002), p. 75.
125 Caroline Constant, ‘From the Virgillian Dream to Chandigarh’, The Architectural Review, 1 (1987), 67 - 69. Constant refers to the Monol type house as Catalan and true to its earthy roots. William J.R. Curtis, Kenneth Frampton, Charles Jencks, Ricardo Gullí are among the notable scholars who refer to the vaults at the Villa Sarabhai as Catalan.
was Corbusier’s response to the vernacular setting.\textsuperscript{126} James Stirling makes a similar claim about the Maisons Jaoul\textsuperscript{127} and - therefore by extension - the Sarabhai House.

The referencing of the Catalan vaults seems to have been fed primarily by Corbusier’s own office through the self-celebratory publication of the Oeuvre that state: “Catalan vaults” but my research on the Villa Sarabhai uncovers contradictory evidence to this claim.

Shortly after returning to Paris from his trip to India in March – April 1951, Corbusier left for Bogota. He had been invited by the Government of Bogota to design a masterplan for the city and took the opportunity to visit a fellow architect Francisco Pisano’s house for a second time. On his first visit to Pisano’s house in September 1950, Corbusier had noted its vaulted roof and was fascinated to learn – for the first time – about Catalan vaulting that had been deployed in its construction making a note of it in his sketchbook.\textsuperscript{128}

\begin{quote}
Above: Le Corbusier’s sketches of tile vaulting at Pisano’s house during his first visit in 1950 which shows only a handful of details captured of what would become a fascination over the next five years.
\end{quote}

In June 1951, when Corbusier visited Pisano’s house again, he made further detailed inquiries into the actual construction technique with sketches showing the salient features of tile vaulting: minimum guidework, layered construction and binding mortar. This must be

\begin{flushright}
\textsuperscript{126} Kenneth Frampton, \textit{Evolution of 20th century Architecture: A Synoptic Account} (Wein, New York: Springer, 2007), Page 40. Stirling echoes this in his essay on the Jaoul houses (see below). Frampton even erroneously refers to Jacques Michel, an architect in Corbusier’s office and in-charge of the Jaoul and Sarabhai projects as the son of Michel Jaoul, the patron of the Maisons Jaoul – a mistake picked up and repeated on Wikipedia.

\textsuperscript{127} James Stirling, ‘Garches to Jaoul: Le Corbusier as Domestic Architect in 1927 and 1953’, in \textit{Le Corbusier in Perspective}, ed. by Peter Serényi (Prentice Hall, 1974), p. 60. Stirling was referring to the Maisons Jaoul being the opposite of a machine (for living) as it was ‘handmade’ and did not represent the technological advancement of structural assembly to begin with.

\textsuperscript{128} Fondation Le Corbusier, Paris. Sketchbook D15 (1950 – 54). Sketch numbers: 83, 84, 85 made around 17 – 18 September 1950 – first visit to Pisano’s house in Bogota clearly show the size of module, layered construction, portable guidework, etc.
\end{flushright}
seen as a vital discovery for Corbusier as it empowered him with new knowledge of a time-tested building technique that had flourished in a climate which resembled India’s.
The vaulted form continued to feature repeatedly in Corbusier’s sketches in the period between 1951 – 1957. With India having provided such a large canvas for his work, Corbusier now had multiple opportunities to deploy the vaulted form constructed using tile vaulting. Projects in Chandigarh such as the High Court and Governor’s Village; and in Ahmedabad such as the Villa Sarabhai, Hutheesing house, Sanskar Kendra (City Museum) all featured vaulted roofs in their initial stages. It would seem that tile vaulting would have a chance again in India.

There is no doubt that the cultural association with the building technique is an important inference to seek – as I have tried to – but should the premise of the building technique itself be misread, one is bound to be misled into drawing displaced conclusions from the relationship. The value of this analytical dissection, especially in the context of India, was well-illustrated by Vikram Bhatt and Peter Scriver’s critical review of Raj Rewal’s Hall of Nations (1972) where the architect’s determination to achieve an end result compromised the intrinsic logic of its construction, thereby creating a structure that merely mimicked the appearance of its precedent and not the principles of structural assembly or prefabrication. This only exacerbated the relationship between source and result as while one pioneered mass production and mechanized construction, the other revealed how tethered the Indian building culture was to hand-reliant labour. To have then attributed the building to Fuller’s notions of geodesic design would be uninformed and ignorant. By extension, this would turn out similar for the Villa Sarabhai.

Grille Climatique (Climate Grid)

It is arguable, that despite the many influences that continued to shape his work in India, the singlemost unifying aspect of designing for Chandigarh and Ahmedabad was the Indian climate. Through his frequent visits to the two cities, Corbusier gradually grew accustomed to the drastic variations in the Indian weather – diurnal and seasonal – and was convinced of having to address the problem of harsh weather conditions that the place presented. Determined to integrate these solutions in his work, his letters and notes between 1951 and 1954 – the early design stages – reflect an ongoing obsession with having to respond to climate. In 1951, he wrote: “For the Capitol, do not hesitate to make grand empty naves (full) of shadow

129 Outside India, Corbusier proposed a number of vaulted structures: a house in Algeria, a large retreat for Roq et Rob in 1949, of which only the Maisons jaoul were completed. The monol-type house, numerous other examples (Weekend residence) where he explored the structural system but it was his visit to Bogota, Colombia that this turned into a persistent theme capable of being realized.
130 The first instance being when it was steadfastly turned down by Herbert Baker in 1920s for the Legislative Building (now, Parliament of India), which could have been built by the Guastavino company itself.
and air currents.” Then, reflecting on his work in 1954: “What counts is the depth of the shadow”

Even the door of the Assembly building in the Capitol Complex is decorated with solar symbolism.

Of the two residential commissions in Ahmedabad that materialized, the Shodan House and the Villa Sarabhai could not be more different in their expression. And yet, Corbusier’s architectural solutions for both seem to stem from his desire to respond primarily to the extreme climate while drawing from architectural references familiar to the Ahmedabads.

While for Shodan, his design references a grander scale of the recently completed La Plata, for the Villa Sarabhai he seemed keen on extending the landscape of the site through his building. The spaces created at the Villa Sarabhai also recall the dark interiors of old Ahmedabadi architecture such as the Hutheesing Jain Temple (1848) and the Islamic buildings at Sarkhej (15th century).

With the climate playing a major factor in defining the Indian experience, the Paris atelier resolved to develop a system that would enable them with the tools to invent, deploy and express architectural tectonic elements and fenestrations that would serve as vital design components in fending the Indian weather while continuing to make bold stylistic statements that Corbusier’s architecture was renowned for.

Members of Corbusier’s studio such as German Samper and Iannis Xenakis were tasked with developing the Grille Climatique (or Climate Grid) which divided the year into seasons charting humidity, temperature, rainfall, diurnal ranges to determine liveable conditions. To help populate this chart, Corbusier asked Gira Sarabhai for Ahmedabad’s climatic data in October 1951; in January 1953, Doshi wrote to the National Physical Laboratory, New Delhi requesting for climatic data which would help the atelier address the climate of Chandigarh while Xenakis in particular developed solar path charts that could help the atelier trace the extent to which sunlight would enter into their designed rooms. Jean-Louis

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132 Sketch 403, Le Corbusier Sketchbooks E19, 1951 India – 2nd Sketchbook March – April 1951
134 And yet they both continue to remain incredibly influential in India offering unique solutions for tropical living. It was indeed the tropical world that offered Corbusier the opportunity to completely refresh his tectonic palette – this time to be driven by climatic elements.
138 Letter G2-14-31 dated 16th January 1953, B.V. Doshi to National Physical Laboratory, New Delhi, Fondation Le Corbusier, Paris.
Veret would later carry Xenakis’s notes with him to Ahmedabad. Thus, a comprehensive exercise was carried out in developing the Grille Climatique.

The influence of the Grille Climatique was considerable and even though Corbusier later regretted that the lessons were not fully understood and therefore not executed to the intended extent, the tectonics of his buildings such as the Villa Shodan, the office of Ahmedabad Mill Owner’s Association and the Chandigarh’s Capitol Complex buildings in particular flaunted bold architectural elements such as large façade-scaled sun-breakers, covered terraces, deep recessed windows, verandahs and voluminous internal spaces. Resonating with similarities to the contemporary work of Maxwell Fry and Jane Drew in Africa, the weather-responsive building elements typified the Chandigarh architectural vocabulary – to be later emulated by architects worldwide.

While almost all of Corbusier’s projects in India reflect the Grille Climatique’s lessons, only two of them actively sought to combine it with the Catalan Vaulting: The Governor’s Village in Chandigarh which was meant to house the workers of the Capitol Complex and the Villa Sarabhai in Ahmedabad – a private haven for an affluent family of three. Diametrically opposite in the scale and purposes they were to serve, the two projects are kindred spirits in their tectonic expression central to this study.

**The design of the Villa Sarabhai**

139 Handwritten notes from Xenakis were found in the JLV archives at Cité in Paris. After working for Le Corbusier for 10 years, Xenakis is said to have been the creative head of the Philips Pavilion in the Expo ’58 in Brussels (1958) and later fell out with Corbusier when the latter took complete credit for the building. He later left the studio and is today recognized as one of the most important composers of 20th century Europe. See The Guardian’s article on Iannis Xenakis from 18th February 2009; https://www.theguardian.com/music/tomserviceblog/2009/feb/18/iannis-xenakis-architecture-classical, last accessed 27th September 2017.
Arguably his most modest commission in India, the Villa Sarabhai was still a prestigious one for Le Corbusier. The house was meant to serve Mrs. Manorama Sarabhai and her two young sons Anand and Suhrid. Even before the arrival of Le Corbusier, the Sarabhai family were well connected to the international world and had a history of being associated with foreign architects and collaborators who often stayed at their house at the Retreat. It is clear that Corbusier was well aware of the informed nature of his Ahmedabadi patrons prompting him to make a note in his sketchbooks as a reminder to himself: “choose someone with great sensitivity to send to Ahmedabad”.

Following three site visits and meeting clients in Ahmedabad, Le Corbusier’s studio was well on its way to producing architectural elevations and plans which were already being discussed for the Villa Sarabhai by March 1952. This was the first drawing attributed to the Villa Sarabhai and was filled with environmental strategies with handwritten notes emerging most likely from discussions that took place on site.

The first proposed plan comprises ten interconnected bays with three in the centre left open-to-sky to serve as a carport. Pink coloured areas on the drawing are demarcated as the main fully enclosed habitable spaces while the walls extend to become deep verandahs. A thumbnail sketch shows verandahs and gable ends playing an important part of Corbusier’s strategy for blocking out the sun by creating a peripheral zone to keep out the sun and rain. Steps leading to a large pool can be seen starting in front of the carport and stretching the length of six bays making a clear reference to Corbusier’s idea for incorporating traditional architectural gestures that he was impressed by in India and specifically in and around Ahmedabad such as the large basin at Sarkhej. The plan is orientated to channel the prevalent wind over the pool and into the house thereby cooling the interiors.

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140 In 1946, Gira and Gautam Sarabhai had approached Frank Lloyd Wright had propose a design an office building for the Sarabhai Calico Mills. During his trip to India in 1955, the artist Alexander Calder was a guest of the Sarabhais at the Retreat and so the family home was a hotbed for exchange in the arts before even before Corbusier’s creation put it on the world map.

141 Sketch 404, Sketchbook E19, 1951 India – 2nd Sketchbook March – April 1951.
Most importantly, the elevation reflects Corbusier’s desire for a continuous band of exposed vaults as an important feature. His desire to build these vaults in the Catalan method is confirmed through his sketches on the very first drawings for the Villa Sarabhai. The thumbnail sketch shows him detailing a square 7” module and explaining the layered construction technique done with basic guidework. Based on the date on the drawing, in all likelihood, this discussion was articulated in the presence of Gira and Gautam Sarabhai during Corbusier’s site visit in March and again in November, when he made three more sketches at site dated 17th November 1952. These sketches most likely enticed the Sarabhais to build a test vault in Corbusier’s prescribed method. The fateful outcome of this experiment was disclosed by Manorama Sarabhai in her letter to Corbusier the following December: “Gira and Gautam tried the brick arch but it collapsed. This is just for your information.”

Seemingly casual yet this is an important event as it is the first occasion when a supposed Catalan vault attempt failed after being directly suggested by Corbusier.

There are no details regarding the span, profile or method of construction used by Gautam and Gira to determine what may have caused the failure of the arch but based on the recorded sketches and discussions, we can deduce that Corbusier had proposed they build the arch in the Catalan method.

Perhaps the arch attempted was single layered or did not have secured supports or perhaps the module used was too heavy and the Sarabhai used full-sized bricks instead of brick tiles. An average full-sized brick in India weighs around 3 kg. The weight of the module is a vital detail that is also easy to overlook. If a full-sized brick was indeed used, it is highly unlikely that the arch would have been erected without formwork using either plaster of Paris or cement. This has been discussed fully in the prototyping chapters.

142 Dates have been derived from the travel schedule detailed out by Corbusier in P3-5-298 FLC Archives when trying to persuade the Ahmedabadi clients to pay him his due fees. See drawing FLC 06688 from November 1952 that has sketches of the Catalan technique again. See FLC sketches: P3-7-35-001 to 002, P3-7-36-001, Fondation Le Corbusier, Paris.
143 Letter P3-4-155 Manorama Sarabhai to Le Corbusier dated 30th December 1952, Fondation Le Corbusier, Paris. Mrs Sarabhai was writing to express her eagerness in seeing the plans for her house and informing Corbusier that Gautam was in London and could bring them back to Ahmedabad if his atelier had finished the drawings.
144 It is difficult to generalize brick sizes especially in the case of India where the brick industry is highly informal and decentralized. However, to match structural dimensions, the most widely used brick in India measures 230 mm x 110 mm x 75 mm and weighs approximately 3 kilos.
Corbusier’s sketches on site dated 17 November 1952 clearly indicating a layered construction system akin to the Catalan principles.

Notes that mention a roof garden atop a continuous band of vaults also depicting interior spaces.

Finding representation and collaboration

The construction of a good building demands a good team of experts working on it in harmony. The importance of collaboration proved crucial when we examine the design development of both the Maisons Jaoul and the Villa Sarabhai and what each was able to achieve. Le Corbusier had his trusted cousin and frequent collaborator Pierre Jeanneret as his chief representative in Chandigarh and as his projects in Ahmedabad grew in complexity and reached construction phase, Corbusier needed someone in the city to represent his studio and bridge the drawings with their faithful execution at site.

To this effect, there is a chain of letters between Corbusier and a young British architect, David Goldhill whom the former was keen on recruiting for Ahmedabad. Corbusier most likely considered this to be an ideal arrangement as Goldhill, familiar with Corbusier’s modernist ideas, would have served the dual purpose of sensitively realizing Le Corbusier’s drawings on site and be able to effectively communicate with the Indian clients through English. Nonetheless, the brief window of opportunity passed all too quickly as the Ahmedabadi bureaucracy were too slow in replying to Le Corbusier and Goldhill was no longer keen on committing to the task.145 With time pressing on, Le Corbusier had no choice but to dispatch a young Jean-Louis Veret to India while Jacques Michel was in charge of the project in the Paris studio. This would be Veret’s first experience of working on site after having graduated from architecture school less than a year ago.146

Veret thus sailed for India on 22nd May and arrived in Ahmedabad on 7th June 1953. Corbusier subsequently visited Ahmedabad on 22nd June when the Ahmedabad Mill Owners’ Association (AMOA) site was finalized and sketches for the Villa Sarabhai continued to evolve with clearer details. It is vital to note that Jean-Louis Veret’s relationship with the various other Ahmedabad projects: Shodan, AMOA, Sanskar Kendra was different than his with the Villa Sarabhai as he was domiciled in a house on the Sarabhai site even though all official correspondence between the Paris and him was directed to the Ahmedabad Mill Owners’ Association address.

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145 See letters in FLC Archives: G2-11-1033 (LC to Goldhill), G2-11-1048 (LC to Deputy City Engineer II of the Municipal Corporation of Ahmedabad), G2-12-163 (where LC’s secretary consoles an increasing impatient Goldhill saying “the orientals are neither rapid nor very clear.” P3-7-183 Goldhill earnest letter to LC’s Secretary explaining his reasons and frustration at the ‘tortuous correspondence’ that led to nowhere.

146 Le Corbusier in India, dir. by Manu Rewal (2001), Duniya Vison (India) Pvt. Ltd. Part 1 – Chandigarh and Ahmedabad. Jean-Louis Veret talks about his time in Ahmedabad in an interview specifically about being a young architect deputed to supervise important commissions in Ahmedabad.
**Beton Brut: From exposed vaults to concealed ones**

The design of the Villa Sarabhai continued to evolve in the meantime and sketches show the initial arrangement of the pool that is set with its longer side perpendicular to the bays of the house in an effort to draw in cool winds. The office toyed with the profile and siting of the pool but the idea of a vaulted elevation remains consistent and important in defining the house’s personality.

These explorations continued in drawings dated November 1952 and the first drawing to that has an exposed concrete band façade wrapped around the house is dated February 1953.

Left
Jean-Louis Veret’s Identity card used in Ahmedabad, India

Bottom left
Corbusier’s Rue de sevres studio with Doshi and Veret (partly hidden behind lamp)

Bottom
Jacques Michel, in-charge of the Maisons Jaoul and Villa Sarabhai projects in Corbusier’s Paris studio
Curtis attributes the change in the elevation treatment of vaults from being exposed to hidden to their being rejected to avoid making the house look as if it was designed to look like a factory. Curtis offers no reasoning or reference for the statement but Suhrid Sarabhai recollected no such discussion having taken place between Corbusier and his mother and in fact felt that she had always given Corbusier a free hand. There is also no evidence of it in the correspondence records or notes on drawings found at the FLC or Cite Archives. So the change can be attributed to one of aesthetic treatment.

This period marked an important phase in Corbusier’s career when he was pursuing his ideal for béton brut, reiterating and asserting it regularly for its clarity of spirit and not of an actor having to smile being dressed up in marble. For some time, Corbusier had also been insisting on the use of rough bricks with somewhat crude masonry saying: ‘We are not bourgeois, we appreciate the roughness of brick’ and his artisan-mason Salvatore Bertochhi was instrumental in realizing this vision at the Maisons Jaoul site which he reminisced with some humble bragging.

It was therefore absolutely crucial for Corbusier to demonstrate and showcase how his buildings had been constructed. For the Villa Sarabhai, Le Corbusier’s office carried out several iterations for how the exposed vaults would be seen and treated externally. The sketches show options that explored an undulating roof terrace and not a flat one, another shows a Jaoul-like option with an arch-profiled concrete beam in the front mimicking the vault behind and a third option looked at projecting the tile vaults beyond the façade to create a rhythmic exterior.

With the thick concrete band and exposed brickwork elevation approved, there were no subsequent changes to the elevations and numerous other details were developed and discussed through regular letters between Veret, Corbusier and Jacques Michel. Mrs. Sarabhai would continue to write to Le Corbusier for matters deemed important or that involved changes to his proposed design.

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148 Interview with Mr. Suhrid Sarabhai at the Villa Sarabhai, Ahmedabad on 1st December 2015
149 See Le Corbusier’s Sketchbooks 1951
151 Bertocchi had completed a house for Prof. Fueter in Switzerland where Corbusier had insisted on rough finishes in exposed masonry. For more details see Maniaque page 85. Corbusier’s wife Yvonne was godmother to Bertochhi’s son – see Caroline Maniaque-Benton page 84
Sketches exploring a variety of options for treating the vaults on the façade and can be assumed to have been made between 1951 and February 1953 when the elevation was changed to have a large concrete fascia.
Corbusier’s transition from a vaulted façade to a modernist one is still deeply rooted in responding to the historical formality and visually arresting context that India offered.

Left: Pavilion at Deeg Palace, Rajasthan, 1772 (RIBA 20058)

Below: FLC.06687 06689, 06695A
Comparisons between the construction of Jaoul + Sarabhai Vaults:
Lack of technical expertise and the handicap of remote quality control

Catalan vaulting was undoubtedly a new technique for Corbusier as he was also completely unaware of its French counterpart: Rousillon vaulting – named after the province in southwest France close to the Catalan border where it was practiced. Perhaps with some sense of caution, Corbusier chose to deploy the Catalan vaults for his domestic architecture only. As the Maisons Jaoul provided the accessibility of home turf, Corbusier’s office sought the expertise of the Catalan engineer-architect Domènec Escorsa for their vaults specifically. Also crucial to the Maisons Jaoul’s construction was Corbusier’s trusted artisan-mason Salvatore Bertochhi.

Although the Villa Sarabhai’s design preceded Maisons Jaoul, detailed drawings for their vaults were developed almost simultaneously in 1953. However, in his correspondences Jacques Michel, who was the architect in-charge for both projects, refers only to the Maisons Jaoul when seeking advice from Escorsa or Bertochhi perhaps because the office was decided on replicating the lessons of the resulting construction system. And to this effect, the Jaoul vaults were the first to be prototyped. Le Corbusier scholar Caroline Maniaque-Benton gives an account of their construction in her interview with Bertochhi whose recollection fits well with the Catalan vaulting method of using a portable formwork made of soft wood shaped to the curvature of the vault over which the first layer of tiles were stuck with plaster which would make serve as formwork for the second layer.

This is consistent with the photographs of the project taken during its construction phase. The vaults at Jaoul, although shown complete and never under construction, confirm the laminated building method dictated by the Catalan technique. Flat tiles set in plaster of Paris bear a second layer of hollow bricks. As a lightweight material, the hollow brick makes for an excellent second layer for Catalan vaulting.

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152 Corbusier never refers to Rousillon vaults in his writings despite the possibility of him having learnt of the technique owing to his imminent interests in vernacular expression, construction technology and geographical proximity to the region.

153 Escorsa evolved into a long-term collaborator with his early correspondences with Le Corbusier and Pierre Jeanneret date back to CIAM meetings in 1949. He was also involved with a 1953 LC sculpture in Beziers and many years later replaced Jacques Michel for a Josep Lluís Sert project Carmel de la Paix, France.

154 However, Bertocchi’s description does not seem to match the site photographs that show a flat tile and a hollow brick as the first and second layers respectively.
Above: (FLC 09903A)
Detail of the Maisons Jaoul vaults clearly showing a double layered construction with waterproofing and earth filling on top.

Left: Zoomed detail of same drawing.

Below: (FLC 06713)
Drawing of the Sarabhai vaults also showing a two layered shell with the first layer as a 2 cm brick and the second a 5 cm one. Details common with Jaoul include earthwork and roof finish. Zoomed detail of same drawing on

Photos of the Maisons Jaoul’s vaults are the only documented record of tile vaulting attempted by Le Corbusier’s office. The photos show a two-layered construction comprising a flat tile at the bottom with an extruded hollow brick over it.

Photos by Lucien Herve, courtesy Fondation Le Corbusier
Vaults dimensions, module and weight

The genius of the Villa Sarabhai’s plan lies in its vaults. Single curved, they allow for an identical, repetitive structural system which makes the experience of the house feel cohesive and yet easily divisible. This is all the more important at the Villa Sarabhai as there are 10 equidistant bays to be connected, unlike the Maisons Jaoul that has just two of unequal spans on each level. It is also worth noting that the tile module used at the Maisons Jaoul is rectangular while the Villa Sarabhai uses a square one. This does not affect the ease of construction as long as care is taken to ensure that masonry joints are broken in successive layers.

Villa Sarabhai’s vaults rest on large concrete beams measuring 0.36 m thickness, 0.69 m wide where they meet the vaults and run the length of the bays. The beams sit on load bearing exposed brick walls that are 0.36 m wide. The vaults span 3.03 m and rise 0.678 m to create grotto-like living spaces to offer thermal comfort from the summer sun and make the residence a porous pavilion that is inserted into the lush landscape.

The terracotta tile module used at the Villa Sarabhai is 40 mm thick, 200 mm x 200 mm (or 8” x 8”). The tiles were sourced from a potter near Sarkhej. Weighing 3.1 kg each, the module is too heavy to serve as a ‘thin’ tile for Catalan vaulting as it would not have survived the construction principle of being set without formwork held only by plaster of Paris. It is of fundamental importance that the tile module used in the construction of Catalan vaults weighs about 1.5 kgs or lesser. This is directly related to the amount of weight that a 10mm joint of plaster of Paris mortar is able to bear. If the tile module is too heavy, you either need formwork to keep the construction of the vault propped or the vouissors will simply fall as you proceed further. Constructing a second layer will become all the more difficult as the first layer is already under considerable stress for self-support.

Further, the terracotta tile used at the Villa Sarabhai has a chamfered profile, which reduces the surface area available for bonding between tiles for the first layer. This makes it a poor choice for Catalan vaulting where the edges of at least the first layer must maximize surface area for better bonding in plaster of Paris so that they are ready to receive subsequent layers without falling. It would therefore make most sense if the vaults at the Villa Sarabhai were clad from below and not constructed in the Catalan method.

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155 Interview by the author with Arvind Talati in Ahmedabad on 13th September 2016. Later confirmed by BV Doshi over email in July 2017.
156 The reasons for not being able to use a heavy module for the first layer are examined first hand in the test arch made out of sandstone bricks, each weighing 1.9 kg, in the Prototype 5 (P5) and findings are presented...
Construction of the Vaults + the lack of photographic evidence

One of the most persistent scholars on Le Corbusier, Tim Benton has written about Corbusier’s eye for photography and on the emphasis laid by the architect on capturing important details of his work on lens. The drama with which tile vaulting manifests itself in a highly expressive, visually appealing manner during its construction due to the cantilevering tiles is something that Corbusier is bound to have been fascinated with. But there is no evidence of him having witnessed the construction process of tile vaulting. The Fondation Le Corbusier’s Archives have a total of only 13 photographs of the Villa Sarabhai from its construction period.157 These photos include those of the completed plinth, half-built walls, formwork for casting of beams and skipping all intermediate stages before finally showcasing the completed house. There are no photos to show the Sarabhai vaults under construction. This contrasts starkly not just with Maisons Jaoul which have excellent record of the two layered vault construction but also with the photographic documentation of Corbusier’s other projects within Ahmedabad such as the Shodan Villa, Mill Owners Association and Sanskar Kendra.158 Furthermore, all of Corbusier’s Ahmedabad projects were being supervised and documented by Jean-Louis Veret who was in fact domiciled at the site of the Villa Sarabhai and whose access to the construction site would have been most convenient to the others.

157 See Fondation Le Corbusier Archives photos: L3-8-99 to L3-8-111.
158 See Fondation Le Corbusier Archives L2-3-37 to L2-3-61 for Lucien Herve’s Jaoul photos.
Most of the Maisons Jaoul photos are also attributed to Corbusier’s preferred photographer: Lucien Herve who was dispatched to the Villa Sarabhai only after its completion and Herve’s photos are featured in the Oeuvre Complete.
The only photo of the Sarabhai vault’s construction that I was able to unearth was from Jean-Louis Veret’s donated collection at Cité Archives in Paris. This particular photograph, dated February-March 1954 and captioned ‘Premiers essais de voûte en place’ (First vault tests in place) shows a Catalan vault made out of the square brick tiles set in plaster of Paris with a second layer in regular sized bricks over it. However, the staggered stereotomy of the vault’s tiles do not match the square grid of the ones that were eventually built and exist today. (See image below) Therefore, this ‘test vault’ in Jean-Louis Veret’s archives is believed to have been the one built over the library area using the finalized terracotta tile (8” x 8”) and had collapsed as recounted by Mr. Suhrid Sarabhai.\textsuperscript{159}

\begin{figure}
\centering
\includegraphics[width=0.8\textwidth]{test_vault_veret.pdf}
\caption{Comparing the completed vaults as they stand today (above left) with Veret’s test vault from February – March 1954 (above).}
\end{figure}

Very clearly, the test vault’s staggered masonry joints do not match that of the one dotting the vault today. Veret’s vault is understood to have collapsed shortly after construction.

\textsuperscript{159} Interview with Mr. Suhrid Sarabhai on 1\textsuperscript{st} December 2015 at the Villa Sarabhai, Ahmedabad.
By contrast, Bertochhi has been recorded to proudly recount being called to check the strength of the Jaoul vault and demonstrating it by climbing over the arch – musing over the fact that workers at site did not fully understand how arches worked because if they did they would not be worried about it collapsing.\textsuperscript{160}

No such procedure has been reported for Villa Sarabhai’s vaults and it is unlikely that such a process could have been replicated in the absence of experts advising directly on the project. Besides, following the first failed attempt at Catalan vaulting at the Sarabhai site in November – December 1952 and the collapse of the full-scale attempt in February – March 1954 must have, in all likelihood, prompted Corbusier’s atelier to revisit their choices for its construction. The lack of reliable collaborators in Ahmedabad as Bertochhi and Escorsa in Paris made Corbusier less confident of attempting the Catalan vaults in Ahmedabad despite having successfully executed them at Jaoul.

There were also numerous other problems with Gannon Dunkerley, the contractor in-charge for all of Le Corbusier’s Ahmedabad projects along with Veret’s regular complaints to Jacques Michel about the work culture\textsuperscript{161} and it is likely that Corbusier’s studio office was unable to transfer their lessons and technical understanding of the Catalan technique while assuring quality control remotely from Paris.\textsuperscript{162}

Furthermore, Jean-Louis Veret had been recalled, for a second time, to France for mandatory military service\textsuperscript{163} which may also have prompted them to adopt a strategy to complete the construction of the vaults to ensure that the superstructure of the house would be finished by the time Veret left. Thus, the lack of onsite expertise and available resources is likely to have prompted Veret and Le Corbusier to proceed with reinforced concrete vaults clad with terracotta tiles from underneath – an easily achievable scenario given the expertise in the material and technique available to them in Ahmedabad through the various other projects that chiefly used exposed concrete. The speed at which the construction of the Villa Sarabhai proceeded from this point onwards also hints that an alternative solution – that of reinforced concrete was adopted in lieu of Catalan vaulting.


\textsuperscript{161} Translated by Anne-Marie Freeman letter talks about vendors not willing to sell and that you have to rummage through their goods. Vaults weren’t the only details Corbusier’s office struggled with. There was the issue of paint (Matroil), electrical fixtures especially fans as well and having to sort out details for pivoted windows, stone flooring, etc.

\textsuperscript{162} Letter and contents – Veret had a stopped works at the AMOA, a matter that escalated to the point of Corbusier having to write to its Chairman to allow the work to continue under Veret’s express supervision.

\textsuperscript{163} This was the second instance while he was in India and Corbusier had already sought an extension in 1953 and again Corbusier seems to have obtained another deferment for him in January 1954. Letter in Veret’s archives at Cite.
On the 10\textsuperscript{th} of April 1954, Jean-Louis Veret wrote to Jacques Michel in Paris: “…5 vaults have been completed and I hope that the work will be finished before the harvest.”\textsuperscript{164} In another letter dated 20\textsuperscript{th} April 1954, Manorama Sarabhai informed Le Corbusier that the construction of the upper storey had already begun and that she wished to discuss the heights of the parapets and other details.\textsuperscript{165} In less than a month, another letter from Manorama Sarabhai to Corbusier dated 15\textsuperscript{th} May 1954 mentions that the house will be ready by end of June.\textsuperscript{166}

The next photograph we have is dated October – November 1954 which shows all vaults of the ground floor completed with exposed concrete surfaces and most waterproofing done. At least two months of heavy rains, that in June and July, impede construction works in India. Given the hand-reliant construction of tile vaulting and the moisture-sensitive nature of plaster of Paris for the first Catalan vault layer, no quality construction could have possibly been undertaken during the monsoon period.

By the time Corbusier visited Ahmedabad again in January 1955, waterproofing was finished for the roofing and he is seen standing inspecting the roof alongside Veret and the Sarabhai family. Given the speed at which the construction of the house was finished it is quite possible that formwork was used to construct the vaults which were later finished with plaster of Paris or even white cement from underneath to give the impression that they were Catalan vaults and to appear kindred spirits of the Maisons Jaoul.

\textbf{Service areas and falling tiles}

Based on site interviews with Mr. Manu Dantani, a caretaker and foreman of the house, nearly 256 pieces of the tiles have come loose and fallen at various points in the last decade and have been subsequently replaced or clad back with white cement.\textsuperscript{167} Although this phenomenon can be attributed to thermal changes between surfaces which induced lack of bonding between layers,\textsuperscript{168} it is more likely to occur in cases of clad layers but is highly unlikely for the bottom layer of plaster clad tiles to lose its bond with the cement layer above in a Catalan vault as the load in compression also helps hold the tiles together.

\textsuperscript{164} Letter P3.7.78-001 from Jean-Louis Veret to Le Corbusier dated 10\textsuperscript{th} April 1954, Fondation Le Corbusier, Paris
\textsuperscript{165} Letter P3.5.199 from Manorama Sarabhai to Le Corbusier dated 20\textsuperscript{th} April 1954, Fondation Le Corbusier, Paris
\textsuperscript{166} Letter P3.5.205 from Manorama Sarabhai to Le Corbusier dated 15\textsuperscript{th} May 1954, Fondation Le Corbusier, Paris
\textsuperscript{167} Interview with Manu Dantani by the author, on 30\textsuperscript{th} November 2015 at the Villa Sarabhai, Ahmedabad.
\textsuperscript{168} The diurnal ranges in the Indian climate are not very different from Spain or Latin American countries where tile vaulting has flourished.
By contrast, the service areas of the house comprising the kitchen, garage and store have a different sectional treatment at the beam and level than the main zones. With tie rods clearly visible, the vaults sit flush with the beams unlike in the main house where the beam is set back an inch to where the vaults spring from. As reinforced vaults in the service areas have also been painted over and lack the surface articulation rendered by the square terracotta tiles in the main living zones of the house making their surface treatment clinical and functional, devoid of any life. Also based on how quickly construction progressed, it is therefore most likely that the rest of the house followed the same construction system of reinforced concrete vaults cast at site.
Sectional drawing of the vault in the later stages of its design showing a brick clad soffit and reinforced concrete structure (FLC 31894)

Top
Photo by Veret taken just after the casting of reinforced concrete roof in early 1954

Middle (left)
Photo by Veret during his visit to the Villa Sarabhai in 1980

Middle (right)
Photo by author in November 2015 of undulating roof revealed when earthwork was removed for essential maintenance

Bottom
Reconstructing the Sarabhai Vault

To examine whether it is in fact possible to construct the Sarabhai vault using the thin-tile vaulting technique, I constructed a vault to the exact specifications of the Villa Sarabhai’s.

A Compressed Stabilized Earth Block (CSEB) of 200 mm x 200 mm and weight ranging between 3.1 – 3.7 kgs – matching the one used at the Villa Sarabhai was used. Dental grade plaster of Paris, cement of M53 grade and mild steel guidework was custom-fabricated to the Sarabhai vault dimensions.

Once the guidework was in place, a first layer of tiles was laid in plaster of Paris. Another row of tiles was stuck to this first arch to make a 0.40 m wide vault of 3.03 m span.

This activity of constructing the vault was completed in 45 mins with 4 artisans working simultaneously, two from each end, now skilled and familiar with constructing tile vaults.169

15 minutes later, the guidework was carefully removed without disturbing the vault above. The plan now was to give the assembly some time to set before loading it with a second layer of cement and bricks after lunch. This was being done in order to stay consistent with the photographic evidence of the Catalan vault constructed at the Villa Sarabhai by Jean-Louis Veret in February-March 1954.

I arrived at site two hours later to find the vault collapsed. There was no visible movement at the springer blocks and the vault had fallen flat. As the POP used in the construction of the vault seemed to have been sufficient to have held it stable during its construction, the reason for failure was difficult to determine but it could have possibly been from the excessive drying and shrinking of plaster of Paris in the sun.

The key to the Catalan technique is that it uses plaster of Paris coupled with thin tiles that typically weigh lesser than 1.3 – 1.5 kgs. If the tiles are heavier than 1.2 kgs, they strain the gypsum mortar beyond controllable margin causing it to fall and as we will see in the experiments of P5, take large parts of the haunches with them.

It is therefore highly unlikely that the Villa Sarabhai module weighing 3.1 kgs would have served as a thin tile in the construction of a Catalan vault and facilitated the quick rate at which the construction of the house progressed.

169 The test vault was being constructed at Hunnarshala in Bhuj. Artisans were introduced to tile vaulting by me in March 2015 while the Sarabhai prototype was being constructed in April 2017.
Vaults at the Villa Sarabhai: As Built

1. Earth filling as required over undulating vault, 127 mm thick at crown
2. 125 mm thick reinforced cement concrete vault
3. 40 mm thick terracotta tile clad from below

Villa Sarabhai
Terracotta Cladding Tile
Thickness: 40 mm
Weight: 3100 gms
**B.V. Doshi’s Interview**

When presented with my findings and interviewed about whether the failed tests in Catalan vaulting led to any onsite decisions that relinquished efforts of building a Catalan vault, B.V. Doshi confirmed that the vaults at the Villa Sarabhai were indeed changed to reinforced concrete ones with the terracotta tiles clad to the soffit. Doshi added that only the Maisons Jaoul carried Catalan vaults.

Doshi was in Corbusier’s Paris office during the years of the Villa Sarabhai’s construction and was directly involved in its design decisions once Corbusier had deemed that Doshi would eventually return to India. Doshi returned to India in January 1955 when the Villa Sarabhai was nearly complete and was involved in a few changes being made following its occupancy.

More importantly, Doshi was also involved in another Indian project that Corbusier’s studio attempted Catalan vaults: the Governor’s Village in Chandigarh. Corbusier started developing details for the Governor’s Village in June 1951. This included housing for the peons. At 110 sq.m. each, the houses were a condensed version of the Villa Sarabhai with their bays capped with vaults. Corbusier attributes the development of this design to his experience of living in the Rest House in Shimla and he was convinced that his solution of the Governor’s village housing was ideally suited for the Indian climate.

By May 1954, estimates and drawings of the Governor’s Village were completed and Doshi was preparing the drawings. Clearly inspired by the Grille Climatique, the sectional drawings feature intriguing double layered shell roofs that were proposed to be built as Catalan vaults. The double vaults were a clever solution meant to be separated by air cavity would have provided thermal insulation to the tenements and if built in the thin tile vaults also reduced heat retention.

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170 Interview with B.V. Doshi over the phone on 31st March 2015 and again over email dated 21st July 2017.
171 See letter P3-7-57 from Doshi to Veret dated 8th September 1953.
172 In a letter found in Veret’s archives at Cite, dated 23rd January 1954, addressed from Corbusier to the Mayor of Ahmedabad, Corbusier discloses that he is keen on Doshi taking over from Veret when the latter returns to France for military service.
A prototype of this roof was proposed to be built in a drawing dated 4th May 1954. By this time the Sarabhai vaults had already been changed to reinforced concrete but the Governor’s village drawings reveals that Corbusier’s office was determined to build a Catalan vault and repeat the method of those successfully executed at the Maisons Jaoul.

Drawn by Olek Kujawski in Corbusier’s Paris studio, notes on this drawing recommend two options for its construction:

“Solution 1. Vault in two thicknesses of bricks layered with plaster and cement (according to the drawing) does not require formwork. It is constructed on a hanger (cintre) which is displaced at the same time as the construction: the lower vault formed of flat brick (tile) hurled to the plaster must form the support sufficient for the upper vault.

Solution 2. Vault in a single brick thickness of 7 cm in cement requires formwork.”

See Drawing FLC 29112. Notes on the drawing are in French and have been translated here.
It is not clear whether this prototype was ever built but two vaults constructed on the site of the Architects’ Office in Chandigarh still survive today albeit in precarious condition. Comparing an archival photo of the vaults with the one taken by me in November 2015 shows that only a single layer of what may have previously been two layers survives today. The module used in the vault for the first layer is a full-sized brick set in cement mortar and not a tile in plaster of Paris.

As for the proposal for the Governor’s Village, P.L. Varma, the Chief Engineer for Chandigarh was not fully convinced with the larger scheme and turned down the proposal for vaulted roofs citing that Indians used flat roofs for storage or sleeping outdoors at night. He further expressed that the cost of houses with vaults would be more than the one with flat roofs as you could no longer use burnt bricks with mud mortar and would have to resort to using burnt bricks with cement mortar.\(^\text{175}\) Thus, the last opportunity for Corbusier’s office to build Catalan vaults in India did not materialize either.

\(^{175}\) Letter P3-7-55-001, PL Varma to Le Corbusier dated 27\textsuperscript{th} October 1954, Fondation Le Corbusier Archives, Paris.
Top and middle: Michel Jaoul visiting the Architects’ Office, Chandigarh c. 1960. The same arches seem to have lost their top layer in November 2015

Right: P.L. Varma’s letter to Corbusier rejecting the idea of vaulted roofs (FLC P3-7-55-001)

Bottom: Details from the arches show it used full brick modules and was not Catalan
No subsequent projects in India used Catalan Vaulting

The Villa Sarabhai has been incredibly influential in inspiring younger generation of architects with its architectural vocabulary. Doshi has confessed the indelible impression that Corbusier has had on his architecture on numerous occasions, even while building his own house that has the Beton Brut aesthetic, as does much of his early work[^76]:

"Architecturally, all my buildings have been influenced by him, though not obviously. In my home, for example, built in 1961, I had been greatly impressed by the Sarabhai house, and I was really trying to create that shadow and that proportion. But I wanted to do something he hadn’t done."[^77]

Doshi’s first independent project after returning to India was the low-cost ATIRA housing project where he was keen to use local materials and technology. Doshi’s solution to the problem of roofing was expressed through segmental brick vaults which he believed would render a sense of volume to an otherwise modest house. Mindful of the scarce availability of steel and cement and with an eye on saving costs, Doshi’s test vault was built without tie-rods and collapsed shortly. Stoking concerns on site, Doshi found assurance in Vikram Sarabhai’s encouragement to find an appropriate solution while pursuing the same aesthetic.[^178] Moreover, vaults recurred frequently and prominently in Doshi’s works in the years to come but not a single one built in the Catalan method.[^179]

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[^76]: Doshi’s early work includes ATIRA, School of Architecture, Tagore Hall, etc all works that flaunt the materials they use in a vocabulary that is Brutalist.


[^179]: William J.R. Curtis’s monograph on Doshi – dated had a section dedicated to commentary on the vaulted form in Doshi’s architecture. It does not however discuss their construction but instead seeks to place his work in the wider context of modern Indian architecture with regionalist sensitivity.
Doshi was also instrumental in bringing Louis Kahn to India\textsuperscript{180} and worked closely as an associate to realize the magnificent Indian Institute of Management (IIM) in what is an embodiment of the Brutalist spirit. No doubt that Kahn’s expression differed from Corbusier’s\textsuperscript{181} but it would be modest to assume that an architect of Doshi’s sensitivity would have turned a blind eye to the Catalan construction technique and not explored it further had it been successfully executed at the Villa Sarabhai.

Likewise, Gautam and Gira Sarabhai too were involved with the Villa Sarabhai in the early design stages of the house. Gautam Sarabhai’s architectural work in the decades to come was highly experimental and varied and it is only fair to assume that he too would have given the Catalan vault a full consideration had he seen its successful execution but he perhaps disregarded the technique following the two failed attempts and lack of available technical expertise on tile vaulting in India at the time.

As Le Corbusier’s work received international attention – especially Chandigarh – his building techniques were widely emulated. The innovative Catalan technique would have piqued the interest of at least some Indian engineers and architects outside the Ahmedabad circle who had either participated or observed Corbusier’s projects but this did not happen. Corbusier’s motivations for building with the Catalan technique can be inferred, his decision to not replicate it for any other project in Ahmedabad, Chandigarh or elsewhere, with the sole exception of the Maisons Jaoul, deserves further assessment which this thesis hopes to have laid the foundation for.

**Conclusion**

There is no doubt that the Sarabhai House sowed seeds for a vocabulary of architecture that transcended typologies. The exposed brick and concrete aesthetic and order was very quickly exploited by leading Indian architects of the era such as Charles Correa, A.P Kanvinde, Hasmukh Patel, B.V. Doshi, Raj Rewal and countless others with Ahmedabad as the epicentre.

\textsuperscript{180} Balkrishna Doshi, Paths Uncharted (Ahmedabad: Vastu Shilpa Foundation for Studies and Research in Environmental Design, 2011), p. 184. Doshi was able to convince Kasturbhai Lalbhai to bring Kahn to Ahmedabad to design IIM.

\textsuperscript{181} The lively interview in El Croquis: Studio Mumbai, Doshi in conversation with Bijoy Jain. Doshi had attempted to imitate the rough-hewn effect of the Sarabhai House’s brickwork at the IIM. Kahn wasn’t impressed and said – “How did you manage this brickwork and pointing? Did you use your finger?”
Nonetheless, the Sarabhai and Jaoul aesthetic has also met its share of resistance which has perhaps been borne by the second generation of the households. Jaoul’s daughter recollected being shamed for living in a factory\(^{182}\) while Suhrid Sarabhai recollecting Ahmedabidis referring to the vaulted spaces as railway bogies. By contrast, Doshi fittingly metaphors the Villa Sarabhai to an accordion\(^{183}\) with its ten fluted bays opening and closing to play a variety of harmonious spatial notes.

The Maisons Jaoul reveal the geometric curve of the vaults behind its concrete pardi wall in the elevation. Nonetheless, in concealing the vaults, there are many meanings in Corbusier’s gesture – a conscious effort to draw distinction from the affordable housing work by Jane Drew and Maxwell Fry in Chandigarh that had already taken shape by 1953 and thereby changing the Villa Sarabhai’s elevation to make it more resonant with his rectilinear compositions for the other projects in Ahmedabad – Villa Shodan, Ahmedabad Mill Owners Association building and Sanskar Kendra, although distinct in surface articulation, experience and scale.

While the vaults were undoubtedly key to the Villa Sarabhai’s composition, it was the vocabulary of the exposed brickwork and concrete beams that was to be universally

\(^{183}\) Le Corbusier in India, dir. by Manu Rewal (2001). Doshi’s interview.
embraced – including the extension of the Department of Architecture building at the University of Cambridge by Colin St John Wilson, where this thesis is being written 50 years later. Therefore, the impact of a successfully completed tile vault in Ahmedabad by an internationally influential personality such as Corbusier cannot be undermined. Akin to the rest of house’s architectural vocabulary, the roof’s construction would have inspired the emulation of the technique across India and bearing in mind its market, would have been remarkable in scale.

This investigation was not initiated to disprove Le Corbusier’s efforts for attempting tile vaulting in India – in fact it started in reverence of his achieving the first Catalan vault there but when research evidence pointed otherwise, I was keen on learning the construction details of how the present vaults were put together and understand the motivations for building in a particular way.
Ceramic Fuses and Burnt Clay Tubes in India

Geographical Distribution of Case Studies
- Star: Ceramic Fuses
- Circle: Production of Ceramic Fuses
- Downward Triangle: Burnt Clay Tubes
- Rightward Triangle: Production of Burnt Clay Tubes

- Surajkund, 1983, Ahmedabad
- School in Ranipur, 1994
- Gujarat Textile Kendra, 1990, Bhujkoda
- Public Toilet, Surat
- Sangan WAGGOS, 1966, Pune
- Centre of Science for Villages, 1979, Wadgaon
- Kendhe House, 2006, Anavade
Chapter 4

Ceramic Fuses, John Soane’s Brick Cones and Burnt Clay Tubes

Summary
Ceramic Fuses are hollow, bottomless terracotta cylinders with a mouth that is pinched to facilitate interlocking. Although formally invented and patented in 1941, such bottomless bottles have existed for many centuries. From its earliest origins in Roman North Africa to post World War II refugee camps in occupied France, from pre-fab building material to its use for low-cost building in India, ceramic fuses have traversed a remarkable journey over the last century - at the very least.

They were industrialized in Europe as part of the evolution of hollow bricks in construction before making their way to India where they took on a new avatar as Burnt Clay Tubes. Serving as excellent examples of frugal engineering: a concept that thrives on achieving the same effective results offered by a product even after trimming its excesses, burnt clay tubes have found wide appeal in the country and provide safe, durable construction primarily to the rural poor.

This chapter discusses the cultural metaphors of the construction techniques through their building modules. Examined over a range of urban, peri-urban and rural settings, I deliberate upon why one has survived while the other is barely known today.
Ceramic Fuses

“A Ceramic Fuse is a structural load-bearing material. It is made from specially selected clays in mechanized factories and is extruded in the shape of a hollow tubular clay casting and subsequently baked, somewhat resembling a bottomless thermos flask…”

In 1941, French architect and inventor Jacques Couelle patented his invention of the fusé céramique referred to as ceramic fuses in English. Couelle’s ceramic fuses have a bottom diameter of 75mm and top diameter of 35 mm. The cylinder is 10 mm thick and the height of the cylinder without tapering is 220 mm with a total height of 270 mm. Each fuse weighs about 940 grams. Along the vertical surface of the cylinder are flutings which serve two purposes: they provide better grip in handling while installing the fuses and create lateral friction to facilitate better bonding when set side by side for a vault.

Over the course of the past several decades, ceramic fuses have received negligible attention despite having contributed to innovative building technology. Despite being used in post world war camps for their quick construction properties, very little information exists of the modules, their manufacture, building technique, benefits and pitfalls and eventual disappearance. It would be safe to conclude that ceramic fuses never achieved enough international renown to be have become a mainstream building module but offered a variety of built forms within the family of arcuate geometries for quick, durable construction.

See Structural Ceramics brochure for Ceramic Fuses distributed for commercial outreach.
Origins of Ceramic Fuses: From Africa to Europe

Ceramic Fuses have existed at least since antiquity, albeit in different avatars and forms. Their predecessors were used extensively across a wide geographic region around the Mediterranean that included present-day Spain and Catalonia, southern France, Tunisia and across large parts of Italy which where most of the construction activity was concentrated. But their sporadic occurrence and inconsistent use through history has perhaps prevented any detailed study on it thus far, which this thesis seeks to address.

An engaging multi-disciplinary study by Lynne Lancaster has revealed that innovative vaulted structures existed in Roman North Africa as early as third century B.C. Deduced to have evolved from bottles first used for preserving olive oil, these terracotta tubes were found – perhaps accidentally – to serve as lightweight yet robust building material for constructing vaults.

Builders further chose to use the terracotta tubes in a variety of ways. For example, at San Vitale in Ravenna, the tubes are fit into each other radially in order to create a chain with the broad end of the modules fitting into the tapered. A translation of this form created a catenary vault of span 17 m of thickness 25 cm. While this formed the main vault, in the bath buildings of Thelepte, Lancaster explains how the same construction system was used to serve as the formwork to support a concrete vault. These construction principles remain largely unchanged even today and are explored by researchers at the ETH, Zurich that integrate two layers of tile vaulting as formwork to receive a reinforced concrete shell above.

Following page:
Lancaster’s sketch of the variety of hollow terracotta bottles used for vaulting with regular pots above.
Section of the San Vitale, Ravenna showing terracotta tubes used for vaulting

186 Ibid. Lancaster explains that olive oil was a vital commodity transcending its use in food – as present day – to include fuel for lamps, base for perfume and a substitute for soap in Roman baths.
187 Ibid. p.3.
188 http://www.block.arch.ethz.ch/bgr/research/Tile-vaults-as-integrated-formwork-for-concrete-shells
The large variety of bottle shapes and sizes only attest the popularity and widespread appeal that the terracotta tube construction technique must have been for its time. While the Mediterranean belt provided conducive environmental conditions for the production and use of terracotta, excellent trade routes between the nations helped proliferate its use. Lancaster concludes that constructing vaults using interlocking terracotta tubes was sought after by the elite classes and must therefore have enjoyed a certain amount of prestige that comes with such association. This is an important point as it contrasts with the way ceramic fuses ended up being used as well as the development of burnt clay tubes in India and the social connotations associated with their architectural production there.

In order to fully appreciate the importance and reasons for inconsistent use of ceramic fuses, we must first place the emergence of ceramic fuses within the context of ‘hollow bricks’ due to the nature of their production and application. Terracotta cones made an appearance in England in the works of Sir John Soane. Soane’s modules and their deployment for constructing the domes of the Bank of England as well as the Consols Office are entirely different from their Roman counterparts. There are two modules that Soane uses. Referred to as Hollow Brick Cones in the Museum’s catalogue, the first module has a square base that slightly tapers to transform into a cylinder towards one end. The side of the square is 105 mm and the diameter of the cylinder is 101 mm. It has a solid base and a thickness of about 15 mm. The second module used by Soane is shaped like a folded newspaper and also tapers at one end. This module measures 104 mm at the top, 106 mm at the bottom, 190 mm height and 61 mm thick.
Both modules have horizontal groves on its surface spaced at about 10 mm and are hollow but with a solid base.

Soane’s modules do not interlock but instead sit side by side and are placed facing downwards onto heavy formwork. Soane seems to have been driven by his interest in using lightweight building material for his Bank of England domes and developed a porous version of the brick which he could use for vaults and domes. While the brick cones were used for the domes, Soane deployed the thinner ‘newspaper’ module for arches as the thinner profile would facilitate a smoother curve in the arch. The newspaper module was additionally used as a quoin module in the arches as seen in Soane’s illustrations.

**Construction with Soane’s Brick Cones**

With the solid square base of the module pointing up, the circular ends of the cones were laid facing downwards to adding more depth to the domes and creating a continuous flush surface on the dome’s top that could be easily plastered and finished. *(See diagram)*

While structurally inventive, these domes were also crucial elements in Soane’s endeavour for creating ‘windowless walls’ at the Bank during his appointment as architect to the bank between 1788 to 1833. Also, keeping with his spirit of self-promotion and social stature, Soane commissioned illustrators to capture his innovative use of hollow bricks indicating clearly the module, formwork and process of construction. These today serve as a vital source of documentation that attest his ideas and innovative building process.

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A painting of the Consols office drawing by Gandy gives an excellent impression of what the modules would have looked like when used for the two buildings before being hidden behind plaster and render for final finishes. The building modules were revealed for a last time during the demolition of the Bank of England which made way for Herbert Baker’s subsequent and controversial remodeling in 1925.\textsuperscript{191} It can be argued that Baker’s remodeling was contentious not only for its new-styled architecture but also because Soane’s building had consciously embodied creative building technologies which Baker’s new project did not offer nor justify in demolishing.

Photographs from the Bank’s demolition in 1925 provide evidence of the brick cones used and Herbert Baker features yet again as an unexpected and perhaps unaware antagonist of experimental building materials and techniques – this time on home turf.

\textsuperscript{191} Iain Black, ‘Imperial Visions: Rebuilding the Bank of England’, in Imperial Cities: Landscape, Display and Identity, ed. by F Driver and D Gilbert (Manchester: Manchester University Press, 2003), p. 98.
Top
Gandy’s rendition of the Consols office clearing indicating the hollow brick cones and ‘newspaper module’ used

Bottom
Demolition of the Bank of England and what it may have looked like in its heydays (shown through a computer rendering).
Soane’s use of the hollow brick cones is a forerunner of its time. As hollow bricks found mainstream appeal, his work received a lot more attention decades after the old Bank’s demolition. An article by S.B. Hamilton in the Transactions of the British Ceramic Society in 1958 suggests that Soane’s brick modules were most likely produced locally by Morris of Child’s Hills near London while tracing the evolution of hollow bricks in England and continental Europe.

However, it is in the formal discussion at the end of the article between six scholars that is of utmost relevance to this study. In the discussion, M.E.C Stedham alludes to the production of a ‘hollow terracotta module’ produced near the town of Troyes in southern France that is:

“...about 10 inches long, 2.5 to 3 inches in diameter, fluted from the outside and coming to a neck at one end. They are extruded on a vertical machine which makes the neck in a single operation and at the time that visited these works I and others with me were quite unable to see how the machine achieved this. These hollow units are used in situations where non-linear load bearing concrete is required, such as in the arches of bridges and to some extent in pillars. There appears to be a considerable local demand in France.” Stedham’s description matches perfectly to what was perhaps Jacque Couelle’s ceramic fuse.

S.B. Hamilton ends the discussion by referring this to his description of the tubes used at San Vitale in Ravenna and Roman North African terracotta tubes at the beginning of the chapter. The exchanged notes therefore reveal two vital points – the first that the use of hollow brick modules has existed in one form or another, whether for bridges, flooring or domes, in a continuous thread of history and second that the concerned scholars of the time had limited familiarity with ceramic fuses with only a vague understanding of it owing to its resemblance to Soane’s hollow brick cones, clearly unaware of the former’s technical term and perhaps also distinct construction technique.

In the ebb and flow of the appearance of various versions of hollow brick cones and tubes from the third century B.C. to the Bank of England, it is the Frenchman, Jacques Couelle who invented his own version of hollow terracotta tubes and christened it fusée céramique (or ceramic fuse), patenting it in France in 1941 and in the U.S. in 1947. A ceramic fuse was now an industrial product, possible to be produced through mechanized means assuring uniformity, quality control and rapid output in large quantities. Interestingly, he promoted

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193 Ibid. page 62.
194 Couelle’s patent number in France: FR52088E, titled: élément tubulaire en matières moulées à emboîtement constituant des fermes portantes, et plus particulièrement prévus pour l’établissement rapide de baraquements.
them for a variety of applications such as use in drainage and water supply pipes and the construction of arcuated building elements as discussed above. Through subsequent years, Couelle continued to tweak the ceramic fuse to develop more applications for the variations explored but the central idea of interlocking terracotta bottles remained largely unchanged. Couelle went on to register 38 patents in France up until 1964 that related to a range of prefabricated building components and mechanized construction which convey a sense of his prolific creative involvement in the building industry.195

Biomimicry

Ceramic fuses derive their strength longitudinally as they form an interlocking chain in a manner that facilitates self-support thus achieving a form-active structure.196 Closely resembling the structural principles of needle-like pine leaves or nodes in tall bamboo shoots, the unusual interlocking construction system created cohesive surfaces that demonstrated unexpected self-support and structural rigidity which became its most

195 See patent numbers under Couelle in France’s online patent directory at: http://bases-brevets.inpi.fr, last accessed 27th September 2017
196 Heino Engel has defined form-active structure systems as those “of flexible non-rigid matter, in which the redirection of forces is effected through particular form design and characteristic form stabilization”
inventive and appealing aspect for rapid construction. It is perhaps in this simple-to-understand construction principle that made it easy to work with even without skilled masons.

Couelle’s involvement in the manufacture and marketing is not entirely clear although he features prominently on commercial brochures distributed in India as ‘architect and inventor’ of the ceramic fuses. Their impressive production method, quality product and architectural potential were quickly appreciated by the Germans during World War II, who used them for bomb shelters, bridges and prisoner of war camps in occupied France. French architect and building contractor Fernand Pouillon was charged with designing the Camp du Grand Arenas in 1945 using Ceramic Fuses. Admittedly driven by patriotic fervour, Pouillon was involved in selecting not just the site but also the building module and the construction of the entire camp.

As an architect who remained interested in affordable building technology, Pouillon admitted to having known about Couelle as “this amazing man, at the same time antiquarian, decorator, architect. It was all with taste, talent and imagination. He had invented the ceramic fuses in the mountain chalet where he had retired during the occupation. A fund-raiser had funded the case and the patent had been sold to the ceramic industry in Marseille. The industrialists entered into a contract with the Todt Organization. The materials were to be used for the construction of shelters in Berlin and elsewhere.”

Pouillon recollected seeing a large number of the modules (or rockets as he called it) not far from the chosen site that lay in a massive pile ‘4 metres high, 4 to 6 metres wide and about a kilometre long’ surrounded by barbed wire and guarded by American soldiers. Wartime induced the dearth of skilled labour, materials and other logistical problems making the Ceramic Fuses a natural choice which given the large programme would require to be used prudently. Pouillon enigmatically states: “One Sunday, with a watch chain suspended with two pins, I traced the future accommodation of six to eight thousand people...” The real challenge was presented in the construction of the vault which Pouillon approached with intuitive resolve while his

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197 Fernand Pouillon (1912 – 1986) was a protégé of August Peret and a contemporary to Le Corbusier. An incredibly colourful personality, who while on one hand earned the reputation of championing affordable and beautiful housing in France and Algeria, was jailed for his role as building contractor in 1961. He later escaped but was recaptured and acquitted from the first case only to be convicted and imprisoned again for having attempted escape from prison. (http://www.bdonline.co.uk/adam-khans-inspiration-la-tourette-and-vieux-port-marseille-by-fernand-pouillon/5039231.article) Adam Caruso, of Caruso St. John co-wrote a monograph on him titled: “The Stones of Fernand Pouillon: An Alternative Modernism to French Architecture” in 2013 which can serve as a good introduction to his life and work. His own autobiography ‘Memoires d’un architecte’ published in 1968 is also an excellent resource on his early work and practical philosophy. His recollections of the Camp du Arenas are candid and very engaging.

199 Ibid. p. 42 (Translated from: “Elles formaient un tas de quatre à six mètres de haut, quatre à dix mètres de large selon les endroits et d’un kilomètre de long.”)
200 Ibid p. 42 (Translated from: “Un dimanche, je tracai à l’aide d’une chaîne de montre suspendue à deux épingles, le future logement de six à huit mille personnes, dans des conditions de confort sommaire.”)
collaborators who, in equal bouts of trepidation and conviction, repeatedly asked: “Do you believe that will hold?”

Pouillon’s unflinching trust in the hanging chain principle and the structural properties of ceramic fuses met success when the formwork of the first vault was dismantled. To further seal the trust of his collaborators, Pouillon demonstrated the strength of the single layered vault by jumping on its crown and was happy with its drum-like resonance.

When the Camp du Arenas was completed, it first served as a hub for prisoners of war and later for hundreds of thousands of refugees mostly immigrating to Israel. All structures on site were demolished in 1966.

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201 Ibid. p. 42 (Translated from: “Croyez-vous que cela va tenir?”)
202 Ibid, p. 48 Pouillon reports that the vault eventually bore two tonnes of wood. (Translated from: “C’etait pour moi une merveilleuse indication: non seulement la voûte ne s’écroulait pas, mais elle supportait deux tonnes de bois.”)
Dutch structural engineer Wim Kamerling has recorded that within a few years of the Camp du Grand Arenas, a factory named De N.V. Nederlandse Fusée Ceramique Maatschappij, Nefumij was established in Echt with an annual production capacity of 10 million fuses. Kamerling has also documented twelve buildings that were built in the Netherlands between 1949 and 1959 that ranged in typology from churches, sports complexes to railway stations and used ceramic fuses for their barrel vaults and even domes. Some of these buildings were in use up until 2011 while most of them have been demolished. The St. Raphael-Exodus Church in Groningen, having a dome spanning 22 metres continues to serve its community to date.

More buildings that featured roofs built using ceramic fuses have been recorded in France and Belgium but they appear to be very sparse. In recent times, many of these have been campaigned for preservation but met with limited success. And over time while Ceramic Fuses have received the attention of a handful of artists and scholars, they remain largely unknown to commercial mainstream building including their peculiar absence in publications that specifically look at post-war building materials developed for rapid construction in continental Europe.

\[204\text{ Wim Kamerling, 'Fusée Ceramic Vaults and Domes in the Netherlands', in Taller, Longer, Lighter - Meeting Growing Demand with Limited Resources (Switzerland: IABSE / IASS, 2011), XCVIII, 593.}\]
\[205\text{ http://archipostalecarte.blogspot.co.uk/2014/12/grandequevilly-la-honte.html and http://archipostalecarte.blogspot.co.uk/2015/10/sauvons-leglise-de-serqueux-avant-que.html (last retrieved 11 September 2017).}\]
\[206\text{ While fusee ceramique has received some attention (Ortar, Lancaster, Kamerling) it is not famous enough (having missed the Pompidou Centre’s exhibition – d’art l’ingeniur by Picon and the book on Post-war building materials.}\]
Ceramic Fuses in India

We have now seen how ceramic fuses had their earliest origins, formalization, use and decline in continental Europe, but there is nothing written about the arrival and evolution of ceramic fuses in India’s building industry. This, I found, has a distinct narrative that reflects preferential building methods and an entirely different set of social connotations and appeal.

The Indian engineer Arvind G. Daftary deserves to be credited for introducing Ceramic Fuses in India. He is said to have learnt about the building modules during trips to Europe in the 1960s and with an already established engineering practice in Bombay, Daftary was prudent to judge the potential of ceramic fuses for the Indian market and determined to pioneer the building modules in the country’s burgeoning building industry.207 The ceramic fuses patent was subsequently registered in India and Arvind Daftary’s office Structural Ceramics Ltd. were appointed sole licensees for India, Burma and Ceylon.208

Daftary still had the challenge of seeking a brick or tile manufacturer capable of producing ceramic fuses to high standards locally. It was during this search for an ideal partner that Daftary and his colleague M.G. Pandey stumbled upon the Bhanabhai Dhurlabhai Company (BDB) in western Gujarat’s then bustling industrial town of Bilimora.209

BDB was founded in 1918 as a manufacturer of terracotta roofing tiles (widely referred to as Mangalore tiles in India) and supplied them to markets across the country. Many factors worked in favour of Bilimora itself: its proximity and trade connections by train and road to Bombay, the business capital of India as well as the commercial markets of Bharuch and Morbi. Bilimora lies close to the Arabian Sea with rivers flowing in close proximity rendering the land an exceptional quality of clay that has birthed a flourishing terracotta products industry.210 Fondly recollected by BDB’s founder and nonagenarian, Mr. Lalbhai Intwala, BDB were the only manufacturers willing to entertain the idea of producing ceramic fuses – an outlandish module that Mr. Daftary wanted to produce in large quantities for the entire Indian subcontinent. Other outfits in neighbouring towns such as Gandevi were perhaps comfortable with the profitable business that the terracotta industry already provided while BDB seemed to retain an air of experimentation.

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207 Interview with Lalbhai Intwala on 28th November 2015 in Bilimora and again on 13th March 2016.
208 Ceramic Fuse brochure shared by BIMCO in November 2015 during my visit.
209 Bilimora was colloquially referred to as the mini-Japan of India. Factories in the city included the manufacture of drilling machines, silk mills, textiles, terracotta, paper mills, 3 castor oil companies, bobbin factories which after 1985 gradually declined.
210 Interview with the engineer Shirish Patel and Dr. VV Nori via email on 21st April 2015 and again 14th January 2016
An agreement was reached upon between Arvind Daftary’s office in Bombay, Structural Ceramics and a new entity Building Materials Corporation (BIMCO) which was created by BDB in Bilimora in 1962. Through this new partnership, Structural Ceramics would solicit new commissions and place orders for ceramic fuses and BDB would supply raw materials to BIMCO for the manufacture of ceramic fuses. The responsibility of disseminating commercial information lay with Structural Ceramics and BDB had no role in this nor could it sell directly. In return, BDB would get royalty of about Rs. 1.7 to Rs. 2 per ceramic fuse. This was considerable given that orders for ceramic fuses would run in tens of thousands.

Following their new partnership, Mr. Daftary accompanied Mr. Lalbhai and his brother, Mr. Gokuldas Intwala to Europe to visit Germany, Italy and Spain in order to see product samples, visit built examples and learn about their manufacturing process. Upon returning to India, a workshop in Bombay named Purshotum was contracted to fabricate the brick press that would produce ceramic fuses using Couelle’s patented process.
This brick press was then installed at the BDB factory in Bilimora and BIMCO would go on to produce all the ceramic fuses that India would see over the next three decades until 1992. The press used for the production of ceramic fuses today lays completely derelict not been used for over thirty years but with its mechanisms in place, one could get a clear sense of its workings.

**Production of Ceramic Fuses**

The Intwala family recounted their method of producing ceramic fuses and below is an account of the process:

A clay mix was prepared using red clay, black clay and very fine sea sand in the proportions 6:4:2 respectively. The mix was cut, added water and mixed again manually and the process was repeated until desired consistency was achieved. The mix was then allowed to cure in a pit for 10 days following which it was dug out and put into a pug mill.

A pug mill was deemed vital as the prevalent climatic conditions necessitated thorough de-airing. In fact, the pug mill was used twice for the mix ultimately used for ceramic fuses content unlike those of Mangalore roof tiles which were fed into the pug mill just once.²¹¹

The clay mix was then extruded into tubes using a die cast and this tube was transferred into the Purshotum press which created the ceramic fuse shape in one motion including the pinched mouth and ribbed surface while extracting the remaining clay from the other end. The discarded clay was mixed with another set and fed into the machine again thereby reducing waste in a highly efficient process. Unlike Stedham’s description of the module being extruded on a vertical machine, the Purshotum press was a horizontal setup.

Freshly extruded fuses were then set aside vertically on racks, 5 in a row, for drying naturally. This period varied from a week in the summer with about an additional 2 days in winter. Dried ceramic fuses were then fed into a draft-type kiln and fired up to 1100 deg c. for 48 hrs. Coal was used for firing the kiln in the early years which was replaced by lignite, a cheaper substitute, and the kiln had a chimney that was 110 feet tall. Ceramic fuses were fired alongside Mangalore roof tiles and the heat generated by these roof tiles helped bake the ceramic fuses and other hollow bricks better. After 2 days, the fuses were removed from

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²¹¹ Based upon prior experience, the Intwalas found that bricks and Ceramic Fuses needed de-airing while Mangalore roofing tile mixes did not. Interview with Lalbhai Intwala on 28th November 2015 in Bilimora and again on 13th March 2016.
the kiln and left open for 1.5 days following which they were ready for use or dispatched to site.

BIMCO were able to produce 5000 – 6000 ceramic fuses a day. The press installed was originally planned to be automatic but due to the local clay’s properties and unforeseen detrimental moisture retention in the automatic system, a manual set up was adopted. Further, the ribs on the ceramic fuse surface were found to be retaining their shape far better in the manual set up compared to the automatic one and therefore this was ultimately followed.

Next page:

Collage of the Purshotum press at the BDB compound in Bilimora that produced ceramic fuses for all of India.
Construction System using Ceramic Fuses

Hand-sized and lightweight, ceramic fuses proved very easy to handle. Their tubular form made them not only easy to work with but also to stack on the ground or while working on the vault. Their robust body ensured that they could be stored outdoors and have minimum breakage during handling and transportation and these factors greatly contributed towards making ceramic fuses an innovative formidable building material in an industry that was not governed by tight regulations for handling of materials or construction processes.

The prescribed laying of ceramic fuses first required sturdy formwork to be erected. However, due to the light weight of the fuses and its construction system, the formwork deployed was also relatively lighter to that of reinforced concrete’s construction and was typically made out of battens, wooden planks or plywood. Once the formwork was propped in place, a steel wire mesh was a rolled out and covered with cement mortar. After the cement mortar was in place but not dry, a chain of ceramic fuses was assembled to serve as a reference line and depending on the length of the vault, more such chains were set up at regular intervals. No specific guidelines dictated what distance these fuse chains ought to be except that they were useful in maintaining right angles to the beams or ground surfaces so that the fuses could be laid parallel to each other.

Due the simple laying operation, skilled labour was not required except for a knowledgeable foreman who was familiar with the various check points set up for construction. Structural Ceramics provided technical expertise to projects disseminated through well-illustrated manuals and pamphlets. Such literature recommended that one or possibly two teams of workmen, each working on one side of the vault proceed with the interlocking of fuses to eventually meet at the crown of the vault.

As there is no distinct ‘key’ module for the fuses to meet into when they converge at the crown, a module’s head was simply cut on spot and sized to match the missing component as part of onsite improvisation. These ‘keys’ were then staggered within a one-metre distance to ensure a breaking of joints. This is similar to the principles of brick masonry where mortar joints are staggered in successive layers to facilitate better bonding but done here along a curved surface.
Above: Extracts from Structural Ceramics’ Brochure for the application of ceramic fuses

Below: Drawings based on technical manuals on ceramic fuses

**Roof permutations with Ceramic Fuses**

**section A B**
section with ceramic fuses embedded in cement

Numerous other combinations were proposed for using ceramic fuses based on their deployment

(i) in infrastructure that required heavy reinforcement
(ii) sound and thermal insulation
(iii) flat vaults with fuses embedded in concrete

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**section with ceramic fuses visible at soffit**

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Ceramic fuses were versatile as they could either be embedded in cement mortar or concrete as done at Sangath (1980) or be left exposed to create an aesthetically pleasing soffit as in the case of Sangam (1966). Both projects are explored in more detail as case studies further in this chapter. A second layer of ceramic fuses could be added if the span of the structure demands for a thicker cross section in order to contain the stress lines induced by resulting thrusts. If layered, the recommended thicknesses of the vault’s cross-section including cement mortar were:
- 11 cm for one layer
- 19 cm for two layers
- 27 cm for three layers

For large spans however, the vaults had to be reinforced which was done by laying a wire mesh or mild steel reinforcements at the intrados before laying ceramic fuses and tor steel reinforcements were used for the extrados. The overall reduction in steel also rendered longer life for structure and greatly reduced recurring maintenance often demanded by reinforced concrete structures.

A vault constructed using one layer of ceramic fuses had a thickness of 4.5 inches weighing only 36 lbs (16.3 kgs) per square foot making it approximately 50% less than a reinforced concrete slab of same thickness. When embedded in concrete, the ceramic fuses also greatly reduced the volume of concrete while retaining the strength of the shell and therefore made the structure not only lighter but also reduced the need for larger foundations and load-bearing structural members. Their interlocking nature also created an impressive amount of static inertia that in turn helped eliminate all steel reinforcement for spans up to 30 feet.
Recommended Type of Structures

According to the literature published by Structural Ceramics, different types of structures were promoted using ceramic fuses. These were:

1. Roofs and vaults
2. Cheap quarters and Industrial Houses for labour
3. Floor-slabs
4. Silos, tunnels, culverts and small bridges
5. Particular works: Vaults with air circulation – flaunting their hollow nature and resulting thermal insulation properties that help reduce reliance on artificial cooling systems.

The brochure also emphasized: “the ceramic fuse structure is a superior and permanent type of construction comparable to, if not better than a R.C.C or Shell-type. Ceramic Fuse Structure is much better than one erected with steel-framework and asbestos cement sheets.”

Promoted also for their fire retardant and sound insulation properties, Ceramic Fuses would have served as ideal roofing elements for factories that generated a lot of noise and vibrations from manufacturing processes. Not only did the literature directly entice architects and contractors into using ceramic fuses for industrial and infrastructure projects in India but it also reflected the core clientele that Structural Ceramics had identified as their primary market. It is not surprising then to learn that the first project to use ceramic fuses in India was the National Rayon Factory in Veraval that had a 40’ span roof over its Boiler House. BIMCO supplied over 30,000 units of Ceramic Fuses for this structure alone that were transported by boat to Veraval.

The largest span structure in India built using Ceramic Fuses was the 45’ span roof of the Dharamsi Morarji Chemical Co. Ltd in Ambarnath, an industrial suburb of Bombay in Maharashtra state. B.V. Doshi credited his visit to this structure as the one that convinced him to consider using Ceramic Fuses for the construction of the semicircular vaults at his studio in Ahmedabad.

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212 This was of course a time when asbestos sheets were considered to offer a cheap roofing solution but also fully safe to use.

213 Interview with Lalbhai Intwala on 28th November 2015 in Bilimora and again on 13th March 2016.
A list of notable projects in India constructed using Ceramic Fuses is below:

1. Indian Rayon Industries, Veraval
2. Dharamsi Morarji Chemical Co. Ltd, Ambarnath, Bombay
3. Refrigeration and Appliances Pvt. Ltd Factory, Pimpri, Pune
4. Sangam, Pune (1966)
6. Gandhi Labour Institute, Ahmedabad
7. Lions Club Pavilion in Bandra, Bombay
8. Public Toilet, Surat
9. Jehangir Art Gallery, Bombay
10. Swaminarayan Mandir, Ahmedabad 1991 *(used 50,000 Ceramic Fuses)*
11. Akshardham Mandir, Gandhinagar, 1992

Decline of Ceramic Fuses in India and BIMCO

After three decades of a flourishing business in the manufacture and supply of Ceramic Fuses, BIMCO and its parent company Bhanabhai Dhurlabhai (BDB) folded operations in 1992.

Over its lifetime, BIMCO had catered predominantly to the Gujarat and Maharashtra region with projects in just these two neighbouring states with no success with outreach to the much wider market of the rest of the country where they continued to supply their Mangalore roof tiles. This was most likely as the use of ceramic fuses was promoted solely by Structural Ceramics represented by Arvind Daftary and M.G. Pandey and without them there was a general lack of awareness about the module and its construction technique in India’s mammoth construction landscape.

Changes in production methods by BIMCO also contributed detrimentally to the decline in use of ceramic fuses. Instead of coal, BIMCO started using lignite as a cheaper substitute for firing their kiln. Lignite’s short shelf life, restricted to about 10 days, turned out to be a debilitating issue when orders were in low numbers added to costs in having to keep the kiln in continuous firing. This compounded with troubles with sourcing raw materials, emerging unreliable labour availability and transport problems contributed to logistical limitations.

Moreover, the neighbouring town of Morbi rapidly developed into a manufacturing hub and wholesale market for a wide range of ceramic products and it continues to supply across India even today. Morbi’s swift rise gave stiff competition to even long-established companies like BDB and although BIMCO retained the rights to producing ceramic fuses,
their demand had never matched the steady demand for Mangalore roof tiles which were in constant demand-supply cycles and had always been the core business for BDB. However, by the early 1990s, Morbi was also producing cheaper Mangalore tiles. Almost simultaneously in Bombay, Daftary and Pandey had stopped taking orders for ceramic fuses and although the reasons for this remain unclear to the team at BIMCO, we could assume that both gentlemen were close to retirement by the early-90s and soliciting of fresh orders would have required persistent efforts.

This was true also for the founder and pioneer manufacturer of ceramic fuses in India, Mr. Lalbhai Intwala who was in his late 60s. Therefore, due to prevailing market conditions and logistical complexities presented, BDB deemed it no longer financially feasible to manufacture ceramic fuses. The family investments and business offered more economic prudence in diversification and through his two sons BDB’s core engagement in producing a variety of terracotta products was disinvested. BIMCO recorded their last sizable order of 9000 Ceramic Fuses in 1992 for the Akshardham Temple in Gandhinagar.

Thus, a number of complex but interconnected issues sealed the fate of ceramic fuses in India. To imagine that all the modules in the country were born out of a monopoly of just two promoters, a single family-run unit and just one brick press! Daftary’s fascination with the ceramic fuses had evolved into a hobby project alongside his thriving engineering practice, never quite seeing the success of other mainstream construction systems such as reinforced concrete.
Ceramic Fuses: CASE STUDY 1
Sangam WAGGGS, Pune 1966

Designed by Messrs. Mody and Colgan, Sangam was inaugurated in 1966 as one of five World Association of Girl Guides and Girl Scouts (WAGGGS) centres around the world. It’s renowned principal designers, Bombay-based architect and statesman, Piloo Mody along with structural engineer Shirish Patel designed the complex with covered walkways and buildings featuring arcuate geometries constructed out of ceramic fuses. Relatively unknown even today within architectural circles, Sangam’s use of the building element is perhaps the most expressive architectural work in India.

The covered walkway adopted a 3.4 m clear square grid which repeats as a module. With square columns measuring 0.3 m a side. The segmental vaults span 3.4m and rise 0.5m resting on precast concrete beams of depth 0.33 m and 0.25 m wide. The beams cantilever 0.3 m beyond the columns and have an arched concrete beam as fascia that forms the basis of the vault followed by the ceramic fuses. This concrete arch is 10 cm thick.

Above

A typical structural grid module at Sangam with reinforced concrete structural frame and ceramic fuses roof

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214 The other four WAGGGS centres are in the UK, Mexico, Switzerland with a ‘roving’ centre planned in Africa.

215 Piloo Mody was educated at U.C. Berkeley and worked with Eric Mendelsohn. He was also part of the bureaucratic order of Chandigarh’s architectural team at the time of its construction. Mody was a Rajya Sabha Member of Parliament championing architectural issues at the policy level such as the Architects’ Registration Bill, 1972 that established a minimum educational standard for a person to be a qualified architect. The bill is still in force today. Shirish Patel read Mechanical Tripos and Civil Engineering at the University of Cambridge and is well known for pioneering numerous precast concrete construction techniques in India. He also co-authored the plan for New Bombay along with Charles Correa and Pravina Mehta and was the structural engineer for the highly acclaimed Kanchanjunga Apartments. Patel and Mody held respective architecture and engineering offices in Bombay.
Another structure on site that is remarkable for its use of the ceramic fuses is the large multi-purpose hall designed as two identically sized, intersecting catenary cross vaults. The north-south vault spans 7.10 m while the east-west vault spans 7.15 m. Both vaults rise 6.3 m from the ground. This hall is loosely modeled on the pavilions built with ceramic fuses for the International Exhibition in Brussels in 1958 and even feature a similar treatment for fenestrations. The cross-shaped hall has a reinforced concrete frame with the ceramic fuses used as infill membranes. At Sangam, the soffits of all vaults created using ceramic fuses are left exposed in their natural earthy hue that contrast strikingly with the white painted structural reinforced concrete frames. For waterproofing, a layer of cement slurry and cement plaster is applied on the external surface.

Mody and Shirish Patel were the very first architect and engineer respectively in the country to have used ceramic fuses. The role of its engineer Shirish Patel is of particular importance, as he was personally known to Arvind G. Daftary. Upon researching the archives at Sangam, no drawings were found for the vaults. Messrs Mody and Colgan also confirmed that the office did not have any drawings in their archives.

216 Featured on page 12 in Structural Ceramics’ Ceramic Fuse brochure.
217 Email interview with Shirish Patel dated: 23rd April 2015 and again 14th January 2016. Shirish Patel also knew Arvind Daftary personally who in fact offered Patel his office for use when Patel had returned to India to start his own practice.
218 While the 50 year-old centre is well maintained, Mody and Colgan’s office now focuses primarily on Interior Design projects. The office also confirmed over the phone that they have unfortunately not maintained an archive of previous works and all drawings, as submitted, lie only with the owners. The only drawings found at Sangam were those prepared by the engineer’s office and had technical details of reinforcements but nothing about the architectural design.
The modulation in roofing at Sangam extends to the playfully bonded brickwork forming the extended screening wall and sculptural water tower.

Left:
The large activities hall at Sangam is similar to the ceramic fuses pavilion constructed in Brussels, published in the brochures distributed by Structural Ceramics.

Above
Some fuses have come loose and fallen but the staggered laying of fuses has certainly helped in holding it together.
Ceramic Fuses: CASE STUDY 2
Public Toilet, Surat Chowpatty

In the city of Surat, 65 kms from Bilimora, the Municipal Corporation constructed a public toilet at the Surat Chowpatty using Ceramic Fuses in the most unusual manner. Set abutting to what is today the parking lot preceding a public park, the toilet building is circular in plan and rises 12 feet. Having a reinforced concrete frame, circular columns prop a ring beam with a reinforced concrete slab that cantilevers out. There is a double door that may have once served as an entrance to the toilet but now has a metal gate and remains locked. The slab is topped with a quirky interpretation of a traditional Gujarati bird feeder made in mild steel and painted over.

The humble structure is remarkable for its most innovative use of the ceramic fuses that are laid on bed to make an encircling curtain wall. Following a dry construction system by simply being stacked over each other without any mortar, the Fuses have been laid with their wider ends facing outwards. As the openings at the heads measure only 1 cm and with a depth of 27 cm, a whole wall of the Ceramic Fuses creates a unexpectedly private screen on the inside making it virtually impossible for the viewer to see through the structure when viewing from outside.

Externally, the ceramic fuses hide the structural assembly of the columns and ring beam to give the impression that the ceramic fuses stretch all the way from the plinth to the cantilevering roof. The porous curtain would also have served as an effective breathing wall providing necessary ventilation.

This unassuming yet charming structure is today in almost decrepit condition with a lot of fuses on the external façade cracked and crumbling but remains structurally sound and continues to conceal in the interior. Clearly having seen better days, it is today used as a storage and resting facility by the park’s employees and security personnel.
Collage of photos of the Public Toilet at Surat

Designed and built by the Surat Municipal Corporation, the structure uses ceramic fuses in an unusual way by laying it on bed. Derelict and in a state of urgent repairs, it is used as a store and resting room by staff.
Ceramic Fuses: CASE STUDY 3
Sangath, Ahmedabad, 1980 by Balkrishna V. Doshi

We return to B.V. Doshi here to examine the construction of his studio, Sangath in Ahmedabad in 1980. Having returned to India in 1955, Doshi zealously followed in the footsteps of Le Corbusier and much of his work bears the mark of Corbusier’s looming influence. Having settled in Ahmedabad for almost three decades with an impressive portfolio of works to his acclaim, Doshi’s work at Sangath is a delightful evocation of regional sensibilities.

The vaulted form had featured prominently in Doshi’s works over the decades and numerous visual references stoked its persistence: Corbusier’s vaults at the Villa Sarabhai, the Nubian vaults of Hassan Fathy and their modest scale greatly appealed to Doshi. But his desire to have vaulted forms for the studio was sealed after Doshi’s visit to the Wissa Wassef Arts Centre in Cairo (completed in 1974).

Disinclined to use the catenary geometry of the Fathy’s Nubian vaults, Doshi preferred a semicircular arch for his studio envisioning mezzanine work areas as well as half-sunken buildings. Set in a lush green campus, Sangath’s design is an ensemble of five barrel vaulted structures, half-submerged, disconnected at the top but interconnected at floor level. The building has been home to Doshi’s architectural office since 1980.

Sangath’s semicircular vaults were created in three layers: the first was a thin reinforced concrete shell cast in situ, the middle layer is ceramic fuses, meant to provide thermal insulation due to their hollow cross section followed by a third layer of concrete over the fuses to fully embed them. All vaults are articulated externally with china mosaic comprised of broken white ceramic tiles set in cement slurry. This lends the roof a highly reflective

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219 Sangath in Doshi’s native language, Gujarati, translates roughly to ‘moving together.’
220 For more details pertaining specific Doshi projects that feature vaulted forms see William Curtis’ monograph on the architect.
221 Doshi lecture at the Royal Academy, London on 10th July 2017 and his email to me. dated: 19th July 2017.
character which further adds to the reduction in heat gain. The interior finish of the vaults is that of exposed concrete.

Sangath’s cave-like sunken interior spaces were created to offer much respite from the harsh Ahmedabadi summers. In the nomination report for the Aga Khan Award for Architecture, Doshi points out that the ubiquitous terracotta country tiles (burnt clay tubes – which have been studied in detail in the next section) used in India may have very well served as a substitute for ceramic fuses but were found to incur a great deal of breakage during handling and practical difficulties prevented their final selection.222

However, the manner in which ceramic fuses have been used at Sangath make them ‘form-inactive’ as they do not serve any structural function nor are self-supporting as they rest on a previously cast concrete shell. Photos from Doshi’s archives reveal that the ceramic fuses were not laid in the prescribed methods i.e. staggering of joints for better lateral inertia, successive ‘key’ pieces to be placed one metre apart, etc; indicating an inexperienced building method most likely executed by masons who were working with ceramic fuses for the first time.

Nonetheless, Doshi seems to have been aware of the technical term for the building elements referring to them accurately in his Aga Khan Award nomination papers. He was also conscious of their capabilities when finalizing their deployment at Sangath having seen the Dharamsi factory in Bombay.223 Satisfied with Sangath, Doshi would go on to use them in another project, the Gandhi Labour Institute (completed 1984) which would be the last work by the architect’s office to feature ceramic fuses.

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223 Doshi confirmed to have seen a factory in Bombay that had a roof made with ceramic fuses and it is my conjecture, based on available evidence of the limited number of industrial projects with such roofs that it would be the Dharamsi factory.
Although Doshi uses ceramic fuses just like Sangam, there are errors in laying and its deployment hinting at a lack of awareness in using the module.
Burnt Clay Tubes: Kindred Spirits of Ceramic Fuses

Ceramic fuses enjoyed a relatively short life in India and are barely known today even within the conservation circles of the fraternity. However, almost simultaneous to their production and use in the country, a similar-looking yet indigenously produced module was used for the construction of vaulted roofs.

Colloquially referred to as Guna or Wardha tiles, possibly named after the place of its first use, in the interest of scientific objectivity and consistency, I prefer using the term Burnt Clay Tubes (BCT).

There are no set dimensions of burnt clay tubes as they are made on a potter’s wheel and similar to the vaulting tubes of Roman North Africa differ slightly from place to place. However, a typical BCT measures 3.5 inches diameter at the large end, 2 inches diameter at narrower other with 8.5 inches length i.e. 90mm dia at wide end, 55 mm dia at narrow end and 220 mm long. A uniform wall thickness of roughly 9 mm is maintained. A burnt clay tube module weighs about 725 gms.

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224 This was first proposed by the architect and engineer couple – Rupal and Rajendra Desai who have made commendable contributions to the BCTs since the 1980s.
The earliest research paper in English written on the creative application of burnt clay tubes that I was able to retrieve was from 1960 published during the directorial tenure of the maverick engineer Guruvayur Ramaswamy at the Central Building Research Institute (CBRI), Indian Institute of Technology, Roorkee titled “Hollow Vault Roofs for Low Cost Houses.” In the paper two CBRI researchers published their cost-saving findings for constructing hollow vault roofs using BCTs (referred to as Guna tiles in the paper) in conjunction with precast concrete structural elements and presents findings from their structural performance. The module they refer to is slightly smaller to the ones developed at Wardha: Guna tiles are hollow conical earthen tiles 4” at the broader end, 3” at the narrower end and about 6-7” long with about a 1/2” wall thickness. The research paper refers to burnt clay tubes in a manner that assumes their existence and further states that these are indigenous, made on a potter’s wheel and available locally. The article does not claim that burnt clay tubes were ‘invented’ at CBRI unlike the other technologies for which they present their findings.

This is of some importance to us as the burnt clay tubes have been compared to ceramic fuses due to their matching shape, size and method of use. However, in the earlier section we have seen that ceramic fuses came to India only after 1962 making it very unlikely that the burnt clay tubes were derived from ceramic fuses directly.

Therefore, while the CBRI may have explored combining the BCTs with precast cement elements, it was the Centre of Science for Villages (CSV) in Wardha near Nagpur in Maharashtra state that consolidated it into a practical building technique by perfecting its use, production methods and conducting thorough structural tests and for confidently propagating its adoption throughout the country. Intriguingly enough, it is also possible that CSV was not aware of CBRI’s research on BCTs and developed a tweaked version of their own.

The Centre of Science for Villages (CSV) was founded in 1976 in Wardha. Its formal campus was built in 1987 just 7 kms from Mahatma Gandhi’s Sevagram Ashram where Gandhi spent the last two decades of his life. Gandhi’s ideas of village democracy, self-sufficiency and rural industrialisation have been crucial in shaping the CSV’s core activities and outlook. Its founder chairman Dr. Devendra Kumar and Gandhi’s close associate and trained economist...
Dr. J.C. Kumarappa saw the CSV as an instrument to realize Gandhi’s vision of Gramudyog or a sustainable rural economy.\textsuperscript{229} The empowerment of rural India was of primary importance in Gandhi’s philosophy of independence. He had articulated the issue on numerous occasions through lectures and writings and his voice continues to offer an alternative to the globalization trend of our times.

The inspiration for creating burnt clay tubes on site stemmed from the fact the CSV had an active pottery section and Dr. Devendra Kumar is reported to have seen ceramic fuses in Gujarat which, he was confident, could be replicated on site in Wardha by its potters.\textsuperscript{230} Around the same time, an architect-engineer couple – Rupal and Rajendra Desai arrived at CSV around late 1984, after having spent many years in the U.S.A. Incensed by the emerging energy crisis and having trained briefly with Nader Khalili\textsuperscript{231}, the Desais were intent on contributing to solving the sustainable housing problem of rural India and saw the CSV as an ideal platform for their intended work. When the Desais arrived at CSV, the campus had already developed the capacity to manufacture burnt clay tubes on site but had not tested them for structural performance nor fully understood its applications.

Rajendra and Rupal Desai thus headed the research and development of using burnt clay tubes and much of the knowledge that emerged from their experiments over the next few years was what formed the basis of the CSV’s systematic kit of parts eventually developed for the assembly of roofs made out of BCTs. Mr. Rajendra Sahu who has been at CSV since 1980 served as foreman to the extensive research conducted by the Desais and continues to remain the vital link in executing BCT roofs at CSV even today.

Aimed primarily at low cost housing due to its simple construction, the Desais brought with them technical knowledge and the sensitivity to develop and implement solutions appropriate to the context of rural India. \textit{We also learnt for the first time a roofing technique of Burnt Clay Tube (BCT) vault. We found it rather suitable for the Indian climatic conditions as also for the socioeconomic conditions. BCT vault has superior thermal behavior to RCC slab. It costs 40% less. It has higher labour component and could provide much needed employment to the rural potters.}\textsuperscript{232}

\textsuperscript{229} Mahatma Gandhi actively championed the strengthening of the rural economy through rural empowerment. His ideas extend to the self-reliance and although not directly commenting on architecture, they can be interpreted to include dignity in living yet frugality of means.

\textsuperscript{230} Centre of Science for Villages, 'Building Dreams in Mud: A Manual on Low Cost Housing and Sanitation' (Manual, Centre of Science for Villages, 1998), page 4. Although this may be true, burnt clay tubes already existed as Guna tiles as is established from the paper published in 1961 by Sharma and Chetty.

\textsuperscript{231} Nader Khalili is a celebrated architect that pioneered Sandbag Shelters and a host of other earth-reliant environmentally friendly technologies. For more on Khalili see: Ceramic Houses and Earth Architecture: How to Build Your Own published by Cal-Earth press.

By the early 90s, the burnt clay tubes began to appear prominently in projects across India. From the nature of projects they feature in, their use seems to have been relegated to mostly low-cost domestic architecture. This may have to do with how it was actively promoted by the Government of India agencies such as the Rural Housing Knowledge Network. Also of note is the appeal that BCTs have had within the NGO fraternity owing to their indigenous nature, ease of production and labour engagement.

What contributed to the quick adoption of burnt clay tubes was the fact that they follow the exact procedure for production as the ubiquitous roofing tiles called country tiles. Country tiles are curved roofing tiles that are a cheaper version of the superior flat and profiled Mangalore roofing tile. Made on a potter’s wheel, while the hollow tapered cylinder is cut into half to give two pieces of country tiles, for the burnt clay tubes the cylinder does not need to be cut but is used whole making its production even faster and easier.

Right:
Construction of vaulted roof using burnt clay tubes. Photo by Anupama Kundoo

Following page:
Collage of the manufacturing process of burnt clay tubes and their application at the Kumarappan Auditorium on CSV campus which is only doubly curved shell made with burnt clay tubes that I was able to see.
Production of Burnt Clay Tubes at Wardha\textsuperscript{233}

A clay-rich mixture was prepared into a lump using 50% white clay, 35% yellow clay and 10% black soil. The clay lump is then placed on a spinning potter’s wheel and turned into a tumbler that is closed from one end. This is then left to semi-dry for two to three hours but not allowed to dry out completely. The potters are also mindful of shrinkage which needs to be accounted for during the process of drying and firing. The tumbler is then placed on the potter’s wheel again with the closed end facing upwards. The potter then opens up the closed end and we now have conical shaped tubes with both ends open. The tubes are then left to dry in the sun. In summers, the tumblers may be left to dry for 3 days while in winters this may extend up to 5. A potter can prepare up to 1000 tumblers a day on his wheel.

Once sun-dried, the tumblers are taken to the kiln for firing. The kiln used at CSV is circular with an internal diameter of 10 feet and 2 feet thick walls and approximately 4 feet height. The kiln is capable of firing 4000 tumblers at a time with four layers of a 1000 each. The tumblers are loaded from the top and laid with their smaller diameters facing downwards. They are then covered fully with a bed of firewood above. To optimize their baking, half tumblers are laid over the firewood and covered with a thick layer of mud and a further layer of half-tumblers is added for more weight from above. This seals the kiln from the top and ensures an airtight arrangement for firing. The kiln is fired for 6 hours reaching 750 deg. C and the tiles are left in the kiln for two to three days. CSV estimates 1000 kgs of firewood for burning 4000 tumblers. CSV claims that this is about five times lesser than firing an equal quantity of bricks.\textsuperscript{234}

Once removed from the kiln, the tumblers are dipped in water and are ready to be used as Burnt Clay Tubes. CSV states that dipping in water after retrieval from the kiln is important due to the high lime content in the local soil and may not required to be done elsewhere. Also, about 10% wastage is estimated during the retrieval of BCTs from the kiln. In 1998, 1000 BCTs cost Rs. 900 – making each cost Rs. 0.9/- only. As of 2017, a burnt clay tube costs Rs. 6/- in Nagpur and have been produced for Rs. 3.5/- and Rs. 2.5/- in the states of Chattisgarh and Bihar respectively. This converts to roughly £0.7/- for Nagpur, £0.4/- and £0.3/- making them extremely inexpensive by any standards.

\textsuperscript{233} This text is based on the interviews I conducted with Rajendra and Rupal Desai in Ahmedabad on 18\textsuperscript{th} March 2017 and Mr. Rajendra Sahu at Wardha on and the literature provided by CSV through its manual on building the ‘Wardha House’.

Construction of Vaults using Burnt Clay Tubes

A superstructure in brick or alternative masonry is first erected followed by the casting of a reinforced concrete ring beam to counter lateral thrusts arising out of the vaults. The beams are L-shaped or preferably chamfered in order to receive the burnt clay tubes perpendicularly.

At Centre of Science for Villages, Wardha (CSV) the Desais were also quick to discover that the catenary form was superior to the semicircular one through their experimental build and break prototypes in the late 1980s. Their methodology for form finding was traditional in the sense that they suspended chains that were secured at two ends of a wall and traced the profile to invert it for a pure compression structure. CSV today operates a template of catenary vault profiles for the most frequently used spans such as 3 m (9 feet), 3.6 m (12 feet) and so on.

Based on their present size and frequently used spans of 3 m, 110 burnt clay tubes cover about 1 sq.m. area. Over the many years of research and building, CSV has developed a systematic kit of parts for quick construction using BCTs. Main components include:

1. Two bowstring trusses made with MS angles 25 x 25 x 5mm. The main arch of the truss has mild steel U-bolts that receive the galvanized iron (G.I.) pipes to act as guides. The bowstring trusses are welded onto base plates that rest on beams concrete beams.

2. The galvanized iron pipes having threaded ends help them to be screwed or unscrewed according to desired lengths. Once set in place, these pipes are meant to serve as robust guides for the curve of the vault and also as temporary purlins that help keep the trusses stable.

The trusses rest on the beams with a wooden spacer block between them. This is crucial in order to adjust the final height and to remove the trusses without impacting the finished vault above. The galvanized iron (G.I.) pipes are then run through the length of the vault passing through the U-bolt loops. The use of lighter guides here is deemed unfeasible as the G.I. pipes are more rigid and help the chain of tumblers to rest on them while being interlocked and subsequently when loaded with layers of cement.

Similar to the Production sub-head, this text is also based on the interviews with the Desais and Mr. Sahu along with the literatures disseminated by CSV over the years in text and audio-video formats.
Above: Collage of images taken from CSV’s brochure showcasing their homegrown technologies
Four to five burnt clay tubes are socketed together and laid in place. The first line of tumblers rests directly on the arch of the bowstring truss and unlike the construction of an arch where two ends meet at the keystone, the burnt clay tubes are laid starting from one end to the other. At regular intervals, the tumblers are secured to the truss using a thin mild steel wire.

We have seen how ceramic fuses can be laid side by side and benefit from flutings that contribute to lateral friction, in the case of burnt clay tubes, rows of tubes cannot be laid side by side due to their tapering profile. This problem is ingeniously dealt with by simply changing the direction of laying the burnt clay tubes and is an important distinction from the laying of ceramic fuses which is otherwise very similar. The handling of burnt clay tubes requires at least three individuals at any given time and more in case of very wide spans to ensure proper interlocking along the curve. It is also important to ensure that the burnt clay tubes are properly interlocked to avoid problems during the application of cement mortar.

Once the desired series of arches is completed along the length of the vault, the upper surface of the vault is sprinkled with water in order to prepare it for receiving cement mortar. This is a precautionary measure exercised to counter masonry bonding problems due to heat gain. Cement mortar is then prepared in 1:4 (cement : sand) ratio and joints between the arches are filled with either a trowel or by hand. The thickness of this mortar is 12 mm.

The removal of centering is considered absolutely crucial and is recommended to be undertaken before the mortar has set, about 12 hours after application. The purlins are the first to be disconnected and slid out from the eaves. Any wires tied to secure the chains of burnt clay tubes to the trusses are undone. Wooden spacers under the trusses, added at the beginning, prove to be crucial at this juncture and upon removal facilitate the smooth dismantling of the truss from the arrangement. During the decentering process, slight movement or ‘sinking’ of the roof is considered normal as the burnt clay tubes adjust themselves to find their optimal geometric line in case of discrepancy. The applied cement mortar offers better binding of the vault’s membrane. This plastered surface is kept hydrated using wet gunny bags all this time.

A second layer of cement mortar mixed in 1:5 ratio is then applied to smoothen out the vault’s plastered surface. Finally, china mosaic utilizing recycled broken tiles is applied in cement slurry as the external finish. The soffit of the vault is almost always left exposed for the burnt clay tubes to be visible from underneath flaunting a pleasing terracotta hue.
Used mostly for single curved structures, the only example of a doubly curved vault constructed with burnt clay tubes that I found was the Kumarappan Auditorium on CSV’s satellite campus.

Due to their low production costs and rapid building technique, vaulted roofs made out of burnt clay tubes are remarkably cheaper than reinforced concrete slabs. A single curved, single layered burnt clay tubes vaulted roof, having a rise to span ratio of 1:4, including waterproofing and china mosaic finish costs Rs. 130 per sq.ft making it cheaper than half of the reinforced concrete flat slab. Other advantages of the burnt clay tubes roofs include rapid assembly and potential 1:1 labour to material ratio ensuring employment to less-skilled workers. Problems with waterproofing have also been found to be recurrent if not addressed thoroughly during construction phase but have not impeded its choice as an appropriate roofing system.237

236 Interview with Mr. Rajendra Sahu on 12th April 2017 at Centre of Science for Villages, Wardha, Nagpur
237 Ibid, This was seconded in an interview with Rajendra and Rupal Desai in Ahmedabad on 18th March 2017.
### Comparative Roofs

#### Room Dimensions
- **Reinforced Cement Concrete**
  - **Flat Slab**
    - Rs. 3,768 / sq.m
    - GBP 43 / sq.m
- **Burnt Clay Tubes**
  - **Funicular Hollow**
    - Mostly single curved
    - Rs. 1,400 / sq.m
    - GBP 16 / sq.m

1 GBP = INR 85.08
Currency exchange as of 27 September 2017
Source: Oanda (https://www.oanda.com)

#### Flat Slab
- Two-way flat slab
- More reinforcement for beams and slab
- Reflection ceiling plan

<table>
<thead>
<tr>
<th>Rise to span ratio</th>
<th>Thickness</th>
<th>Labour</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.15 m</td>
<td>6 persons</td>
<td>3 days</td>
</tr>
</tbody>
</table>

| 1:4                | 0.12 m    | 6 persons | 3 days |

#### Advantages
- "Standard" technique.
- Materials easily sourced.
- Easily replicable due to ubiquity.
- Cost of construction considered "normal".

#### Disadvantages
- Requires sturdy formwork + reinforcement design.
- Requires repairs within first few years of completion.
- Not ideally suited for tropical regions due to heat gain.
- Uses a lot of steel and water: energy intensive materials + processes.

- Module produced on potters wheel.
- Easy to assemble.
- Very strong and durable.
- Aesthetically pleasing.
- Extra volume through vaulted ceiling.

- Requires more guidework than tile vaulting.
- Cannot be left exposed to sky - needs cement plaster and waterproofing layer.
- Needs reinforced edge beams to counter thrust.
- Modules need to achieve uniform firing to become robust and minimize breakage.
Research and Development: Adding vents to burnt clay tubes

During their time at the CSV, Rajendra and Rupal Desai also explored the creation of a modified burnt clay tube module to facilitate heat escape and enhance the vault’s thermal resilience. This is perhaps the only time that the thermal performance of burnt clay tubes or that matter even ceramic fuses has been scientifically evaluated. As ceramic fuses and burnt clay tubes followed a construction process that created chains of the modules that were resting on beams and covered with cement mortar from above, the heated air remained trapped inside the hollow modules unable to escape the chains. Thermal insulation of both these hollow tubes would be barely effective useful appropriate vents were offered for heated air to escape and be replaced by cooler air, thereby setting up a cyclical convection current.

The slender profile and light thermal mass of the fuses would also further contribute to their heating up quickly in a climate like Western India’s that includes the states of Maharashtra and Gujarat. In the case studies that use ceramic fuses, none of the buildings are mindful of such a problem which may also lead to the cracking of fuses in extreme cases. This has led to occupants complaining about interior spaces becoming extremely hot during daytime which is primarily due to the low thermal mass of a single layered burnt clay tube roof.²³⁸

The Desais addressed this problem by modifying the BCTs and created a Vented Burnt Clay Tube that featured a simple protruding nozzle to serve as a vent. Such vented modules were placed at the springers and the crowns for rising hot air to escape. The Desais conducted a series of experiments to monitor their thermal performance with encouraging results.²³⁹

With the departure of the Desais from CSV, further research on BCTs virtually ceased. However, their comprehensive experiments have laid the foundations for technically sound building methods with BCTs that are followed by CSV personnel such as Mr. Sahu even today.

²³⁸ There are some signs of this having taken place also at Sangam which uses ceramic fuses, as documented during site visits in June 2014 and again in April 2017.
Vented Burnt Clay Tubes

Uniform thickness: 9 mm
Weight: 725 gms
Burnt Clay Tubes: CASE STUDY 1
Gramin Takniki Kendra, 1990 (Village Polytechnic)

Research conducted by the Desais on Wardha tumblers at CSV saw fruition in one of their most accomplished projects – the Gramin Takniki Kendra.

Built in Jhagadia village in the Bharuch district of Gujarat, the Gramin Takniki Kendra (GTK) was established to provide vocational training to the tribal youth of Bharuch and neighbouring areas. Championed by a local NGO named SEWA-RURAL and funded by Council for the Advancement of Peoples’ Action and Rural Technology (CAPART), the Desais envisioned the design and construction of the GTK campus as a demonstration of their ideology: using local construction materials, exercising discretion when using energy intensive materials such as cement, steel and even burnt bricks. As the primary funding agency, CAPART asserted its preference for mud construction technology as well as labour-intensive and local resources for the campus’ construction. All other constraints were self-imposed by the architects to create conditions for applying their technical knowledge whetted during their time at CSV.

Based upon the guidelines mandated by the Indira Awas Yojana, a Government of India’s pro-employment policy, CAPART allocated a budget of Rs. 60 per sq.ft which the Desais observed would be sufficient for houses but not institutional buildings as the latter required upgraded specifications. A deductive process between client-engineer and architect was employed to arrive at the most viable construction system for the roof: reinforced concrete slab was the first to be rejected due to its heavy reliance on energy intensive materials and the stake holders’ already established resolve to demonstrate appropriate construction. Pitched tile roof too was eliminated, as GTK’s management did not wish to invest in a technique that would warrant frequent maintenance and was susceptible to insects and dust. The Desais were eventually able to gain consensus to primarily build curved roofs in BCT due to their confidence in the system’s structural efficiency, long-term performance and as the campus buildings were all meant to be ground storied it would add variety to the architectural expression. More importantly, building with BCT would facilitate the production of tubes on site and engage both skilled and unskilled labour with equal ease and

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240 In 1987, CSV’s Training Centre at Dattapur was also built through CAPART funding.
242 Indira Awas Yojana allotted Rs. 60 / sq ft for building small houses sized approx. 180 sq.ft for the rural poor for Rs. 6000/-. 
in this manner sufficiently meet the Indira Awas Yojana criteria for balancing labour and materials.

Surprisingly, it was the production of BCTs that proved most challenging. The Desais had been relying on potters from a neighbouring village to produce BCTs on site but discovered that the latter had ceased producing country tiles as there was barely any demand for it. With the infrastructure to produce BCTs in place on the campus, the Desais were forced to source a potter from north Gujarat but he too left as thieves raided the campus a few nights later scaring him off.²⁴⁴

The production of BCTs never resumed at site and much to the Desais’ disappointment all BCTs were eventually sourced from the villages of Dholka and Limkheda, both around 200 kms away, where potters still made country tiles.

BCTs used for all buildings on campus were of length 9”, large diameter 4” and small diameter 2”. With the kit of parts already sound and systematic, the BCTs were deployed quickly and successfully to create a variety of roofs which included single curved roofs of varying rise as well as inclined vaults that successfully integrated north lighting.

To showcase and critically evaluate their efforts in appropriate technology, the Desais carried out an assessment study in 1997, seven years after completing the project and published their findings which insist upon diligent execution of the vaults citing problems in maintaining its consistent curve during construction, appropriate treatment of gable ends and better methods in waterproofing to ensure long-term solutions.²⁴⁵

Following page:

Collage showing construction of Gramin Takniki Kendra roofs in 1990 using burnt clay tubes

²⁴⁵ A rare example of long-term critical evaluation of one’s own work, the excellent and candid report by the Desais is not widely available but can be sourced. They donated a copy to the University of Cambridge which I was delighted to carry and have greatly benefitted from.
Burnt Clay Tubes: CASE STUDY 2
Ratanpar School, Kutch, 1994

Located in the Rann of Kutch, 175km from Bhuj, the Ratanpar school was constructed in 1994 to serve neighbouring villages as well as a residential school for children who come from afar. Ratanpar is just 12 kms from the historical site of Dholavira – a constituent city of the ancient Indus Valley Civilization famous for its advanced city planning and water conservation features alongside an extremely refined ceramics legacy.

The Tropic of Cancer passes through the Rann of Kutch, one of the largest seasonal salt marshes in the world, located along the border with Pakistan. Temperatures in the Rann can rise to 49 deg. C in summers and drop to 0 deg in winters making it an extremely challenging environment to build in without the facility of robust materials. The air is also heavily laden with salt making it extremely corrosive thus dramatically reducing the life of contemporary building elements made in steel and concrete. Therefore, the choice of making roofs in burnt clay tubes offers resilience to the harsh weather conditions and reprieve from the heat through effective volumetric treatment.

The building and structural design for the Ratanpar school was carried out by Ahmedabad-based NGO, Ahmedabad Study Action Group (ASAG) which the Desais provided technical expertise to.

Their experience and ideas from building the Gramin Takniki Kendra are seen put to use in the Ratanpar school. A typical classroom at Ratanpar measures 14.76 m x 5.47 m with vaults of 3.526 m span rising 0.88 m over four bays. The vaults sit on reinforced concrete beams measuring 0.66 x 0.23 m and each bay has 4 tie rods to secure to vaults.

Burnt clay tubes used have all been painted from the inside except for the toilets in the hostel where they remain exposed. The burnt clay tubes at Ratanpar measure 180 mm long x 130 mm dia. at base and taper to 60 mm dia at top with uniform 8 mm thickness. The modules were reportedly supplied from Bavda, a town 30 kms from Ahmedabad. The school extended their facilities to include a Science Centre that comprises three domes made in reinforced cement concrete. The idea behind the domical shape was to resist seismic movement without damaging the structure but following the 2001 earthquake of 7.7 Mercalli scale in Bhuj, the vaults made with burnt clay tube withstood the earthquake without any visible damage while the Science Centre developed structural cracks. Due to this, occupants of the school have renewed confidence in the burnt clay tube roofing technology.

246 Interview with Rajendra and Rupal Desai in Ahmedabad on 18th March 2017.
247 Observations from field visit in March 2016 and interview with Mohan bhai, the school’s warden.
CONCLUSION – Chapter 4
Ceramic Fuses and Burnt Clay Tubes

It is clear that Ceramic Fuses and Burnt Clay Tubes transmit very strong cultural links that have contributed to their respective origins, proliferation as well as rejection.

In her recent works, artist and scholar, Ilana Salama Ortar has created many art installations using the idea of ceramic fuses for evoking images of the Camp du Arenas. The time spent in concentration or refugee camps evidently has extreme connotations and feelings associated with it and for those who lived there, the ceramic fuses evoke a sense of temporality; that of caves and tents. Almost all occupants of the Camp du Arenas interviewed in 2003 by Ortar recounted the *barrels and arched barracks* that they inhabited and continue to relate to them with informality and uprooting.

This certainly has to do with the structural form deriving its shape from a module that is left visible when completed. What could thus have been a timeless building module steeped in simple biomimetic construction principles instead echoes of geopolitical upheavals and mass displacement. It can be argued then that while on one hand while ceramic fuses offered desirable qualities sought in post-WWII building materials: lightweight, prefabricated, quick to build and durable; their association with refugee camps led to their being shunned by other builders. Ceramic fuses also lost its likely champion in Pouillon who had once marveled at their potential but later lamented about the unfortunate mismatch of their production in a conservative ceramics industry in Marseille and expressed disappointment on the Camp having been operated like a military compound with watch towers and barbed wire fencing thereby robbing it of the humanitarian purpose that it was originally meant to serve.

Restricted by patents and closely controlled in wide market by a handful few, it would be fair to conclude that the production of ceramic fuses was atypical, not fully understood to be easily replicable and not economically lucrative enough to meet commercial appeal in an increasingly consumerist world. As the appeal of cement concrete surged in the post war period, such a marginalized building technique could not have survived the competition without persistent promotion. This proved true for its life on the European continent and India alike.

250 Ibid, p. 57.
Burnt clay tubes on the other hand in India remain open-source: providing access to anyone interested in working with it. Perhaps no other building material used in India, with the exception of the brick, embodies the principle of Gandhian self-sufficiency better than the burnt clay tubes. Besides superior manufacturing methods and an expectedly better compressive strength, ceramic fuses have few advantages over burnt clay tubes. While the former can be seen as a capitalist, upmarket building module, burnt clay tubes are an empowering agent of self-reliance and community participation through their frugal production method, modest form and rapid construction system.

However, the aura and reputation that burnt clay tubes have garnered in being associated with building for those with financial constraints has rendered it somewhat undesirable to more affluent clients of the burgeoning Indian economy.\textsuperscript{251} Despite the potential to be produced indigenously almost anywhere, and even as resilient and sustainable building module, burnt clay tubes are almost never used in commercial projects. But this is a matter of perception that has its nemesis in modernity’s preference for cement concrete and the formal trabeated aesthetics it brings. It is as the Desais state about its parent ingredient - clay: “Being inherently labour intensive, it is the material for the rich in the U.S.A. where as in India only the poor use it since all it costs them is their own labour.”\textsuperscript{252} Perhaps it takes the rich to attest the value of something and ideologies too trickle down only when endorsed by the privileged, diluting the appeal of sensibility in traditional wisdom.

The intense period of development in burnt clay tubes and other cost appropriate technologies at the CSV was fueled at least in part by the international collaboration and exchange in expertise on the CSV campus. CSV’s resolve to not accept foreign funding unless donors were also partnering on research or execution drew experts from countries such as France and Uzbekistan to their campus for developing rural technologies.\textsuperscript{253} However, such collaborative efforts waned in the following decades.

Burnt clay tubes have further witnessed a surge in popularity in recent decades through their use in Auroville – chiefly due to their prolific experimental decade of building since the 1990s and effective dissemination of literature of their architectural work in English.

\textsuperscript{251} CSV’s employees confirm this sentiment and we can deduce this association through the projects that BCTs have been used in.
Auroville’s predominantly expat community’s connection to the world has no doubt helped put BCTs on the world map alongside other remarkable building techniques.

As an excellent example, Anupama Kundoo’s installation of burnt clay tubes at the Venice Biennale in 2012, built by Indian masons, is perhaps a showcase of the highest standard that an otherwise low-cost construction technology has been afforded yet. Even within India, have the burnt clay tubes not received such a deserving audience. Peculiarly, the Venice installation uses superior quality burnt clay tubes unlike the more rustic ones used across India. This draws a distinct analogy with the tile vaulting prototype built by a Spanish mason also for the Venice Biennale in 2016 by Foster + Partners. Incidentally, this particular prototype is a precursor for a comprehensive Droneport Project in Rwanda. Tile vaulting too is seeing a surge in scholarship and deployment and with high visibility showcases, architects will take note of its potential while considering its hand-reliant system of construction to assess its place within their own building cultures.

Despite the many centuries that testify their competence, the irony with which once established yet now peripheral building technologies need to be showcased for their gestural or structural performance potential may somewhat be peculiar, even demeaning. However, as is the case with the burnt clay tubes, with more awareness of its production and building technique, there is little doubt that tile vaulting’s roots too can be strengthened for serving as appropriate technology across markets and budgets, perhaps in ways not explored before.

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Below:

Collage of Anupama Kundoo’s installation at the Venice Biennale in 2012 using burnt clay tubes
Reinforced Brick Vaults and Muzaffarnagar Vaulting in India

Geographical Distribution of Case Studies

- Traditional Masonry Shells
- Modified Traditional Masonry Shells
- Reinforced brick vaults

Map showing various locations in India with case studies highlighted.
“Things men have made with wakened hands, and put soft life into are awake through years with transferred touch, and go on glowing for long years. And for this reason, some old things are lovely warm still with the life of forgotten men who made them.”

- D.H. Lawrence

Chapter 5

Reinforced Brick Vaults at National Institute of Design, Ahmedabad and the Muzaffarnagar Vaulting Technique

The National Institute of Design, Ahmedabad

The National Institute of Design (NID) was founded in 1961 in Ahmedabad to serve as India’s premier institute for teaching design. Originally planned to be established in Bombay, Gautam and Gira Sarabhai along with the textile-scholar Pupul Jaykar actively championed for the institute to be established in Ahmedabad. With Charles and Ray Eames appointed as key curriculum advisors, several other high profile international experts on design were invited to contribute to the initial years of NID. The background of NID’s establishment is important to reflect upon because of its resolute credo for designing appropriately for India, despite having a battery of international – mostly American and European – consultants in its nascent stages. Over the years, NID has retained its ideology to celebrate homegrown crafts in the midst of novel design, which has actively promoted an introspective approach towards tradition while looking outwards.

In a decade-old independent nation, securing NID’s establishment in Ahmedabad was yet another achievement by the city’s intelligentsia for establishing institutions of national and international recognition in their city. Gautam Sarabhai not only served as the NID’s

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256 Peter Scriver and Amit Srivastava, India: Modern Architectures in History (London: Reaktion Books, 2015). The splitting of Bombay Presidency, doubts were cast on its foundations and immediate future which promoted Ahmedabad as a strong contender.
257 The seminal ‘India Report’ by Charles and Ray Eames in 1958 emphasizes the importance of not reinventing the wheel – their pot analogy is particularly fetching. Besides the Eames, the earliest collaborators at NID were George Nakashima, Frei Otto, Louis Kahn as well as representatives of design schools in Ulm, Basel, etc.
inaugural director but was also the architect of its buildings. He was also most likely the one who ensured that architectural design was at the heart of NID’s originally proposed core curriculum. NID’s 50-years commemorative volume attributes his approach to be one that was influenced by the Bauhaus that promoted learning by doing and working in guilds. It must be noted that Gautam Sarabhai himself wasn’t formally trained in architecture but gained architectural experience by first working with Santiniketan architect Surendranath Kar in the design and construction of their ancestral home at The Retreat in Shahibaug, Ahmedabad. In later years, Gautam Sarabhai collaborated with numerous eminent architects, engineers and designers including Buckminster Fuller and Frei Otto.

Located across the road from Le Corbusier’s Sanskar Kendra (city museum), NID borrows Corbusier’s Brutalist idiom of *beton brut*. NID’s framed reinforced concrete structure is characterized by concrete columns and beams with exposed brickwork for wall infill. The columns follow a square grid of 40’ capped by shallow vaults making the structure extremely flexible as an institutional building that allows for rearranging workshops and classrooms. However, it is the vaulted ceilings of NID that deserve special attention for their construction technique.

The structural engineer for NID was Dr. Guruvayur S. Ramaswamy who researched reinforced shell structures for nearly a decade before building the NID roof. Ramaswamy explained the rationale behind the design of the shell at NID as one taking advantage of reversing the traditional sequence of determining the shape of a structure first and then calculating induced forces to instead assuming the desired stresses in the material before proceeding to find a shape that will contain arising forces. Despite the heavy but deemed necessary steel reinforcement, Ramaswamy notes that the shells were ‘lightly’ reinforced. As a result of Ramaswamy’s interest in form and structural optimization, NID’s vaults are extremely thin at 4.5 inches (115 mm) of thickness with only waterproofing adding over.

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259 Santiniketan was the Nobel-laureate Rabindranath Tagore’s abode and gurukul system that freely promoted fine and performing arts.
260 This building is today the Calico Textiles Museum overseen by Gira Sarabhai. The Retreat campus is also of course home to Le Corbusier’s Sarabhai House.
261 Bengali architect Surendranath Kar (1892 – 1970) also designed buildings at Tagore’s Santiniketan.
263 Ibid, p. 255
Having 115 mm thickness for a span of 12.5 m makes the NID vaults remarkably thin.

Also, a rise: span ratio of about 1:10 makes the vaults almost flat to the naked eye.
Construction of the Reinforced brick vaulted roof of NID

NID’s cushion vaults sit on a square plan of 41’ (12.5 m) side and rise 4.5’ (1.37m) with a rise to span ratio of nearly 1:10. The beams that the shells rest on are 14 inches (0.35 m) wide, and 42 inches (1.14 m) deep. Relative to the large span of the vault, the rise is not immediately obvious to the eye and it therefore gives the impression of being almost flat. The only exception to this module is a slightly larger vault that is raised from the rest of the structure at NID and sits on a 45-foot span (13.71 m) being the only exposed vault on its façade flaunting its innovative structural roof.

The diagonally laid, unidirectional stereotomy of the bricks are also unlike a conventional vaulting system that would proceed from beams to meet at the centre indicating that they were placed onto formwork and secured by tensional forces. This intriguing stereotomy and geometry continues to lend NID’s vaults distinct personality unlike those other vaulted constructions of the time in the country.
Archival research at NID revealed the heavy formwork prepared using wooden trusses and curved plywood. Given the low rise:span ratio, the formwork can be deemed to have been very well resolved for its geometry. It further incorporated a component of ‘assisted’ building by providing a grid made in wooden strips for the placing of bricks. Bricks were laid on edge at a distance of ½” to 1½” between them for receiving steel reinforcement and cement mortar. Following a template grid for laying of bricks would no doubt have made the process extremely accurate and quick by resolving the problem of compensating dimensions along the geometric curve. This method of using a template for assisted construction is akin to the methods used even today in other parts of the world.264

The shells have two-way reinforcement bars 3/8” dia. at 10.5 inches c/c which translates to a square grid of steel bars between three sets of bricks. The reinforcement is evidently heavy but well detailed and well executed at site with bent bars, cross laying at corners and tying with wires at regular intervals. The joints between bricks were subsequently filled with cement mortar. Archival images of NID’s construction show two different kinds of brick modules were used although not entirely clear where these were deployed. The soffit of the vaults is exposed brick with recessed pointing that accentuates the unidirectional coursing pattern of the shell. Despite the reinforcement at every 10.5 inches, the soffit of the shell is uniform and reveals no such details.

The NID’s vaults share their structural semantics with the exceptional Uruguayan engineer Eladio Dieste’s reinforced brick shells. Their atavistic relationship is not merely aesthetic but also shares similarities in construction methods. Dieste constructed his first reinforced brick shell in 1947 but had virtually abandoned the building method until 1958 when he constructed the now renowned Cristo Obrero Church in Atlantida.265 Following the publication of his paper on the church, his structural design for reinforced brick vaults received international recognition thus influencing many other engineers around the world to test the now established technique which resulted in unprecedented forms and tectonic compositions.

The parallel with Dieste here is not just technological and aesthetic but also cultural – one that allowed for a traditionally handcrafted building to now be combined with the evolving pre-stressed concrete technology of its time. In these terms, Dieste’s working context of

264 Chicago vaults by MHR that facilitate rapid construction. Elaborated in detail in the concluding chapter of this thesis.
Uruguay, Argentina and Brazil was similar to one presented to Gautam Sarabhai and his engineer at NID - G.S. Ramaswamy.

The architect, the engineer and the craftsman:
Gautam Sarabhai and GS Ramaswamy were both well-travelled and abreast with developments around the globe in the architectural realm. Given their resources and disposition for structural statements, it is very likely that they knew of Dieste’s works. And while this is not enough evidence to say that the NID’s vaults borrow from Dieste, it is within reasonable justification to conclude some influence.

Gautam Sarabhai further extended his experiments in funicular vaults at NID by creating 2 variants of the vaults within the same parametric modulation. The first is the above-mentioned reinforced all-brick vault spanning 41 feet a side and the second is a part-concrete, part-brick vault which is on the first storey and is visible in the workshops while maintaining the same rise: span dimensions.
Above:

Collage of NID’s archival photographs from its construction phase
Gautam Sarabhai’s preference to work with methods that artisans and masons could relate to is emblematic of his vision for NID’s engagement with the crafts. The building no doubt makes a social statement through its choice of materials and the construction methods, especially at a time when concrete shells and folded plate structures were gaining prominence.266 In a relationship between materials, engineering and desired aesthetics, the craftsmen are likely to have played a part and as was later revealed that the choice of materials were credited to the head mason, Premji Kaka Mistry who along with a handful other artisans working on the project enjoyed the confidence of not only Gautam Sarabhai but also Louis Kahn and Doshi who subsequently built IIM together. 267

Gautam Sarabhai continued to build several other experimental structures, both ephemeral and durable, that served for decades and became part of the public sphere in Ahmedabad. His celebrated five-pointed geodesic dome at the Calico factory (1962) was a Fuller-esque structure which was fiercely fought for by citizens against demolition in 2013 and is now being replicated by the Ahmedabad Municipal Corporation. For the BM Institute of Mental Health (1977) he collaborated with Eda Schaur at Frei Otto’s Institute of Lightweight Structures to create a highly complex roof constructed out of modest materials: bamboo, wire mesh and finished with cement plaster.268 This unique roof boldly embodies the spirit of collaboration by combining the German engineer’s highly sophisticated methods for form-finding with the hand-dominant building methods of the Indian artisans.269

Gautam Sarabhai’s brother Dr. Vikram Sarabhai died in 1972, leaving him as the sole patriarch of the large family business which may have restricted his architectural experiments in later years. Doshi also established an architecture school in 1962 and this is believed to have played a role in the phasing out of architecture from NID’s core curriculum.270

266 Charles Correa’s Hindustan Lever pavilion, Rewal’s Hall of Nations and Doshi’s Tagore Hall (seen across the site from NID) are all reinforced structures around the same time.
267 Amit Srivastava, ‘Encountering Materials in Architectural Production: The Case of Kahn and brick at IIM’ (PhD Thesis, University of Adelaide, School of Architecture, Landscape Architecture and Urban Design, 2009). Louis Kahn’s official appointment was as chief mentor for the IIM Ahmedabad. The NID was official Architect of Record with Doshi at its helm. NID also played a vital role in coordinating the architectural works of IIM with students contributing to drawings and studies conducted in Delhi, Bombay, etc.
268 Site visited on 30th November 2015 and again in 14th March 2016.
Experiments in reinforced brick slabs continue to be undertaken today and architects such as Laurie Baker and Anupama Kundoo have also demonstrated how the volume of concrete in reinforced concrete slabs can be reduced by using Mangalore roofing tiles as well as terracotta pots as fillers. Colloquially referred to as filler slabs, these slabs receive inverted pots (with their open mouths facing downwards) and have reinforcement around them. The process requires skilled to semi-skilled labour and yields results that are aesthetically pleasing as well as economical to build when compared to reinforced concrete construction due to the reduced volume of concrete. A chart comparing the two techniques is provided on the following page.
**COMPARATIVE ROOFS**

**ROOM DIMENSIONS**
3.5 m x 3.5 m
12.25 sq.m. / 132 sq.ft

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**Reinforced Cement Concrete**

**Flat Slab**
- Rs. 3,768 / sq.m
- GBP 43 / sq.m

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**Reinforced Brick**

**Funicular Shallow Doubly Curved**
- Rs. 3,985 / sq.m
- GBP 45 / sq.m

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**Advantages**

- "Standard" technique.
- Materials easily sourced.
- Easily replicable due to ubiquity.
- Cost of construction considered "normal".

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**Disadvantages**

- Requires sturdy formwork + reinforcement design
- Requires repairs within first few years of completion
- Not ideally suited for tropical regions due to heat gain
- Uses a lot of steel and water; energy intensive materials + processes

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1 GBP = INR 88.08
Currency exchange as of 27 September 2017
Source: Dandli (https://www.dandli.com)
Muzaffarnagar Vaulting Technique

The district of Muzaffarnagar in the northern state of Uttar Pradesh (U.P.) has been home to magnificent Mughal monuments dating back to the 17th century. Mughal architecture in India succeeded the Turko-Iranian tradition and its buildings imbue not only similar aesthetics but also similar building techniques. With the Mughals particularly active in the Muzaffarnagar region up until the establishment of British colonial rule, their influences in the architectural milieu of the region are evident in the surviving buildings of the era.

Due to its strategic location for trade and proximity to the Gangetic plain, Hunnarshala found that Muzaffarnagar had a remarkable building tradition in bricks. The Gangetic plains provide excellent quality clay for bricks capable of rendering strength between 14.71 MPa to 17.16 MPa and has found widespread use as a building material in the area. Even today, the region is home to a large brick manufacturing industry that serves a large catchment of the north Indian market.

Muzaffarnagar was the epicentre of communal riots in November 2013 which resulted in the displacement of thousands of people in the region. In the following months, a series of community rehabilitation and reconstruction initiatives were undertaken by NGOs and related agencies. Hunnarshala was invited to explore appropriate roofing solutions and provide overall technical support for the construction of houses as part of this post-conflict intervention.

Hunnarshala's fieldwork began its involvement by engaging the community and visiting victims in U.P. through dialogue and gauging the scale of the intervention. The task at hand was to assess capacity of the community, find a local technique of making roofs that was culturally accepted, cost appropriate and had local expertise which could either be strengthened or borrowed from. Many of the affected families had lived in Muzaffarnagar and their neighbouring villages for several generations in multi-generational houses that had developed organically and were built in traditional construction techniques.

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271 Hunnarshala Foundation for Building Technology and Innovation are a Bhuj, Kutch-based NGO that work towards For a more detailed introduction, please see Prototypes chapter of this thesis.
272 Hunnarshala Quarterly Newsletter, April 2017, Issue V, page 5, edited by Bhawna Jainini
274 Interview with Mahavir bhai at Hunnarshala on 2nd December 2015.
275 Ibid.
To this effect, Hunnarshala found numerous examples of domestic architecture featuring brickwork and six different types of roofs – most notably of which were two kinds of shallow shell roofs. The most recent shells were constructed using bricks and cement mortar alone and were no more than two decades old which offered the possibility of an active building craft that could be further nurtured.

Upon investigation, Hunnarshala discovered a master-student team of masons, Ustaad and Nawab, skilled in the construction technique that had been building shells in the same method. The masons exhibited refined understanding of the structural behavior of shells that included uniform distribution of loading conditions in single or double curved shells, distinct compression and tension components, the limited life for reinforced concrete slabs due to their direct reliance on poor quality steel. Most importantly, the master mason had learnt the technique by trial and error before teaching it to his student and building numerous projects.

The masons also followed rules of thumb to determine a shell’s proportion to respond to different sized room configurations. They were also found to have developed subtle

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276 Interview with masons – Nawab at Hunnarshala on 2nd December 2015.
variations to the technique over the years in order to achieve a range of aesthetic finishes while retaining their form-active structural principles.

For the sake of consistency and lack of another formal technical term, I have referred to their building method as the Muzaffarnagar technique in this thesis. There are two variants of the vaults made in the Muzaffarnagar technique which Hunnarshala refer to as the ‘inverted bowl’ or the ‘inverted tray’ type.

Below is an account of the inverted bowl prototype structure built at Hunnarshala by the two masons Nawab and Ustaad, for Ultimate Load Testing to determine structural safety of the system and assess costs. The tests carried out by Hunnarshala served as the basis for my own tile-vaulted prototypes P3 & P4 and help compare results against similar parameters.

**Construction of Muzaffarnagar Technique**

As is consistent with all seismic-resilient buildings built by Hunnarshala, a reinforced concrete lintel was cast before bringing the superstructure up to beam height. Photos on the following page illustrate the construction process.

**Formwork and Earthwork**

In the inverted bowl system, once the walls are built, shuttering is assembled for a ring beam to be cast in reinforced cement concrete. This tension ring beam having an L-shaped cross section is meant to receive the vault and serve to counter the shell’s thrusts. Next, formwork suitable for casting a flat reinforced concrete slab is erected. This set up usually comprises of horizontally laid plywood planks or mild-steel plates propped with locally sourced logs or galvanized iron pipes – or a convenient combination of the above elements. The reinforced concrete peripheral beam is then cast and allowed to cure.

The formwork is then checked for flat levels and is subsequently layered with sieved dry earth. The earth is gently watered ensuring that it remains pliable and not sludgy. Using diagonals, the centre of the shell is marked and a wooden peg is inserted at the point. The peg serves dually as the centre and indicates the maximum rise of the earth mound. Using a trowel, the earth is then graded down gently from the centre to meet the beam. The result is a doubly curved convex surface with the centre rising only 9”– 10” (0.22 m – 0.25 m) for a 12 feet (3.6 m) span. Using flat wooden bats, two masons level and compact the earth to the desired curve.
Next, the wooden peg is replaced with a slender aluminium hook with a string having a nail at the other end. The hook is meant to go through the vault plane and receive ceiling mounted fans or light fixtures. Using the nail, a circle of brick-length radius is marked about the hook which serves as a rough outline for the following task. This circle is raised by about an inch using a rich mix of clay and earth. Using the hook as the centre, the mason draws yet another circle on the freshly laid mix. The excess clay is removed and we are left with a perfect circle rising an inch above the compacted surface below. The mason then divides the circle into 8 parts resulting in an 8-pointed star pattern. He then removes the clay from the 8-pointed star leaving behind a raised pattern of pizza-sliced exterior. The resulting profile of the earth is meant to serve as the concave mould of the shell’s soffit and can vary depending on the desired final finish. All earthwork is now complete and ready to receive bricks.

**Laying of blocks**

The bricks used for this prototype were Compressed Stabilized Earth Blocks (CSEB) of size 190 x 115 x 95 thk which were made in the brick press at Hunnarshala and fully cured. The blocks exhibited an average compressive strength of 5.5 MPA to 6 MPA.\(^{277}\)

Bricks are placed on edge in concentric circles starting outside the raised star pattern. They are laid an inch to half an inch apart in order to receive cement mortar. Placing bricks on edge is advantageous for many reasons: it allows more mortar between them which in turn provides better bonding, the shell gets more depth and creates a smoother curve.\(^ {278}\) Towards the beams, the bricks progress in arcs and the bricks are sized and shaped accordingly to meet edge conditions. Although regular bricks can also be used, this prototype was constructed with Compressed Stabilized Earth Blocks (CSEB) having a rough top surface to give better bonding with the concrete layer poured above it next.

\(^{277}\) Interview with Mahavir bhai, Hunnarshala over email on 13\(^{th}\) September 2017.

\(^{278}\) This contrasts with the Rat Trap bond used in wall masonry to save bricks in the vertical plane but works perfectly well for the horizontal (or curved) roof plane!
Pouring of concrete

A rich mix of cement mortar of 1:3:5 (cement: sand: aggregate) is prepared and using a trowel, gaps between bricks are filled to ensure that all the mortar joints are diligently filled before proceeding to pouring the plain cement concrete mix evenly from above. Only an inch to \(\frac{3}{4}\)" (about 20 mm) of plain cement concrete is poured above the curve of the vault which is evenly distributed using box-section aluminium pipes or a suitable tool.

For a final finishing layer of the roof, Nawab offered three solutions:\footnote{Hunnarshala Quarterly Newsletter, April 2016, Issue IV, page 15, edited by Bhawna Jaimini}

1. Earth fill with a layer of gutka (thin tiles)
2. Fine aggregate with flooring over it
3. Use the residue of overburnt bricks from kilns which he recommends as it is light in weight from porosity.

Once plain cement concrete is evenly spread over the surface, it is allowed to cure for 7 -12 days with frequent watering. After this period, supporting formwork is removed along with any earth that may be stuck to the underside of the vault. When cleaning is completed, a shallow vault having bricks in concentric pattern is revealed. The most striking feature of the...
shallow dome is undoubtedly the central stellate pattern resulting from the play of depressed and raised earth carving exercise done prior the placing of bricks on the vault and thereby signifying the hand of the craftsman in its construction process. The craftsmen have developed a variety of patterns that are generated from the brick laying process which are shown in the image above.

With the thrusts of the shallow vaults secured by the peripheral beams, the structure is ready for use. It is apparent that the Muzaffarnagar technique has adapted itself to present building materials through the passage of time and that the peripheral tension beams are a modern intervention made with contemporary materials. Historically, thick masonry walls would have contained the thrusts exerted by the shallow vaults but their use in today’s reinforced concrete construction requires informed technical expertise in design and supervision during construction which especially in seismic zones deserves utmost attention.

**Loading tests and construction costs**

Load tests conducted by Hunnarshala on the prototype shallow vault constructed in the Muzaffarnagar technique testified its robust strength. When tested for Ultimate Loading, the prototype vault withstood 131 kN (13 tonnes kgf) for 7 days, for a shell of thickness 6” (0.15m) resting on a reinforced concrete beam and 9” (0.23m) thick brick walls. The results exceeded the stipulated load bearing capacity of a domestic reinforced concrete slab by five times.

![Diagram of L-shaped roof beam in RCC and 3xØ10mm bars with Ø6mm stirrups at 6" c/c as per the details and 9" thick masonry wall.]

While being labour intensive, the Muzaffarnagar technique uses inexpensive and ubiquitous building materials thus making it cheap to build. As of 2017, Muzaffarnagar shells can be constructed at Rs. 180 / sq.ft (i.e. Rs. 1938 / sq.m or GBP 22/sq.m) making them an extremely affordable choice for constructing durable roofs. The cost is for the shell only and does not include additional expenses for the ring reinforced concrete beam. As mentioned

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280 Interview with Mahavir Acharya, Hunnarshala over email on 17th September 2017.
earlier, any funicular structure is susceptible to damage from earthquake and required structural design of its shell, ring beam as well as superstructure must be taken into account before executing any such roofs.

See chart on following page for more details on its advantages and disadvantages compared to the standard reinforced concrete slab construction.

<table>
<thead>
<tr>
<th>COMPARATIVE ROOFS</th>
<th>Reinforced Cement Concrete</th>
<th>Muzaffarnagar</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROOM DIMENSIONS</td>
<td>Flat Slab</td>
<td>Funicular Shallow</td>
</tr>
<tr>
<td>3.5 m x 3.5 m</td>
<td>Rs. 3,768 / sq.m</td>
<td>Doubly curved</td>
</tr>
<tr>
<td>12.25 sq.m.</td>
<td>GBP 43 / sq.m</td>
<td>Rs. 1,938 / sq.m</td>
</tr>
<tr>
<td>/ 132 sq.ft</td>
<td></td>
<td>GBP 22 / sq.m</td>
</tr>
</tbody>
</table>

1 GBP = INR 88.08
Currency exchange rate of 27th September 2017
Source: Aanda (https://www.aanda.com/)

![Module](image1)

![Two-way flat slab](image2)

![Reflected ceiling plan](image3)

![Two-way slab, more reinforcement for beams and slab](image4)

![Compressed stabilized earth block](image5)

![Reinforcement only on edges, modules laid concentrically from centre](image6)

<table>
<thead>
<tr>
<th>Rise to span ratio</th>
<th>Thickness</th>
<th>Labour</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>6</td>
<td>3 days</td>
</tr>
<tr>
<td>0.15 m</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>‘Standard’ technique.</td>
<td>Requires sturdy formwork + reinforcement design</td>
</tr>
<tr>
<td>Materials easily sourced.</td>
<td>Requires repairs within first few years of completion</td>
</tr>
<tr>
<td>Easily replicable due to ubiquity.</td>
<td>Not ideally suited for tropical regions due to heat gain</td>
</tr>
<tr>
<td>Cost of construction considered normal.</td>
<td>Uses a lot of steel and water: energy intensive materials + processes</td>
</tr>
<tr>
<td></td>
<td>Traditional technique updated to modern materials and methods,</td>
</tr>
<tr>
<td></td>
<td>Extremely strong and durable,</td>
</tr>
<tr>
<td></td>
<td>Flexible module + vertical expansion,</td>
</tr>
<tr>
<td></td>
<td>Semi-skilled labour.</td>
</tr>
<tr>
<td></td>
<td>RCC-equivalent formwork required,</td>
</tr>
<tr>
<td></td>
<td>High initial cost - but long-term return value on investment,</td>
</tr>
<tr>
<td></td>
<td>Minimizes labourers needs and can be easily done with 2 - 3 persons for given roof size.</td>
</tr>
</tbody>
</table>
CONCLUSION: Chapter 5
Reinforced brick vaults and Muzaffarnagar vaulting

Many parameters make the Muzaffarnagar technique successful: the primary economical advantage of working with this method is that it eliminates the need for curved formwork by simply having to shape earth over a flat platform. The Muzaffarnagar technique is undoubtedly labour intensive, relying heavily on the deft skills of its masons across a variety of stages: ensuring the right rise to span ratio and tension beam design, mixing the right proportions of earth and grading it, making patterns for brick stereotomy and so on; but it is also very flexible.

Like tile vaulting, the Muzaffarnagar technique facilitates the construction of double curvature shells which are less practical using burnt clay tubes. This offers a distinct advantage as shallow masonry domes can be used as floor slabs as well as masonry foundations thereby expanding their application. As cement concrete is poured over the masonry course, it is important to take shrinkage into account when designing and executing such shells.

Further, the Muzaffarnagar technique provides freedom for adapting the roof for different sized rooms – which in case of minor changes would warrant alteration of formwork curvature but now can be easily reshaped in earth. Earth itself is recyclable and can be reused with minimal losses. The alignment of such a facility offered by the building technique alongside a predisposition to invest prudently in reusable materials lies at the heart of frugal engineering making it more appealing to the Indian building culture.

Masons in north Indian states seem to have some familiarity with it, which is evident from some of the built projects especially in Delhi. Delhi-based architect, Anil Laul has been experimenting with a variety of vaulting techniques at his home-workshop Anangpur Building Centre, located in Faridabad, on the outskirts of New Delhi. Through regular collaborations with local artisans and training workshops for students and professionals alike, Mr. Laul has explored different configurations for the Muzaffarnagar technique. His works seem to blend the labour intensive components with mainstream reinforced concrete construction thus balancing craft and economy.
In a similar vein, domes at the Holcim Award winning Development Alternatives in New Delhi by Ashok B. Lall, built in 2012 deploy a similar construction system where bricks are laid on a graded earth mound and bonded with cement mortar. Using a daring surface finish, the shallow domes over the cafeteria are plastered in cow-dung with broken mirror.
work rendering an unexpected gesture that marks the hand of the craftsmen as a reminder of tradition and technological convergence.

Cow dung cakes can also be used as a substitute for earth in the stages of grading the negative convex mould of the vault. The familiarity of the rural population in working with cow dung cakes for a range of uses from cooking to wall plaster and floor plaster in turn makes the Muzaffarnagar technique more favourable for deployment.

There is also ample opportunity to improve the Muzaffarnagar vaulting system. One possible modification is to use lime concrete for the roof for lower environmental impact and extended durability. Another is to modify and design better reinforced beams that perform to a variety of loading conditions and resulting stresses. Hunnarshala applied their building expertise to recommend building the walls with a Rat Trap bond that uses 25% less bricks and provides thermal insulation through the resulting air cavity.

Following its successful demonstration on their campus, Hunnarshala have built 10 domes in the technique in Muzaffarnagar, two houses in Bhuj and have a total of 36 new projects in tow that are scheduled for completion by mid 2018. Kolkata-based French architect

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282 Interview with Mahavir Acharya, Hunnarshala over email on 17th September 2017.
Laurent Fournier has also collaborated with Nawab for using the Muzaffarnagar technique at the Institute of Indigenous Food and Culture in the state of Odisha in east India.\textsuperscript{283}

The handful examples of innovative masonry vaulting in India studied in this section give a sense of the sheer variety and diverse construction systems still actively practiced across the country. Nonetheless, the persistent theme here remains social and cultural where the role of the craftsman is central to the sustenance and transmission of building systems and must be strengthened in order to ensure the development of traditional building crafts in tandem with progressive technologies of the time.

The informed deployment of crafts in buildings further contributes to appropriate and economical use of materials and techniques that are unique to their place which, in other settings, may be considered outlandish and bizarre. This lends buildings, and its creators, a sense of identity and helps reinstate in them the confidence of time-tested methods of construction.

Experiments in reviving tile vaulting in different parts of the world have been conducted in a similar way: craftsmen not aware of the system have been educated in its potential, trained in its construction and selection of materials, allowed to internalize structural principles before fully engaging with the building process.\textsuperscript{284} Budget constraints, contextual choices in materials and construction have undoubtedly yielded distinct approaches and results in each iteration.

Encouraged by the fertile building crafts culture of India, I propose to introduce tile vaulting to the Indian vaulting traditions. The next part of this thesis sheds light on the tile vaulting prototypes constructed explicitly for this research in collaboration with artisans in India. The relationship of my tile vaulting prototypes in India to those by others from around the world have been examined in greater detail in chapter 7 to further contextualize its appropriateness and future in the Indian construction landscape.

\textsuperscript{283} Hunnarshala Quarterly Newsletter, April 2017, Issue V, page 5, edited by Bhawna Jaimini

\textsuperscript{284} See Peter Rich and Michael Ramage’s Interpretation Centre in South Africa, Lara Davis’s SUDU in Ethiopia, Pines Calyx and Crossway House both in the United Kingdom also by Ramage.
PART III

Prototypes | Comparatives | Conclusion
Chapter 6

Prototyping Five Tile Vaults in India: *Frog to Phoenix*

Aims of Tile Vaulting Prototypes in India

With the recent revival in research on tile vaulting over the past decade, builders around the world are now trying to recreate the centuries old tile vaulting techniques but there is no single, clear and consistent method dictated for its construction. The guidelines available are: Guastavino’s Essay on the Theory and History of Cohesive Construction, Angel Truno’s Bovedas Tabicadas and a handful other works, each having illustrations that prescribe a layered tile construction system in fast-setting gypsum and cement mortar while comparing it to other masonry vaulting methods.

For a more contemporaneous approach, a handful built examples from recent times are also useful to explore the feasibility of tile vaulting today: Pines Calyx (2004) and Crossway House (2009) in the United Kingdom, Sustainable Urban Dwelling Unit (SUDU) in Ethiopia and the Mapungubwe Centre (2010) in South Africa, each offer a range of lessons arising out of their distinct typologies and contexts.

In an attempt to transfer the skills associated with tile vaulting to India, there are numerous other conditions that can very easily be overlooked which have to do with cultural proclivities of the place. These include, but are not limited to: guidework, available tiles, peculiarities in cement-sand mixes and quality, gypsum and plaster mixes, handling and sourcing of materials, climatic elements and so on.

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This study makes contributions to the transfer of tile vaulting to India by engaging with craftsmen in the country in two different locations: Bhuj in Western India and New Delhi in the North. In order to ascertain the feasibility of tile vaulting in India, I constructed a total of five prototypes. The aims of all prototypes include:

1. Assessing effective transmission of skills
2. Identifying regional peculiarities in adoption or rejection of methods
These peculiarities were anticipated to be largely labour-based: lack of skill, inability or resistance to work with new methods (reluctance or preference in sequence of construction).
3. Structural performance of tile vaulting by load tests
4. Comparative Data
Compare above findings with other practices in vaulting viz. Muzaffarnagar, burnt clay tubes and tile vaulting alongside conventional reinforced cement concrete construction.

Caveat for Building in Seismic Zones
According to the Indian Seismic Design Code (IS 1893), the Kutch region of Gujarat lies in Zone V, the highest vulnerability afforded in the country, and Delhi lies in Zone IV. Much of India is seismically active and as architects we must be mindful of our choices in technology and its deployment.

The design of buildings that are adequately braced for seismic safety is of paramount importance. Shell structures are sensitive to seismic movement and their thoughtless emulation in active zones without safe, technically informed engineering can be highly ignorant and cost lives in dire cases. Studies that help understand shell behavior, particularly that of tile vaulting, are important to take fully into account.\(^{286}\)

I chose to work in Kutch and Delhi as the two places provided me with the necessary technical facilities on ground to engage with craftsmen and build prototypes for testing. No prototypes were built for habitation and served only to evaluate the aims listed above.

Tile Vaulting Prototypes in India

Geographical Distribution of Case Studies

- Tile Vaulting Prototypes
- Art out of Architecture
Partner Profile: Hunnarshala Foundation for Building Innovation

Based in Bhuj, the Kutch region of Gujarat, Hunnarshala was set up as a post-disaster mitigation institution for helping locals rebuild their habitats following the devastating earthquake in the region in 2001.

Hunnarshala works towards social empowerment and in the strengthening of traditional crafts, at times with modern interventions. It has run a comprehensive vocational training school named Karigarshala, for school dropouts or those lacking access to good education and teaches the young students carpentry and a host of walling systems. Hunnarshala has been widely recognized for their work and won the Curry Stone Design Prize in 2013. They also provide on-field technical expertise to the MIT-Tata Centre and have cooperated on a number of research projects with the institute.

While Hunnarshala offered excellent facilities for experimentation, it is important to point out that the decision to collaborate with them was also due to their ethical practice and exceptionally high regard for artisanal engagement.

Mr. Kiran Vaghela, former Managing Director and Mr. Tejas Kotak, Executive Director – both civil engineers who are actively involved with the research of innovative building methods at Hunnarshala, were instrumental in the construction of the tile vaulting prototypes on their campus, frequently sharing their expertise and ideas.

Prototype 1: Design

The design was based on a catenary and two scaled versions of the same catenary joined by an inverted trough. These were based on the loose hypothesis that the two crests would successfully counter the trough and the large catenary at the front would function help prop the structural assembly.

Size of the structure: 1.8 m x 1.8 m (roughly 6’ x 6’)

Plaster of Paris

Unbranded plaster of Paris was bought off-the-shelf. Sold loose in cement bags, it came with no other details of shelf-life, manufacture or expiry.

Cost: Rs. 9/kg, 26 kgs were used.
**Tile vaulting module**

Flat terracotta tiles that are widely used for cladding building facades to give the impression of exposed brickwork were used as the tile vaulting module.

The size of the tiles: 3” x 9”, 10 mm thick, each weighing 345 grams.

Cost: Rs. 2.25/- each - 660 tiles were used.

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![Terracotta Cladding Tile](image)

**Cement**

**M53 Grade, Ordinary Portland Cement**

Sold as 50 kg bags @ Rs. 320/ bag (per kg price Rs. 6.4)

Approx. 3 bags were used.

Used in different mixes 1:4 (cement:sand) and slurry.

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**Days + Workforce**

5 days with 7 persons working on the vault at any given time.

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**Drawings and setting out requirements**

When I shared my drawings and photos of the 3D printed model with Hunnarshala, they wished to attempt and build the shell independently to try and understand the tile vaulting technique without any further detailed instructions from me. Therefore Hunnarshala were only remotely briefed on the method when they set out building the ‘Frog’.

With artisans at Hunnarshala already trained in walling systems, they were already familiar with handling cement but this was their first time working with terracotta tiles and plaster of
Paris. The artisans studied preliminary drawings sent to them: plan, elevations, sections and images of a 3D computer model, and requested for seven sections be provided at a foot each in order to understand the form of the vault better at 1:1 scale.

Construction of the ‘Frog’

The Hunnarshala team then proceeded to make seven 1:1 plywood sectional cut-outs to match the changing vault profile at every foot and erected the assembly at site with thoughts applied for its construction. *(Collage of photos illustrates the sequence)*

Next, they completed constructing supporting piers in random rubble masonry and plastered the top of the wall with cement to a smooth surface in order to serve as a springing plane for the shell. In order to deal with the complex form of the shell, the artisans filled the gaps between the seven plywood sections using sawdust sourced from the neighbouring wood workshop. Once sawdust was filled in, it was layered with clay which revealed the vault’s profile to the artisans at full scale.

The artisans then constructed the first layer of the vault using the terracotta tiles and plaster of Paris. Working with plaster of Paris can prove very challenging in the local weather conditions – the mix dries out very quickly due to the heat or gets lumpy if made in large quantities and not mixed properly. Its consistency can change and render it useless if made too thick and therefore the proper handling of plaster of Paris is a crucial element when working with tile vaulting’s first layer. Persistent delays would make the building method no better than conventional vaulting methods that do not rely on speed of construction and are more accommodating to lapses in material handling.
In their predisposition to using cement, the artisans then applied a 125 mm thick layer of 1:4 cement mix over the first layer. This unusually thick layer was smoothened out according to the shell’s surface and allowed to dry.

The second, and final, layer of tiles was set in cement at 90 degrees to the first, creating a smooth external surface. The tiles for this layer were cut as dictated by the changing profile and were squarish in profile towards the centre. Joints on the top layer were cleaned to give a smooth final surface finish. The guidework was removed from underneath and the sawdust and clay was cleaned to reveal the first layer constructed with the help of plaster of Paris.

At the end of the building exercise, the shell was 145 mm thick with a total of three layers: 10 mm thick tile, 125 mm thick cement and a final 10 mm tile layer.

**Loading Tests**

The structure took five days to construct and was cured using wet gunny bags regularly for a week. Sand bags weighing 13 kgs were used for loading the vault and placed gently on the surface mindful of not inducing any impact loading. The structure was left loaded for a week and survived live loading conditions of 75 kg/sq.m. (735 N/mm²) without any signs of structural movement or failure.²⁸⁷

**Observations**

Except for the use of plaster for the first layer, almost no aspects of the construction technique align to that of tile vaulting. The artisans chose to interpret tile vaulting in ways that were already known to them which resulted in improvised self-directed construction. The topmost tile layer was not laid to laminate with the first to create a masonry unit but instead more like a finished cladding layer which was incorrect.

Nonetheless, the exercise brought the artisans a step closer to tile vaulting which was taught to them through the next prototype: ‘Cromwell.’

²⁸⁷ Fascinated by the form of the structure, the artisans at Hunnarshala had climbed on the shell without prior warning within days of it being completed. Although the shell survived the adventure, a notice was scribbled on the neighbouring walls asking artisans not to climb or jump on the shell as it was meant to be tested for structural performance at a later date!
Cromwell was the first example of introducing the principles of tile vaulting to artisans at Hunnarshala: laminated construction, handling of fast-setting gypsum, sequence of construction and demonstrate its structural performance upon completion. It was hoped that the lessons would later enable them for further independent experimentation.

Materials
As Cromwell was being built less than a month after completing the ‘Frog’ prototype, the same specifications for materials: cement, plaster of Paris and terracotta tiles were used.

Setting out and Construction of Cromwell
Once the structure was set out, the mason and supervisor constructed four corner piers out of compressed stabilized earth blocks. The assembly was allowed to cure for the rest of the day while the guidework for arches and the vault was prepared.

Guidework for arches was made at site using soft hollow PVC pipes that were bent to match the curve from a 1:1 drawing. The pipes were secured in place with nails and steel wires. Only one guidework was prepared to be used for all four arches.

The following day, artisans completed constructing two, double layered arches in plaster of Paris. No cement was used in the construction of the first two arches as I had not accounted for the minimum 5-hour setting time of cement mortar and we had just one guidework for the arches. So we proceeded making both layers in the fast-setting gypsum that would allow us to remove the guidework and reuse it for the other arches. This is a limitation dictated by single-curved surfaces whereas for doubly curved shells, one can proceed laying successive layers in tiles set in cement almost immediately over the first layer as in brick masonry walls.

The guidework was then removed and used to construct the other two arches, each having the first layer of tiles stuck with plaster of Paris and the second in cement mortar.

Guidework for the vault was readied in the afternoon session. Compared to the arches, this was more difficult to achieve with two iterations done: the first attempt was in trying to bend steel at site to match the catenary curve but this was not achievable with the limited means at

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288 The prototype was named Cromwell after the Morbi-based tile manufacturer: Prajapati which in Hindi roughly means ‘Protector of the People.’

289 As day time temperatures soared upto 38 °C, work hours comprised largely of working in the mornings from 8.30 am until 11.30 am with work resuming at 3.30 pm until 6.30 pm.
hand. A second full scale print of the diagonal section was traced in chalk onto a finished floor surface and the profile was transferred onto two identical plywood planks.

The following day, the construction of the vault began and it is important to note that with the geometry of the vault indicated by the diagonal guideworks, placing the tiles was not a problem and work progressed very quickly. As is suggested for tile vaulting, we had to construct the vault in a rotational sequence, progressing towards the crown. This is an effective way to build a tile vault without loading it prematurely. (See collage of photos)

On the fifth day, with the help of two persons mixing plaster of Paris and cement respectively, two brick layers and one cutting tiles, a single layer dome was completed. We determined a pattern for the 2nd layer of the dome and a 3rd layer for all arches. As we now proceed onto working only in cement, the artisans found themselves on familiar territory quickly working with the rich cement : sand ratio of 1:4 to set the tiles in. Once again, it was important to maintain the rotational laying of tiles as in the first layer. No single part of the dome must be covered all at once but instead the vault’s quadrants must be simultaneously built which allows for the even distribution of loads. The breaking of joints creates a masonry unit of the vault which is also a crucial component of tile vaulting. Cement joints were cleaned as we progressed.

On the final day, cement slurry was filled into joints between the tiles and once completed, the dome and arches were watered for curing.

Load tests
Based on their availability, 3 different types of loads were used: Sand bags weighing 13 kgs each, compressed stabilized earth blocks (CSEB) of 8.5 kgs each and wedge-shaped cement blocks of 12 kg each.

The test was initiated by first loading all four arches at the centre proceeding symmetrically along the curve towards the ground. This was done in order to assist countering any thrusts arising from adding of loads on the main vault. The main shell was loaded next – beginning from the crown and proceeding in all four directions until fully covered. Once the vault surface was covered with weights essential for testing live load test of 75 kgs/sq.m. (735 N/mm²) additional loads were added until we ran out of measured weights.

At the end of the loading cycle, the vault resting on four arches with the entire assembly
having a self weight of approx. 200 kgs withstood 1192 kgs (about 11.7 kN). The vault was left loaded for a week and showed no cracks in its surface, signs of neither structural damage nor displacement. This was also not the ultimate strength of the structure, which was explored in subsequent full-scale prototype.

Observations

Learning tile vaulting for the first time, the artisans showed enthusiasm and reluctance in equal measure. They were predisposed to using cement and having done so in the ‘Frog’ prototype, were convinced that it was the only way to construct the vault.

However, when they experienced that the plaster of Paris was capable of holding the tile stuck to just one or two sides, they opened up to the possibility of a new method of vaulting. The small scale of the dome (4’ span) and the 9” tile were not best suited and every new tile had to be cut which was most time consuming and slowed down work. This was a lesson to be learnt and applied in subsequent prototypes.

Proper layering is important for strong bonding and breaking of joints. A rhythm can also be set up for the coursing patterns – which in my case – the arches and the dome ended up having the same patterns because of the alternating layers. This, however, was not detrimental to the strength of the structure.

Following page:

Collage of photos from the construction of Cromwell at Hunnarshala in March 2015
In order to progress from small-scaled prototypes to a full-scale architectural interventions, Prototypes 3 & 4 were constructed in the February - March 2017 period.

Both vaults were built to matching specifications to those constructed by master masons from Uttar Pradesh at Hunnarshala in December 2015 using the Muzaffarnagar technique. The matching specifications were limited to reinforced concrete beam details, room size, rise: span ratio of the doubly curved shell while the shell thickness and construction technique were retained as per tile vaulting principles. The shells were constructed in only two layers of terracotta tiles to correspond with the scaled prototypes Frog and Cromwell.

The matching specifications would help compare the two techniques for speed of construction, volume of material used and structural performance.

**Aims of Prototypes P3 and P4:**

1. **Assess effective transmission and retention of taught technique** – it would be 2 years since I had first taught tile vaulting to Hunnarshala in March 2015 and with a fresh cohort of students, only the supervisors and engineers remained acquainted with tile vaulting. It would therefore serve as a useful assessment of well tile vaulting was executed autonomously based solely on drawings.

2. **Construction grade materials used to simulate real-world construction**

While the specifications were derived from earlier prototypes and the Muzaffarnagar vault, the materials used for the construction of these thin-tile vaults were of a higher order than their scaled predecessors. Medical grade plaster was used for plaster of Paris, cement mixes were 1:4 and a larger tile (8” x 8” tile) was used as a module.

3. **Compare construction costs and structural performance** of tile vaults relative to the structurally safe and economical construction of Muzaffarnagar vaults.

**Materials for Construction**

M53 grade Ordinary Portland Cement,
Plaster of Paris: Dental grade plaster Type II
Terracotta tile: 200 mm x 200 mm x 12 mm thick.
Weight of each tile: 1.12 kgs.
Rise of the vault = 200 mm (~8"). Span: 3.5 m
Rise to Span ratio = 1:14.5, making it a very shallow vault – same as the one built in the Muzaffarnagar technique.

Guidework: Made of Medium Density Fibreboard: used for P3 and reused for P4. It was propped onto a steel pole in the centre and radially arranged to meet the L-section of the reinforced concrete beam that would receive the tile.

Notes on the Construction and finishes of P3 and P4
Vaults P3 and P4 were finished to have different roof surfaces. While P4 was left as a curved surface, P3 had plain cement concrete (to a mix of 1:3:4 i.e. cement: sand: aggregate) poured over its double curved shell to provide a flat roof of matching reinforced concrete flat slab construction. While this would make the completed unit comparable to that which can be made multi-storied, it was also done to counter the recurring critique of curved rooftops as being unusable and therefore wasteful and undesirable. I was mindful of the fact that the additional plain cement concrete would add to the mass over the vault as well as to the strength of the roof during testing, if not collapse while pouring of concrete in case the shell itself could not take bear the load of the laid concrete.

P3 and P4 were both cured for 21 days (23rd February through the 16th of March) with regular watering in the initial days.
Above:
Before and after construction of P3 & P4 vaults. The superstructure of the walls was created as part of the annual walling exercise. While they are generally left open-to-sky before being demolished, P3 (left, flat surface with vault underneath) and P4 (right, curved top surface) became fitting partners to the ritual.
P3 – Construction peculiarities

Prototype 3 was constructed in 5 days with 4 to 6 artisans (including one supervisor and one who was cutting tiles) working on the vault at a time.

P3 strictly followed the construction process of tile vaulting as adopted for the prototype Cromwell i.e. 1st layer tiles stuck with plaster of Paris followed by a quick second layer of tiles laid in cement at 45 deg to the preceding one. It was also important that the 2nd layer had begun while the 1st was still incomplete. A full tile module (8” x 8”) was used for both layers with cement mortar of 25 mm in between. Plain cement concrete was poured over the vault and leveled flat. The total thickness of the vault at the crown was 90 mm.

Loading Tests P3

Each bucket of sand weighed 22.98 kgs without the weight of the aluminium bucket itself which weighed 1.02 kgs.290 An independent scaffolding was erected without disturbing the structure to allow a human chain that passed sand buckets to the rooftop where two artisans emptied them gently – mindful to avoid inducing an impact loading condition.

Sand was poured at the central parts of the shell and then evenly distributed to the four corners of the curved surface using spades. As the rooftop surface of P3 was a flat slab of plain cement concrete, uniform distribution of sand was much more easily achieved than in P4 where it had to be ensured that sand did not accumulate in any one corner.

Once the loose sand reached the parapet, sand bags were lined along the inner edge of the parapet to allow for additional sand to be added for load testing. The weight of the sand bags has been included in the load calculation.

No failure

The structure was loaded with sand over a period of 3 hours with 600 buckets of sand equivalent to a weight of 13.79 tonnes (135.23 kN) without any signs of structural failure. As we ran out of sand to be loaded, we could no longer add weights to the structure. The loaded structure was observed for a period of 48 hours and did not display any structural distress. As the intention of the test was to check for ultimate loading until collapse, no dial gauges were used to measure any deflection at the crown.

290 A new truck of sand was used for P3 and so the weight of the sand was slightly different from the one used for P4.
P3 IN NUMBERS:

 Thickness of shell at crown: 90 mm *(50 mm tile vault + 40 mm plain cement concrete)*

 Area of vault under clear span: 3.5 m x 3.5 m = 12.25 sq.m

 No structural failure observed @ 13.79 tonnes (135.23 kN)

 Load borne by shell of 90 mm thickness per sq.m. = 1.15 tons/sq.m. (11.27 kN/sq.m.)

 Days of construction: 3 – without concreting.
Above:
Collage of the construction of P3 with its two-layered tile vault over minimal guidework and plain cement concrete poured at the top.
Above: Collage of P3 loading tests underway. As P3 was actually tested for loads after P4, we can see the collapsed P4 vault. With no failure, the sand from P3 was finally removed by breaking the parapet wall (last image on bottom right).
P4 – Construction peculiarities

Prototype 4 was also constructed in 3 days with 4 to 6 artisans working at a time.

As the artisans were not happy with the faceted surface of P3’s shell resulting from the use of a full tile, they chose to work with half a tile (200 mm x 100 mm) for first layer and a full tile for the second. Further, the guidework for P3 was reused for P4.

P4 was constructed based on the indigenized technique explored by Kiran-bhai for Brahmand therefore deviated from the mandated tile vaulting technique. The first layer of tiles stuck in plaster of Paris was fully completed and on the following day artisans applied a layer of 18 mm thick cement plaster which was allowed to dry.

Work on the second tile layer then commenced from all four ends gradually converging to meet at the centre. This time tiles were used in their full size (200 mm x 200 mm) and the bonding pattern was rotated 45 degrees to the one below which was now fully covered in cement.

Photographs (see collages) taken during the construction of the vault reveal the casual manner in which artisans continue to work on the second layer while standing and keeping their tools on the plastered first one. It must be pointed out that the total thickness of the shell at this point was only 30 mm for a span of 3.45 m! While the MDF guidework was present below during this period, that a layer of tiles stuck in POP having an 18 mm thick cement plaster above would perform (let alone survive) so well under uneven loading conditions was remarkable. The deviations therefore made from the prescribed tile vaulting technique were seen to have no detrimental effects for a shell of this scale and in fact only eased the construction of the second layer by allowing workers to move about on the doubly curved shell.

Loading Tests P4

Weight of sand per bucket was 21.7 kgs per bucket (without the weight of the aluminium bucket). As was for P3, a human chain was set up to pass the sand buckets to the rooftop where two artisans emptied them gently – mindful of avoiding an impact loading condition.

291 Please see a full description of this in next section: ‘Art born out of Architecture’ under Brahmand. The Catalan technique dictates that we ought to start a least a second – if not more subsequent – layers in cement while the first layer of the shell is still unfinished.
Sand was poured at the crown first and then evenly distributed to the four corners of the curved surface. Once the sand had reached the parapet, sand bags were lined along the inner edge of the parapet to allow for additional sand above the roof surface for load testing.

**Structural Failure**

The shell structure or walls showed no signs of movement or failure through 3 hours of loading when it finally collapsed at 10.15 tonnes (99.53 kN) – equivalent to 468 buckets of sand. The failure was brittle in nature and came with no prior warning. Video stills reveal slight movement of the parapet walls at lintel level that confirm excessive lateral thrusts before failure which also indicate that had the beams been better secured or designed to a different cross-section, the vault could have withstood more load.²⁹²

Large parts of the vault up to 0.7m x 1m were found on the floor indicating good bonding between the three layers: tile, plaster, tile. Although this incident is not fully analogous to an accident that occurred during the construction of the Boston Public Library by Guastavino’s company, there are resemblances in the large sizes of the collapsed remnants.²⁹³ The reinforced concrete L-beam showed some hairline cracks while more visibly the shell’s loading induced torsional forces on the L-beam having lifted it in parts at lintel level leading ultimately to its collapse. The L-beam sections at the four corners of the vault retained pieces of the tiles that survived.

**P4 in numbers:**

Thickness of vault: 57 mm (2x12mm thick tiles, 18 mm plaster, 15 mm mortar)

Area under clear span of the vault: 3.45 m x 3.45 m = 11.9 sq.m ~ 12 sq.m.

Structural failure @ 10.15 tonnes (99.53 kN)

Load borne by structure of 57 mm thickness per sq.m. = 0.85 tonnes/sq.m. (8.46 kN /sq.m)

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²⁹² Samuel Wilson, ‘Structural Design of Shallow Masonry Domes’ (Master’s Thesis, Massachusetts Institute of Technology, Department of Civil and Environmental Engineering, 2016). Wilson talks about alternatives for beams for the Muzaffarnagar system which can be applied here as well.

²⁹³ John Ochsendorf, *Guastavino Vaulting: Art of the Structural Tile*, 1st edn (New York: Princeton Architectural Press, 2010), p. 58. Unfazed by the accidental collapse of a section of the vault at the Boston Public Library in 1889, Guastavino used the incident to his advantage to flaunt the other parts of the vault that remain undisturbed.
Above: Collage of P4 under construction. Images clearly show artisans standing on the vault when its thickness would have been only 30 mm. The smaller sized tile also made for a smoother curvature.
Above: Collage of P4 after load testing showing a collapsed vault with movement at the beam and sections of the tile vault retained at corners.
COMPARING P3 & P4 with Muzaffarnagar Vault

Prototype P3
Thickness of shell at crown: **90 mm**
(2x12 mm tiles + 26 mm mortar + 40 mm cement concrete)

Area under clear span of the vault:
3.5 m x 3.5 m = **12.25 sq.m**

**No structural failure** observed
@ 13.79 tonnes (135.23 kN)

Load borne by shell of 90 mm thickness
per sq.m. = 1.15 tons/sq.m.
(11.27 kN/sq.m.)

Prototype P4
Thickness of vault: **57 mm**
(2x12 mm thick tiles, 18 mm plaster, 15 mm mortar)

Area under clear span of the vault:
3.5 m x 3.5 m = **12.25 sq.m**

Structural failure
@ 10.15 tonnes (99.53 kN)

Load borne by structure of 57 mm thickness
per sq.m. = 0.85 tonnes/sq.m.
(8.46 kN /sq.m)

**Shell thickness vs. geometry**

It is vital to point out again that P3 and P4 were built to the same specifications as Muzaffarnagar vault (i.e. span, rise, beam design) but as tile vaults, their respective vault thicknesses were different to the Muzaffarnagar prototype.

P3 was 90 mm thick while P4 was only 57 mm against Muzaffarnagar’s 115 mm thick shell. While a deflection of 1.78 mm was observed at the crown for the Muzaffarnagar vault at 131.26 kN, loaded for 7 days, P3 showed no failure at 135.23 kN while P4 collapsed at 99.53 kN for a shell of half the thickness, thus having demonstrated remarkable load bearing capacity.

This also confirms that the geometry of the structure takes precedence over shell thickness in its structural performance.

Following page:
Comparing tile vaulting construction costs with standard reinforced concrete construction in India
## Comparative Roofs

<table>
<thead>
<tr>
<th>Room Dimensions</th>
<th>Reinforced Cement Concrete</th>
<th>Tile Vaulting</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5 m x 3.5 m</td>
<td>Flat Slab</td>
<td>Funicular</td>
</tr>
<tr>
<td>12.25 sq.m.</td>
<td>Rs. 3,768 / sq.m</td>
<td>Doubly curved</td>
</tr>
<tr>
<td>/ 132 sq.ft</td>
<td>GBP 43 / sq.m</td>
<td>Rs. 2,370 / sq.m</td>
</tr>
</tbody>
</table>

1 GBP = INR 80.08  
Currency exchange at 27 September 2017  
Source: Oanda [https://www.oanda.com/]

### Advantages
- ‘Standard’ technique.  
- Materials easily sourced.  
- Easily replicable due to ubiquity.  
- Cost of construction considered ‘normal’.
- Quick to build. No formwork used.  
- Extremely strong and Durable.  
- Flexible module + vertical expansion.  
- Extra volume through vaulted ceiling.

### Disadvantages
- Requires sturdy formwork + reinforcement design.  
- Requires repairs within first few years of completion.  
- Not ideally suited for tropical regions due to heat gain.  
- Uses a lot of steel and water: energy intensive materials + processes.  
- Heterogeneity of materials: Tiles + POP + Cement adds to material handling issues as they are often simultaneously required.  
- Requires skilled supervision.  
- Initial cost - but very good value on investment due to durability.

<table>
<thead>
<tr>
<th>Rise to span ratio</th>
<th>Thickness</th>
<th>Labour</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.15 m</td>
<td>6 persons</td>
<td>3 days</td>
</tr>
<tr>
<td>variable</td>
<td>0.057 m</td>
<td>4 persons</td>
<td>2 days</td>
</tr>
</tbody>
</table>

- reflected ceiling plan  
- module  
- two-way flat slab  
- two-way slab, more reinforcement for beams and slab  
- terracotta tile / Catalan vault  
- reinforcement only on edge beams, clear span - modular expansion
This prototype was constructed to mark the entryway to the Aga Khan Trust for Culture’s head office in New Delhi, India. Some background is necessary to establish the context justifying the choice of materials, onsite decisions and methods of engagement:

**Partner Profile: Aga Khan Trust for Culture, New Delhi**

Since 2007, the Aga Khan Trust for Culture, Delhi has been involved in an Urban Renewal Initiative in the historic district of Nizamuddin in New Delhi. A multi-faceted project that encompasses health, education and social engagement at one end has most visibly been associated with the conservation of the Humayun’s Tomb (completed 1572), a UNESCO World Heritage Site that was a precursor to the Taj Mahal (completed 1653).

The Aga Khan Award for Architecture is another programme of its parent agency headquartered in Geneva.

The craftsmen working on the project bring years of experience to their specific métiers. The chief engineer for AKTC, New Delhi Mr. Rajpal Singh, handpicked three master craftsmen for the construction of the vault: Amirakh, Attar Singh and Dhani Ram (Dhanna), experts in intricate incisive carving of lime plaster, stone carving and restoration of historic masonry respectively.

**Aims of the prototype ‘Phoenix’**: 

1. To teach tile vaulting to a fresh set of master craftsmen skilled in working with stone and lime plaster and observe nuances in their approach to construction.

2. To explore the possibility of working with sandstone instead of terracotta for tile vaulting.

3. To explore a new geometric and tectonic configuration for various elements of the structure: springers, shell and supports.

**Materials**

Cement: M43 grade Ordinary Portland Cement mixed with coarse Jamuna sand (1:2 ratio)

Terracotta Tiles of size and weight: 3” x 9” of weight 400 grams
**Design and modification**

The design of the triangular vaulted form was defined by the existing parameters presented at site. The idea was to create a billowing sail-like structure above the roughly finished external wall to mark the entrance to the AKTC office. The vault was initially proposed to sit atop the pilasters of the external wall but after a few iterations it was found that the triangular vault would be scalene and create additional complications:

1. Unique guidework would be required for all three supporting arches as well as the shell and 2. The pilasters would need to be strengthened by increasing their size to counter the resulting uneven thrusts exerted by a scalene shell above. We would have had to allow for the setting of mortar used in widening of pilasters before proceeding with the construction of the shell and supporting arches which would have impeded completion of work within the stipulated timeframe of 5 days. It was therefore determined best to modify the design at site and change it to an equilateral shell for ease of construction and even distribution of thrusts.

**Setting out**

With the availability of multiple experts at hand, it was possible to mobilize different teams to assemble the various construction components. Spare galvanized iron pipes from site were used to facilitate faster erection of vertical supports and serve dually as tension supports. All methods used for preparation were simple and straightforward and as closely associated to those that the craftsmen were familiar with. Gusset plates welded atop would bring together a trio of columns to receive sandstone blocks to act as springers for the shoulder arches. Secondary bars were cross-welded on vertical pipes to improve load distribution by linking the columns.

Stonemasons were provided with 1:1 plans and sections of the sandstone blocks which due to the triangular shape of the shell resulted in interesting 3D configurations. Two sets of lightweight guidework were created in anticipation that only two arches would be constructed at one time and when finished, the guidework would be used for the third.

Setting out for the vault’s spans also turned out challenging as it required the springer blocks to be accurately aligned and its surface was rubbed using a grinder until the required angle was achieved. With the columns and springer blocks secured, the assembly was ready to receive the three arches.
Teaching Tile Vaulting to Craftsmen at AKTC

Simultaneously, Amirakh, Attar Singh and Dhanna’s teams were taught tile vaulting by way of building a test arch of the same span as those supporting the vault. This opportunity was afforded by the clear distance between two stone columns in the southern verandah of the office. As an experiment, sandstone bricks of weight 1.9 kgs were used for the first layer stuck together with plaster of Paris with subsequent layers in cement mortar and sandstone tiles at 45 or 90 degrees to the preceding one in order to break the masonry joints.

Previous page:
Collage of experimental arch constructed in sandstone bricks at the AKTC office. The bricks were found to be too heavy even at 1.9 kgs each, unable to be set in dental grade plaster of Paris and were eventually abandoned.
Weight matters and its correlation to Sarabhai and Jaoul

It was observed that although the initial bricks bonded well, as we proceeded towards the crown, large sections of the arch moved during application and lost bonding with previously laid ones. The stone bricks also took longer to set in plaster of Paris than the thin terracotta tiles and the guidework could be seen to bear at least some of the weight of the arch. This was very different from the tile vaulting experience at Hunnarsala where we used lightweight terracotta tiles of no more than 1.12 kgs.

At 1.9 kgs and of smaller size, the sandstone bricks were very heavy and needed to be kept in place for longer periods. They were more susceptible to errors caused due to haste and even minor readjustments for matching the curve of the guidework. Moreover, when they fell, the stone bricks took with them other parts of the haunches that they are plastered to causing a lot more redoing of sections than observed in tile vaulting with terracotta tiles.

The difference in weight here is no more than 0.8 kgs but this is sufficient to render the fast setting gypsum mortar useless in holding tiles together. The Villa Sarabhai module weighed 3.1 kgs which is considerably more than the module above and it is therefore very unlikely to have served as a usable module for tile vaulting that relies on achieving a first layer stuck with gypsum mortar.

Due to their low weights, thin terracotta tiles weighing under 1.5 kgs have a far reduced effect on other tiles in the rare event of their collapse during construction making the terracotta tiles the ideal module to work with alongside fast setting gypsum.

The craftsmen were quick to decipher the logic of breaking joints in subsequent layers and continued to construct the second and third layers in cement mortar and sandstone bricks. They exploited the 45 degree rotation of the middle layer to create an dog-tooth bond to a pleasing visual effect. This modification offers a new variety for exposed edge conditions in tile vaulting – opening up a range of possibilities for flaunting its lamination characteristics when using a module of more width but light weight such as hollow brick which have been used at the Maisons Jaoul. A hollow brick module of 230 mm x 110 mm x 55 mm can weigh about 0.875 kgs making it a favourable option for tile vaulting.
Lessons from using a heavy module compelled us to reject it and instead purchase thin terracotta tiles found in a Delhi market. The tiles in turn were sourced from Morbi in Gujarat and were of matching specifications to the ones used for the tile vaults at Hunnarshala. With the springer blocks in sandstone, the assembly of three arches and a doubly curved shell over them was all constructed out of terracotta tiles.

**Constructing the Phoenix: Challenges of a doubly curved triangular vault**

Now that the craftsmen were familiar with the construction sequence of tile vaulting, the three arches for the main vault were very easy and quick to build.

The craftsmen proceeded with building three two-layered arches – with the first layer in plaster of Paris and the second in cement – finishing the construction in 5.5 hours and let it to set for 18 hours. Guidework for the vault was put in place the same evening and it was Amirakh’s idea to use plaster of Paris on the centroid to give more stiffness to the assembly.

Guidework for the arches was removed the next day to demonstrate to the craftsmen strength and self-supporting nature of tile vaulting as they proceeded with the construction of the main shell springing from the three arches.

Here, it is important to point out that there was unanimous reluctance amongst the craftsmen to test this thin – two layered – arch that they had constructed the day before. While on one hand they were convinced that it was safe to start constructing the shell over the three finished arches, they expressed serious concerns about testing it with their own weight.

**Deliberations on coursing pattern**

As the craftsmen involved were not acquainted with constructing doubly curved surfaces, there were initial challenges in negotiating the rising curve of the vault along with determining the optimal bonding pattern for the vault’s layers.
The first layer of the vault – made with thin terracotta tiles stuck in plaster of Paris – was completed within 4 hours. I entrusted the drawings and instructions to the craftsmen to implement and complete the second layer of the vault in my absence. This was not perceived as a problem as they had already constructed a test arch and working in cement was something that they were well-trained and comfortable with.

Next page:

Collage of the Phoenix under construction with the layered tile vaulting system left exposed at the edges. The joints were left uncleaned as there was a proposal to plaster and carve an intricate pattern in lime plaster for the soffit.
Collapse and Revision

Just an hour into applying a second layer of tiles in cement the following day, a large part of the vault and supporting arch collapsed as the craftsmen continued to work on it. The cause of failure was traced to the vertical column which had not been secured by cross bracing and stood independently and highly susceptible to movement. The addition of loads by the materials in the second layer as well as asymmetrical loading induced from working on a part of the vault caused the unsecured column to move up to an inch which was sufficient to cause failure.

Masonry in compression is vulnerable to the slightest changes at its supports and the failure of this vault proved it by demonstration. Frustrated at first but unfazed, the craftsmen showed formidable resilience and reorganized all materials to start another vault within a matter of hours. With the setting out, guidework and methodology in place, this was an opportunity to rebuild faster and better. In the meantime, the rogue column was embedded in concrete and allowed to set for 24 hours and Amirakh independently prepared a new drawing of the bonding pattern for the new vault – one that was based on his idea of minimum cutting of tiles for speedy construction and yet ensure that the principles of tile vaulting were maintained for structural integrity. As it was not possible for the artisans to show me their new proposal and they proceeded to construct the vault.

Due to the savings in time from not having to cut a significant amount of tiles, the second vault was finished in two days. Arches received three layers of thin tiles and the vault’s shell two. Amirakh even deployed his herringbone ‘tractor’ pattern for the topmost layer of the arches giving the structure distinct personality.
Once the finished vault was allowed to cure, the artisans stood on the vault to test its structural strength which it withstood without any problems. At the time of writing this thesis, the vault has stood for 5 months without further incident except for the flaking of two brick tiles in the northern arch! Amirakh – who works primarily in lime carving, has proposed to create an intricate pattern for the vault’s soffit. The joints on the three supporting arches have been cleaned to flaunt the layering of the tiles.

Above:
Images of the finished vault at the AKTC, Delhi office
The tractor pattern at the top gives the vault more personality.
Conclusion: Chapter 6
Prototypes

Synergy with craftsmen
In all prototypes constructed – at Hunnarshala and AKTC, the craftsmen tended to predict the construction sequence based on former knowledge. However, with each subsequent prototype, they grew more assured of the new construction system of tile vaulting and their methods of engagement become more resolved and sophisticated.

There were also conscious efforts in exploring and suggesting alternatives to prescribed methods which at times yielded better results than its precedent as in the case of Phoenix. The previous working knowledge of lime and gypsum was also an asset when it came to working with plaster of Paris.

The tile vaulting prototypes constructed each demonstrated, in varying capacities, the internalization of principles within the craftsmen’s existing knowledge systems thus making the construction process more inclusive and rewarding. Given the short time and handful of structures built, this is reassuring for gauging possible autonomous uptake of the technique to those introduced.

Cost and speed of construction
The first two prototypes built, Frog and Cromwell, cost almost 1.5 times that of P3 & P4. For roughly the same amount of materials used, Frog cost Rs. 3550/ sq.m. (£40.38/-) while Cromwell cost Rs. 2850/sq.m. (£58/-). Whereas, P3 (without the plain cement concrete topping) and P4 both cost about Rs. 2370/sq.m. (£27/sq.m) each. The higher costs incurred initially were largely due to the inexperience of working with tile vaulting and time spent understanding the technique that resulted in more material being used than required. Once the craftsmen were familiar, they were able to build faster, with fewer hands at site and minimize wastage in materials mostly from improper mixing of plaster of Paris and tile cutting.

At Rs. 2370/ sq.m. (£27 /sq.m), tile vaulting is a very affordable option for constructing roofs and other building elements. The costs have been derived based upon the sourcing of materials in Kutch, Gujarat and will vary with changes in geography subject to labour and material availability.
Heterogeneity of materials: Plaster of Paris and Cement

The necessary mixing of different mortars of plaster of Paris and cement was also generally resisted by the craftsmen and they preferred to finish one material layer at a time. Doing so may be satisfactory for small-scaled structures but layering of tiles is necessary in case of larger shells and in fact facilitates faster, more stable construction by allowing of thrust lines of rising shells to be contained within the materials.

Nevertheless, onlookers often inquired what ‘white chemical’ was being used for the construction of the vault being amazed at its ability to make the tiles cantilever. The dramatic quality in the construction using thin-tiles and plaster of Paris is accentuated in a doubly curved shell as they can be built with minimal guidework and therefore make tiles stuck in gypsum mortar look like they are floating overhead.

Frog and Cromwell have since become a proud showcase in the ‘experimental courtyard’ on the Karigarshala campus having withstood weather elements for over two years now while the Phoenix hovers lightly over the entryway to the AKTC’s office.
Art born out of Architecture

At this juncture, it is important for us to examine some notable structures and art pieces that have been constructed under direct influence of their architectural precedents.

The selected artworks exhibit familial relationship to their neighbouring building or the building method, asserting the emotional connection as well as internalization of construction principles by the artists and craftsmen who created them. The analogous relationship further extends to demonstrate the engagement between craftsman and technique, showing the potential of their synthesis beyond technical prescriptions.

Brahmand294 | October 2016, Bhuj

A year and a half after prototyping Cromwell on the Hunnarshala campus, Kiran-bhai’s eponymous studio was commissioned by artists Ganga Kadakia and Savia Mahajan to design a meditation centre for their art village in Karjat, Maharashtra in October 2016.

Arriving intuitively at an egg-shaped form for the building, Kiran-bhai was keen on using tile vaulting to build it having witnessed its construction sequence and structural performance in March 2015. Together with artisan, Sunil Jhaniya, he set out by constructing a 1/3rd scale prototype. The elliptical shape of the egg was first traced on a cement floor based on anthropometric relationships that would later guide the construction of the shell by a single artisan.

Using a central pole as a marker for changing radii, a first layer of terracotta tiles was laid vertically. Due to the small diameter of the structure, the resulting surface was faceted and was smoothened over by applying cement plaster and allowed to dry for several days. Tile vaulting principle dictates that the second layer of tiles be laid in a manner to break the joints of its preceding layer in order to form a masonry bond. With this indicative idea, Kiran-bhai traced lines in pencil at 45 degrees over the plaster to determine the cladding pattern the second layer of tiles. Terracotta tiles were then clad in cement mortar as a second layer with them being cut at angles to sit on the changing geometry of the shell. The result is a beautiful cladding system having an intrinsic logic dictated by the surface it clads and not of a predetermined pattern that is simply applied over.

294 Named Brahmand (meaning universe in Hindi)
Not only was Kiran bhai’s building method an indigenized version of tile vaulting distinct but the solution deployed for surface articulation expresses a fresh and clever alternative to solving a complex problem by hand at site with minimal means. Such thinking lies at the heart of frugal engineering.

Above: Collage of photos from Kiran bhai’s construction of Brahmand together with artisan Sunil Jhaniya. Clearly inspired by tile vaulting, the structure deviates to develop a refreshing solution for surface articulation.
Sculptural pit at National Art Schools, Cuba

Built in the 1960s, the National Art Schools in Cuba were highly expressive works of architecture that used tile vaulting as the primary roofing technique. The dominant curved geometries of the shells capping its buildings are captured in an organic sculptural spout that lies above a water basin. Made out of broken tiles, the sculpture seems to have deliberately broken away from the regular geometry of the buildings and assembled itself as a mosaic in landscape.

Gumersindo, a Spanish mason skilled in tile vaulting who was visiting Cuba at the time was hired to teach the technique to masons at site and provide expertise for its construction. Designed by a trio of young architects, the mature expertise of Gumersindo and other workmen at site is considered to have contributed considerably to the project’s success. There are also built-in seats in some classrooms that are clad with thin tiles and the complex is filled with sculptural gestures that are made of brick or brick tiles. It is possible that these gestures were the product of onsite discussions or improvisations and serve as a playful extension of the more formal tectonic gestures to reflect the synergistic nature of collaboration between architects and craftsmen.

Left: The sculptural water basin at the National Art School, Cuba contrasts with the formal expression of its architecture

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295 John A. Loomis, Revolution of Forms: Cuba’s Forgotten Art Schools (New York: Princeton Architectural Press, 1999), p.33. Loomis provides an excellent account of the various artisans involved on the project with first-hand accounts by the architects.

296 Ibid. p.33. Also see page 80, 81 for views of the classrooms with built-in masonry seats.
SkyQutb, Delhi, 2005

Fascinated with the scale and texture of monuments in Delhi, including those half-built, British artist Andrew Burton commissioned the SkyQutb at the Sanskriti Foundation, New Delhi in 2005. Built by locals, Burton provided a design for the corbelled brick structure to be constructed by laying thin bricks on edge, the masons seem to have enjoyed a free hand in giving it final form. Echoing site-specific and regional aesthetics ranging from an inverted anthill to that of the unfinished Alai Minar in (an unfinished ambitious version of the Qutb Minar), the final tower is a curiously familiar modern edifice to the traditional artisanal skills.297

The brick contractor, Mohammad Moti, also talked about having migrated from the state of Bihar to Delhi in search of work and how he has greatly benefitted from the construction boom in urban India.298

Below:

Andrew Burton’s SkyQutb (2005) at Sanskriti Foundation, Delhi

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298 Ibid. p. 72. Mohammad Moti also mentions that nearly 70 – 80% of men from his village now work as brick masons in Delhi as there is no employment for them back home.
**Spheres, Villa Sarabhai, 1990s**

The next example of art created through brick masonry is the sphere at the Villa Sarabhai. Created by the renowned artist Anish Kapoor in the 1990s, a set of two orbs lie on a terrazzo platform in the Villa’s gardens.

The first orb is black made of metal while the other gives the impression of having been made by reshaping a clumped a pile of brick masonry. While both creations are spectacular, the one in brick masonry is an unmissable ode to the Brutalist expression of the Villa Sarabhai itself. Its roughly hewn masonry joints and curved geometry are derivative of the vaulted ceilings of the house’s interiors and would not make a better companion to another work of architecture.

![Two spheres at the Villa Sarabhai made by the artist Anish Kapoor in the 1990s](image)

**Camp of the Jews, 1990s**

Discussed earlier in chapter 4, ceramic fuses carry very strong connotations of displacement that have been employed in the art created by Israeli artist, Ilana Salama Ortar. Her work espouses emotions of transience and fragility of life and which she expresses through interlocking of coloured glass bottles directly reminiscent of ceramic fuses and their construction system. Ortar’s conversations with the architect Zvi Efrat touch upon the ideas of how spatial configurations of the Camp du Arenas have informed human experience.
and in an attempt to cater to the humanitarian crisis of the time created spaces that were in fact torturous due to curved corners constantly nudging you towards a less claustrophobic centre, making it the only really usable space.

The cultural survival of the building crafts relies on their transfer and transmission of knowledge systems to younger generations. Explaining the etymology and nature of tradition as that of relinquishing or ‘handing on’, Paul Connerton attributes the hand as being vital to cultural survival in its role for the transmission of knowledge and asserts that it will never become obsolete no matter how much mechanization takes over. The deployment or rejection of each of the vaulting techniques explored in this thesis conveys a sense of society’s considerations for capacity building, resistance to change and an appetite for internalization through frugal or indulgent means.

“All new technologies really represent a new life-style, therefore a new ideology. Therefore, they are political. When we architects pretend they are not, we are very naïve, or we want to be very naïve.”

Charles Correa

CHAPTER 7: CONCLUSION
Tile Vaulting for India in the 21st century

Tile vaulting and its modified versions prospered in the United States, Uruguay, Cuba, Colombia and Mexico through the very conditions that we find in the Indian market today: skilled masons and abundance of affordable labour, living crafts-based building traditions and a favourable building market. However, to conclude of tile vaulting’s suitability for India for just the above reasons would be to recklessly overlook the deploying existing policy mechanisms to enhance an intrinsic quality of collaboration that exists in India’s building crafts culture. Both issues are intimately linked with the success of tile vaulting in India and articulated in greater detail further.

Just as tile vaulting is not tethered to typology or tectonics, its application can be made across urban and rural India. While the two are distinct, they remain in a constant state of flux, animated by people, and therefore do not exist as rivals but as ones offering insights on intermediate overlap states that either may not be able to independently provide. However, the massive lacuna in housing rural India has become too alarming to ignore further thereby creating the opportunity for my proposing tile vaulting for that sector. Justifications for my proposal are presented in the following sub-heads.

Comparing Roofing Techniques

Not only are roofs archetypal symbols of shelter, they are also often the most expensive building components. The charts that follow compare various roofing techniques explored in this thesis to give an overview of their salient features alongside advantages and disadvantages relative to reinforced cement concrete slabs as the benchmark.

Square-shaped plans require a conventional reinforced concrete slab to be reinforced with tor steel bars in both directions, i.e. as a two-way slab and require more steel reinforcement than a rectangular one-way slab which only needs the main reinforcement along the shorter span. Remarkably, vaulting is best suited for squarish or circular plans and doubly curved shells can further reduce the reliance on steel reinforcement by up to 60% for such configurations.\footnote{303 Samuel Wilson, ‘Structural Design of Shallow Masonry Domes’ (Master’s Thesis, Massachusetts Institute of Technology, Department of Civil and Environmental Engineering, 2016). p 47.}

Consistent with the full-scale tile vaulting prototypes constructed at Hunnarshala, a room size of 3.5 m x 3.5 m is taken as standard in the charts in order to compare the vaulting techniques against reinforced cement concrete. The common criteria for which each vaulting technique has been evaluated include:

- Cost of construction per sq.m. in Indian Rupees (Rs.) and British Pounds (GBP)
- Module used relative to the human hand
- Rise : span ratio
- Shell thickness
- Man days taken to construct the shell

The costs taken into account are for the shell only and do not include costs for edge beams or supporting arches. Also, construction time indicated is based on time taken to set up guidework and build the shell but not curing.
### Comparative Roofs

**Room Dimensions**

3.5 m x 3.5 m
12.25 sq.m.
132 sq.ft

1 GBP = Rs 88.08
Currency exchange as of 27 September 2017
Source: Oanda (https://www.oanda.com)

<table>
<thead>
<tr>
<th>Reinforced Cement Concrete</th>
<th>Reinforced Brick</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flat Slab</strong></td>
<td><strong>Funicular Shallow</strong></td>
</tr>
<tr>
<td>Rs. 3,768 / sq.m</td>
<td>Doubly Curved</td>
</tr>
<tr>
<td>GBP 43 / sq.m</td>
<td>reduces cement content - uses bricks / terracotta products</td>
</tr>
<tr>
<td></td>
<td>1:9.1</td>
</tr>
<tr>
<td></td>
<td>0.115 m</td>
</tr>
<tr>
<td></td>
<td>7 persons 4 days</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rise to span ratio</th>
<th>0</th>
<th>1:9.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>0.15 m</td>
<td>0.115 m</td>
</tr>
<tr>
<td>Labour</td>
<td>6 persons</td>
<td>7 persons</td>
</tr>
<tr>
<td>Duration</td>
<td>3 days</td>
<td>4 days</td>
</tr>
</tbody>
</table>

### Advantages

- "Standard" technique.
- Materials easily sourced.
- Easily replicable due to ubiquity.
- Cost of construction considered "normal".
- Thin-section, lightweight, saves material.
- Builds upon RCC construction systems.
- Can use a variety of terracotta products.
- Vertical expansion possible.

### Disadvantages

- Requires sturdy formwork + reinforcement design.
- Requires repairs within first few years of completion.
- Not ideally suited for tropical regions due to heat gain.
- Uses a lot of steel and water: energy intensive materials + processes.
- Heterogeneity of materials.
- Costly curved formwork and casting.
- Construction requires skilled supervision and advanced version of RCC construction.
- Larger quantities of steel used.
- Predominantly concrete construction.
<table>
<thead>
<tr>
<th>Burnt Clay Tubes</th>
<th>Tile Vaulting</th>
<th>Muzaffarnagar</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Funicular Hollow</strong>&lt;br&gt;Mostly single curved</td>
<td><strong>Funicular</strong>&lt;br&gt;Doubly curved</td>
<td><strong>Funicular Shallow</strong>&lt;br&gt;Doubly curved</td>
</tr>
<tr>
<td>Rs. 1,400 / sq.m&lt;br&gt;GBP 16 / sq.m</td>
<td>Rs. 2,370 / sq.m&lt;br&gt;GBP 27 / sq.m</td>
<td>Rs. 1,938 / sq.m&lt;br&gt;GBP 22 / sq.m</td>
</tr>
<tr>
<td><img src="image1" alt="burnt clay tube / wardha tumbler / guna tile" /></td>
<td><img src="image2" alt="terracotta tile / Catalan vault" /></td>
<td><img src="image3" alt="compressed stabilized earth block" /></td>
</tr>
<tr>
<td>reinforcement only in edge beams, burnt clay modules used</td>
<td>reinforcement only on edge beams, clear span - modular expansion</td>
<td>reinforcement only on edges, modules laid concentrically from centre</td>
</tr>
<tr>
<td><img src="image4" alt="1:4" /></td>
<td><img src="image5" alt="variable" /></td>
<td><img src="image6" alt="1:14.5" /></td>
</tr>
<tr>
<td>0.12 m&lt;br&gt;6 persons 3 days</td>
<td>0.057 m&lt;br&gt;4 persons 2 days</td>
<td>0.115 m&lt;br&gt;3 persons 2 days</td>
</tr>
</tbody>
</table>

- Module produced on potters wheel.
- Easy to assemble.
- Very strong and durable.
- Aesthetically pleasing.
- Extra volume through vaulted ceiling.

- Quick to build. No formwork used.
- Extremely strong and Durable.
- Flexible module + vertical expansion.
- Extra volume through vaulted ceiling.

- Traditional technique updated to modern materials and methods.
- Extremely strong and durable.
- Flexible module + vertical expansion.
- Semi-skilled labour.

- Requires more guidework than tile vaulting.
- Cannot be left exposed to sky - needs cement plaster and waterproofing layer.
- Needs reinforced edge beams to counter thrust
- Modules need to achieve uniform firing to become robust and minimize breakage.

- Heterogeneity of materials: Tiles + POP + Cement adds to material handling issues as they are often simultaneously required.
- Requires skilled supervision.
- Initial cost - but very good value on investment due to durability.

- RCC-equivalent formwork required.
- High initial cost - but long-term return value on investment.
- Minimizes labourers needs and can be easily done with 2 - 3 persons for given roof size.
Building Lightweight and Cost Appropriately

Of the roofing techniques surveyed for this thesis, vaults made with burnt clay tubes were found to be the most affordable in India at Rs. 1400/sq.m, about £16/sq.m.\(^{304}\) This is chiefly due to the cheap building module which costs a miniscule Rs. 6/- each (under £0.10/-). Rates vary by region owing to production peculiarities and labour engagement. At Rs. 2370/sq.m, tile vaulting costs almost twice that and is not necessarily faster to build, but offers other relative advantages such as flexibility of vertical expansion and longer life. Besides, we have also seen how sourcing of burnt clay tubes can be a problem despite its simple manufacturing process.\(^{305}\)

One distinct advantage of tile vaulting is that of lightness.\(^{306}\) Having the least shell thickness, therefore least material of all the compared vaulting techniques, without compromising structural performance, tile vaulting epitomizes structural efficiency. This was demonstrated in the comparative data presented in load tests conducted on Prototypes P3 and P4 relative to the Muzaffarnagar vaults with the latter being twice the thickness of the tile vaulting prototypes. In contemporary architectural design that champions environmental sustainability criteria, the notion of an optimized structure may be considered as one having long-term investment benefits through the building’s life cycle from low carbon impact.

Well-designed lightweight roofs in subtropical India that incorporate convectional air changes offer much desired thermal comfort. One proposal for such vaults was made by Corbusier’s office for the unbuilt Governor’s village.\(^{307}\) Two tile vaults separated by an air cavity were expected to provide superior thermal comfort by reducing heat gain in interior spaces at presumably little extra cost. This contrasts with the heavy section of the reinforced concrete vaults at the Villa Sarabhai that heat up during the day and radiate it back into the house by night due to its heavy thermal mass.\(^{308}\) With the creative application of such double-skinned tectonic arrangements, tile vaults can be deployed for creating desired thermal conditions in India.

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\(^{304}\) Currency exchange as of 27 September 2017, 1 GBP = INR 88.08. Source: Oanda (https://www.oanda.com)

\(^{305}\) See Rajendra and Rupal Desai’s report on Gramin Takniki Kendra where they were unable to produce burnt clay tubes at site despite setting up all required infrastructure. Moreover, potters from neighbouring villages no longer worked in making country tiles, the prerequisite to learning to make burnt clay tubes.


\(^{307}\) See Chapter 3: Villa Sarabhai of this thesis for more details on the project.

Savings in the construction of tile vaults can further be made by producing and curing tiles at site as demonstrated in the Earth Pavilion by Michael Ramage (2010, photos below) that used pressed soil bricks with very low compressive strength of 5 MPa while retaining its structural merits. Each tile measured 115 mm x 225 mm x 18 mm and weighed 860 gms. On-site production of the core building material also reduces construction costs and eliminates the need for having to source it from long distances, making the technique more affordable.

![The Earth Pavilion, UK (2010) used tiles made at site having very low compressive strength of 5 MPa](image)

**Tile vaulting is not meant for roofing alone**

To look at tile vaulting for merely roofing would be selective vision. It can be deployed for foundations, staircases and independent structures such as water tanks and toilets for example. Mies van der Rohe’s famous German Pavilion in Barcelona for the International Exposition in 1929 had foundations made with tile vaulting.\(^\text{309}\) Due to its cost-effective, lightweight and rapid building properties, tile vaulting can also be deployed to serve as formwork for casting of concrete shells or structures. Some research towards this end is already underway although the idea dates back to antiquity where hollow terracotta bottles were used as a first layer upon which lime concrete shells were cast.\(^\text{310}\)

Therefore, it is a matter of fully understanding and appreciating the technical possibilities of tile vaulting’s construction system and as documented and demonstrated in this thesis – Indian craftsmen have the necessary disposition to respond and adapt the guidelines of tile vaulting most proficiently without evangelical direction.

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“Unfortunately we, who learn in colleges, forget that India lives in her villages and not in her towns.”

Mahatma Gandhi, 1925

Policy Intervention and Sustained Implementation in India

The construction industry in India contributes over 7% to its GDP and is expected to grow steadily from an annual 2281 Billion INR to 2530 Billion INR (£25.89 to $26.28 billion) by the year 2020.\(^{312}\) It is important here to contextualize the problem faced by the Indian housing sector and examine relevant policies that directly impact meeting those demands. The enormous housing shortfall in urban and rural India has been unmet for decades with the government envisaging to build 10 million houses over a three year period between 2016-2019 and a ‘Housing of All’ aim by 2022.\(^{313}\)

Among the several issues that fuel inequity in affordable housing, is one of displaced market offerings where builder investments have all concentrated on 21.5% of the real estate in urban areas ignoring the 78.5% that reside in peri-urban and rural areas with a monthly household income of below INR 15,000 (or £170 approx).\(^{314}\)

Incidentally, India operates one of the world’s largest rural social housing programmes under the aegis of the Pradhan Mantri Awas Yojana (PMAY), formerly Indira Awas Yojana.\(^{315}\) Originally launched in 1985 catering to the rural population, the scheme has been recently remodelled and relaunched in April 2016 with additional provisions to serve the urban poor.\(^{316}\) The central and state governments collaborate on the scheme and split contributions while the latter often has further customized guidelines. At the village level, local governance bodies known as Gram Sabhas play a vital role in the selection of beneficiaries and the disbursements of funds. Therefore, although driven by the central government, the modus operandi of the scheme is largely decentralized and participative.

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\(^{313}\) Framework for Implementation, Pradhan Mantri Awas Yojana – Gramin, November 2016 published by the Ministry of Rural Development, Government of India. This is declared in the opening paragraph of the Executive Summary and reiterated in subsequent sections: 4 and 7.1


\(^{315}\) According to the Ministry of Rural Development, Government of India, a public housing programme has been in force since independence, however a structured policy was created only in 1985 and named Indira Awas Yojana. Its success has been regularly reviewed and updated since. Source: Framework for Implementation, Pradhan Mantri Awas Yojana – Gramin, November 2016

\(^{316}\) See page vii of the Framework for Implementation, Pradhan Mantri Awas Yojana – Gramin, November 2016 published by the Ministry of Rural Development, Government of India.
The PMAY-G offers beneficiaries upto INR 1.3 lakhs (£1,500) for the construction of houses primarily in rural areas. The minimum size of tenements is prescribed as 25 sq.m.\textsuperscript{317} Emphasis is laid on using appropriate technology and capacity building of locals as this is widely considered to be a self-build exercise. The use of contractors for construction is expressly prohibited although technical assistance of NGOs and government agencies such as the Rural Housing Knowledge Network may be sought.\textsuperscript{318} Since its inception, millions of houses have been built under the scheme while also spurring creative solutions for rural housing and institutional building of which projects such as the Gramin Takniki Kendra (see case study under burnt clay tubes) serve as good examples.

By contrast, Singapore uses a Labour Saving Index (LSI) to discourage the use of labour intensive building elements or components – where prefabricated elements are also bracketed within this group. The LSI is applied to a building system and is an intelligent index that is updated regularly to reflect any changes in technology. “A high index indicates that the design is more buildable and fewer site workers are needed.”\textsuperscript{319} The system also allocates bonus points for using prefabricated reinforcement, walling or other structural systems that effectively contributes to a total Buildable Design Score.

No doubt that the measure is intended for reducing reliance on mostly foreign labour, it is likely to prove detrimental to the cultivation of novel or adaptation of existing traditional building crafts of the region making the construction process a mechanized output than one that allows any creative participation from those involved in its realisation. And therefore, although the steps outlined make for admirable policy documents, it is also a definitive recipe for the creation of an elitist culture of architectural production that distances the craftsman from what could be a potentially collaborative culture.

For India, the emerging argument here, therefore, is of scale and the empowerment or denigration of craftsmen. While Singapore is a highly developed economy with no rural

\textsuperscript{317} The amount has been raised from Rs. 70,000 to upto Rs.1.3 lakhs in 2016 along with the size of the houses increased from 20 sq.m. to 25 sq.m.
\textsuperscript{318} See Section 5.5 – Mode of Construction, pages 29 - 30 of the Framework for Implementation, Pradhan Mantri Awas Yojana – Gramin, November 2016 published by the Ministry of Rural Development, Government of India.
\textsuperscript{319} Building and Construction Authority, Singapore, ‘Code of Practice on Buildability’ (Building Guidelines, 2015), p. 6. The Labour Saving Index is defined as: “A value given to a particular building system which reflects the relative difference in site labour productivity associated with the various structural and wall systems. In certain instances, the LSI could be further lowered to discourage the use of labour intensive elements or components. A LSI is also given for the use of prefabricated reinforcement/cages in cast in-situ components.” (page 22, November 2015)
areas to construct for, India lives in its villages. As of 2016, 66.86% of India is still rural by population and for the massive housing gap to be bridged, artisan culture, largely prevalent and afforded by rural and peri-urban India, must be strengthened and empowered with appropriate scientific backing. As part of the 2016 overhaul, the central government has proposed setting up a National Technical Support Agency to oversee a more efficient implementation of the scheme.

Undoubtedly, there is potential in the provisions of the PMAY-G for promoting building craftsmen to play a vital role in, if not lead, this process. Not everyone who needs a house may be trained in building or even interested in the trade while craftsmen can be employed to guide and assist this self-build process. This would still uphold the underlying principle desired by the PMAY-G of not outsourcing the work to a contractor and for beneficiaries to be part of the design choices for their eventual home. In instances where this has been holistically achieved, as in the case of the Muzaffarnagar technique and burnt clay tube houses of Wardha, people have been found to build their own dwellings with dignity bringing cohesion to the community, economic prosperity while attaining enhanced capacities.

Two examples from outside of India that deploy tile vaulting with similar objectives deserve mention: The Crossway House in Kent, UK (2009, photos below) features an overarching tile-vaulted parabolic roof with living spaces underneath. All tiles were sourced from a neighbouring Kent peg tile manufacturer: Babylon Tile Works located just 4.5 miles away. A portion of the business from constructing Crossway thus went back into the immediate community and in turn forged long-term relationships between the various agencies involved. Crossway’s architect and owner, Richard Hawkes continues to engage Babylon for other his projects that use Kent peg and Mathematical tiles while its structural engineer used Babylon to supply tiles for his London-based project at Pall Mall.

Another example is the Sustainable Urban Dwelling Unit (SUDU) in Ethiopia by Lara Davis in 2010 that features low cost tile vaults. Lessons from her experiments have also been encouraging of investing in the community directly thereby sustaining the labour-reliant

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320 Ashutosh Pandey, ‘Gandhian Perspective of Rural Development’, The Indian Journal of Political Science, 69 (2008), p.141. Pandey cites Gandhi and further states that about fifty percent of the 5.76 lakh villages of the country are situated in different terrain characterized by poor socio-economic conditions.


322 Ibid. See section 7.1, page 43, Implementation Support Mechanism.

323 Interview with Richard Hawkes on 12th November 2015 at Staplehurst, United Kingdom. The form of Crossway House itself was a matter of contention in the community and Hawkes defended his idea by drawing an analogy to the barn-like houses of the surroundings that suited the agrarian society of its time which were no longer the case and therefore irrelevant.

construction processes due to benefits in economy, ownership and lower environmental impact.

![Crossway House, Kent, 2009. The laminated structure of a four layered tile vault is visible in the detail. The tile module used here measured 123 mm x 250 mm x 25 mm and weighed 1435 gms.]

Lessons from similar projects, even if they don’t use tile vaulting, can be extended to build a case that favours the adoption of tile vaulting in India and especially through the PMAY-G scheme.

**Mono-materiality and Tile Vaulting**

“For concrete is but one symptom of our discomfort with modernity and everything that comes with it.”

Adrian Forty, 2012

Gujarat based NGO, Unnati’s survey of rural housing projects in 2012 constructed under the Indira Awas Yojana reveals that although 48% projects in Gujarat use fired brick for walls but only 1% use it for roofing.\(^{325}\) Reinforced cement concrete is the most preferred roofing material at 41%. This preference is shared by other states with natural variances according to proximity to urban areas, materials availability but the general perception of cement concrete offering permanent or ‘pucca’ (to use a colloquial term) construction seems unanimous. In earlier chapters, we have seen how cement concrete continues to carry deeply rooted meanings of urbanity and progress in the postcolonial landscape and therefore the underlying problem of perception manifests in society’s choices when bridging the urban-rural divide.

The masonry vaulting techniques examined in this research offer the robustness of ‘pucca’ construction without the energy intensive construction processes demanded by reinforced

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\(^{325}\) Unnati Organisation for Development Education, *Disaster Resilience of Indira Awaas Yojana Houses: Pilot Study in Six States* (Ahmedabad, Gujarat: Unnati Foundation, 2012), p. 75 – 76. This is an excellent report that also sheds light on house sizes, material distribution across building elements as well as softer issues such as home insurance and programmes for educating beneficiaries in structural safety.
cement concrete. By eliminating its reliance on steel and inevitable problems arising out of corrosion in later years, unreinforced masonry vaults also have superior durability. PMAY-G is also assisting the exploration of mono-materiality most likely out of frugality and prudent use of material rather than architectural evolution. Nonetheless, the scheme expressly encourages the use of masonry walls, arches for fenestrations, built-in furniture, \textit{jaali} walls as well as roofs made of bricks which, if harmonized in architectural expression are capable of creative the \textit{definitive unity} that a one material building of nearly any scale can offer.\footnote{Robert Grant Irving, \textit{Indian Summer: Lutyens, Baker and Imperial Delhi} (New Haven and London: Yale University Press, 1981).}

From among the plethora of building techniques in India that can be deployed for construction in areas not prone to seismic activity, tile vaulting too can further serve the concept of mono-materiality. It must also be noted that housing is but one of the many typologies that it can be applied to. Also, the intention here is to demonstrate that tile vaulting should be applied according to the scale and requirement dictated by building typology and not be relegated to only institutions or houses in rural areas alone.

In keeping with the times of emerging technologies, the idea of mono-materiality can be extrapolated to 3D printing. With the advent of affordable and scalable technologies that allow for 1:1 scale 3D printing of ceramics, there is little doubt that the idea of mono-materiality will receive renewed attention in India and abroad. There is a possibility that the scale afforded by the housing sector in rural India will help economize the unprecedented application of these technologies and with a conscious effort for collaboration between artisan and architect, the former will not be alienated but instead involved in such a process. Craft has been essential to architecture due to the numerous agencies that the latter deploys in the construction process. Better understanding of the construction systems allows architects to play a proactive role in integrating design and production processes better.
**Computation, Craftsman and Scale**

“...artists are now turning to ceramic’s messy materiality in reaction against the increasing virtuality of our digital culture.” 327

**Tanya Harrod**

Computational tools are increasingly pervasive in contemporary architecture from the preparation of architectural drawings and visualisation to complex Building Information Management systems. They also guide form finding as well as the production of building components. On the other hand, the idea that craft is more art than science has impoverished all three of them. Whether it is the drawing or the actual construction of buildings, craft is informed, at all times, by the artistic and technical faculties of the mind. Craft also facilitates (as it often requires) collaboration with others. This kind of synergy has always been central to the creation of remarkable architecture. Advancements in computational technology have prompted practices to question the role of the craftsman and two notable practices have demonstrated how traditional building methods can be balanced with computation.

The first is Mark Burry, chief architect for Gaudi’s unfinished Sagrada Familia. Burry explains that while his own work at RMIT, Melbourne is steeped in pushing the limits of computational form finding, reliance on historically sustained local skills has proven indispensible in the case of completing the Sagrada Familia. 328

In another project by Michael Ramage of Light Earth Designs, a series of mini tile vaults were designed using Grasshopper scripting and Rhino 3D modeling software to optimize the size and coursing of the vaults so that they could be handled easily for rapid assembly at site in Chicago, U.S.A. Ramage’s prototyping sequence involved first hand carving a 1:3 model to arrive at proper coursing of tiles, then a 1:1 CAD model was prepared which was 3D printed at 1:10 scale. This was checked and milled on a CNC machine to generate a 1:1 timber positive on which multiple silicone vaults were cast to clearly show tile coursing patterns for masons to work on simultaneously. (Photos from the process on following page)

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While the complex prototyping sequence eased construction of the vaults thousands of miles away from its designer thus raising the question of genus loci, it is important to note that the solution for coursing was arrived upon through consultation with experienced craftsmen, which in this case was the vault’s mason, Sarah Pennal who is also UK-based as Ramage.\textsuperscript{329} This approach of ‘assisted construction’ closely resembles the one used by Gautam Sarabhai at NID, Ahmedabad (Chapter 5) but is explored by Ramage using computational tools of rapid prototyping before being transferred to site for assembling by hand by artisans.

Renowned engineers such as Torroja, Candela and Dieste all credit tile vaulting for having inspired in them the idea of optimization of form and building for economy.\textsuperscript{330} In optimization, the generation of architectural form is primarily determined by the lines of thrust, an ideology which Dieste has aptly described as: “to resist through form.”\textsuperscript{331}

Testing new territory for a computational approach to tile vaulting is the research initiated by the Block Research Group (BRG) at ETH, Zurich that has extrapolated the ideas of the Thrust Network Analysis and broken new ground for unprecedented vaulted forms. However, in wanting to achieve novel tectonic expression of unreinforced masonry, it tends


to also modify the core discipline set by tile vaulting’s principles of minimizing guidework by using ‘falsework’.\textsuperscript{332} It must be appreciated that the proliferation of tile vaulting across the world was possible because its construction principles were simple, time-tested and scientifically sound. They dictated a certain discipline in building where forces need to be contained within the materials. Materials themselves have and will change with time but when we compromise straightforward principles of tile vaulting by using falsework and its versions, we insert unnecessary heterogeneity into a system which is by itself efficient and durable therefore undermining its intrinsic logic of construction. Therefore, while I fully appreciate that there is a time and place appropriate for the approach explored by the BRG, in the context of building in rural India, it would be an unjustified indulgence that undermines the deployment of tile vaulting by the local workforce already familiar with some of vaulting’s characteristics that make it cost-appropriate and sustainable.

Notably, in contemporary India heritage conservation as well as ‘design + build practices’ are gaining greater visibility and momentum.\textsuperscript{333} Articulating the relationship between craft and architectural production has come to the fore and embracing craft in practice has become a test in not only conservation but also contemporary design. It is only a matter of time before craftsmen and architects using computational technologies actively seek middle ground for collaboration and production, which in the context of India, I believe can mature into a technological thought tool that enriches both process and product.\textsuperscript{334}

There is, however, an inherent problem of scale that seems to distance the craftsman from mainstream architectural production. For a hand-reliant building method, the time taken for delivering a project is directly proportional to its scale and is often the reason why the participation of craftsmen is diluted to a minimum thereby making way for mechanized approaches to take over to meet the economy of scale. Also, the iterative process of craft contributes to its relegation in what may be considered as a delay-inducing factor.

For example, without the opportunity of prototyping new building techniques at smaller scales before full scale experimentation, one is practically less likely to stumble upon solutions that involve a reassessment of approach for better results – as witnessed in the Brahmand and Phoenix prototypes in Bhuj and New Delhi respectively. Only when do

\textsuperscript{332} Philippe Block, Lara Davis, ‘Efficient and Expressive Thin-tile Vaulting using Cardboard Formwork’, 35th Annual Symposium of IASBE Paper, 2011. Instead, the idea of falsework for unreinforced masonry works remarkably well for projects like the Armadillo Vault, also by the BRG constructed in 2016 for the Venice Biennale.


craftsmen reflect upon their methods and improve them or adapt them to unprecedented conditions can crafts or building traditions truly thrive. Is there a way for the predominantly urban and urgent economy to afford craftsmen such space? Or is the domain of craft meant to be limited to the peri-urban, rural and the urban exotic?

The praxis of a handful exemplary NGOs and architectural offices in India may offer answers to these questions. From the prototypes and case studies in this thesis, we have already seen Hunnarshala’s commitment to elevating the role of the artisan in the building process. Another notable example from urban India is that of Studio Mumbai. Headed by Bijoy Jain, the studio employs over a hundred craftsmen alongside trained architects and has a thriving culture of collaboration. Jain has said: “In our practice there is no separation between artisan and architect. Every part of the process is exposed and everyone takes their share of responsibility.” Jain refrains from being sanctimonious about whether this ought to be the new model for architectural practice in India and perhaps even the west but the fruits of a successful marriage between the multifarious traditional building crafts and contemporary design are self-evident through his works. Similarly Laurie Baker’s COSTFORD in Thrissur, Mrinmayee in Bangalore and the Auroville Earth Institute in Tamil Nadu all seek to empower artisans through their architectural works and year-round training modules in sustainable building crafts.

It would not be unreasonable to extrapolate that over the years through sustained institutionalized sanctioning of traditional crafts by such organizations and practices, attitudes will trickle down into mainstream architectural production and make the crafts more accessible and affordable. Among these are the building techniques such as Muzaffarnagar vaulting, burnt clay tubes and potentially tile vaulting that perform at the peripheries of architectural production in India today but with sustained efforts can earn the confidence of more mainstream building.

India’s demographics are also likely to play a crucial part in this change. As of 2017, India may be the world’s second most populous country after China but by 2020, the average age in India is estimated to be 29, making it the world’s youngest country with 64% of its

population in the working age group. These are remarkable numbers and have the potential of shaping India’s future choices for many decades to come. The opportunity at hand to engage a younger generation of craftsmen to take pride in their metiers and evolve them for the future, therefore, is quite remarkable and worthy of actively shaping.

Tile Vaulting for India in the 21st century

“Without modifications to the social and material environment, there can be no change in mentalities. Here, we are in the presence of a circle that leads me to postulate the necessity of founding an “ecosophy” that would link environmental ecology to social ecology and to mental ecology.”

Felix Guattari

Ignoring the multitude of skills that artisans in India bring with them is to inflict injustice on both tradition and future. From the British conservationist Sir John Marshall and iconic builders such as Edwin Lutyens to Laurie Baker and Hunnarshala, those associated with building in India have all recognized and relied on the strength of the country’s building crafts traditions. Today, the proposition of using the term craft may be both promising and problematic but it is as Omar Abdelaziz Hallaj suggests that anybody who views craft as a static thing of the past, preserved for the sake of posterity, is mistaken. This is a view seconded by Alvaro Siza who says: “Tradition without innovation gets lost. Its time runs out.” Appreciating that craft is a constantly evolving practice is vital for its existence and personalization by every generation that engages with it. This credo is has been central to my proposal for extending the repertoire of vaulting in India by introducing tile vaulting.

We have also seen how cultural perception lies at the heart of embracing new technology and building methods. Tile vaulting is determined suitable for Indian conditions because it resonates with the culture of artisan-architect collaboration and frugal-engineering mindset, i.e. of making the most with limited resources. Alfonso Ramirez’s elegant shell structures in Mexico built using the leaning brick technique stand testimony to such possibilities. Eladio Dieste too has spoken eloquently of the casually accepted ease of working with planar designs for clarity of drawings, calculations and composition. However, he has drawn our attention to the beauty of seemingly complex, but highly resolved architecture of Gaudi, and goes on to cautiously remark that the structure must hold precedence over the plan thus echoing Jose Luis Sert’s dictum of liberating ourselves from the ‘tyranny of the drawing board’ which may be possible through active collaboration across skills.

339 Sir Christopher Frayling, On Craftsmanship: Towards a New Bauhaus (London: Oberon Masters, 2011). Frayling elaborates the multiple meanings that the term ‘craft’ carries for the many people who like to use it, ranging from craftsmen themselves to mass-market businesses, from social scientists to politicians.
341 Having a Cigarette with Alvaro Siza, dir. by Ian Dilthey (Koenig Books, 2017).
India’s public housing scheme for rural areas – the PMAY-G – is also a crucial link to tile vaulting’s potential uptake. To help achieve the government’s ambitious and ever-evasive target of 10 million houses for rural India by 2019 and possibly equally more by 2022, it is clear that craftsmen must be more explicitly empowered to assist the government through a policy that already honours a heterogeneous and decentralized culture of implementation. And although construction in the urban areas is perhaps the largest component of India’s GDP figures, the health of the rural economy will truly reflect the economic vitality for a county with India’s diversity and scale.

As the first phase of India’s economic growth, establishment of institutions and political maturity ascends and begins to plateau in coming decades, the nation will enter its second phase of growth when it will be important for India to look outwards. Thus, it is in this moment, when India has all eyes on it, that it must choose to not only shape itself in a manner most suitable to its economic sustenance but also consolidate its cultural soft power from within by demonstrating that a model which celebrates craftsmanship while pursuing economic growth is achievable in the building sector.

Furthermore, as criteria for environmental sustainability in construction materials and processes are being examined constantly upgraded, more architects in India are appreciating the advantages of natural materials for construction. More specifically, as new directions in ceramics and materials research continue to make advancements, they must be channeled to enhance rather than destroy the fertile building crafts culture that India offers. The more aware we are the better prepared we can be to shape policies for the preservation of our past and the building of our future.

By facilitating to build lightweight and in spirit with timeless Vitruvian virtues of Firmitas, Utilitas, Venustas as well as the Gandhian principles of frugality and grassroots empowerment, tile vaulting offers India an opportunity for using a sustainable, cost-appropriate and robust construction system while persuading a new generation of craftsmen to build upon existing strengths with renewed pride.

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344 Which country does the most good for the world (TED, 2014). Simon Anholt is an independent scholar and international policy advisor and was referring to the process of inward and outward transformation of a progressive nation’s perspective. He does not refer to India specifically. That is my implication.

345 Dr. Sameer Maithel and Dr. R. Uma, Brick Kilns Performance Assessment: Monitoring of brick kilns & strategies for cleaner brick production in India (Research Paper, Shakti Sustainable Energy Foundation & Climate Foundation, 2012).
Limitations and Extension of Research

This thesis hopes to have laid the foundation for using tile vaulting within the context of innovative masonry shell construction in India. There are many emerging threads here that may be developed into independent research and have been detailed below:

Histories of Vaulting

My study has primarily looked at vaulting techniques in use in India today i.e. India of the post-colonial period. With its vast geographic expanse and innumerable subset of cultures within, India offers the great opportunity to explore many more histories of vaulting used across the country and offer insight into their choice of materials as well as their socio-cultural impact.

India’s geography is also varied and climatic conditions demand appropriate architectural solutions. This is further complicated by seismicity as much of the country is seismically active and will dictate whether or not vaulting is right option for that particular region.

Tile Vaulting: Further Research & Development

The prototypes constructed for this thesis can only help lay the foundations for more inquiry into the application of tile vaulting. Its reliance on simple geometric principles, quick building method, durability and artisanal engagement make it a competitive choice within those already offered. However, more structural and material tests must be carried out before formally adopting tile vaulting for the construction industry in India.

Some of the ideas for future prototypes include a combination of the following:
Constructing tile vaults with new, flexible reinforcements such as the Tensar Geogrid or more traditional ones such as ferrocement and conducting structural tests for comparative results. Some work on this has already been initiated by DeJong and Ramage.  

As noted earlier in Chapter 6, the tile vault prototypes constructed were meant to be tested for ultimate loading strength and other detailed analysis of its structural performance lay beyond the scope of present research. Due to their novelty, it is vital to examine each component individually for testing across the criteria of structural and environmental

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performance. This includes but is not limited to: testing different grades of gypsum plaster and cement mixes sold in India, testing compressive strengths of terracotta tile samples from marketplace or those produced at site and finally conduct lab testing of shell behavior built using these materials.

Building and testing tile vaults using tiles made on site and documenting their production, performance and impact on structural strength will also help address cost differences but also make it possible to build without relying on transportation ultimately resulting in low carbon footprints.

India also has a long tradition of working with lime. Replacing cement mortar with lime for tile vaults, as they were traditionally built before the advent of cement, will help ascertain its place today. Lime has a much longer setting time and can be more tedious to produce and storage but it is environmentally friendly and for structures of institutional scale can become a viable option to be used alongside tile made in-situ.

As referenced earlier, a thermal performance study of shells constructed in a variety of tectonic compositions would also contribute greatly to the understanding of its appropriate deployment in various parts of India that no doubt have different climatic conditions.

While proposing tile vaulting for India on an encouraging note, I must point out to an important study that expresses concerns of ethical sourcing of gypsum in India. Lara Davis’s independent report on Glass Fibre Reinforced Gypsum shines light on the reckless use of phospho-gypsum by-product by the fertilizer industry without necessary environmental regulations to contain its potentially hazardous use. Although not directly related to the superior dental grade plaster of Paris commercially sold, having the same source does raise concerns that need to be addressed before deployment especially for habitation.

**Villa Sarabhai – 3D Laser Scanning**

As part of the study to decipher the vaulting technique used for the Villa Sarabhai, I had carried out 3D Laser Scanning of the house in March 2016. The intended purpose of the scan was to be able to compare the vaults in the 10 bays for regularity, consistency in geometry and detailed structural analysis that would help shed light on its construction system. It was found that processing the enormous amount of data generated as part of the

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exercise exceeded the scope of my doctoral research but the data will no doubt prove a useful vehicle for analysis in the future.

**Burnt clay tubes and ceramic fuses: Indian origins and possible use in the U.S.A.**

This research has traced the arrival and use of ceramic fuses in India but the exact origins of burnt clay tubes is more complicated and also deserves further research. As mentioned in Chapter 4, the tubes are colloquially referred to as Guna tile, Wardha tumblers or Wardha tiles, owing largely to the Centre of Science for Villages work in Wardha (CSV).

However, it is also most likely to have been used in India before the arrival of ceramic fuses in 1962 as established in this research. The possible motivations that led to its independent development and informal adoption across the housing sector even without the validation of institutions such as the CSV will most certainly shed light on whether the tiles are descendants of their Mediterranean cousins perhaps making their way into India through trade routes, or have a completely disconnected history of their own having been indigenous from the beginning.

Similarly, with ceramic fuses, as Jacques Couelle had filed a patent for the modules in the U.S.A, were there any buildings or structures built there using the material? Given his entrepreneurial spirit, Couelle is likely to have tried building in the U.S.A and especially with the American military familiar with the vaulting modules, there would have been some interest in using them. With no literature available on the subject, this would also be an interesting study to embark upon.

**The structural analysis of burnt clay tubes and ceramic fuses**

Kamerling’s structural analysis of vaults made using ceramic fuses is the only scientific research on their structural performance. The application of graphic statics to analyze the vaults offers another approach for structural form finding and optimization while retaining the construction system.

The hollow section of both, burnt clay tubes and ceramic fuses means that the force lines are distributed circumferentially. This is bound to be an interesting study on transfer of forces with the line of force often contained within the hollow portion of the vault analogous to Robert Maillart’s methods for the Salginatobel Bridge.348 This deserves detailed study for the

348 Corentin Fivet and Denis Zastavni, "Robert Maillart’s key methods from the Salginatobel bridge design process (1928)", Journal of the International Association for Shell and Spatial Structures, 53 (2012), 39-47.
finer understanding that it has to offer about containing the line of force ‘within’ the load-bearing material.

**Development of Research initiated by the Desais on burnt clay tubes**

The creative research work already carried out by Rajendra and Rupal Desai on burnt clay tubes must not only be duly acknowledged but also further consolidated. Numerous lessons from their experiments have already been incorporated in the manual that the Centre of Science for Villages (CSV) now promotes for the construction of burnt clay tube vaults. Most of their valuable research deserves to resurface as it has direct benefits to offer now that CSV’s construction systems are finally receiving overdue recognition. which will otherwise be lost knowledge or result in the wasteful and unnecessary reinvention of the wheel. Some of the work that they have already carried out is:

1. Testing vaults that were double layered for structural advantages (as most constructed vaults using burnt clay tubes are single layered)
2. Exploring the use of burnt clay tubes lime-based plasters which are rarely used in India today and are an environmentally sensitive choice to make.
3. Long-term tests conducted to assess the structural and thermal performance of burnt clay tubes

This may be further extended by constructing vaults with differently sized burnt clay tubes to examine scope for improvement and by using burnt clay tubes having different profiles to assess shape optimization with respect to the catenary form, in order to further fine tune the construction technique and reduce material wastage. Finally, burnt clay tubes production can most certainly be optimized by better firing methods which deserve to be explored and assessed.
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