

Formwork as Design Tool

by

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B.Eng., Architecture
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Submitted to the Department of Architecture
in Partial Fulfillment of the Requirements for the Degree of

Master of Architecture

at the

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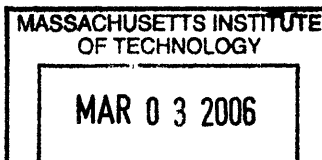
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ABSTRACT

An integral counterpart to the free form potential of concrete is the formwork which gives it its solid shape and texture. Naturally, the formwork takes up a bulk of the cost and labor time in reinforced concrete construction. However, despite its importance, formwork currently receives little attention from architects and is rather innovated by contractors. Therefore, in hope to align architecture and engineering through an interlacing of knowledge that have developed on each side of the concrete divide, this thesis reexamines formwork as an instrumental tool of formative process and investigates new potentials for concrete structures, reconsidering the material, fabrication, and construction methods of formwork and ultimately introducing digital technologies that might inform these aspects from design to construction.

Thesis Advisor: J. Meejin Yoon
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FORMWORK AS
DESIGN TOOL

SHUJI SUZUMORI

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INTRODUCTION

‘Despite the dissociation between architectural representation and tectonics, the true novelty is not a growing gap between design and materiality, but rather their intimate interaction that might eventually challenge the traditional professional identities of the architect or the engineer.’

- A. Picon, *Architecture and the Virtual: Towards a New materiality*

Just as mortar played a significant role in the success of the Roman Empire, concrete has shaped our built environment for the past century—and most likely, it will continue to be the dominating construction material. To cast and shape this concrete is the formwork.

Formwork and its materials are the integral counterparts to concrete’s free form (malleable potential). In reinforced concrete construction, up to 70% of the cost and a bulk of labor time is associated with the formwork. However, with an exception of a few architects, most do not consider formwork as a means of design. It is in most cases a temporary tool, its existence traced only by its imprints on the concrete surface. Ironically, it is the contractors and not the architects who have advanced the technological innovation of formwork. With economical and environmental reasons as their driving force, the contractors have brought forth creative ways to optimize construction in areas where there is less specific direction by the architect.

As if to differentiate the role of the architect and the builder, Peter Collins in *Concrete* states that the application of steel, its standardization then

needed in the building industry, marked the inception of the divide between the two. Nearly a century later, the application of concrete, which involves greater technological complexity, called for such divided roles to coalesce. However, because this integration did not take effect, it resulted in delays in the development of concrete structures. Today, emerging digital technologies are beginning to bridge these divides between disciplines and professions.

The premise of this thesis highlights the point that direct interface between materials, their histories of craft, and the potentials of digital technology remain an underdeveloped area of research. Thus, this is a reinvestigation of formative material, namely formwork, and the possibilities it brings to concrete structures. It examines formwork in terms of its materials, fabrication, construction methods, and also ways in which digital potential might inform these aspects from design to construction. This thesis attempts to suggest that architecture and engineering might begin to align again through the sophisticated interlacing of knowledge that has developed on each side of the concrete divide, and to advise architects to learn from the technical innovation of construction methods and implement them into the design process. It proposes that digital technology can contribute to the construction of concrete structures through formwork innovation, or completely change the notion of formwork all together.

OVERVIEW

The research process was comprised of three phases: formwork history, formwork typology, and formwork design.

Formwork History is a historical research that unveils a different side of concrete history through the examination of formwork. First is a historical review of roman and modern concrete construction, their similarities and differences, advantages and disadvantages, and roles in history. Through documentation analysis, concrete history is put in social context and compared to the development of other materials, namely steel. Secondly, we list several case studies to show innovative concrete structures produced by creative use of formwork. Each case study exemplifies concrete innovation lead by engineers and not architects. Thirdly, we focus on the formwork history of Japan, a country whose technology was mostly imported from Europe or the United States and is now one of the leading countries in formwork innovation. Historical data pertaining to concrete formwork history in Japanese architectural/engineering journals of the past 30 years were analyzed.

Formwork Typology is centered on the study of current formwork technology and expertise. Data was obtained through visits to leading prac-

titioners and researchers in the field, including interviews with construction managers of Tadao Ando and designers of Toyo Ito. Experiments at CAST, a fabric formwork research lab lead by Mark West, showed many advantages of fabric formwork and put light on some of the issues still open for research. Information gathered was analyzed in a matrix and was texted out by conducting small plaster cube casts. Here we introduce different formwork styles by various materials and discuss the merits and demerits of their nature. Also included in this section are records of hands-on experience of the construction of a rammed earth wall. The formwork was manufactured on site at 1:1 scale; specific adjustments to the formwork improved the efficiency of the ramming process and produced a more durable wall.

Formwork Design is a design proposal of a concrete wall that uses formwork systems developed from the first two phases of research, with digital design and fabrication systems. Using noise barrier alongside a highway as program, various forming methods were tested at multiple scales; both constructability and acoustical properties of the wall were considered. Models designed in the computer were tested in full scale concrete casts for constructability. Working with an acoustic engineer, 3D printed models were used for sound testing. Such tests gave continuous feedback between physical casts and digital model. Construction methods were designed and tested in the manufacturing of the formwork, installation on site, and casting. The process ultimately produced a design of a wall that was determined by properties of the formwork.

FORMWORK HISTORY

Formwork History is a historical research from an architectural vantage point – unveiling a different side of concrete history through the examination of formwork. First is a historical study of concrete in order to understand some of the reasons why potentials of concrete as a building material were not fully explored in the early stages of application. Secondly, innovative concrete structures with creative use of formwork are exemplified in a case study, showing that concrete innovation was led by engineers and not architects. Actual historical analysis of formwork data in the third section pertains to Japan; Japan's technology was mostly imported from Europe or the United States and its accurate documentation is accessible. Today, Japan is one of the leading countries in formwork innovation, largely due to its wide application of concrete. The first phase is concluded with a research paper that focuses on the texture of concrete surfaces and its relationship to formwork.

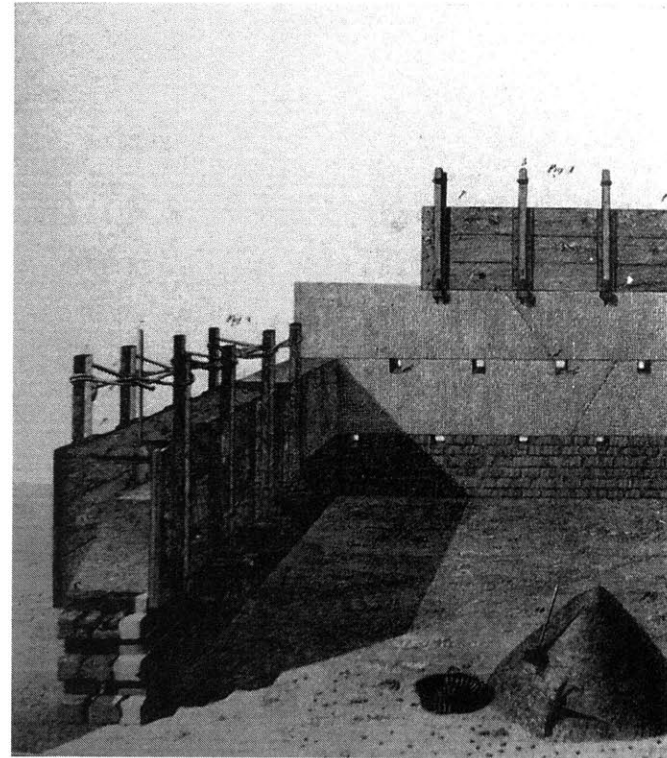


Fig. 1. Early Pise (rammed earth) Formwork.

HISTORY OF CONCRETE CONSTRUCTION

Roman Construction

One of the signatures of Roman construction, the arch, is not only a result of efficient masonry construction but also the result of innovation in concrete construction. Roman concrete is a mixture of pozzolan mortar (pozzolan ash, lime, and water) and aggregate, which had a much longer curing time compared to concrete used today. The builders placed brick, used as formwork, in a form of an arch so it would withstand the weight of the concrete placed above. With this method, they were able to minimize the use of wood, limiting it to scaffolding used to initially place the brick, which was very precious at the time. The load-bearing walls of the Pantheon is made in a similar manner, actually embedding arch structures within the wall. Romans not only had great knowledge of concrete but understood its properties and applied them to the design of the formwork.



Fig. 2. Drawing of formwork used to construct Roman arches.



Fig. 3. THE PANTHEON

Reinforced Concrete Development

Modern concrete chemically produced unlike Roman concrete was not invented until 1824 (by Joseph Aspdin), and was not fully applied until the second half of the nineteenth century, after the development of steel construction. Perter Collins in his book *Concrete* argues that steel construction was the beginning of the separation of “art and science” in architecture, which is one of the major reasons why concrete construction greatly suffered a similar divide in its early applications. The Crystal Palace is a strong image of steel construction and reveals its new possibilities in the age of industrial revolution. Concrete, on the other hand, lacks image or design as a new building material.

“In the seventeenth and eighteenth centuries, architects were well aware of the close relationship between the two (art and science), since they lived before the age of standard sections, and were obliged to master personally the principles of stone-cutting before they could design a three-dimensional arch or vault. At the end of the nineteenth century, however, the **introduction of steel construction suddenly divorced the technique of structural design from the realities of structural execution**, as engineers calculated the size of members by formula, and entrusted the work to a new class of operatives, for whom questions of final appearance were irrelevant. Constructional design was no longer a matter of geometry but of arithmetic; no longer a matter of shape but of graphs and equations. Little wonder, then, that **when this same general method was applied to concrete construction in the following decade, it proved powerless to advance the evolution of a concrete architecture, or make any vital contribution in the search for appropriate forms.**”

Collins P., *Concrete, The vision of a new architecture*

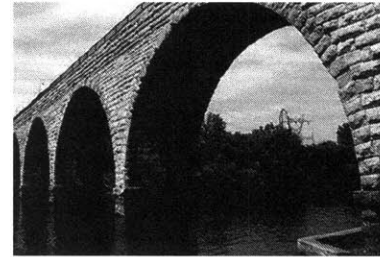


Fig. 4. Roman Arch Bridge.

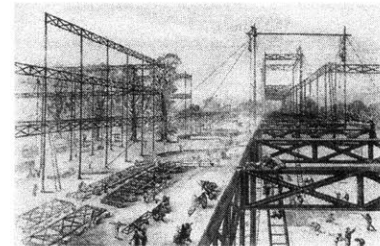


Fig. 5. THE CRYSTAL PALACE 1850.

1836	Uses of concrete described in George Godwin's paper at the Royal Institute of British Architects
1854	System for reinforced concrete patented (Britain) by W.B. Wilkinson
1867	Joseph Monier patents (France) his system of reinforced concrete, exhibits at the Paris Exposition
1873-76	Construction of the Ward House, Port Chester, New York
1875	Residential construction with concrete panels patented (Britain) by W.H.Lascelles
1877	Thaddeus Hyatt published An Account of Some Experiments with Portland Cement Concrete
	Monier patents (France) a method of reinforcing concrete beams
1884	Ernest L. Ransome patents (U.S.) the twisted square bar as the basis of his system
1892	Patents of Francois Hennebique give rise to an international enterprise
1900s	Flat slab construction developed by C.A.P. Turner and Robert Maillart
	Introduction of construction using precast structural elements
	German, French, and British regulations published for design of reinforced concrete structures
1903	Ingalls Building, Cincinnati, Ohio, the first skyscraper of reinforced concrete
	August Perret's apartment building at 25 Rue Franklin, Paris
1903-06	Housing built in Liverpool using John Brodie's system of precast panels
1910s	"Unit systems" of precast concrete construction introduced by Ernest L. Ransome and John E. Conzelman.
1918	Duff Abrams publishes results of his test on the water-cement ratio in concrete
1922	Z-D thin-shell dome constructed in Germany for use as a planetarium

Fig. 6. History of Reinforced Concrete from Elliott C., Technics and Architecture

Concrete was used early in the field of civil engineering near the water. Large concrete blocks were manufactured to construct ports in Algeria and Marseille and bridges in Europe. Image of the material as an artificial stone was strong in architectural applications as well, where even concrete cast on-site were designed to look like traditional masonry construction.

Technological development was lead by construction companies, who rapidly grew in scale, due to patents of building systems and advertisement. Such buildings systems were combinations of beams, columns, and floor panels, which were used to construct fire-proof frame buildings, mostly industrial. Therefore, concrete as a material was evaluated first for its fire-proofing quality but the application of it was through building systems, again lacking in design and image of a new material.

“Fireproofness is a cardinal necessity of the modern factory building.”
 Kahn, M., *The Design and Construction of Industrial Buildings*

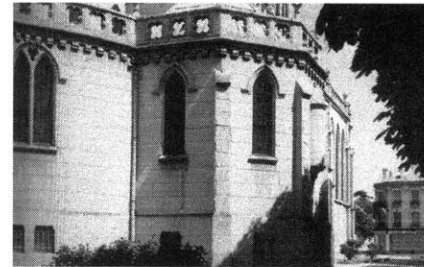


Fig. 7. PARISH CHURCH, 1864
 Contractor: Francois Coignet

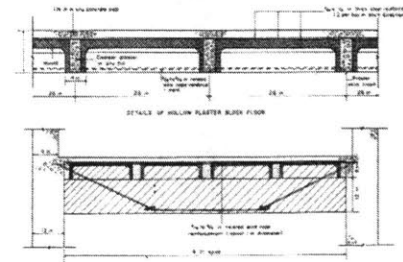


Fig. 8. WILKINSON FLOOR SYSTEM
 Cecil Elliot (Structural Concrete, July-August 1965.)

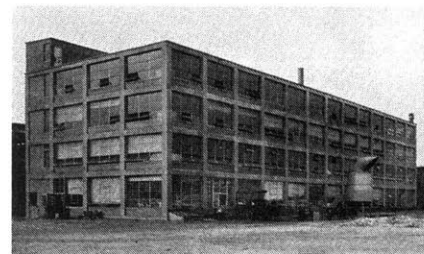


Fig. 9. Typical Industrial Building
 Engineering shop of the Burroughs Adding Machine Co., Detroit

FORMWORK INNOVATION AND CONCRETE CONSTRUCTION

This is a precedent study of innovative concrete structures. Most of the projects listed are designed by engineers or architects working closely with them. It is clear how the creative use of formwork and understanding of construction method is closely related to innovation in concrete structures.

Fig. 10. SALGINATOBEL BRIDGE Robert Maillart
1930



Fig. 11.
Formwork/Scaffolding designed to hold only the weight of the arch. Once set, arch became the working ground for the structure above.



Robert Maillart

Swiss engineer, Robert Maillart, pushed the envelope of concrete structure with his designs of efficient bridges. He was commissioned many projects because it was the cheapest design, mostly due to efficiency in the use of concrete. Salginatobel Bridge constructed in 1930 is unique in the planning of its formwork. It was designed to only withstand the weight of the arch. Once the arch cured, it became the new working ground for the construction above, and the formwork was completely removed.

Felix Candela

Hyperbolic Paraboloid (HP) shells are curved surfaces which can be generated only using straight members. Architect, structural engineer and contractor Felix Candela was a master of such shell structures made with concrete. Due to the nature of the form, the formwork for HP shells were made by stacking straight wood members. Excess water was able to seep out from the gaps between the formwork, resulting in a stronger surface.

Eugène Freyssinet

French builder Eugène Freyssinet was first to use sliding formworks for efficient construction of large concrete structures. Hangers of Orly was constructed in small sections using formwork that slides as the concrete sets. The undulation of the ribs are designed so the formwork can easily be removed. The Plougastel Bridge was constructed using floating formwork.

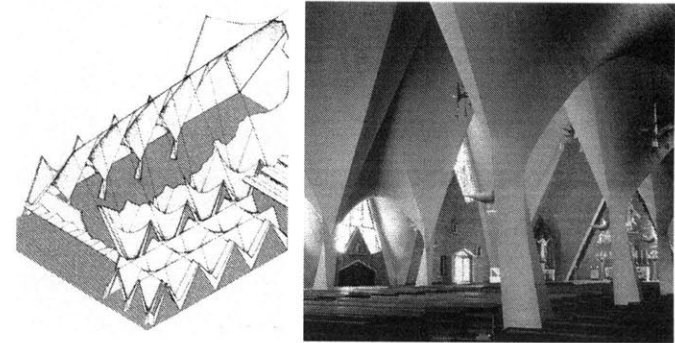


Fig. 12. CHURCH IGLESIA DE LA VIRGEN .
Made with a combination of 80 HP shells

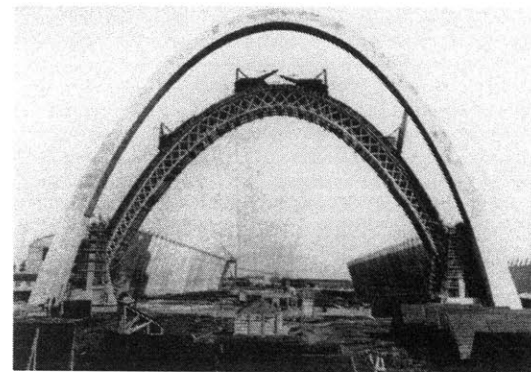


Fig. 13. ORLY HANGAR 1916.
Limousin and Company (Freyssinet Technique.)
Giedion

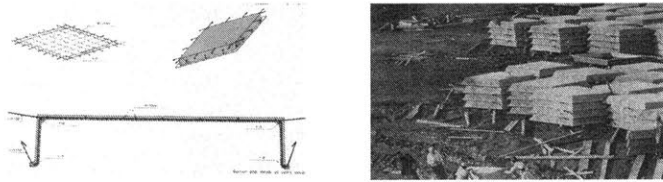


Fig. 14. Ferro Cemento Pieces.

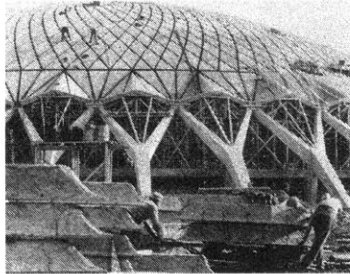


Fig. 15. PALAZZETO DELLO SPORT.
Rome, 1957.

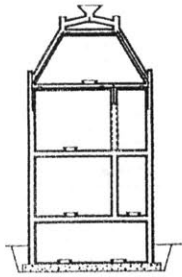


Fig. 16. Formwork Of An Entire House.

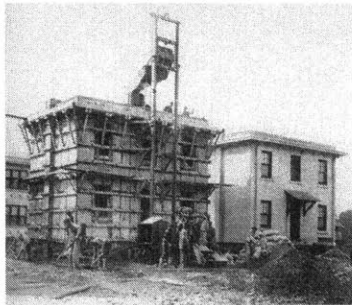


Fig. 17. MONOLITHIC HOUSE,
Manning & Macneille
Inventor:
Thomas Edison, 1906

Pier Luigi Nervi

Italian engineer Pier Luigi Nervi used ferro cemento (thick concrete plastered over steel mesh) to build large complex structures with very little material. Individual ferro cemento pieces are the formwork but become part of the structure once the concrete is poured. At a time when labor was cheap and material was precious, this process proved very successful and produced in complex concrete structures.

Thomas Edison

Inventor Thomas Edison owned a cement manufacturing plant; in order to sell more cement, he developed casting methods for mass produced housing. The idea was to construct the formwork for the entire out of steel and cast as one piece. Although it proved to be too complicated, a few houses were made using this method.

“The form-work consisted of 2,600 metal castings of a size and weight convenient for handling, and was held together by 10,000 nuts and bolts. It took eight days to erect and two days to dismantle.”

Peter Collins, *Concrete, The Vision of a New Architecture*

FORMWORK DEVELOPMENT IN JAPAN

Concrete technology was mostly imported to Japan from Europe and the United States. Thanks to frequent earthquakes and a long tradition of wood carpentry, concrete adapted very quickly to the Japanese building industry. Today, Japan is one of the leading countries in formwork innovation, largely due to its wide application of concrete.

“In Japan, it is customary to make a building one integrated mass of reinforced concrete for reasons of seismic design..”

Utida Yoshitaka, *The Construction and Culture of Architecture Today*

“Few Japanese realize that Japan is able to adopt a method of construction that is unique to this country only because a tradition of wooden architecture has produced so many carpenters.”

Utida Yoshitaka, *The Construction and Culture of Architecture Today*




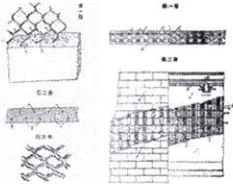


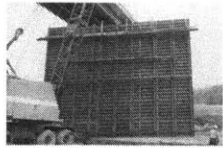
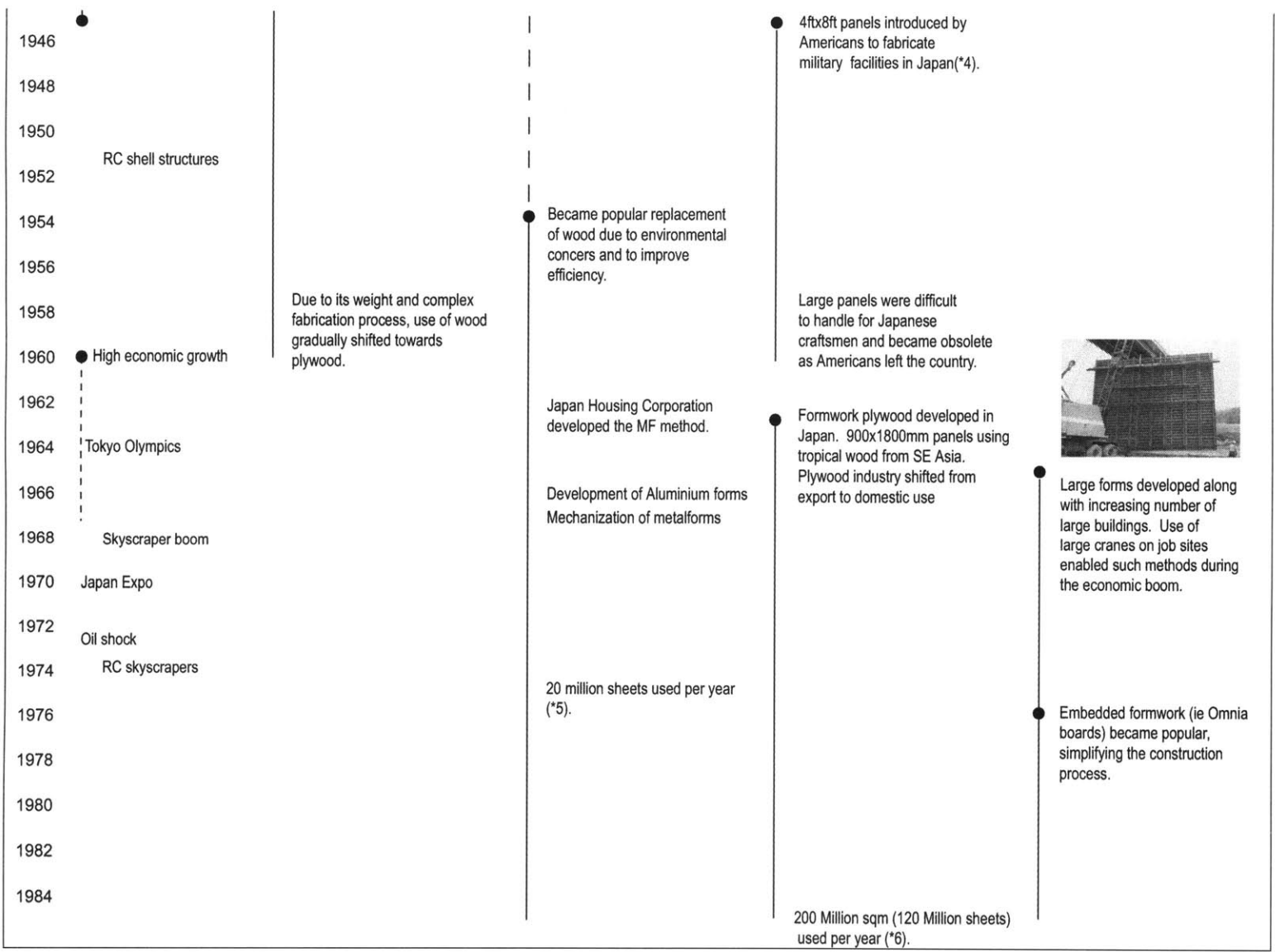
Fig. 18. 1923 KANTO EARTHQUAKE



Fig. 19. Traditional Wood Carpenters

History of Formwork in Japan

Historical Events		Wood Panels	Metal Forms	Plywood	Others
1896	Reinforced Concrete construction introduced to Japan. Importing patents from Europe				
1914		<p>Kojima Yasaburo of Shimizu Group introduced Kamachi(interlocking frame) panel formwork. Used in 1917 for construction of Fuji Kawara Factory (*1).</p> <p>There are records of using wood for formwork on earlier building(*2) but Kamachiformwork is considered the first system.</p>	<p>Metalforms were used for construction of a cement factory in 1912(*7).</p>	<p>Plywood import began after the earthquake. (not used for formwork yet)</p>	<p>Fireproofing wood buildings were the first priority in urban environment. Applying concrete over metal mesh (left) and use of concrete blocks (right) was both appreciated for having to use no formwork (*3).</p> <p>Sliding form used to construct a silo in occupied China.</p>
1916					
1918					
1920	Brick used for formwork				
1922	Kanto Earthquake destroys Tokyo				
1924					
1926					
1928	World Depression				
1930					
1932					
1934					
1936					
1938					
1940	WWII				
1942					
1944					



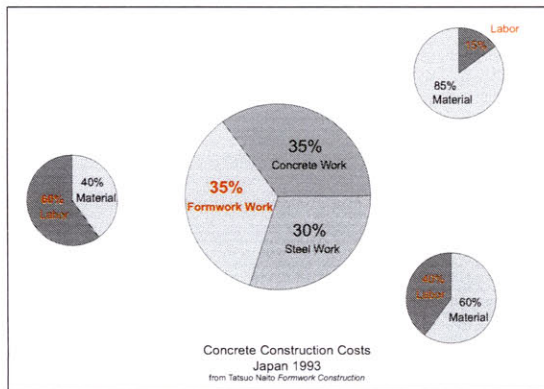


Fig. 20. Concrete Construction Costs

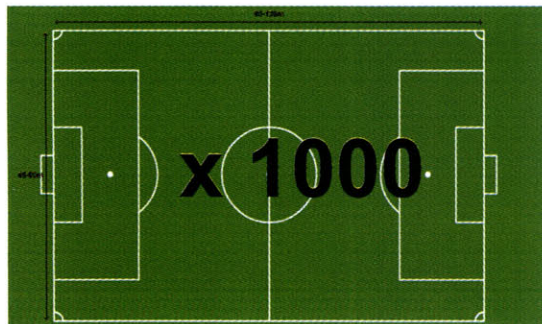


Fig. 22. Wood Formwork = 7million sqm per year (1998).
Kenchiku Gijutsu 99.11

Formwork Data

“Since formwork generally is temporary installation, it may be that little attention is given to the formwork specification – even though it has a vital bearing on cost and quality of the concrete.”

Snow F., *Formwork for modern structures*

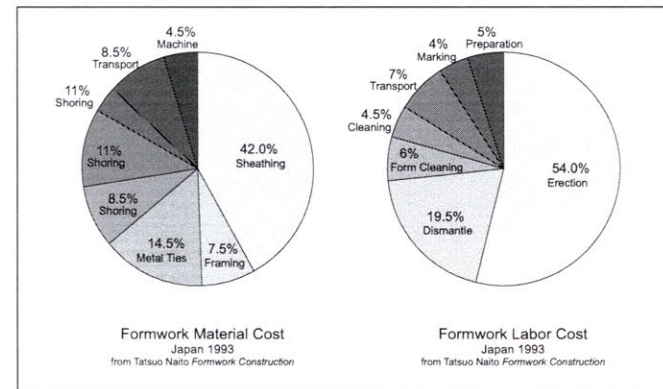


Fig. 21. Formwork Costs

One third of the cost of concrete construction in Japan is related to formwork, of which 60% is labor and 40% material. Out of the three major components of concrete construction, formwork costs have the largest percentage of labor. It is clear from this that more designing efficient formworks will help reduce costs of concrete construction.

Formwork plywood was blamed for the destruction of the tropical rainforests of Lauan, from where most of the wood is imported. The increase in environmental concerns has led to the development of other materials uses in formwork, such as conifer, sheet steel, and plastic.

Current Formwork Research and Future Direction

There has been a lack of long-term vision in improving formwork. Until now, its development was simply a short-term answer to the economy of the building industry instead of an opportunity to improve the quality of construction, working environment, and construction process. Current research focuses on using recycled material instead of wood as formwork and improving the efficiency of formwork and the casting method.

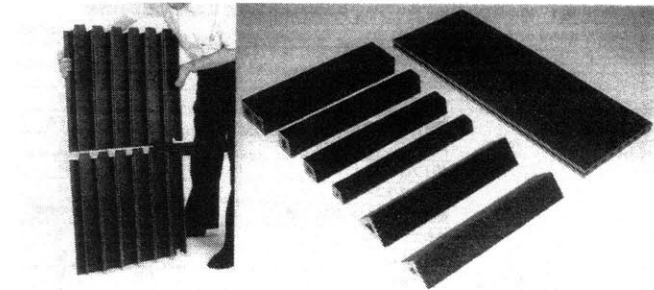


Fig. 23. (Recycled/Recyclable) Plastic Formwork
Kenchiku Gijutsu 99.11

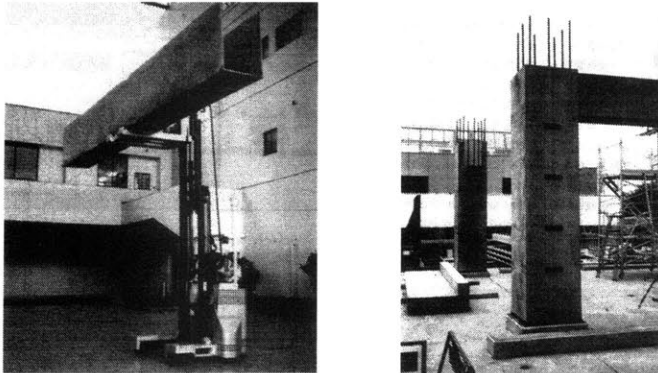


Fig. 24. Embedded Precast Concrete Formwork
Kenchiku Gijutsu 92.08

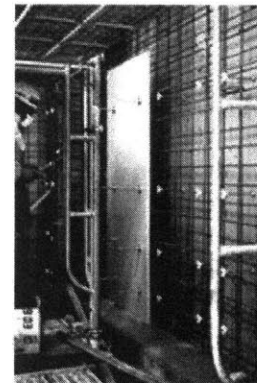


Fig. 25. Insulation Formwork
Kenchiku Gijutsu 99.11

CONCRETE TEXTURE AND FORMWORK

This paper was originally written for

GSD 4355 (Fall 2004)
ARCHITECTURE, SCIENCE, AND TECHNOLOGY:
XVIIIth CENTURY-PRESENT
Prof. Antoine Picon

Introduction

“Regarding the question of materiality, the digital landscape provides numerous new opportunities like the possibilities to design materials, to shape their properties and appearance, instead of using them in a passive manner.” --- A. Picon ¹

These words by A. Picon would still stand even if the term “digital” was replaced by “concrete.” With emergence of reinforced concrete all but digital technology nearly a decade ago, architects had similar opportunities of designing material used in their architecture. Unlike traditional materials such as stone, brick or even materials like steel, architects with reinforced concrete were able to specify the texture of the material and generate forms less regulated by standardization and force of gravity. Yet, similar to hesitant reactions towards digital architecture today, many architects were then hesitant towards new expression of concrete even when while benefiting from the structural and economical properties. As mentioned by Banham in *A Concrete Atlantis*, reinforced concrete (RC) buildings developed in Europe, mainly in France were brought to America’s industrial society and re-imported back to Europe, its design possibilities later to be revealed. There have been many studies on the structural contributions and effects of RC on architecture. But as symbolically expressed in *Villa Savoye* (1931), a building with a surface of concrete painted white, where Le Corbusier used RC to realize his five principles of architecture, there seems to be a history of materiality of concrete which has a different time flow than that of structural history. Looking at the history of concrete texture, especially the form-work, may give us

clues as to how architects struggled and developed a new materiality with new material.

With advancement in digital technology and materials, the design process of the architect is being questioned in search for new architecture. Gradually, architects are freeing themselves from standardized materials and new possibilities for the use of concrete are expanding. Therefore, paradoxical as it may seem, it is important at this point to learn from the struggles and mistakes from the past when the material first developed and came into use.

Technological background of reinforce concrete – starting from history of form-work.

There are many studies on concrete architecture, yet very few focus or even mention the tectonic behind the materiality of the concrete used. Many references introduce different results and basic principles to achieve acceptable quality of concrete, yet unlike the detail drawings of famous projects, they stop short of going into any kind of detail. The reasons for this may be that it is a secret recipe which required great investment of time and money of the architect and the engineer. Or it may simply be beyond the knowledge of the architect, who is mostly interested in the final result and not the process of which it went through. Or the qualitative aspect which is not expressed in abstract representation of the architect may have lead to the difficulty of documenting the process.

According to Peter Collins in *Concrete* published in 1959, there is an out cry of separation between design and engineering.² His theory on the inability of architects to produce new forms unique to concrete is condensed in the paragraph below:

“At the end of the nineteenth century, however, the introduction of steel construction suddenly divorced the technique of structural design from the realities of structural execution, as engineers calculated the size of members by formula,

and entrusted the work to a new class of operatives, for whom questions of final appearance were irrelevant. Constructional design was no longer a matter of geometry but of arithmetic; no longer a matter of shape but of graphs and equations. Little wonder, then, that when this same general method was applied to concrete construction in the following decade, it proved powerless to advance the evolution of a concrete architecture, or make any vital contribution in the search for appropriate forms.”³

A similar argument could be made for the texture of concrete as well. It is no accident that many of the early RC buildings, expressing the bare texture of concrete, was a result of collaboration between an architect and an engineer (Le Corbusier with his cousin Jeanneret, Louis Kahn with August Kommendant, Tange Kenzo with Yoshikatsu Tsuboi) or challenging architects who had strong engineering background (Auguste Perret, Felix Candela). Similar to the slow achievement or complete lack of new forms, new materiality did not develop until few decades after. A study of the tectonic behind the color and texture of concrete surface reveals its complexity of the special knowledge and experience necessary in working with this material.

Three Factors of Concrete Texture: Form-work, Mixture, Finish

There are three main factors which decide the texture and color of the concrete surface: form-work, concrete mixture, and finish, all of which are related to each other. Form-work leaves imprints on the surface of the concrete, allowing designers to actually “form” the surface in detail. Mixture component is responsible for the color and tone, giving impressions of hard or soft concrete. After the form-work is removed, concrete surface can be manipulated similarly to stone, and the minimal treatment necessary is to apply a protec-

tive layer to prevent water penetration and weathering.⁴ They are all inter-related and all require quality of craftsmanship constrained by budget and culture.

The necessity of form-work to create form and texture is what makes concrete unique compared to other modern materials. Due to its labor intensive process, the cost of form-work range between 20% and 75% of the total cost of the structure.⁵ Besides cost, other criteria to be concerned are the structure of the form-work which must withstand irregular loads of concrete and men while pouring concrete. Here, the main focus will be on the texture of the concrete created by the shutter (the surface material) of the form-work.

It is known from the imprints left on the surface that wood form-work was used by the Romans to temporary support the concrete mixture.⁶ One of the early known form-works was used to form pisé, a primitive type of concrete similar to mud, used in Europe in the late 18th century.⁷ It consisted of tongued and grooved timber boards held in place between vertical timber posts which are almost identical to what is still used today. Similar timber form-work was used, even as the mixture developed into beton and eventually concrete. Joseph Tall, an English building contractor developed a system in 1864 similar to the one described above, trying to cut cost of concrete construction by standardizing the form-work and reusing it multiple times.⁸ The types of timber and surface treatment are unknown, but concrete texture at the time was fairly rough and full of faults by today's standards. The raw surface was usually covered by an additional layer of concrete or by other materials such as brick or tile. The form-work was occasionally designed so that the imprints left would resemble traditional tiles or brick. However, the idea of improving the form-work for its texture was not a major concern at this point. Besides timber, metal form-work was first suggested around the same period by one of Tall's employees.⁹

Typical materials used for shutters today are timber, plywood, metal, and glass fiber.¹⁰ Metal and glass fiber, due to its initial high costs, are only used when high quanti-

ties of the same shape are guaranteed. Metal also tends to leave release agent faults on the surface, as well as any rust if not cleaned thoroughly.¹¹ Timber was used mostly before the development of external grade plywood and in cases where the texture of the wood was desired. Plywood is most commonly used today and is where most of the technological advancement has occurred.

According to the American Plywood Association (APA), plywood became an industrialized material in the early 20th century but fully waterproof adhesive, necessary for external grade plywood, was not developed until the 1930s.¹² Wood used as the shutter must have a layer of releasing agent which does not interfere with either the component of the concrete mixture or the desired texture of the shutter. To obtain a highly smooth surface of concrete, which is desired by many architects today, a layer of silicone or plastic coating is applied to the surface of the plywood. One of the paradoxes in this is that “crazing” (small cracks created by expansion on the surface of concrete wall) occurs more often and are more visible when the surface finish is smoother.¹³ Therefore, the mixture component and the final finish process must be carefully chosen to work with the form-work. Bare concrete, due to its character to leave imprints, expresses the process of making that architects have been using this as part of their design. The industrial standard dimensions of the plywood are revealed by the groove left by the joints of the boards. Tie cones, or traces of the rods to hold the form-work from separating while pouring the concrete, are left intentionally to express the tectonic behind the form-work.¹⁴

Timber form-work is used to express the rough texture of wood and/or the linear directional character of the combined boards. Linear members are beneficial when creating complex curved surfaces. This was especially effective in forming hyperbolic paraboloid (HP) shell structures where the entire curved surface can be constructed using only linear members.¹⁵ The technical difficulty lies in understanding the material properties of the wood. Wood with high sugar content, such as cedar and birch, interfere with

the chemical reaction of cement and water, and special care is necessary in coating the surface.¹⁶ Controlling the humidity of the boards is critical in keeping the boards from deforming, due to moisture in the concrete mixture. Also, controlling the amount of water seeping through the joints is important in achieving the desired texture. Some woods actually absorb the air in the concrete, helping prevent air holes to remain on the surface. Compared to the smooth finish of the plywood, timber leaves a rough texture; this actually helps prevent stains, blotches and “crazing”.

Other methods of designing the texture of concrete are more decorative and ornamental. Embedding other materials such as polystyrene (foam blocks) on the surface of the form-work will produce deeper patterns.¹⁷ Aggregate transfer is a method in which the aggregate designed to be exposed on the surface of the concrete is embedded in the form-work and actually transferred on to the concrete. In the early stages of development, pre-cast concrete panels or brick/tiles were used as form-work, similarly to the process of aggregate transfer. One must question at this point the difference between texture and decoration or ornament, yet from understanding the entire process of forming concrete, the “truthfulness”¹⁸ of texture itself needs to be brought up. This will be discussed further in the finishing process of concrete.

Mixture component determines the color and tone of the concrete. In the late 19th century during the development stage of the material, surfaces of cast concrete were hardly exposed. They were covered in thin layers of mortar or plaster, painted, or covered by tiles and brick. The color of concrete was considered to be “ugly”¹⁹ and the preferred texture of traditional architecture in Europe gave designers and clients easy excuse from investigating new aesthetic. As mentioned earlier, the quality of concrete at the time was poor with air holes and irregularities. Even among professionals who were critical of imitating another material in concrete, the main discussion was ‘what kind of covering is consistent

with the honest expression of the material beneath.’²⁰ John Ruskin, who was the center of such discussion in England ‘encouraged architects to deprive concrete of any structural character in might possess, and treat it as a core for more seemly veneers, or a background for coloured designs.’²¹ Therefore, it is no surprise that the first project to expose the bare surface from the form-work was in America (California) by Ernest Ransome in 1891, where new material was brought and developed without constraints or fixed ideals.²²

Concrete is a simple mixture of cement, aggregate and water. Aggregate accounts for about 80% of the mix, thus critical in determining the color of concrete.²³ Color of cement is important especially when the mixture is trowelled to bring the finer particles to the surface of the form-work.²⁴ The difficult point for the architect in specifying the color of concrete is well explained by D. Bennett:

“There is no definition by which the quality and colour tone of the finish can be unequivocally described by specification alone. The same concrete mix poured into different form-work or placed in the same form-work at different temperatures, or retained in the forms for different length of time will result in colour variations. The longer the concrete is cured or left in the forms the darker the surface tone. The lower the water-cement ratio the darker the tone.”²⁵

Furthermore, the workability of the mixture component must be considered according to the complexity of the form and the machinery used. Complexity increases with properties such as water-cement ratio, which not only determines workability of the mixture but directly relates to the strength of the material.

As bare concrete surfaces gives an unfinished or untreated impression, less focus is on the finish; this is where the biggest misunderstanding between the architect and the contrac-

tor seem to occur. Shoji Hayshi, founder of one of the largest corporate design firms in Japan, mentioned a question he had early in his career about concrete construction, and how the repair fee was always included in the cost estimate even when not specified by the designer.²⁶

Traditionally, concrete structure was something to be covered by another material. Therefore, the wall was built by unskilled labor and skillful craftsmen worked on the treatment of surface after the concrete was cast.²⁷ Even in the project by Ransome mentioned earlier, the surface of the concrete was tooled to expose the aggregate. The necessity to reverse the focus of craftsmanship to achieve quality of surface that does not require additional material on the surface was understood and tested by Sir Arthur Blomfield in late 19th century, but at the time did not become a major movement throughout the profession.²⁸ The bare expression of concrete was developed in American industrial buildings by engineers without architecture education.²⁹ The plain surfaces without any ornament or decoration were considered to reflect the “absolute truthfulness to materials,” and was admired by architects from Europe who later developed the International Style.³⁰ Even so, the expression of bare concrete was considered to be ugly.

The struggle of exposing concrete today still seems to occur due to the context in which the buildings exist. As described earlier, smooth surfaces tend to create minor faults such as crazing. Even in rough surfaces, minor faults such as air holes is almost unavoidable. In the urban context, such faults, if not repaired, are exaggerated by minor particles in the air and are in contrast of other smooth surfaces which never seem to weather. For in situ concrete the only option is to repair as much as possible and coat with a transparent protective layer. Basic repairing process is to fill in any faults with mortar, trying to match the existing color and tone. When the surface has specific imprints from the shutting, one must match the pattern sometimes going as far as drawing the grains of the wood by hand.³¹ One way designers and contractors have avoided this problem is to treat the entire

surface after the form-work is removed. Most commonly used processes are washing, acid-etching, and sand-blasting, which are all ways to remove the surface layer of concrete to expose the aggregate.³²

Another step all bare surfaces go through is application of protective layer. For long life of concrete, it must be protected from the rain (acid in the water neutralizes the concrete) and pollution. The complexity lies in the selection and application of the material as it can drastically change the texture and color of the surface. Clear acrylic is a popular material that is preferred for its subtle finish. However it enhances the repaired areas.³³ Finishing material and process require a high level of knowledge and experience.

Considering this finish process of site in situ concrete, one must question the underlying principle for the selection of the material. In some cases, the repair of texture and the color control of the concrete can be perceived as a type of decoration or ornament, dispersed along the entire surface. Collins makes a distinction between successful and unsuccessful use of concrete by focusing on the process of building the form-work. The form-work must be made from architectural drawings just like a piece of furniture and cannot be a negative of some object already existing in other materials.³⁴ In adapting such theory to the aspect of finish and repair work, the only repairs acceptable should be on true accidents which were unexpected, even with deep understanding and the limitations of the material. Repair to cover up faults as result of ignoring the material properties is an addition of decoration without the intent of the designer.

Looking at the three main factors which determine the texture and color of concrete reveals the complexity with-in each factor and the relationships between them. Not only is it difficult to quantify the data but its specificity to weather, location and level of craft makes data inaccurate and meaning less.

If steel was what caused the standardization that lead to the separation of archi-

itects and engineers, concrete was what necessitated such divides to come together. From the history analysis of concrete that focused on texture and color, it is surprising to see how little concrete technology has advanced in the past century. This seems to reflect the gap still existing between the various professions. With the revolutionary advancement of digital technology, this necessity is even stronger and the technology itself is the means in which to help such collaboration. This may call for the time to investigate once again new forms of concrete.

‘Despite the dissociation between architectural representation and tectonics, the true novelty is not a growing gap between design and materiality, but rather their intimate interaction that might eventually challenge the traditional professional identities of the architect or the engineer.’ --- A. Picon³⁵

Notes

¹ Picon A., “Architecture and the Virtual Towards a New materiality,” in A. Reeser (ed.), Praxis Vol 6, New Technologies://New Architectures, New York, Praxis Inc., 2004, p.120.

² Collins P., Concrete The vision of a new architecture, London, Faber and Faber, 1959.

³ Ibid., p. 94.

⁴ Saito Y., Essence of Architecture, Tokyo, A.D.A EDITA Tokyo Co., 2000.

⁵ Snow F., Formwork for modern structures, London, Chapman and Hall Ltd, 1965, p. 1.

⁶ Ibid.

⁷ Collins, Concrete, p. 21.

⁸ Ibid., p. 40.

⁹ Ibid., p. 40.

¹⁰ Snow, Formwork for modern structures, pp. 73-78.

¹¹ Ibid.

¹² APA-American Plywood Association (http://www.apawood.org/level_b.cfm?content=srv_med_new_bkgd_plycen)
“A breakthrough came in 1934 when Dr. James Nevin, a chemist at Harbor Plywood Corporation in Aberdeen, Washington finally developed a fully waterproof adhesive. This technology advancement had the potential to open up significant new markets.”

¹³ Bennett T. P., Architectural Design in Concrete, London, Ernest Benn Limited, 1927, p. 20.

¹⁴ Examples of works by Louis Kahn, explained in:
Frampton K., Studies in tectonic architecture. The Poetics of construction in nineteenth and twentieth century architecture, Cambridge, Massachusetts, The M.I.T. Press, 1995, p. 242.

¹⁵ Saito Y., Essence of Architecture, pp. 86-87.

¹⁶ Ibid., p. 91.

¹⁷ Snow, Formwork for modern structures, p. 76.

¹⁸ Slaton A., Reinforced Concrete and the Modernization of American Building, 1900-1930, Baltimore, The Johns Hopkins University Press, 2001, p. 175.

¹⁹ Collins, Concrete, p. 30.

²⁰ Ibid., p. 100.

²¹ Ibid., p.101.

²² Ibid., p. 62.

²³ Fröhlich B. (ed.), Concrete Architecture Design and construction, Basel, Birkhäuser, 2002, p. 9.

²⁴ Bennett T. P., Architectural Design in Concrete, p. 20.

- ²⁵ Bennett D., *Exploring Concrete Architecture Tone Texture Form*, Basel, Birkhäuser, 2001, p. 8.
- ²⁶ Sakaushi T., “Practicing Concrete Waterproofing and repairing of concrete,” in Y. Futagawa, *GA Material Space 01*, Tokyo, A.D.A EDITA Tokyo Co., 2000, p. 131.
- ²⁷ Collins, *Concrete*, p. 105.
- ²⁸ Ibid.
- ²⁹ Slaton A., *Reinforced Concrete and the Modernization of American Building*, p. 169.
- ³⁰ Ibid., p. 175.
- ³¹ Sakaushi T., “Practicing Concrete Waterproofing and repairing of concrete,” p. 132.
- ³² Fröhlich B. (ed.), *Concrete Architecture Design and construction*, pp. 60-61.
- ³³ Sakaushi T., “Practicing Concrete Waterproofing and repairing of concrete,” p. 132.
- ³⁴ Collins, *Concrete*, p. 148.
‘The nature of concrete is derived from the nature of the formwork, and it is in the making of the form-work that the craftsmanship must mainly reside. If the form-work is produced merely by pouring plaster of Paris on to a carefully prepared model in clay, then it becomes a mechanical system of reproduction, and not a creative process in itself. If, on the other hand, the form-work is made from plans, sections, and elevations, in the way that a carpenter constructs timber buildings, or a cabinet-maker creates furniture, then that form-work is a work of genuine art even if, like an engraving or an intaglio, it can only achieve fulfillment when transposed on to another medium in reverse.’
- ³⁵ Picon A., “Architecture and the Virtual Towards a New materiality,” p. 120.

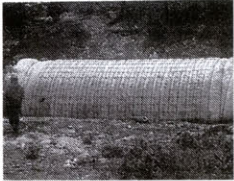

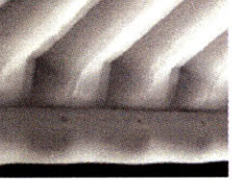
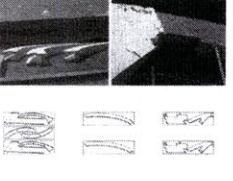


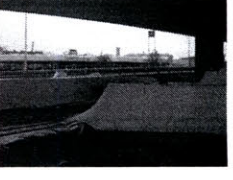
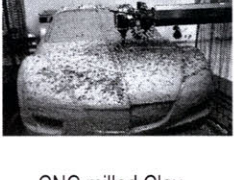


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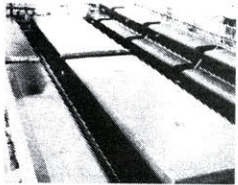
FORMWORK TYPOLOGIES

Formwork typology was conducted by collecting information on various materials used as formwork. Information was gained mainly through concrete-related publications and journals; current practice methods were obtained from construction site visits in Japan—works by Tadao Ando and Toyo Ito. Hands-on experience and detailed information on fabric formwork was gained through working with Professor Mark West in Winnipeg, Canada. Information gathered was analyzed in a matrix, its goal to find areas for further investigation and to consider combining different materials for new means of casting. Knowledge learned from the matrix was tested by conducting small plaster cube casts. More than ten cubes were made to experiment the nature of formwork material under the pressure of the plaster at its liquid state. Also, full-scale experience was gained through working on a research project for a rammed earth wall construction, where its 1:1 scale wooden formwork was manufactured on site. Adjustments on the formwork greatly improved the efficiency of the ramming process and resulted in a more durable wall. Also included, a research paper on concrete formwork focuses on the texture of the concrete and its relationship to formwork.

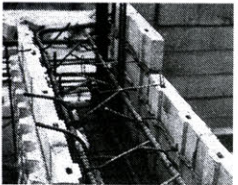
MATRIX

	Air	Dirt	Fabric	Foam (insulation)
Removed Formwork	 <p>Inflatable formwork</p>	 <p>© Paolo Soleri</p>	 <p>© Mark West</p>	 <p>CNC Milled for Belt House © William Messier</p>
Left In Place Formwork		 <p>Foundation</p>	 <p>Geotextile used on river bank</p>	 <p>© Carve</p>
Digital Technology Application And Potentials		 <p>CNC milled Clay</p>		 <p>Digitally controlled hot wire cutter © 3eI</p>
PC Units			 <p>© Mark West</p>	

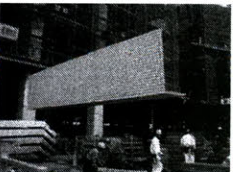
Concrete



Concrete formwork for Precasting

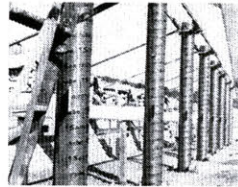


Concrete Panels

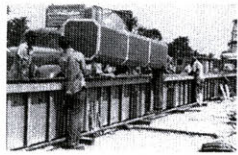


Half PCa System

Paper

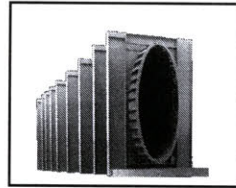


© Sono Tubes



© Surevoid

Steel



© Special Formwork Limited

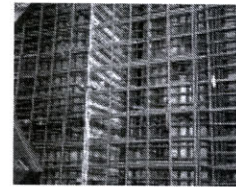


Mikimoto Ginza
© Toyo Ito



Beam Prototype

Steel Mesh

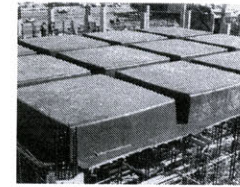


RAS system
©Toho Const.



Ferro cemento by Pier Luigi Nervi

Plastic



Glass Fiber Reinforced Plastic Panels

* Most common material Wood will be explained in the following section.

PRECEDENT STUDY BY MATERIAL

Air / Inflatable Formwork

The advantage of air/inflatable formwork is its light weight and ability to create smooth continuous surfaces. However, due to the complexity in the installing process, it demands experience and special knowledge. Large applications are limited to military purposes.

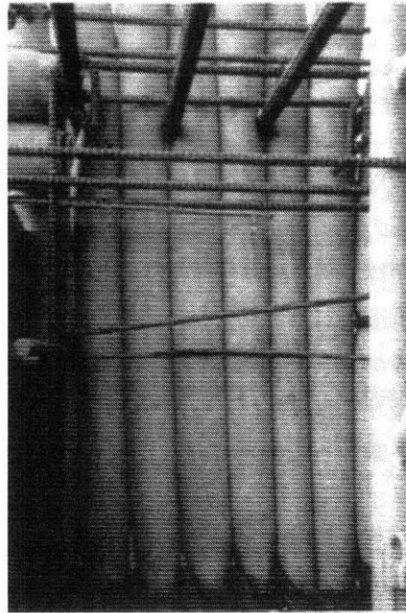


Fig. 26. AIR FENCE.
(Toho Construction)
Air tubes connected to form a temporary wall for casting a segment of a large structure.

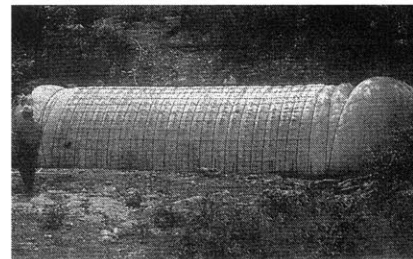


Fig. 27. Vault Construction.
Inflatable formwork was used mainly for military application to create temporary shelters out of concrete.. (formwork book)



Fig. 28. Tube in a Beam.
Shows how air tubes are used to create holes in a beam. (formwork book)

Earth / Dirt Formwork

Using earth as formwork allows one to control the formwork very precisely. It has great potential if used in a very specific manner (i.e. TRD construction mentioned below) and costs very little. However, it can lead to a very labor-intensive process and therefore digital technology can perhaps be introduced for fabrication of formwork.

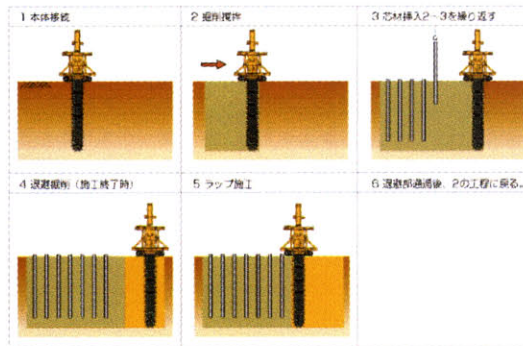
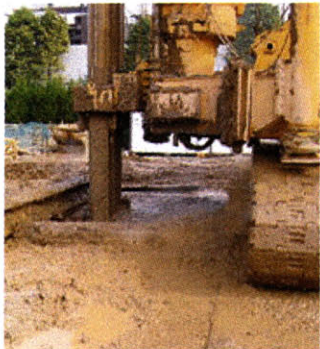


Fig. 30. TRD CONSTRUCTION (RAITO INDUSTRIES)
Construction of a slurry wall using the earth itself as formwork.

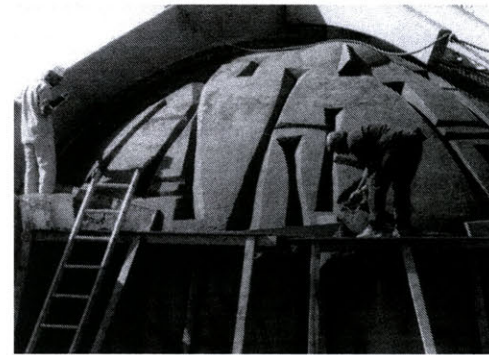


Fig. 29. Casting In Earth.
Work by Paolo Soleri in Arizona.

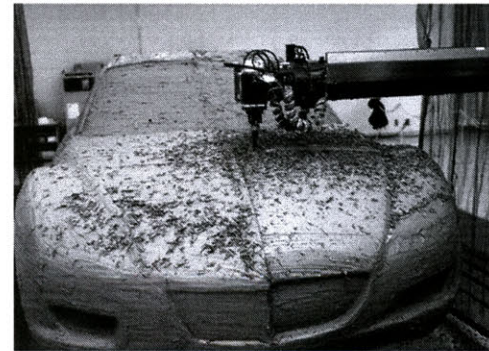


Fig. 31. Clay Model of a Car.
CNC milling machines are used to make clay prototypes of cars.

ADVANTAGES OFFERED BY FLEXIBLE FABRIC FORMWORKS by Mark West

1. The provision of an inexpensive, extremely light weight, and globally available formwork material in place of wood (which is generally hard to find in building economies that rely on reinforced concrete construction).
2. A new and unprecedented level of refinement in the surface finish and texture of cast concrete.
3. The automatic production of stronger and less permeable concrete surfaces.
4. The creation of a new class of highly efficient, complex, yet easily formed structural shapes based on pure tension geometries, and their inversion as pure compression geometries.
5. A new “language” of architectural form, providing a radically different understanding of what reinforced concrete architecture can be like.”

Fabric Formwork

As previously studied by Mark West, fabric has many advantages. There are, however, undeveloped areas of research, especially on on-site construction methods where the availability and reusable properties of the material may benefit the most. Introduction of digital technology (i.e. 3D modeling options) will open new potentials for wider application of this method.

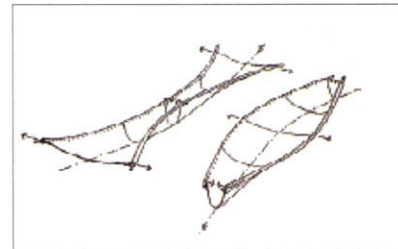


Fig. 32. Form of Fabric.
Efficient forms naturally generated by self-weight of concrete in fabric.

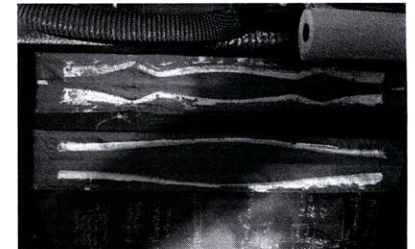


Fig. 33. Plaster Tests.
Fabric used to cast. by Mark West

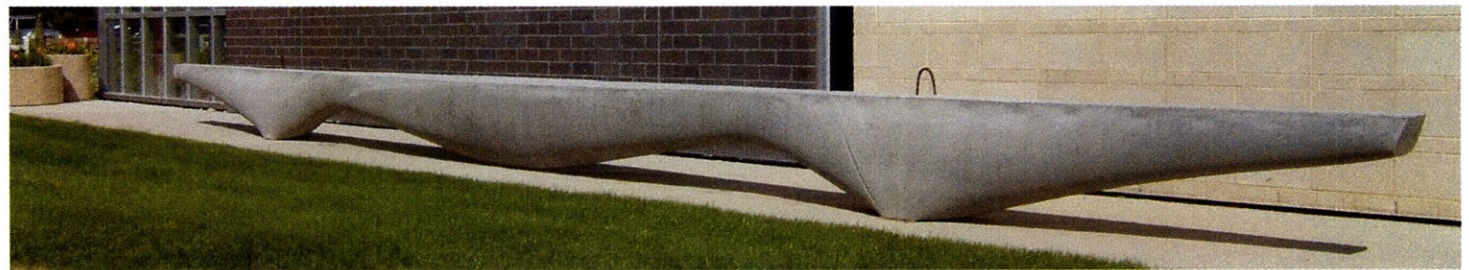


Fig. 34. Full size cast of a concrete beam made by Mark West.

Foam / Insulation Formwork

With the development of the CNC milling machine and other digitally controlled machines, foam has great potential for forming complex shapes, due to its workability. The material may not be durable for numerous casts but is recycled in many cases after its use. The size of the formwork is limited by the size of the sheet stock and the bed and depth of the milling machine.

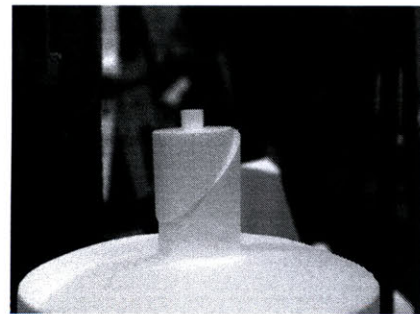


Fig. 36.
Digitally Controlled Hot Wire Cutter.



Fig. 37.
Skate Bowl Construction Using Foam.



Fig. 35.
INSULATION FORMWORK.
Formwork left in place after casting as insulation.

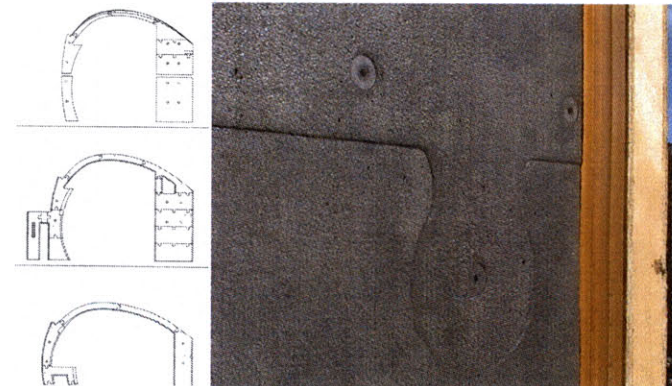


Fig. 38. BIG BELT HOUSE.
CNC milled foam used as formwork. (by William Messier)

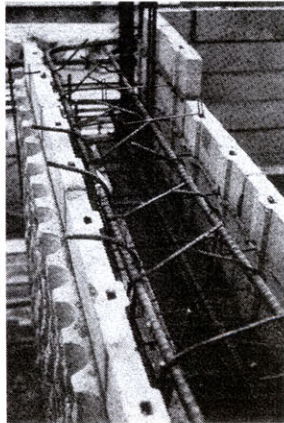


Fig. 39. FORMWORK SETUP.
Flat panels assembled for casting of a wall.

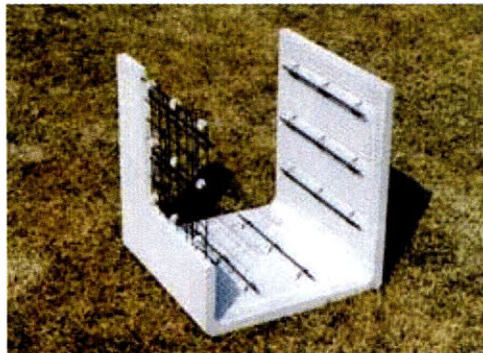


Fig. 40. Mock Up of a Beam Section.
Shows the steel reinforcements already attached to the inside surface of the formwork. (Nishimatsu Construction Co., Ltd.)

Precast Concrete Formwork

With the development of different types of concrete, thin yet durable concrete panels are produced and used as embedded formwork. Highly controlled, lightweight precast units are brought to the site and easily assembled for efficient on site casting. This process requires very little substructure, due to the rigidity of the pre-cast unit; since embedded, removal and surface finish process is not required after the concrete is cured. However, this method is not cost-efficient unless there is multiple use of the same element.

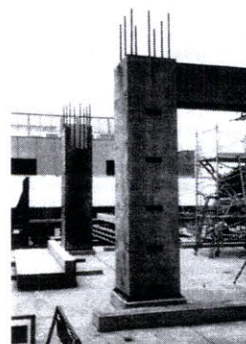
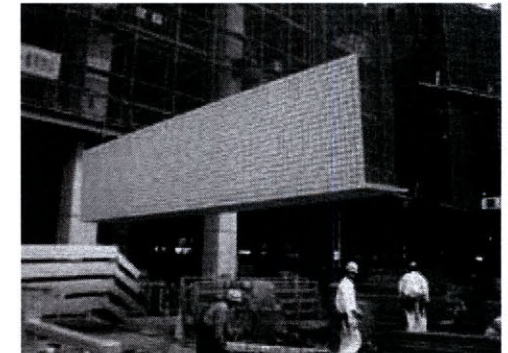


Fig. 41. HALF PCA SYSTEM.
Column and beam formworking using pre-cast formwork. (Nishimatsu Construction Co., Ltd.)



Paper Formwork

Paper has been used as formwork in very specific areas of construction. Tubes (Sono tubes) are widely used for casting circular columns, the formwork either removed or left in place. Compared to wood, it lacks workability (i.e. no use of nails) not allowing to fabricate or make adjustments on site..

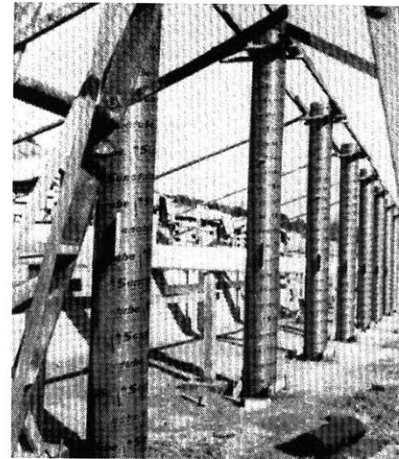


Fig. 42. Paper Tubes.

Paper tubes used for casting cylinder columns.

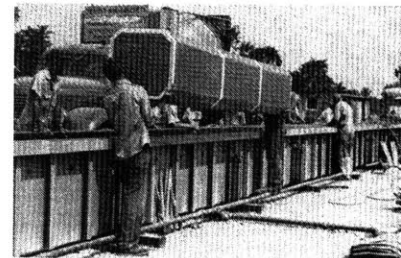
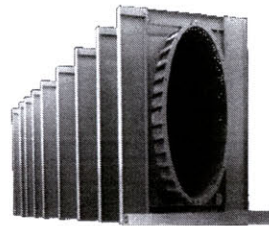


Fig. 43. Paper Box.

Embedded in the center of beam to reduce use of material where structurally is not necessary.

Fig. 44. Steel Formwork for a Column.

© Special Formwork Limited



Steel (Metal) Formwork

Steel has the advantage to be reused many times, therefore often used in making pre-cast elements. Large formworks made of steel are sometimes left in place to act as a tensile member in the composite (concrete and steel). Cost becomes an issue if not used in large quantities. It also requires special tools for erecting on site.



Fig. 45. MIKIMOTO GINZA

Left in place steel formwork © Toyo Ito



Fig. 46. OMNIA DECK PLATE FORMWORK.

© Kajima

Steel Mesh Formwork

Steel mesh can be used as a flexible guide in shaping semi-fluid materials. Ferro Cemento is a famous example where a thick concrete is manually plastered onto the steel mesh. Pier Luigi Nervi used this in the past to create panels, which became the formwork for constructing a dome. Due to its labor-intensive process, it has not developed since then. Steel mesh is used during the casting process to temporarily hold back concrete when built in segments. In this case the mesh is left in place.

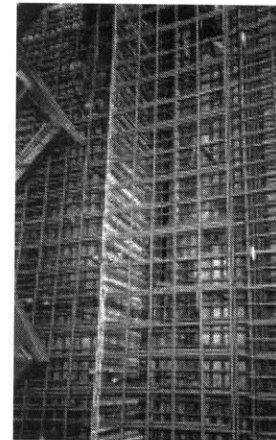


Fig. 47. RAS CONSTRUCTION.

Steel mesh used to temporarily hold back concrete during construction.

TohoKenzai.Co

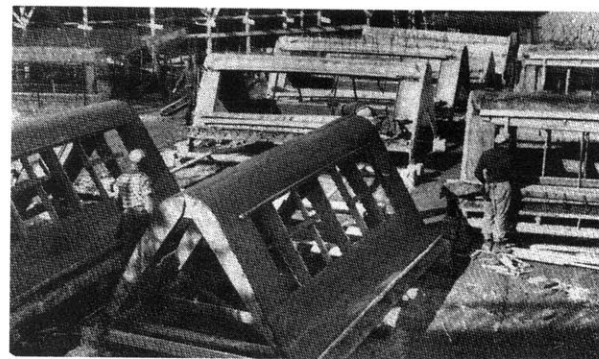


Fig. 48. FERRO CEMENTO UNIT.

Pier Luigi Nervi.

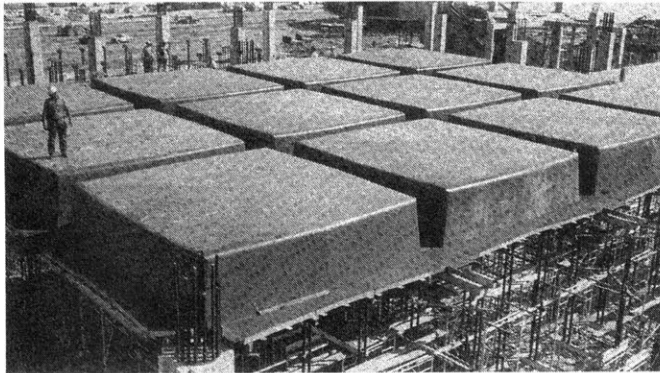


Fig. 49. Image of Slab Construction.

Formwork slides and moves to the next section once the concrete above is set.

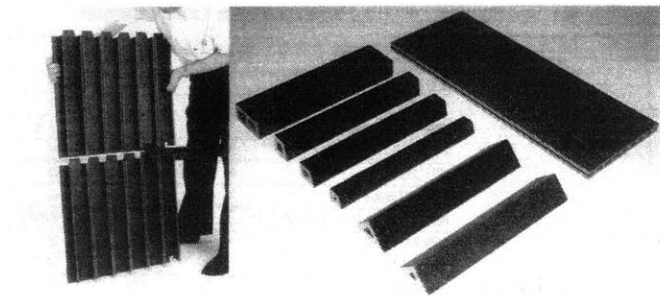


Fig. 50. RECYCLED PLASTIC.

Plastic Formwork

Plastic is considered as a material to replace wood as formwork. It has similar properties as wood but is more durable. When semi-transparent plastic is used, the worker is able to check whether the concrete fully filled all the gaps within the form. For environmental reasons, companies are developing ways to use recycled plastic for formwork.

Wood Formwork

Wood/plywood is the most popular material used for formwork. In most cases wood is covered with waterproof coating for longer life span and for smoother texture of the concrete surface. For environmental reasons, contractors are looking for alternative materials to replace wood or extending the life cycle of one panel.



Fig. 52. I PROJECT.

Flat panels assembled to create a complex surface.
Toyo Ito.



Fig. 51. WALL FORMWORK.

of project by Tadao Ando.

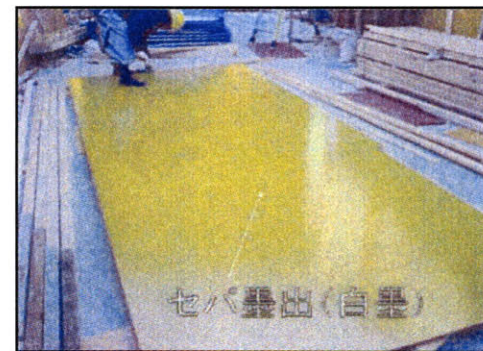


Fig. 53. One Unit of Wood Panel.

Special handling is required for Tadao Ando's
concrete formworks.

CUBE EXERCISE

Cube exercise was a material investigation, using various materials and combinations as material for forming plaster cubes. The main purpose was to understand the nature of the formwork material under the pressure of plaster at its liquid state. Some unexpected results opened possibilities for further investigation.

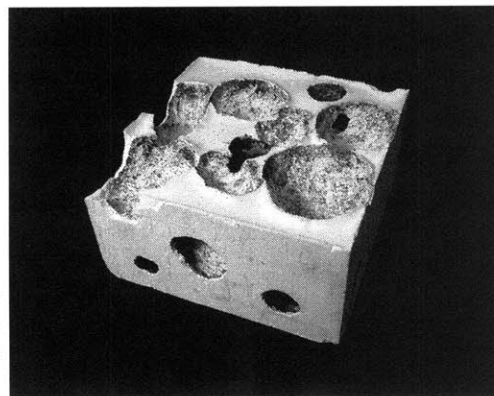


Fig. 54.
Plaster Model
Made Using
Sand.
Small Voids created by the sand are connected to each other.

Sand

Depending on the moisture content or temperature, sand can become a solid or a granular powder. This property was tested by making small balls out of sand and cast between them. No matter how complex the shape, sand can be removed if there is a small opening for access.



Fig. 55. Process Images

Fabric

Multiple layers of fabric were stacked and sewn together to create an enclosed envelope. They were connected by puncturing holes in the fabric where the plaster was poured after the fabric was delaminated as much as possible. Any loose ends or fabric with slack sagged under the pressure of plaster.

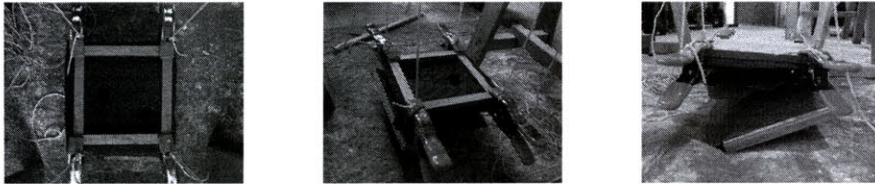


Fig. 56. Process Images

Fabric + Sand

While working with Mark West in Winnipeg, sand was added to the outside cavity of fabric formwork in attempt to gain better control over the final shape. Result was a new, softer texture of plaster free from the pressure of its own weight.

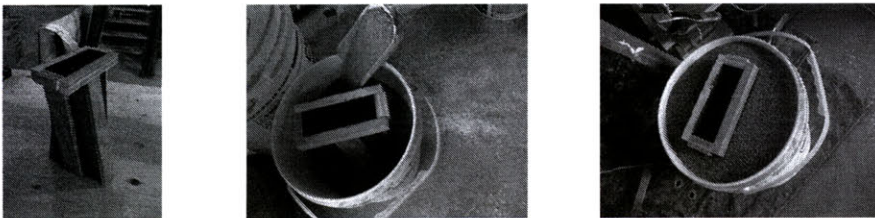


Fig. 58. Process Images



Fig. 57. Plaster Model.

Three envelopes connected internally.

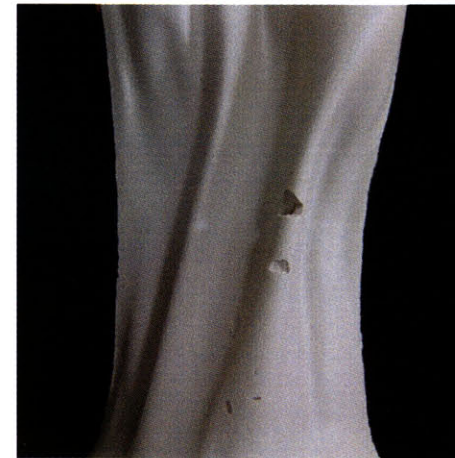


Fig. 59. Detail of Plaster Model

Soft, relaxed texture of plaster.

Fig. 60. Plaster Model

Three pieces which interlock to each other are created in one cast.

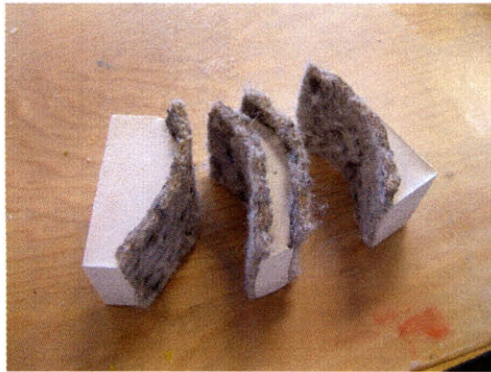
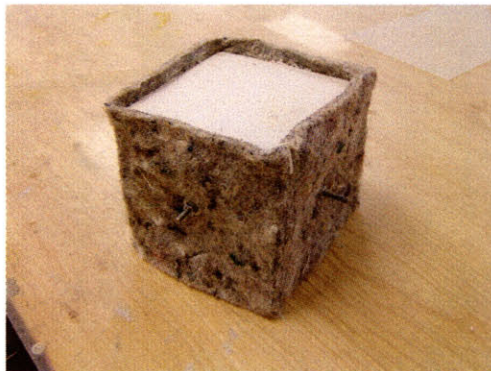


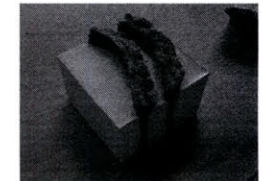
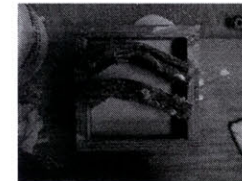
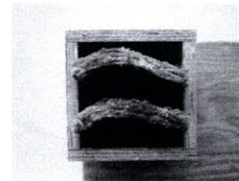
Fig. 62. Plaster Model.



Felt (Layered)

Small fibers of the felt were weaved into the plaster when used as formwork making a very strong connection. Two layers of felt (each layer composed of two sheets of felt) were used to make three individual plaster casts which fit perfectly into each other.

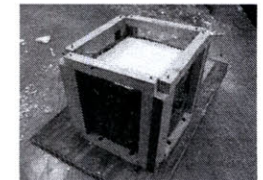
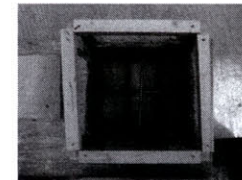
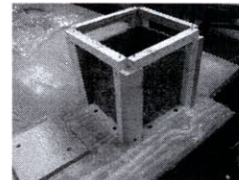
Fig. 61. Process Images



Felt (Stretched)

Felt cube was made by stretching on the corners. Steel rods were added to keep the center of the felt from bulging out under the pressure of the plaster.

Fig. 63. Process Images



Air Packing

Cube was made using air packing sheets held up by four corners. When plaster was poured, the air shifted towards the top of the packing sheet where there was less pressure from the plaster.

Fig. 64. Process Images

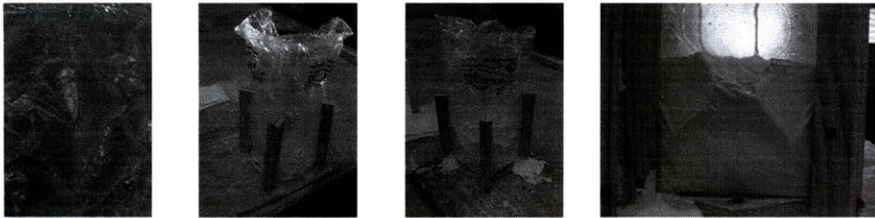


Fig. 65.
Plaster
Model.

Ballons

Ballons (inflatable tubes) were used to create cavities within concrete slabs and beams. The cube on the right was created by first making a cube with one large balloon cavity in the middle. Six balloons were used to fill the six circular openings, and plaster was poured in the extra cavity. In theory, this process can keep on repeating itself, with smaller balloons as the scale becomes smaller.

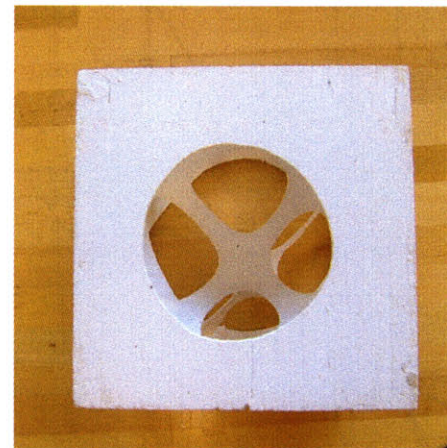
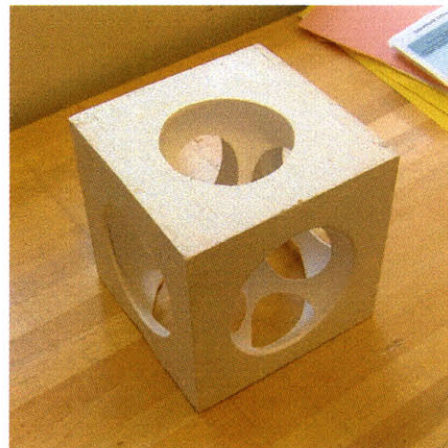


Fig. 66.
Plaster
Model.

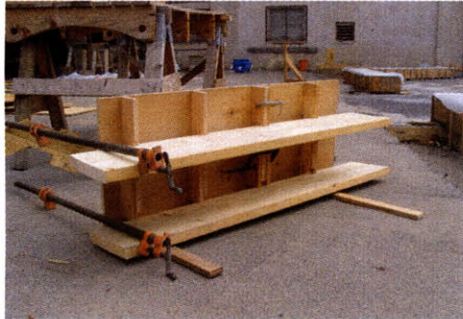


Fig. 67. Formwork 1 Mock-up
Horizontal support members are held together by pipe clamps, which go through the wall..



Fig. 68. Actual Setup of Formwork 1.



Fig. 69. Construction Image.
Horizontal support is used as footing for the workers.

RAMMED EARTH FORMWORK

Involvement in Rammed Earth N51 (Project Leader: Joe Damon) was a full-scale hands-on experience of formwork construction. Formwork for a rammed earth wall (18" thick, 6' high) was made out of 3/4" plywood for sheathing a, 2x4s, 2x8s, and pipe clamps for structural support. Two types of formwork were tested. Formwork 1 (images on the left) uses the 2x8 supporting beams in the horizontal direction, resulting in pipe clamps penetrating through the wall. This necessitated drilling holes in the plywood sheathing, which was problematic for multiple reuse of the material. Furthermore, pipe clamps interrupted the ramming process and areas directly below were relatively unpacked compared to other areas. One advantage of this system was that workers were able to use the beams as footing during construction.

Formwork 2 (images on the right) rotated the entire configuration 90 degrees to avoid pipe clamps penetrating through the wall. Vertically placed 2x8 supports were fixed below and above the wall. This improved the efficiency of the ramming process and resulted in an evenly packed wall.



Fig. 73. Inside of Formwork 2. Space is free of pipe clamps.



Fig. 70. Image of Formwork 2.
2x8 supports are placed vertically and fixed at top and bottom of the wall.



Fig. 71. Image of Formwork 2.



Fig. 72. Image of The Wall.
Made using formwork 1.

FORMWORK DESIGN

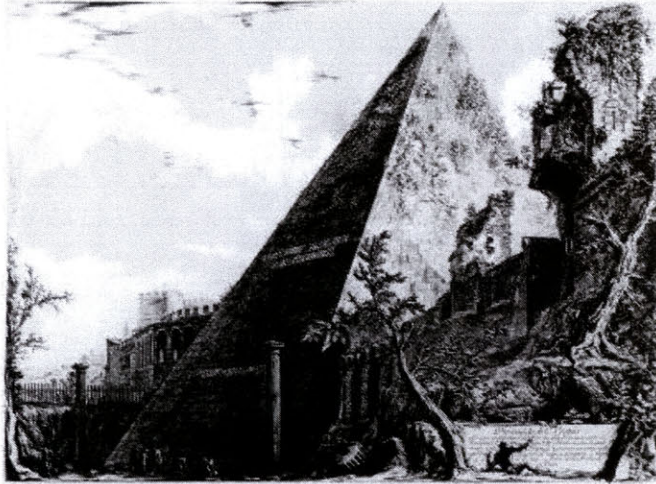


Fig. 74. PYRAMID OF CESTIUS, Engraving by Piranesi for Vedute Di Roma. During the Roman period many buildings were included in the wall in order to quickly build walls around the city for military reasons.



Fig. 75. WESTERN WALL OF JERUSALEM. Example of how one wall can be significantly complex.

Building off of the previous research, this section consists of testing various forming methods for real scale applications. Process consists of repeated feedback between full scale testing and the digital model, which reflects properties of the formwork material and the behavior of the concrete in it. Digital technology is used both in the design phase (software) as well as in the construction phase (hardware), which are seamlessly linked. In order to mainly focus on the construction and properties of the material, research was narrowed to design of one wall. In this case, the program for the wall is a noise barrier along the highway (mass pike). Sound properties, structural properties, and construction properties of formwork and concrete construction became the evaluation criteria.

NOISE BARRIER AS PROGRAM

In order to find larger yet affordable plots near the city, more people are willing to live near large highways. For such reasons, more private money is used on constructing noise barriers —barriers traditionally funded by the public. With the potential of people living near one, noise barrier is a great yet challenging design opportunity. According to the Boston Globe, existing barriers along the Mass Pike cost \$400 per linear foot, or more than \$2.1 million for a mile. Various materials are effective in reducing sound, as long as it is rigid and has at least a density of 20 kilograms/ square meter *. Concrete is used in many cases not only for its density and cost but for its durability and lifespan. The challenge is to improve on its design both from the point of the driver and the residents living near it without sacrificing its acoustic properties and cost.

* U.S. Department of Transportation
Federal Highway Administration
Noise Team, Washington, D.C.



Fig. 76. Existing Noise Barrier.
Not pleasing from the drivers view point but also from the people on the other side.



An aerial view of Wildwood Drive in Southborough, a group of newer homes built alongside the Massachusetts Turnpike.
With buildable land scarce, new houses coexist with highway.
Pike-side living

Fig. 77. THE BOSTON GLOBE ARTICLE June 5, 2005.
More people are willing to live near highways.

SITE



Fig. 78. View of the Site

First clear view of the Boston skyline when driving in to the city. Four lanes of cars in each direction plus a commuter rail track on the right side of the highway.

Site for the wall is a narrow strip of land between the Mass Pike and a neighborhood street. Driving towards Boston, the driver has a clear view of the city skyline following the area of the test site and the noise barrier will act as a gateway into the city. The surrounding condition on the site, such as building height, is used to determine the shape of the wall. The design of the wall is considered both from the view of the driver moving at high speeds and the pedestrian on the other side having very close relationship to the wall. Unlike constructing a new highway, adding a noise barrier to an existing wall requires thorough preparation to minimize work on site and keep costs low.

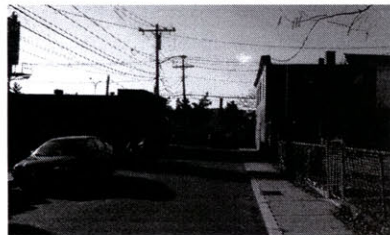


Fig. 79. AERIAL VIEW OF SITE marked in red. Narrow strip of land between highway and the neighborhood. (The Boston Atlas)

Fig. 80. Image of Location of Measurement.



(Above)
Looking back towards the Mass Pike from location 2.



(Below)
Location 3

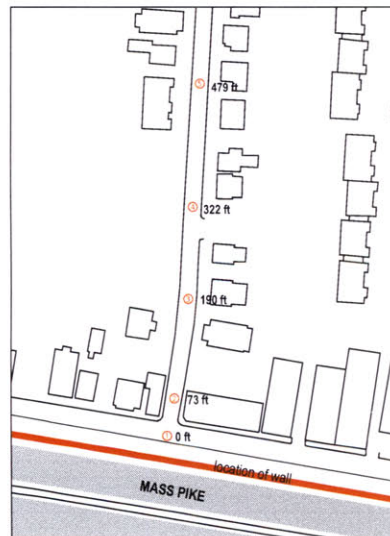


Fig. 81. Location of Measurement Points. Five locations, moving perpendicular to the highway.

Noise Measurements

To evaluate the effect of the wall, noise levels of the actual sound from the highway were recorded on the site. Moving farther away from the highway on a street running perpendicular to it, measurements were taken at five locations. It is obvious from the graph that cars and trucks generate higher levels of low frequency noise. Based on a personal comfortable level, noise roughly 250ft away from the wall was considered below the tolerance level. Based on that the goal for the wall became 15-20dB attenuation of sound level.

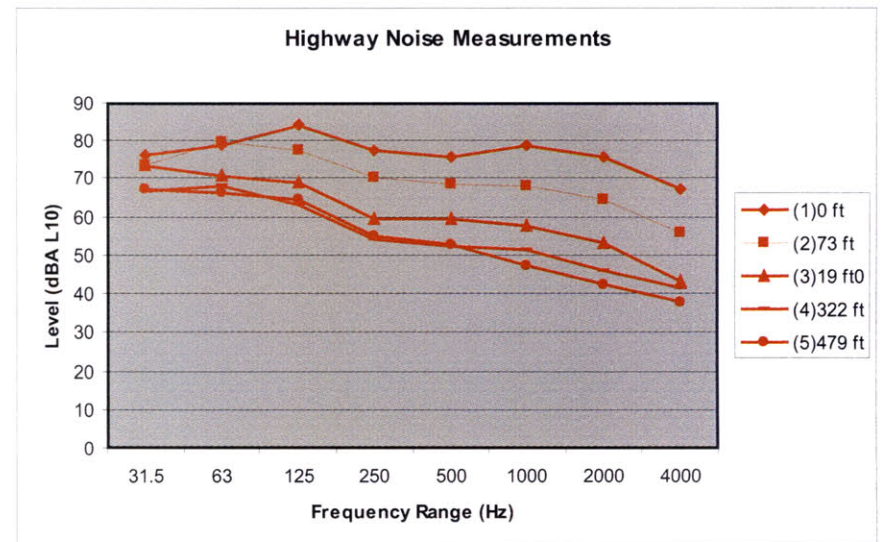


Fig. 82. NOISE MEASUREMENTS. Octave band data.

SOUND PROPERTIES

If the wall itself did not let any noise through, the effectiveness of the barrier is relative to its height. The attenuation level depends on the extra distance the sound needs to travel to avoid the wall. This principal was applied to the selected site to determine the necessary height of the wall.

Besides simply blocking/reflecting noise, walls can absorb sound using air cavities within the walls. This is called the Helmholtz effect. Combining this with the kinematic effect created by the speed of the driver, the ultimate goal was to design a wall which will block most of the sound but allow drivers and pedestrians to see the other side.

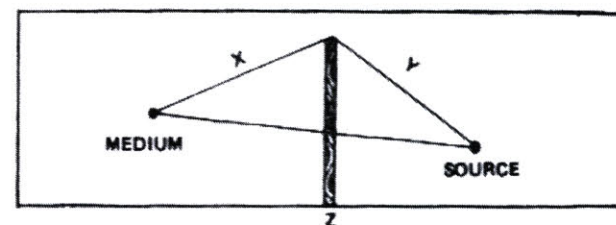
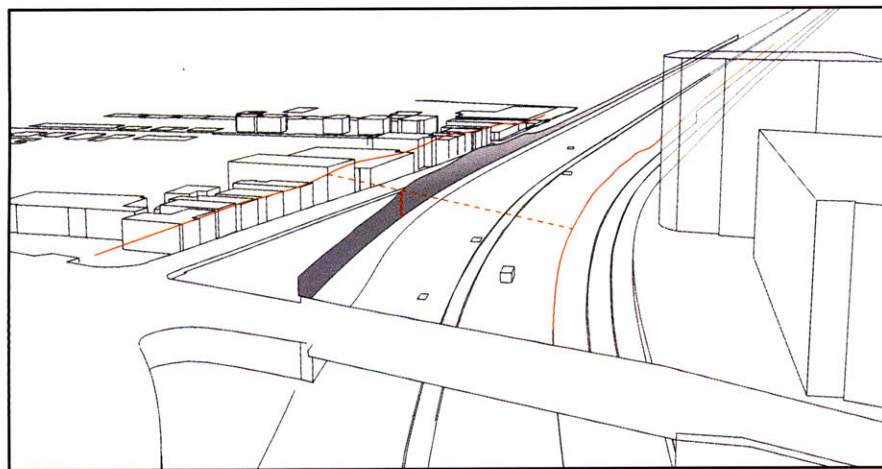


Fig. 83. BARRIER DIAGRAM.

Effectiveness of the wall is related to its height.

$$R = 10 \log(3 + ((40fd) / c))$$

where

R = the reduction (dB) over the inverse square law,

f = the frequency (Hz),

d = X + Y - Z

and

c = the speed of sound (usually taken as 343m/s)

Fig. 84. AERIAL VIEW OF SITE AND WALL (Left).

Shows how the height of the wall is determined by the height of the neighboring building and the distance away from the highway.

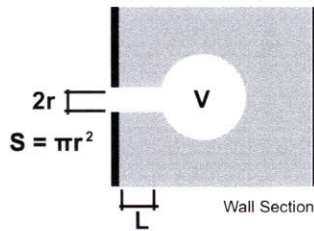


Fig. 85. SECTION DIAGRAM.

Relationships of various variables which determine the frequency is listed below.

$$Fr = (340/2\pi) \times (S/VL)^{1/2}$$

Fr (Hz) : Frequency of absorbing sound

V (m³) : Volume of cavity

S (m²) : Area of opening

L (m) : Length of neck

Car Noise: 500~1000 Hz

Truck Noise: 200~500 Hz

1. Helmholtz Absorber

The Helmholtz absorber uses the trapped air within the bottle shaped cavity to absorb sound. The frequency range of each bottle is determined by the volume of the cavity, surface area of the bottle neck, and the length of the bottle neck. The absorbers can be designed precisely to capture the noise generated by cars and trucks. Since each bottle absorbs only a narrow range of frequency, various types of bottles need to be scattered within the wall to capture the diverse range of noise generated by cars and trucks, . First exercise was to design such a wall using generative algorithms. Keeping the bottle neck length constant, volume of cavity and surface area of the bottle neck were individually adjusted, then combined for desired frequency.

The algorithm on the right uses a random generator for sizing the bottles and its placement. The frequency it covers is output as numerical data, which is listed on the far right.



Fig. 86. SIDE VIEW OF THE WALL. Bottles of various sizes are placed inbetween two walls.

```

//generate cylinder and sphere
//print frequency
for($y=0; $y<10; $y++){
  for($x=0; $x<10; $x++){
    $r = rand(-0.02,0.02);
    sphere -r (0.1+$r);
    if($y % 2 == 0){
      move (($x+0.5)*0.25) ($y*0.25) (-$r); // move and align top of sphere
    } else {
      move ($x*0.25) ($y*0.25) (-$r); // move and align top of sphere
    }
    sphere -r (0.12+$r);
    if($y % 2 == 0){
      move (($x+0.5)*0.25) ($y*0.25) (-$r); // move and align top of sphere
    } else {
      move ($x*0.25) ($y*0.25) (-$r); // move and align top of sphere
    }
    $t = rand(-0.005,0.005);
    cylinder -ax 0 0 0 -r (0.025+$t) -hr (0.05/(0.025+$t));
    if($y % 2 == 0){
      move (($x+0.5)*0.25) ($y*0.25) (0.12); // move and align top of sphere
    } else {
      move ($x*0.25) ($y*0.25) (0.12); // move and align top of sphere
    }
    cylinder -ax 0 0 0 -r (0.035+$t) -hr (0.05/(0.035+$t));
    if($y % 2 == 0){
      move (($x+0.5)*0.25) ($y*0.25) (0.12); // move and align top of sphere
    } else {
      move ($x*0.25) ($y*0.25) (0.12); // move and align top of sphere
    }
    $s = 2 * 3.14 * pow (0.025+$t,2); //section area of cylinder
    $v = 0.33 * pow (0.1+$r,3); // volume of sphere
    $sv = $s / (0.05 * $v);
    $f = (340 / (2 * 3.14)) * sqrt ($sv); //frequency
    print($f + "\n"); // print results
  }
}

```

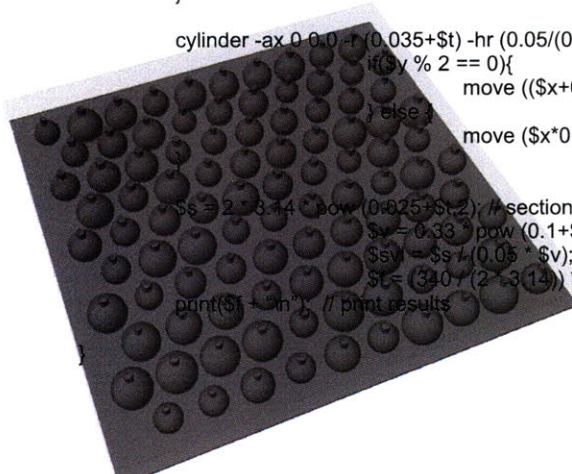


Fig. 87. AXONOMETRIC VIEW of wall.

934.04	897.29
985.12	1077.15
759.37	748.11
1085.04	940.99
806.82	712.53
1120.13	978.11
675.44	1205.33
662.57	1354.35
579.11	847.29
897.63	1098.46
685.29	738.56
665.50	1068.09
613.25	658.87
692.13	1006.36
1241.95	686.70
542.34	875.09
746.77	1034.00
976.96	617.64
1093.89	624.60
807.28	766.22
579.97	935.58
660.36	883.13
863.87	788.93
1019.54	1246.31
769.15	831.55
703.81	805.83
641.72	870.70
796.78	1005.20
868.75	765.09
1168.26	802.69
755.17	1007.31
1331.97	965.96
770.73	588.44
800.57	1089.91
847.45	905.07
876.89	819.74
857.63	1249.74
836.52	916.29
945.68	1177.32
886.26	907.86
869.10	926.20
770.33	689.67
754.91	739.88
1133.74	1016.67
852.98	767.29
1023.26	718.66
753.67	756.02
1127.80	775.86
693.64	787.10
1088.59	791.27

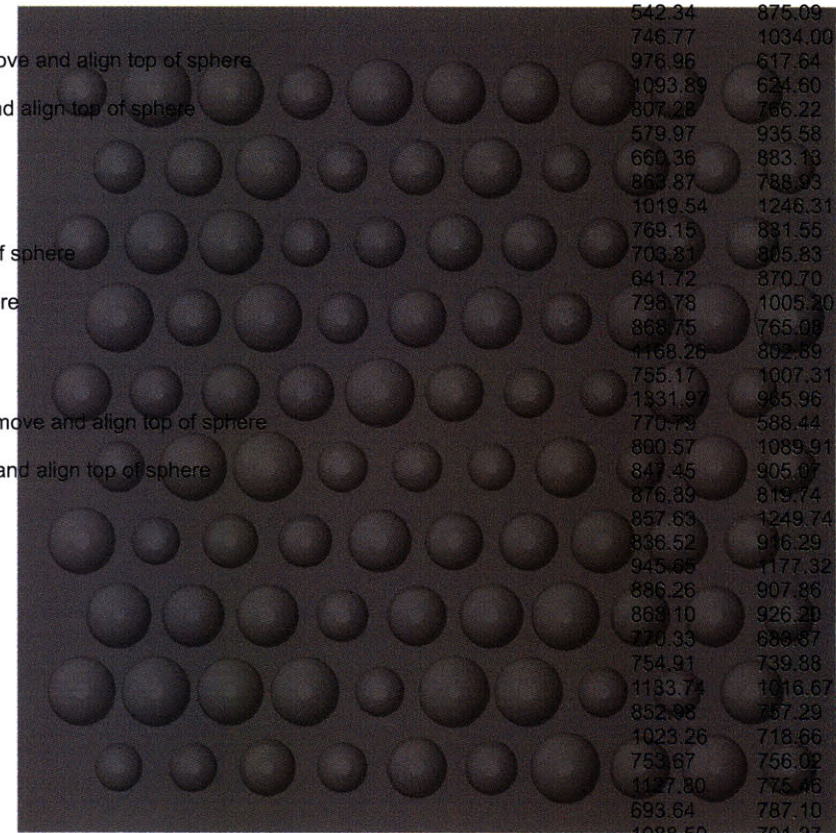


Fig. 88. PLAN VIEW. Each bottle has a unique volume and neck surface area.

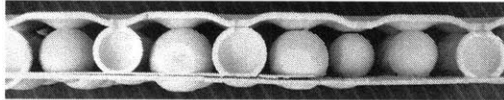


Fig. 89. Section of 3D Model.

The cavity inbetween the bottles will act as a large bottle to absorb sound.

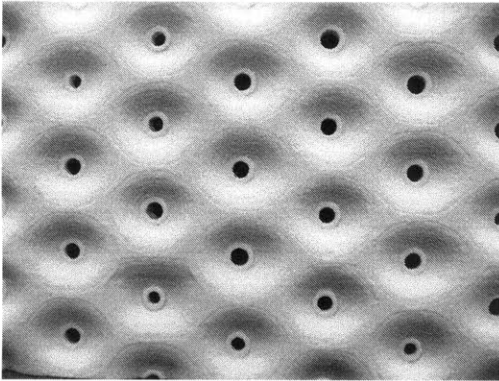


Fig. 90. Surface Facing Highway.

Undulating surface will reflect in multiple directions whatever noise not absorbed .

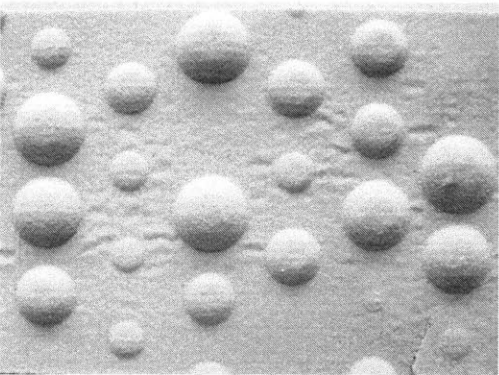


Fig. 91. Surface Facing Neighborhood.

Bottle size variation is expressed on the opposite side.

Test model was printed using the Zcorp 3D printer at 1:10 scale. The wall is 16" thick. 2" thick surfaces sandwich the bottles form both sides creating a honeycomb like structure. The surface facing the highway is perforated with smaller holes in between the bottles so the cavity in between the bottles will act as a holmholtz absorber as well (holes too small to be printed at this scale), Even with such thin surfaces, concrete has enough density to block any sound from penetrating the wall.

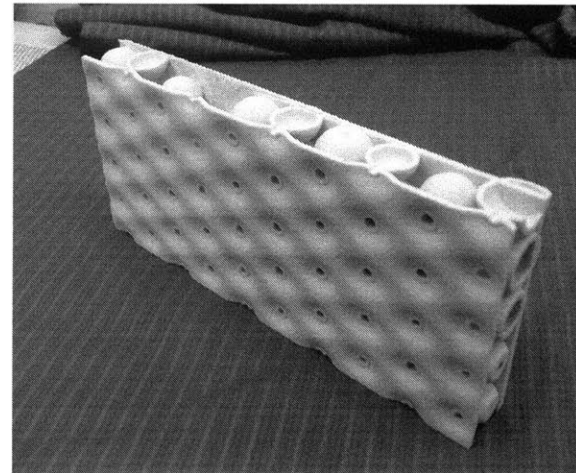


Fig. 92. Image Of 3D Model Printed on the Zcorp Machine.

1:10 scale model of a wall segment 16" thick. Flat sheets holding the bottles are 2" thick, front side perforated (not shown on this model) to use the spaces between the bottles as another absorber.

2. Kinematic Effect

A flip book uses the kinematic effect to animate series of still images. In a flip book, series of discontinuous images being exchanged in succession appear as if they are in continuous motion caused by persistence of vision. Using the similar effect, perforated surfaces when put into motion will increase in visual transparency even if the individual holes are small and difficult to see through.

Noise barrier is unique in the way which it is experienced. On one side, people will perceive the wall moving at very high speeds while the other side is typically experienced from a relatively static observer. Typically noise barriers enclose the driver between two blank surfaces eliminating any kind of visual experience of the surrounding environment. Kinematic effect takes advantage of the unique condition of a noise barrier for possibly improving the driving experience without sacrificing the acoustic properties of the wall.

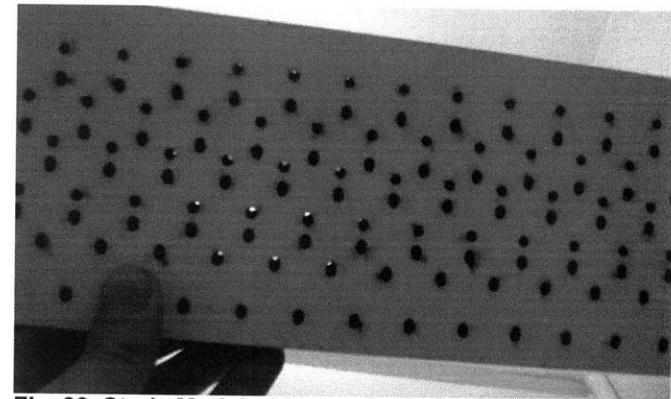


Fig. 93. Study Model of Kinematic Wall.
Small holes allow very little visibilitiy through the wall.

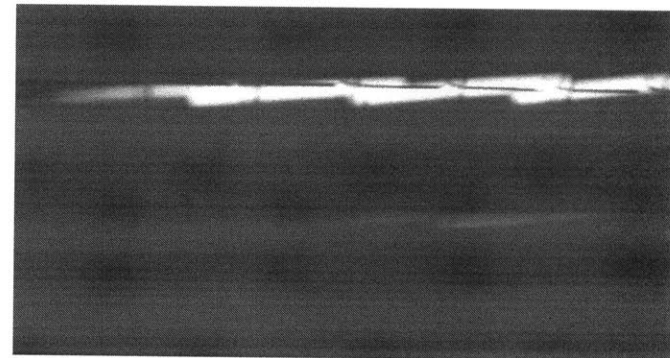
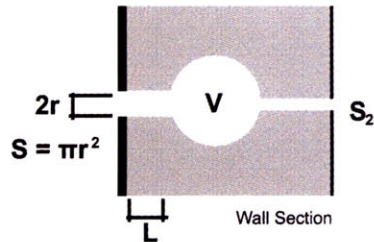


Fig. 94. Image of Moving Kinematic Wall .
When seen at high speeds, the small holes combined will allow one to see through the wall much clearer.



$$Fr = (340/2\pi) \times ((S+S_2)/VL)^{1/2}$$

Fig. 95. SECTION DIAGRAM.

Adding another hole is equal to increasing the size of one hole. Noise penetration through the small opening was tested (page 104).

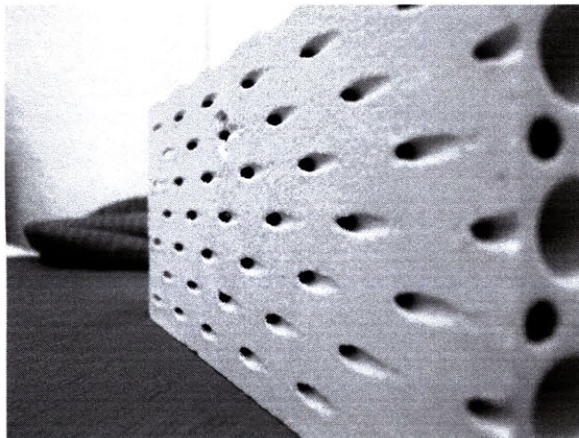


Fig. 96. 3D PRINTED MODEL.

Holes were opened diagonally considering the typical view angle of the wall from the point of a driver.

3. Helmholtz + Kinematic Combination

The aim of combining the Helmholtz and the Kinematic effect is to generate a noise barrier which will block most of the traffic noise but still allowing the driver to see through the wall while driving. The premise of the modified helmholtz absorber is that most of the noise will be absorbed before it travels to the other side of the cavity. Scaled down sound testes were conducted (page 104) using 3D printed models. Here the main focus of the study was to test different configurations of the bottles and the angles of visual connection (drawing on right). The wall performed best when the bottles are placed densely in the vertical direction compared to the horizontal direction. Out of the three studies done on the right, model 3 performed the best, mostly due to the amount of holes covering the vertical direction of the wall.

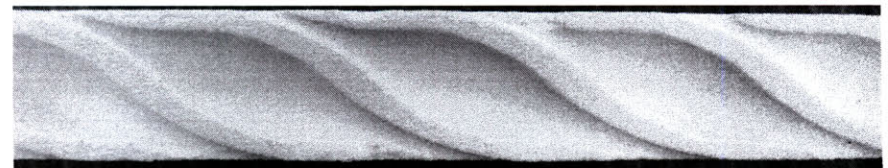


Fig. 97. SECTION of MODEL.

Two small openings are created on both sides of the air cavity in the wall.

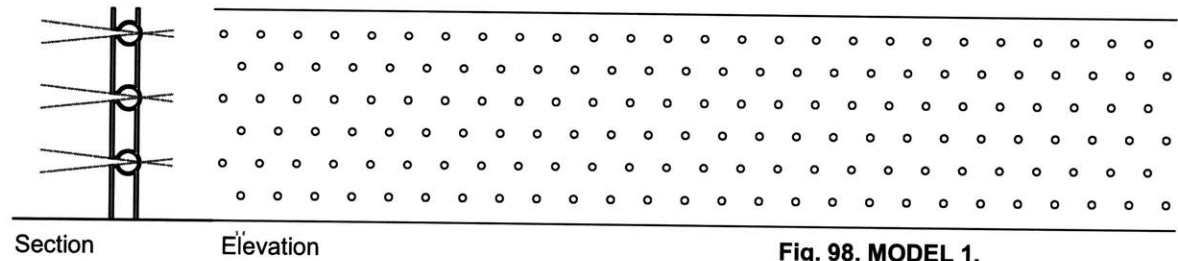
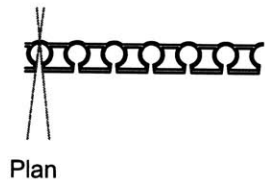


Fig. 98. MODEL 1.
Even distribution of bottles with one hole penetrating the wall perpendicular to the surface..

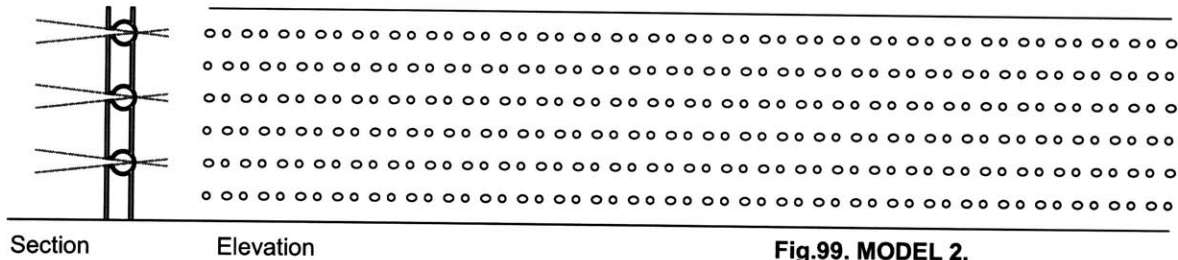
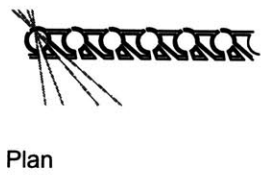


Fig.99. MODEL 2.
Same distribution of model 1 but another is added to the bottle in the horizontal direction. The hole faces diagonally in the direction most likely that of the driver.

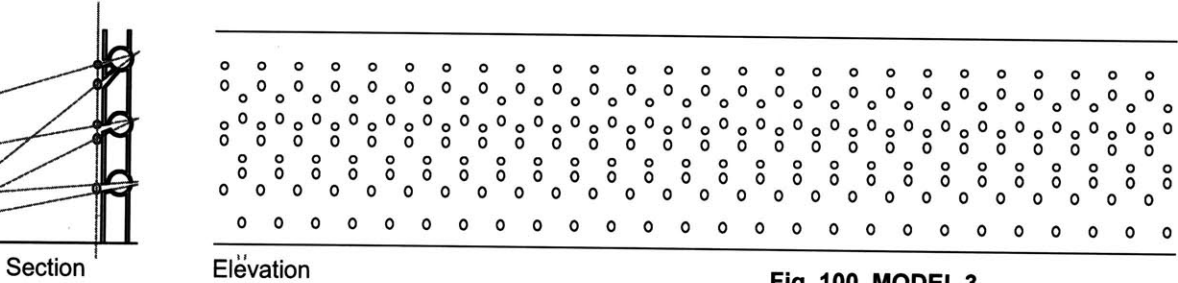
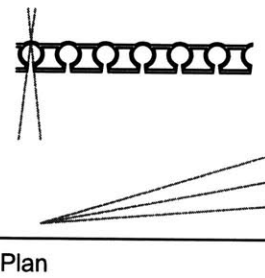


Fig. 100. MODEL 3.
Similar to model 2 but the extra hole is added in the verticle direction.

CASTING I

The initial design direction focused on acoustic properties of the wall. This step re-considers the design by thinking about the formwork and the construction method. Learning from the precedent studies and the earlier cube exercises, two methods were tested; repetition and layering. Materials used for formwork are fabric, ballons, and sand, all widely available and affordable. Full size mock-ups were made using a mixture of white cement, sand, and perlite. Using simple materials but being creative in the method, lead to new possibilites of forming complex shapes efficiant in the amount of concrete used.

Repetition

This method repeatedly builds off of the previous cast/formwork by flipping the object and adding/subtracting elements to/from it. Similar to a tilt-up construction used in precast concrete, one surface of the cast usually stays flat due to the act of pouring liquid. Repetition uses such properties to create panels which are assembled together back to back to create complex casts using very basic materials and simple procedures.

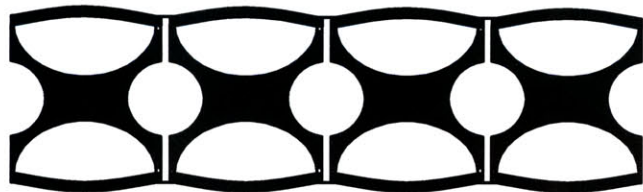


Fig. 102. Section of Wall.
Three layers of sound absorbing cavities are created.



Fig. 101. Full Size Mockup Using Concrete.
2' x 3' segment of a wall.

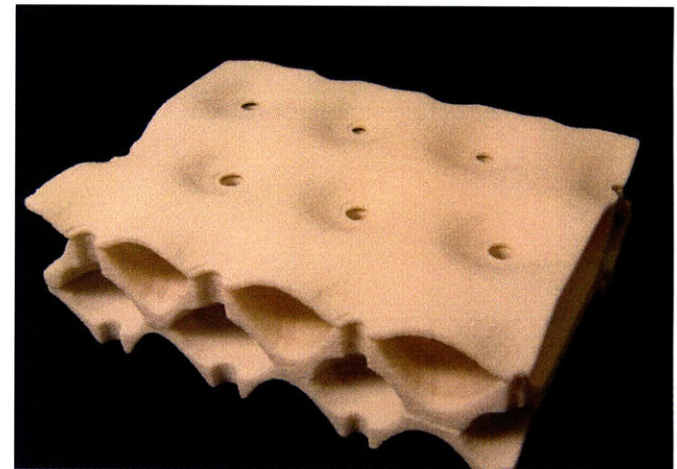
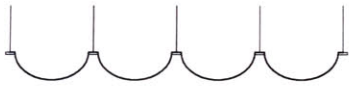


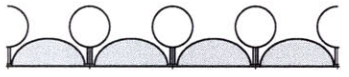
Fig. 103. 3D Printed Model Of Final Assembly.
Composed of 4 separate pieces.



Fabric is hung with slack to allow concrete to generate its own form



Cast piece is flipped and used as the formwork for the next cast

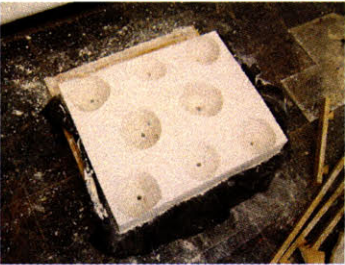


Ballons attached to formwork with hollow tubes



Concrete poured halfway up the ballons

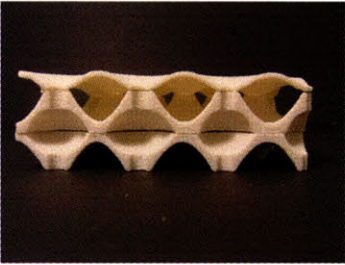
Fig. 104. Costruction Sequence Diagrams and Images of the Mock-up.



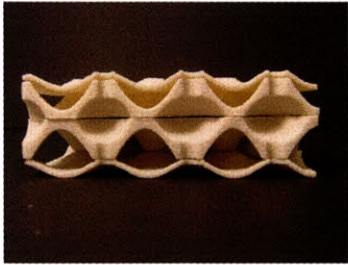
Ballons and hollow tubes create cavities in the concrete



Two pieces are attached back to back to create a panel.



Outer panel is created by hanging fabric from the inner panel.



All four pieces assemble to create a wall with three layers of cavities.

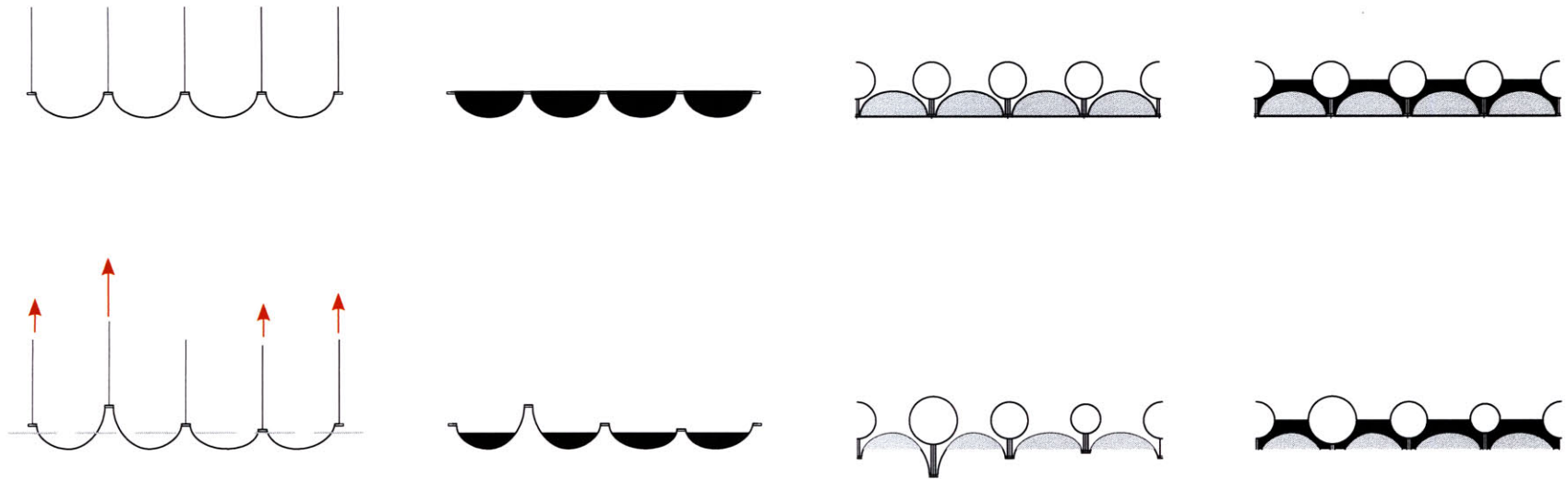


Fig. 105. Method to change size of cavity.

Diagram on the top shows the method tested.

Below is an alteration of the method to create different size cavities.

Layering

Layers of fabric were hung vertically, each separated by steel rods and foam spacers. By pouring all the layers at once, the individual panels (they may be different types of concrete) will fit together perfectly even after they are separated to remove the fabric. This example uses the outside layer to control the size of holes for sound absorption, the inner layer is the cavity which controls the volume of air trapped inside.

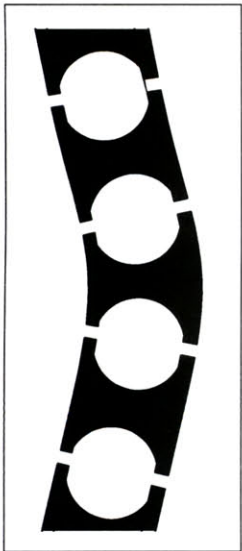


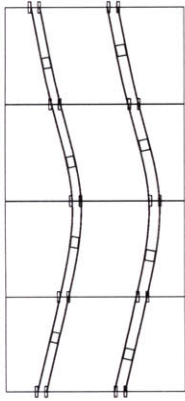
Fig. 106. Section Diagram of the Wall.

Composed of three layers of concrete panels.

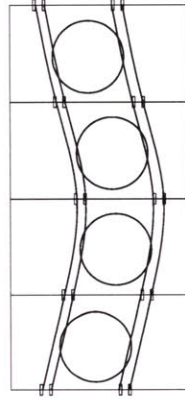


Fig. 107. Image of Mockup.

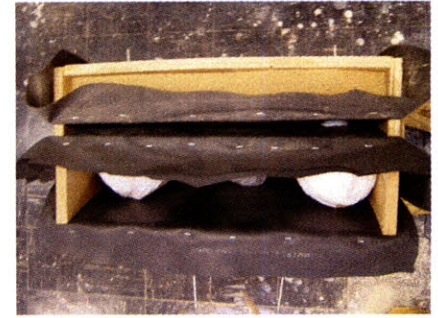
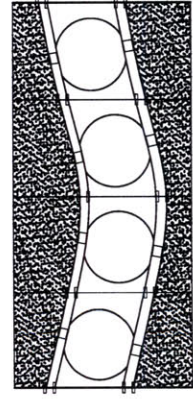
White cement is used for the center piece and regular cement for the outside panel.



Fabric is hung vertically using steel rods and spacers. Four layers of fabric used to create three panels.

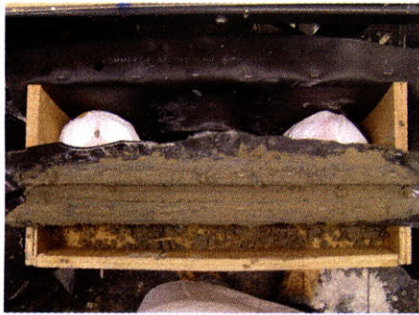
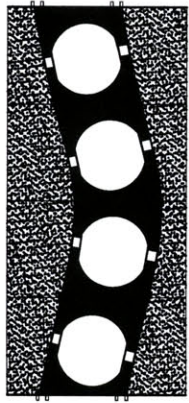


Ballons inserted between two layers of fabric.



Outer layer is filled with sand to prevent the fabric from bulging.

Fig. 108. Costruction Sequence Diagrams and Images of the Mock-up.



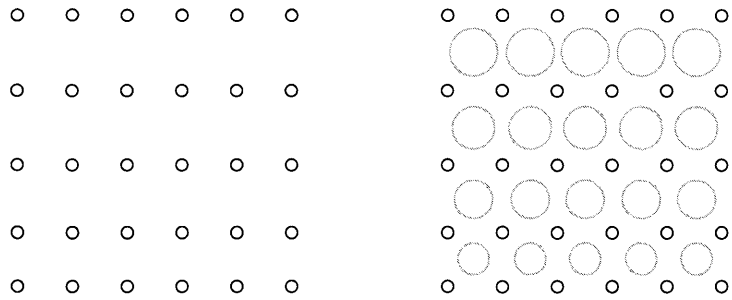
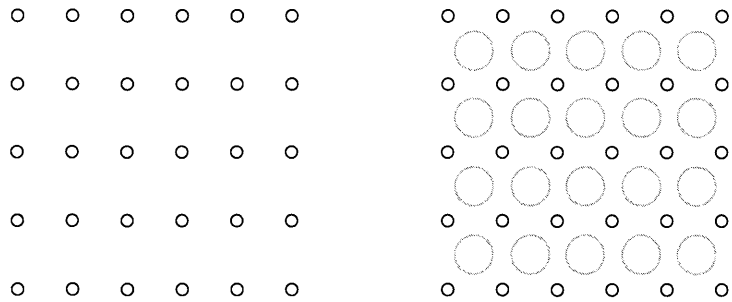
Concrete poured on all the layers at the sametime.



Layers are separated and fabric removed.



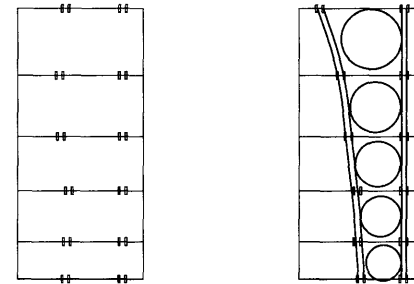
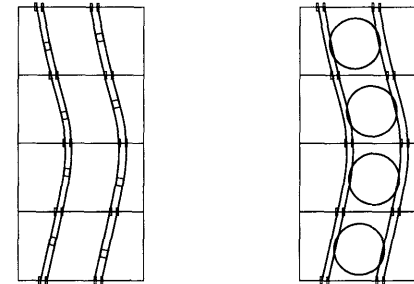
Layers put back together to create panel.



ELEVATION

Fig. 109. Method to Change the Size of Cavity.

Small circles represents the spacers used to hold the fabric up. By changing the distribution of the spacers, cavity size (large circles) can be controlled



SECTION

The size of the cavity will effect the thickness of the wall and in this case the curvature of the surface. .

Remarks on CASTING 1

Although it may still seem too complicated for large scale applications, these methods opened up possibilities for casting complex shapes in concrete using only generic materials and simple processes. It was a result of understanding the behavior of concrete and the formwork material. Designing the formwork is the first step in developing interesting concrete casts.



Fig. 110. CASTING PROCESS.

Small device was needed to separate one concrete cast from the formwork made also by concrete.

CASTING II

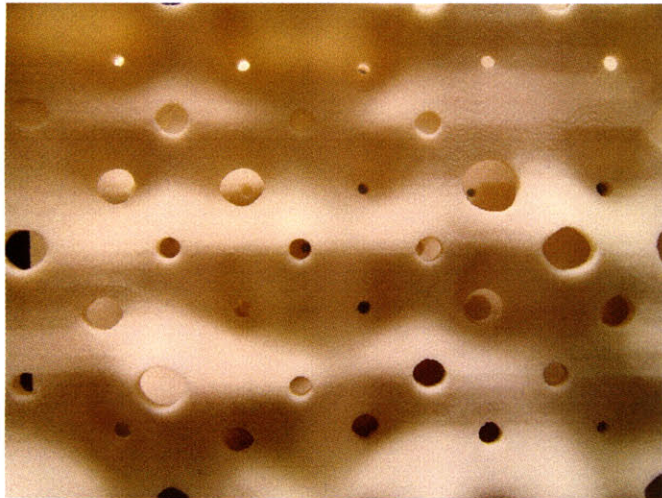


Fig. 111. 3D printed model of wall deigned based on CASTING II method.

While the two methods tested in Casting I are more likely to be pre-cast panels, Casting II is a cast on site application. On-site construction has the benefit of being able to fabricate larger pieces in one cast since there is no worry about transportation and assembly. The down side is the longer amount of time workers will have to spend on site. This can be greatly reduced however, with careful planning and preparation, especially on the erection of the formwork.

Fabric again was the main envelope to hold in the concrete. Spacers which were milled out of foam was used to separate two sheets of fabric. The spacers were also used to attach the fabric to the steel rods which held the fabric in place. Again the design of the wall itself is a result of the properties of the forming material and the behavior of the concrete in it. The most significant property in controlling the shape is the amount of fabric stretching under the pressure of concrete. The system uses the spacers and steel rods to pre-stretch the fabric before pouring in the concrete.



Fig. 113. Image of the formwork system.

Another sheet of fabric is added on top of the spacers to create the gap where concrete is poured..

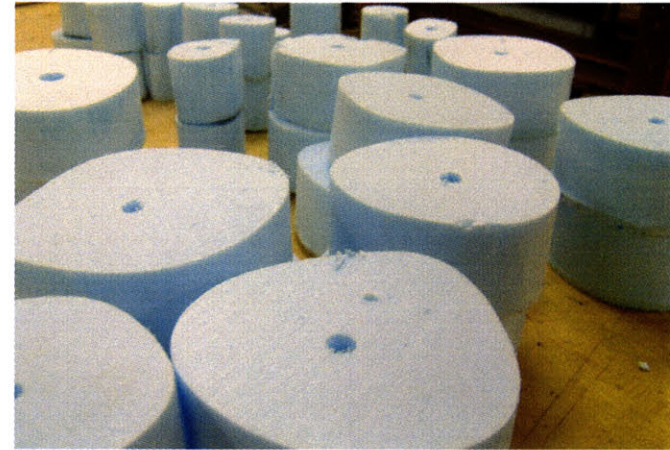


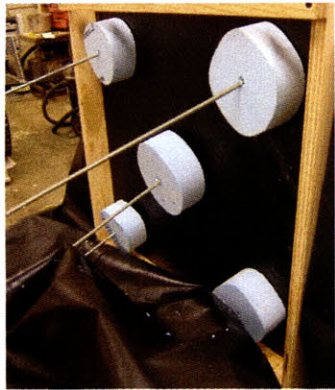
Fig. 112. Image of spacers.

Milled out using the CNC Milling Machine from 2" thick sheets.

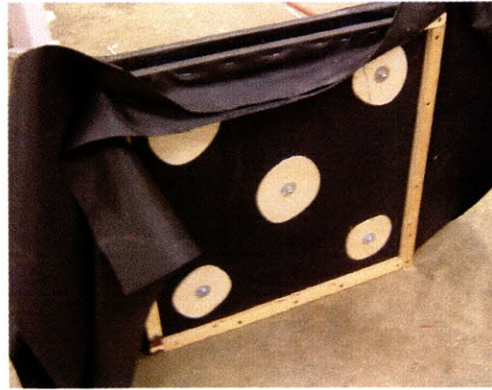


Fig. 114. Fabric used to cast concrete.

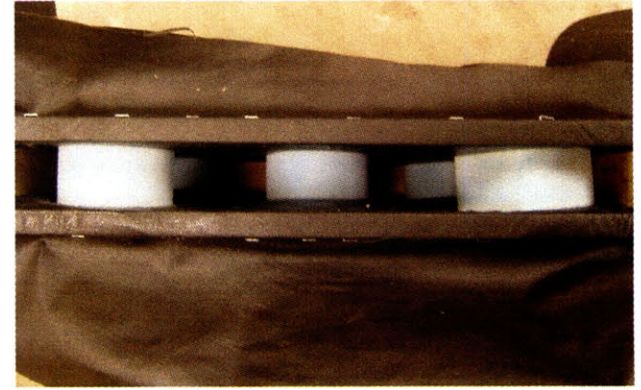
Found in the gardening section of the hardware store, this fabric is usually used to keep the soil in place.



Spacers and steel rods attached to the fabric.



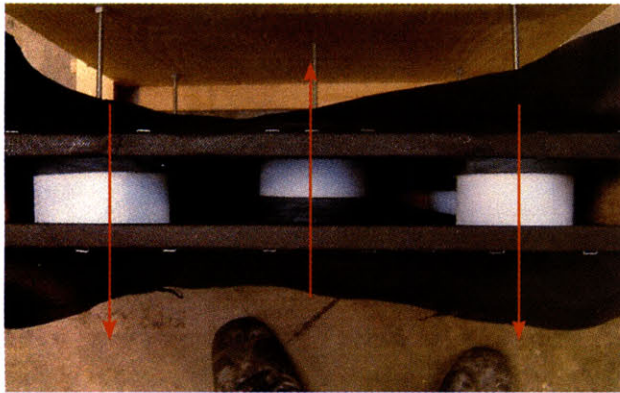
Wood disks (milled out identically to the shape of the spacers) hold the fabric to the foam spacers.



View of the gap created between the fabric.

Fig. 115. Construction Sequence of Mock-Up.

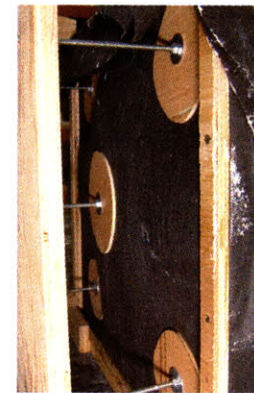
One of two mock-ups built to understand the behavior of fabric under pressure of concrete.



Fabric is stretched much as possible by sliding the spacers perpendicular to the surface of the fabric. The fabric can be made taught with very little effort when forced is applied in this direction.



Outside view of fabric stretched tight.



Even with concrete poured, the shape does not deform.



Shape of the cast piece reflects the process of pre-stretching the fabric before the pour.

Fig. 116. LARGE SPACERS.

With larger spacers, there is less fabric in between to stretch. The final shape relatively flat.

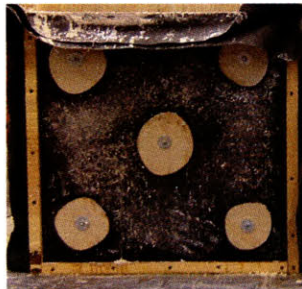
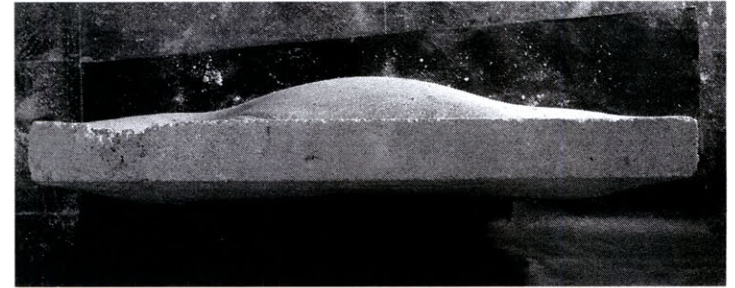
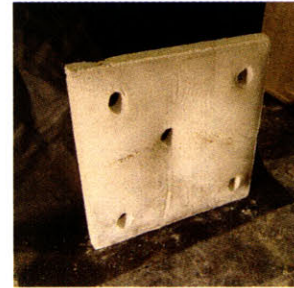
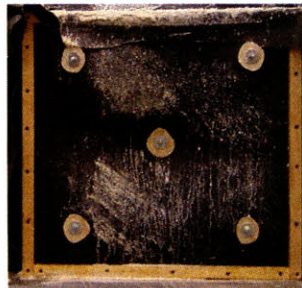


Fig. 117. SMALL SPACERS.

Small spacers leave a lot of space in between each other, making the fabric stretch. The final shape reflects that and has greater undulation.



SPAPCERS

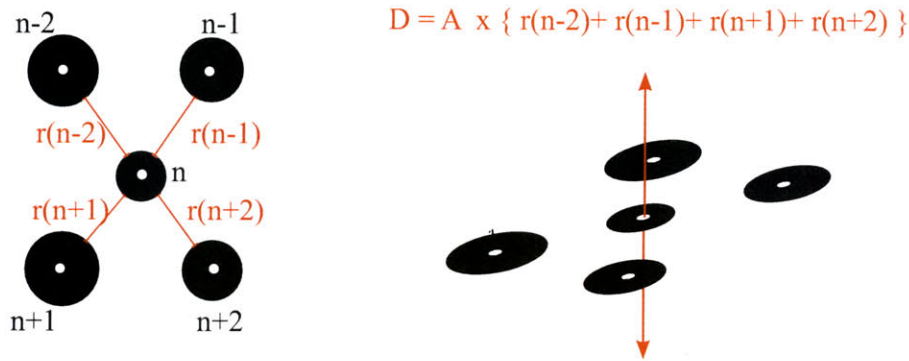


Fig. 118. DIAGRAM OF SPACERS AND DISTANCE IN BETWEEN THEM.
 The amount of offset is relative to that of the distance between the spacers.
 (A is a constant multiplier)

The relationship between the size of spacers and the amount of stretch in the fabric is used as a variable to control the shape of the wall. The data collected through the mock up testing is put into a generative algorithm based on a system of cellular automaton. Each spacer looks for its neighboring spacers and moves based on the amount of fabric that exist between them. It is a digital simulation of the formwork which allows one to design the final shape of the concrete structure based on the properties of the formwork.



Fig. 119. RENDERINGS OF FABRIC FORMWORK.
 Show the undulation of the fabric based on the size of spacers.
 Spacers not expressed in this rendering.

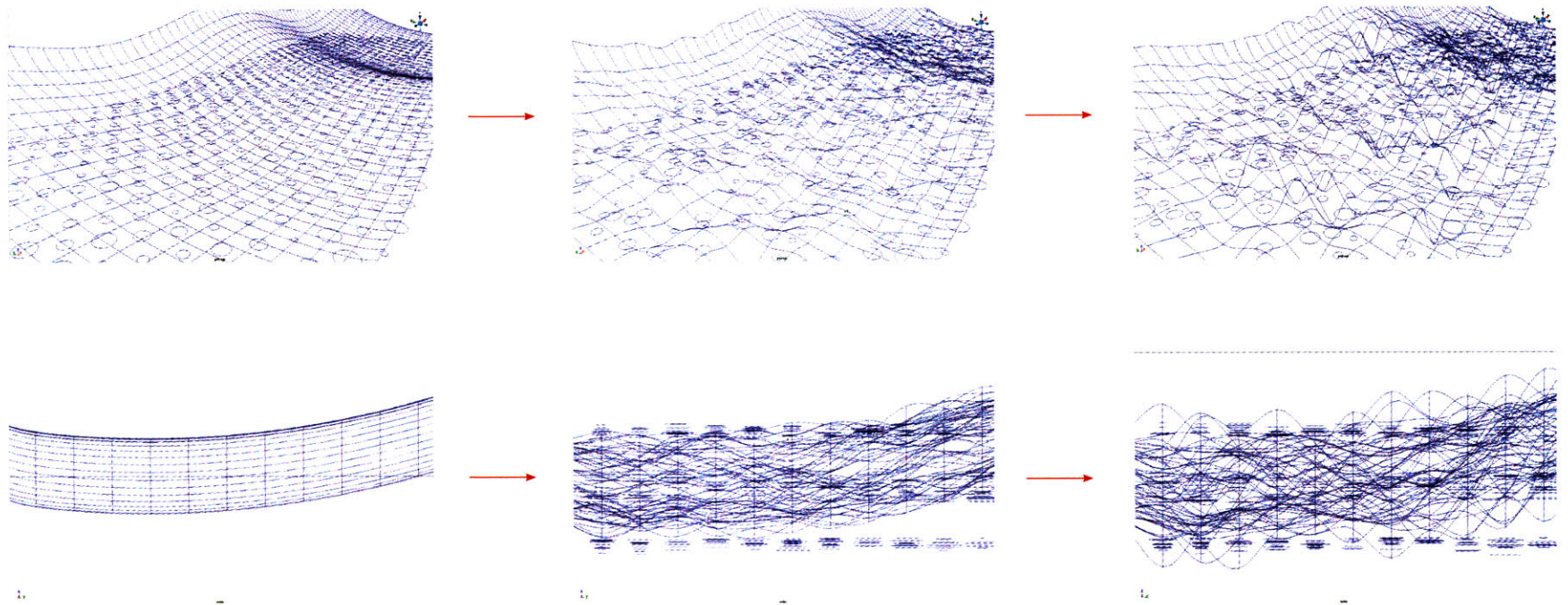


Fig. 120. SURFACE FORMATION SEQUENCE.

(top: Axon, below Elevation)

Shows the gradual formation of the surface as each spacer is moved based on cellular automaton.

```

//*****
//cellular automaton
//for sound wall based on
//size of spacers
//
//05/12/1 number of circles adjustable
//
//only CA after circle and surface is made
//
//shuji suzumori
//*****

int $sizeX = 60;
int $sizeY = 10;

float $total[]; //keep a memory of the current state of each cell

for($gen=0; $gen<3; $gen++) { //the number of trials (generations)

int $idx = 0; //initialize a counter
for($y=1; $y<$sizeY-1; $y++)
  for($x=1; $x<$sizeX-1; $x++){ // loop
    $name = ("circle" + $x+ "x" + $y);
    $dist = 0.0;
    for($i=-1; $i<=1; $i++) // loop two behind
      for($j=-1; $j<=0; $j++){
        if($i==0 )continue; // exclude the other cells
        $nameNeighbor = ("circle" + ($x+$i)+ "x" + ($y+$j));
        $nameSelf = ("circle" + $x+ "x" + $y); //get own radius
        $v = eval("getAttr "+$nameNeighbor+".scaleX"); //get their value
        $r = eval("getAttr "+$nameSelf+".scaleX"); //get own value
        // here is where we collect information from the neighbors
        float $diff = 1.61 - $v - $r;
        $dist += $diff; //add them
        //print ($dist + "\n");
      } //for j

    $total[$idx] = $dist; //remember each cell's neighborhood condition
    print $total[$idx];
    $idx++; //increment the counter
    //print ("in" + $idx + "\n");//print($name + "=" + $cc[$k] + "\n");
    //print to see values

```

```

} // for x

$idx = 0; // initialize the counter
for($y=1; $y<$sizeY+1; $y++)
  for($x=1; $x<$sizeX; $x++){ // loop
    $name = ("circle" + $x+ "x" + $y);
    $nameSurface = ("wall1.cv[" + ($x+1)+ "]" + ((($y*2)+1)+ ($x%2))+ "]" );
    // print ($nameSurface + "\n");
    int $a = rand(0,2);
    $Zsm = rand(-0.4,0.4);
    $Zlg = ($total[$idx]) * (pow ((-1), $a));
    //print($j + " " + $Zlg);
    //here is where we impose a simple rule that may amount into a
    complex pattern
    if($total[$idx] < 4.0){ //rule 1
      eval("setAttr "+$name+".translateZ " + $Zsm); //move small
      select -r $nameSurface;
      // move $x ((($y*2)+($x%2)) ($Zsm); //move small
      move -r 0 0 $Zsm;
      print "a";
    }
    else if($total[$idx] > 4.0){ //rule 2
      eval("setAttr "+$name+".translateZ " + ($Zlg/3)); //move big
      select -r $nameSurface;
      //move $x ((($y*2)+($x%2)) ($Zlg/3); //move big
      move -r 0 0 ($Zlg/5);
      print "b";
    }
    select -cl ;
    //print ($gen + "x" + $idx + "\n");
    $idx++;
  }

refresh; //show the pattern as it evolves
//setKeyframe; //save the frame

} // next generation

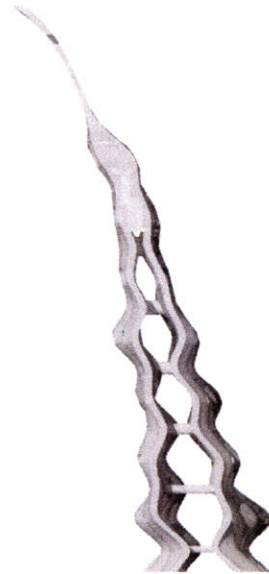
```

Fig. 121. SURFACE FORMING ALGORITHM BASED ON CELLULAR AUTOMATON.

CONSTRUCTION METHOD

Fig. 122. Section Rendering of the Proposed Wall.

Two undulating walls create the air cavity in between to absorb the sound. The two sides meet at the top.



Following is a study for on-site installation of the formwork system developed earlier. Constraints of construction methods and site conditions are taken into account as well as the acoustic and structural properties of the wall itself, all feeding back to design of the formwork system.



Fig. 123. OVERVIEW OF CONSTRUCTION METHOD.

1. Steel posts are placed and fabric is draped over the top rail. 2. Spacers and steel rods attached to the fabric. 3. Another layer of fabric is added to both sides of the wall. 4. Outer fabrics connected at top with spacers. 5. Concrete poured and formwork removed.

STEP 1 : Location of the foundations determine overall foot print of the concrete wall

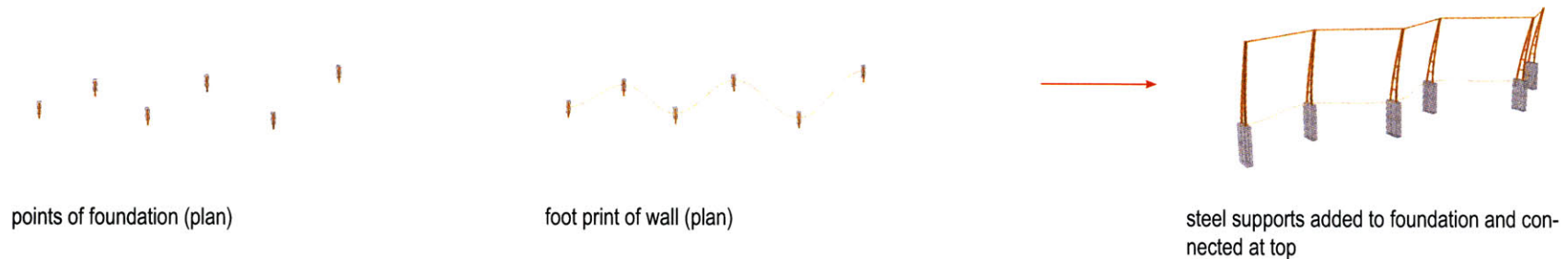


Fig. 124. Diagram of Steel Supports.

```

int $sizeX = 60;
int $sizeY = 10;

//makes surface with cv points from 0 to sizeX +2
nurbsPlane -n wall1 -ax 0 0 1 -u $sizeX -v ($sizeY * 2);
scale $sizeX ($sizeY * 2) 0;
move ($sizeX /2) $sizeY 0;

for($x=0; $x<=($sizeX + 2); $x++){
    $b = 30;
    for($y=0; $y<=($sizeY *2)+2; $y++){ // loop
        $a = 2;
        $nameSurface = ("wall1.cv[" + $x+ "]" + $y+ "]"); //select point
        float $moveY = (pow (($y-5), 2))/50;
        float $moveZ = $a * cos(deg_to_rad((360/$b)*$x)); // wave length is 30 or $b
        select -r $nameSurface;
        move -r 0 0 ($moveY+$moveZ);
        select -cl ;
    }
}
refresh;
}

```

Fig. 125. Algorithm determining overall shape of the wall.

STEP 2 : Steel supports which hold up the fabric formwork is used to determine section shape of the wall
Thin concrete walls will be created on both sides of the support.

Steel Supports

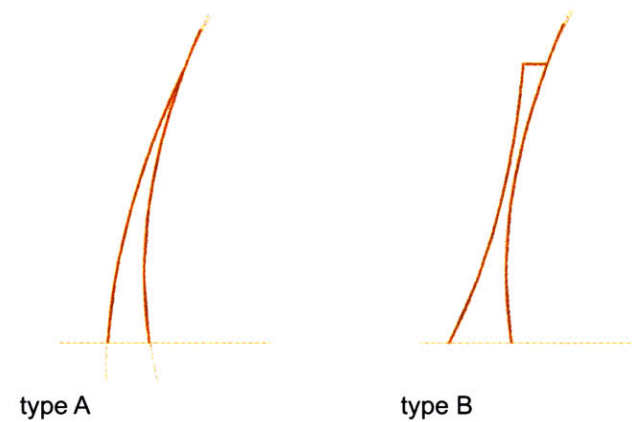


Fig. 126. Sections of the Different Options of Steel Supports.

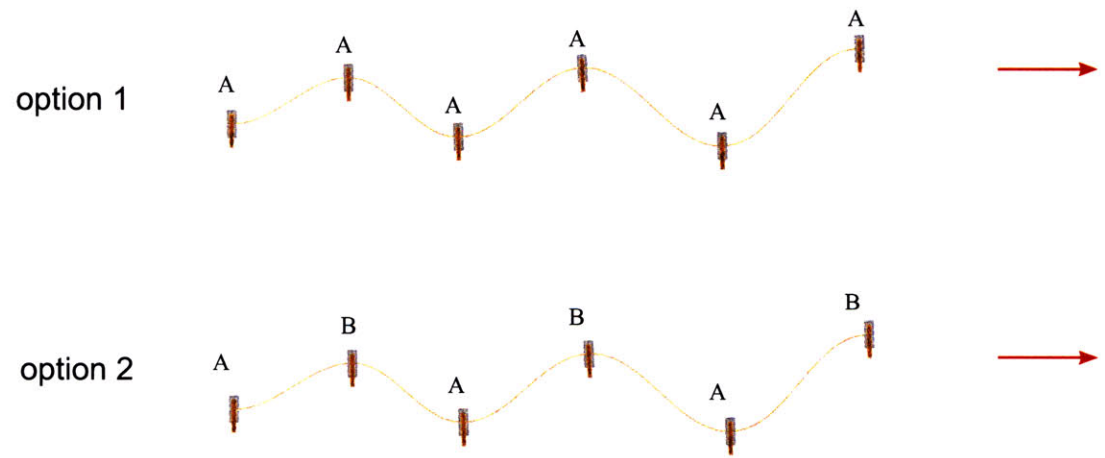


Fig. 127. Plan Diagram for Placement of Steel Supports.

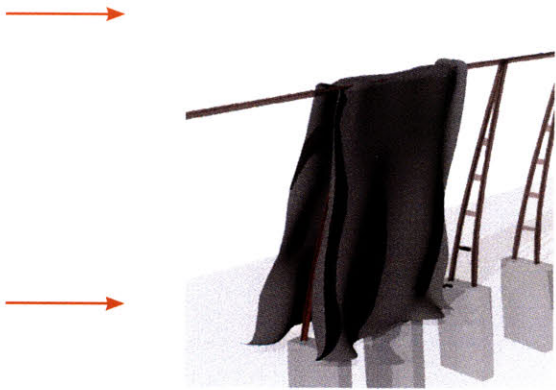


Fig. 128.
fabric formwork is draped on both sides of the steel support. This fabric will be left in place acting as a sound absorbing layer.

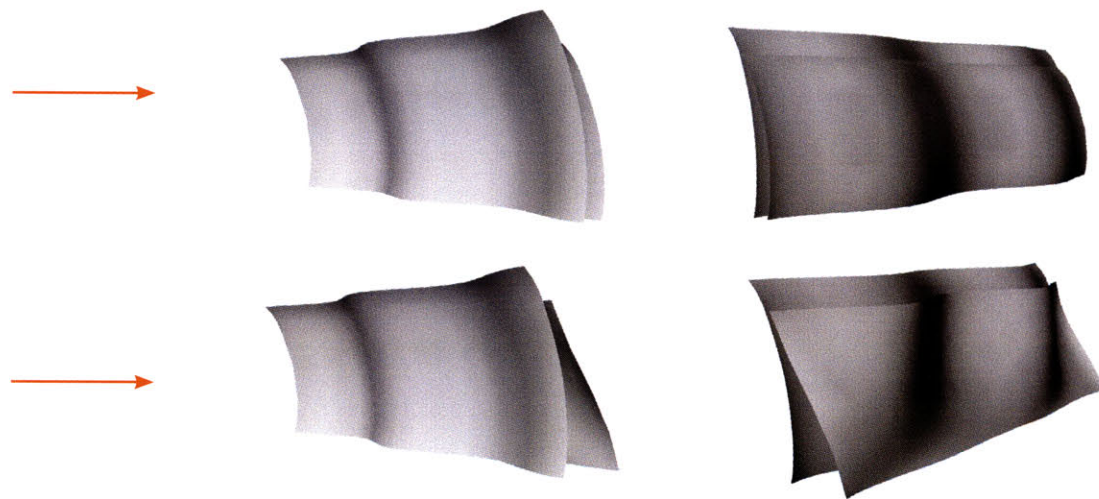
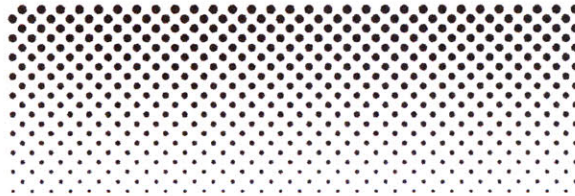


Fig. 129. Different options of the wall based on the combination of steel supports

STEP 3 : Spacers are attached to the fabric with tie rods to create the gap between two sheets of fabric.
 Distribution and size of spacers determine acoustic/structural/texture properties of the final concrete wall

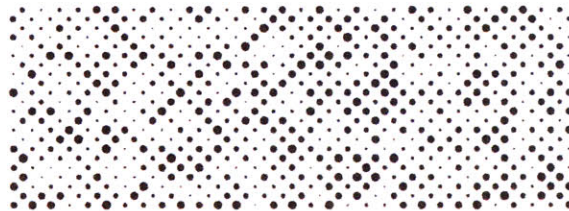
Spacer Distribution

type 1



small spacers (more concrete) at bottom
 large spacers (less concrete) at top

type 2



various sized spacers evenly distributed

Fig. 130. Initial Distribution of Spacers.

```
int $sizeX = 60;
int $sizeY = 10;

for($y=0; $y<$sizeY+1; $y++){
  for($x=0; $x<$sizeX+1; $x++){
    $i = 0;
    $r = rand(0.1,0.5);
    circle -n ("circle" + $x + "x" + $y);
    eval("setAttr circle" + $x + "x" + $y + ".scale "+ $r + " " + $r + " " + $r);
    //move ($x*2) (($y*2)+($x%2)) 0; // move and align top of sphere
    move $x (($y*2)+($x%2)) 0; // move and align top of sphere
    $i++;
  }
}
```

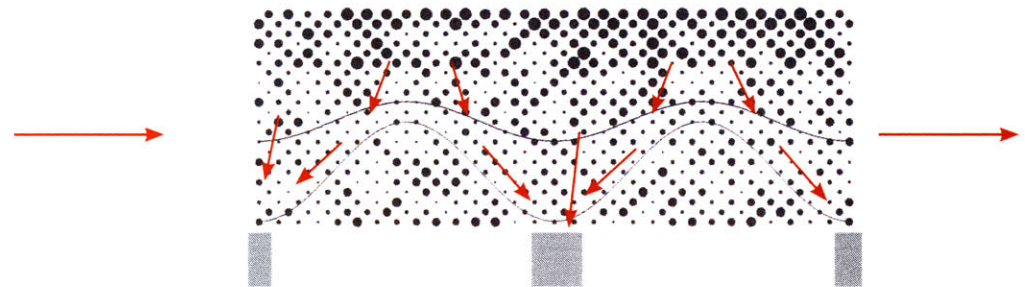
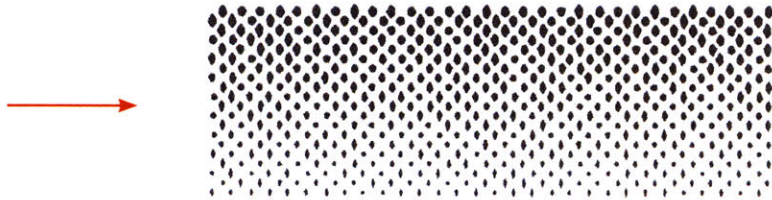
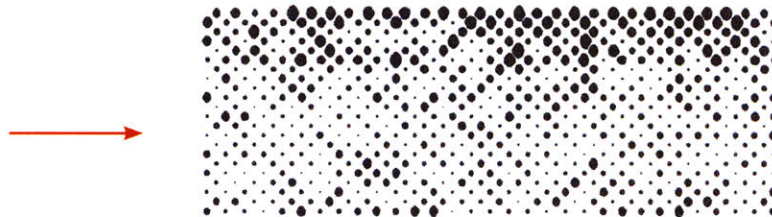


Fig. 131. Structural Diagram of Wall.

spacer sizes adjusted so forces concentrate on foundation
 spacers in between two lines made smaller for more material
 spacers near top of wall made larger



spacer shape optimized for better concrete pouring.



spacer shape optimized for better concrete pouring.

Fig. 132. Spacer Shapes Modified

```

//*****
//circle distribution along cos curve
//for sound wall based on
//size of spacers
//shuji suzumori
//*****

int $sizeX = 60;
int $sizeY = 10;

$hh = 10;
$hl = 5;

curve -d 2 -p 0 0 0 -name lowCurve; //lower limit
for($x=1; $x<=$sizeX; $x++){
    float $y = (-$hh / 2) * cos(deg_to_rad((360/30)*$x));
    curve -a -p $x ($hh/2+$y) 0 lowCurve;
};

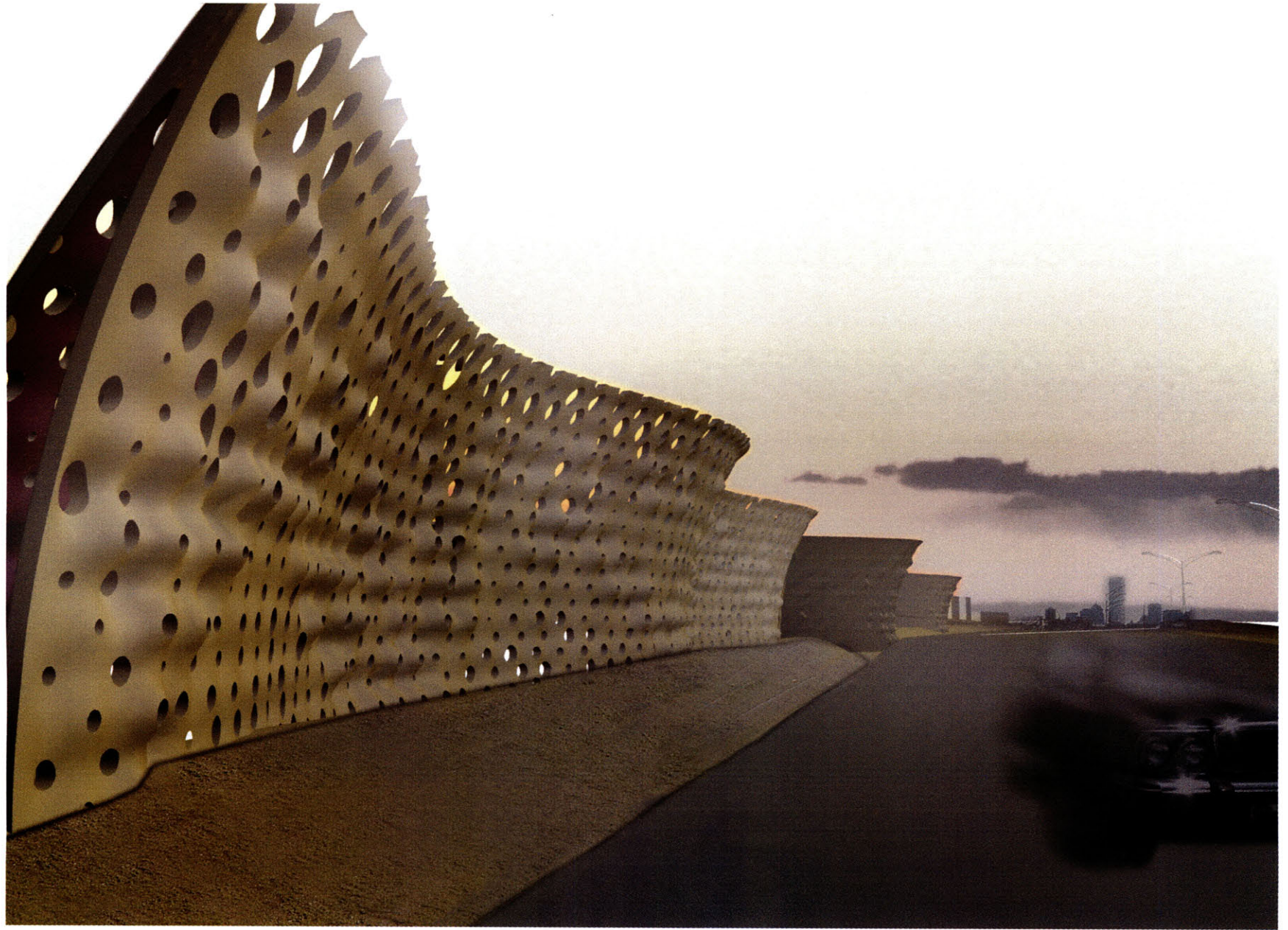
curve -d 2 -p 0 8 0 -name highCurve; //higher limit

for($x=1; $x<=$sizeX; $x++){
    float $y = (-$hl / 2) * cos(deg_to_rad((360/30)*$x));
    curve -a -p $x (($hl*2)+$y) 0 highCurve;
};

for($x=0; $x<$sizeX; $x++){
    $ymin = (($hh/2) + (-$hh / 2) * cos(deg_to_rad((360/30)*$x)) - ($x%2))/2;
    $ymax = (($hl*2) + (-$hl / 2) * cos(deg_to_rad((360/30)*$x)) - ($x%2))/2;
    print ($ymin + " " + $ymax + "\n");
    for((int) $y=$ymin; $y<$ymax; $y++){
        $name = ("circle" + $x + "x" + $y); //get own radius
        $r = eval("getAttr "+$name+".scaleX"); //get own value
        if( $r > 0.4){
            eval("setAttr circle" + $x + "x" + $y + ".scale "+($r/2)+ " "+($r/2)+ " "+($r/2));
            //move ($x*2) (($y*2)+($x%2)) 0; // move and align top of sphere
            //move $x (($y*2)+($x%2)) 0; // move and align top of sphere
        }/if
    }/for
}/for

```

Fig. 133. Algorithm for Spacer Adjustment For Structural Efficiency.



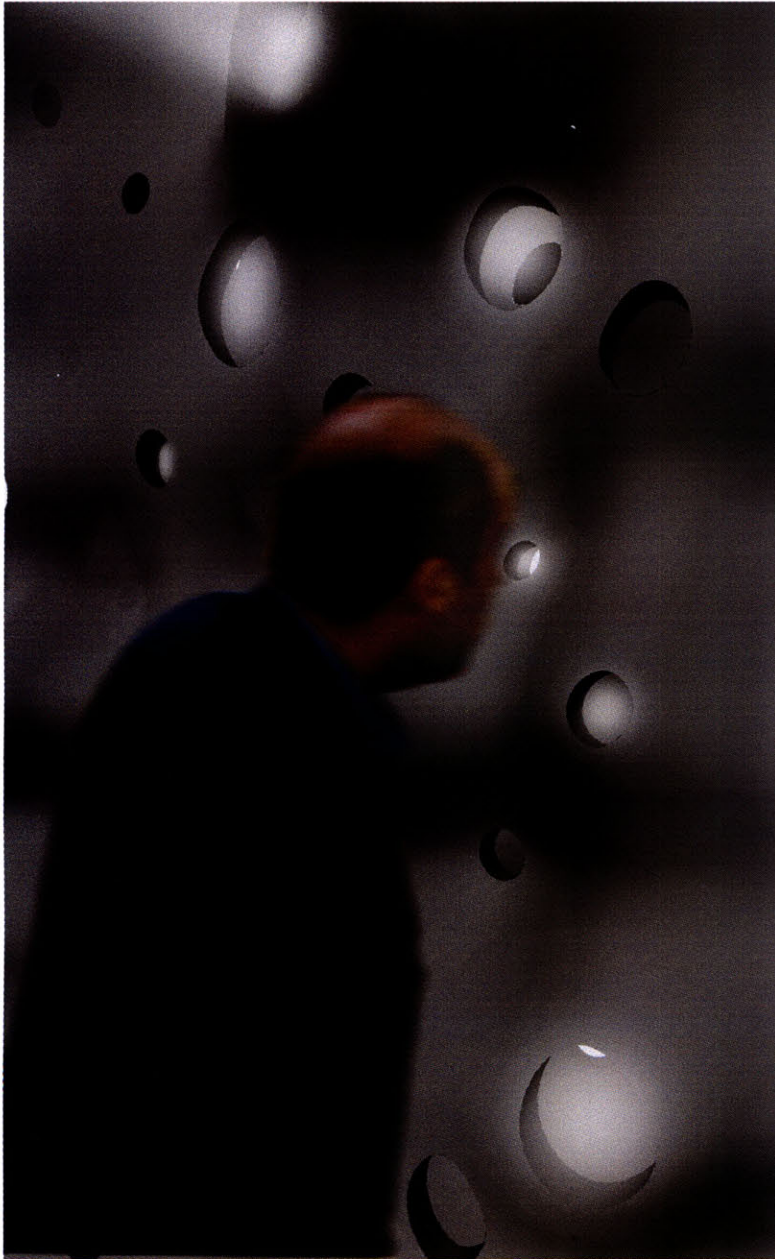


Fig. 134. (Left) RENDERING OF NOISE BARRIER ON SITE.

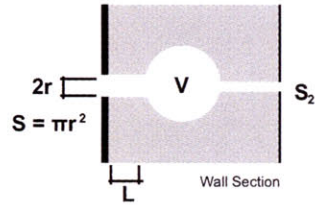
The large undulations help the rigidity of the self-standing wall. Continuous arch of large bumps created by controlling the location of small spacers can be observed. Forces from the self weight of the wall is focused on the foundation. Small perforations allow some visibility through the wall in the rendering but will improve by the kinematic effect from the moving driver. The uneven top edge of the wall helps scatter the noise, helping reduce the amount of noise passing over the wall. Furthermore, the density of the wall becomes lighter near the top creating an illusion of the wall disappearing into the sky when perceived at high speeds.

Fig. 135. (Right) IMAGE OF WALL FROM THE OPPOSITE SIDE OF THE HIGHWAY.

Pedestrians are able to walk up to the wall and experience it at a tangible scale. Small perforations become peek holes to see the other side of the wall. At night time, the lights from the vehicles will pass through some of the holes illuminating this side of the wall.

Fig. 136. Modified Section of the Helmholtz Absorber.

In theory, the frequency of the noise absorbed changes according to the increase in the surface area of the opening.



$$Fr = (340/2\pi) \times ((S+S_2)/VL)^{1/2}$$

Fr (Hz) : Frequency of absorbing sound

V (m³) : Volume of cavity

S (m²) : Area of opening

L (m) : Length of neck

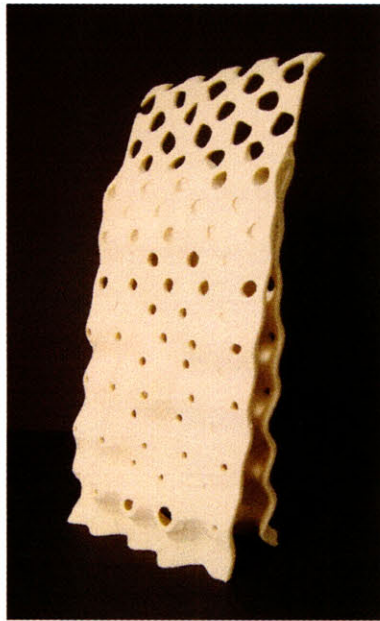


Fig. 137. Section Model Of The Wall
(first test print)

SOUND TESTING

The acoustic properties of the wall (helmholtz + kinematic effect) was tested using scaled down 3D printed models. Felt was added to the model to simulate the embedded layer of sound absorbing fabric used to cast the inside surface of the wall.

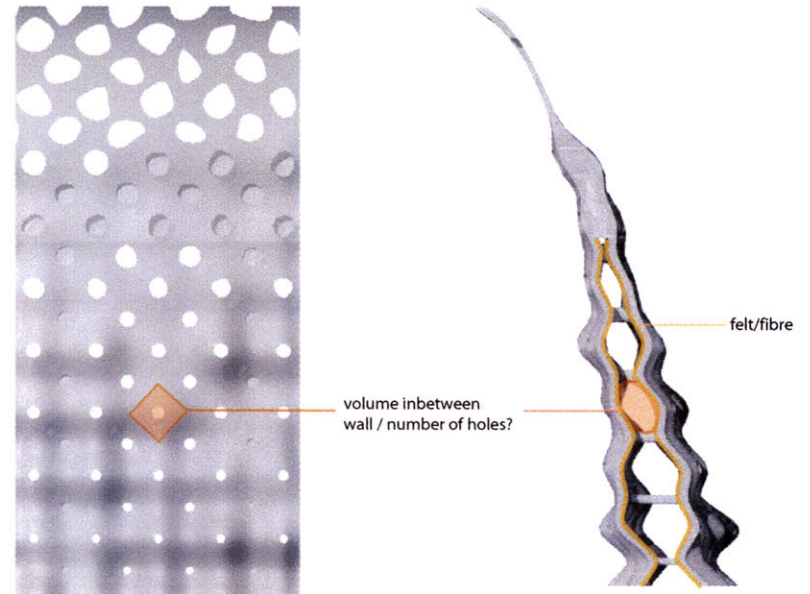


Fig. 138. Diagram of how the wall works in theory

Instead of gathering small bottles with individual holes, one large cavity has many small holes. In theory, the volume of the cavity used for calculation is **TOTAL VOLUME / NUMBER OF HOLES**

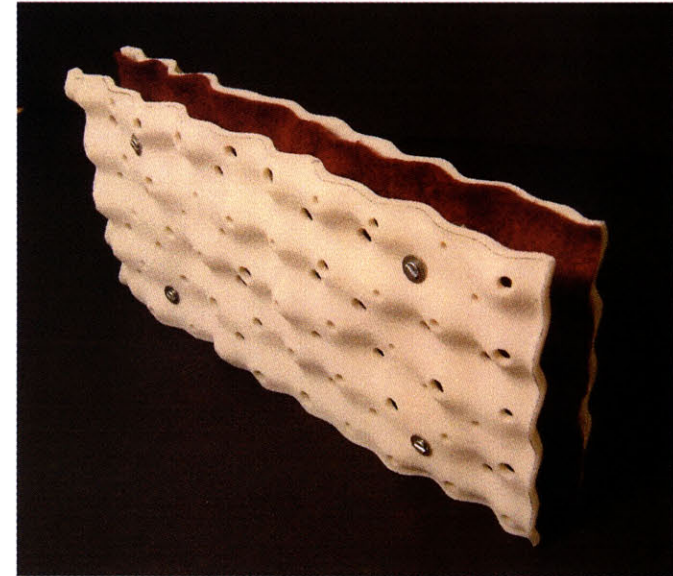


Fig. 139. Model for Sound Testing

Zcorp model is lined with a layer of felt. At full scale, a sheet of sound absorbing fabric is used as left-in-place formwork for the inner surface of the wall.

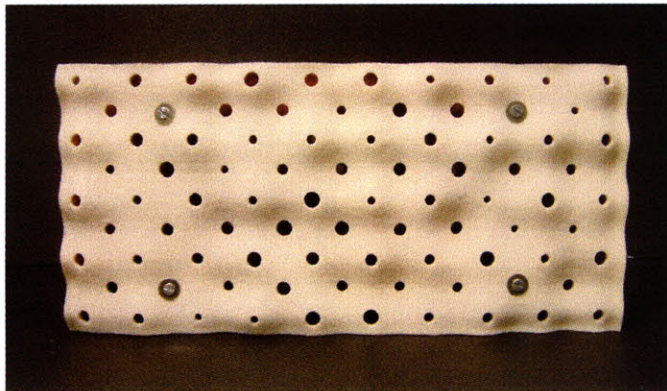


Fig. 140. Side Facing Highway.

Shows the perforations at different sizes.

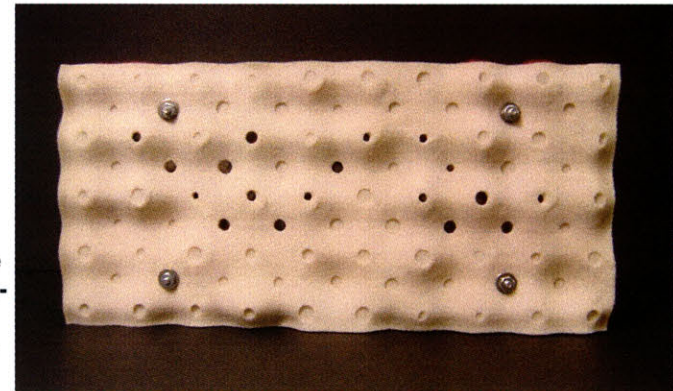
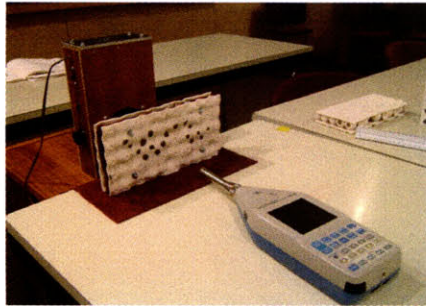


Fig. 141. Side Facing Neighborhood.

Some holes are filled in.

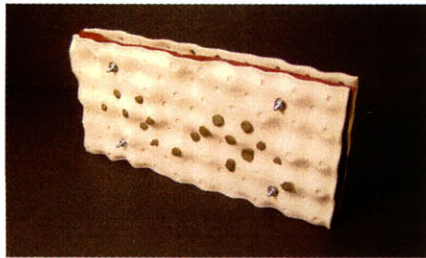
**Fig. 142. TEST-
ING METHOD.**
Wall is placed in
between the speaker
and the recorder.



**Fig. 143. MODEL1
(with holes).**



**Fig. 144. MODEL1
(no holes).**
Holes are filled in with
clay.



Noise blocking test

Using clay to fill in the holes, noise attenuations levels were measured for the wall with holes and walls without holes. Also, as a comparison, the performance of the test model was compared to a solid wall of same dimension. The results show that the test model behaves better acoustically compared to a solid model which uses much more material and holes do not have a large effect on the attenuation levels.

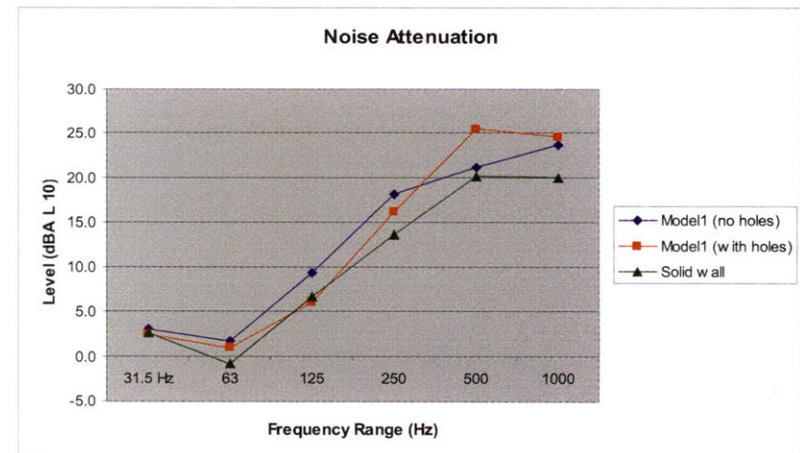


Fig. 145. GRAPH OF NOISE BLOCKING TEST.
Shows that Model1 behaves better than a solid wall and the holes do not make a major difference in the attenuation levels.

Noise reflection test

Amount of noise reflected off the wall was measured. Compared to a solid wall with no absorbing properties, the test model reflected less noise. Combining with the results of the block test, the test model is not only blocking noise but absorbing it even with small perforations extruding through the surface.

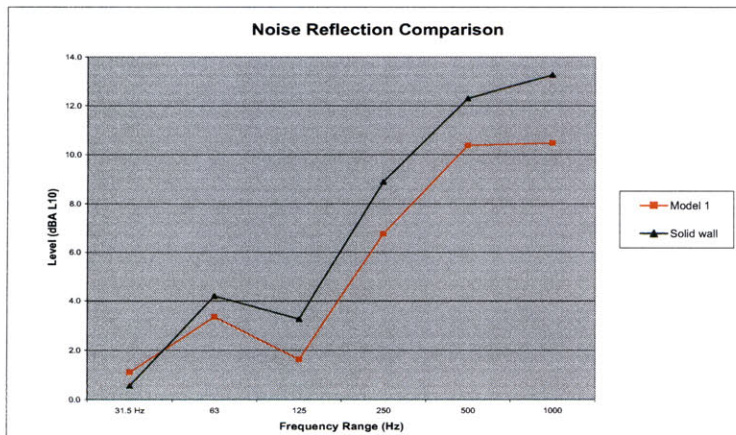


Fig. 148. GRAPH OF NOISE REFLECTION TEST.
Less noise is reflected when using Model1 compared to a solid wall.



Fig. 146. TEST-ING METHOD.
Wall is placed in front of the speaker and the recorder behind the speaker.



Fig. 147 MODEL1.

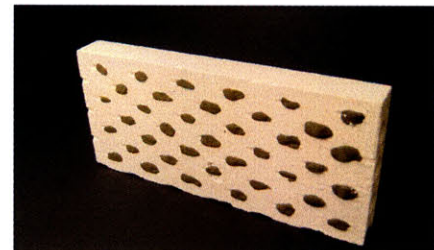


Fig. 149. SOLID WALL.

Top Edge Condition

Top part of the wall has larger perforations for two reasons. First reason is to use the kinematic effect to make the wall more transparent near the top, creating an illusion that the wall is lower than its actual height. Second is based on a study done by Eric J. Busch-Vishniac, arguing that making the top edge of the wall random helps reduce the amount of noise reaching over the wall.

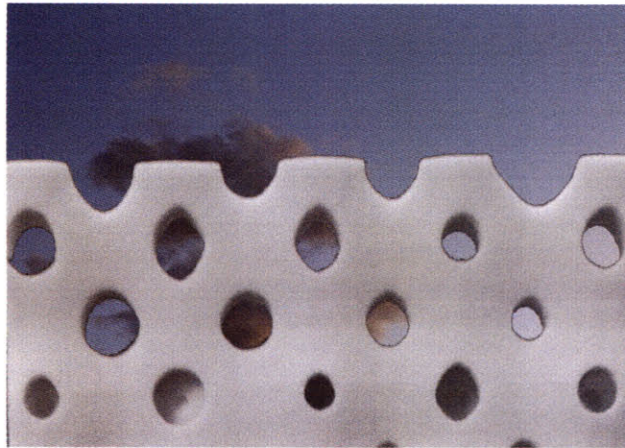


Fig. 150. TOP EDGE OF WALL.

The walls becomes more transparent as one perceives it at faster speeds.

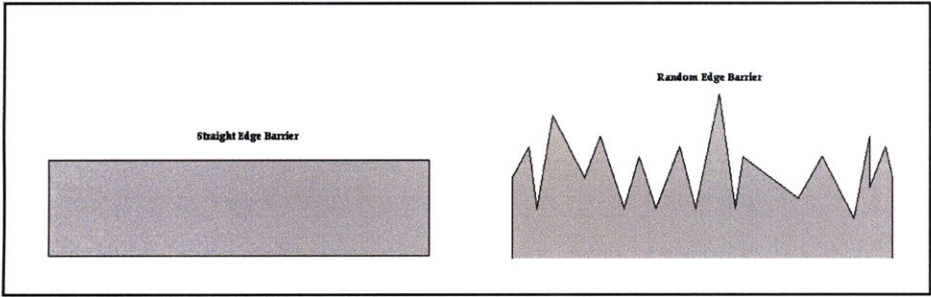


Fig. 151. STRAIGHT EDGE AND RANDOM EDGE. (Same average height)

Eric J. Busch-Vishniac's (Univ. Texas at Austin) studies show that compared to straight edge barriers, noise barrier with random edge conditions reduce sound energy between 16-50% by scattering diffraction noise caused at the top of the wall.

Acoustical Society of America 133rd Meeting Lay Language Paper 2pNSa4



MOCKUP

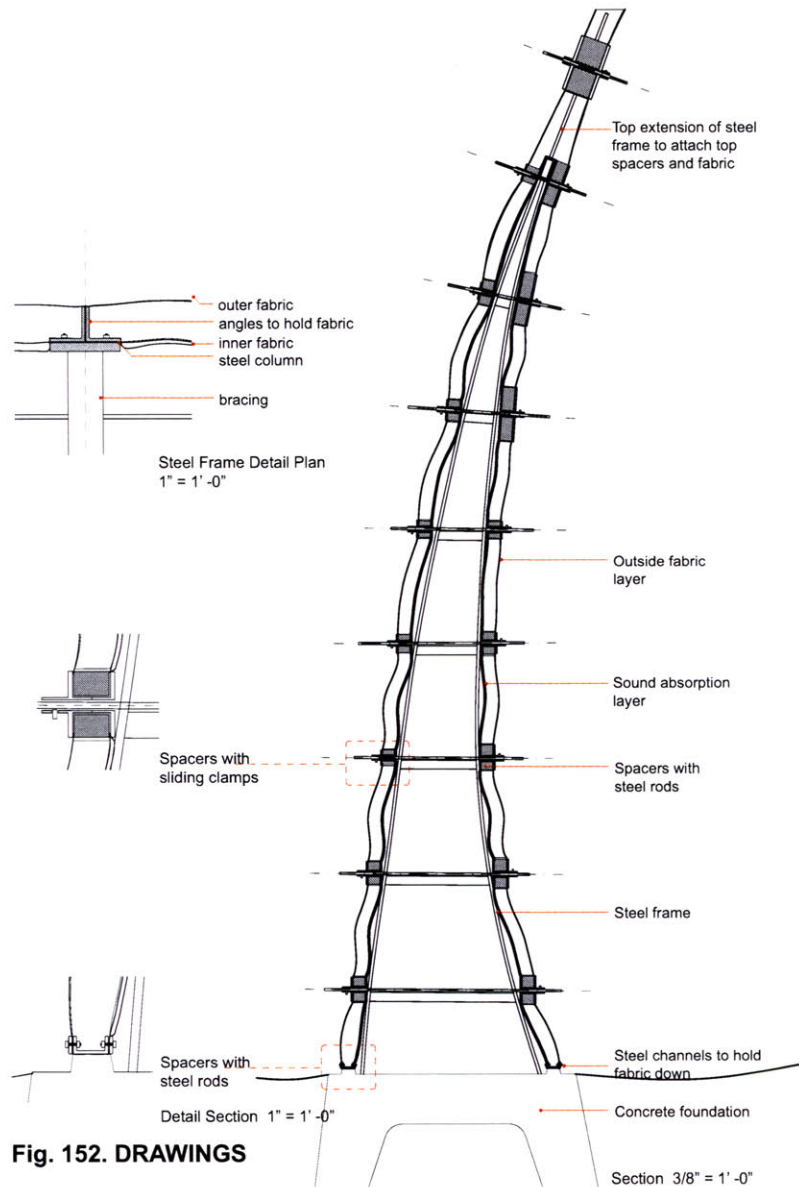


Fig. 152. DRAWINGS

1:2 scale mock up of the formwork system was built to test out the proposed construction method. Using very simple rules mostly dependant on the size and location of the foam spacers, there is no complicated shop drawings for the formwork (drawings on the left describes how the system will be installed on site but are not construction drawings for the formwork). However the end result of the wall will be precisely controlled and efficient in terms of structure and acoustical properties. Most of the formwork construction will be done off site to minimize working time on site. Using fabric and foam is a great advantage in terms of storage and transportation. Outer layer fabric and spacers will be removed and recycled.



Fig. 153. CONSTRUCTION SEQUENCE 1. Sound absorptive fabric is attached to the fabric.

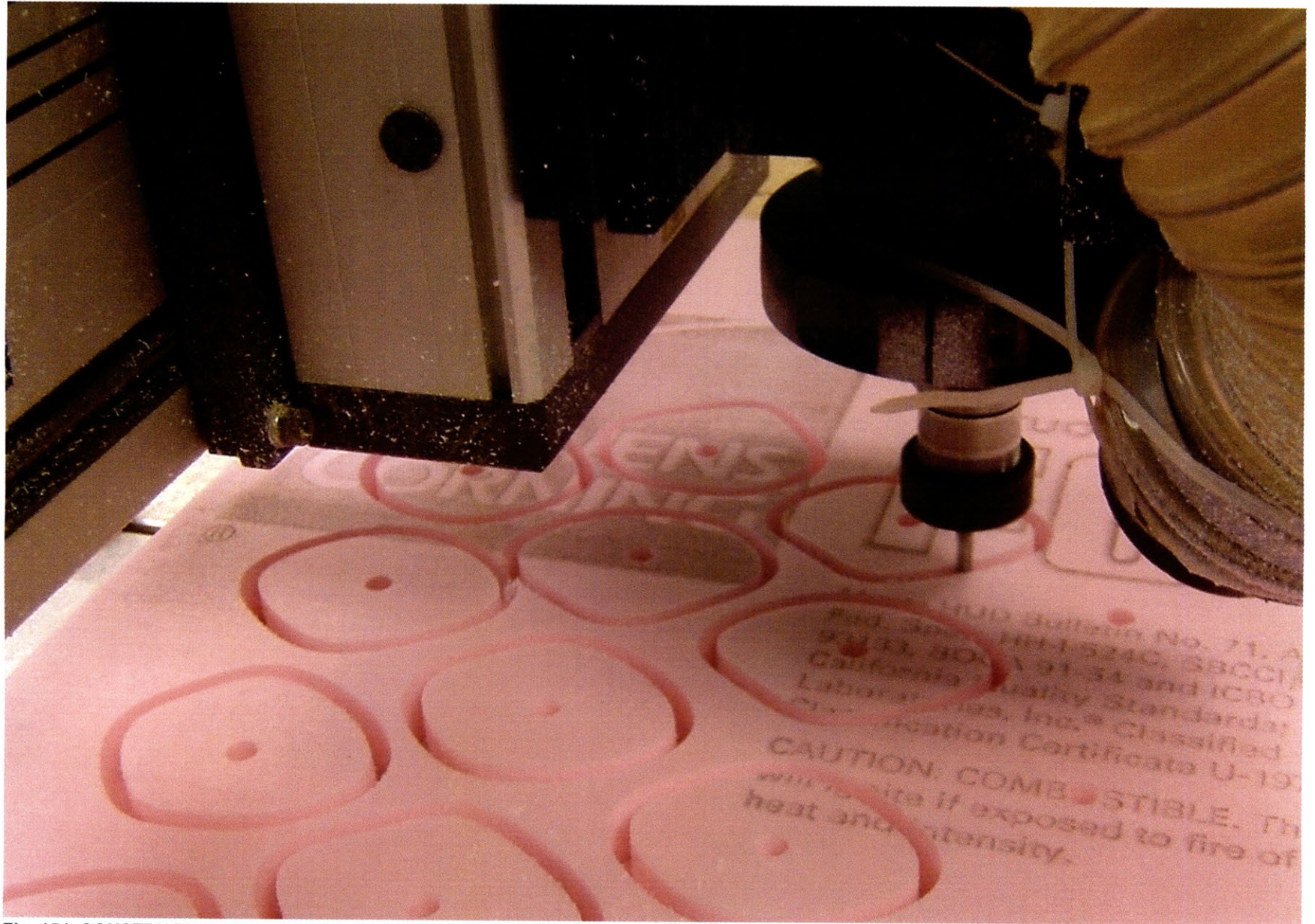


Fig. 154. CONSTRUCTION SEQUENCE 2. Foam spacers are milled on CNC controlled milling machine.

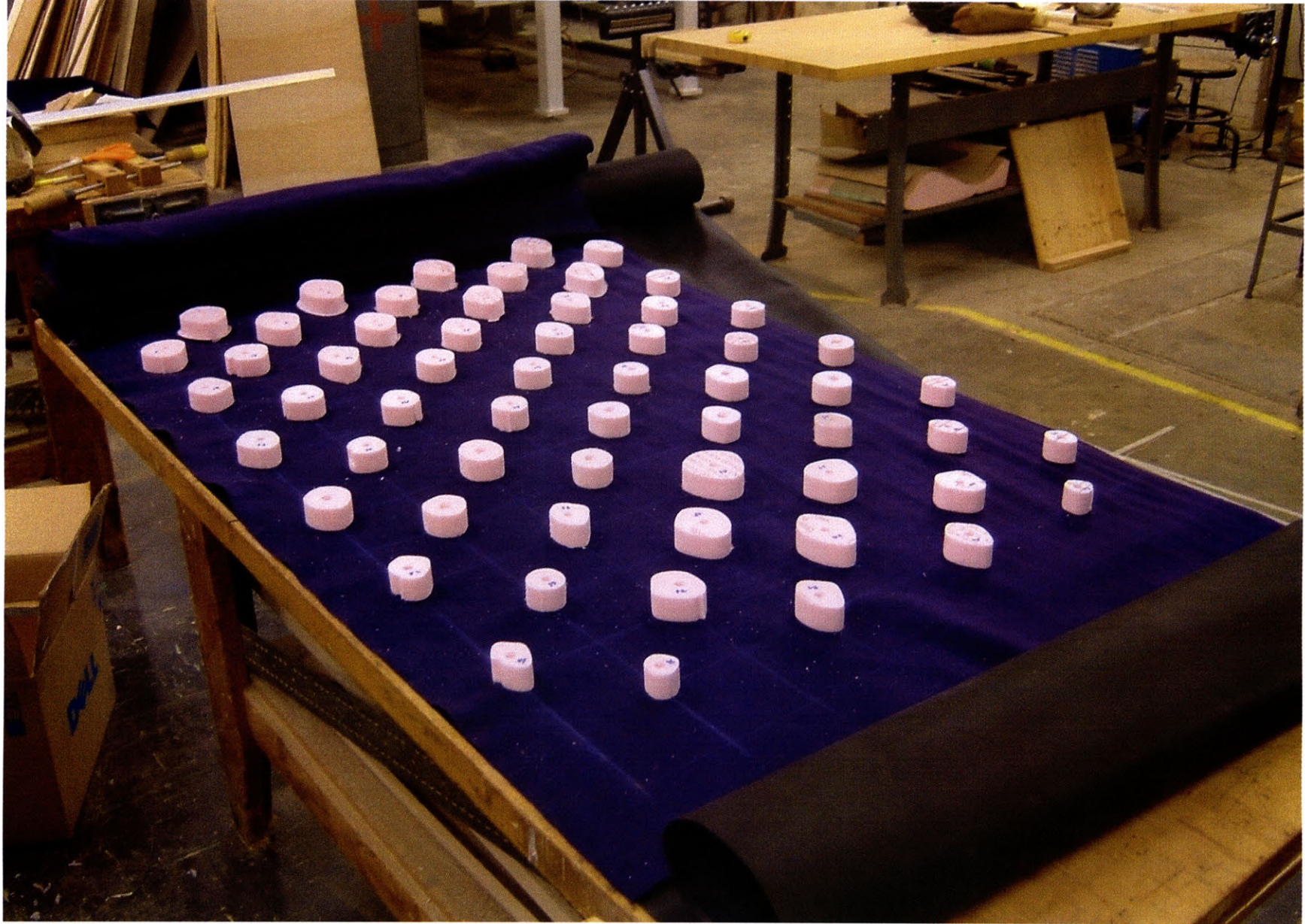


Fig. 155. CONSTRUCTION SEQUENCE 3. Foam spacers are attached to the fabric.



Fig. 156. CONSTRUCTION SEQUENCE 4. Steel rods are attached to the fabric by the foam spacers..

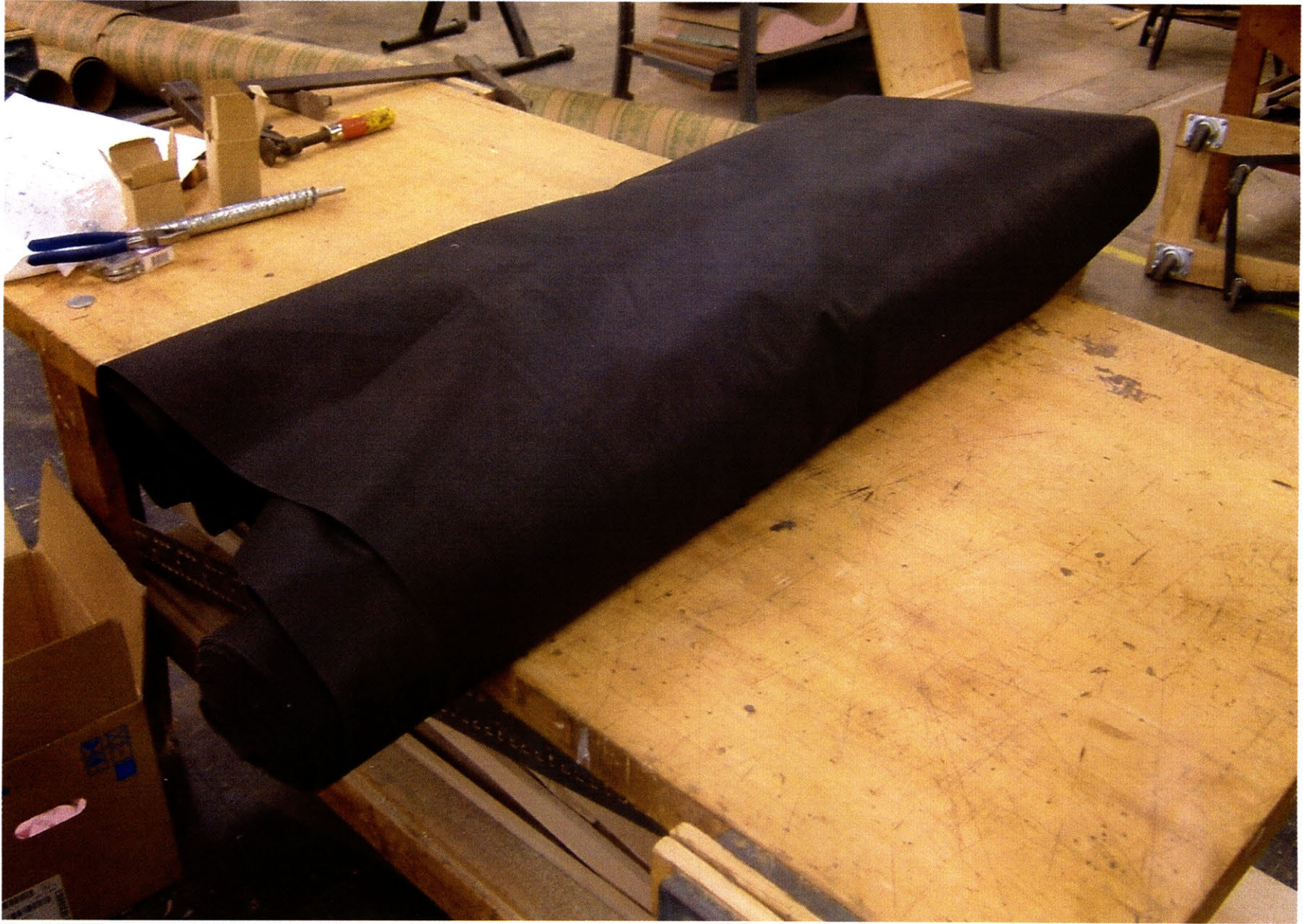


Fig. 157. CONSTRUCTION SEQUENCE 5. Fabric is rolled up for transportation to site..

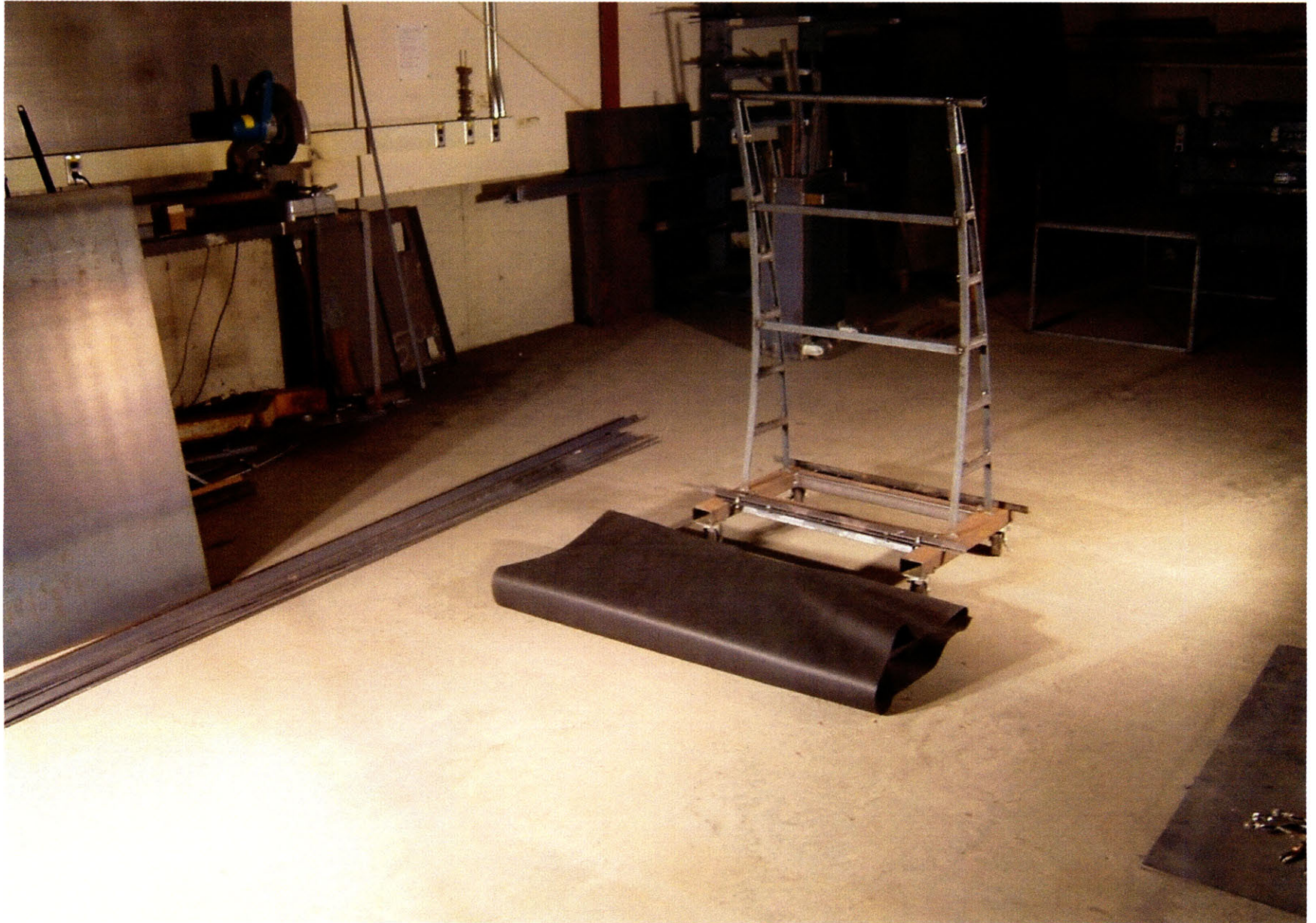


Fig. 158. CONSTRUCTION SEQUENCE 6. Steel supports and foundations are installed on site.

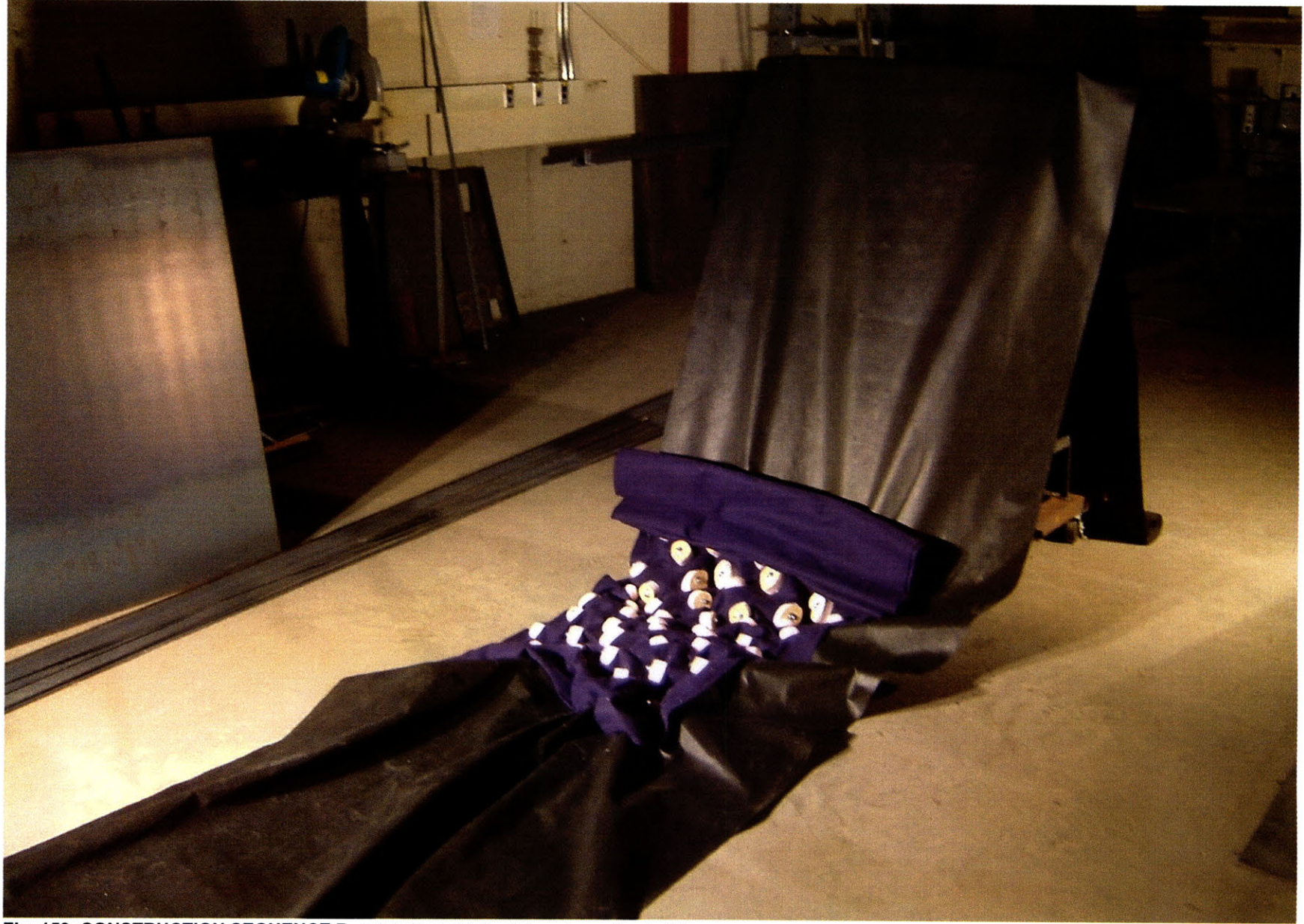


Fig. 159. CONSTRUCTION SEQUENCE 7. Fabric is unrolled and draped over the steel frame..

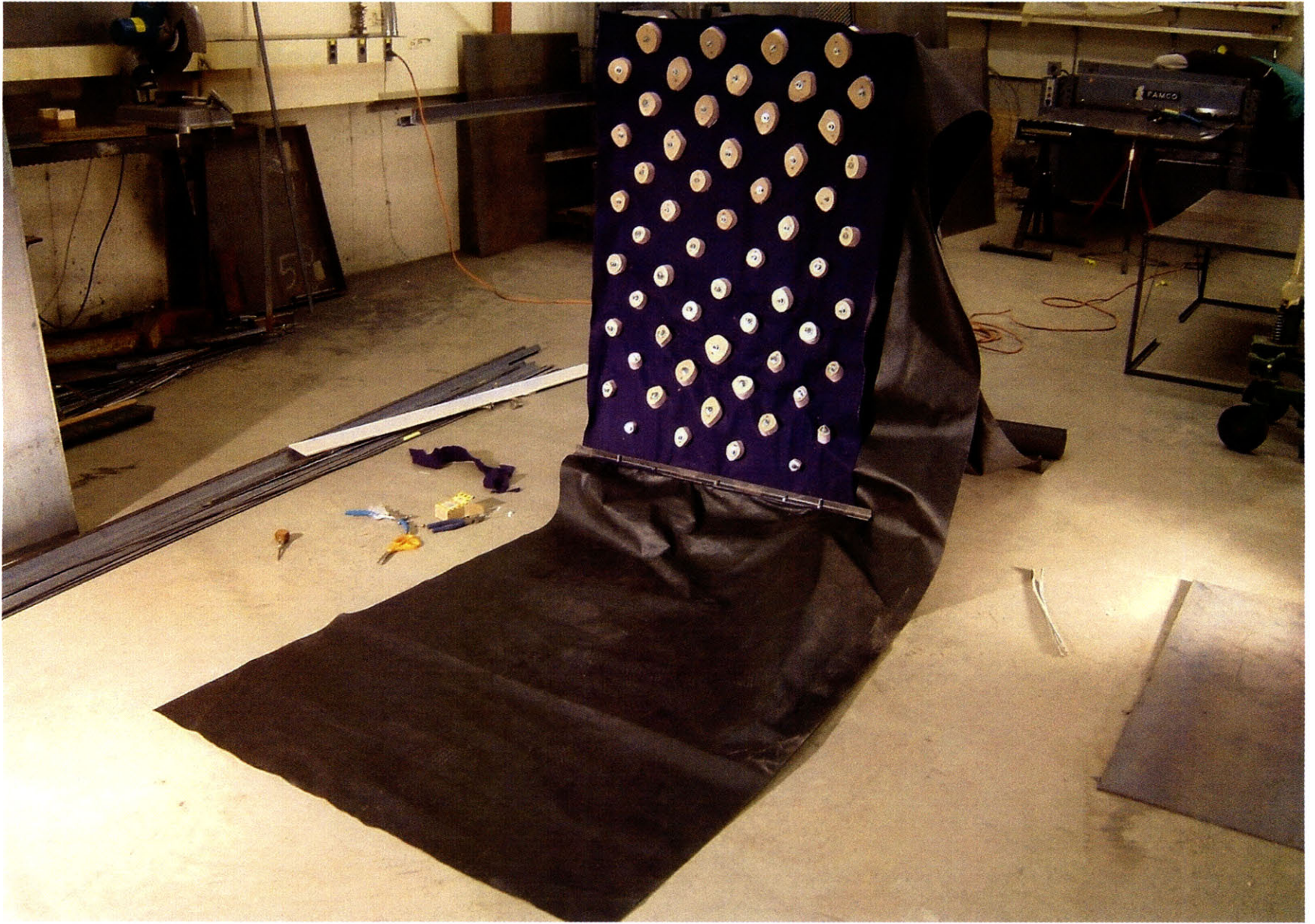


Fig. 160. CONSTRUCTION SEQUENCE 8. Fabric is fixed to the steel frame at the top and bottom.

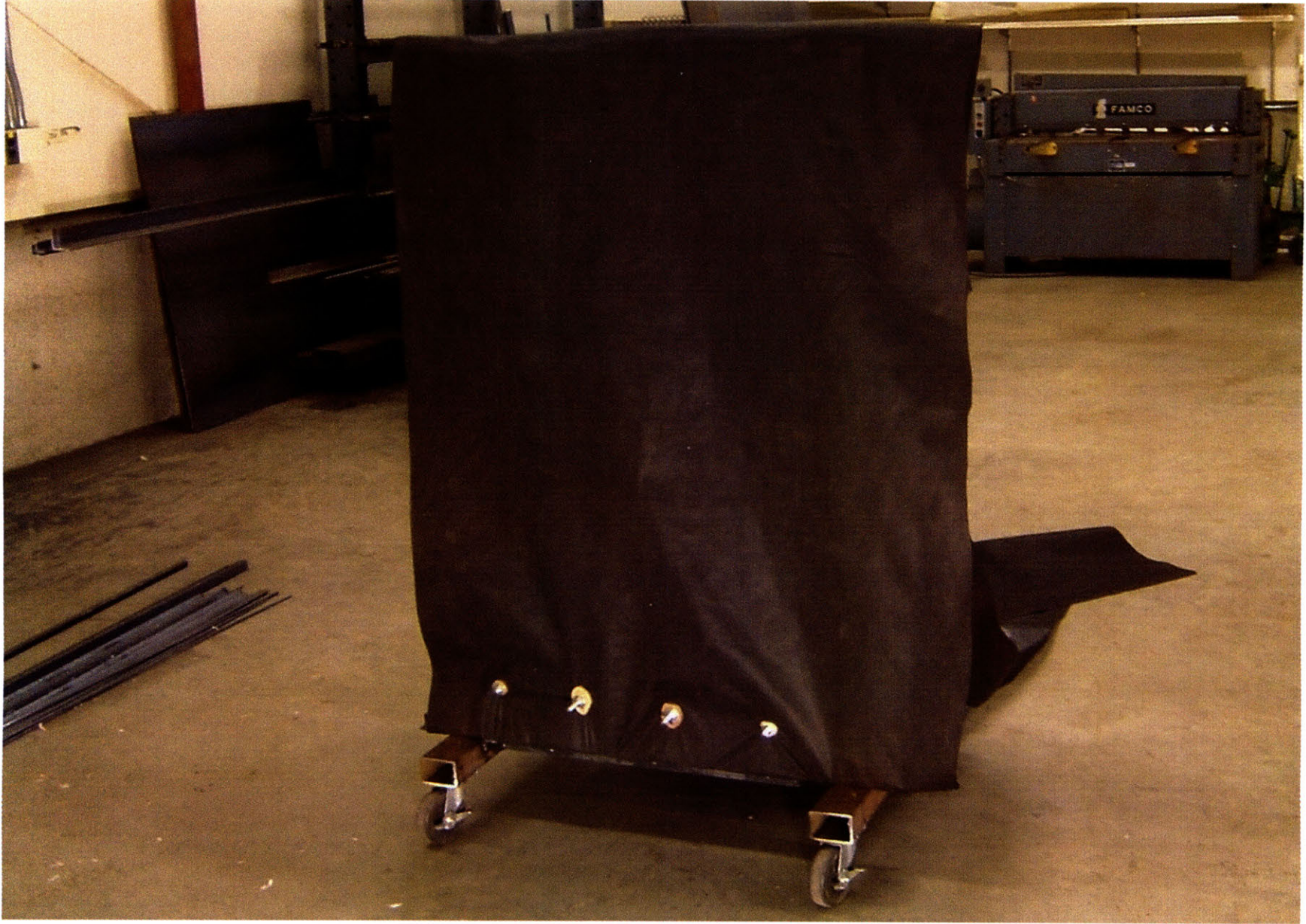


Fig. 161. CONSTRUCTION SEQUENCE 9. The outer fabric is folded backup and fixed to the spacers.



Fig. 162. CONSTRUCTION SEQUENCE 10. Spacers adjusted to stretch the fabric tight.

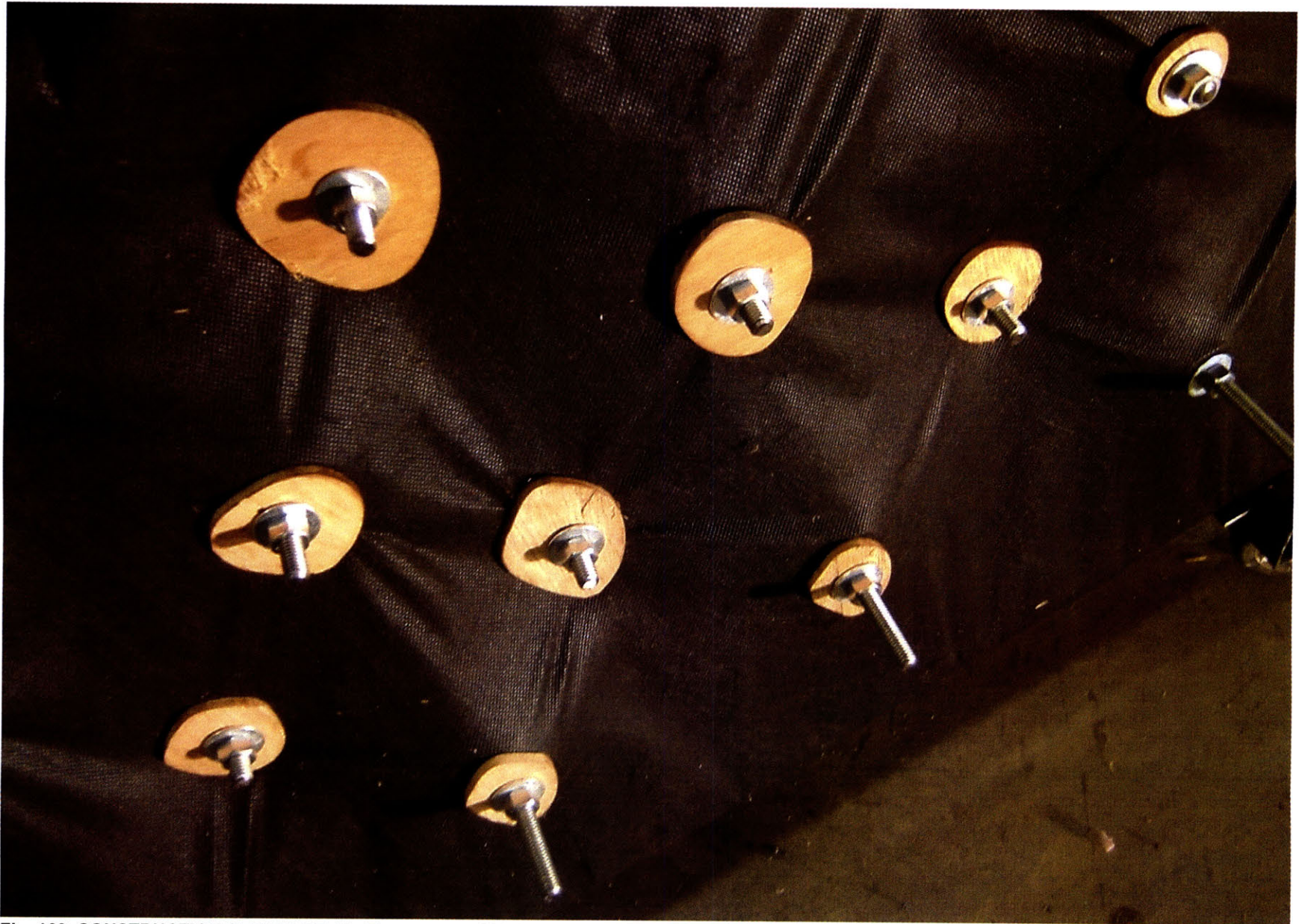


Fig. 163. CONSTRUCTION SEQUENCE 11. The curvature of fabric after adjustment of the spacers.



Fig. 164. CONSTRUCTION SEQUENCE 12. The outer fabrics are brought together at top of the frame.

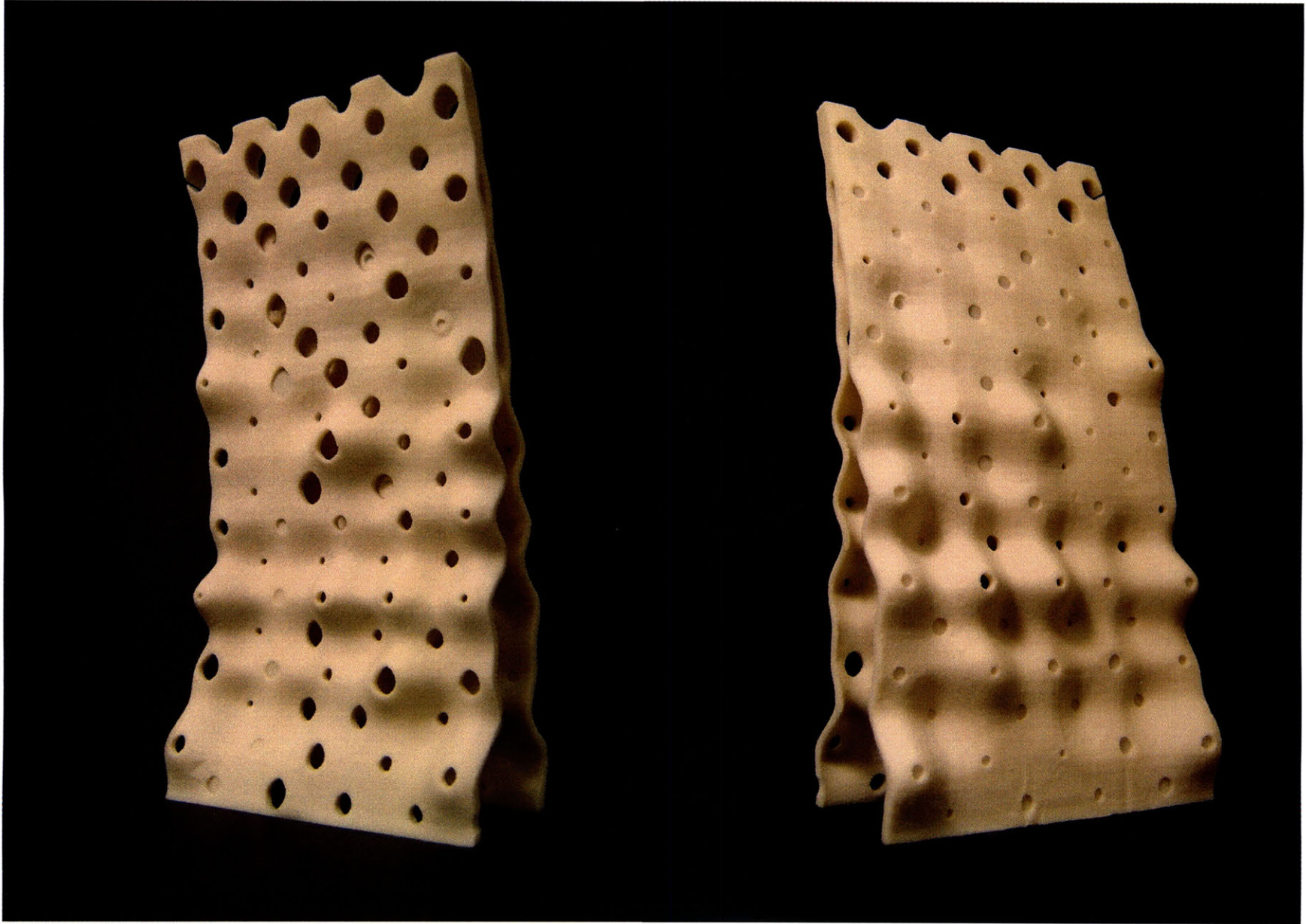


Fig. 165. WALL SECTION. 3D printed scaled down model.

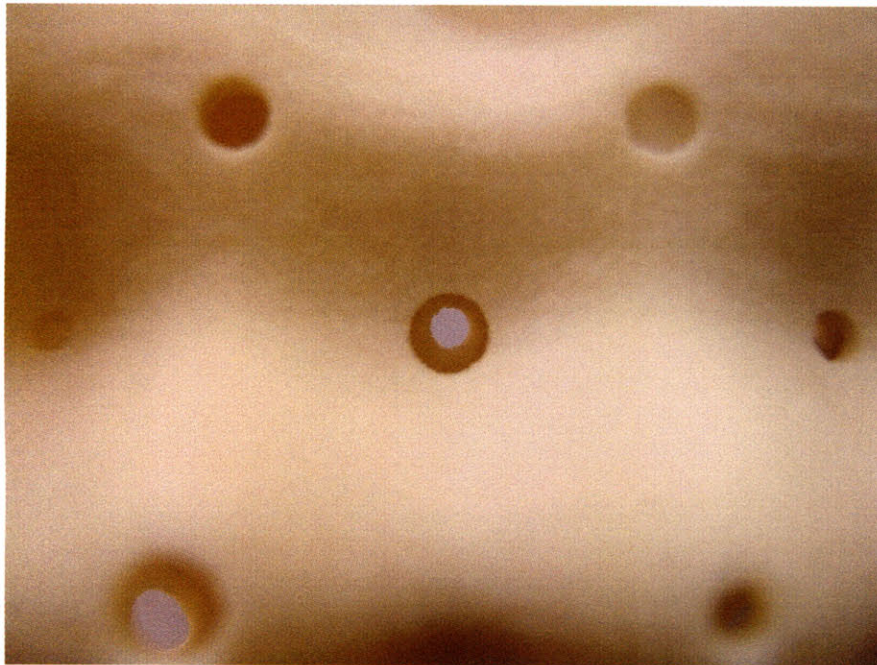


Fig. 166. 3D PRINT MODEL.
Close up view of the wall and the hole.

**Fig. 168. (RIGHT)
ELEVATION VIEW**

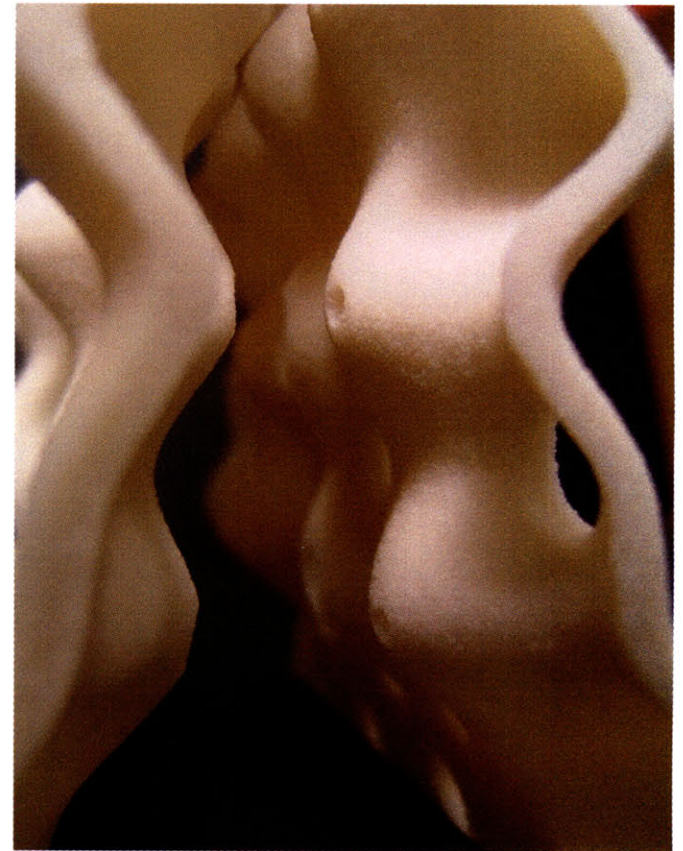


Fig. 167. INSIDE OF THE WALL
The air trapped inside will absorb the sound..

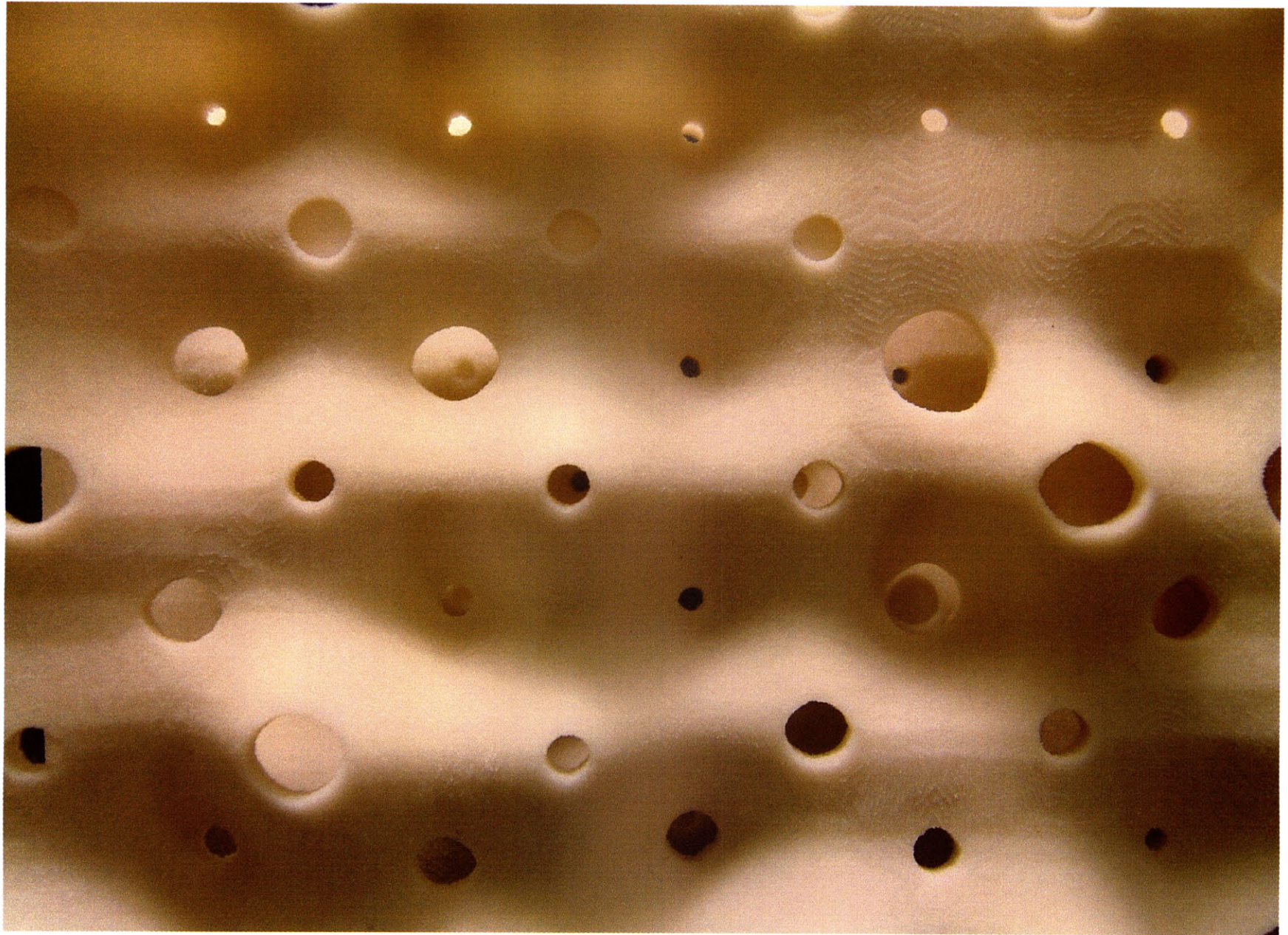


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