I, Troy W Newell, hereby submit this original work as part of the requirements for the degree of Master of Architecture in Architecture.

It is entitled:
Emerging Concrete Technologies: Architectural Implications

Student's name: Troy W Newell

This work and its defense approved by:

Committee chair: Michael McInturf, M.Arch.

Committee member: Aarati Kanekar, Ph.D.
Emerging Concrete Technologies:

Architectural Implications

A thesis submitted to the Graduate School of the University of Cincinnati in partial fulfillment of the requirements for the degree of

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ABSTRACT

Throughout architectural history, concrete in one form or another has been closely associated with stone materials because it achieves a comparable affect while having technical benefits. As a result, the architectural expression of concrete has generally embraced an archetypally massive affect. However, during the twentieth century, increasing sophistication in concrete reinforcement has allowed a progressively thinner concrete section. Textile reinforcement allows an extremely thin concrete to achieve an architectural affect similar to steel or wood, with technical benefits over either material. Designers should understand that the architectural-technical role of concrete is at a dramatic turning point.

Over the past two decades, researchers at the RWTH University in Aachen, Germany have conducted experiments in a revolutionary strategy for concrete reinforcement using plastic-based textiles. They have created structural prototypes which redefine the architectural possibilities of concrete. Textile reinforcement also naturally warrants a much finer degree of control and optimization for the placement of reinforcing elements, as integral components of formwork. Although current methods for placement of reinforcement are rather unsophisticated, digital CNC tools allow for a high degree of accuracy and precision in the design and production of concrete formwork and reinforcement.

This project will examine strategies for design and realization of precision reinforcement. Furniture designers have already successfully applied the technology to small-scale projects. Therefore, the project attempts to build upon the technical research of the RWTH University studies and to offer architectural resolution to one of the first building-scale implementations of textile-reinforced concrete.
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1: INTRODUCTION
Architectural innovations throughout the twentieth century are closely tied to technological developments in reinforced concrete. It would be easy to assert that engineers and architects have pushed design and construction to realize the full potential of concrete (due to the realization of long spans and complex forms), but it would be more accurate to acknowledge that universities and professionals throughout the world are continuing to redefine the potential roles of one of the most versatile building materials available. Translucent concrete, aerated concrete and super-thin textile-reinforced concrete are examples of projects which represent unexplored potentials for design and fabrication.

Essentially, continuous advances in material sciences and manufacturing will allow further hybridization of concrete design with alternative materials which will redefine the role of concrete in the built environment. Designs for concrete sea vessels, for example, were among the first conceptions resulting from “associative thought” (Moe, Kiel & Smith, 24) during the early twentieth century (Kind-Barkauskas, 12). Although a number of limiting factors prevented the practical implementation of such concepts, advances in concrete technology could allow the execution of similar designs and the realization of heretofore undiscovered possibilities for the material.

Specifically this paper will examine how the combination of technical textiles and concrete (“textile reinforced concrete”) allows an unprecedented reduction in thickness of concrete structures. Reduction of thickness has multiple benefits which forthcoming chapters will discuss. This principle has yet to be implemented on the scale of industrial production of concrete—research and experimentation has yielded a small number of built prototypes with debatable degrees of architectural resolution. However, these incipient research projects suggest potential benefits of borrowing fabrication techniques from industries in which technical textile production is a highly sophisticated technically and aesthetically resolved process (automotive carbon fiber, for example).

To understand the problem and proposed solutions of this paper, it is necessary to briefly explain some fundamental concepts of concrete design such as material properties, manufacturing, structural applications and construction of concrete systems.

Figure 1.1 A chair made of carbon-fiber reinforced concrete. Notice the extreme thinness, similar to a fiberglass or plastic version.

Figure 1.0 The future of concrete reinforcement? A scanning electron microscope image shows a bundle of carbon nano-tubes, the ultimate in strength to weight ratio.
2 : CONCRETE ESSENTIALS
SYNTHETIC STONE

“The recognition of the hydraulic properties of certain combinations of materials enabled the development of opus caementitium—Roman concrete—and its use in building work” (Kind-Birkauskas, 9). Reaching back to at least 184 B.C.E., architects have used what could be called some form of concrete—a mixture of slaked lime, sand and water. Although the middle ages saw a decline in the knowledge of concrete technology, the design of hydraulic composites reached a modern level of refinement by the late nineteenth century.

HETEROGENEOUS MATERIAL

Although the fundamental concepts of modern concrete have existed for centuries (Pantheon), during the industrial revolution advancements in material science and structural engineering allowed architects and engineers to more fully realize the true potentials of the emerging technology of concrete. What made concrete a revolutionary material was its “heterogeneous” nature, whereas other materials used for building are “homogenous” (Kind-Barkauskas, 17). This is another way of saying that concrete is a composite material, meaning it employs an amalgam of “simple” materials, each with their own distinct role, to obtain a resultant “composite” which has overall superior properties.

“For thousands of years, structures had mainly been constructed from primary, i.e., from the technological viewpoint, homogeneous materials, e.g., stone, timber, loam, fired lime, straw or reeds. It was not until the mid-18th century that the Industrial Revolution added iron to this list, and steel production first began in the 19th century. Both these materials were new, and although not primary, they were still homogeneous materials...

The development of reinforced concrete marked the dawn of a new age. Reinforced concrete was the first heterogeneous building material—in this case using steel, cement, sand, gravel and water—whose artificial composition, possessed much better properties than its individual components” (Kind-Barkauskas, 18).

CENTURIES OF CONCRETE

MATERIAL PROPERTIES, HOW CONCRETE IS MADE TODAY

In the construction industry a wide variety of ingredients are used to make what is generally called “concrete,” and the ingredients can be somewhat varied in their quantities depending upon the design requirements for the mix. The design of the concrete mixture has a dramatic effect on the properties of the cured...
concrete structure in terms of aesthetics, tactile qualities, environmental performance and structural performance. So the designer should be aware of some of the nuances of the material composition of concrete. Essentially, basic concrete is composed of 3 to 4 essential elements: cement, aggregate, water and additives.

Refer to Appendix C for more information about the composition of concrete.

STRUCTURAL CONCERNS

The fundamental properties of structural behavior have driven the design and construction of concrete systems since their inception, so it would be prudent to examine some of these fundamental concepts in order to frame the discussion on structural thickness of concrete. Structural analysis in architecture is often defined through the lens of statics which establishes predictive formulas for the behavior of structural systems which are “at rest” (Sandaker, 26). Throughout the past several centuries engineers and scientists developed numerous exhaustive volumes which now enable accurate predictions of structural behavior. A thorough discussion of statics is beyond the scope of this paper but several key concepts are important to grasp: stress, tension, compression and bending.

“Tension force is the effect of two loads pulling away from each other in opposite directions... Compression force is created when two loads are pushing against each other... Bending is the effect of transverse loads being applied to the element [a linear beam element, see diagram]... Shear force is the effect of two loads of opposite direction acting in two different planes within the structural element” (Sandaker, 24). Stress for our purposes is average force per unit area (Sandaker, 85). “Many materials will show great differences in ultimate stresses when subjected to tension forces as opposed to compression forces or shear forces. Materials like stone, clay bricks, unreinforced concrete, and cast iron are relatively strong in compression, but quite weak in tension. In such cases, then, we need to identify the type of force we are referring to when we give figures for ultimate stresses” (Sandaker, 85).

Framing structural issues in general terms, two essential methods of spanning have dominated architectural history: the arch and the beam. Both of these structural elements achieve spanning through somewhat different, although related, methods. Arches are structures which are designed to transfer gravity loads primarily through compression. However, in practice, all structures are subjected to more than the ideal load conditions and more than simply the dead weight of the structure. Thus even an arch designed according to an ideal funicular geometry will experience some amount of flexure due to bending (Sandaker, 327). But it should be evident why stone and masonry structures throughout history employ the arch repeatedly—due to the tensile stress response of these materials. Regarding the beam, although the operation of bending is slightly more complex to model, the illustrations demonstrate how this action can be described in terms of tension and compression, where tensile stresses occur on the side opposite from the applied load. Therefore concrete needs a secondary reinforcing material to transfer tension forces, especially when designed to operate as a beam or slab:

“...cracks will develop in the lower part of the beam where tension needs to be present in order to develop the resisting couple—and those cracks will tend to open up. Effectively preventing them from doing so, however, are steel reinforcing bars placed near the bottom of the concrete section (or near the top in a cantilever beam because of the reversal of internal moment direction)...So concrete on its own, like stone and masonry before it, is virtually useless as a contemporary material for beams, but by combining it with steel the composite material of reinforced concrete can be made to be highly effective in resisting flexure, as its omnipresence in building structures around the world today would suggest” (Sandaker, 161).

REINFORCEMENT AND COVER

Stone structures had employed metal reinforcing for at least several centuries prior to the development of modern concrete (Sandaker, 160). By the end of the 15th century, the first structures made entirely of concrete began to appear (Kind-Barkauskas, 15). Aside from addressing a detailed history of the development of reinforcement, it is valuable to note that French stonemason François Hennebique “...perfected the construction of the beam-and-slab floor connected monolithically with iron-reinforced concrete columns. So...
he succeeded in producing what is for reinforced concrete probably the most typical type of construction. Even at this early stage, the arrangement of the reinforcement in his very economical building system corresponded exactly to the flow of forces in the structural analysis” (Kind-Barkauskas, 13). Between 1890 and 1900 factories and warehouses were built using the patented “Système Hennebique.” By 1902 the Ingalls Building, a 16-story skyscraper in Cincinnati, used a frame based upon this system.

As a tension resisting element, naturally the reinforcement takes the form of rods or “bars.” The rods must mechanically engage with the concrete matrix so instead of being smooth they have a pattern of “threads” which prevents them from slipping through cured concrete. The degree of mechanical engagement is defined by the length of the rods (for any reinforced concrete design there is a minimum engagement length, called the "development length"). Their diameter depends upon the tensile forces they are designed to resist. Larger diameters can withstand higher amounts of stress (because they have more area to distribute the stress). Additionally, in order to achieve the necessary mechanical engagement, the rods must have a specific minimum depth of concrete surrounding them which is called “cover.”

“The minimum dimensions for concrete cover to reinforcement mainly depend on the ambient conditions to which the component is exposed and the diameter of the reinforcement...In order to ensure that this minimum concrete cover is reliably attained on site, an allowance...is allocated to each minimum value. The nominal concrete cover...is based on the minimum cover...and the allowance” (Kind-Barkauskas, 60).

Another technology which has dramatically increased the efficiency of concrete structures is based upon the concept of “pre-stressing,” which builds in a counteractive load in structural elements. Not unlike the idea of a weight, pre-stressing anticipates the dead- and live- design loads imposed upon the structural element, and seeks to establish a counterbalancing force which will be resolved once the structure is loaded. This can result in a much more efficient weight, less “wasted” material and much longer spans of equivalent designs which do not use pre-stressing. Pre-stressing is often accom-
3 : FORMWORK
Like the design of any cast product, the resultant form and character of cast concrete depends highly on the quality of the mold used to control the conditions under which the "plastic" material will cure. The primary concerns in the design of formwork are: access to distribute concrete, speed of concrete distribution, mounting reinforcement (including form ties), counteracting fluid pressure of the poured concrete, vibration methods, compaction, environmental conditions of curing (temperature, humidity), troweling, surface lining, release agents, and reusable versus "lost" formwork.

ACCESS & SPEED

There must be adequate space to effectively maneuver the equipment which will distribute the liquid concrete. The equipment could range from hand pouring methods to pumping from a truck, for large-scale projects. Speed is important because the goal is to distribute concrete evenly while liquid, to retain consistent mechanical properties throughout the pour.

REINFORCEMENT & FORM TIES

Reinforcement must be kept within the necessary tolerance of "cover" (see previous chapter) established in the design. A wide variety of techniques are used but in general, it would be appropriate to say that contractors will attach the steel to areas which will be cosmetically irrelevant in the finished concrete. However, sometimes form ties are needed to counteract the lateral fluid pressures of liquid concrete. These are permanently embedded, and the designer can choose to expose form ties or conceal them once the formwork is removed. Pre-stressing components can present a similar design decision, as the ends of the cables must somehow be resolved.

For façade panels, ceiling panels, wall panels, furniture, etc., light weight Glass-Fiber Reinforced Concrete (G.F.R.C.) has become more popular. Instead of steel, these panels are reinforced with a continuous mesh of technical textiles. Rather than mounting the mesh in a form, the concrete is built up in layers, and the mesh is placed between layers. This method allows control of the surface quality of one side of the piece, but the back side remains an "unfinished" surface.

FLUID PRESSURE

The formwork is a structure which must resist the fluid pressure of liquid concrete as it tries to "slump" downwards and outwards. This structural requirement defines the appropriate deflection and thus the spans and depths of the members used to construct the formwork. Naturally if members deflect too much, it will result in an undesirable effect in the finished concrete where it was allowed to "bulge."

VIBRATION & COMPACTION

When concrete is mixed with water it is inevitable that some amount of air will infiltrate the mixed product. The air will remain in the mix in the form of bubbles unless some method is used to encourage the air to escape. This means, as in bronze casting, some openings must be present to allow air to escape. It also means, due to the material properties of curing concrete, high speed mechanical vibration has proven an effective method to remove air bubbles. Air in finished concrete means decreased weight with the compromise of decreased strength. Thus air content is also a factor of mix design.

Compaction has to do with the amount of air in the curing concrete and the "water-cement ratio" affects this most dramatically. "The measure of concrete’s workability (stiffness) is its consistency. We distinguish between seven consistency ranges, and each one of these demands its own form of compaction...Consistency range F 6 (very fluid) denotes self-compacting concrete in which gravity alone is sufficient to deaerate the concrete and allow it to flow in a dense layer until it finds its own level" (Kind-Barkauskas, 51).

ENVIRONMENTAL CONDITIONS OF CURING

The goal of curing is to maintain the proper amount of water during a phase in which the concrete matrix is developing its ultimate strength. “Curing is crucial to the durability of components and structures...in addition, the heat of hydration that ensues during setting should be maintained until the tensile strength required for accommo-
Refer to Appendix F for more information about release agents.

SURFACE LINING & RELEASE AGENTS

Formwork has a distinct impact on the surface quality of the cured concrete. As evidenced in many contemporary concrete projects, concrete is capable of adhering to and preserving a high resolution of surface detail from the formwork such that the finished concrete can take on the character of other materials—wood, fabric, glossy plastic, and so forth. Depending upon the surface area contact and the smoothness or coarseness of the formwork lining, release agents may be necessary. For example, a grease or wax-like substance is often used where plywood is the formwork liner. Otherwise the plywood will most likely permanently bond to the concrete. If a smooth material such as fiberglass is used, release agents might not be necessary. Finally, most formwork designs include areas of concrete which are simply exposed on the top, which require troweling. Troweling uses flat-edged hand tools to refine these exposed surfaces.

The aforementioned points are intended to provide a general introduction to the essential considerations of formwork design, without being particularly exhaustive.

TECHNICAL DESIGN OF FORMWORK

In the traditional design-bid-build project delivery method, the role of the architect does not typically include designing the technical aspects of formwork. This approach can be relatively effective for orthogonal, straightforward designs. But one of the architectural potentials of concrete lies in its sculptural nature. Any forms that are geometrically irregular require more challenging formwork solutions. Traditionally, a contractor would design in detail the conditions of formwork, and the architect would approve—thus the contractor determines the achievable tolerances in construction. However, increasingly routine use of digital fabrication workflows and alternative project delivery methods is giving architects more direct control over the technical aspects of formwork. This equates to more control over the resultant concrete product.

The Mercedes-Benz Museum was a highly complex project especially from a constructability standpoint. The substantial completion of this project involved a long list of organizations led by Dutch architects UNStudio (founder, Ben van Berkel). In an interview with van Berkel, regarding the construction process he states: “Because we have so much 3D information in the [digital] model, contractors will often come to us and request detailed production drawings. They often ask us to produce the fabrication drawings from our 3D model, for which we get an additional fee. We have now developed this capability that gives us more control to maintain the design throughout the construction process. There is no additional liability because after the contractor takes the 3D model, they confirm that all of the drawings produced from the model are correct and then assume responsibility. This is a very new way of working and although there are many obstacles at the moment, architects have to take a more proactive position to overcome these..." (Marble, 82).

Here it would be helpful to examine some contemporary solutions to challenging formwork. A number of standard, reusable formwork systems are well-suited to orthogonal construction. However, in creating a form with custom, irregular geometry, “lost” formwork systems are commonly employed, where the custom form is wasted following the curing period. The following case studies represent reusable, lost, and hybrid systems in contemporary formwork.

FORMWORK CASE STUDIES

Although the following examples represent some of the most progressive thinking in concrete design and construction, an emerging technology could revolutionize the role of concrete in architecture and engineering.

Figure 3.4 A basic idea of concrete formwork - plywood sheathing supported by lateral framing and bracing

Figure 3.5 The complex mesh of steel reinforcement common in many concrete structures represents a laborious undertaking as well as significant investment in an expensive, heavyweight material.
SPENCER DOCK BRIDGE

ROYAL CANAL, DUBLIN, IRELAND
DEMOULDING: NOVEMBER 2011
ARCHITECT: FUTURE SYSTEMS
ARCHITECT: AMANDA LEVETE ARCHITECTS
STRUCTURAL ENGINEERING: ARUP
CONTRACTOR: LAING O’ROURKE
FORMWORK FABRICATION: NEDCAM

ESTIMATED COST: $6.8M
FUNDING/CLIENT: DUBLIN DOCKLANDS DEVELOPMENT AUTHORITY
AWARDS: BEST STRUCTURAL DESIGN AWARD 2009 FROM LEAF (LEADING EUROPEAN ARCHITECTS FORUM)
FORMWORK: RESIN-COATED HIGH DENSITY EXPANDED POLYSTYRENE

A Solidworks model was used to mill foam. The foam was coated with resin for superior surface finish. Then it was installed on plywood falsework with registration keys.

CAST SURFACE UNDER BRIDGE
Over the last fifteen years digital design technologies and techniques have emerged as a primary focus of avant garde view of project.

**Advantages**
- Refined surface quality

**Disadvantages**
- High investment in onsite labor
- Waste of many formwork components

Introduction

Case Studies

1. **Spencer Dock Bridge, Dublin with Future Systems**

   - Digital fabrication technologies are required to optimise production and coordinate complex assemblies.
   - Design variation is systematic and design parameters can be linked reciprocally to create constrained design models.

2. **AKT p.art**

   - The pavilion was initially modelled as a skin or topological volumetric form, and is materialised through the sectioning of the skin with a series of fanning arrays of planar cuts which produce set out of section array from a central point.

   - Finaly, digital fabrication technology is leveraged to economically manufacture these highly differentiated elements or through which contemporary design teams interact and communicate.

   - In addition, parametric models become the medium to coordinate and optimise multiple design and production constraints. In addition, parametric models become the medium to coordinate and optimise multiple design and production constraints.

   - Variation may consist of elements, assemblies or surface variation but in all cases the transformation tends to be coherent.

3. **Dempsey & Huang AKT p.art**

   - The bridge is 40m span structure in Dublin City centre that carries road, rail and pedestrian traffic and explores the possible integration between urban infrastructure, public space and landscape. The bridge is a double curved curved asymmetric structure.
BOSTON HARBOR ISLANDS PAVILION

DOWNTOWN BOSTON, MASSACHUSETTS
COMPLETION: JUNE 2011
ARCHITECT: UTILE DESIGN
STRUCTURAL ENGINEERING: SGH ENGINEERING
CONTRACTOR: TURNER CONSTRUCTION
FORMWORK FABRICATION: C.W. KELLER OF PLAITON, NEW HAMPSHIRE
ESTIMATED COST:
FUNDING/CLIENT: BOSTON HARBOR ISLAND ALLIANCE

FORMWORK: PLYWOOD, LAMINATED TIMBER JOISTS, FIBERGLASS, FINNFORM SHEETS

Finnform is veneers of Finnish White Birch coated with phenolic film which gives it a red semi-gloss appearance. Phenolic gives a high-quality, “well-compacted” surface finish.

BOSTON HARBOR ISLANDS PAVILION
DOWNTOWN BOSTON, MASSACHUSETTS
COMPLETION: JUNE 2011
ARCHITECT: UTILE DESIGN
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FORMWORK FABRICATION: C.W. KELLER OF PLAITON, NEW HAMPSHIRE
ESTIMATED COST:
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FORMWORK: PLYWOOD, LAMINATED TIMBER JOISTS, FIBERGLASS, FINNFORM SHEETS

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BOSTON HARBOR ISLANDS PAVILION
DOWNTOWN BOSTON, MASSACHUSETTS
COMPLETION: JUNE 2011
ARCHITECT: UTILE DESIGN
STRUCTURAL ENGINEERING: SGH ENGINEERING
CONTRACTOR: TURNER CONSTRUCTION
FORMWORK FABRICATION: C.W. KELLER OF PLAITON, NEW HAMPSHIRE
ESTIMATED COST:
FUNDING/CLIENT: BOSTON HARBOR ISLAND ALLIANCE

FORMWORK: PLYWOOD, LAMINATED TIMBER JOISTS, FIBERGLASS, FINNFORM SHEETS

Finnform is veneers of Finnish White Birch coated with phenolic film which gives it a red semi-gloss appearance. Phenolic gives a high-quality, “well-compacted” surface finish.
ADVANTAGES
Refined surface quality

DISADVANTAGES
High investment in onsite labor
Waste of many formwork components

CONCRETE POUR
PLYWOOD WITH PHENOLIC FILM
EMBEDDED WIDE FLANGE
LAMINATED JOISTS
TIMBER BEAMS
ADJUSTABLE STEEL FALSEWORK

ADVANTAGES
Refined surface quality

DISADVANTAGES
High investment in onsite labor
Waste of many formwork components

FORMWORK PROTOTYPE
CONSTRUCTION OF FORMWORK ON SITE
FINNWORK COVERS JOISTS
SECTIONAL VIEW SHOWING FALSEWORK BELOW
INSTALLATION OF FORMWORK PANELS
BENDING OF STEEL BEAMS
NEWWORK COVERS JOISTS
SECTIONAL VIEW SHOWING FALSEWORK BELOW

FORMWORK - SECTIONAL VIEW

12"
The structure contains some of the most complex and demanding concrete geometry ever designed. UnStudio used a data workflow which enabled them to provide fabrication drawings for concrete and formwork, rather than relying on outside fabrication drawings. The formwork uses straightforward materials, but an interesting problem they have solved is mounting form ties normal to the surface of compound curvature.
ADVANTAGES
- High speed erection relative to complexity
- Precise control of compound curvature

DISADVANTAGES
- High investment in onsite labor
- Waste of many formwork components

UNFOLDED FORMWORK DRAWING

FORMWORK DRESSED WITH FORM LINER

FLATTENED FORMWORK COMPONENTS

FORM TIES, NORMAL TO SURFACE
SUPERMANOUVRE: PRE-VAULT

UNIVERSITY OF TECHNOLOGY, SYDNEY, AUSTRALIA
COMPLETION: 2011
ARCHITECTS: DAVE PIGRAM, NIELS MARTIN LARSEN, OLE EGHOLM PEDERSEN
FORMWORK FABRICATION: UNIVERSITY STUDENTS
ESTIMATED COST:
FUNDING/CLIENT: BOSTON HARBOR ISLAND ALLIANCE
AWARDS: FEATURED IN ACADIA 2012 CONFERENCE
FORMWORK: LASER-CUT AND FOLDED PET-G PLASTIC SHEETS.
A software enabling “dynamic relaxation” simulation allowed the design of a pure compression structure. However, the components of the vault were given tolerance with the acknowledgement that errors in fabrication would allow for shear forces to occur where an ideal structure would have overcome this. Research continues with this method which could increase the already high level of precision—for example, cast joints could be included to more precisely align the components. Overall this project makes a convincing case for high-precision, pre-cast concrete components.

ASSEMBLED PAVILION
ADVANTAGES
- Glossy surface quality
- Lasercutting is cheap and fast tech

DISADVANTAGES
- Bulging of material over large span
- Human error of joint accuracy

FORMWORK ASSEMBLY PROCESS
- LASERCUT CARDBOARD FALSEWORK
- HAND-TROWELING OF PRECAST PIECES
- CASTING FROM FORM

INDIVIDUAL PRECAST FORMWORK ELEMENT

CONCRETE POUR
FOLDED PET-G FORM
STEEL REINFORCEMENT ROD
EMBEDDED ZIP-TIE SLEEVES
TABLE SURFACE
FOLDED PET-G ‘LEG’
C.A.S.T. FABRIC-FORMED TRUSS

CENTER FOR ARCHITECTURAL STRUCTURES AND TECHNOLOGY, UNIVERSITY OF MANITOBA, CANADA

COMPLETION: ONGOING RESEARCH

ARCHITECT: MARK WEST, LANCELOT COAR, PATRICK HARROP
PARTNERS: LAFARGE BUILDING MATERIALS GROUP, CANADIAN PRECAST CONCRETE ASSOCIATION

FORMWORK: FABRICATION: STUDENTS, FACULTY

AWARDS: HOLCIM AWARD FOR SUSTAINABLE CONSTRUCTION

FORMWORK: PLYWOOD FORMS WITH VARIABLE “BLOCK-OUTS,” WOVEN POLYOLEFIN FABRIC LINER

One of the most elegant consequences of fabric forming is the fabric’s tendency to create 3-dimensional fillets which mitigate stress concentrations at joints. The main benefit to these methods is the inexpensive and re-useable nature of the fabric formwork. It is also important to note that these methods do not require a release agent, because the fabric is water-resistant.

PROTOTYPE TRUSSES IN PLASTER

VARIABLE FORMS FROM ADJUSTABLE FORMWORK

CABLE TENSIONED TO FORM FABRIC

COLUMN & TRUSS CONCEPT
ADVANTAGES
- Refined surface quality
- Inexpensive fabric form

DISADVANTAGES
- Limitations of fabric size, possibly
- Fabric deformation can be unpredictable,
- Difficult to design

ADVANTAGES
- Refined surface quality
- Inexpensive fabric form

DISADVANTAGES
- Limitations of fabric size, possibly
- Fabric deformation can be unpredictable,
- Difficult to design

HALF OF MOLD WITH BLOCKING VISIBLE
FABRIC STRETCHED OVER FORM
FABRIC TENSIONING ELEMENTS
ASSEMBLED FORMWORK WITH TIES
POURING INTO ASSEMBLED FORM
PROTOTYPES SHOWING SURFACE QUALITY
HIGH-EFFICIENCY SAND & WAX CASTING

ZURICH, SWITZERLAND
COMPLETION: ONGOING RESEARCH PROJECT
ARCHITECT: MATTHIAS KOHLER
AWARDS: HOLCIM AWARD 2011
FORMWORK: MACHINABLE WAX NEGATIVE, CAST AGAINST SAND POSITIVE

This process is designed to function as a “zero-waste” casting solution. Both the sand and wax are flexible materials which can be easily reused for future castings. A robot arm sculpts sand in a simple coddle form according to a computer model. Then, machinable wax is poured into the coddle form and upon curing, forms the inverse of the sand “positive.” The wax, having a flat surface (the top cured surface) is compatible with existing orthogonal formwork systems, and thus provides a renewable form to cast against which is also highly adaptable to complex geometry.

EXAMPLES OF PATTERNING
PROPOSAL FOR IMPLEMENTATION - SMALL-SCALE STRUCTURES
ADVANTAGES
- Easily machinable, low-investment casting materials

DISADVANTAGES
- Surface quality is unpredictable

TYPICAL FORMWORK SYSTEM
- Wax "negative" form
- Formwork ties
- Concrete pour

ROBOTIC MANIPULATION OF SAND

PATTERN IN SAND

SAND IN COUDLE-FORM, CONTOURED BY ROBOTIC ARM

POURING WAX OVER SAND

WAX FORM (LEFT) AND RESULTING CONCRETE (RIGHT)

PATTERNED PANEL
4 : TEXTILE REINFORCED CONCRETE
TEXTIL BETON (TEXTILE CONCRETE)

In the annals of 20th century architecture one of the questions which embodies the spirit of modernism is Fuller’s question to Foster: “...how much does your building weigh?” This reflects concerns of what could be termed “efficiency” which, in the age of digital fabrication could be more appropriately described as “optimization” (Marble, 18). Fuller was partly referencing the achievements of automotive and aerospace design which have, in ever-increasing levels of refinement, optimized fundamental design aspects throughout the twentieth century, not the least important of which is mass. Common sense predicts that weight savings has advantages for architecture. One advantage is the reduction of foundation requirements. Another is the savings offered in transporting components (THE DETAILS OF MODERN ARCHITECTURE, VOL. 2).

Concrete is an almost archetypally massive material, due to its role as a sort of synthetic stone throughout architectural history. It has been demonstrated how the typical thickness of concrete is essentially a function of the necessary “cover” surrounding traditional steel reinforcement. However, steel is not the only material which can effectively perform reinforcing in concrete. Advances in technical textiles have made them viable materials to provide the same function as steel.

G.R.F.C.
Glass Fiber Reinforced Concrete is a conceptual predecessor to textile reinforced concrete. Generally, it consists of a small aggregate mix into which short (less than 1 inch) glass fibers are placed. Through the mixing process the fibers are more or less evenly dispersed although this method of distribution is known as “random” fiber placement. This method has proven effective for relatively small, low-stress applications. But obviously this gives the designer little control over the ultimate effectiveness of the fibers in any given portion of the structure. The method for applying this type of concrete to formwork involves several “layers,” as it is often used in forming regular or irregular forms which are topologically sheet-like. First, a fine-aggregate “mist-coat” is sprayed into the formwork using a pressurized spray-gun. Then, hand-packing is often the preferred method for applying a “structural” layer behind the mist coat. The hand-packed layer includes the glass fibers. The final thickness then is dependent upon the layer or multiple layers of hand-packing. It is therefore difficult in large areas of the mold to accurately estimate the thickness of the concrete. However, for self-supporting façade panels this is not a critical issue. For something like a chair or a table this estimation would be more important. But overall, random fiber placement represents a first step in a method which will be refined throughout the next several decades. It is not difficult to imagine the disadvantages of having the costly fibers clump together where they are not needed, for example. Another issue is with surface finish: the fibers can occasionally penetrate the mist-coat and become visible on the finished surface.

T.R.C.
In a report entitled “Textile-reinforced concrete” by Christian Schatzke and Hartwig N. Schneider (Peck, 32), the authors examine in detail some of the emerging research in textile-reinforced concrete: “Textile-reinforced concrete is a further development of fibre-reinforced concrete, but differs from this in that this new building material contains no short fibres. Instead it uses commercial textiles—weaves and nets—made from glass, carbon or aramid fibres as the reinforcing material, which enables the reinforcement to be incorporated exactly as required and hence much more economically.” This statement reflects the idea of optimization of the textile materials.

Again, it is important to realize the potentials of this reinforcement system in terms of weight: “The use of textile reinforcement obviates the need for a deep concrete cover to protect the reinforcement against corrosion. This in turn leads to components with thin walls of just 10-20 mm. Furthermore, thanks to the self-compacting property of the fluid, fine concrete, it is possible to produce high-quality fair-face concrete surfaces and very accurate contours” (Peck, 32). This suggests that the designers and fabricators of the formwork system have perhaps a higher degree of responsibility with this more nuanced, lower-tolerance method of fabricating concrete.

The authors name many of the advantages of T.R.C. in terms of sustainability: “Considering,
in particular, the aspects of the production of a structure and the transport of its components and materials, it is advisable to work with lightweight building materials and forms of construction that save materials...Lightweight supporting frameworks, the reduction in thickness of external walls, simple erection and dismantling, plus the use of light-duty cranes and hoists are the principal advantages”(Peck, 34). These are immediately intuitive advantages, and they go on to discuss benefits more specific to particular design problems: “…shell structures in single or double curvature which due to intelligent form-finding—also in the sense of a low consumption of materials—represent very efficient structures. Forms of construction resolved into individual members, e.g. lattice shells...are also conceivable. In such cases it is the high degree of prefabrication that provides advantages over other materials such as steel or timber” (Peck, 34). The statement suggests that the authors are addressing the idea of embodied energy, without actually directly stating it. With the immense heat needed to produce steel elements it is easy to imagine that concrete is a more sustainable choice. It is still important to consider the environmental impact of cement manufacture although cement production is now legally required to incorporate recycled materials (Kind-Birkskaskas, 18). Comparison of the embodied energy of concrete versus steel versus timber could easily result in an extensive paper in itself and is beyond the scope of the current discussion. But this is not the only advantage of using concrete over steel or timber.

“Building performance characteristics also benefit from the dense microstructure of the fine concrete mix. Despite such thin components, it is possible to build waterproof elements and also achieve relatively good fire resistance figures...such properties lead us to expect the widespread use of textile-reinforced concrete in all branches of architecture. From the loadbearing structure to the building envelope...” (Peck, 32).

Another possibility afforded through the use of T.R.C. is alternative means of joining prefabricated elements. Types of connections previously only available to steel and wood systems could now be similarly achieved with concrete, due to thin sections. “...[T.R.C.] offers other opportunities in terms of prefabrication and jointing such as bolting and bonding with adhesive, which could lead to concrete being chosen for delicate lattice structures...thin-wall components (25 mm) also permit the use of simple bolted connections at the nodes...The extremely slender textile-reinforced concrete components result in a delicate appearance that was not associated with concrete in the past...The fluid, fine concrete mix enables the formation of grooves and recesses for fasteners, which leads to elegant joints” (Peck, 36). The aspects of thickness and precision fabrication of joints means that concrete is poised to attain a tectonic quality which is unprecedented in the history of concrete, though the potential was always available, due to its nature as a composite material.

The report goes on to examine the following project for a “diamond-shaped lattice structure” completed at RWTH University in Aachen, Germany.

In this structure the promise and incipience of the T.R.C. technology is evident. The sectional dimensions of the diagrid components are impressively thin. Combined with the bolted connections (the small scale and precision of which are unprecedented in concrete construction) the architectural effect is highly elegant. But it is easy to argue, the project warrants further degrees of resolution, architecturally and technically. Architecturally, the end conditions of the structure, and the attitude toward enclosure, light, and various architectural conditions could be further addressed. Technically, the approach to textile placement could be more sophisticated, especially in light of emerging technologies in textile production.
5 : ADVANCED REINFORCEMENT
TEXTILES AS THE BASIS FOR STRUCTURES

In the following images RWTH University provides, (left) the woven nature of the textile reinforcement is clear. According to Schatzke and Schneider, “The individual diamond-shaped elements are reinforced with two layers of carbon-fibre nets. Stainless steel sleeves cast in at the corners of the elements are used for fixing the reinforcement…” (Peck, 37). Reinforcing mats of this nature are commonly applied by hand, between “hand-packed” layers of stiff concrete. Naturally this method of hand application can result in inconsistencies and errors as previously discussed. The addition of steel mounting plates represents a step towards refining the process of placing reinforcement. It should be immediately apparent that utilizing a prefabricated textile element is in itself a much more sophisticated method of fabricating concrete structures, because it eliminates the laborious hand construction process of fabricating a metal mesh from rebar. However, this begs the question: how could the designer go one step further in conceiving the textile reinforcement? How would the application be different? To answer this one might look towards emerging technologies in the technical textiles industry.

HIGH-TECH WEAVING

Technical textiles are fabric-like products manufactured for (primarily) non-aesthetic purposes (Wikipedia). Carbon fiber cloth in particular is used extensively in the automotive and aerospace industries due to its strength-to-weight ratio, and its ability to function as a monocoque structure. The concept of monocoque involves eliminating inner framework and transferring stress through the “skin” or “shell” of a structure. In contemporary engineering computerized Finite Element Analysis is often used to optimize the form of structures (such as airplane wings) to transfer loads efficiently. Carbon fiber cloth is used to form structures according to the direction of its constituent fibers. However, in finite element modeling, load paths are generally analyzed in three dimensions, so it is natural that the resultant structural component should be resolved in three dimensions. Automotive and aerospace engineers have approached this concept in various ways (reference).

One of the most impressive examples of three-dimensional structural design uses carbon fiber in the form of yarn. By using yarn instead of cloth, designers can more precisely control the finished form to conform to ideal structural proportions. A highly sophisticated loom arranges the strands according to the ideal force lines predicted through finite element analysis. This represents an approach to textile fabrication pushed to the limits of mechanical technology and digital fabrication, and perhaps demonstrates a method which could become more widely adapted in the future. At the time of this writing, the loom used to produce this part is a prohibitively expensive technology, but it is worth studying as an example of an innovative solution to the problem of turning textile materials into structural components which embody a sort of new modernism (video reference).

Use of so-called “3D” textiles is becoming more widely available in a multitude of industries. Again, as increasingly more structural problems are understood 3-dimensionally, it seems logical to pursue the reliable manufacture of 3D textiles: “Research conducted on textile structural composites indicated that they can be considered as alternative materials since they are delamination-free and damage tolerant. From a textile processing viewpoint they are readily available, cheap, and not labour intensive. The textile preform fabrication is done by weaving, braiding, knitting, stitching, and by using nonwoven techniques, and they can be chosen generally based on the end-use requirements. Originally three dimensional (3D) preforms can be classified according to fiber interlacement types. Simple 3D preform consists of two dimensional (2D) fabrics and is stitched depending on stack sequence. More sophisticated 3D preforms are fabricated by specially designed automated loom and manufactured to near-net shape to reduce scrap” (Bilisik, 79).

HIGH-TECH MOLDS

Fabrication of molds known as “tooling” allows carbon fiber cloth to be bonded with resin and precisely formed into highly effective structural shapes. This method, used (for example) in the manufacture of the Lamborghini Aventador, is currently the preferred method of turning (relatively) two-dimensional carbon fiber cloth into three dimensional forms. The basic concept has
been used in producing fiberglass parts for decades. But the challenge in carbon fiber has to do more with the size of parts which can be reliably structurally created without air bubbles which will disrupt the load-transferring capacity of the part. Lamborghini is one of the leading manufacturers of carbon fiber manufacturing because it has invested in research which allowed the reliable manufacture of automobile components which meet the high safety standards of the United States and Europe (reference).

Carbon fiber used in this manner is thus a composite material, consisting of resin and cloth. As we have seen concrete also functions best in a composite state, which depends upon mechanical engagement between the concrete matrix and the reinforcement. This engagement happens in steel through “threads” on the rebar but with fibers the same action is not possible. Research in T.R.C. has shown that “...so far it has not been possible to activate (for loadbearing purposes) all the filaments of a roving to an adequate extent...To accomplish better utilization of the reinforcement, it is necessary for the fine concrete mix to achieve greater penetration of the rovings. Dispersions or synthetic resins can be used to bond together the filaments in a roving and thus activate them all for load-carrying purposes” (Peck, 33). Thus perhaps using precision forms to bond fibers with resin is a good solution to provide full structural engagement to all fibers in the mat.

Prefabrication of stiff fiber elements would also help to address the following problem: “...how to fix the textile reinforcement in the formwork. The majority of uncoated textiles are highly flexible, which results in them dropping to the bottom of the forms, rising to float on the wet concrete, or being pressed against the sides of the formwork, all of which can have a detrimental effect on the surface finish, durability and loadbearing capacity of a component” (Peck, 34). Steel reinforcement does not suffer from this problem due to the inherent stiffness of the rods. But this is one of the main technical challenges that must be addressed in the pursuit of optimized, prefabricated textile-reinforced concrete structures. Automotive and aerospace designers and engineers have specified “cast” textile-based structures for some of the most demanding structural applications ever devised (retrofitted carbon-fiber wings on a 747, for example). Surely some of the lessons derived from these design and fabrication legacies can be effectively applied to the conception of a new concrete architecture.

---

The monocoque begins as an assortment of rolled textiles. Workers arrange the fabric pieces on precision molds called “tooling.” Well-designed molds allow layup of large components with precision. The autoclave combines heat and pressure to strengthen the CFRP. Attachment points are CNC-drilled into the cured monocoque. The chassis is mounted in custom jigs for further assembly. This example shows the pristine surface quality of the tooling. This example shows the pristine surface quality of the tooling.

Figure 5.3      Constructing the structural chassis of the Aventador using an industrial textile: carbon fiber cloth.
6 : DESIGN PROJECT
AN EXAMPLE DESIGN PROJECT

The following project demonstrates an architecture which takes advantage of the benefits of T.R.C. This version of the project features a design for a transit shelter in Cincinnati, Ohio. The goal is to use T.R.C. as an alternative to steel for a durable, lightweight prefabricated shelter. The concrete forms from which the structure is derived are made of precast T.R.C. components with optimized reinforcement. Fabrication of the precast components is achieved with high-precision robotically manufactured formwork. Reinforcement is also automatically manufactured to a high degree of tolerance. This allows cost-effective (reusable formwork) fabrication of repetitive components. A fine-aggregate mix and plastic-lined formwork results in a pristine surface which is water- and impact-resistant. Plastic-lined formwork also means that parts are relatively easy to remove from forms. The scale of precast pieces is designed to encourage easy transportation and erection of the primary structure. Finally, the architectural effect helps to redefine the role of concrete in architecture and provoke possibilities not yet imagined for this versatile building material.

The project is for a simple transit shelter in downtown Cincinnati, Ohio. This drawing shows the city context, streetcar route and site location.
Plan drawing of urban context. Court Street runs east-west, Walnut Street is on the left, running north-south, Main Street is on the right, running north-south.
Elevation - North on Court Street.

Elevation - South on Court Street.
Detail of Mold for Concrete Ribs
APPENDIX A

A catalogue of types of concrete for quick reference.

- AUTOCLAVED AERATED CELLULAR CONCRETE
- LIGHT AGGREGATE CONCRETE
- GLASS FIBER REINFORCED CONCRETE
- TRANSLUCENT CONCRETE
- "REGULAR" CONCRETE
- HEAVYWEIGHT CONCRETE
- SHOTCRETE
- ULTRA HIGH PERFORMANCE CONCRETE
- MICRO REINFORCED ULTRA HIGH PERFORMANCE CONCRETE

APPENDIX B

A collection of projects which take advantage of textile reinforcement

B.1 from Concrete: Design, Construction, Examples (see Bibliography)
B.2 http://urbanconcretecountertops.com/portfolio/custom-bathroom-designs
B.4 from Concrete: Design, Construction, Examples (see Bibliography)
B.5 http://urbanconcretecountertops.com/portfolio/custom-bathroom-designs
B.8 from The Robotic Touch (see Bibliography)

A.1 Images from Wikipedia http://en.wikipedia.org/wiki/Concrete
CONCRETE COMPOSITION

The design of the concrete mixture has a dramatic effect on the properties of the cured concrete, in terms of strength, durability, workability, and structural performance. So the designer should be aware of some of the nuances of the material composition of concrete. Essentially, basic concrete is composed of 3 to 4 essential elements:

CEMENT
A hydraulic binder which hardens or "sets" when exposed to water.

AGGREGATES
A huge variety are available and are generally classified according to size and density.

WATER
An essential factor in concrete strength. Too much water will produce a weak concrete whereas too little is difficult to pour.

ADDITIVES
Beyond the 3 basic ingredients there are many optional ingredients which can alter properties such as compressive strength, cure time, color, surface quality, etc.

The term "sand" most commonly refers to a fine powder product recognized as Portland Cement. This type of cement is manufactured by grinding limestone and clay which are then mixed in a rotary furnace. The resulting product is called Clinker. Then after further grinding, gypsum is sometimes added to the clinker. Finally the cement is distributed by truck, rail, etc.

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ADDITIVES
Beyond the 3 basic ingredients there are many optional ingredients which can alter properties such as compressive strength, cure time, color, surface quality, etc.

It is also worth noting that production of cement is highly hazardous to the environment, in terms of chemical byproducts released in the operation of the kiln. Through modifying the chemistry of cement, the industry hopes to lessen the environmental impact of cement production.

CONCRETE COMPOSITION

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AGGREGATES
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ADDITIVES
Beyond the 3 basic ingredients there are many optional ingredients which can alter properties such as compressive strength, cure time, color, surface quality, etc.

4 essential elements:

CEMENT
- Portland Cement. The final product is a familiar grey powder, although white cement is also produced at a somewhat higher cost due to modified manufacturing processes.

AGGREGATES
- A huge variety are available and are generally classified according to size and density.
- Micronized, often selected for smooth surface finish or preservation of detail from formwork.

WATER
- A critical factor in concrete strength. Too much water will produce a weak concrete whereas too little is difficult to pour.

ADDITIVES
- Beyond the 3 basic ingredients there are many optional ingredients which can alter properties such as compressive strength, cure time, color, surface quality, etc.

Materials from which concrete is made

All images obtained from http://en.wikipedia.org/wiki/Cement

APPENDICIES

APPENDICIES
A catalogue of types of concrete for quick reference.

Images from Concrete Construction Manual (see bibliography).
Comparison of thickness between various reinforcement strategies

Drawings by the author.

<table>
<thead>
<tr>
<th>STEEL MESH REINFORCEMENT</th>
<th>TEXTILE REINFORCEMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rdim : Cmin : Tcon</td>
<td></td>
</tr>
<tr>
<td>A RATIO OF CONCRETE TO REINFORCEMENT</td>
<td></td>
</tr>
</tbody>
</table>

Rdim = Sectional dimensions of reinforcement
Cmin = Minimum concrete coverage over reinforcement
Tcon = Resulting thickness of concrete

"The typical dimensions of textile reinforcement and resulting TRCs are one order of magnitude smaller than that of RPC providing totally new opportunities for the construction industry."

Concrete is a composite material. On its own the concrete matrix cannot transfer tension as steel or iron has been shown to be the most effective reinforcement for this purpose. Steel reinforcement has been the typical solution throughout the 20th century. However, FRP can be used to provide many benefits such as:

- Strength to weight ratio
- Thinner concrete
- Longer service life
- Low-maintenance cost

A reinforcing material for concrete must have the following properties:

- High relative tensile strength
- High deformation to stress ratio
- Thermal compatibility with heat of hydration
- Resistance to the alkaline environment of concrete

Carbon fibers, glass fibers or kevlar fibers provide these basic requirements, along with the aforementioned benefits. Framework is often the driving factor in determining the reinforcement to use. However, the most common method of fiber layup even in precast components or hand layup if the practice of concrete design is to take advantage of polymers for reinforcement, it should also take advantage of the sophisticated techniques for layup used in the aerospace or automotive industries.
Comparison of traditional and GFRC application methods.

TRADITIONAL PROCESS EXAMPLE
A mixture of maximum 0.5 water-cement ratio is poured into a form with integral steel reinforcement rods. Then the mixture is vibrated, to draw air bubbles to the surface (bubbles will compromise structural integrity). Then a coagulum will trail the "unfilled" face which does not contact the formwork. Following this, some amount of curing time will pass when the casting can be demoulded. Often a "mist" layer is applied first, to capture surface bonding to the concrete. The sheet material easily peeled away from the casting upon demoulding. The "structural" elements of the formwork from bonding to the concrete. Then a more "dry" hand-packed fine "mist" layer is applied first, to capture surface bonding to the concrete. The sheet material easily peeled away from the casting upon demoulding.

Release is a crucial part of formwork design. In this example the designers achieved a mold which did not use release agents, as the cast surface was a polished concrete. Sometimes a more "dry" hand-packed layer is applied behind the mist coat. This layer is often intended to be used as-is, without additional finishing. The demoulded product is often intended to be used as-is, without additional finishing. Some detail work is done by hand. The demoulded product is often intended to be used as-is, without additional finishing.

GFRC PROCESS EXAMPLE
Glass-fiber reinforced concrete is sometimes used where only one face needs to be finished. Often a thin "mist" layer is applied first, to capture surface bonding to the concrete. Then a more "dry" hand-packed layer is applied behind the mist coat. This layer might include glass fibers. The mold often has a refined edge to screen off excess material. Finally the "unfinished" face which does not contact the formwork. Following this, some amount of curing time will pass when the casting can be demoulded and possibly covered to retain water while curing and reduce cracking. Bubbles will draw to the surface (bubbles will compromise structural integrity). The demoulded product is often intended to be used as-is, without additional finishing.

REINFORCEMENT METHODS
Reinforcement is a central design factor, as concrete cannot transfer tension. Materials for reinforcement have advanced over the past few decades. Steel fibers, glass fibers, polymeric mats, and hooked steel fibers are commonly used. Reinforcement can be categorized into three basic sections: Steel, Glass, and Polymeric. The demoulded product is often intended to be used as-is, without additional finishing.
A project which uses 3D printed plastic as a reinforcing mesh, and then applies shotcrete robotically.


3D PRINTED REINFORCEMENT
Norman Hack & Will Viktor Lauer
ETH Zurich
Future Cities Laboratory

This project presents an alternative method to securing reinforcement.
Manufacturing process of the Lamborghini Aventador.

http://www.topspeed.com/cars/lamborghini/2012-lamborghini-aventador-lp700-4-ar100112.html

LAMBORGHINI AVENTADOR
SANT’AGATA BOLOGNESE, ITALY
INITIAL PRODUCTION: FEBRUARY 2011
LEAD DESIGNER: FILIPPO PERINI
PRODUCTION & ASSEMBLY: SANT’AGATA BOLOGNESE, ITALY
ESTIMATED COST: $397,000
2,000th UNIT SOLD JUNE 2013
FORMWORK: CARBON FIBER

INSPECTION OF SURFACE QUALITY
APPENDIX I

Precedent projects for Cincinnati design project.

photos obtained from http://static.panoramio.com/photos/large/20484763.jpg

PARIS METRO ENTRANCES

ARCHITECT: HECTOR GUIMARD
STRUCTURAL SYSTEM: CUSTOM CAST IRON

Drawings obtained from http://www.greatbuildings.com/buildings/Paris_Metro_Entrances.html
RALEIGH BUS SHELTER

RALEIGH, NORTH CAROLINA
COMPLETION: 2009
ARCHITECT: PEARCE BRINKLEY CEASE + LEE
STRUCTURAL ENGINEERING:
CONTRACTOR:
FORMWORK FABRICATION:
ESTIMATED COST:
FUNDING/CLIENT:
AWARDS:
STRUCTURAL SYSTEM: REINFORCED CONCRETE, STEEL FRAME CANOPY
BIBLIOGRAPHY


WEBSITE CITATION