FABRICATION OF CONCRETE MODULAR SURFACES FOR ARCHITECTURE

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December 17, 2010

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Introduction

This is an examination of the past, present and future of concrete surface structures, and an argument for the continued and expanded application of these structures through the use of modular design and fabrication with the use of textiles. In order to reinforce this argument, it is necessary to define what the early pioneers of thin-shell concrete surfaces discovered, developed and contributed with their methods. These methods include the topics of design, formwork and construction. Developments in the areas of these topics are based on the initial groundwork by those early pioneers. All this leads to the understanding of thin-shells structure as we know them today, and how they are affected by geometry. Originally, those who designed geometrical surfaces did so with a hardy amount of calculations by hand. Thanks to recent advances in three-dimensional digital software, textiles and innovations in fabric formwork, a whole world of new opportunity has presented itself.

While preparation for this document started with the concept of digital fabrication, it is necessary to understand the methods of construction of concrete thin-shell surfaces, both past and present as a point of departure. An understanding of this background helps provide an essential foundation for the exploration of new potential advances in the field of thin-shell construction. This paper will examine how traditional methods of thin-shell construction can now be transformed with fabric formwork and recent advances in three-dimensional software in order to produce a modular building system.

The reason for tying into modular building systems as an end goal was due to the influence of mostly research and a bit of intuitiveness. Through research and examination of certain pioneers, the author realized that not only was the idea of modular systems intuitive, but was also an endeavor that some pioneers both past and present have been seeking. What's more is that in order to conclude this exercise, it is important to offer not just methods and techniques of thin shell, but to describe a truly holistic manner in which to deploy the concepts resulting from this investigation.

In their book Refabricating Architecture, Stephan Kieran and James Timberlake make an argument for modular construction by comparing the building industry with other industries already employing modular production. As part of their research they traveled across the country to large manufacturing facilities such as Boeing Aircraft in Everett, Washington and Detroit automaker DiamlerChrysler. They also looked at smaller companies such as Delphi Systems, an electronics component manufacturing firm in Troy, Michigan. In addition they visited the Kvaerner Shipyard in Philadelphia, Pennsylvania, site of one of the most innovative shipbuilding companies in the world. The most important issue their research pointed out was that while design engineers have accomplished great strides in making use of new strategies in manufacturing, architects have remained satisfied in their old "tried and true" methods. Architecture is more than just designing the images and documents used for construction; it also encompasses describing the methods and technologies to be used to erect a building. From their beginnings, the concepts of architecture have built upon the idea of jointure, where each piece is placed one by one, with each dependent upon the preceding one, and all having a relationship with one another. This is what is referred to as "bottom-up" construction. Kieran and Timberlake make the distinction between architecture's current methodologies, which are still closely linked to its original concepts of piece-by-piece construction, in contrast to the possibility of new methods of building through assemblies or "topdown" construction (Kieran & Timberlake, 2004).

> "This new architecture requires different theories and forms of joining. The joint used to be a part-by-part certainty. If you had a part, there would be at least one, or even many, joints between it and other parts. When assemblages, be they cars, ships, aircraft, or buildings, were constructed one part at a time, from the bottom up, then from the frame inward and outward, the art of joining was a craft that developed to resolve the relations among a vast number of parts."

Kieran and Timberlake inform the reader that, "Construction is no longer linear and it no longer proceeds from the bottom up." They illustrated this using several terms such as blocks, chunks, and modules, which were all terms used by those other industries mentioned previously. The idea is that the hierarchy of building a final product is not a matter of individual pieces, but rather an assemblage of pre-built or pre-constructed modules or components which produces a better end result. This top down thinking of construction is now producing tighter tolerances, fewer parts and higher quality items such as that of cars, planes and ships.

Architecture is already beginning to see the gradual incorporating of off-site and on-site premade components. However it seems currently that building construction is still predominantly top down in its methods with some exceptions. Kieran and Timberlake's argument has merit in that construction of architecture will benefit from the lessons learned in these other industries.

A History of Thin Shell Construction

In discussing the history of thin-shell concrete there are four individuals who are among the most frequently mentioned. They are Pier Luigi Nervi, Eduardo Torroja, Anton Tedesko, and Felix Candela. Together these four architects, engineers and designers became known as the "New Expressionists," and their movement as "The International Style."

The oldest, although not necessarily the first, was Italian Pier Luigi Nervi. Born in Sondrio, Lombardi in 1891 and educated at Bologna University, Nervi was part of the postwar movement of Italian Creativity. He began work as an Engineer and contractor in 1923, and promoted bringing engineering and architecture back together. As a builder and a mentor, just as structure was important, he put an emphasis on esthetics as well (Huxtable, 1960).

Nervi first worked with conventional reinforced concrete, and stressed the role of intuition in building with these materials. This led to his development of Ferro-Cement a thin, flexible, and

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elastic material. Composed of several layers of fine steel mesh that was ductile, it turned out to be very strong. Because of this, Nervi was able to make a revolutionary advancement in form-making, allowing the elimination the wooden planking, which had been responsible for limiting forms to rectilinear shapes. And with the use of Ferro-Cement, it became possible to prefabricate parts; and putting these Ferro-Cement forms on movable scaffolding made speedy accurate construction possible (Huxtable, 1960). Plus, they made it so that any desirable shape could be built, such as curving ribs or undulating slabs. This allowed Nervi to try new aesthetics. Among Nervi's successful designs using this idea were the Grand Solone "B" of the Turin Exposition Hall, built in 1948 and 1949 (see fig. 1 and 2), the Tobacco Factory at Bologna, completed in 1952 (see fig. 3), the Turin Fiat Plant, finished in 1955 (see fig. 4), and the UNESCO headquarters in Paris in 1957 (see fig. 5).



Figure 1 - Nervi's Grand Solone "B" of the Turin Exposition Hall Built 1948 - 1949 (Pica, 1969).



Figure 2 -Section of Nervi's Grand Solone "B" of the Turin Exhibition Hall (Jurgen Joedicke, 1957).



Figure 3 - Interior of Tobacco Factory Bologna completed 1952 (Jurgen Joedicke, 1957).



Figure 4 - Fiat Factory Interior which now serves as a mall and university, Turin, completed 1955 (www.benedict-evans.com).



Figure 5 - UNESCO Headquarters, Paris 1957 (Jurgen Joedicke, 1957).

Finally, not only did Nervi's works show the efficacy of this process, but they also proved that the monolithic qualities were not disturbed by breaking the structures down into prefabricated parts. In fact, the strength of this prefabricated construction was demonstrated after the war when the Germans tragically dynamited hangers he had designed. Even after demolition, the joints still held together.

Born later, in 1899 in Madrid, Spain, Eduardo Torroja probably began working with concrete structures somewhat earlier than Nervi. According to Garlock and Billington, Torroja started designing concrete structures in the late 1920s, and the mid- 1930s. At that time, interest in concrete structures spread internationally and was especially intense in both Germany and Spain, but with different expectations. In Spain, this difference was because of the regional influence based upon Catalan culture. For example, the architect Gaudi was notorious for rejecting nineteenth century façade design methods, and this would influence Spanish designers like Torroja to emphasize "smooth ribless surfaces."

Torroja's education was in Civil Engineering. By 1934 he had an accomplished history of designs in concrete shell structures and along with Jose Maria Aguirre, founded the Experimental Institute for New Uses and Theories for Reinforced Concrete. Later, in 1958, he would organize the First Congress of International Association for Shell Structures. Organizing this was in part due to the need for answers and further papers stemming from a paper written by German Heinz Isler, called <u>New Shapes for Shells¹</u>.

One of Torroja's important projects in concrete shells was the roof of the Zarzuela Hippodrome, a racetrack in Madrid, upon which he constructed a hyperboloid shell to cover the stands (see fig. 6 and 7). At approximately the same time, 1935, he also built the Fronton Recolectos. Using a single-barrel shell and lacking the stiffening effects of a double curvature system, this project was weaker than the Hippodrome, and was destroyed in the Spanish Civil War.



Figure 6 - Torroja's Hippodrome, Madrid, built 1935 (Garlock & Billington, 2008).

¹ Hienz Isler is well recognized as another important pioneer of shell design. He further invented the first pneumatic form. For more information see Felix Candela: Engineer, builder, Structural Artist (Garlock & Billington, 2008).



Figure 7 - Section of Torroja's Hippodrome (Garlock & Billington, 2008).

1935 was also the year that Felix Candela graduated from La Escuela Superior de Arquitectura (Madrid Superior Technical School of Architecture). After graduating from the Madrid Superior Technical School, he went to Germany to further his studies, where he studied Materials under Professor Luis Vegas. He came back to Spain with the outbreak of the Spanish Civil War, where he sided with the Republic against Francisco Franco and the Nationalists. After Franco won the war, Candela was exiled to Mexico, where he began his career.

Being Spanish-born, he was an avid admirer of Torroja's works, which helped him develop the belief that that strength should come from form not mass. It was certainly Torroja's influence that would eventually lead to Candela's extensive use of hyperbolic paraboloids, for which his name would eventually become virtually synonymous (South, 2005). And although Candela was not the first to use thin shells, from 1949 on he designed and built many ferro-concrete structures. By 1953 he had fully developed as perhaps the greatest practitioner of shell design, and became known as "The Shell Builder." Among the many examples of his work showing his development and skill in

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these areas are the Cosmic Ray Pavilion built in Mexico City in 1951 (see fig. 8 and 9), the Santa Fe Band Shell, Mexico City, 1956 (see fig. 10), and the Los Manantiales Restaurant at Xochimilo completed in 1958 (see fig. 11 and 12). In 1960 he built the Bacardi Rum Factory, in Cuautitlan using three groined vaults. Later in 1971, he expanded it to six (see fig. 13) (Garlock & Billington, 2008).



Figure 8 - Candela's Cosmic Rays Pavilion (UNAM, Mexico City 1951) as it looks today (Garlock & Billington, 2008).



Figure 9 - Cosmic Rays Pavilion exploded view and section (Garlock & Billington, 2008) (Bechthold, 2008).



Figure 10 - Santa Fe Band Shell, Santa Fe, Mexico City 1956 (Garlock & Billington, 2008).



Figure 11 - Los Manantiales Restaurant at Xochimilo 1958 (Garlock & Billington, 2008).



Figure 12 - Section and Elevation of Los Manantiales Restaurant (Fabor, 1963).



Figure 13 - Interior of Bacardi Rum Factory showing vaulted ceilings 1960 with more vaults added onto in 1971 (Garlock & Billington, 2008).

The last of the "New Expressionists" was Anton Tedesko, born in Germany in 1903. And even though he was born after both Nervi and Torroja, and was educated in Austria, he became the first notable shell builder in the United States. Todesko came to the U.S. in 1932, when he was sent here by his German employers, Dyckerhoff and Widmann, who had been hired by the Carl Zeiss Company to help build the Dome on the Hayden Planetarium in New York, to house their Zeiss Projector (South, 2005). This dome, according to Eric Hines and David Billington, was the first fullscale concrete thin-shell built in the US (see fig. 14). Tedesko went on to build two more notable structures including the Brook Hills Farm's dairy exhibit at the 1933 World's Exposition, and the Hershey Sports Palace in Hershey, Pennsylvania completed in 1936. The Hershey Sports Palace is notable for its use of the large-barrel ribbed vault design, which according co-authors David Billington of Princeton University and Eric Hines, in their November, 2004 article in the ASCE Journal of Structural Engineering, is one of two major innovations that Tedesko is known for. The other, according to their article was "ribless shell." For the Hershey Sports Palace, the large barrelribbed vault was used by Tedesko in a component or modular fashion (see fig. 15) (Billington & Hines, 2004).



Figure 14 - Hayden Planetarium, New York 1939 while under construction (Bechthold, 2008).



Figure 15 - Hershey Sports Palace, Hershey, Pennsylvania 1936 (Huxtable, 1960).

Geometry and Structures

One of the goals of this paper is to explain the importance of geometry in determining surface structures. According to Martin Bechthold in his book <u>Innovative Surface Structures</u>: <u>Technologies and Applications</u>, one cannot discuss surface structures without also bringing into context surface geometry. Hence, this paper will treat both "structures" and "geometry" as integral sciences (Bechthold, 2008).

Bechthold places surface structures into two categories, "Rigid," and "Non-Rigid." Rigid systems are made from "rigid materials that can be subject to compression, tension, bending and shearing," while Non-Rigid surfaces "consist of tension-only materials, fabrics, foils and cables." Non-Rigid equates to mechanically stressed and pneumatically pre-stressed structures, while Rigid equates to grid shells, shells and folded plates, hybrids and free-forms (Bechthold, 2008).

Bechthold further describes spatial structures as being divided into 3D systems and 2D systems. The three-dimensional structural approaches can be derived from the two-dimensional structural systems. The difference between these two systems, are that the two-dimensional systems can be analyzed using 2D modeling, and they can be supporting systems for other structural surfaces.

Basic shells and folded plates are related in that they behave like vaulted systems. An example of a vaulted system is a barrel vault, which behaves similarly to beam-like structures, and what Bechthold calls a 2D system. The same is true of folded plates. One problem with these 2D systems is that they tend to push outwardly and laterally at the bottom. Through Finite Element Analysis, FEA, a "double-curvature system," which Bechthold describes as a hybrid, but is also known as a 3D system, has the benefit of taking on greater loads and stresses. Double-curvature systems spread their loads evenly in all directions. The monolithic dome could be considered an

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example of one of these structures, as could an egg. In further defining a double-curved system, it could be described as a simple plane that is curved in more than one direction.

These systems themselves can be divided into two forms. The first being the "Positive Gaussian Curvature," also formally and more rarely known as a synclastic system (see fig. 16). The second is the "Negative Gaussian Curvature" or anticlastic system (see fig. 17). Positive Gaussian Curvatures are similar to the shapes of domes in found nature, such as the fore-mentioned egg. In architecture, an example of this type of curvature is Richard Meier's construction, Jubilee Church, in Rome, Italy (see fig. 18). The church's façade consists of three Positive Gaussian curved surfaces.



Figure 16 - Positive Gaussian Curvature (synclastic surface) (Bechthold, 2008).



Figure 17 - A Negative Gaussian Curve (anticlastic surface) (Bechthold, 2008).



Figure 18 - Richard Meier's Jubilee Church, Rome, and example of a Positive Gaussian Curve (Archnewsnow, 2003).

A major reason for their structural strength is that double-curvature systems spread their loads evenly in all directions. This can be illustrated examining the strength of the previously mentioned "egg." The ends are naturally-formed Positive Gaussian Curves, and are why the ends of an egg are stronger than its sides. Similarly, the Hyperbolic Paraboloids, like those employed by Candela and Torroja are so symmetrical that they work to cancel out much of the load (see fig. 19).



Figure 19 - A diagram showing a Curved Edged Hyperbolic Parabaloid (Billington & Hines, 2004).

Formwork Used in Concrete Construction

Formworks are used to make the molds needed to create the required shapes or forms for structural surfaces. Because their accuracy is crucial for structural integrity, they are among the most technical and critical concerns. Even after design analysis, the formwork itself must be an accurate representation of its design. If this is not the case it may not have the intended, and needed, structural strength, and therefore might not perform to load expectations (Bechthold, 2008).

Formworks for concrete construction, or Temporary Rigid Formwork, as Bechthold categorizes them, because of its low cost and availability, along with the lack of a suitable technology to otherwise, have historically been built out of timber. However, there are other considerations, its real cost. Even though timber is renewable, building wooden formwork is labor intensive, and the forms are usually discarded after a single use. This can be even more costly when considering the methods of many shell builders, such as Nervi and Candela, who not only used wooden formworks, but also wooden scaffolding; both of which they used very extensively. At the time, it worked well, as they were good for holding the weight of the construction workers as well as for the shoring of the concrete (Bechthold, 2008)(see fig. 20).



Figure 20 - Candela's Los Manantiales Restaurant showing immense timber formwork needed for support of concrete, workers and machinery (Fabor, 1963).

Another way of building rigid formwork is by using steel, which is more expensive. But steel formworks can reused, especially to make smaller serial type thin shell structures productions. Bechthold points out that the platform canopies for the Shawnessy light rail commuter station in Calgary, Canada, built in 2004, used a single steel formwork, which was repeatedly moved for each successive section. However, to this point, steel formwork has been limited in its use, primarily because of the cost, and size limitations. However, in his book, <u>Innovative Surface Structures:</u> <u>Technologies and Applications</u>, Bechthold notes that because of the prototyping and tooling work being done in both the aircraft and marine (shipbuilding) industries, medium to large milling machines are becoming increasingly common (Bechthold, 2008).

Recently, there has been an ongoing emergence of interest in alternatives to rigid formwork. New technology, including the new digital software, has created other reliable possibilities, including the use of fabrics and other materials. Among the reasons for this are cost and portability. One such possibility is CNC milled foam. This material is mounted onto a rigid based element for stiffening or support. This is similar to the technique used by Frank O. Gehry for an office complex in Dusseldorf, Germany. According to Bechthold, he did this to create complex wall shapes. Bechthold pointed out that even though there were no shell designs using this methodology at the time of the release of his book, accurate work could be generated from 3D software in this manner. Because the new digital software makes CNC milling possible, this type of production appears to be very credible, and is worthy of future investigation and research (Bechthold, 2008).

Another method of generating formwork is the use of previously placed concrete as a form. This method is used in tilt-up construction, but still requires timber or steel to form sides. Similar to this is the use of preformed concrete shells.

There are other materials used for formwork which may further prove to have the ability to resolve additional problems. Steel is not only used as formwork, it is also commonly used as shoring material. Because of its high strength, for less shoring material is needed, which in turn means there less congestion on the formwork (Mehta, Scarborough, & Armpriest, 2008). This reduces the waist of using wooden shoring, which requires more material, and can only be used once. Recently, also because of its strength, aluminum is becoming more frequently used. Plus because of its lighter

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weight, it is easier to use (Mehta, Scarborough, & Armpriest, 2008). Another new material that is finding its way into formwork development is glass-fiber reinforced plastic (GFRP). Because it is easily molded into shape and has a smooth surface is commonly used for floor systems and might also be a good possibility to making of components. GFRP can also be used to make molds of previously formed casts. It is a light weight, strong thermosetting plastic with glass fibers. GFRC is both strong in tension and compression. It is currently used in everything from boats to cladding used in architecture.

Fabric Formwork

Although there are many types of formworks to use, because of its potentially unique qualities, in this paper there is an added focus on the feasibility of fabric formwork. With its numerous advantages, combined with the use of digital software, fabric formwork deserves greater attention and exploration.

Among the main reasons are weight, cost, and reusability. Being lightweight fabric formwork has the ability to be easily shipped around the world (West, Thin-Shell Concrete From Fabric Molds, 2008). In addition to lowering transportation costs, it also creates savings in materials and storage, and because of their properties, they have the added advantage of being reusable.

As previously mentioned, due to the state of the current technology, stiffness in formwork was the only option in early shell building. The issue then is how this limitation can be overcome; how can work be produced by flexible materials, and yet still handle the rigors of construction such as equipment, workers and especially wet concrete? Accomplishing this will require new concepts in fabrication, such as those postulated by people like Mark West, the Director of the Centre for Architectural Structures and Technology, C.A.S.T, at the University of Manitoba in Winnipeg, Canada, and David South, founder and President of Monolithic Domes Inc., in Italy, Texas. Additional research on fabric formworks comes from N. Cauberg, and B. Parmentier of the Belgian Building Research Institute, in Brussels, D. Janssen of Centexbel, in Ghent, Belgium, and M. Mollaert of the Vrije Universiteit Brussels, in Brussels. They produced a paper <u>Fabric Formwork for</u> <u>Flexible, Architectural Concrete</u>, where they have focused on the general outline of fabric formworks. They discussed the parameters of various textiles along the lines of stiffness and permeability, while also exploring the concepts of software modeling. "Critical to fabric formwork is the textile stiffness and permeability, the quality of the concrete surface... (Janssen, Mollaert, & Parmentier, 2009)." In their paper they list the minimum technical requirements for the different types of concrete elements which include both types of flexible formworks.

The first element is that an early high modulus is necessary for reducing deformations, called creep, which are commonly caused by bending and/or pressure stresses. This is particularly important for shell structures and less so for columns. The second required element is "a well-adapted surface quality, allowing for good demolding of the concrete" which should allow for "further reusability and surface enhancement, which wholly depends on the permeability of the fabric (Janssen, Mollaert, & Parmentier, 2009)."

Typically, fabric forms are made from either sewing or welding together of panels of material of equal size and shape. Woven materials such as nylon are common and can be both coated and non-coated. However, Professor West supports the use of polyolefin fabrics as being the best suited for most applications of this sort. He notes it is inexpensive and available world-wide. West also points out one of the things that makes this material ideal is that it doesn't need any releasing agents as concrete doesn't adhere to it, making it reusable many times (Bechthold, 2008).

As to coated versus uncoated, there are advantages for each, depending upon the application. According to Cauberg, Parmentier, Janssen, and Mallaert, coated fabrics are not permeable and can give either a smooth or textured surface, while non-coated textiles are more

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permeable (Janssen, Mollaert, & Parmentier, 2009). Gary Clark, Vice President of Production at Monolithic Constructors, reported that their choice of materials for the panel is usually a heavy polyester nylon fabric coated with polyvinylchloride (PVC). Professor Mark West in his paper <u>Fabric-Formed Concrete Structures</u> argues that permeable membranes allow air bubbles and excess mix water to bleed out, which produces a "flawless, cement-rich finish, and a stronger, more durable case-hardened concrete (West, Fabric-Formed Concrete Structures, 1994)."

There are two general types of flexible or fabric formwork. One is a "hanging fabric" type, and the other is pneumatic membranes. Both types have had ongoing research, and many of the problems originally thought to be barriers have been overcome (Schmitz, 2010). Through this ongoing research, not only have design possibilities improved, but new solutions to things such as portability and structural issues have been found (Bechthold, 2008).

The first applications of pneumatic formwork were only used on simple shapes such as cylinders, domes, and spheres². The formwork is usually, in this case, shipped to the site where it is pressurized or inflated with air in order to gain shape. For structural strength, steel reinforcement is added to the underside/interior of the shape. The technique called shotcretting is then applied to the underside/interior of the surface (Bechthold, 2008). This method is a significant move forward in saving time and construction materials when compared with older methods using timber formwork and scaffolding. Bechthold also mentions another method using this approach. Instead of applying concrete using a one-time application, California Architect Wallace Neff applied concrete in multiple thin layers (Bechthold, 2008)

Although rigid formwork has been around for a while, it did not generate formal study until 1963. According to R. P. Schmitz, PE, in an article written for Concrete Plant International Issue 3 (June/July) 2010, "ACI (American Concrete Institute) Committee 347 has addressed rigid formwork

² Hienz Isler is noted as being the first to experiment with pneumatic formwork (Garlock & Billington, 2008).

since 1963 but it was only recently (2005) that ACI Committee 334 introduced the construction of shells using inflated forms even though several methods of construction using inflated forms which have been experimented with since 1940's. It is hoped standards and guidelines for using flexible fabric formworks will be developed in a timelier manner for the design community to take full advantage of this method of forming concrete members." Schmitz feels that flexible fabric formwork can used nearly anywhere a rigid formwork is used, but is convinced that there is still a lot of research that remains to be done to make their use common in the construction industry (Schmitz, 2010).

As a more recent adopter of pneumatic formworks, David South of Monolithic Constructors had started working with pneumatic formwork as early as 1975 and became instrumental in putting together ACI Committee 334. The purpose of ACI Committee 334 was to open the way for further research. He emphasized these types of organizations tend to be backwards thinking, as it took him nearly ten years to convince the ACI of its importance.

The alternative to pneumatic formwork is hanging fabric formwork. It not only looks interesting but could prove useful in the fabrication of components for assembly and construction. Under the leadership of Professor Mark West, the students at C.A.S.T. have been successful in producing thin shell vaults and beams from experimentations in hanging fabrics (see fig. 21). Using a simple perimeter frame, they have draped a single sheet of fabric to form double-curvature volumes and shaped columns. Schmitz wrote that C. A. S. T. research has focused on these "shell concrete vaults formed from wholly from fabric formed molds." He further states the vaults themselves can "serve as molds for stay-in-place pans or glass fiber reinforced concrete (GFRC) applications (Schmitz, 2010)."



Figure 21 - Thin shell fiber-reinforced wall panel formed from a hanging wall form (West, Thin-Shell Concrete From Fabric Molds, 2008).

There are two ways to utilize hanging fabric formworks. They can be employed either directly or indirectly (see fig. 22). The direct method is similar to the methods used by early pioneers such as Felix Candela, where the castings were made with the fabric that was used directly on the construction. There is however a materiality problem with this. Even though there is a low cost of materials, one can produce only a limited number of serial shells, and with the direct method the upper rough surface of the concrete becomes the interior surface which will require further work to make it finished and a more desirable surface (Bechthold, 2008).



Figure 22 -Hanging fabric mold before and after inversion (Garlock & Billington, 2008).

For this reason, the indirect method becomes more attractive. In this method, when making serial casts, the fabric formwork once concreted and inverted allows fabricators to use the smoother surface as the bottom of the mold and in turn produces a smoother interior surface (Bechthold, 2008).

Modular Systems

In the last few years the concept of modular systems, also known as "chunking," has been growing increasing in the production of automobiles, ships, and airplanes. In the past, the general concept of modular systems for buildings conjured up the prefabrication of mostly temporary structures, i.e. mobile homes, modular class rooms, construction site buildings, etc., including the infamous shoebox style of constructing mobile homes and/or trailer parks. However, Kieran and Timberlake make the point that modular assembly and prefabrication in other industries have been progressing from mass production to mass customization (Kieran & Timberlake, 2004).

And in fact, currently, "prefab" encompasses a bit more. The largest productions are generally concrete, commonly known as "precast" systems. This term is used to describe castings of a variety of products, ranging from façade walls to tunnel or storm sewer drainage components. And there are, in fact, several manufacturers who produce casts made to order based on the current construction techniques. They argue in the past it was deemed (and maybe rightly so in the building industry) that off-site fabrication or production meant "sameness (Kieran & Timberlake, 2004)."

These concrete precast systems are created in a controlled environment, usually at a precast plant, in order to control the quality. This eliminates the problems related to changing weather conditions. This greater control means better material consistency and strength. The most common elements fabricated at precast plants are façade and exterior walls, floor plates, and infrastructure parts such as storm sewage drainage components. However, although this comprises what is currently being done in the building industry, the possibility for using these same modular construction methods for more unique buildings components could easily be derived (see fig. 23 and 24).

La Corbusier and every generation of architects since, has in some way approached the concept of prefabrication. For example, La Corbusier wanted to establish architecture for the common man. He was widely known for the concept of adopting mass production techniques in order to give the working class the improved "machine for living." Unfortunately, he never saw this realized. Similarly, Buckminster Fuller, F.L. Wright, and Walter Groupius had all experimented with their own concepts of modular construction of one type or another (Kieran & Timberlake, 2004).

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However, with new technological advances in digital technology, architecture itself may be at the threshold of being able to make these long-envisioned and needed changes.



Figure 23 - Transporting of thin shell panels to building site (Bechthold, 2008).



Figure 24 - Panels being lifted into place for assembly (Bechthold, 2008).

Digital Technology

One prime example of a needed transformation which has occurred is in documentation. In only a short period of time, we have gone from hand drawings, to 2D AutoCAD, to 3D modeling, and recently to BIM (Building Information Management). BIM with such programs as Revit has architects and engineers producing drawings as componential elements. Whole components can be constructed using BIM as opposed to a line by line method of drawing construction documents.

Architects have been drawing in digital format for approximately thirty years. Computer Aided Design (CAD) software programs made two-dimensional drawing quicker, more efficient, and easier to edit. An important historical perspective of development in architecture's transition was defined in <u>Digital Fabrications: Architecture and Material techniques</u> authored by Lisa Iwamoto. She states, "Even as the process of making drawings steadily shifted from analog to digital, the design of the buildings did not really reflect the change." In other words, even though CAD software replaced handmade drawings of parallel bars and graphite, this new digital media had little effect on design.

On the other hand, she stated that with the rapidly growing availability of three-dimensional software, there has been an increasing interest in exploring new form making in architectural designs (L. Iwamoto). For example, in 1989, Frank Gehry's office started using CAD/CAM software to develop and test the constructability of The Disney Concert Hall. Iwamoto discloses that, "Initially physical models were reversed engineered using a digitizer to take coordinates of a model's surface and import it into a 3D digital environment. The design subsequently moved back and forth between physical and digital surface models – physical models for aesthetics, digital models for "system fit.""

Because of this, Gehry's office adopted software used by the aerospace industry called CATIA, Computer Aided Three Dimensional Interactive Application. It was this software that they

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used to model the exterior of the concert hall (L. Iwamoto). What makes this particularly important is that this was the first architectural application of this software, which up to then had primarily been used in the physical production of parts by digitally driven machines. Another current pioneer who has integrated been an advocate in the field of CAD/CAM architecture is William Massie. He conducted experiments early on as the Coordinator for Building Technologies Research at Columbia University. Massie later taught at the University of Montana. While there he focused on the tectonic potential of using a CNC router. In 1997 his research project called, "Virtual Model to Actual Construct," the start of the first architectural instances of making use of the computer-driven process to make a full scale wall surface. Later Massie designed a residence for himself known as the, "Big Belt House," in Montana's Big Belt Mountains. The house is a variation of the techniques he used for the concrete wall. The process was one where curved ribs were cast in CNC-routed foam molds (Iwamoto, 2009). The fabricated pieces were then fit together at the site (see fig. 25and fig. 26). The process eliminated the need for traditional construction drawings while allowing for precision. Massie's project was built in 1999 previous to Gehry's. "In their respective projects, Massie and Gehry both investigate digital forming at the scale of building by innovating formwork for cast concrete (Iwamoto, 2009)." In other words, thanks to their explorations, the quest for new techniques and methods can continue for new and younger designers. There are now other firms both large and small embracing digital fabrications. Some examples of the most recognizable firms are Foster & Partners and Shop/Sharples Holden Pasquarelli who have investigated digital fabrication methods in various types of materials other than concrete (Iwamoto, 2009).



Figure 25 - Massie's "Big Belt" house while under construction made use of digital modeling and fabrication using CNC milling of Styrofoam molds, Montana 1999 (Fields, 2005).



Figure 26 - Gehry and Associates Zolhof Towers Dusseldorf also employed the use of CNC milling machines.

Conclusion

The explorations of William Massie and Frank Gehry can be described as merging the concepts of formwork and mold making with digital processing. Both Gehry and Massie established a real working relationship between digital design and digital fabrication. However, Iwamoto's conclusion of this is that the forming processes are never digital themselves. None the less, she does imply that digital fabrication has created an ability to conceive and create customizable formwork (Iwamoto, 2009). Furthermore, the research for this paper has shown that fabrication can be done through digitally controlled machines. And in fact, Massie has worked extensively in mating the two concepts as a focus for his career both in teaching and building.

Another example of experimentation which further established a conceptual working relationship between digital design and digital fabrication is a group of students at The University of Michigan. In a project called Fatty Shell they orchestrated the design and construction of a concrete "cell like" structure using an inflatable pneumatic formwork made via digital algorithmic design. Then rubber sheets were cut to pattern using a robotic arm that received the digital information. (Sturgeon, Holswart, & Raczkoski, 2010). Their design, being experimental and therefore not yet having a real world application, still contributes towards the idea of the digital processes and the relationships of those processes to concrete shell construction. This experimentation helps further establish methodologies discussed here in the paper.

It is therefore, reasonable to say that the combined concepts discussed in this paper can and should be implemented as methodologies which when incorporated into construction will lead architecture forward on a major basis. When and how this occurs is dependent not only on future architects, but public mindset as well, as their acceptance will also have a prominent influence. Their acceptance, in addition to being influenced by the architectural community, will also be influenced by politics, economics and sustainability.

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During his lifetime, La Corbusier was frustrated by the fact that the mindset was not yet right for modular construction. However, because of the rapidly changing technical environment, architecture may at last be receptive to these changes. In the last few years, the software program BIM (Building Information Modeling) software has begun to replace CAD/CAM drawings. BIM is a 3D software program where all the parts are digitally stored, which allows the user to access any and all systems, as opposed to having to read page by page, a myriad of construction documents. The fact that you can access for example a wall section, a roofing system, or the MEP (Mechanical Electrical Plumbing), or even a look at it as a 3D model, gives architecture the accessibility of new ideas. As we see costs escalate, and building codes become more complex, the time move into modular construction is upon us.

BIBLIOGRAPHY

- Archnewsnow. (2003, Oct. 23). Iconic Arcs; Jubilee Chruch by Richard Meier & Partners. *Archnewsnow*, p. online.
- Bechthold, M. (2008). *Innovative Surface Structures_Technology and Applications*. New York: Taylor & Francis.
- Billington, D., & Hines, E. (2004). Anton Tedesko and the Introduction of Thin Shell Concrete Roofs in the United States. *ASCE Journal of Stuctural Engineering*, 1639-1650.
- Fabor, C. (1963). Candella/The Shell Builder. New York: Reinhold Publishing Corporation.
- Fields, J. (2005). Curvature, Concrete and Computers. Hanely Wood LLC.
- Garlock, M. E., & Billington, D. P. (2008). *Felix Candela: Engineer, Builder, Structural Artist.* Princeton: Princeton University Art Museum.
- Huxtable, A. L. (1960). Pier Luigi Nervi. New York: George Braziller, Incorporated.
- Iwamoto, L. (2009). *Digital Fabrications: Architectural and Material Techniques*. New York: Princton Architectural Press.
- Janssen, D., Mollaert, M., & Parmentier, N. (2009). *Fabric Formwork for Flexible, Archtiectural Concrete.* Sydney, Austrailia: FRPRCS-9.
- Jurgen Joedicke. (1957). *The Works of Pier Luigi Nervi*. New York: Fredrick A. Praeger, Incorporated.
- Kieran, S., & Timberlake, J. (2004). *Construction, Refabricating Architecture: How Manufacturing Methodologies Are Poised to Transform Building*. New York: McGraw-Hill Companies.
- Mehta, M., Scarborough, W., & Armpriest, D. (2008). *Bulding Construction*. Upper Saddle River: Pierson Prentice Hall.
- Pica, A. (1969). Pier Luigi Nervi. Barcelona: Garriga Impresores, S.A.
- Schmitz, R. P. (2010, June/July). Fabric Forms For Architectural Concrete. *Concrete International*, pp. 1-8.
- South, N. (2005). A Finite Element Analyiss of the Monolithic Dome. Pocatello: Un-published.

- Sturgeon, K., Holswart, C., & Raczkoski, K. (2010, May 19). FattyShhell (V.01) . *DeZeen Digital Magazine*.
- Thurnauer, Mark. (2006). *From Design to Fabrication: Precast Concrete with Form Z.* Cincinnati: Glaserworks Architects.
- West, M. (1994, July). Fabric-Formed Concrete Structures. *Progressive Architecture Magazine*, p. 114.
- West, M. (2008). Thin-Shell Concrete From Fabric Molds. Manitoba: Un-published.

West, M., & Araya, R. (2009). FABRIC FORMWORK FOR CONCRETE STRUCTURES AND ARCHITECTURE. *International Conference on Textile Composites and Inflatable Structures*. Barcelona: B. Kröplin and E. Oñate, (Eds).

West, M. (2008). Thin-Shell Concrete From Fabric Molds. Manitoba: Un-published.