From the Protean to the Systematized: The Development of Novel Construction Methods Utilizing Bio-based Polymer Composite Materials

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Abstract

While an increasing body of materials science research has brought numerous bio-based polymer composites into existence, this new class of materials has been the subject of little investigation for its potential roles within structural architectural applications. This research seeks to uncover and rigorously define a set of guiding design criteria that may act as a framework for the development of novel construction systems based on this new palette of materials. It is the position of this research that such a construction system must satisfy a broad spectrum of criteria to arrive at a viable design solution that can find widespread implementation. This spectrum ranges from technical solutions based on material properties and manufacturing methods, to environmental and regulatory concerns, and design methodologies and cultural forces. A novel moldless construction system based on bio-polymer composite sandwich assemblies is presented as an example of how such a range of criteria might be satisfied in an integrated and holistic manner to arrive at a prescriptive yet flexible and robust solution.

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GLOSSARY

Bio-based- Biobased content is defined as the fraction of the carbon content which is new carbon content made up of biological materials or agricultural resources versus fossil carbon content (ASTM D6866).

Biodegradable Plastic : a plastic that undergoes biodegradation (a process in which the degradation results from the action of naturally_occurring micro_organisms such as bacteria, fungi, and algae) as per ASTM D6400, ASTM D6868, ASTM D7081 or EN 13432.

Bio-derived high density polyethylene- Produced from ethanol that is fermented from agricultural feedstocks. Has chemical and mechanical properties that are identical to petroplastic polyethylene. Does not biodegrade.

Bioplastic- plastic that is biodegradable, has biobased content, or both.

Biopolymer- Polymer produced by living organisms. Nearly always have oxygen or nitrogen atoms in polymer backbone, rendering them biodegradable.

Celluloid- The first thermoplastic polymer, produced from nitrated cellulose and camphor.

Cellulose- A polysaccharide organic compound. It forms the structure of plant and algae primary cell walls and is the most abundant organic compound on the planet. It can be used to produce celluloid, cellophane and rayon.

Composite material- A solid material that is made of two or more distinct materials, typically a binding material (matrix) and a particulate or fibrous material. The constituent materials remain distinct.

Compression molding- Manufacturing method of molding a material that is already placed in a cavity by applying pressure, and often heat.

Copolymer- A polymer produced from more than one monomer.

Epoxy- A copolymer consisting of a short chain polymer resin with an epoxide at each end, and a catalyst.

EPS- Expanded Polystyrene

EVO- Epoxidized Vegetable Oil

Lignin- Organic polymer that forms the secondary cell walls of plants and algae, filling spaces in the cell wall between cellulose.

Oxo-biodegrdable- A plastic that "degrades" by oxidation from sunlight. Does not meet the definition of biodegradable as it breaks down into microscopic particles that cannot be further broken down by micro-organisms.

PBAT- Biodegradable copolyester.

Petroplastic- Plastic produced from fossil carbon sources.

PHA- Polyhydroxyalkanoates. Polyesters produced by bacterial fermentation of lipids or sugar. Can be either thermoplastic or elastomeric.

PHB- Polyhydroxybutyrate. A polyester produced by bacteria processing glucose or starch. Characteristics similar to petroplastic polypropylene.

PHBV- Poly(hydroxybutyrate-co-hydroxyvalerate)

PLA- Polylactic acid. A transparent plastic produced from cane sugar or glucose. Resembles conventional petrochemical mass plastics (such as polyethylene or polypropylene) in its characteristics. Can be processed on standard equipment.

Plastic- a material that contains as an essential ingredient one or more organic polymeric substances of large molecular weight, is solid in its finished state, and, at some stage in its manufacture or processing into finished articles, can be shaped by flow (ASTM D883.)

PMC- Polymer Matrix Composite

Polymer- a substance consisting of molecules characterized by the repetition (neglecting ends, branch junctions and other minor irregularities) of one or more types of monomeric units (ASTM D883).

PUR- Polyurethane

PVA- Polyvinyl alcohol. A polymer often used as raw material to make other polymers.

Resin- A solid or pseudosolid material of high molecular weight. Used generically to designate any polymer that is used as a basic material for plastics.

RTM- Resin Transfer Molding- A molding method in which resin is injected or drawn into a mold under low pressure. Fibers are pre-placed in the closed mold cavity.

SMC- Sheet Molding Compound

TPS- Thermoplastic starch.

XPS- Expanded Polystyrene

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PART I

THE DEVELOPMENT OF A BUILDING SYSTEM -THE SEARCH FOR GUIDING CRITERIA

At the one end, raw, telluric matter, at the other the finished human object... more than a substance, plastic is the very idea of its infinite transformation.

-Roland Barthe*, Plastic*

1. INTRODUCTION

The trajectory of a material as it evolves from being a mere *substance* to becoming the basis of a legitimate construction *system* is rarely a straightforward process. As the vast archive of filed, yet irrelevant, patents will attest, the invention of a construction system has a scope that somehow expands beyond the mere solving of a straightforward technical problem. Even those materials that are as old as the act of building itself, such as wood and stone, which would appear to have long ago arrived at fixed and entrenched methods of use, are continuously subject to re-evaluation of how they are best deployed as a system of construction. The 19th century evolution of timber framing to balloon framing, and eventually to platform framing, illustrates this process. (Fig 1.1) This gradual evolution of traditional materials stands in stark contrast to episodes of more conscious invention that accompany the arrival of truly new materials that have significantly new properties. From the late 18th to the early 20th century there was a visible struggle and a questioning of what forms cast iron, steel, and concrete should assume. Arriving during the age of invention, with its mechanistic world view, these struggles typically focused on finding the expressions and configurations that were most appropriate to their unique mechanical properties. Concrete presented perhaps the most radically different set of material properties when compared to the existing palette of building materials, and the proposed building systems, such as those by Hennebique and LeCorbusier illustrate, often took significantly different approaches. (Figs 1.2 and 1.3)

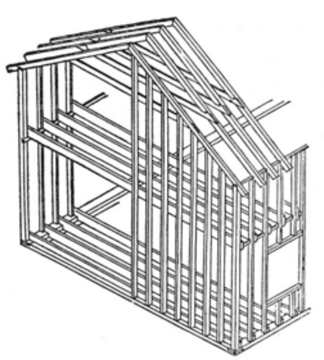


Figure 1.1

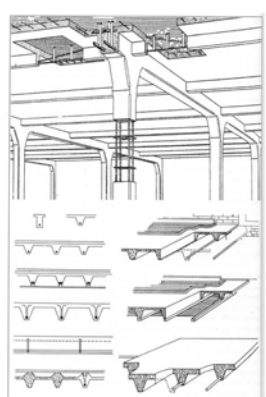


Figure 1.2

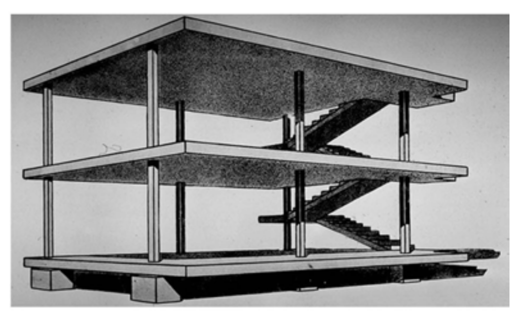


Figure 1.3

1.1 *Criteria for the Development of a Novel Construction System*

The success or failure of a new construction system may be understood as a function of how well it satisfies a vast number of criteria and goals. For example, a system that is based solely on efficient use of the material, yet avoids issues of manufacturing efficiency, building codes, transportation costs, labor required for on-site assembly, or flexibility in accommodating program, has little hope in gaining widespread adoption. A system must adequately satisfy many, often competing, criteria to find success. Furthermore, the criteria that a construction system must satisfy are constantly shifting. Each criterion is vulnerable to changing conditions, as new technologies are introduced, building codes adopt new content, and cultural tastes in form-making change, to name but a few. Therefore, a construction system is not merely an expression of what the material ideally wants to be, and configuration of a system cannot be based solely on a bottom-up investigation of material properties. The designer of such a system must be cognizant of the full range of governing criteria.

This paper shall focus precisely on this process of developing a *material* into a viable novel construction *system*. A viable construction system may be defined as one that satisfies the complete encompassing range of constituent activities, including design, engineering, manufacturing, and assembly. This range of activities must be reducible to a codified prescriptive method that provides a degree of consistency and predictability. The result is a rules driven conceptual framework which both satisfies these myriad practical requirements while accommodating a range of spatial configuration and architectural expression. While this is a rules based framework, it should avoid reduction to overly idealized and inflexible models.

1.2 *Class of Materials being Investigated*

This thesis will investigate the potential suitability of an emerging class of materials, and how they may be utilized in a structural capacity through the development of new construction systems. The class of materials being investigated are bio-based polymer composites. Specifically, sandwich assemblies that utilize facings of natural fiber reinforced bio-resins over low density cores of bio-based polyurethane foams. The plastic polymers in these materials are derived from feedstocks such as soybeans, corn, sugar cane, nuts, and pine, while the reinforcing fibers are sourced from plants such as industrial hemp, flax, jute, abaca, and kenaf.

There is a rapidly expanding body of related research within the materials science arena, as well as existing implementation of these materials within products outside of the field of architecture. Bio-based polymer composites were chosen as a material to investigate for potential architectural applications for several reasons. The first is that the building industry is already a significant consumer of petroleum based polymers, being the second largest single market for plastics. The largest category of plastics use is product packaging which accounts for 29% of total production, with building construction claiming 16%, or greater than 20 billion pounds (Society of the Plastics Industry). Consumer products use less than the building industry, accounting for 14% of total plastics production. While some of the plastic that is consumed by the building industry is easily recognizable as "plastic", such as exterior vinyl products or rigid foam insulation boards, a considerable portion also finds use as adhesives and binders in engineered wood products.

Driven both by environmental concerns, as well as long-term economic stability of feedstocks, significant research has occurred within the plastics industry over the past decade in an attempt to shift production to plastics that are derived from renewable biological sources rather than petroleum products (Stephen Myers, OBIC). Numerous new polymers are currently in production, typically as direct replacements for traditional petroplastics. These sometimes comprise the entirety of a manufactured object, while more typically they are used as an extender, blended with traditional petroplastics. Plastic packaging has been a natural focus of these new materials as it comprises the bulk of all plastics production, and is typically perceived as disposable. Other early adopters of the new materials have been automotive manufacturers, utilizing bio-based composite materials in numerous interior trim components and non-visible panels that have low structural requirements. Exterior body panels of bio-composites have also been proposed and exhibited in prototype concept vehicles.

While production of bio-plastics has been steadily climbing and finding its way into an increasing number of products, there has been little research into the implications of having a new class of materials available to the field of architecture. Current proposed architectural applications of bio-plastics are limited to either substitutes for current substrates such as medium density fiberboard (MDF) and particleboard, or to non-structural envelope components (Christian; Isaac).

The second reason for investigating bio-based polymer composites as a structural building material is that they could offer many potential benefits in that role. Among these are high thermal insulation value with no bridging, lower building weight resulting in a reduction in the sizing of foundation and secondary structure, quality control of factory produced components, fast on-site erection, lighter weight installation equipment, and lower transportation fuel costs. Other potential benefits include lower embodied energy, use of carbon neutral materials, and the ability for the material to biodegrade or be reclaimed at the end of its service life. Perhaps of the greatest interest to architects is the potential ability to realize a wide range of formal architectural expression due to the material's inherent plasticity.

1.3 *Research Questions*

The primary research question is stated as:

How does a new material become configured into a viable construction system?

Underlying this question are the research problems of uncovering, understanding, and weighting the relative importance of the full range of criteria that any proposed novel construction system must satisfy. These research questions are encompassed by the more broadly stated question of *what form should a material assume, and why?*

1.4 *Research Hypothesis*

Bio-based composite materials are suitable for structural architectural applications within certain applications. While the materials being investigated bear many similarities to petroplastic composites utilized in a small number of prior architectural structures, they have important peculiarities which must be taken into account, and must satisfy a range of criteria and conditions that these prior structures never completely addressed. It is the hypothesis of this paper that *within the current landscape of these criteria and conditions there exists the possibility of successfully solving their needs with a novel construction system that utilizes bio-based polymer composite materials.*

1.5 *Research Methodology*

The research methodology operated within four primary areas. The first was materials research, which included a survey of current materials science literature, literature relating to product development using these materials in non-architectural fields, and direct experimentation with the materials themselves. Secondly, a series of architectural case studies were undertaken, along with a survey of the history of the use of related materials. These were used as a primary tool in identifying criteria that construction systems must address. Third, research within the domains of each of these addressable criteria was undertaken. Fourth, design research was utilized as a means of synthesizing the knowledge accumulated from each of the previous research activities and to propose a novel construction system that would satisfy these uncovered criteria. It should be noted that although these four modes are listed here suggesting a linear sequence, the related research was executed in parallel, often resulting in circular loops of inquiry.

1.6 *Contributions*

This research demonstrates the viability of bio-based polymer composites to operate within a systematized structural system. While this research proposes a single novel solution, the analytical framework that was used to arrive at the criteria that generated this proposal can be utilized to develop other construction systems using this material. This proposed system serves primarily as an illustration of the necessity of employing a rigorous methodology to discover such criteria, and furthermore illustrates their continuously evolving nature. It also demonstrates the potential opportunities of new situations, knowledge, and methods, such as those presented by the development of computational tools, to become integral components of a new construction system.

2. COMPOSITE MATERIALS

Composite materials are defined as those consisting of two or more constituent materials that retain their individual physical identities. They typically consist of a binding material (matrix) and particulate or fibrous reinforcement materials. Many types of materials fall under this broad definition, such as reinforced concrete, plywood, particle board, and fiberglass. Wood can be understood as a natural composite consisting of a matrix of lignin that binds reinforcing fibers of cellulose. While all of these materials correctly fit the broad definition, the class of materials typically referred to as *composites* fall within the subcategory of Advanced Composite Materials (ACM.) Advanced composites are those materials that are characterized by high strength fibers that constitute a high percentage of the total volume and are bound together by a lower strength matrix material. Advanced composites are further classified by their matrix materials: Polymer Matrix Composites (PMC), Metal Matrix Composites (MMC), and Ceramic Matrix Composites (CMC). The colloquial usage of the word *composite* generally references this first category of advanced composites, those that employ a polymer matrix material.

Commonly known PMCs are glass-fiber reinforced plastic (GFRP, or *fiberglass*) and carbon fiber. The former typically uses a polyester matrix material and has been widely used in consumer products, such as automobile bodies, furniture, boat hulls, and bathroom components such as shower surrounds and sinks. Of considerable higher strength and cost, carbon fiber uses an epoxy matrix material and is used for higher performance applications such as aerospace, military, race car chassis, and elite sports equipment such as golf clubs, tennis rackets, and bicycle frames.

2.1 *Sandwich Construction*

In addition to a focus on bio-based PMC, this paper will investigate their specific application within sandwich structured composites. These consist of an assembly that is characterized by thin outer skins (facings) that exhibit high tensile strength and are separated by a core of low density, low strength material. Through an adhesive bond with the skins, the core material provides shear strength, which results in an assembly that exhibits high bending stiffness while maintaining an overall low density. Common core materials that have been used in sandwich structures include balsa wood, open and closed cell foams such as polystyrene and polyurethane, and honeycombs of Nomex or phenolic impregnated paper. Sandwich structures also exist that utilize these same core materials but use wood or sheet metal skins rather than polymer based materials. Relative to the thickness of the core, the facings of a sandwich panel are very thin and thus act as membranes that are weak in shear compared to the core material, which therefore resists almost all of the shear force. The stiffness of the sandwich panel is therefore directly related to the shear rigidity of the core (Koschade 29).

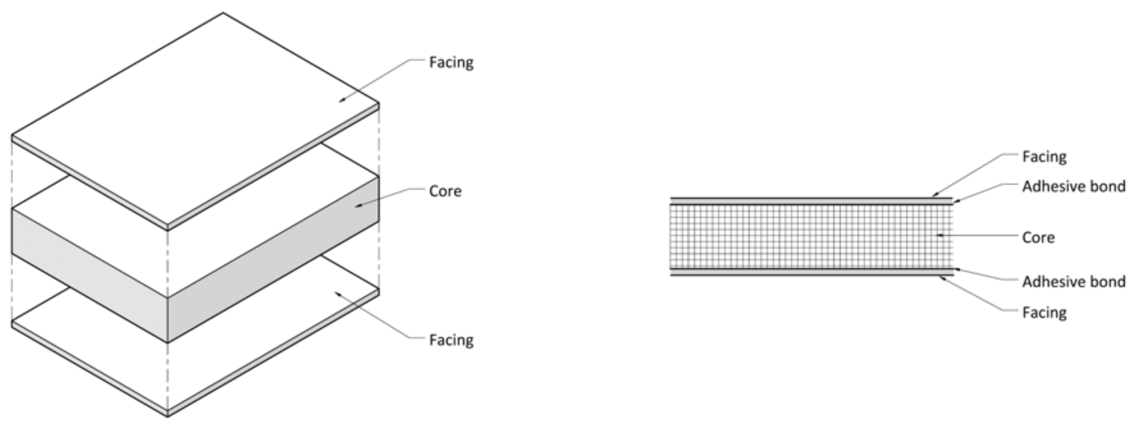


Figure 2.1 Sandwich assembly.

The research in this paper will focus on bio-based polymer composite sandwich structures for several reasons. Firstly, due to the relatively high overall strength that can be achieved in this type of structure compared to the strengths of the constituent materials. Single skin composites have a significantly shorter spanning capacity. Secondly, there is a history of sandwich panel use in the building industry and thus exists a body of knowledge related to their specific application in building envelopes and structures. Lastly, sandwich structures allow thermal insulation materials to be conceptualized not as merely an infill material within a building envelope assembly, but rather as providing a significant structural role.

2.2 *Precedents of Sandwich Structures in Architecture*

The use of sandwich panels extends back to the post World War II era, when increasing numbers of cold storage freezers began to be constructed (Koschade 14). These sandwich panels provided a non-structural enclosure and were thus attached to a load-bearing framework. Cold storage facilities were the primary application of sandwich panels until the past several decades, which has seen increased application in other roles.

2.2.1 Metal Faced Sandwich Panels

Descendents of the panels that were originally developed for freezer applications, metal faced sandwich assemblies have increasingly found applications in building types such as office buildings, retail, large warehouses, and residential. A large number of European manufacturers produce a wide range of panels for these applications with a considerable selection of facing appearances. They typically have a corrugated metal facing, which acts as finish surface, and a rigid polyurethane foam core. They are manufactured as modular, pre-engineered "totally integrated systems" which are designed to be attached to a primary structure, which is typically steel or concrete (Koschade 14). The stiffness of the panels does allow them to function as secondary structure, including roof spans between widely spaced purlins, which can result in a material savings in the primary structure when compared to other envelope systems.

While the panels offer many advantages, such as high strength to weight ratios, ease of handling, prefabrication, and elimination of thermal bridging, one study reports that 96% of architects who used them did so for their ability to accelerate building erection and the associated cost savings resulting from compressed construction schedules. Studies have shown installation times average 10 minutes/m2 for wall installations and 8 minutes/m2 for roofs (Koschade 32).

The typical European metal faced panel is 1000mm in width and is available in lengths up to 20m. Their edge connections are typically through some variation of a tongue and groove, often incorporating a sealing strip. The facings often overlap each other in some manner to improve weatherability. Most manufacturers have developed proprietary systems for connection to the primary structure, typically by concealed bolts or screws, which allow for ease of disassembly at the end of their service life.

In addition to the typical flat panel, manufactures often provide a range of shaped components such as curved panels, corner sections, or those that integrate fenestration, doors, louvers, eave profiles, and photovoltaic panels. Metal faced panels are manufactured using a double belt continuous lamination process in which top and bottom facings are simultaneously unrolled from coils of sheet material and liquid polyurethane is foamed between them. The expanding liquid foam adheres to the facings, eliminating the need for a separate adhesive application. Profiles may be rolled into the facings before the foaming process occurs. The continuous panel is then cut into lengths.

2.2.2 Structural Insulated Panels (SIPs)

While the insulated sandwich panels that evolved from cold-store construction rely on a separate structural frame as armature, another type of architectural sandwich panel product is employed as primary building structure.   Gaining popularity in the construction of energy efficient single family homes and light industrial applications, is the Structurally Insulated Panel (SIP). (Fig. 2.2)

Figure 2.2 Structural Insulated Panel construction. [*Morley*]

While insulated sandwich panels had been in limited use in the United States since the 1940's, the first structural panel was developed in 1950 by Alden B. Dow, the brother of the Dow Chemical Company founder, and a student of Frank Lloyd Wright (Morely 9). Inspired by non-insulated structural panels that Wright was developing for potential use in his Usonian houses, Dow improved upon the concept by basing them around an expanded polystyrene (Styrofoam) core, a material recently brought to market by Dow Chemical. These were assemblies of 5/16" plywood facings adhered to 1 5/8" Styrofoam core material, and the first houses built using his system were constructed in Midland, Michigan in the mid 1950's. Most utilized the insulated panels as fully load bearing exterior walls, and were installed as a secondary roof system over widely spaced framing. Dow began to mass produce his new product in 1959 in a converted Detroit automobile manufacturing facility. (Fig. 2.3) Due to low energy costs and relatively low labor costs at the time, the benefits of additional thermal insulation and prefabrication were not great enough to cause significant demand and the venture was short lived. It was not until the early 1980's that the concept was revisited and commercial SIPS became available once more.

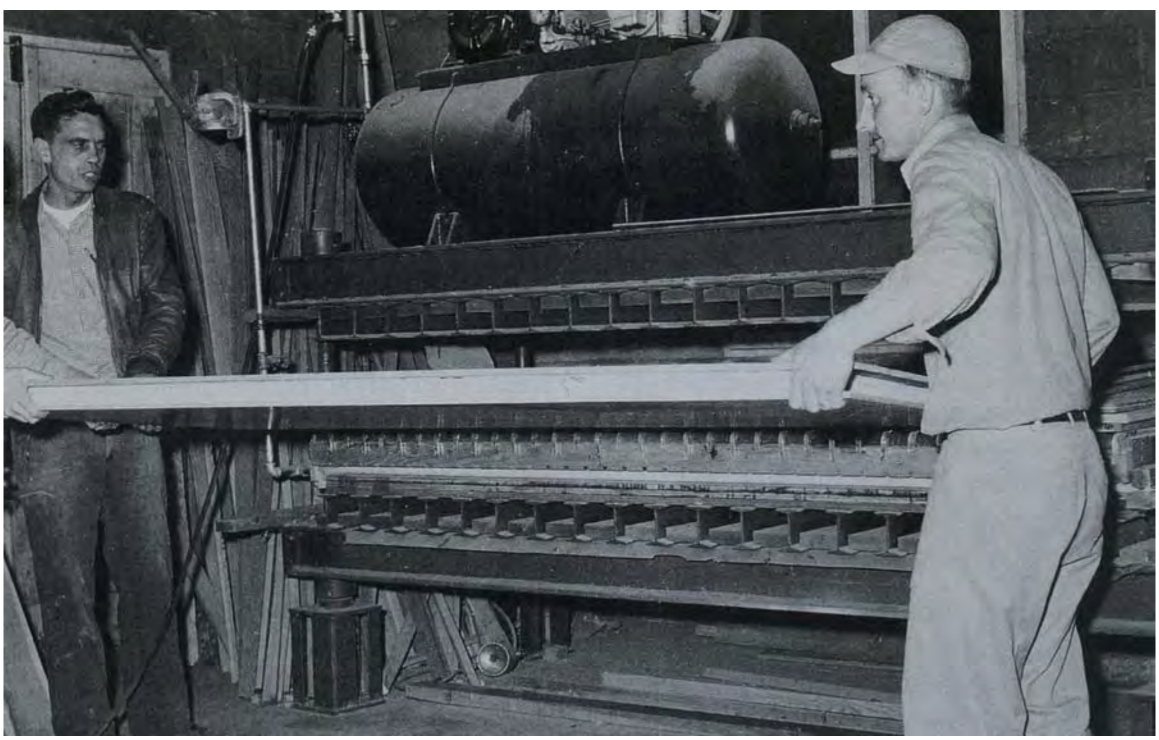


Figure 2.3 Dow Structural Insulated Panel manufacture, 1959. [*Morley*]

Modern SIPS employ a core of rigid foam, most commonly expanded styrene (EPS), although extruded styrene (XPS) is occasionally used, as is higher performing but more expensive closed cell polyurethane. Facings may be plywood, gypsum board (as a secondary lamination), or OSB (Oriented Stand Board), which is most common due to its ability to be produced in lengths up to 28 feet. (Fig. 2.4) Approximately 90% of SIPs are constructed with 7/16" OSB facings on both sides of the panel, which is treated with an edge sealant to prevent moisture absorption during construction site weather exposure (APA- The Engineered Wood Association). Modern SIPs come in a standard range of thicknesses, from 4 ½" to 12 1/4".

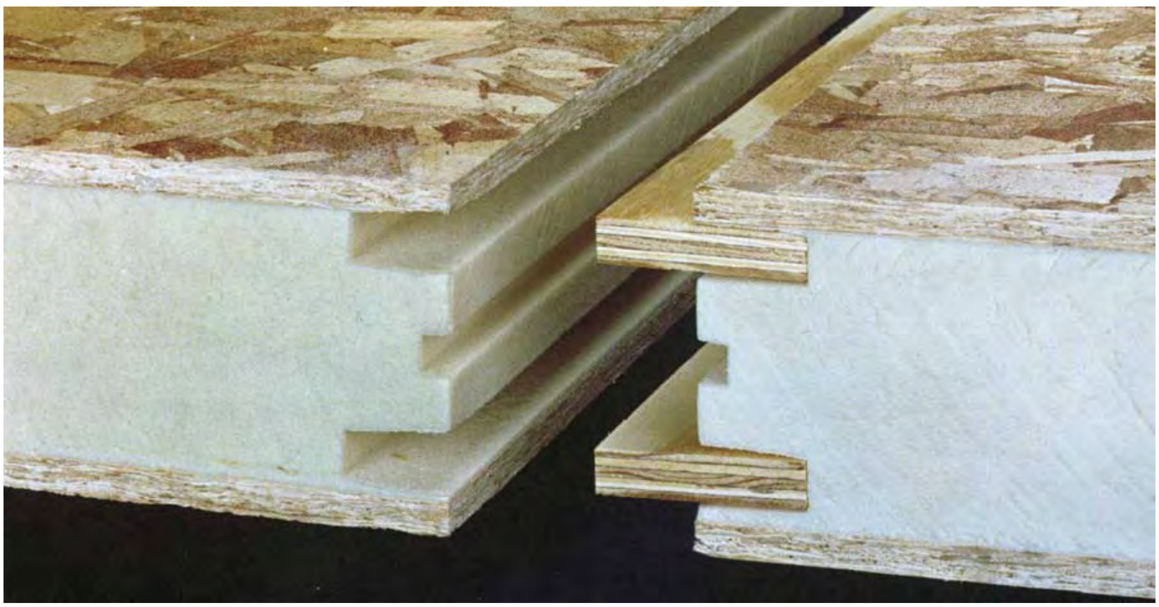


Figure 2.4 Structural Insulated Panel spline joint. [*Morley*]

The majority (85%) of SIPS are manufactured with an EPS core, which is a closed cell foam that typically has a 1 pound per cubic foot (pcf) density and a R-value of 3.85 per inch. Facings are bonded to sheets of EPS with a urethane adhesive under pressure. While more expensive, expanded polystyrene (XPS) is occasionally used due both to its higher compression strength and, more importantly, its higher resistance to moisture penetration. This latter attribute makes it more suitable for refrigeration walls than EPS. The XPS core material typically has a density of 1.5 pcf and an R-value of 5.0. It is only available in sheets up to 4" thickness due to material manufacturing limitations, and is not as dimensionally stable as EPS, which can cause problems in adhesive bonding of facings. The third type of foam that is used in SIPS production is polyurethane. It is typically 2-2.2 pcf density and has a higher R value than either EPS or XPS, although it is susceptible to thermal drift over time. It has an R-value of 7.0 when new, but levels out at around 5.8 per inch. Low-permeability facings prevent moisture from reaching the polyurethane core, which can reduce the amount of thermal drift. Polyurethane cores are typically foamed in place between the facing sheets, which are backed up with rigid steel platens, eliminating the need for adhesives. Inconsistencies in the foaming process may result in surface irregularities of the finished sheet. Polyurethane foam is more rarely cast into sheets and then facings bonded to it, much like the EPS/XPS process.

SIPs are most typically available in 4 foot wide panels. Curved panels are also available, as are other specialty panels such as those with a double outer layer of OSB facings with an air cavity between for integral roof ventilation capabilities. The panels are typically joined together with a simple tongue and groove system that is milled into the foam core, as well as OSB spline plates that provide some amount of continuity between facings of adjacent panels. (Fig. 2.4) The tongue and groove configuration in the foam core often incorporates a void space that is filled on-site with an expandable foam to provide a thermal seal. While the 4 foot width is an industry standard, there has been a movement toward the use of significantly larger panels, often encompassing entire walls. The ability to manufacture OSB facing in very large sheets has made this a possibility. The monolithic nature of these panels increases their structural performance while leaving fewer joints that require thermal sealing, yet they are still easily transportable and more quickly erected with the use of a light duty crane. (Fig. 2.5)

Figure 2.5 Structural Insulated Panel erection. [*Morley*]

In addition to performing well thermally due to their high R-value and lack of bridging, SIPs also perform well as wall panels in compression, with the skins behaving as continuous thin bearing members and the foam core providing resistance to their out of plane buckling. Since the OSB skins are an engineered material, and the panels are manufactured in a controlled factory setting, they can function as a predictable engineered construction system with consistent mechanical properties. SIPs are extensively tested in transverse, axial, and shear load tests, safety factors are added in, and charts are published with span and axial loading data. The panels provide significantly higher shear strength than conventional light wood framing. The availability of load charts and construction conventions result in an ease of implementation with relatively low levels of project specific engineering.

2.2.3 Composite Sandwich Buildings

Numerous examples exist of small-scale buildings, typically residential, that have been built of petroplastic composite sandwich construction with inner and outer skins of glass-fiber reinforced plastic and a foam core. The result of architectural experimentation during the 1950's-70's, these were most typically fabricated by producing the outer skin in a mold, and then spraying polyurethane foam onto the rear of this surface. A second skin was then either hand-laid over the foam, or resin and chopped strands of fiber were spray applied. Due to the requirement of a mold for each unique panel, these structures usually sought to reduce the number of unique panels to an absolute minimum, typically utilizing a building morphology that was an aggregation of one or two repetitive units. Connection of these individual repeating panels was typically by flanges along their edges, which were oriented normal to the face of the panel, and allowed simple bolted connections as well as providing mating surfaces for adhesives and sealants. (Fig. 2.6)

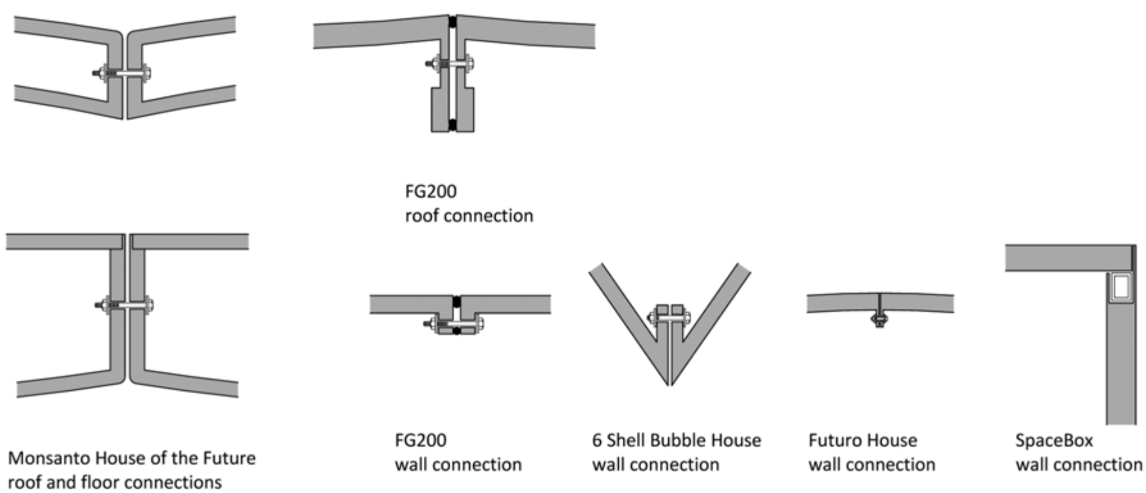


Figure 2.6 Composite building, joint details.

3. CONSTITUENT MATERIALS IN COMPOSITE SANDWICH ASSEMBLIES

3.1 *POLYMER MATRIX: The Composition of Plastic*

The American Society for Testing and Materials (now known as ASTM International) defines the group of materials that is considered to be "plastic" as "a material that contains as an essential ingredient one or more organic polymeric substances of large molecular weight, is solid in its finished state, and, at some stage in its manufacture or processing into finished articles, can be shaped by flow"(ASTM D883). However, while some substances such as rubber, textiles, many types of adhesives, and paint, may meet this definition, they are not generally considered plastics (Stevens 38).

Polymers are substances consisting of molecules that are composed of chains of repetitive units of monomers, which are of low molecular weight and built primarily of carbon and hydrogen atoms. Polymerization is a process of chemical reaction in which monomers join together to form three-dimensional networks of chains. Although the polymer thus has a complex structure with a large number of atoms, its chemical formula can often be simply represented, as it is composed of repeating units that are identical. Polymerization can occur with either identical monomer units (homopolymer) or by linking together multiple types of monomers (copolymer.) Polymerization can also result in either monomer chains that are linear or branched . The *degree* of polymerization is the number of monomer units in a chain.

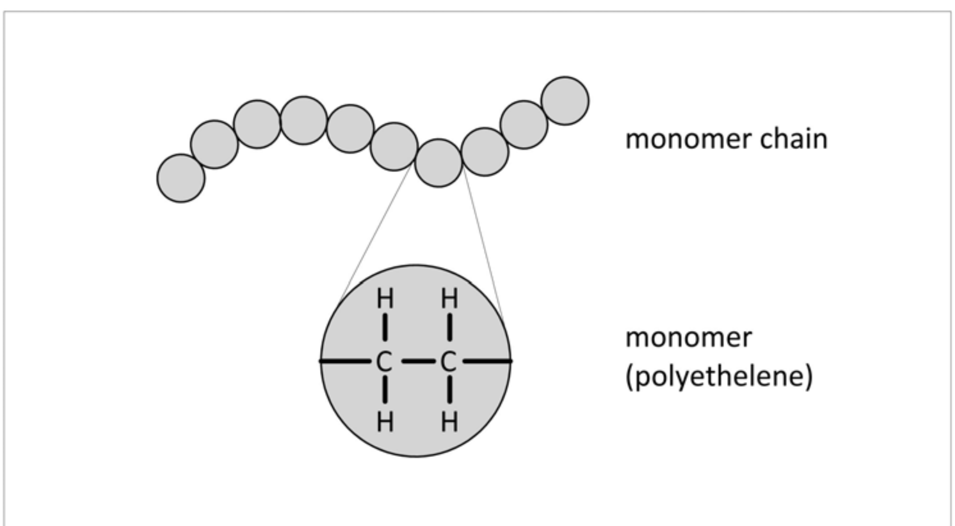


Figure 3.1 Polymer chain.

3.1.1 Categories of Plastics

Plastics are categorized as two general types: thermoplastics and thermosets. Thermoplastics can be softened by heat and re-solidified by cooling, and are able to be formed plastically (such as by extrusion) while in their softened state. The polymer chains of thermoplastics are primarily linear, with few branches. Thermosets are cured by heat or other reaction and once formed are mostly insoluble and cannot be softened for processing by the application of heat. Thermosets form a complex three dimensional cross-linking of monomers, and it is during this cross-linking (curing) process that the material is manipulated into its desired form. They cannot be reworked after the cross-linking process is complete.

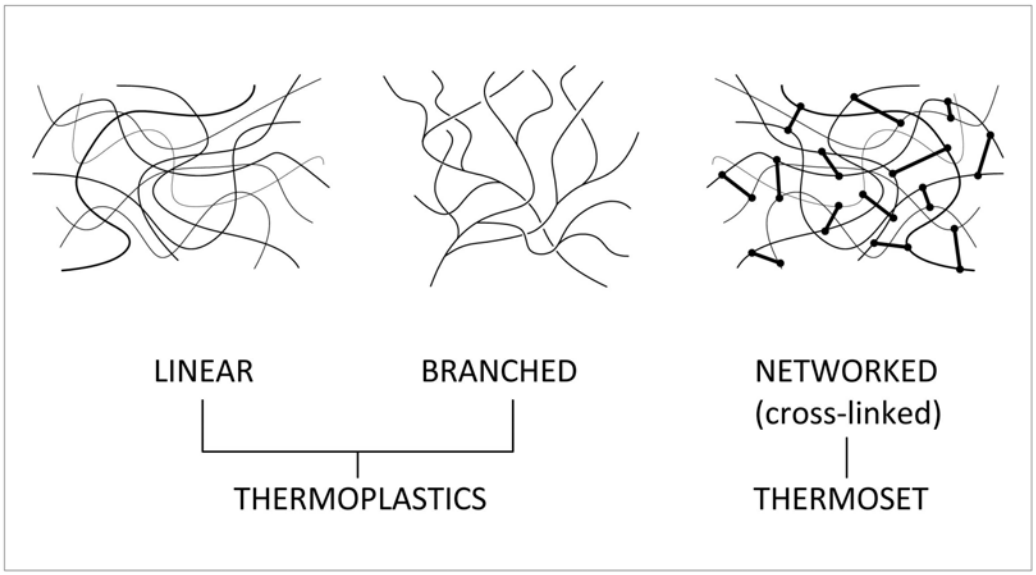


Figure 3.2 Thermoplastic vs. thermoset polymer chains.

Thermosets such as polyester, vinyl ester, and epoxy, which are common petroleum-based resins employed in the manufacture of fiber reinforced composites, cure by an *addition* reaction. These plastics are typically liquid at room temperature, and when two components are mixed together they begin to cross-link and cure. This can either occur at room temperature, or at an elevated temperature for faster curing, depending on specific polymer formulation. Addition reactions are typically exothermic, producing internal heat as the two components generate chemical bonds, which further quickens the curing process. Some types of these resins require care in the quantity of material that is combined at once, as the exothermic heat can cause a runaway reaction, causing premature curing and possibly producing enough heat to initiate combustion.

3.1.2 Glass Transition Temperature

While thermoplastics can repeatedly be heated and cooled without altering their physical properties, cured thermosets undergo irreversible molecular changes when exposed to elevated temperatures. As their temperature rises when exposed to heat, they precipitously change from a hard, rigid consistency to a rubber-like condition. The temperature at which this occurs is known as the *glass transition temperature* (Tg). This number may actually represent the ultimate temperature within a range that spans 5-10 degrees C, rather than at a sharp threshold such as the melting point behavior of most thermoplastics. When the Tg is crossed, the polymer loses its structural characteristics as it becomes soft and rubbery. At this temperature it undergoes a crystalline change where additional polymer cross-links are formed, resulting in brittleness and reduced structural properties when the material is returned to a sub-Tg level. Thermosetting resins that are commonly used in face laminations of sandwich panels exhibit this behavior, having glass transition temperatures in the range of 100-250 degrees C, which can result in catastrophic loss of structural integrity when exposed to the heat of a fire.

3.1.3 Additives

Polymers by themselves often exhibit poor physical properties and thus require chemical additives to enhance desired characteristics, including those required for manufacture or processing. Thus, plastics are rarely composed of polymers exclusively. (Fig. 3.3) Additives are commonly used to to stabilize the material against heat, light, oxidation, and attack from micro-organisms, or to enhance performance properties, such as by the inclusion of fillers or fibers to add strength . One of the most common groups of additives are plasticizers, which are softening agents that add flexibility or toughness, and also facilitate handling by processing equipment. The process of combining polymers and additives is called *compounding*.

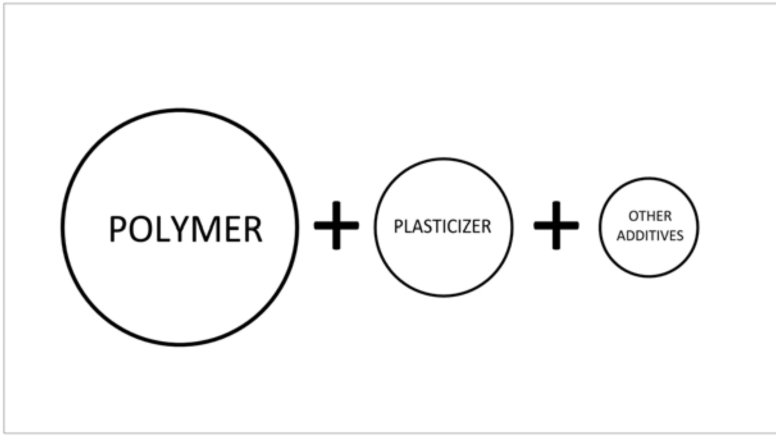


Figure 3.3 Plastic additives.

3.1.4 Plastic Alloys

Another method of improving the properties of plastics, typically thermoplastics, is the process of alloying.   Known as *blends* or *polyblends*, two or more types of plastic are combined together to improve a weak performance characteristic of a base material, and often result in a synergistic improvement. To be considered an alloy, there must be a minimum of 5% alloy content, although ratios often approach a 50:50 mix in an effort to positively effect properties such as processibility, impact strength, and fire resistance. Such blending of different plastics in an alloy is not a chemical process, rather the bond between the dissimilar materials is strictly mechanical. Thermoplastic alloys typically maintain a single melt-transition temperature.

3.2 *REINFORCING FIBERS: Processed Fiber Formats*

Raw individual fibers are processed into various formats for handling and placement in molds. These can be described by two general categories: woven and non-woven. The fiber format can greatly impact the mechanical characteristics of the composite. Fibers that are organized into directional orientations, such as woven textiles, generally result in composites that exhibit anisotropic behavior, while randomly organized fibers in a non-woven mat exhibit close to isotropic properties. An optimal performance for a particular application can be achieved by varying the density and orientation of the fibers in response to load stresses. This can be seen as similar in principle to the varying composition of plant fibers that occur through growth, as they respond to mechanical stresses they encounter in their environment.

3.2.1 Woven Textiles and Types of Weave

Woven textiles are the most common delivery method for handling and placing fibers within a mold. The type of weave can affect the drapability of a fabric over complex mold surfaces, wet-out qualities, and the strength of the finished laminate. The latter is due to fibers being strongest when they are straight, or with the fewest over/under crosses occurring in a weave. Thus the same amount of reinforcing material may contribute differing amount of strength to a laminate depending on the type of textile weave that is employed

Fibers are first spun into yarns that are then used to weave textiles. Within this woven textile, the yarns that are oriented longitudinally to the loom are called *warp* yarn and those that are transverse are variously known as *cross*, *fill*, *woof*, or *weft* yarns. The simplest weave is plain weave, in which the crossing warp and weft yarns alternately go over one yarn and then under one yarn. This weave has several disadvantages. Due to the large number of yarn crossings, the majority of the fibers are not oriented directly along the in-plane axis of the cloth and are thus less effective as reinforcement. The density of crosses also results in a “stiff” textile with poor drapability, that does not easily conform to complex surfaces.

Weaves have been developed to combat both of these problems in reinforcement textiles. These weaves distribute the cross yarns such that they pass above multiple warp yarns before tucking beneath a single warp yarn. There are different designations for these weaves depending on the number of warp yarns that are crossed over. (Fig. 3.4) In *twill* weaves, two strands are crossed over, in *crowfoot* weaves three or four are crossed over, and *satin* weaves cross over five or more warp yarns. These weaves result in both straighter yarn orientations for higher strength and superior drapability. Disadvantages are that they may be more difficult to handle while placing in a mold due to the tendency of the fabric to shift obliquely, as well as there being longer loose yarns at cut edges. The latter is often dealt with by taping or lightly stitching the cut edges to prevent fraying.

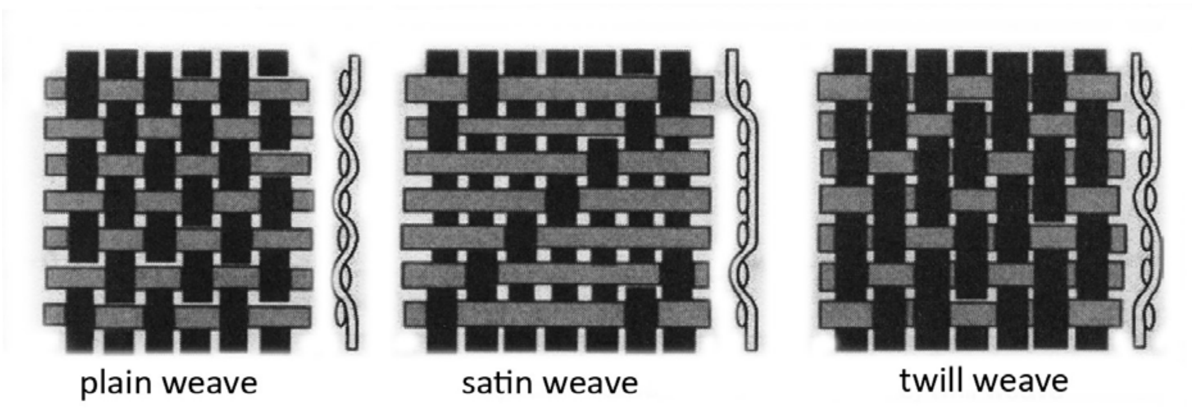


Figure 3.4 Textile weaves. [*Gay*]

Another class of reinforcing textiles are *hybrid fabrics*, which combine multiple types of fibers woven together to either adjust mechanical properties or to reduce cost by placing stronger and more expensive fibers in orientations where they are most needed.

Woven textiles that have not been further processed, bleached, or dyed are known as *greige goods* (pronounced "grey") or *loom state* fabrics. These may contain light machine oil that is used in processing equipment, or other substances that effect the bond between fiber and polymer matrix. These substances may also be present and cause similar problems in non-woven textiles, as light machine oil is often used in this processing equipment as well.

3.2.2 Non-wovens or Minimally Woven

Non-woven “fabrics” are those that are neither woven nor knitted (knits are rarely used as reinforcing fibers) and have a web-like random distribution of fibers. Produced in thin sheets or mats, they may superficially resemble woven fabrics but have significant differences. Fibers are not spun into yarn, but rather are processed into the sheet individually, they are typically short in length, and have homogenous mechanical properties in all in-plane orientations. Natural fiber non-wovens are typically manufactured by either mechanical needle-punching or carding. Their web-like characteristics results in a mat of fibers that is highly conformable to mold surfaces and is easy to handle (Mueller 32).

Individual strands of thick yarn, known as *roving*, may also be used as reinforcing fibers. This allows the placement of fibers in precise locations and orientations within a component. Multiple rovings may also be combined together to form a *unidirectional tape*, employing widely spaced rows of thin stitching to hold them together for handling. Wider versions of unidirectional tapes are known as *unidirectional fabrics*, in which the ratio of longitudinal yarns to cross stitching may be up to 50:1. Figure 3.5 illustrates a plain weave fabric of roving, and a non-woven mat textile of synthetic fibers.

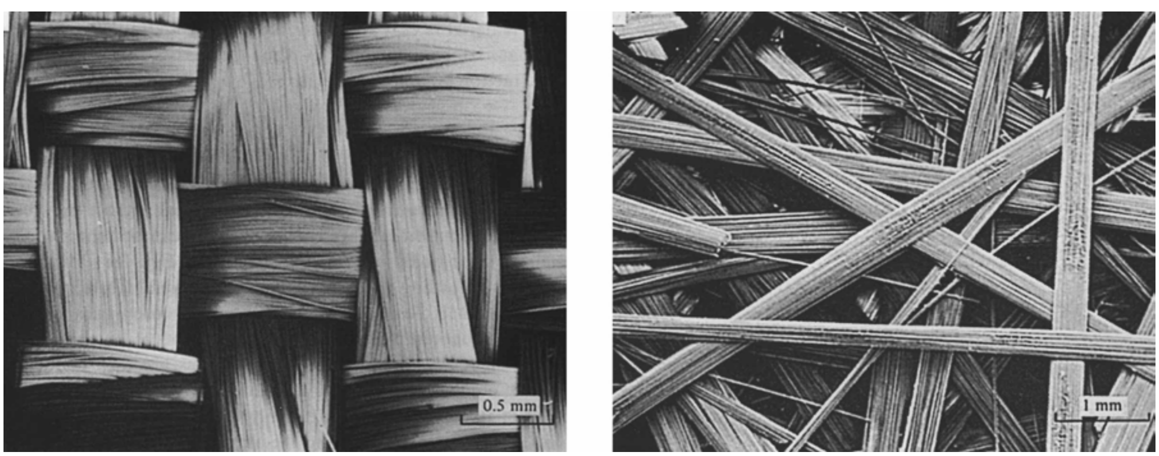


Figure 3.5 Woven vs. non-woven textiles. [*Hull & Clyne*]

3.2.3 Effect of Fiber Orientation on Mechanical Properties

The distribution and orientation of fibers within differing woven/non-woven formats has a significant effect on the mechanical properties of the final composite laminate. The homogenous distribution of fibers in non-wovens results in nearly isotropic properties, while the directionality of other formats results in an anisotropic condition. The wide range of fiber delivery formats allows tailoring of the mechanical properties of a composite to the structural loads it is anticipated to encounter.

3.2 *CORE MATERIAL: Rigid Polyurethane Foam*

As previously discussed, the function of a core material within a sandwich construction is to separate the facings and provide compressive and shear strength to transmit forces between them. Numerous types of material have been employed as cores, such as balsa wood, honeycombs of paper or Nomex, and plastic foams. This research will focus on materials that have both structural value within an assembly and high thermal insulation values, specifically rigid closed-cell polyurethane foams.

The majority of conventional petroleum derived polyurethane (PUR) material is produced as foam, both rigid and elastomeric, and the largest market segment, nearly 27%, is the building and construction industry, where it is primary used as a rigid insulation material (Center for the Polyurethanes Industry, Feb.2004 report).

Polyurethanes are reaction polymers in which polymer chains are produced by reacting an isocyanate group with a hydroxyl group (alcohol.) When the two components are mixed, a chemical reaction begins and a gas is produced causing foaming to occur. This reaction generates heat, and the material expands in volume by a factor of 4x to 140x depending on exact formulation and working temperature. Polyurethane foam may be placed by either mixing the two liquid components and pouring into a mold cavity for casting, or may be sprayed with the aid of a propellant. (Figs. 3.6, 3.7) During this phase the expanding foam is very tacky and will adhere to a wide range of materials. If PUR is not foamed up against a surface, the free exposed surface will form a hard skin. Each closed cell of the foamed PUR is filled with the gas, typically methane or carbon dioxide, that was produced by the chemical reaction of the two components. This trapped gas contributes to the high thermal insulation values of PUR foams, which are often around R7.0 per inch. After a period of thermal drift, R-values typically stabilize at around R5.0 to R6.0 per inch.

Figure 3.6 Injection of polyurethane foam into mold cavity. [*Greene Associates*]

Figure 3.7 Spray application of polyurethane foam. [*Moser Roofing*]

4. MANUFACTURING PROCESSES

There are multiple manufacturing methods of traditional fiber reinforced plastic laminate, most of which are directly transferable to the use of bio-based materials. Each process accommodates the following general steps in the formation of a lamination: placement of reinforcing fibers, resin impregnation, consolidation of the laminate to achieve desired resin to fiber ratios and to remove trapped air, and curing of the resin. The different manufacturing processes have varying degrees of control over these factors, therefore each manufacturing process results in differing quality levels in the final product. Due to this, each process dictates particular limitations on structural design (Barbero 43). Generally, there is a direct correlation between process cost and how well these four factors are satisfied.

In addition to processes for the manufacture of composite laminations, this section will also briefly discuss methods of producing other types of plastic components, as they they may be applicable to the production of types of elements that could be incorporated within construction systems.

4.1 *Composites Manufacturing Processes*

Below is a description of manufacturing methods that are employed in the production of components with traditional polymer composite materials. Not all processes of traditional manufacture are applicable to use of natural fiber reinforcement, however, all are compatible with various formulations of bio-based resins.

4.1.1 Hand Lay-up

Hand lay-up, or wet lay-up, is a manual process in which both reinforcing fibers and resin are manually placed in an open mold. Fibers are typically a woven textile or chopped strand mat format. Resin is applied to the surface of the fibers and they are impregnated with resin by wetting out with brushes or rollers. (Fig. 4.1) Consolidation is also accomplished by hand, typically with rollers to force resin through the fibers and removing excess. Curing of the resin polymer typically occurs at room temperature and atmospheric pressure, but may also occur at an elevated temperature in an oven. The use of an open mold results in high VOC emissions due to lack of containment of the materials, and the large surface area of wet resin.

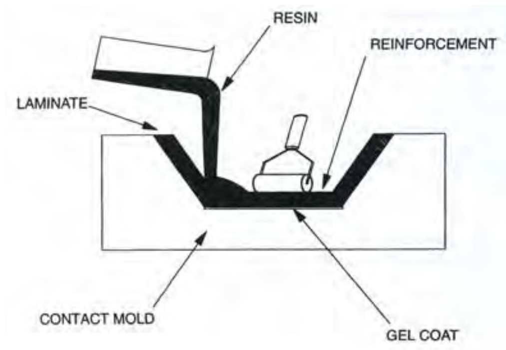


Figure 4.1 Hand lay-up manufacturing process. [*Barbero*]

The hand lay-up process is the most economical and can be accomplished with a minimum of equipment and tooling investment. It is thus suitable to the production of very large parts, such as boat hulls, swimming pools, aircraft parts, and architectural components. It also accommodates the lay-up of sandwich construction and the integration of local reinforcement. Disadvantages are that it is a labor intensive process and is vulnerable to the inconsistencies of craft work. Consolidation of material is limited, and thus parts with a high resin to fiber ratio are produced. Another inherent quality issue is that it is only possible to achieve a finish surface on one side of the part. As it is a relatively slow process it is therefore suitable to low production rates.

4.1.2 Spray-up

The spray-up process is a partially automated version of the wet lay-up method. The type of mold is the same, and the labor is primarily manual, but the placement of both resin and fiber is accomplished with a "chopper gun." As the gun sprays catalyzed resin, it is combined at the nozzle with short strands of glass fiber that are "chopped" from a continuous spool of roving. The process results in a resin-rich mixture being sprayed into the mold. (Fig. 4.2) The thickness of deposition is controlled by the operator, and is thus dependent on operator skill. Varying thicknesses of material can be achieved within the mold. Due to inferior strength characteristics resulting from the resin-rich mixture, the material is often applied in much thicker applications than with hand lay-up, resulting in heavier parts. The material may be consolidated in the mold with a roller for increased strength and lower weight, but it typically is not.

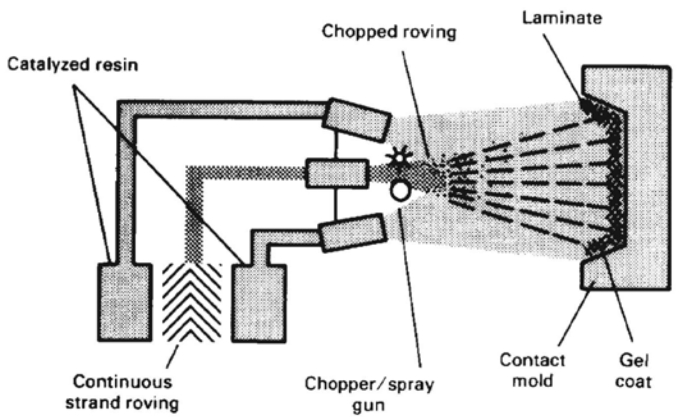


Figure 4.2 Spray-up manufacturing process. [*Greene Associates*]

Spray-up manufacturing is commonly used for lower cost items where high strength or low weight is not a critical factor, such as truck bodies, automotive parts, shower stalls and bathtubs, and furniture. The process lends itself to higher production rates than hand lay-up, but has higher equipment investments.

4.1.3 Vacuum Bag Molding

The direct correlation between material consolidation and strength of the final part has led to the development of manufacturing techniques to increase the compaction of the material in the mold and result in a more ideal resin to fiber ratio. One of the most common of these, and applicable to both hand lay-up as well as prepreg material (reinforcing fibers pre-impregnated with catalyzed resin) is vacuum bag molding, in which the mold and uncured lamination is placed within a flexible sealed bag and a vacuum is drawn with a pump. (Fig. 4.3) The surface of the bag places even pressure across the surface of the curing laminate, consolidating the material. With a vacuum of one atmosphere, 14.7 pounds per square inch of pressure are applied evenly to the surface. This results in over one ton per square foot. Special fabrics are placed between the surface of the laminate and the inside of the bag to aid in the even distribution of vacuum, provide a smooth surface on the bag side of the finished part, and to trap excess resin that is forced out of the fibers. The most typical combination of fabrics used is a *peel ply* that is placed against the laminate, and a *bleeder cloth* between the peel ply and bag. The peel ply is a nylon material that will not adhere to the cured laminate, and is perforated with very fine holes to allow resin to pass through. As resin passes through the peel ply it is trapped in the bleeder cloth, which is a thick non-woven fabric that is both absorbent and provides a porous route for vacuum to distribute evenly. Once vacuum is drawn, the bagged mold is often placed in an oven for curing at an elevated temperature. Resins are formulated for both higher temperature cure and proper viscosity for the vacuum bagging process.

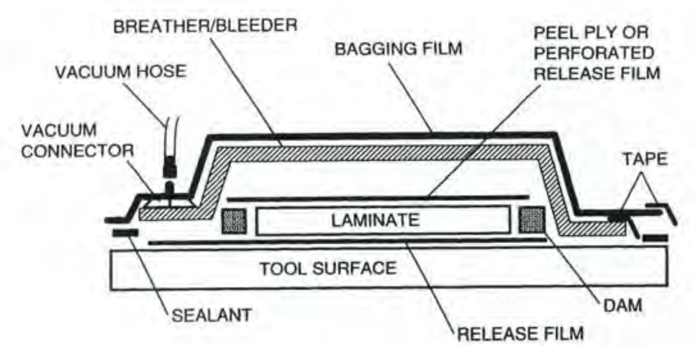


Figure 4.3 Vacuum bag molding process. [*Barbero*]

The vacuum bag technique is a relatively low cost improvement to the had lay-up process, resulting in production of higher quality parts. Production rates can often be higher due to heat curing of the resins. Bags are reusable and can be used for molds of multiple configurations. Very large components can still be produced within a vacuum bag. The encapsulation of the mold during curing results in lower VOC emissions, and the air that is removed as the bag is evacuated is typically routed through filters and traps.

Vacuum bagging can also be used for sandwich construction, to bond core material to previously cured laminates. This is known as *dry-bagging*, as only an adhesive is used, rather than resin. This is an effective way of causing flexible foam core sheet material, such as PVC, to conform to the surface of a complexly shaped mold surface. A vacuum bag may also be used to pull foam core material onto the surface of an uncured laminate (*wet-bagging*.)

4.1.4 Resin Infusion

In addition to the need for proper consolidation, proper wet-out of the fiber reinforcement is also necessary to achieve high structural performance. One such development of improved resin delivery to the fibers is the resin infusion method. This utilizes a network of perforated flexible plastic tubes within a vacuum bag to deliver pressurized resin to the fibers. (Fig. 4.4) Used in conjunction with a vacuum bag for consolidation, this method can result in high fiber to resin ratios, and thus high strength composite products. The containment of the resin within the tubing system results in very low emissions of VOCs, and the resin is typically mixed in a closed vessel to complete the separation of resin from atmosphere. The resin infusion method may be used in most vacuum bagging applications, including those of very large components as it can quickly and effectively distribute resin to a large area.

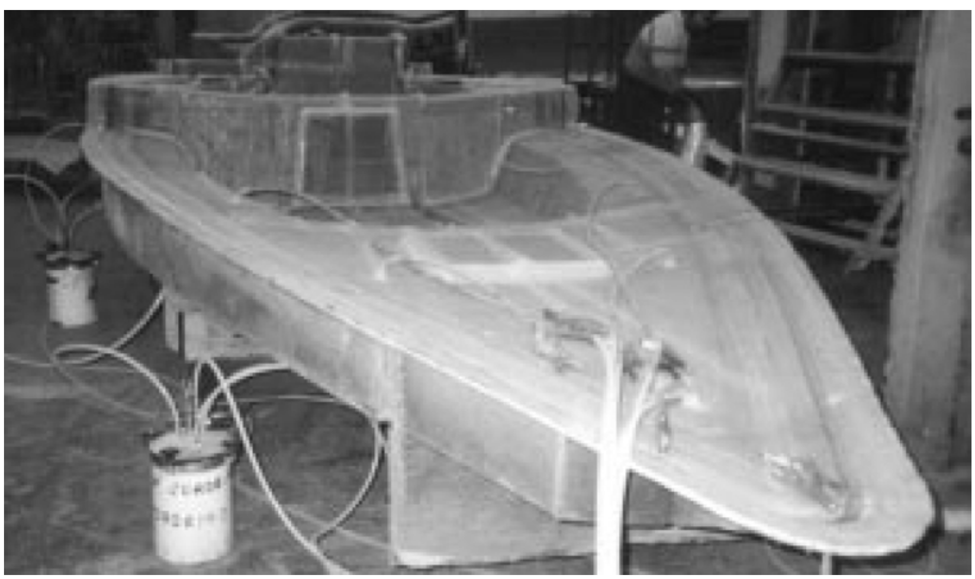


Figure 4.4 Resin infusion manufacturing process. [*Mosher, TPI*]

4.1.5 Resin Impregnator

A resin impregnator is a device used in the lay-up of very large open mold surfaces, such as ship building. Reinforcing fabric is directly impregnated with resin as it is unrolled and placed into the mold. The roll and impregnator are often mounted on a large gantry device which can maneuver the roll into position above the mold, and travels to unroll the fabric in the desired location. (Fig. 4.5) This equipment typically deposits a 60" width roll of impregnated cloth into the mold. It greatly increases the production rates of very large molded components, although VOC emissions are extremely high (Greene 262).

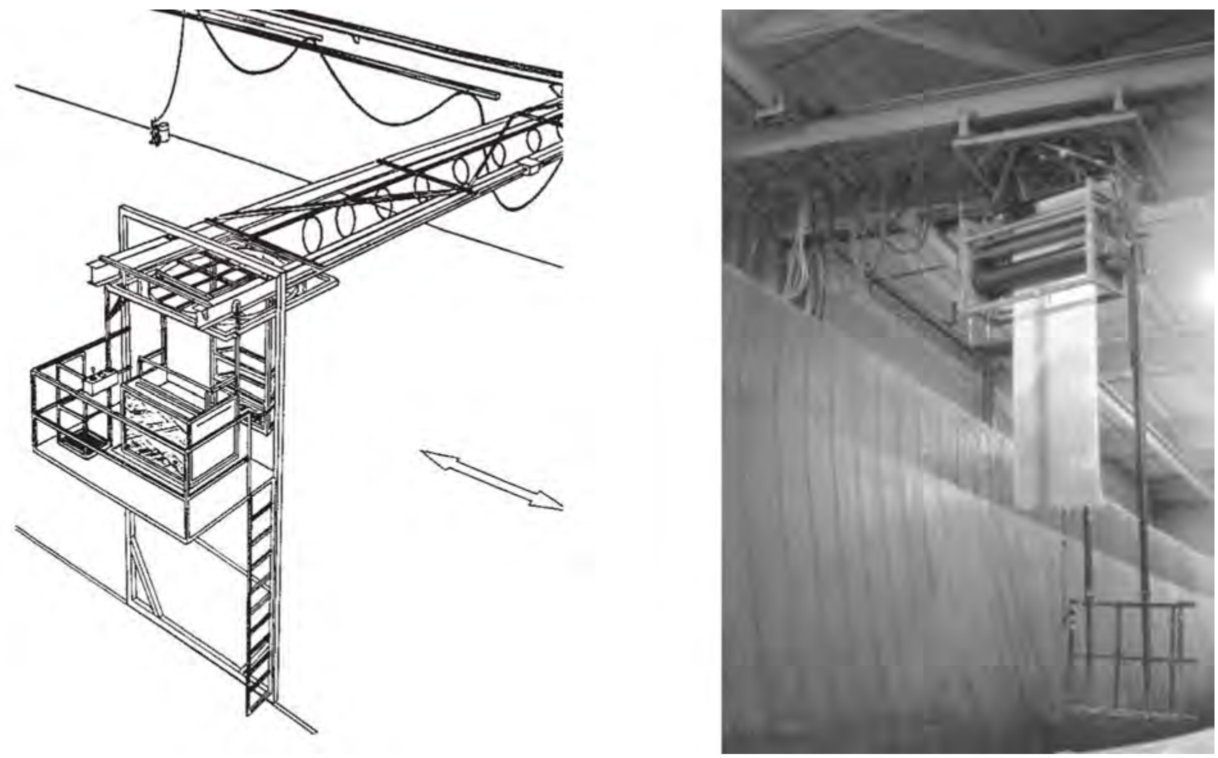


Figure 4.5 Resin impregnator on gantry. [*Greene Associates*]

4.1.6 Compression Molding

The processes discussed so far have utilized an open mold and relied on an external method of consolidation, either through hand rolling or pressure applied from the use of a vacuum bag. Compression molding uses a matched male and female mold, into which a pre-measured quantity of resin and reinforcing fiber are placed. (Fig. 4.6) The mold is then closed under high pressure, typically delivered via a hydraulic press, and heat is applied to cure. Whereas the open molds used in the previous processes only required enough strength to withstand relatively low forces being applied, and are therefore typically constructed of composites themselves, the pressure of compression molding requires a set of expensive metal dies, typically of tool steel.

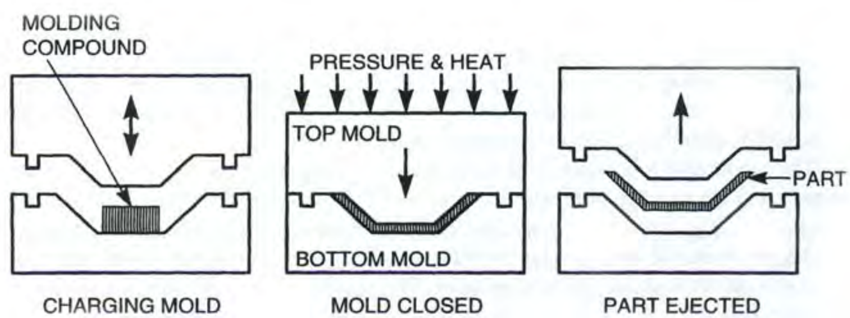


Figure 4.6 Compression molding. [*Barbero*]

A charge of material is placed in the lower mold, most commonly either *bulk molding compound* (BMC) or *sheet molding compound* (SMC). BMC is a dough-like consistency mix of resin and fiber, often in low concentrations of 20-50%, while SMC contains higher fiber ratios. The fibers in SMC are also longer and more continuous to maintain integrity in thin section moldings. Compression molding is suitable to integrating relatively deeply drawn ribs and flanges, resulting in parts with high stiffness due to geometry. Although high stiffness can be attained, difficulty in maintaining fiber continuity in these situations often relegates them to non-structural or secondary structural applications.

Compression molding has the advantages of producing high strength parts, little or no waste material, and high production rates. Disadvantages include very high equipment and tooling costs, and size limitations.

4.1.7 Resin Transfer Molding

Resin transfer molding (RTM) also typically uses a two part closed mold.(Fig. 4.7) Dry fiber reinforcement is first placed in the mold, it is closed, and liquid resin is pumped into the mold under pressure. The resin saturates the fibers and air and excess resin escape through bleeder ports. There are multiple variations on this basic process, such as vacuum assist to help evacuate the mold and pull the resin through the fibers, or the use of flexible elastomeric diaphragms in place of rigid molds.

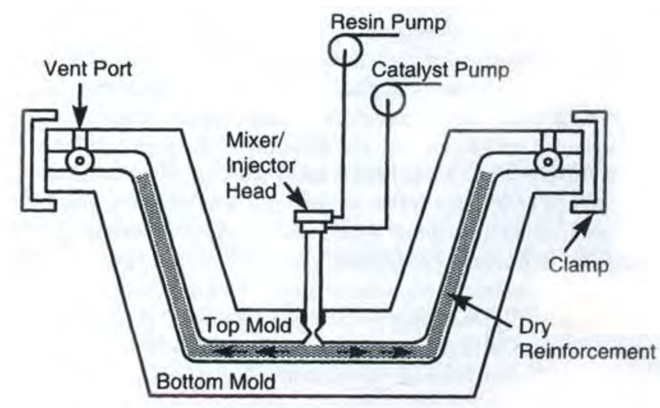


Figure 4.7 Resin transfer molding. [*Barbero*]

The primary advantage of this technique is the control over fiber placement within the mold. Orientation of the fibers can be accurately constrained for increased structural characteristics of the finished part.

4.1.8 Autoclave Molding

Generally restricted in use to very high performance applications such as aerospace, autoclave molding is a process utilizing both high temperatures and high pressures. An open mold, with or without a first stage vacuum bag, is placed inside of a pressure vessel, which is filled with nitrogen or carbon dioxide at pressures near 100 psi. (Fig. 4.8) Temperatures above 200 degrees Fahrenheit are used for resin curing. Rather than wet layup, the reinforcing fibers are typically pre-impregnated for placement in the mold. The very high pressures and cure temperatures result in a composite of the highest strength.

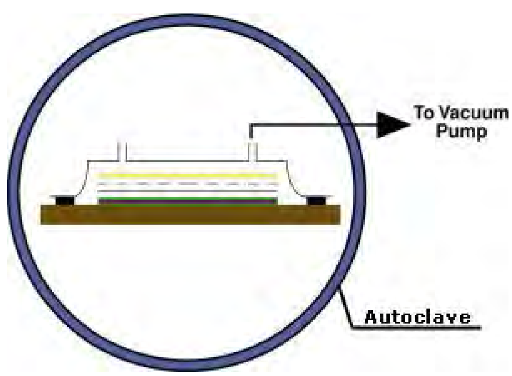


Figure 4.8 Autoclave molding process and equipment. [*Advanced Lightweight Engineering; Composiflex*]

These so-called *prepreg* materials are impregnated with an epoxy resin and are partially cured to a sticky consistency. This "B-stage" of curing requires that the prepreg material be stored in a freezer to inhibit further curing. The resins are formulated to fully cure at considerably higher temperatures than other resins, typically around 250 degrees F, although very high performance prepregs may cure at over 350 degrees F. A class of "low energy cure" prepregs that cure at between 140 and 220 degrees F have been developed and very large laminations can be cured in temporarily constructed ovens. This method is common for America's Cup racing yachts (Green 273).

4.1.9 Pultrusion

Pultrusion is a continuous process for manufacturing elements with constant cross sectional profiles, such as beams and columns. Fibers and fabrics are pulled through a resin bath and through a heated die in which the resin cures. (Fig. 4.9) While pultrusion is most commonly used for manufacturing straight lengths, shaped elements may also be produced. In this situation the extrusion die is not heated to a temperature to cause full curing, and the pultruded piece is therefore soft enough to be post-formed into shape by passing through rollers. Most common is a constant radius curve. Full curing of the element occurs in an oven subsequent to this forming stage.

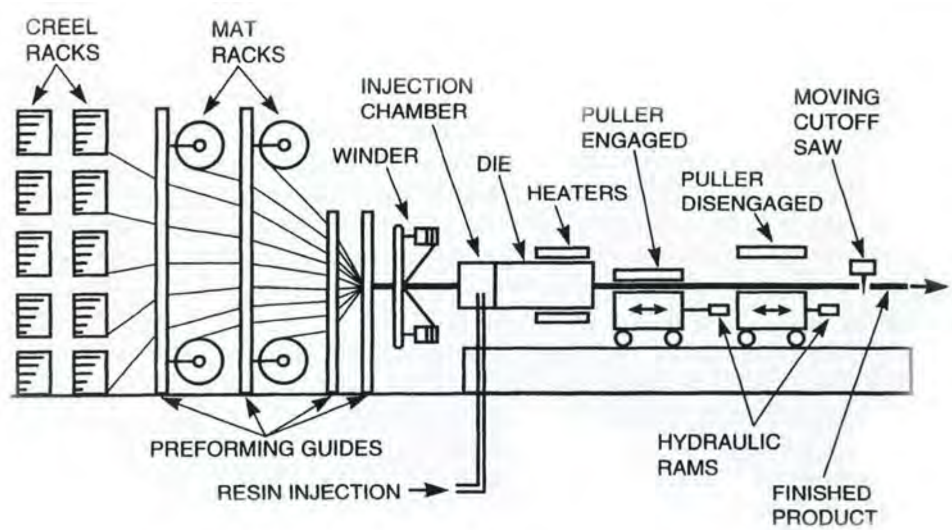


Figure 4.9 Pultrusion manufacturing process. [*Barbero*]

4.2 Boatbuilding Methods

The boatbuilding industry provides a precedent for potential manufacturing processes of architectural composites, due to both the large scale of components and structural requirements. The majority of composite boatbuilding is single-skin, produced in an open female mold by either hand lay-up or spray-up technique (Greene). Although used less frequently, cored sandwich construction is also a conventional boat building technique.

Female molds are produced from a full scale model *plug*, typically built of wood and finished with a syntactic putty made of polyester resin and micro-balloons and/or talc for ease of sanding and final fairing. Reinforcing ribs are typically bonded to outside surface of the mold to prevent deflection during the lamination process. The female mold is most typically used for single skin construction as it results in a finished surface on the visible exterior of the part. A gel-coat finish is first sprayed into the mold, and composite laminations are then applied. Reinforcing materials are typically precut and laid out on a table in the appropriate sequence for placement in the mold. A reinforcement schedule may be used to organize the order, shapes, and placement locations of the cut fabric. Resin is applied by brush from a bucket, or by spray-up, and the material is consolidated by rolling with mohair or grooved metal rollers to fully saturate the fabric, maintain correct resin/fiber ratios, and to remove trapped air bubbles (Greene 254).

Cored sandwich construction can also be accomplished in female molds, with a technique that is similar to that used for single skin laminations. After the lamination that will become the outer facing is complete, the core material is bonded into the mold. This may be done either with the facing lamination still wet, or more commonly after it has fully cured. The placement of core material into a female mold presents several drawbacks. Placement of core material that is flat sheet material into a curved mold may result in springback from its elastic behavior, even when vacuum bagging techniques are used. A second problem is that foam placement and bonding is a “blind” operation, where is it is difficult to ascertain if voids are present between the foam and facing. Both of these problems are somewhat alleviated by using pre-curved sheets of foam. With some foams, such as PVC, this is accomplished by heating.

Due to the problems of bonding core material into a female mold, sandwich construction is often done over a male plug. In addition to eliminating the time and cost involved in constructing a female mold, a better quality bond can often be achieved over a convex surface rather than into one that is concave. With this technique, the core material is placed over the plug before any facing laminations are produced. After the core material is fastened to the plug the outer facing laminations are applied. When fully cured, the hull is removed from the plug and the inner facing laminations are then applied. An advantage of this technique is that the male plug does not need to be a complete finished surface, but can rather be a series of closely spaced battens, significantly reducing cost and construction time.

Within this basic conceptual framework of single skin vs. cored construction, and female vs. male mold, exists a wide variety of lay-up techniques and materials depending on performance and cost requirements of the craft. These range from single skin chopper-gun spray-ups in glass fiber/polyester resin, to autoclaved racing hulls of prepreg carbon fiber.

5. A BRIEF HISTORY OF PLASTICS IN ARCHITECTURAL CONSTRUCTION SYSTEMS

Attempts at developing construction systems out of new plastic materials date back to the early 20th century. However, plastic materials from this era were ill suited to structural applications at an architectural scale, and thus these early proposals were not viable solutions. A 1922 patent illustrates the desire to implement these new materials, and reveals the beginnings of a search for structural forms they might assume. (Fig. 5.1) This patent demonstrates a striking resemblance to reinforced concrete systems of the era, with a nearly direct substitution of the new plastic materials.

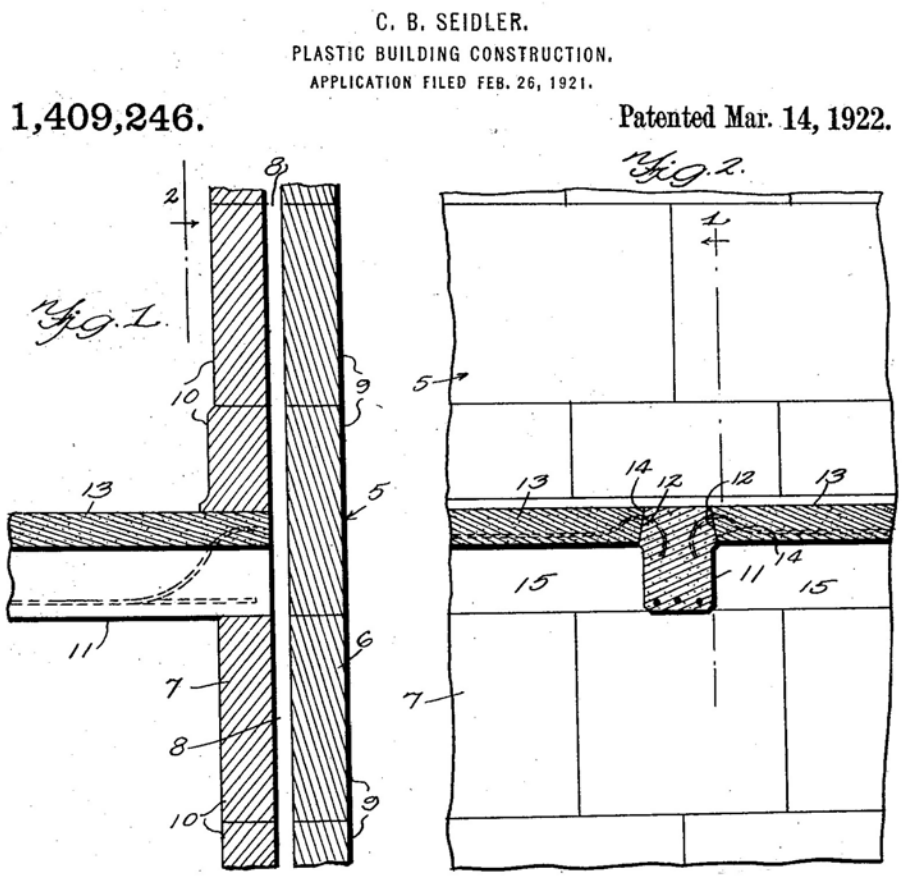


Figure 5.1 Plastic construction system patent drawing, 1922. [*US Patent Office*]

The inadequacies of these early plastics to fill such structural roles began to change as World War II precipitated the development of a wide range of new petroleum based plastics, including polyester, which was introduced to market in 1951. Polyester resin reinforced with glass fibers quickly gained popularity for use in a range of larger scaled plastic products such as boats, automobile bodies, and aircraft fuselages. Not only did the mechanical properties of glass fiber reinforced polyester allow a shift in product scale, but the material also brought a shift and expansion of production settings (Meikle 196). Products made from this composite material could be successfully produced without specialized equipment in relatively low cost molds, which were typically constructed of the same material. As a result, there was a proliferation of small-scale backyard manufacturers producing everything from surfboards to airplanes. This combination of ease of manufacturing and suitability to production of larger scaled parts led to experimentation within the field of architecture.

5.1 ***Architectural Experiments***

The earliest experiments in glass fiber reinforced plastic construction occurred during the early 1950's and followed two general lines of investigation. The first approach, which was quickly abandoned, was a replication of existing construction techniques with a simple substitution of plastic for other materials. A single story ranch style house constructed by Russell Reinforced Plastics in Florida was among the first of these, utilizing GFRP members in place of traditional wood studs, clad with GFRP panels (Meikle 206). The second approach speculated on possible structural forms that would take better advantage of the inherent material properties of plastic. Looking to existing thin shell concrete structures as precedents, Eliot Noyes proposed his General Electric sponsored Wonderhouse in 1954. (Fig.5.2) This unrealized load-bearing shell structure quickly became the model which most plastic buildings would follow. The most well known plastic structure to follow this example was the Monsanto House of the Future, developed by the MIT department of architecture and exhibited at Disneyland in Anaheim California from 1957 to 1968. (Fig.5.3) Lesser known, but perhaps among the purest expressions of plastic composite shell structures are three exhibition pavilions built for the 1964 World's Fair in Flushing Meadow, New York. (Fig. 5.4) Designed by Peter Schladermundt and built by Owens Corning Fiberglass, they were directly inspired by the concrete shell structures of Felix Candela, who has often been mistakenly identified as their author.

Figure 5.2 Eliot Noyes, Wonderhouse [*Meikle*]

Figure 5.3 Monsanto house of the Future [*Life Magazine*]

Figure 5.4 1964 World's Fair Pavilion ("Candela Structures"), Peter Schladermundt.

Many other designs followed the basic scheme of the Monsanto house, which had utilized identical repetitive segments to reduce mold tooling costs to a minimum, such as Jean Maneval's Six Shell Bubble House of 1964 and the Futuro House designed by Matti Suuronen in 1968.(Figs. 5.5, 5.6)

Figure 5.5 Six Shell Bubble House.

Figure 5.6 Futuro House. [*Home & Tannila*]

During the late 1960's and into the 70's, a third line of investigation briefly gained popularity. These were more expressive free-form structures, typically consisting of monolithic foam shells that were sprayed in-situ over various types of formwork or substrates. Leading this movement was professor Felix Drury at Yale University, whose students experimented with spraying polyurethane foam over netting during 1968 and 1969. (Fig. 5.7) A similar approach was taken with Winslow Wedin's 1969 Ensculptic house in Minnesota, with polyurethane foam sprayed over burlap. (Fig. 5.8) A more refined version of this spray foam technique was patented by fellow Yale professor Valeria Batorewicz, and a single house was constructed in New Haven in 1973. (Fig. 5.9) Both the Ensculptic House and the Batorewicz house are still existing, with the latter still inhabited. These spray-foam structures differed from the other examples in that they were not sandwich constructions. The netting which acted as formwork became embedded in the thick polyurethane foam, providing minimal reinforcement, while the foam itself carried the majority of structural loads. This foam was protected from environmental damage merely by a coat of paint.

Figure 5.7 Felix Drury [*Yale Univ. Archives*]

Figure 5.8 Ensculptic House

Figure 5.9 Valeria Batorewicz House. [*author*]

While born amidst a free-spirited environment of architectural expression, the Batorewicz house was a legitimate attempt at developing a viable, and marketable, construction system. (Fig. 5.10) One of its designer's goals was factory prefabrication of a significant portion of the building. In this scheme, satellite rooms would extend outward from a central core construction, which contained plumbing and other services. During shipping, these satellite rooms would consist merely of floor plates, which would be hinged and folded flat against the sides of the core. On-site assembly would consist of placement on a foundation and lowering of the satellite floors, which would then provide support for a stretched membrane formwork to be sprayed with polyurethane foam.

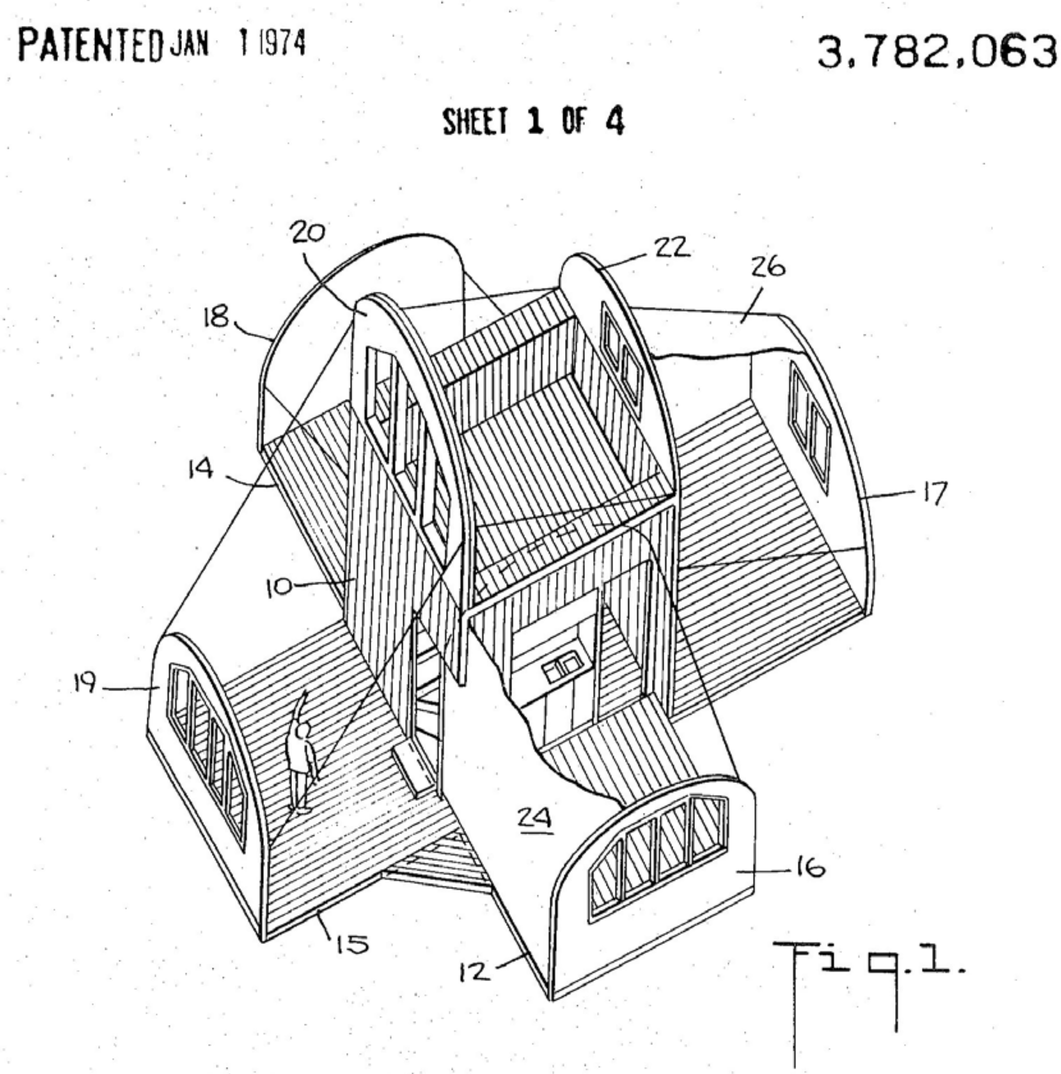


Figure 5.10 Batorewicz House patent drawing. [*US Patent Office*]

The period between the mid-1950's-70's saw an explosion of experiments with plastic architectural structures. By the mid 1970's over 200 built projects existed, and thousands of construction ideas had been patented. These patents ranged in scale from joint and connection details, to methods of constructing entire buildings. The latter, such as illustrated in Figure 5.11, were most often unrealistic schemes that were impractical on numerous counts. This patent from 1976 proposes the use of building-scale molds for on-site injection molding of monolithic houses, including interior bearing walls. Despite the extremely radical nature of the manufacturing process, the resulting house is depicted as a banal replica of existing ranch-style homes, complete with simulated clapboard exterior. In this respect there is a striking similarity to the monolithic poured concrete houses invented and realized by Thomas Edison, where development of a new system of construction failed to find an integrated design language.

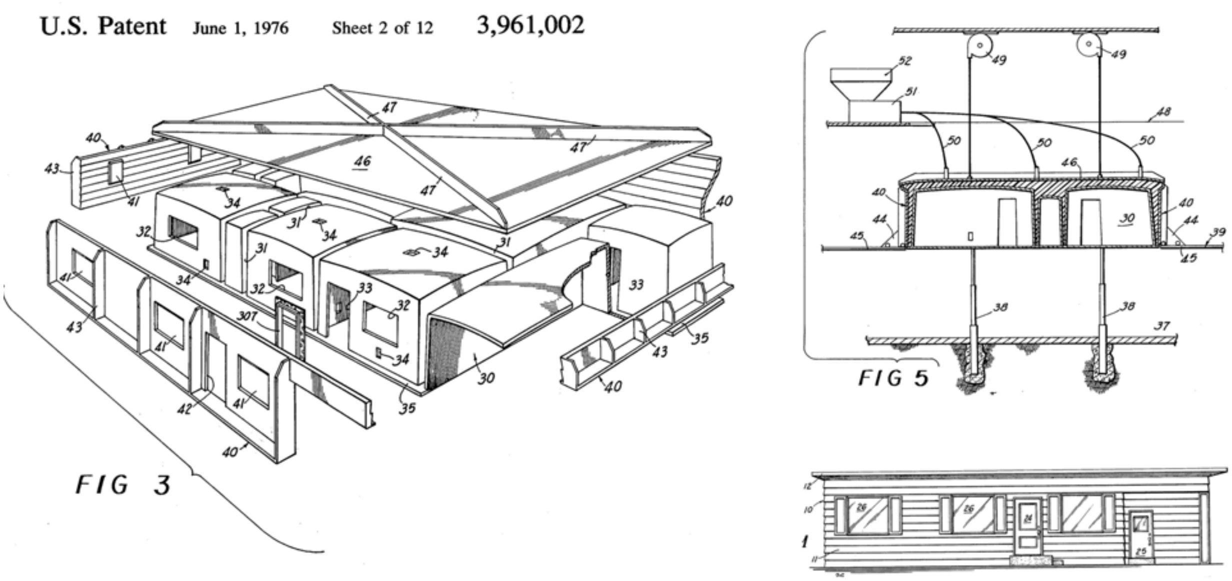


Figure 5.11 Injection molded monolithic house patent drawing [*US Patent Office*]

With more than fifty years between them, the patents of 1922 and 1976 demonstrate a continuing theme within the lineage of proposals for plastic structures, and that is the equating of this material with concrete. With nearly direct copying of production methods and forms that were applicable to concrete, many designers repeatedly failed to recognize the unique properties of plastic, focusing on the superficial similarity of being able to be shaped while in a liquid state.

The proliferation of experiments with plastic during this period came to a close during the early 1970's, and is typically attributed to a combination of rapidly rising petroleum costs during the oil crisis, in combination with the failure of designers to arrive at forms that could find broad consumer appeal (Meinkle 270; Home & Taanila 164). However, in addition to these two factors, few plastic structures had satisfied a wide enough range of design criteria to poise themselves as viable methods of construction. After fifty years of experimentation they had still not resolved fundamental issues such as accepted design and engineering practices, building code approval, or flexible accommodation of program. The combination of these factors effectively spelled the end of the development of plastic buildings for several decades.

Recent years have seen some small renewed interest in utilizing advanced composites in construction. Built examples have primarily utilized composites as a means of formal expression, and they have rarely been used as primary structure. Examples such as the Chanel Pavilion by Zaha Hadid and a series of Pavilions by UN Studio have utilized composite panels strictly as a cladding applied to a separate structural armature. Other recent examples, such as the Novartis Entrance Pavilion in Basel, Switzerland (2006), and the Yitzak Rabin Center in Jerusalem by Moshe Sadfie, have created hybrid structures that embedded structural elements of other more traditional materials within the thickness of a composite sandwich. (Fig. 5.12, 5.13) The Novartis Pavilion also utilized varying densities of core foam to correspond to structural loads. Outside of these mostly pavilion scaled structures, recent composites research in the construction industry has focused primarily on civil engineering applications, such as fiber reinforced concrete and the use of pultruded fiberglass elements in lightweight bridge construction.

Figure 5.12 Novartis Pavilion

Figure 5.13 Rabin Center [Octatube]

One notable exception to recent non-structural composite constructions is *Postcards*, the Staten Island 9/11 Memorial by Masayuki Sono. This structural composite sandwich is built of glass fiber (E-glass) reinforced vinyl ester resin, and polyurethane foam core. (Fig. 5.14) It was constructed in 2004 by resin infusion method at a boatbuilding facility in Portsmouth, Rhode Island. The composite construction replaced the originally intended concrete material as it provided "elegant solutions to structural problems" of the large vertically cantilevered design (David MacBain, New England Boatworks).

Figure 5.14 *Postcards* 9/11 Memorial.

5.2 *Case Studies*

While no architectural examples currently exist of structures built of bio-composite materials, the extensive number of built works utilizing petroplastic composites can prove useful as precedent studies to analyze how materials with similar properties were developed into construction systems.   Five buildings were analyzed as case studies: The Monsanto House of the Future, Six Shell Bubble House, Futuro House, FG2000, and the SpaceBox.

Computer models of all five structures were constructed to gain a complete understanding of their forms, connection details, assembly methods, structural strategies, secondary support structures, etc. The figure below illustrates the five buildings modeled at the same scale. (Fig 5.15) They are shown without fenestration, focusing on the structural components.

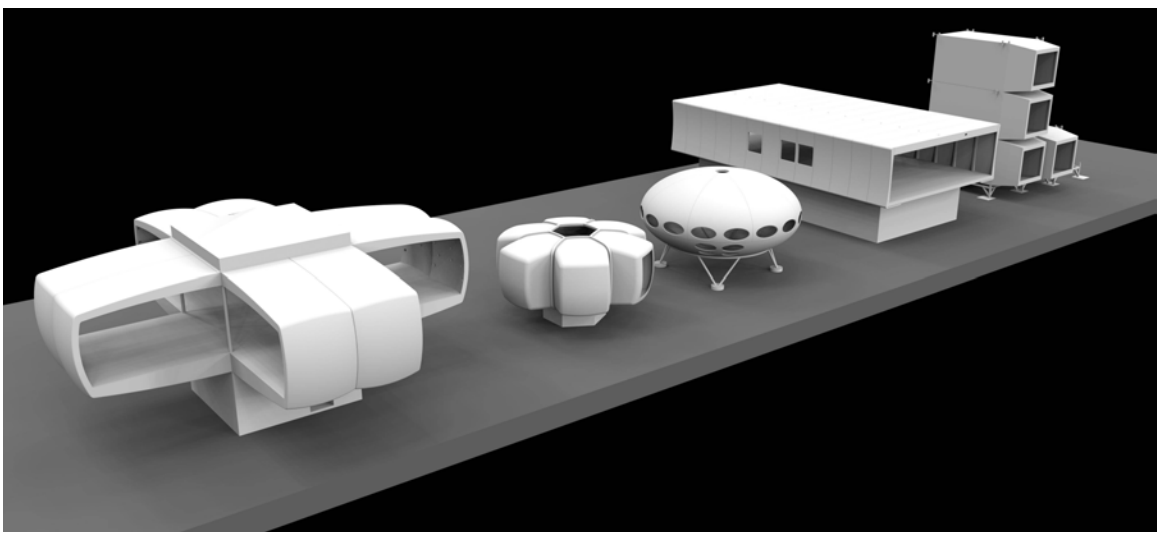


Figure 5.15 Computer models of case study buildings.

5.3 *General Observations of Case Study Buildings*

As many of the case study buildings have attempted to solve for the same, or similar, sets of problems, general observations will first be presented here. Discussion of each individual building will then focus on particularities unique to that design. All of the case study examples are constructed of composite materials based on petroplastic polymers. These were typically polyester resins, glass fiber reinforcement, and polyurethane foam cores.

The formal expression of the buildings is generally the result of a combination of factors. As noted earlier in this paper, the Eliot Noyes designed GE Wonderhouse of 1954 served as a model in which many plastic structures attempted to find shell forms that exploited the structural properties of the material. However, a pure shell structure was never realized in any of these case studies, and rather they largely remained symbolic expressions of shells. To construct a shell typically would require constantly varying surface geometry, and corresponding molds. By contrast, concrete structures with true shell forms, which influenced these plastic structures, were much more common during this period. A significant difference between the two materials is that concrete can be cast against much more primitive formwork. The fiberglass construction of the plastic structures requires a much more precise mold with a highly polished surface finish to allow demolding. Thus the cost of molds for the two materials differed by a substantial magnitude. The result was that the plastic structures typically attempted to utilize the fewest number of molds possible. Manufacturing costs therefore played a significant role in the overall forms of the buildings, which tended to have a morphology of repetitive forms, directly expressing the high manufacturing cost of producing unique molds.

The forms of the structures were also limited by the techniques available to fabricate the molds themselves. While a pure shell structure relies on complex compound curvature, not all types of these surface geometries were straightforward to construct during this era. As as result, the surfaces of the case study buildings all utilize surface geometries that rely on simple methods of geometrical construction, such as surfaces of revolution, translational surfaces, constant radius fillets, and flat planes. While some appear rather complex, all of the case study buildings have surface geometries that are combinations of these simple strategies. (Fig. 5.16)

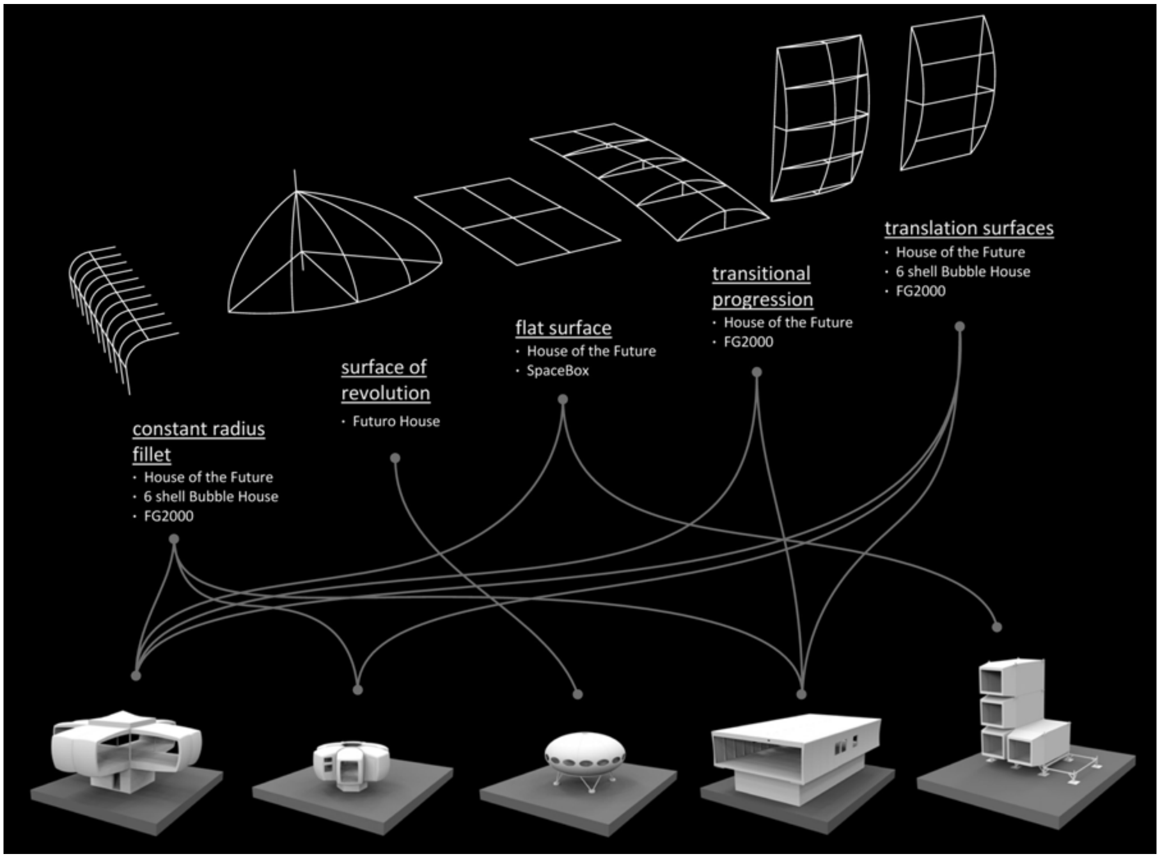


Figure 5.16 Surface geometry analysis of case study buildings.

In addition to being driven by mold fabrication limitations, the forms of many of the case study buildings were influenced by cultural factors. The examples from the 1950's and 60's came about during an era when plastic as a material was associated with positive hopes for the future, as Dustin Hoffman's character was famously counseled in *The Graduate*. Meanwhile, Andy Warhol quipped that he wanted to "*be plastic*." Hence many of these architectural forms, and related imagery, intentionally mimicked stylistic trends that were associated with the future and were influenced by Cold War space-race hardware. Many of the marketing images that accompanied the houses directly referenced a future of increased leisure time and hedonistic lifestyles. (Figs 5.17, 5.18) The very desire to investigate plastics as an architectural material was undoubtedly driven as much by these positive associations with the future as it was by advantageous engineering properties.

Figure 5.17 Futuro. [*Home & Taanila*]

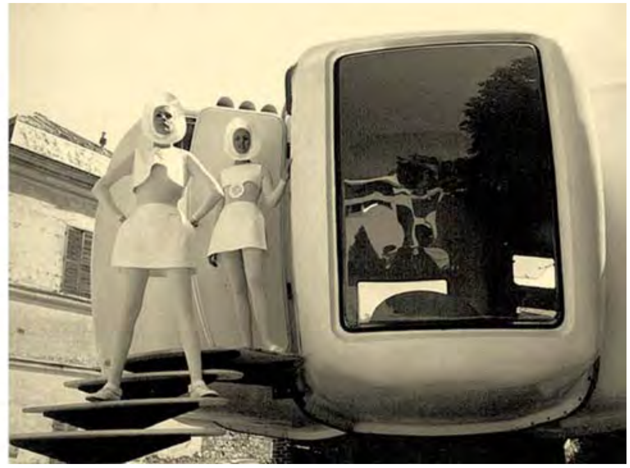


Figure 5.18 Six Shell Bubble House.

Conversely, the use of plastic in single family houses could also be understood as an attempt to domesticate a material that carried significant negative associations. Plastic was often seen as representing the Cold War fears of technology and in particular served as a symbolic representation of nuclear weapons, as illustrated by 1950's essays by Roland Barthe and Norman Mailler, as well as beat era poems by Alan Ginsberg and Jack Kerouac. (Meikle 246) By domesticating plastic it could function as a surrogate for nuclear technologies that were beyond the control of citizens (Meikle, 128; Winkler, 32).

While the imagery presented with many of these houses depicted “futuristic” lifestyles, it is notable that within these scenes is a strong message of continuity, as domestic, family, and gender roles remain intact.(Figs. 5.19- 5.21) Also shown intact in these images is the natural environment, with the most common placement of these houses being remote wilderness locations. Even the House of the Future at Disneyland was placed in front of a fiberglass replica of the Matterhorn and surrounded with highly manicured underbrush. The resulting message was that a future containing plastic buildings was also one that was safe, the environment undamaged, and was a comfortable version of the present.

Figure 5.19 Monsanto House. [*Life*]

Figure 5.20 Futuro House. [*Home & Taanila*]

Figure 5.21 Monsanto House of the Future domestic imagery. [*Life Magazine*]

CASE STUDY **<u>5.3.1 Monsanto House of the Future</u>**

Designer: Marvin Goody, Richard Hamilton, MIT architecture department, USA.

Year: 1954-57

Number produced: 1

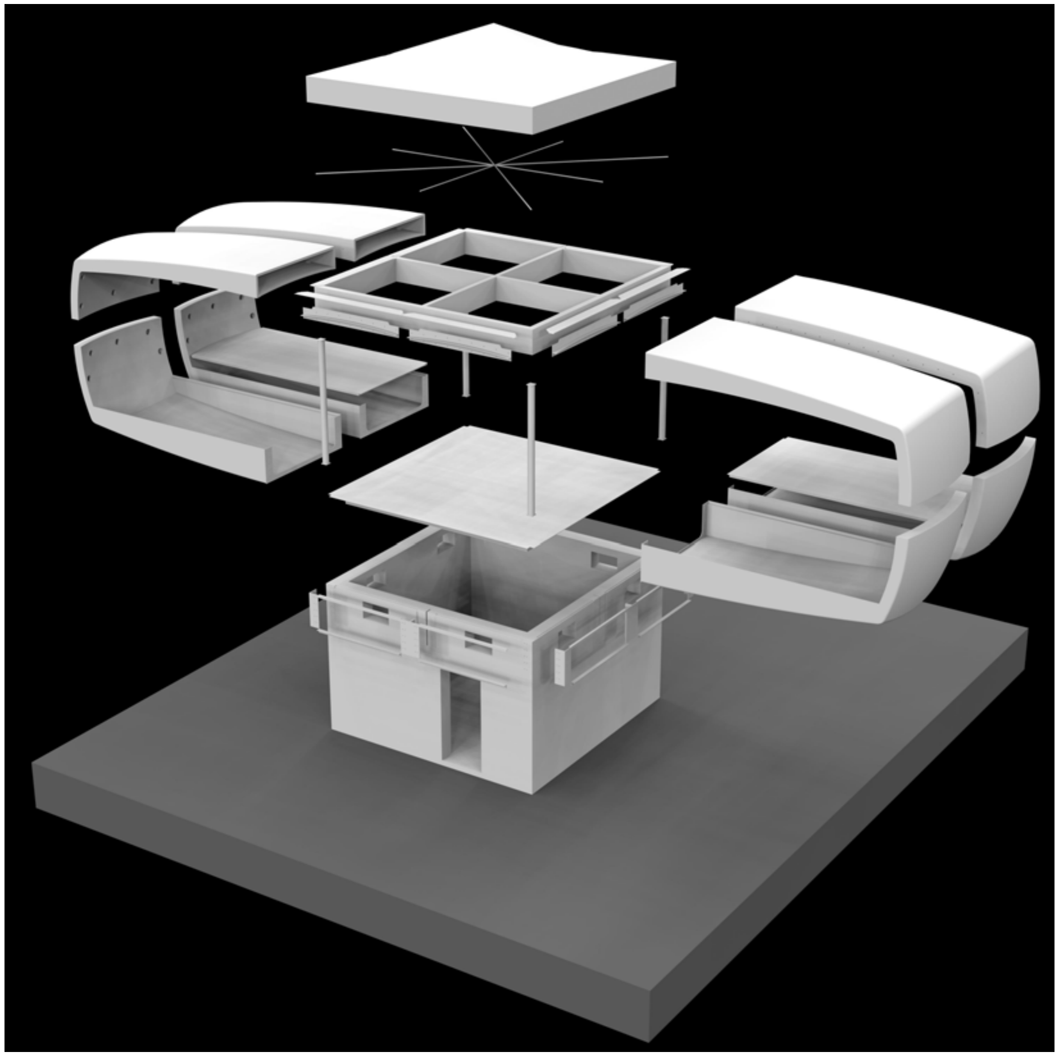
Program and design goals: Single-family home designed as an exhibition and demonstration of the uses of plastics in architecture. Was open for public touring at Disneyland in Anaheim, California, from 1957-1968.

Materials and manufacturing: Constructed of hand laminated fiberglass sandwich construction with lay-up in female molds. Facing laminations were of polyester resin and a combination of fiberglass cloth and chopped strand mat, with a white gel coat finish. Core material was polyurethane foam.

No. of unique segments: 1 upper, 1 lower bent. The top bents consisted of two individually molded components bonded together.

Segment connection method: Adjacent bents joined together along flat faces, via bolted connections. Adhesive was also applied to the adjoining faces, primarily as a sealant rather than structural connection. Access holes were molded into the bents so that workers could reach into the interior space of the box beam to install bolts, nuts, and washer plates.

Fenestration strategy: Fenestration and door openings were entirely within nonstructural infill panels on the sides of the bents. This avoided structurally compromising the bents, as well as giving design flexibility to the fenestration scheme.



Structural strategies: Four radially symmetrical fiberglass wings cantilevered from a square central foundation core of reinforced concrete. Foundation walls protruded from the ground to the elevation of the main floor level, approximately 9 feet above grade. The wings cantilevered approximately 18 feet from the core, and each was an assembly of four "bents", two upper and two lower. The bents cantilevered independently of each other and were field connected and finished at their point of junction. The lower bents were attached to the top sides of the foundation walls via steel attachment plates that were embedded in the concrete. The top bents were attached to a square ring of laminated plywood beams at roof level that were supported on 5" diameter fiberglass columns. Attachment of top bents was via steel plates bolted to the beams. The beams had a network of steel tensile members spanning between them, as well as secondary wood beams to combat torsional forces introduced by the bents.

The bents were designed as box beams, with a hollow cross section. The lower bents used the floor panels as a stressed component that is adhered during assembly to complete the box beam. These floor panels were honeycomb sandwich construction. The hollow space within the lower box beam bent was used as an HVAC plenum space.

Assembly strategies: All eight of the lower bents, and their floor panels, were first bolted to the tops of the foundation walls with the use of a crane. Fiberglass corner columns and laminated wood beams at their tops were next installed. Top bents were installed in opposing pairs to balance the forces acting through the top beams and their tension rods. The visible exterior seam at the joints where top and bottom bents connected were finished, as were the access holes used for reaching bolts. The square core area was crowned with a roof composed of four fiberglass hyperbolic paraboloids.

End of life: The house was demolished and removed in 1968. It proved resistant to demolition efforts, with a wrecking ball merely bouncing off of its surface. After failed attempts to cut it apart, it was ultimately removed by tightening chains around it and crushing it into smaller pieces.

Analysis:

The formal expression, the House of the Future was in part driven by the chosen structural scheme of cantilevered wings. The tapering form of the box-shell elements as they cantilever is directly informed by the structural diagram of decreasing bending moments. While never explicitly stated as such, the central concrete core which supports the elevated cantilevering wings bears a striking similarity to the backyard fallout shelters that were constructed during this period. Heavily promoted by the Civil Defense Department, over 1 million such shelters were constructed during the late 1950's (Winkler 121).

The aggregation of the repetitive wing elements intentionally implied the possibility of multiple configurations, modularity, and an ease of expansion that could accommodate a growing family.

CASE STUDY

5.3.2 Six Shell Bubble House

Designer: Jean Maneval, France.

Year: 1968-70

Number produced: ~30

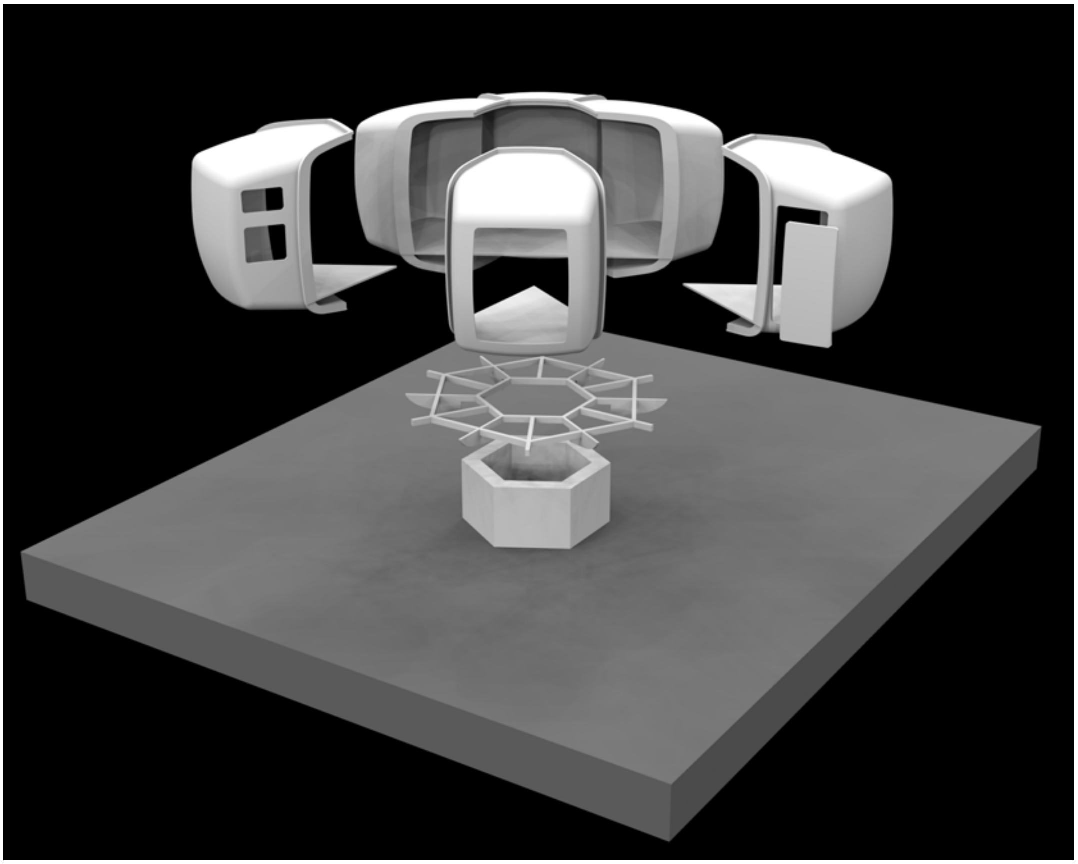
Program and design goals: Designed as a weekend leisure house. Primary use was ultimately as rental units at a rural retreat.

Materials and manufacturing: The shell segments were constructed of hand laminated fiberglass sandwich construction that were layed-up in female molds. The foam core material appears to have been sprayed into the outer facing, and the inner facing applied by spray-up.

No. of unique segments: 1 basic unit. Multiple variations provide for fenestration and door openings.

Segment connection method: The shells segments were molded with an integral edge flange with a flat face for joining to the adjacent segments. Connection was via bolts, and a sealant/adhesive.

Fenestration strategy: Fenestration and door openings were molded into the surface of shell segments. It is likely that a single primary mold was used, and molded frames for multiple types of openings were bonded into penetrations cut into the shell.



Structural strategies: Six radially symmetrical individual shell segments were supported on a central concrete core. Rectangular steel tube members spanned the concrete core, cantilevering beyond it. The floors of the shell segments were internally supported by these steel tubes. Lower flanges of the segments bolted to the faces of the concrete foundation walls.

Assembly strategies: Placed on supporting framework and bolted together at flanges.

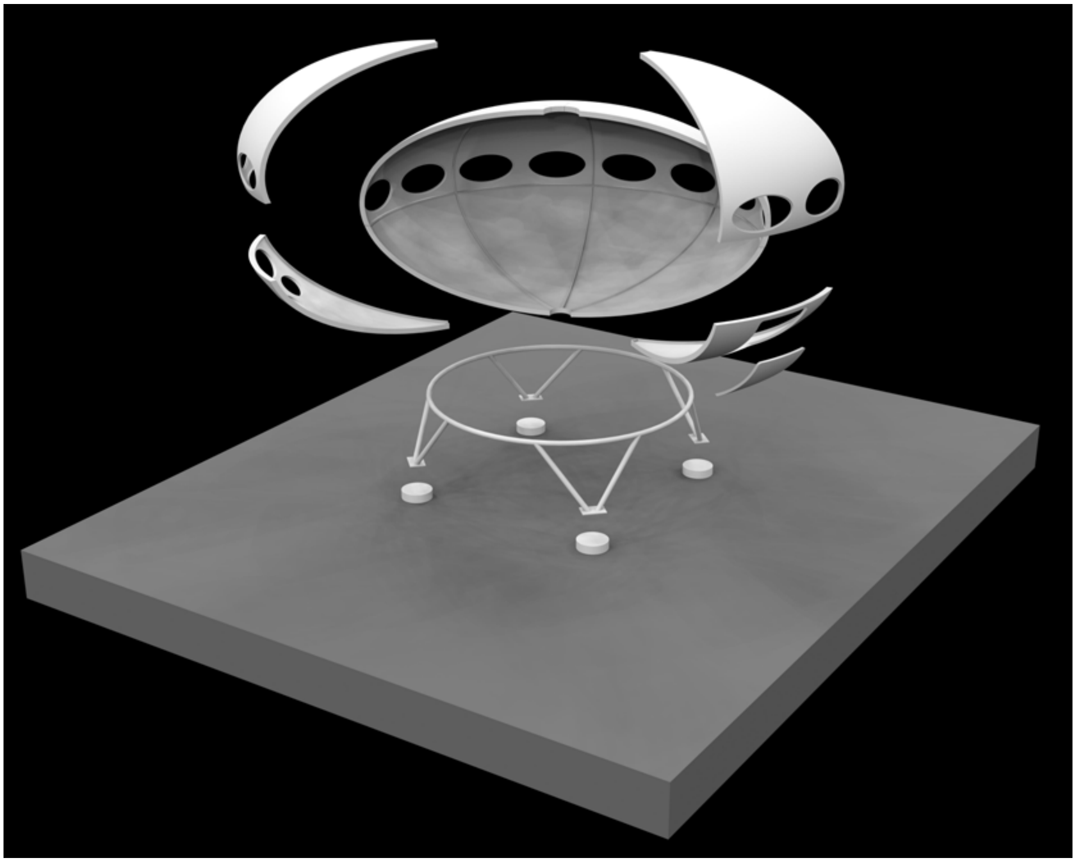
End of life: The majority are still existing in their original locations, primarily in the French Pyrenees. Several are known to have been disassembled.

Analysis:

In addition to its radial array of repetitive elements, the limitation of mold cost is apparent in the very small scale of these components. The diminutive size of each segment, as well as their form, was also driven by the ability to nest all six tightly together for transport on a flatbed truck.

CASE STUDY **<u>5.3.3 Futuro House</u>**

Designer:	Matti Suuronen, Finland.
Year:	1969-74
Number produced:	~90
Program and design goals:	Designed as a weekend ski cabin for a remote mountain location. Design criteria were light weight for delivery via helicopter, and high thermal insulation value for fast heating in cold climate. Originally designed as a one-off structure, due to public interest it was marketed and manufactured under license in numerous countries as a weekend leisure house. Many were inhabited full time.
Materials and manufacturing:	The sandwich shell segments were hand laminated in a female mold, included flanges for attachment of segments. Polyurethane foam was sprayed onto the inner surface of this skin, and the inner facing lamination were applied by chopper gun spraying, resulting in a slightly bumpy surface texture.
No. of unique segments:	1 upper, 1 lower. Variations to provide fenestration and door openings.
Segment connection method:	Flanges at the edges of each panel were bolted together, with a sealant applied.
Fenestration strategy:	Windows were ellipse shaped, blown acrylic, with two in each shell segment. Total number of windows was optional. The entry door was also incorporated into a shell segment and was a hatch that lowered down to the ground via gas charged struts. The rear side of the hatch had integral entry stairs, similar to an aircraft entry door.



Structural strategies: The geometrical form of the fiberglass shell was an ellipsoidal surface of revolution, 26 feet in diameter. The form was divided into sixteen segments, 8 upper and 8 lower, with a horizontal joint beltline below the midpoint. Sandwich construction was 6 cm thick. The shell structure rested on a ring of steel tubing, with welded tubular steel legs resting on concrete pads. The majority of Futuros used this simple “egg cup” system of support, while those produced under license in North America embedded the steel ring into the thickness of the sandwich construction. This provided a cleaner exterior appearance but increased thermal bridging. It also necessitated dividing the shell into half as many segments, as it was desirable to not use an excessive number of bolted connections in the steel ring. This resulted in components that were large enough to cause difficulties with road transport.

Assembly strategies: Location of assembly varied. Some were factory assembled and delivered via helicopter or flatbed truck,

	with the concrete pads being the only site work required. Others were delivered in segments and assembled on-site.
End of life:	Many are still existing. Due to the inherently transportable nature of the structure, many have been relocated, often several times. The typical strategy for relocation has been by disassembly, although several have been relocated via helicopter, and several were relocated by truck in their assembled condition. Many have been abandoned and exist in a state of ruin.

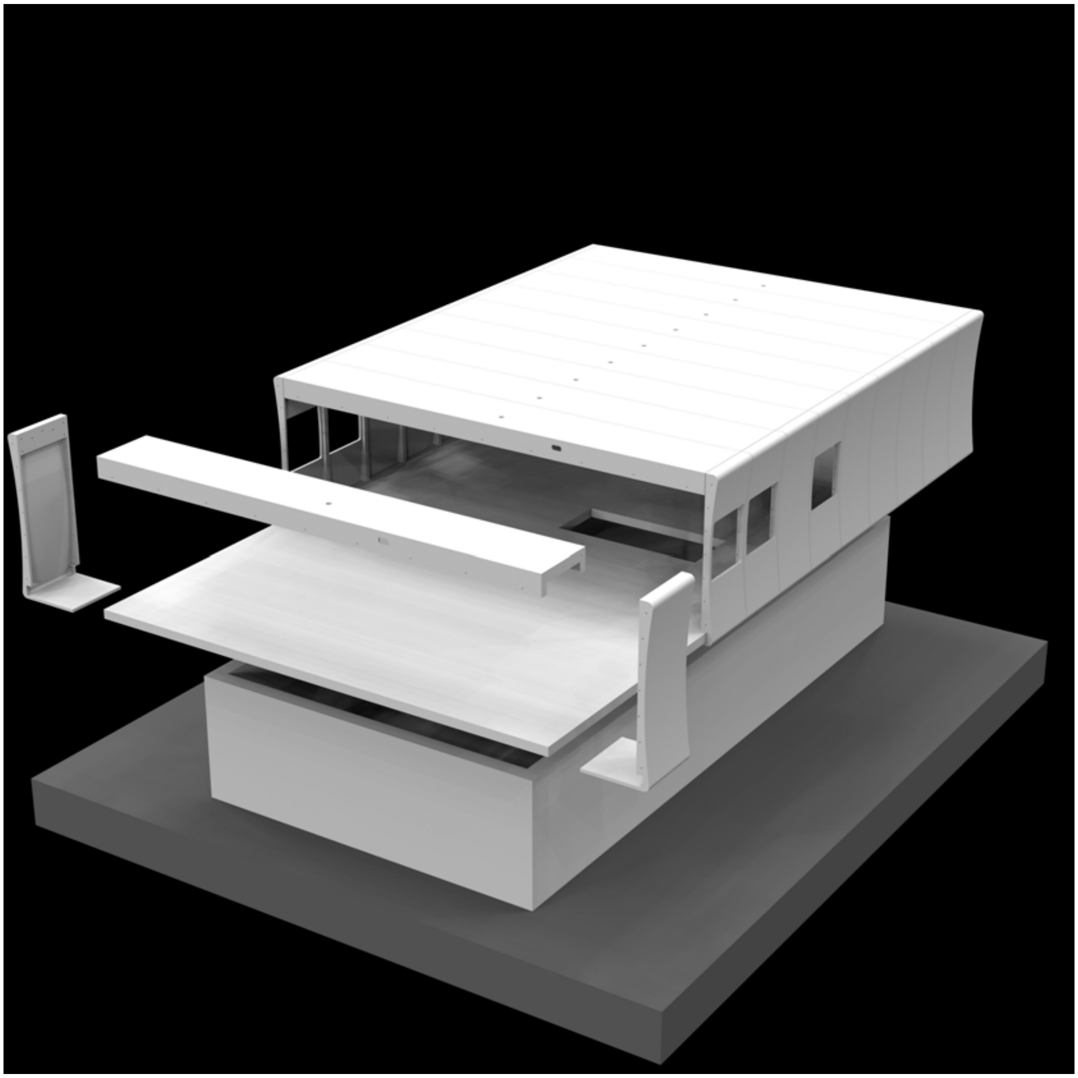
Analysis:

Perhaps the most overtly influenced by space-age imagery, the Futuro house was introduced to the public during the same month as the moon landing. However, its designer claims its form was driven entirely by matters of material efficiency and was mathematically derived, and its resemblance to popular UFO imagery was strictly coincidental.

Initially designed as a remote mountain ski cabin, it was intended to be delivered in its fully assembled state by helicopter and lowered into position. This may have influenced the choice of a radial form, which would have a predictable center of gravity for lifting. This delivery method also resulted in the tubular steel “egg cup” cradle on which the building rests. In practice, a majority of the Futuros were delivered via truck, either fully assembled or in knocked-down kit form to be assembled on-site.

CASE STUDY **5.3.4 FG2000**

Designer:	Wolfgang Feierbach, Germany.
Year:	1968-76
Number produced:	35
Program and design goals:	Single family house. Designer was previously involved in the production of fiberlgass furniture, and the FG2000 was an experiment in plastics manufacture at an architectural scale. Designed to provide program flexibility through alternate configurations.
Materials and manufacturing:	Hand laminated fiberglass sandwich construction, with lay-up in female molds. Polyester resin and fiberglass cloth face laminations, with an exterior gel-coat finish. Unknown method of integrating foam core.
No. of unique segments:	2 basic units. 1 roof and 1 wall segment. One wall mold variation to provide fenestration openings. Later version of the building system included corner components to increase the flexibility of potential floor plan arrangements.
Segment connection method:	Roof to wall panel connection by a bolted connection at a large flange area that provided moment resistance. Adjacent bents were bolted together, with a neoprene sealing gasket between flanges. Lower wall panel flanges provide direct bearing on the edge of the concrete floor slab, as well as bolt fasteners.
Fenestration strategy:	The majority of fenestration occurred at the nonstructural ends of the building. Small windows were incorporated into a wall panel variation.



Structural strategies: A one way spanning system of narrow 1 meter wide bents. Each bent consisted of 3 components, two wall panels acting in compression, and a single roof beam spanning between them. Deep edge flanges on the components provided stiffness as well as connection surfaces. Outside surfaces were curved to increase stiffness, and the roof surface tapered toward a central drainage point. Wall panels were supported on a simple reinforced concrete slab.

Assembly strategies: Roof panels were manually lifted into position by four workers and supported on two tall sawhorses. Wall panels were raised into position by two workers and bolted into place by two others. Each band of three components took 45 minutes to assemble, and the entire building envelope was erected in one day.

End of life: Most still standing in original locations in Germany. One FG2000 was constructed as a demonstration house and was later disassembled and erected at another site.

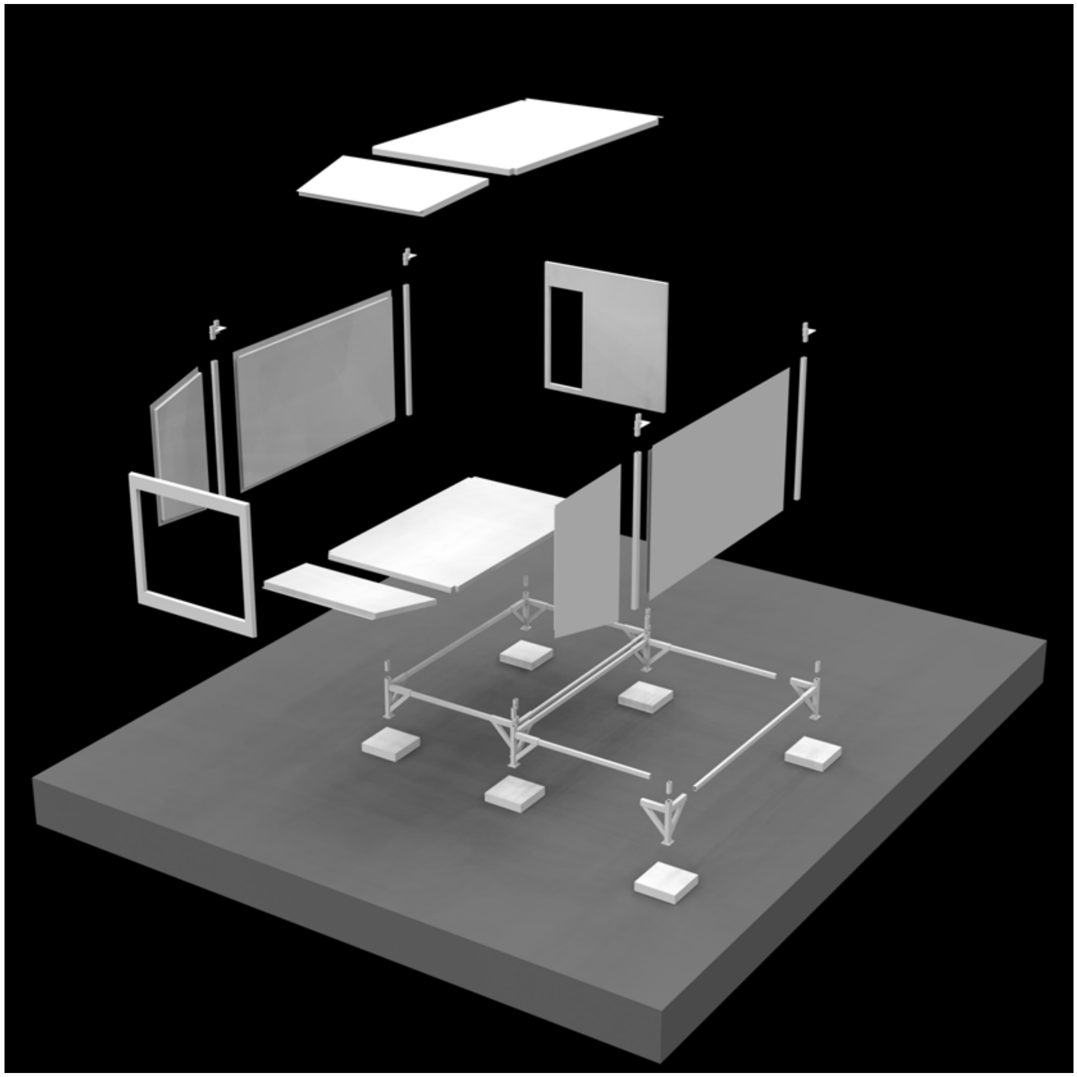
Analysis:

Unlike the previous examples, the aggregation of repetitive molded components of the FG2000 did not follow a not a radial arrangement. This was likely due to the intention of the designer to pursue approval of his building system from the German Ministry of Housing. The design decision to utilize a simple one-way spanning system undoubtedly simplified the engineering and testing required for this certification process, final approval of which was granted in 1973. With the addition of very few additional components, the one-way spanning system could be reconfigured into more complex arrangements, often utilizing additional internal load-bearing partitions.

The design was also informed by the desire for a straightforward method of on-site assembly. With the use of a simple temporary support for each overhead spanning element, the system could be manually assembled with a crew of six workers and without the aid of lifting equipment. The fiberglass structural components of the pictured house were assembled in one day, with each of the thirteen segments requiring about 45 minutes for placement. Thirty five houses of this system were constructed in Germany through the 1970's. The designer's own home is still inhabited, with no claimed deterioration of the structure. The Ministry of Housing approval conservatively estimated the lifespan of the building to be twelve years when it granted certification in 1973 (Feierbach).

CASE STUDY **5.3.5 SpaceBox**

Designer:	Mart de Jong, Netherlands.
Year:	2003-present
Number produced:	1100+
Program and design goals:	Designed as semi-permanent housing units for students and workers. Design criteria were that units were easily transported via truck, and could be stacked vertically as cellular units. Each unit has an integral bathroom and kitchenette unit. All utilities have a single connection at the rear of the units for a "plug-and-play" assembly. An external system of steel stairs and walkways provides access to the units.
Materials and manufacturing:	The composite sandwich panels use a styrene free resin and E-glass reinforcement cloth. A polyurethane core material is formulated for increased flame resistance. The units are available in a range of colorful gel-coat finishes.
No. of unique segments:	The unit is assembled of components cut from sheet stock rather than molded components as in the other case studies.
Segment connection method:	Panel edges are bonded together, with no mechanical fasteners used.
Fenestration strategy:	Fenestration is restricted to one end wall of the unit, encompassing nearly the entire wall surface.



Structural strategies: A simple box form is assembled of flat sheets of composite sandwich construction, bonded at the corners. Walls are 80 mm thick, and floor/roof panels are 100 mm. The wall panels incorporate steel tube columns embedded within their thicknesses. These extend out of the bottom of the SpaceBox unit and provide a vertical load path as well as an easily bolted connection point between units and foundation.

A second generation design uses thicker wall panels to eliminate the embedded steel. These second generation units mount within a steel skeletal framework that is entirely external to the units. This change was driven by a design for disassembly philosophy.

Assembly strategies: The units are factory assembled and delivered to the

	site for placement. They are lifted into position via crane, and stacked units are bolted together at steel connector plates.
End of life:	The units are designed to be easily and quickly disassembled and removed from the site.

Analysis:

The formal expression of the SpaceBox is influenced by several factors. One factor is its manufacturing method, in which it is assembled from panels cut from standard sheets of composite sandwich that are then bonded at the corners. The subtle faceting of the window end of the unit both accentuates this origin as flat sheet, as well as being an expression of structural requirements, providing stiffening at the large opening. Its form is also influenced by its delivery method, arriving to the site by flatbed truck.

One of the important factors in the formal expression of the SpaceBox is one that was not seen in any of the previous examples, and that is a regulatory environment which directly influenced its program. A change in Netherlands zoning codes in 2002 allowed the temporary construction of student housing on empty lots, for periods of up to five years. The rectangular form of the units was determined not only by manufacturing technique, but by the necessity of stacking the modular units into a compact aggregation. The stipulations of this code change allowed building heights to three stories, determining the need for minimal steel columns embedded in the SpaceBox walls to transfer loads to the foundation. Building codes also influenced the materials that were used, as resins and core foams were chosen that would meet strict fire regulations of the Bouwbesluit (Building Act) of The Netherlands.

PART I CONCLUSION

CONSTRUCTION SYSTEMS AS RESPONSES TO GOVERNING CRITERIA

The structures discussed thus far, ranging from unrealized concepts, and radical experiments with built form, to the case study examples, can all be understood as attempting to propose a solution for the question of how to build with this palette of materials generally known as composites. Some of these proposals exhibited some degree of success, in that they were constructed, were inhabitable, and solved a narrow set of goals that their designers set forth. The satisfaction of this focused set of criteria resulted in schemes with a restricted range of application, limiting themselves to niche roles. None of these examples satisfied a broad enough set of criteria to render them as viable construction systems with broad application. All bear significant enough shortcomings to be relegated to categories of specialty buildings at best, and awkward novelty at worst.

The case study examples revealed a wide range of factors that influenced their morphologies and choices of construction system configuration. Interestingly, even though most attempted to formally express the engineering properties of their materials, or the *idea* of these properties, they were typically not the primary design factor, but merely one of many criteria that were considered.   Technologies and costs related to manufacturing were often among the most important factors, along with the influences of cultural forces such as interests in particular formal languages.

The broad spectrum of design proposals is indicative of a range of criteria that they were attempting to satisfy. This wide variation in form resulted from the differences in the particular set of criteria on which a given designer chose to focus, and the emphasis on one particular set typically came at the expense of others. As the goal of this research is to propose a method of arriving at a solution to a similar problem, that of developing a construction system based on composite materials, it is crucial to comprehensively uncover all the criteria that must be met for such a system to be broadly successful. The research outlined in the bulk of this paper served to parse out a such a guiding set of design criteria and considerations. They are introduced here to provide a framework and analytical lens through which to view and organize the vast array of factors related to this particular material, at this particular point in time. They will provide a guide and metric for proposing and evaluating a novel structural system.

The primary criteria identified as relevant to this particular material are the following:

1. Material properties

2. Manufacturing/fabrication/assembly technologies and methods

3. Environmental concerns

4. Design and engineering tools and methods

5. Regulatory and building codes

6. Cultural factors

This is not an exhaustive list of every possible factor, as they are myriad, but a truncated list of the current primary forces related to this particular material. It is a general mapping of the design space that will provide a framework for situating and understanding precedents, research of pertinent background material, and a design research methodology.

PART II

BIO-COMPOSITE MATERIALS AND THEIR DESIGN CONSIDERATIONS

6. BIO-COMPOSITES

Over the past decade, advances in materials science have resulted in experimentation and application of PMCs that employ polymer matrix materials formulated from bio-based content such as plant oils derived from soy and corn feedstocks. These bio-based resins are often combined with natural fiber reinforcement, such as hemp or jute, resulting in a composite material with a high percentage of renewable content. These composites are finding increasing consumer markets in applications such as nonstructural panels in automobiles and farm machinery. It is this combination of bio-based matrices and natural fiber reinforcement that the research in this paper will focus.

6.1 Bioplastics

While the definition of *plastic* is well established, there are multiple interpretations of the term *bioplastic*. The SPI Bioplastics Council defines bioplastics as plastic that is biodegradable, has biobased content, or both. Others more strictly define the term as referring only to that class of materials that is derived from bio-based content. Depending on formulation, these bio-based materials may or may not be biodegradable under typical environmental conditions. Furthermore, some define bioplastic as those materials that are both derived from bio-based content *and* are biodegradable. Some go as far as reversing the order of emphasis, calling bioplastics those materials that are foremost biodegradable, and are derived from varying amounts of bio-based content (entirely or *almost* entirely) (Stevens 104).

6.1.1 Bio-polymer Composition

While nearly all plastics manufactured today are made of synthetic polymers that are derived from petroleum sources, polymers also occur in nature. Natural polymers are known as biopolymers and are produced by plants, animals, and microorganisms through bio-chemical processes (Stevens 83). Biopolymers are amongst the most common materials within the natural world, and include substances such as carbohydrates, proteins, and nucleic acid. Carbohydrates alone account for approximately 75 percent of all organic matter on the planet, one of the most abundant of which is cellulose (Stevens 84). There also exist bio-polymers which more closely correspond in their physical properties to synthetic plastic polymers, such as amber, shellac, bitumous materials, and natural rubber. Uses for these naturally occurring materials date back millennia.

One significant difference between natural and synthetic polymers is that bio-polymers typically have increased levels of oxygen and nitrogen atoms within their chains, whereas synthetics are primarily built of carbon and hydrogen. (Fig. 6.1) This difference renders the bio-polymers completely biodegradable, so that they can participate in natural cycles of material renewal, while synthetics are highly resistant to degradation.

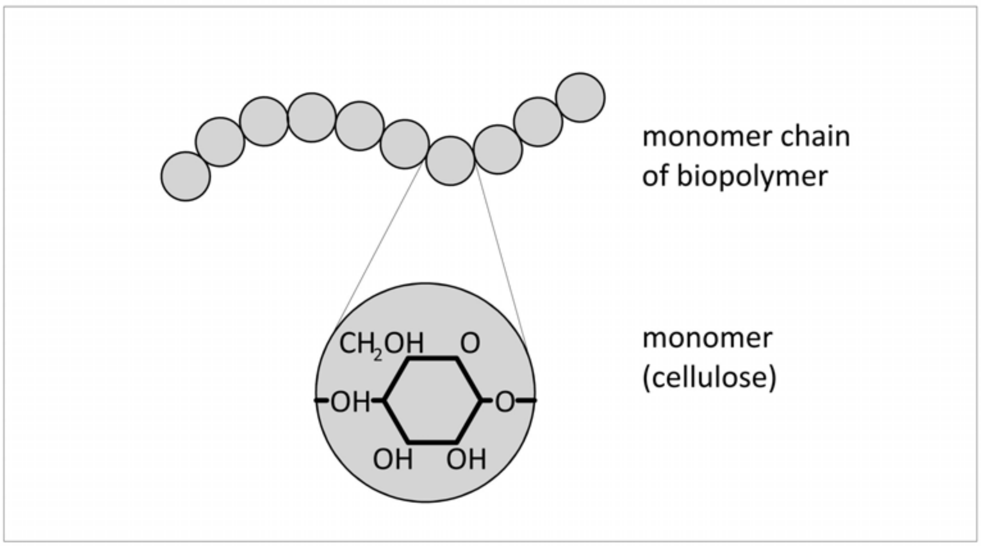


Figure 6.1 Bio-polymer chain.

6.1.2 Brief History of Plastics and Bio-content

While bio-based content is often perceived to be a recent development in the production of plastics, naturally occurring bio-polymers provided the building blocks for the chemistries of the earliest materials known as *plastic*. An early milestone in the production of plastic was the 1839 discovery by Charles Goodyear that the addition of small quantities of sulphur while heating natural rubber allowed it to remain elastic over a wide range of temperatures, as well as improving its resistance to solvents.   Although not understood at the time, this process was forming cross links between polymer chains. The addition of larger percentages of sulphur resulted in a harder material known as vulcanite and was marketed under the trade name Ebonite. Finding use in a wide range of products, this material was the first plastic to be produced by chemically modifying a natural polymer.

Advances in organic chemistry during the 19th century resulted in a class of materials known as semi-synthetic plastics, which were also chemically modified natural polymers. The first of these was discovered in 1846 by treating paper (a cellulose material) with a mixture of sulfuric and nitric acids. The resulting material, cellulose nitrate, could be softened by heat and molded, but had a high shrinkage rate and cracked during cooling. Due to its highly flammable nature, it was primarily used as an explosive known as gun cotton. At the 1862 International Exhibition in London, Alexander Parkes displayed an improvement upon this material, which he achieved by adding camphor to cellulose nitrate, which acted as a plasticizer and prevented shrinkage. Camphor is a naturally occurring material that is produced from the roots and branches of the *cinnamomum camphora* tree that is native to parts of Asia. This new material was marketed as a replacement for Ebonite in items such as buttons and combs. The material was further developed in 1870 when an American inventor mixed cellulose nitrate with camphor and molded it under heat and pressure into billiard balls. This material became known as celluloid and found wide applications in replicating expensive materials such as ivory and tortoiseshell. Eastman Kodak began producing celluloid film stock in 1889 and it would become the material on which the film industry was based.

Celluloid was still a highly flammable material and this prompted searches for a safer substitute. Cellulose acetate was created by treating cellulose with acetic acid rather than nitric and sulfuric acid and became widely used in sheet, rod, and tube forms, as well as a molding powder. During the 1920's cellulose acetate was used to create Rayon fibers for use in textiles, and is still used in its production today, along with its use as film stock.

Another cellulose substitute was created by treating paper with casein, a protein found in cow’s milk, and then treating this substance with formaldehyde. The resulting material, known as casein-formaldehyde, was resistant to moisture and could be formed into a wide variety of objects such as buttons and jewelry. It was in general production until as recently as the 1980's (Shashoua 25).

6.1.3 Shift to Synthetic Plastics

The first fully synthetic plastic was *Bakelite*, developed in 1907, which was a thermosetting phenol-formaldehyde polymer strengthened with wood flour. The development of semi-synthetic plastics, as well as Bakelite, had occurred primarily by empirical trial and error experimentation, with little understanding of the underlying chemical principles. It was not until advances in organic chemistry during the early twentieth century that fully synthetic plastics began to be widely developed. Among these early developments were the discovery of poly vinyl chloride (PVC), polystyrene, and nylon. Research during World War II brought polyethylene, polyester, silicone, Teflon, and polyurethane. This development continued in the post war period, bringing epoxy, high-density polyethylene, polypropylene, and polybutyl.

Even with the discoveries of many new fully synthetic plastics, through the 1950's the feedstock for many of these materials continued to come from natural sources. Until World War II, cellulose from vegetable matter provided raw material for cellulose nitrate and cellulose acetate. Ground nuts and vegetable oils were used after the war to produce acids for nylon, and cane sugar provided ethanol for polyethylene (Shashoua 33). Between the end of the 1950's and the 1970's, the raw materials for plastics production switched from plant based to coal distillation and petroleum sources.

While petroleum based polymers would dominate from that point forward, there was occasional continuing experimentation with plant based plastics. In 1941 Henry Ford unveiled a “soybean” plastic concept car, and demonstrated the durability of its body panels with blows from a sledgehammer, which were easily deflected. (Fig. 6.2) These panels were constructed of a material that consisted of 70 percent cellulose fibers in a phenolic resin that was extended with soybean meal. While Ford’s experiments were interrupted by World War II and not continued in its wake, beginning in the early 1960's the East German Trabant used a similar material for the duration of its 30 year production run. (Fig.6.3) Driven by the high cost of steel in Eastern Europe, external body panels were made of “Duraplast” which consisted of recycled cotton fibers reinforcing a phenolic resin. It was formed into body panels in high pressure molds.

It became notorious for causing a disposal problem as the panels would not decay and could not be recycled in any useful way.

Figure 6.2 Ford Soybean Car [*Ford Museum*]

Figure 6.3 Trabant body. [*Richard Baker*]

6.1.4 ***Current Bioplastic Production***

During the past decade, materials science research that focuses on bio-based plastics has increased dramatically. This has been driven by multiple factors, such as the desire to produce biodegradable products, increased marketability of "green" products, the use of more carbon neutral materials and technologies, and the search for chemistries that rely on replenishable feedstocks. According to Stephen Myers of the Ohio BioProducts Innovation Center (OBIC), it is this last issue that is the primary driving force in the development of novel bio-based chemistries. Large chemical corporations view the shift toward renewable resources as a necessary undertaking, as a means to move toward increased production sustainability, risk mitigation, and source diversity. The current raw materials for bio-plastic production are myriad, being derived from natural substances such as starches, sugars, cellulose, and plant oils.

These driving factors have also resulted in the search for bio-based plastic formulations that are direct replacements for current petroplastics. The research emphasis has thus far been on the development of new materials that have the same engineering properties and can be processed in existing equipment, rather than a search for entirely new classes of materials with new properties. Current bio-plastics are therefore often used as extenders, blended with traditional petroplastics.

6.1.5 Commercially Available Bio-plastics

Polylactic Acid (PLA)

One of the most common bio-plastics in current production is PLA. Produced primarily by NatureWorks (a joint venture of Cargill and Teijin, Tokyo) and marketed under the *Ingeo* trade-name, it is derived from No. 2 yellow dent field corn. Sugars are extracted from the corn feedstock and undergo a fermentation process which convert them to lactic acid, which is used to create a polymer. The resulting thermoplastic can be used in a wide variety of manufacturing processes, including thermoforming, extrusion, injection molding, and compression molding. Thus far it has primarily been used for food containers, packaging, and service ware, but can also be used to produce textile fibers for t-shirts and sweaters. Applications with higher structural needs are being investigated by combining PLA with reinforcing fibers.

During normal service use PLA is not degradable, nor is it degradable if disposed of in the environment, however it is easily compostable using widely available industrial composting equipment. This process requires control of elevated temperatures and humidity levels. NatureWorks claims that after an initial industrial composting duration, in which the plastic loses molecular weight, it is then capable of being further biodegraded naturally by microorganisms. However, during composting PLA does produce methane gas. The material may also be incinerated, or can be converted back to lactic acid through a hydrolysis process. This latter method hints at the possibility of a closed system of material recycling, with a conversion back to raw materials at the end of its life span and suffering no loss of quality or downcycling.

Polyhydroxyalkanoate (PHA)

PHA, an aliphatic polyester material, is produced primarily by Metabolix under the brand name *Mirel*, and is manufactured in Clinton, Ohio. Like PLA, it is derived from plant sugars, primarily corn and soybean. Unlike PLA, PHA is biodegradable in a wider range of conditions such as soil and water environments, and can be low-temperature composted in home composting equipment. Thus far it has been primarily used in the production of consumer packaging and biodegradable films, such as agricultural cover.

Epoxidized Vegetable Oil (EVO)

Epoxidized plant oils are used to produce epoxy resins as well as vinyls, polyurethane foams, and stabilizers for PVC. The feedstocks vary widely, ranging from nut oils, beans, pine derivatives, and linseed oil. While PLA and PHA are often formulated from 100% bio-based material, the epoxidized oils are typically blended with traditional petroleum based materials in various quantities. The percentage of bio-based content may range from less than 20% to over 90%. Resins from epoxidized oils are marketed under several trade-names, such as *EcoPoxy* and *Entropy SuperSap* epoxy resins, and *Arkema Vikoflex* plasticizer for polyurethane foams and vinyls.

Epichlorohydrin

Using rapeseed glycerine as a feedstock, a byproduct of biodiesel production, it is used to replace propylene in the manufacture of epoxy resin. It is produced in Tavaux, France by Solvay SA and by Dow Chemical at a facility in Shanghai, China.

Polyester Resin

Ashland Chemical produces a bio-based polyester resin under the trade name *Envirez*. Derived from soy oil and corn ethanol, it is blended with traditional unsaturated polyester resin in ratios from 25-50%. A 100% bio-based version of Envirez called *GreenBMC* has been developed and is targeted at automotive applications. Envirez resins are available in a variety of formulations for manufacturing processes ranging from hand-layup of laminations and vacuum bagging, to resin transfer molding. It is most commonly available in sheet molding compound (SMC) and has been used since 2003 as body panels for heavy agricultural and construction equipment.

Soy Polyurethane filaments

In addition to multiple manufacturers who produce soy based polyurethane foams, Urethane Soy Systems produces a soy based polyuethane for filament production. The reinforcing fibers can be used for pultrusion and filament winding applications. Although it has lower tensile strength than glass fibers, its manufacturer claims a higher strength to weight ratio due to lower density, as well as environmental benefits.

6.1.6 Current Bio-plastics Research

Current research, which has been rapidly increasing during the past decade, has focused primarily on bio-polymer chemistry and the materials science of bio-based plastics and composites. There have been extensive studies of matrix and natural fiber reinforcement materials as separate realms, as well as studies of their combined properties as a composite. A growing body of test data exists from performance testing of properties such as strength, elasticity, elongation, creep, and UV resistance. A secondary focus of research has been on the environmental aspects of bio-plastic and bio-composite production. These include topics such as carbon footprint of raw materials, embodied energy of manufacture, impacts of feedstocks on food production and potential deforestation, levels of biodegradability, impacts on waste-streams, and use of anaerobic bacteria to break down polymers that are not degradable during normal environmental exposure (Billington).

While the growing literature on bio-plastics material science is extensive, there is limited literature on potential new applications. A review of information from plastics processors as well as industry groups such as the Bioplastics Council reveals that the goal thus far has been to produce new bio-based materials that serve as a direct replacement for existing petroleum-based versions. This approach requires little product re-engineering, and existing manufacturing equipment can typically be used. There has been little speculation of new application possibilities for these new materials, or how new material properties could engender new types of products and designs.

6.2 Natural Reinforcing Fibers

6.2.1 Fiber Composition

Vegetable fibers are the structural components of plants, and their properties are determined by both the functional role they play within its overall morphology, as well as the environmental conditions in which the plant grows. Natural plant fibers (in addition to wood) have been used by humans for thousands of years, for uses such as clothing, rope, sails, and paper.

Plant fibers are composed of varying ratios of four primary components: cellulose, hemicellulose, pectin, and lignin. Cellulose is an organic compound, the most abundant on earth, built of linked glucose units and forming the structure of cell walls in green plants. Wood has a cellulose percentage of 40-50%, while cotton contains around 90%. Hemicellulose is also formed of linked chains of glucose molecules and is also present in cell walls. Unlike cellulose, it has significantly shorter chains, thus is lower in strength. Most plants contain around 20% hemicellulose content. Pectin is also found in cell walls and acts as a permeable matrix in which cellulose and hemicellulose are held, and also binds individual cells together. Lignin, the second most abundant organic compound on earth after cellulose, is a biopolymer material that fills in the space in plant cell walls between cellulose, hemicellulose, and pectin, adding mechanical strength to the cell. The distribution of lignin within a plant varies based on the local mechanical stresses that are placed on the plant. Lignin is typically most abundant in the areas of plants that are under compression, and absent in areas of tension. The varying ratios of these four components determine the structural properties of the plant, with the highest strength fibers generally being highest in concentrations of cellulose.

6.2.2 Fiber Categorization

Vegetable fibers are categorized in several ways. The most common classification is by the region of the plant from which the fibers originate, and include stem (bast), stalk, leaf, fruit, and seed. This categorization generally corresponds to some typical differences in properties of fibers that come from different parts of the plant. However, a single plant species may produce usable fibers of several types, therefore fibers are also occasionally categorized simply by botanical name. There are two other less used categorizations and these are based on the processing consequences for different types of fibers, and on functional criteria. Because fiber length directly effects the technological means of processing fibers, they are sometimes divided into so-called *long-staple* fibers (those over 120mm in length) and *short-fiber* (typically under 60mm) (Lewin 54).   The functional criteria sometimes used is based on fiber diameter, due to fibers of small cross-section having low bending stiffness, and hence being softer to the touch than large diameter fibers which are stiff and course. These are simply divided into two headings of *soft* and *hard*, and generally correspond to which fibers are suitable for clothing textiles and which are not.

6.2.3 Types of Vegetable Fibers

This paper will adhere to the common classification of fibers by the area of the plant within which they are found, as there is generally a high correlation between which part of the plant a fiber comes from and its structural properties, and thus its suitability as a reinforcing fiber within a polymer composite.

Bast - Jute, Kenaf, Flax, industrial hemp, Ramie, Rattan

Bast fibers come from the zone that surrounds the stem of a plant, and is beneath the bark or skin. Due to their location within the plant, a process is required to separate them from the surrounding tissue by removal of the binding pectin. This process is called *retting*, and may be accomplished in several ways. The traditional method was by employing micro-organisms found in water, through a process of soaking the stems in ponds for a prolonged period of time. More common modern methods are dry processes using micro-organisms, or through chemical treatment.

Bast fibers are typically of high strength and the majority of crops grown for tensile fibers are of the bast variety. Most have very high cellulose content, and often low lignin. For example, hemp has over 70% cellulose and only 8-10% lignin. Due to this high strength, bast fibers are the primary type of fiber that have been investigated for use in polymer composite reinforcement, and are seen as the most promising (Rouisson).   One disadvantage of bast fibers is that they have nodes, which are a structural weak point. Most bast fiber crops are fast growth, such as jute which is grown and harvested in 4-6 months, and kenaf in as short as 100 days. Kenaf is also of special note as a potential reinforcement fiber as it is grown in significant quantities in the United States, primarily North and South Carolina, mainly for use as livestock bedding and feed. This gives it a distinct transportation energy advantage over most other plant fibers, which are grown on the Pacific Islands or in eastern Africa.

Leaf- Fique, Sisal, Banana, Agave, Abaca(Sinamay)

Leaves of different species have varying morphologies, thus leaf fibers come from multiple plant locations. What these fibers have in common, much like bast fibers, is that they require a method of separation from the leaf. Some species employ a method that is similar to the retting of bast fibers, while others can use a strictly mechanical process called *decortication*. Leaf fibers tend to be lower in tensile strength than bast fibers, although the abaca fibers exceed the strength of most bast fibers. Leaf fibers are also typically much stiffer and coarser than bast fibers, and often shorter length. Many leaf fiber crops are grown only for their leaves, resulting in a high level of waste as the remainder of the plant is discarded, often through incineration.

Seed/ Fruit- Coconut (coir), Cotton

While cotton has been used as a traditional rope fiber, it is relatively low in tensile strength and generally undesirable as reinforcing fibers. Coir is extracted from the husks of coconuts and the short, stiff fibers have been used for upholstery padding, stiff brushes, and doormats. Its fibers exhibit a high enough tensile strength that they have been investigated as reinforcing fibers, primarily within a thermoplastic matrix such as polypropelyne (Beckermann).

Stalk- Wheat, Rice, Bamboo, Grasses, Tree Wood

These fibers are actually the entire stalks of plants, or significant portion of the stalk, thus they do not require a separation process other than simple mechanical cutting. They generally have lower tensile strengths than bast fibers and have not been used as reinforcing fibers in polymer composites. However, wood fiber (in the composite form of OSB) is the common facing material in SIPs panels, and its higher lignin levels are well suited to this application, in which panels are often oriented to resist primarily compressive loads.

6.2.4 Variability of Fiber Properties

Because plant fibers are a natural product there is a wide range of variability in their properties. These are directly effected by variables in the plant's growing environment such as temperature, humidity, soil composition, and air quality. These variables effect plant characteristics such as height, strength of fibers, density, and yield per hectare.

Methods of harvesting and processing also effect the mechanical properties of fibers. Many fiber crops are grown on small scale cottage-industry farms and plantations, and the hand-craft nature of harvest and processing introduces a broad variable (Lewin 408). An example would be small scale operations that use traditional methods of bast retting. This is done by soaking in a body of water to cause natural decay of the outer bark, exposing the bast fibers beneath. Variation in thickness of bark and bast fibers can cause those fibers that are exposed for longer durations, or those that are thinner, to be over-retted. Retting in small uncontrolled ponds also means that many damaging micro-organisms are introduced into the fibers.

	SPECIES	TENSILE (MPa)	ELASTIC (GPa)	ELONG. (%)	ENERGY (MJ/kg)
BAST (stem)	Jute	300-700	20-50	1.2-3.0	4-15
	Kenaf	400-930	25-53	1.7-2.1	4-15
	Flax	500-900	50-70	1.5-4.0	4-15
	Hemp	350-815	30-60	1.6-4.0	4-15
	Ramie	600			4-15
	Rattan				4-15
LEAF	Fique				4-15
	Sisal	300-500	10-30	2.0-5.0	4-15
	Abaca	965			4-15
	Banana				4-15
STALK	Bamboo	500-740	30-50	2.0	4-15
	Grasses				4-15
	Tree Wood				4-15
SEED	Cotton	400	6-13		
	Kapok				
FRUIT	Coconut (Coir)	150-180	4-6	20-40	4-15
SYNTHETIC	E-Glass	1800-2000	72	2.5	30-50
	S-Glass	3800	75	2.5	
	Kevlar 49	3600-4100	130	2.8	
	Carbon	4000	235	2.0	

Table 6.1 Natural fiber properties.

6.2.5 Natural Fiber Treatments

Natural fibers can be treated to enhance certain properties. These include treatments to facilitate handling, processing by equipment such as looms, and increasing the fiber strength by chemical removal of pectin and lignin. There are two types of fiber treatment that are important when natural fibers are used as reinforcement within a polymer composite. The first is to enhance wet-out of the fibers with resin. This is typically a treatment to reduce atmospheric moisture absorption through an alkaline treatment (mercerization) that modifies the polymer chain of cellulose, significantly reducing its ability to attract moisture (Westman 6). The presence of moisture is also a problem as it both creates voids in the composite where is displaces resin, reducing strength, and the weight of the absorbed moisture negates the weight savings from the low density of the natural fibers (Westman). Moisture in natural fibers has also been found to increases creep (Georgia Tech report, 3).

The second type of treatment, which often coincides with the first, are those that improve the interfacial bond between fiber and the matrix material. Making the fibers more hydrophobic can increase their bond with most thermosetting resins (Rouisson 25). Alkaline treatments have been researched which increase bond strength, as have silanes, which are commonly used as coupling agents in glass fiber production (Westman 6). Other fiber treatments to increase bond are based on current paper sizing technologies, such as the use of rosin acid (Rouisson; Beckwith). Many of these fiber treatments actually result in a decrease in fiber strength, but the increased bond results in a net increase in the strength of the composite material. This illustrates the importance of analyzing the composite as a whole, rather than just its constituent parts.

6.2.6 Fiber to Matrix Bonding

The problem of poor bonding between natural fibers and polymer matrices is generally understood to be the primary technical problem that needs to be solved in order to produce composites that have strength characteristics that are competitive with glass fiber composites (Westman; Beckwith, 12). While the unit strengths of natural fibers are significantly lower than those of E-glass, the specific strengths are comparable and may occasionally be higher

(Westman). The poor bond between natural fiber and matrix results in a lower overall performance. A Department of Energy study comparing Kenaf fibers to E-glass fibers found that the strength of the Kenaf composite was only slightly lower than the e-glass, but only if the fibers had been treated to make them more hydrophobic and to improve wet-out (Westman 10). Another study of jute fibers in polyester resin matrix, formed into thin panels by resin transfer molding, resulted in a product that only had about half the strength of a similar E-glass panel, even though a higher quantity of jute fiber was used. Scanning electron micrographs showed fiber pull-out indicating poor bond between fiber and matrix (O'Dell 284). This same study also found that the weak fiber to matrix bond was detrimental to crack propagation. However, the slippage of fibers within the matrix was beneficial in the absorption of impact energy, resulting in superior performance to the glass-fiber panel in this regard.

The general conclusion from multiple studies is that natural fiber products can potentially have a higher strength than glass fiber versions. The specific modulus (tensile modulus divided by the density of the fiber) has been called the most realistic performance parameter of reinforcing fibers, and many natural fibers such as hemp, flax, ramie, and sisal outperform E-glass (Beckwith 14). Some studies of fiber treatments have found that such processing resulted in both hemp and flax reinforced composites with higher specific tensile strength than E-glass, as well as an increase in transmission of strain energy between fibers, of 80-100% (Mueller; O'Dell 284).

It is worth noting that the primary problem in GFRP is also the bond between fiber and matrix (Marshall). The initial bond to untreated glass fibers is adequate, however, the bond strength deteriorates over time and may drop by as much as 70% over one year. To combat this problem, untreated glass fibers are first "heat-cleaned" to burn off any light oils that were used to facilitate processing. They are then treated with a coupling agent to provide a "finish" on the fibers. The most common E-glass coupling agent treatment is known by the trade name *Volan*. While these fiber treatments increase the bond to glass fibers, it does not entirely eliminate bond degradation.

6.3 Bio-based polyurethane foams

Rigid closed cell polyurethane foams are produced by reacting vegetable oil polyols, most typically derived from soy or peanut, with isocyanate. Rigid polyurethanes have always been manufactured with some quantity of bio-based content, using sucrose derived from sugar beets or corn. As per ASTM standards for measuring bio-based content, the figures published by manufacturers represent the quantity of bio-content that is replacing petroleum sources. Thus this percentage must be calculated and added to the bio-content already existing in a polyurethane formulation. A PUR foam advertising a 50% bio-content, for example, would in actuality have a total bio-content that is higher than this figure. Soy based PUR foams are available with bio-content from 50-100%. The soybean oil that is used to manufacture polyol is pressed from the skin of the bean, which is considered a waste product, and thus does not compete with food sources.

Like traditional PUR foams, those with high bio-content are available both as a spray product, utilizing water as a blowing agent, as well as a castable 2-part liquid. The spray foam is finding broader implementation as a building insulation product, being sprayed between stud cavities in wood light frame construction.

In addition to the benefit of increased renewable content, plant-based PUR is free of volatile organic compounds (VOCs) and formaldehyde, along with requiring less energy to produce (United Soybean Board). These foams are also typically biodegradable through an elevated temperature composting process.

7. ENVIRONMENAL IMPACTS

7.1 Embodied Energy and Carbon Footprint

Embodied energy is an inventory of the quantity of energy that is consumed during the life-cycle of a product. This is typically expressed as either the quantity of energy per quantity of material (such as MJ/kg or MJ/m3) or as the quantity of carbon emissions released (kgCO2/Kg.) Ideally this accounting would extend from extraction of raw material through manufacturing and processing, to disposal and end of life processes. In reality, the boundaries of what is included vary widely and there are few established standards. While published charts listing embodied energy for various materials are common, and typically express embodied energy as an apparently definitive single number, published data for a material typically reveals a wide range of reported results. The compilation of embodied energy data is complicated by the many types of energy phases that can potentially be included.

7.1.1 Databases

One of the most comprehensive databases for embodied energy is maintained by the University of Bath (UK), Department of Mechanical Engineering, and is known as the Inventory of Carbon and Energy (ICE.) This database compiles energy studies published in journals, books, conference papers, and life cycle assessments, compares methodologies that were employed, and determines a statistically relevant range of results. Along with these results, the ICE publishes full information on the data sets from which they were calculated, including number of records analyzed, high and low figures, standard deviations, and comments of what boundaries were used by various methodologies. The ICE also includes data on energy production sources for different materials, making transparent what percentages of their embodied energy came from coal, hyrdoelectric, nuclear, or renewables.

7.1.2 Standards and Methodologies

There are few existing standards for the calculation of embodied energy. The most established is ISO 14040/44 for life-cycle assessment (LCA) of carbon emissions, and it is data that is based on this standard that the ICE prefers. ASTM D6866 establishes standards for measuring the renewable carbon content of bio-based products. Boundary conditions represent the most problematic factor in calculating embodied energy. Difficulties arise in determining where to begin and end counting the energy use that is associated with a material. For instance, many LCA methodologies do not count either recycled or renewable content, thereby conveniently dismissing energy contained in its processing. The processing of some types of recycled material, such as glass and paper, may consume as much energy as when using virgin materials.

7.1.3 Embodied energy in Building Materials

As the energy performance of buildings continues to improve, the embodied energy becomes increasingly important as it represents a higher proportion of total energy consumed over its lifetime. Recognizing that the typical life-cycle of a building material often differs from that of materials used in other products, the calculation of their embodied energy has often used alternate methodologies. These sometimes assess not only the energy contained in the "as-built" structure, but also include life-cycle energy consumption such as contributions of heating and cooling loads, or energy required for maintenance or replacement of the item. Studies that attempt to factor in the lifetime contribution by overall energy performance of the building often reveal that a material appearing to have a negatively high embodied energy may offset this deficit with a net energy savings when compared to lower embodied energy building materials that perform poorly during their life spans (Studies by University of British Columbia's School of Architecture , 1992, and University of Canterbury in New Zealand).

The American Institute of Architects (AIA) also defines embodied energy in terms of life-cycle that includes the types of energy use that are unique to buildings (Demkin). These types of energy include the typical categories of raw material acquisition, processing, and manufacturing, but also include transportation to the building site and energy consumed during the construction process. Also included in this energy inventory are life-cycle costs such as energy to maintain, repair, restore, refurbish, or replace building materials and components.

Recognizing the overwhelming complexity of calculating all of these energy paths, the

AIA recommends an integrated approach to energy reduction in buildings that has four categories. These include reducing overall life-cycle embodied energy, energy efficient equipment and technologies, use of renewable materials and energy sources, and the education of owners and occupants about energy efficient operation. Taken together, the categories suggested by this approach recognize that it is necessary to balance the many energy consumption avenues and not focus on only one category (Demkin).

7.2 *Environmental Impacts of Bio-based vs. Conventional Composite Materials*

The constituent materials (resins, reinforcement fibers, foam) in bio-composites are all indisputably lower in both embodied energy and in carbon footprint than petroleum based counterparts. For example, Ashland Chemical claims that production of one batch (17,000kg) of their *ENVIREZ 1807* resin results in a savings of 10 barrels of crude petroleum and a 15,000kg reduction of CO2 emissions. These calculations consider the manufacturing process as well as the farming and processing of soybeans and corn feedstocks. However, reductions such as these may not necessarily translate as equal savings in a finished composite product, as the quantity of material needed to achieve equal performance may offset any savings.

In a study by BRE (Building Research Establishment), multiple composite materials and multiple manufacturing processes were compared, to analyze the environmental impacts of changing these variables. Test components were fabricated with these various materials and processes, with structural and performance characteristics kept constant. Three types of components were used for comparison in the BRE tests: a doubly curved panel, 1m x 1m, with stiffness equivalent to a 4mm chopped strand mat construction; a flat sandwich panel, 1m x 8m, with a 25mm core, and having a bending strength equivalent to construction with 4mm CSM skins; and a complex molded component with a volume of 770cm3. Resins compared were all traditional petroplastics, such as polyester and epoxy, but the study thus allowed the comparison of the environmental impact of using natural fibers in varying manufacturing scenarios.

Although the environmental impact of producing natural reinforcement fibers is undoubtedly lower than synthetics such as glass or carbon fibers, in some situation the overall environmental impact was higher when the natural fibers were used. This was due to the structural efficiency with which the fibers were used and if their mechanical properties were being fully exploited. In some scenarios hemp had higher environmental impacts than both glass and carbon fiber due to the increased quantity required to produce a product with the same performance properties. Other scenarios did result in significantly lower impacts when using the natural fibers, but the study reveals the complex combination of manufacturing and engineering factors that must be balanced in order to realize these environmental benefits. Simple substitution of the natural fibers was not an automatic guarantee of lower environmental impact.

A study by Audi that compared panels constructed of fiberglass/epoxy to those of hemp/epoxy resulted in a 43% reduction in energy consumption (Joshi 373). This study found that the energy savings were great due to the higher ratio of fiber to resin matrix when using hemp. The energy and emissions contained in the epoxy matrix dominated the overall composite, thus any reduction in epoxy use had a significant overall impact.

A study that compared LCA reports of energy and emissions of natural fiber vs. fiberglass reinforced composite concluded that the benefits and savings are significant and robust under all conditions (Joshi 380). This study identified four modes by which natural fibers reduced environmental impact:

1. Lower impacts associated with the production of fibers.
2. Higher volume percentage of natural fibers in a composite material, resulting in less polymer matrix material being required.
3. Higher volume of lower density natural fibers may result in lower weights.
4. End of life incineration results in carbon credits due to the sequestering of carbon dioxide during the service life of the material.

Potential negative impacts associated with natural fibers include higher nitrate and phosphate emissions from fertilizer use, which could result in decreased water quality. This is linked to geographic location in which fiber crops are cultivated, as many have the advantage of being hardy species which require little or no use of fertilizers, pesticides, or irrigation when grown in native regions (Joshi). Another potential disadvantage is a shorter operating life when used in some composite applications (Westman).

7.3 *Environmental Impacts of Composites Manufacturing Processes*

In addition to production of the constituent materials, the manufacture of composite components also has environmental consequences, with some processes having considerably greater impacts than others. These fall into three general categories; the energy used during manufacture, emissions of volatile organic compounds, and the production of waste. While some processes, such as hand lay-up, which uses primarily manual energy inputs, use little energy during manufacture, others, particularly those that cure resins at elevated temperatures or pressures, use large amounts of energy. VOC emissions is directly linked to both the type of resin used, as well as the amount of atmospheric exposure it is allowed during the liquid and curing phases. The use of vacuum bags and closed mixing containers can prevent VOCs from entering the atmosphere. Traditional petroleum based resins, such as polyester, emit very high levels of VOCs, styrene in particular. However, many formulations of bio-based resins have either very low, or zero VOC emission. This could potentially allow the use of open mold techniques that would typically cause the release of extremely high VOC levels, such as resin impregnators or spray-up. Other environmental impacts come from mold release compounds, mold cleaning agents, consumables such as peel plys and bleeder cloths, and scrap edges that are trimmed from parts.

7.4 *Genetically Modified Organisms*

While most fiber crops remain unmodified, the majority of feedstocks for the manufacture of bio-based plastics comes from genetically modified crops such as soybeans and corn. These patented organisms are currently genetically modified primarily to provide resistance to pesticides and herbicides, however, the ability to custom design a plant and its bio-polymers, opens up vast possibilities for advances in bioplastic chemistry. The mission statement of the Ohio BioProducts Innovation Center at the Ohio State University declares that the program is “designed to meet the needs of the materials market.” To this end, director Stephen Myers remarked that “basically, we're looking at projects that use genetics to biologically modify materials for use in composites and other materials” (Composites Technology, April 2008). While the topic of potential environmental consequences of GMOs is beyond the scope of this paper, increasing demand for bio-plastics will undoubtedly result in genetic modification specifically designed for this market.

7.5 *Bio-degradability and End of Life Scenarios*

For most of the history of plastics production, material degradation was considered a negative effect and the goal of chemists was to formulate plastics that were stable and resisted decay and polymer break-down (Stevens 52). As a result, most plastics are highly resistant to most types of decay and may be pervasive in the environment for many decades, or even centuries. Plastics generally have high strength that resists mechanical break-down into smaller fragments, are water resistant, and are not attacked by microorganisms.

While generally highly resistant, plastics do degrade by multiple mechanisms, both mechanical and chemical, many of which are not completely understood. Further complicating study of degradation are the interactions of multiple modes, which may occur simultaneously or consecutively. While discrete classifications of how plastics degrade in explicit environments are made, the real-world mechanisms may be more complex and overlapping (Stevens, 52-79).

7.5.1 Photodegradation

By modifying the polymer chain with the addition of a photosensitive group, radiation from sunlight exposure can cause a breaking of the chain (*scission*.) As the polymer chains are broken at multiple sites, the plastic material is fragmented into smaller and smaller particles. To some degree, the time duration of this process can be controlled, resulting in a material with a programmable life span. Although the material is ultimately broken down into a fine powder, the grains may or may not be able to be broken down further by other processes. As a result, they may still be pervasive in the environment.

7.5.2 Oxidative Degradation

While photodegradation requires sunlight exposure, a similar process of polymer chain scission can be triggered by the inclusion of a molecular group that degrades by oxidation. Oxidation is a chemical process in which an atom or molecule loses electrons as they are transferred to an oxidizing agent (direct contact with oxygen or with an oxygen containing chemical.) In addition to breakdown through contact with oxygen, many formulations of these types of plastics are *wettable,* meaning they can oxidize through contact with water. Plastics of this type are intended to degrade through earth burial or other environmental contact with moisture, and are commonly employed in agricultural covers which are plowed into the soil after use.

Like plastics that photodegrade, those that oxidize may or may not be broken further down by other processes. While plastics that undergo oxidative degradation have been termed "oxo-biodegradable" they are not biodegradable by most current ASTM definitions which state that degradation "results from the action of naturally_occurring micro_organisms such as bacteria, fungi, and algae" (ASTM D6400, ASTM D6868, ASTM D7081). However, due to inconsistent use of terminology, ASTM D6954 considers a material "biodegradable" if it fragments to 60% within a given period of time, and therefore many oxo-degradable plastics have been marketed as "biodegradable" as they meet this less rigorous standard. These plastics typically do not meet the more stringent definitions outlined in ASTM D6400 for compostable plastics.

The Society of the Plastics Industry Bioplastics Council has taken the emphatic position that this class of oxo-degradable plastics are not "biodegradable" and thus should not use the term in any manner. They instead propose the use of the term "Oxo-fragmentable" as it is more accurately descriptive of the actual end-of life process and environmental persistence of the remaining particles. The objection to the misapplication of the term "biodegradable" has also been pursued by the U.S. Federal Trade Commission as well as the U.S National Advertising Division of the Better Business Bureau, both of which have taken legal action against manufacturers using the term "100% biodegradable" in the marketing of oxo-degradable plastics (Position Paper on Oxo-Biodegradables and Other Degradable Additives, Society of the Plastics Industry Bioplastics Council, January 2010).

7.5.3 Biodegradation (biotic degradation)

Biodegradation is a type of chemical degradation that, as mentioned above, occurs due to micro-organisms such as bacteria, fungi, and algae. These micro-organisms contain enzymes, which are proteins that act as degradation catalysts and cause bio-chemical reactions. During these reactions the material is converted to gases, water, salts and minerals, and residual biomass. This process is called *mineralization*, and is considered complete when all biomass is consumed and all of the carbon in it is converted to carbon dioxide. During mineralization, the constituent elements re-enter biochemical cycles.

The rate of mineralization may vary considerably due to environmental conditions. Various combinations of micro-organisms work in concert during this process and may be aided by macro-organisms such as insects and invertabrates, which mechanically break down material into smaller fragments. Mineralization rate is dependent on environmental conditions for these micro and macro-organisms, such as temperature, moisture level, acidity, and aeration levels. Aeration levels effect oxygen content and determine whether aerobic or anaerobic bacteria are at work in the process, with aerobic varieties being more common in natural environments.

The process of mineralization releases carbon that was sequestered in the polymer chains back into the ecosystem in a manner in which they are again available as part of the carbon cycle. Photosynthesis consumes carbon dioxide and removes it from the environment, balancing the release of carbon from the degradation of bio-based plastics.

Another type of gas that may be produced during the mineralization process is methane. Research on controlled anaerobic bacterial degradation of a hemp-PHB (polyhydroxy_butyrate) composite has focused on capturing this gas, and then employing additional microbes which can in turn make PHB from methane. This result is a closed loop recycling of the material with no material down-cycling (Billington).

The use of bacteria to cause biodegradation of plastic can also be done selectively. Plastic can be chemically formulated such that it will not degrade when exposed to bacteria that it would typically encounter in its service environment, yet will degrade if exposed to less common types. The result is a material that is effectively not degradable during normal service conditions, yet can be truly biodegraded on demand. This happened inadvertently with the East German Trabant automobile. Due to materials scarcity in Eastern Bloc countries, it utilized exterior body panels made of a phenolic resin/cotton fiber reinforced composite material that was compression molded. After Reunification, disposal of the over 2 million obsolete Trabants proved problematic as the decay-resistant composite defied any known type of recycling. Scientists developed and patented microbes that would digest both the cellulose fibers as well as the resin.

8. DESIGN CONSIDERATIONS

It is the position of this paper that the development of a construction system must extend beyond a mere solving of straightforward technical problems related to the unique properties of bio-based composite materials, and requires an uncovering and elucidation of a more complete and complex set of governing criteria that must all be satisfied. To this end, Part I concluded with a broad list of criteria categories that may act as a framework for such a development. It is also the position of this paper that a proposed construction system must satisfy these criteria in a holistic and integrated manner. These stated criteria are:

1. ***Material properties***
2. ***Manufacturing/fabrication/assembly technologies and methods***
3. ***Environmental concerns***
4. ***Design and engineering tools and methods***
5. ***Regulatory and building codes***
6. ***Cultural factors***

Each of these categories carries a set of design considerations for the implementation of this particular palette of materials at this particular point in time. This temporal aspect is crucial, as the guiding criteria within each of these categories is constantly shifting and evolving. With time, new categories may appear or existing ones cease to be of importance. With this understanding, it is seen that the true value of case studies and precedents is not to provide direct examples of solutions, but rather to reveal that there were frameworks of guiding criteria that shaped those past schemes. The identification these frameworks can then be used as a tool to construct a valid set of criteria to map the current solution space. These criteria are of practical use in the guiding of research, which may in turn provide adjustments to these criteria, as well as clearly identifying direct design considerations that must be made.

8.1 ***Bio- based Materials***

While bio-polymer composite materials may generally bear similarities to more traditional petroplastic composites, there are differences that must be taken into consideration.

8.1.1 Design Considerations for Bio-polymer Matrix Materials

Two types of bio-plastics are currently most suited for use in architectural structures, and those are the epoxidized vegetable oils and polyester resins. Both are suitable for use within composite laminations produced by conventional manufacturing practices. Currently, the epoxidized vegetable oils both have a higher bio-based content as well as greater mechanical properties than bio-based polyester resins. They have also been formulated primarily for use in composite lamination. For these reasons, EVO will be used in this research. Below is a table of properties from several epoxy manufacturers, comparing those with bio-based content to common traditional petroleum based formulations with zero bio-content.

	Type	TENSILE STRENGTH (psi)	TENSILE MODULUS (psi)	ELONG. (%)	FLEXURAL STRENGTH (psi)	FLEXURAL MODULUS (psi)	VISCOSITY (cps)	ULTIMATE Tg (degrees F)	BIO-CONTENT (%)
ENTROPY Super Sap	100/1000	9,000	3.6E+05	7	12,000	3.0E+05	2,000-3,000	120c	55
	HVA	6,200	2.9E+05	15	7,500	2.5E+05	4,000-7,000	80c	67
	CPM	8,700	4.5E+05	3	14,000	2.9E+05	5,000-7,000	120	45
	CLR	9,410	5.0E+05	5	13,534	4.0E+05	1,500-2,000	120	35
	INF	10,100	6.2E+05	2	16,000	5.5E+05	500-1,500	120	30
ECOPOXY.	SLOW	9,692	3.93E+05	3.65	14,434	3.64E+05	600-650	188	50
	MEDIUM	9,692	3.93E+05	3.65	14,434	3.64E+05	600-650	188	50
	FAST	9,692	3.93E+05	3.65	14,434	3.64E+05	600-650	188	50
WEST SYS.	105/205	7,846	4.1E+05	3.4	14,112	4.6E+05	975	142	0
	105/206	7,320	4.6E+05	4.5	11,810	4.5E+05	725	139	0
	105/209	7,280	4.0E+05	3.6	12,459	4.0E+05	650	130	0
MAS	Low Viscosity						2,000-4,000		0
	Infusion	10,200	3.6E+05	7.2	24,000		150-200		0

Table 8.1 Comparison of epoxy resin properties.

The epoxy resins with bio-content exhibit properties comparable to traditional resins. Furthermore, they can be formulated to suit particular applications, altering properties such as strength, flexural modulus, working time, and viscosity. Thus they require no special considerations beyond coordination with a manufacture to provide a formulation that is best suited for a particular manufacturing process.

8.1.2 Design Considerations for Natural Fiber Reinforcement

There are numerous advantages and disadvantages associated with the use of natural fibers as composite reinforcement. (Table 8.2)

Natural Fiber Design Considerations	
Advantages	**Disadvantages**
Low carbon footprint and embodied energy.	Some reduction in strength over time
Low fiber production cost.	Absorb moisture. Must be fully encapsulated.
Low density. Potentially lighter weight composites.[1.]	Degradation from UV light exposure. Must be protected.
High ratios of fiber to resin.	Lower mechanical properties than synthetic fibers.
High impact strength and energy absorption.[2.]	Some types have high elongation and low modulus of elasticity.
Renewable resource. Rapidly replenishable.	May be difficult to wet-out with some resin types.
High yield per hectare. Over 2 tons of fiber per hectare.	Lack of fire resistance.
Low thermal conductivity.[3.]	Thermal degradation. Lignin begins to degrade at 70+ deg. C.[4.]
Low tool wear.	High cost relative to production cost of raw fibers.
Potentially biodegradable.	
Can be safely incinerated.	

1. DOE 2010 Study.
2. Mueller, 2.
3. Rouisson.
4. Georgia Tech report.
5. Beckwith, 14.

Table 8.2 Natural fiber advantages and disadvantages.

Many of these factors have direct implications on general design for the use of natural fiber reinforcement, and some have potential implications on building morphology. For example, having a lower strength and modulus of elasticity than synthetic fibers such as E-glass indicates the importance of geometry as a means to increase stiffness and thus reduce deflection under design loads. The tendency for fibers to absorb moisture introduces a vulnerability at any joint condition, especially if it is designed such that holes need to penetrate the laminate. This leads to the desirability for monolithic assemblies with few, or no, joints or exposed edge conditions.

The problem of poor interfacial bond between fiber and matrix material requires either designing for this weak bond, or sourcing fibers that have been treated to decrease this problem. The sourcing of fibers in general may be problematic, as it may be difficult to trace the origins of the product. Natural fiber textiles may often be distributed as though they are fungible goods that are freely interchangeable, and assumed to be equal in quality, yet this contradicts the highly variable nature of these crops. Thus, the mechanical properties must be assumed to be those of the lowest quality product that may enter into distribution networks.

Other factors may not be as crucial as they would seem. The lack of fire resistance, and thermal degradation of lignin are both situations that occur either at temperatures that are higher than the glass transition temperature of most resins, or require prolonged heat exposure. Some factors represent situations that could potentially change with time. For instance, while the cost to produce most natural fibers is very low, there is no existing infrastructure for their specific manufacture or distribution to the composites market as a reinforcement product. The types of fabric weaves currently available are not those ideally suited for use in composites, resulting in either the need to source fabrics intended for other industries or for custom weaves (Beckwith 14).

8.1.3 Design Considerations for Bio-based PUR Core

Current bio-based polyurethane foams exhibit mechanical properties that are comparable to traditional petroleum derived foams, as illustrated in the table below. (Table 8.3) They are effectively interchangeable with traditional petroleum based PUR. They greatly exceed the strength of typical 1pcf expanded polystyrene used in SIPs panels, and some studies suggest that certain formulations exceed the strength of petroleum based polyurethane foams in some categories, while decreasing slightly in others (Tu 60). Most important is an increase of shear strength, which benefits use in sandwich assemblies.

	Density (pounds/ cubic foot)	Compression Strength (psi)	Compression Modulus (psi)	Shear Strength (psi)	Tensile Strength (psi)	Flexural Strength (psi)	Flexural Modulus (psi)	R-value (per inch)
BIO-POLYURETHANE	2	14.7	372	29.5	46.0	48.0	997.0	4.6
	4	33.1	722.0	35.0	51.8	56.7	1262.2	4.6
EXPANDED POLYSTYRENE	1 (type I)	10-14		18-22	16-20	25-30		3.85
	1.35-1.79 (type III)	15-21		26-32	18-22	40-50		3.85
POLYURETHANE	1.6	9	340	13	18	22	400	5.3
	1.8	21	450	13	20	30	700	5.3

Figure 8.3 Comparison of Bio-PUR to conventional foams.

Soy-based PUR for use in construction industry is typically treated with flame retardants, and has similar flame spread and smoke index performance as petroleum based counterparts. It also provides no food value for insects or rodents, and is inherently resistant to mold growth.

8.2 *Design Considerations with Composite Materials- Engineering Properties*

Polymer composites, and plastic materials in general, have numerous engineering properties that directly impact design. These properties and conditions are exhibited by both traditional petroplastics as well as those that are bio-based, although they are often significantly more pronounced in the latter.

8.2.1 Stiffness and Form

The modulus of elasticity of plastics is considerably lower than most other structural materials. Furthermore, the modulus of elasticity in tension is not necessarily the same as that in compression. The implication for the low inherent modulus of polymer composites is that the gaining of stiffness through the careful consideration of geometry becomes an important design strategy (Benjamin 4). While designing for deflection is often the governing factor with many structural materials, it may be more difficult to achieve acceptable deflection limits with plastics. During the engineering phase of the Monsanto House of the Future, its designers concluded that "the low inherent stiffness of plastics as reflected in their low elastic moduli, is a serious limitation and maximum use must therefore be made of inherently efficient, stiff structural forms such as shells, to provide the necessary rigidity in the structure" (Goody & Hamilton 20).

8.2.2 Nonlinear stress-strain curves of plastic

The stress-strain curves of polymer composites may not be linear up to the yield point. Furthermore, yield and ultimate strength may be identical, with little or no plastic flow occurring between these two points. This lack of ductility prevents the internal relieving of stress concentrations. The result may be rapid crack propagation and fracture with little warning. Areas of high stress concentrations such as holes, sharp radii, and fastener attachment points should be avoided.

8.2.3 Creep

When composite materials are subjected to constant stress, over time the strain will increase in areas of load paths. This occurs with short-term and long-term loading conditions. With long-term creep, the behavior is characterized as *viscoelastic*, a combination of elastic behavior where the structure returns to the original shape when stress is released, and viscous, where the material strains linearly with time (Benjamin 6). Such viscoelastic behavior in composites is effected by loads, temperature, and exact material composition. Creep is represented by plotting strain versus time. Other engineering materials, such as steel, are considered time independent, and structures built of them are thus designed by linear elastic theory (Benjamin 8).

While these general composite properties were known at the time of the design of early plastic buildings, their long term effects were not. Nor did there exist adequate methods of complete structural analysis that could mathematically model these behaviors. Thus, the conclusion of the engineering team for the Monsanto House of the Future was that composite materials could be treated in the same manner as traditional materials if design stresses were kept low (Hamilton & Goody 36). By doing so, the design stresses fall at a point on the material's stress-strain curve where nearly linear elastic behavior is exhibited and creep does not become a significant concern. They further concluded that by satisfying deflection requirements through the use of geometric strategies, the material stresses were low enough to fall within this range on stress-strain curves.

8.2.4 Variable conditions

Polymer composites also exhibit several variable behaviors. The first variable is one that can be controlled, and that is the anisotropic nature of the material. While the use of non-woven reinforcing fibers can result in a nearly isotropic condition, the more typical linear reinforcement strands of woven textiles introduce directional variation. This can be used to advantage in the design of composites by orienting fibers along lines of principle stresses.

Other variable conditions are not directly controllable by the designer, such as environmental effects. The mechanical properties of composites can vary considerably with changes in temperature. Other environmental forces such as UV light exposure and moisture can also have both long and short term consequences, and may require protecting the material from these conditions.

8.3 *Manufacturing*

In general, processes that are suitable for production of traditional sandwich composites can be used with bio-based materials. In particular, those that are employed in the manufacture of large scale components, such as resin infusion, may be used. A study of hemp/polyester resin composites at the University of Toronto found that resin transfer molding of bast fiber reinforced composites is suitable for large complex parts such as automotive, aircraft, and structures (Rouisson 4). Natural fibers exhibit different wet-out properties than synthetic fibers, and minor adjustments may need to be made to the manufacturing process to address this condition.

Other manufacturing processes that may not intuitively appear to be suited for bio-based materials may be adaptable. For example, hemp fibers, as well as some other natural fibers, can be strong enough to be suitable for the pultrusion process and the high forces required to pull the material through the die (Lewin 442).

Advances in digital manufacturing technologies provide opportunities that were not available during the period of most previous plastic building construction. Multiple axis cutting tools allow the realization of complex mold or sandwich core geometries. Digital tools allow for the accurate cutting of materials such as reinforcing fibers, and automated equipment can place them with a corresponding accuracy. Computer controlled adjustable fixtures can allow for a wide range of accurate and rapid reconfiguration.

8.4 *Environmental Design Considerations*

The consideration of environmental impacts places an increasing pressure on architectural design. The first solution is the minimizing of material quantity and making the most efficient use of their mechanical properties. Sandwich construction utilizes thermal insulation material in a structural manner, making more efficient use than systems where insulation is merely an infill material that serves one role. Regardless of reductions in the quantity of material that may be accomplished, the amount of embodied energy and carbon footprints must be carefully weighed against the long-term energy performance. This is currently a difficult arena in which to make direct comparisons between various materials and construction systems.

End of life scenarios are also complex and may be difficult to characterize. While the constituent materials in composites from bio-based feedstocks have a much greater possibility of providing environmentally benign disposal methods, combining them together into a bonded assembly may make this a complicated process. Each constituent material may ideally require a different mechanism for end of life reclamation.

8.5 *Building Codes*

A major factor that must be considered in the proposal of any new construction system is the satisfaction of building code regulations. Two of the case study examples have gone through processes of testing and certification to meet existing building code regulations: the FG2000 and the SpaceBox. Two main categories of testing were required in both cases; the load bearing capacity of the structure, and fire-spread ratings.

8.5.1 Structurally Insulated Panels in the International Residential Code

In addition to these two examples, another relevant precedent can be found in the example of Structurally Insulated Panels. Until recently, this system was not adopted by model building codes, requiring each construction project to undergo a separate process of approval through the local authority having jurisdiction. This typically consisted of submission of proprietary code evaluation reports and engineering test reports from independent testing agencies to prove code equivalency. This often required full scale testing as proof of structural ability. (SIPA)

However, in 2007 SIPs were adopted into the International Residential Code as an approved building system. This prescriptive code describes design provisions and sets limits for use. It furthermore lists performance properties of the panel as well as its constituent materials, and quality control measures that must be met by manufacturers. This has meant that manufacturers can produce panels to these specifications and they can then bear a label indicating that they meet minimum requirements for use as outlined in the code.

The International Residential Code also lists addressable and non-addressable conditions of SIPs use. Addressable conditions are those code limitations that can be removed by meeting specific additional testing requirements. Examples of this type of condition are eccentric and side loading of panels, concentrated axial loads, and voids within the core material. These are limitations normally prohibited by code but may be removed by providing adequate testing evidence. By contrast, non-addressable conditions are those that cannot be removed under any circumstances. Examples of non-addressable SIPSs use include seismic design limits, the requirement to be designed by a registered design professional, manufacture by a listed facility, and use in Type V construction (combustible) only.

The description of allowable materials for SIPs is of particular note. The foam core material must meet ASTM C 578 for strength requirements, must be at least .90 pounds per cubic foot density, and must meet fire spread ratings as outlined in other code sections. It does not state any specific limitations on bio-based foams as a material. The facing material is listed as structural wood panels, however, this is an addressable condition and the Structural Insulated Panel Association lists polymer composites as a material that can meet code requirements if it meets required testing criteria (SIPA). Thus, it is feasible that bio-based polymer composite panels could be engineered, tested, and approved for use as conventional SIPs under the existing International Residential Code.

8.6 *Design and Engineering Methods*

Most of the case study examples which utilized traditional fiberglass materials in their construction were realized nearly a half century ago. It must be noted that even if that same GFRP material were to be used today, there would be significant differences in both design and engineering practices. Within the design domain there now exists the ability to easily manipulate complex geometries within digital environments. Coupled with digital fabrication methods, this now allows the execution of significantly more sophisticated design forms. The simple flat planes, translational surfaces, and surfaces of revolution are no longer a design constraint.

Corresponding developments exist within the engineering domain, where computational methods of analysis correlate to a more sophisticated understanding of the material behavior of composite materials. Structural engineering of the case studies typically consisted of strength testing of sample coupons of the sandwich assembly to be used, and then employing conventional engineering practices for structural calculations (Goody & Hamilton). This required the sandwich assembly to be treated much in the same manner as structural members of other materials, assuming consistent material and sectional properties as well as linear elastic behavior. While these assumption made the hand calculations of the time possible, it denied the material its inherent ability to exhibit a variability of composition. The localized altering of material properties was restricted to the use of additional lamination plies being added to regions of higher stress, but they were added to assemblies that were otherwise consistent. (Goody & Hamilton).

8.6.1 Computational Methods and Material Properties

The inherent anisotropic properties of composites can today be more fully exploited. Ubiquitous composite engineering software employs Finite Element Method analysis based on Classical Laminate Theory, which is in turn based on Plate Theory. Many software programs also utilize micromechanics to build a computational model of composite behavior based on the properties of each of its constituent materials, and on factors such as ply orientation and degree of material consolidation. These new computational tools can solve for local material variation, rather than requiring an assumption of a global average, and can accommodate the continuously varying properties that the material is capable of exhibiting.

8.6.2 Design Workflows

These computational tools have allowed a workflow in which a desired form can be generated and then software applications can determine the required local material properties that will be necessary for adequate structural performance. An example of this is the series of GFRP roofs atop the the Yitzak Rabin Center in Jerusalem, designed by Moshe Safdie. The desired expressive form of the roof, evoking the flight of a dove, was the primary requirement, rather than a form that was generated by structural suitability. Structural analysis by Finite Element Method allowed engineering the core structure with internal stringers such that this non-optimal form could perform as required (Eekhout). (Fig. 8.1)

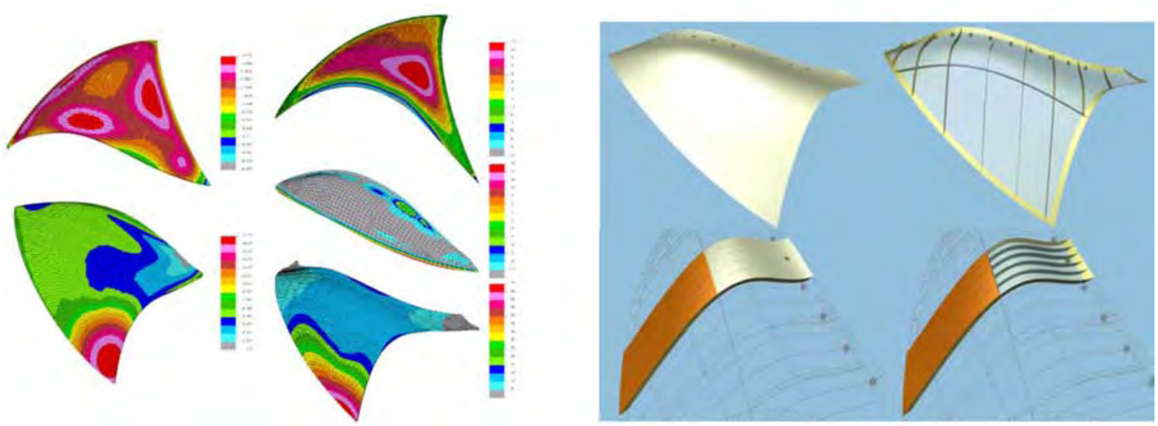


Figure 8.1 Rabin Center structural analysis. [Octatube International BV]

This type of workflow within composites design can often allow a design proposal to be realized even when its geometrical form is far less than optimal. The ability for the material to be locally configured can allow it to compensate to some degree for geometrical shortcomings. As with any design process, the ideal situation is to iteratively adjust the geometry to better meet design criteria, whether those are structural in nature or otherwise. However, this is not always possible or desired, and in these situations computational methods can allow composite materials to bridge this gap.

8.6.3 Performance, Simulation, and Optimization

When geometrical form is negotiable, computational tools can also be utilized to determine morphological changes that would increase performance. Not only can software determine required material properties to realize a design, such as core properties, number of plies in a skin lamination, ply orientation, etc., but they can adjust geometry to make more optimal use of materials. The result is a design environment in which the software itself contains the iterative feedback loop, often utilizing a genetic algorithm, that alters and refines an initial proposal by breeding successive generations of improved solutions.

While this can be understood as an evolution of any typical design workflow (an initial proposal which is then subject to a series of iterative alterations), computational tools can take this process one step further. In addition to searching for minor adjustments to a proposed solution, computational tools can be used to find the entirety of a geometrical solution, both form and topology, based only on constraints, boundary conditions, and load case.

The simulation and analysis of material behaviors within design environments opens up many possibilities, particularly with the design of structures utilizing composite materials, as they have many variables and are difficult to analyze by simple methods. Material simulations within design environments can allow the designer to nearly instantly witness the effects and implications of design decisions and changes. This conflation of design, analysis, and simulation into one environment can not only fundamentally change the design process, but could potentially be an integral component of a new construction system. The prescriptive rules-based nature of building code requirements could potentially be parameterized and directly integrated into a digital design and analysis environment.

8.7 *Cultural Factors*

The final criterion to be discussed is the influence of cultural factors on the design of construction systems. While it is often easiest to focus strictly on technical criteria that must be satisfied, no less important are the often nearly invisible cultural forces that are at play. As was mentioned in section 5.3, the very investigation of plastic as a construction material during the 1950's-70's may have been driven largely by cultural values that were associated with the material.

During the case study analysis of section 5, multiple cultural factors were discussed as generating forces behind the designs, and their influence on particular formal expressions. However, it is equally instructive to consider the disadvantages that many construction systems were encumbered with due to either excessive adherence to immediate cultural situations, or by completely ignoring them. As was witnessed in several of the case study examples, the development of construction systems was driven by the desire to realize certain types of building morphology based on stylistically popular forms. As construction "systems" they lacked the flexibility to render alternative forms without effectively becoming a nearly altogether new system. A lack of flexibility is also seen in the inability of these forms to easily accommodate programmatic requirements. The extremely rigid adherence to a particular form, as in the Futuro for example, came at the expense of internal spaces that were ill suited to programmatic needs. There was no possible negotiation between the building geometry, the resulting construction system, and the program within.

This lack of flexibility resulted in similar problems with other structural systems that were also proposed during this era. While based on materials other than plastics, they focused largely on issues of material efficiency. The geodesic dome of Buckminster Fuller perhaps being the most inflexible system proposed, with no possibility of compromising the basic spherical form to better allow either architectural expression or the spatial needs of program. (Fig. 8.3) Similar problems were encountered in the concrete shell structures of designers such as Nervi, Candela, and Isler. (Fig. 8.2) The reliance on strict geometries to realize their high material efficiencies came at the expense of other considerations. Despite the inherent beauty of many of these structural solutions, their inflexibility limited them to few architectural applications, typically those requiring long-span structures . Thus, inherent limitations of these systems prevented their success and widespread adoption.

Figure 8.2 Heinz Isler shell structure.

Figure 8.3 Fuller dome.

While cultural forces obviously play a large role in both the development and success or failure of a new construction system, they are possibly the most difficult criteria to isolate and accommodate. While they often become apparent within the context of studying historical examples of systems, by their very nature they are often nearly invisible at the time of a system's inception. Despite this difficulty, it is possible to recognize general disadvantages of resulting inflexiblity that burdened many prior construction systems. While no single construction system should be expected to be able to universally meet all architectural needs, it can be generally considered advantageous to be able to accommodate a range of formal expression and spatial conditions beyond those that are immediately desired. A system with an inherently flexible conceptual framework will also have a greater ability to provide a platform to symbiotically evolve in step with architectural languages and tectonic expressions.

PART III

PROPOSAL OF A NOVEL BIO-POLYMER COMPOSITE CONSTRUCTION SYSTEM

If, forgetting the respect due to the creator,

I were to attempt a criticism of creation, I would say "Less matter, more form!"

-Bruno Schulz, *The Street of Crocodiles*

9. DESIGN RESEARCH AND CONSTRUCTION SYSTEM PROPOSAL

The research, information, and analysis presented thus far served to define a set of criteria that would provide a framework for the development of a novel construction system utilizing this palette of bio-based polymer matrix composite materials. These criteria were identified as domains containing design considerations that must be satisfied and balanced against each other. These categories of criteria were defined as:

1. Material properties
2. Manufacturing/fabrication/assembly technologies and methods
3. Environmental concerns
4. Design and engineering tools and methods
5. Regulatory and building codes
6. Cultural factors

With this cataloging of criteria, it becomes possible to develop a design methodology that operates within this abstract framework and results in a proposed construction system. This phase of design research consciously operated in two directions simultaneously.

The first mode of design research was a hands-on investigation of materials and fabrication methods. This “bottom-up” strategy consisted of material experiments to gain a tactile understanding and insight into the behaviors that these materials exhibit. Experiments were conducted both with individual materials as well as in combination, which revealed potential opportunities for fabrication methods. These bottom-up investigations were intentionally executed without reference to, or attempt to satisfy, any other category of criteria. They exclusively focused on materials and fabrication methods.

Conversely, a more “top-down” strategy was also employed. A series of strictly bottom-up investigations, by necessity, focus narrowly on single sub-systems, and while they may reveal potential solutions that satisfy a single criterion these may conflict with the needs of meeting other criteria. For this reason, a strategy of proposing more holistic and integrated solutions was also employed. This strategy allowed the synthesis of knowledge and research from within each category, thus attempting to satisfy all criteria simultaneously. This strategy was also the realm where global decisions were made, such as the rejection of certain design avenues. As an example of these types of decisions, it was determined that manufacturing methods based on unique molds would not be considered.

9.1 Materials and Fabrication Investigations

Several levels of experimentation with materials were undertaken. The first were experiments with a single material, such as 2-part bio-based polyurethane foams. Next were experiments with composite materials, where 2 materials were tested in combination, such as various types of natural reinforcement fibers within bio-based epoxy resin matrices. Lastly were experiments with the combination of all of these constituent elements into sandwich assemblies. This last category began to overlap with, and transition into, experimentation with fabrication methods.

9.1.1 Bio-based Polyurethane Foam

This rigid closed-cell foam is generated by mixing two equal volumes of liquid components. This initiates a chemical reaction that both catalyzes the polyurethane as well as releasing gas bubbles,which result in the foamed consistency. After mixing of the two components there is approximately 20 seconds of working time before rapid foaming action begins. During this foaming phase, the material quickly expands in volume approximately 25-30 times.

Initial experiments were intended to witness the growth behavior during the foaming phase. Mixed liquid foam was placed on a flat plane and its expansion was measured in several directions.(Fig 9.1) Similar experiments were undertaken with the plane being inverted immediately after the foaming reaction began. When free to expand in multiple directions, the foam assumed a lens shaped mass, thickest at its center. When inverted, the aspect ratio was decreased, with the height nearly equaling the width.

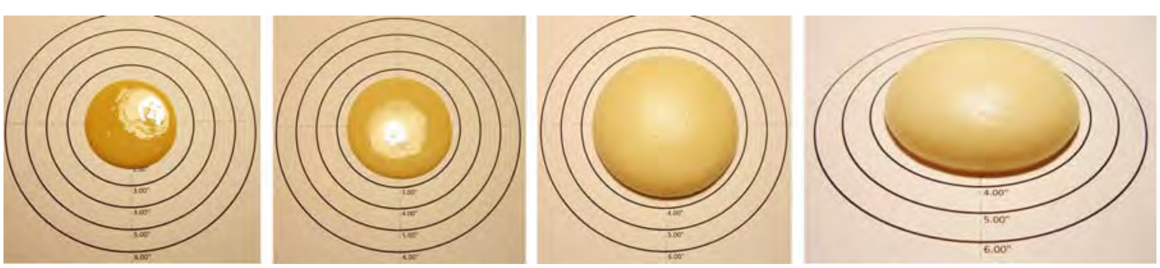


Figure 9.1 Expansion of 2-part polyurethane foam.

Foaming experiments were next undertaken in more constrained areas, with the foam expanding outwards against boundary surfaces. It was found that it would expand in all free directions until hitting an obstructing surface, at which point it would continue to expand in the free directions.(Fig. 9.2) Little to no pressure was observed against the initial surfaces that constrained the expanding foam. Cuts through the cured foam revealed little visible variation in cell density.

Figure 9.2 Expansion of 2-part polyurethane foam.

Final foam experiments occurred within completely enclosed volumes. In this situation, the foam would again expand until hitting boundary surfaces and then continue to expand in any free directions. However, when the cavity was entirely filled, the still expanding foam would exert considerable pressure against the last surfaces that it touched. If too much liquid foam was injected into the closed cavity, it could exert pressure forceful enough to cause considerable distortion of the mold, or even complete destruction. (Figure 9.3) Dissections through the cured foam revealed considerable increases in cell density in the regions that were against these final expansion boundaries. The left images in the figure below illustrate the distortion from excessive pressure, as well as the increased cell density in the regions against those surfaces.

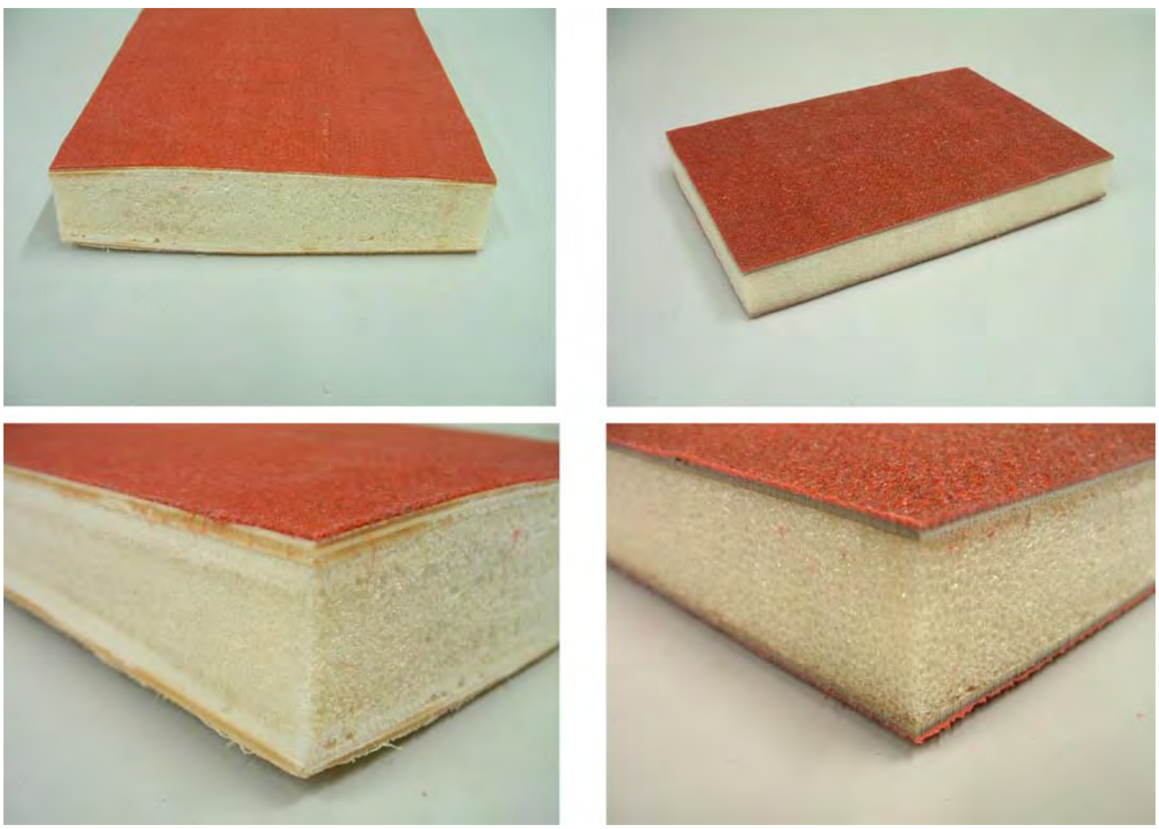


Figure 9.3 Increased foam density from excessive cavity pressure.

Two strategies were developed to mitigate the effects of the foam expanding in a closed cavity. The first was the careful calculation of the required volume of liquid polyurethane that would be required to fill the cavity. As their needed to be exactly the correct amount to fill the void, and the expansion rate is variable with temperature, this was not an entirely reliable method. This is, however, a technique that is commonly employed in industrial manufacturing environments, with a quantity of liquid foam placed in the cavity that is calculated to very slightly overfill the void. The mold is this scenario is required to be of considerable strength to resist deformation under the resulting pressure. This method does result in some local variation of cell density.

The second method that was investigated was the inclusion of holes in the face of the final surface that the expanding foam would reach. These holes served to bleed off the final pressure of the foam, and when used in concert with careful calculation of liquid foam volume, this method successfully prevented excessive pressure against all surfaces. The image in figure 9.4 is of a panel that successfully employed both methods to handle the pressure from the expanding foam.

Figure 9.4 Flat sandwich assembly.

However, two aspects still required careful consideration. The volume of injected liquid required exact calculation, as the bleeder holes would not be sufficient for an excessive quantity of expanding foam. The second consideration was the geometry of the cavity and where the initial charge of liquid foam was placed within it. The bleeder holes were more successful at mitigating pressure when they were placed along a smaller internal face, and the mold was oriented such that the expanding foam traveled in a vertical direction toward these holes. (Fig 9.5) This allowed the expanding foam enough time grow along the larger interior faces of the cavity first, and slightly cure, while the last of the expansion occurred along an interior face with less relative surface area, thus being more inherently stiff.

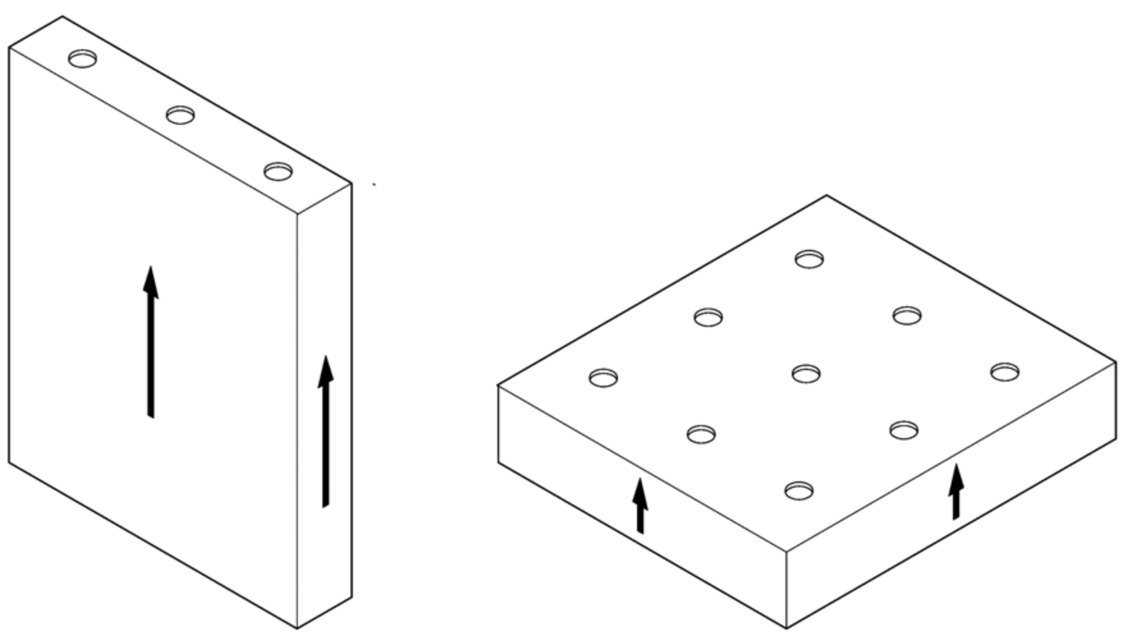


Figure 9.5 Effect of foaming orientation and bleeder hole location.

In addition to experiments with the behavior of expanding polyurethane foam, cured blocks of the material were shaped for use as a sandwich core. (Fig. 9.6) As this is an established practice, it was briefly investigated merely to gain a more direct understanding of the process and its potential opportunities and disadvantages. Blocks of the bio-based polyurethane foam were milled on a 3 axis CNC knee mill to an arbitrary compound-curved surface geometry. Laminated facings of jute reinforced bio-based epoxy resin were later applied to this core, and consolidated in a vacuum bag apparatus.

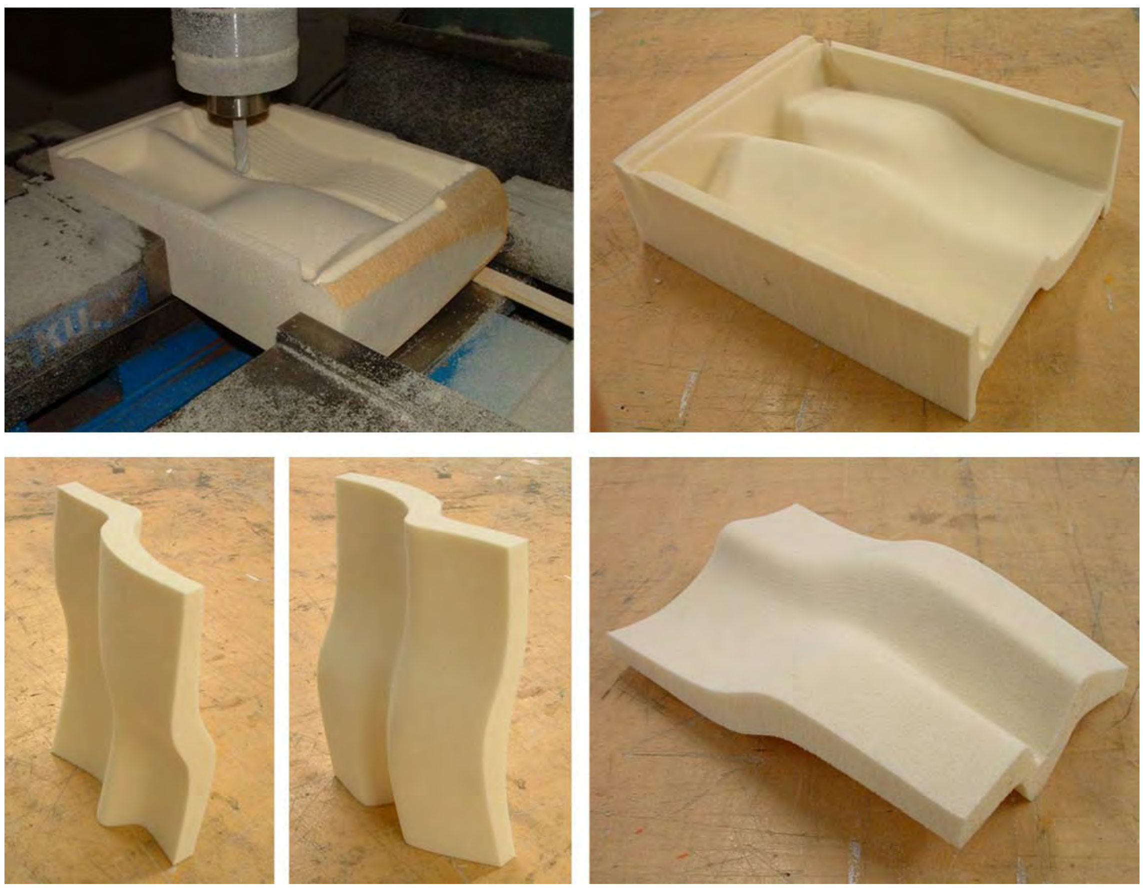


Figure 9.6 Milling of foam sandwich core.

While this method allows for realization of a wide range of complex geometries, as a subtractive process it produces a large quantity of waste. This process is also relatively slow and time consuming.

9.1.2 Natural Fiber Reinforced Composites

Multiple types of natural reinforcement fiber were tested in a matrix of bio-based epoxy resin. The fibers tested were hemp, jute, and abaca, and all were sourced in a plain-weave textile format. (Fig. 9.7) Using a vacuum bag method, the textiles were wet-out with resin and cured against a flat mold surface with a release agent, resulting in a thin flat sheet of laminate. (Fig. 9.8)

Figure 9.7 Hemp, jute 1, jute 2, and abaca fibers.

Figure 9.8 Laminate of jute composite.

The types of fiber exhibited considerable differences in wet-out characteristics, with the hemp fabric proving the most difficult to saturate. However, the weave density of the various fiber textiles was not consistent, thus this behavior can not be conclusively attributed to the fiber properties alone. Other fiber characteristics could also be observed, such as the stiffness and pliability of the textiles. The abaca fibers were the stiffest observed, proving difficult to place flat against the surface of the planar mold, even with the increased weight of resin saturation. The other two fibers were flexible enough to lie flat against this surface from their own weight, although the hemp retained any existing wrinkles in the fabric, even when wet-out. These appeared to be characteristics of the fibers themselves and not dependent on textile weave. The density of the weaves did however result in a considerable variation in the ability of the fabric to shift obliquely. This appeared to be a property largely driven by the tightness of the weave, and is an important consideration for the ability of a textile to drape smoothly over a compound-curved surface.

9.1.3 Fabrication Methods

Multiple fabrication techniques were investigated, with the goal of achieving a process that could flexibly accommodate considerable variation in geometry of sandwich assemblies. The first investigation was of milled foam cores, as previously discussed. The remainder of investigations involved in-situ foaming between pre-existing facings.

As previously shown, flat sandwich assemblies were constructed in this manner. These were typically constructed by completely constraining the facings along their boundary edges with a frame, and injecting liquid foam into the cavity between them. The facings themselves were typically unsupported to more easily witness pressures exerted against them.

Similar experiments were executed with the goal of fabricating sandwich assemblies of compound curved geometries. Digital 3d modeling software was used to generate desired surface geometry, which was sliced into parallel strips. Each of these was replaced with a strip of developable ruled surface that would approximate its geometry. These developable strips were cut from flat sheet material and joined along their edges. When held in a frame with appropriate boundary conditions, the assembled strips would assume a surface condition that closely approximated the original digital model.(Fig. 9.9) Two such surfaces were attached to either side of a boundary frame, and liquid foam injected between. After curing, the frame was removed and an additional facing lamination was added. (Fig. 9.10)

Figure 9.9 3-axis CNC cutting of developable surface strips.

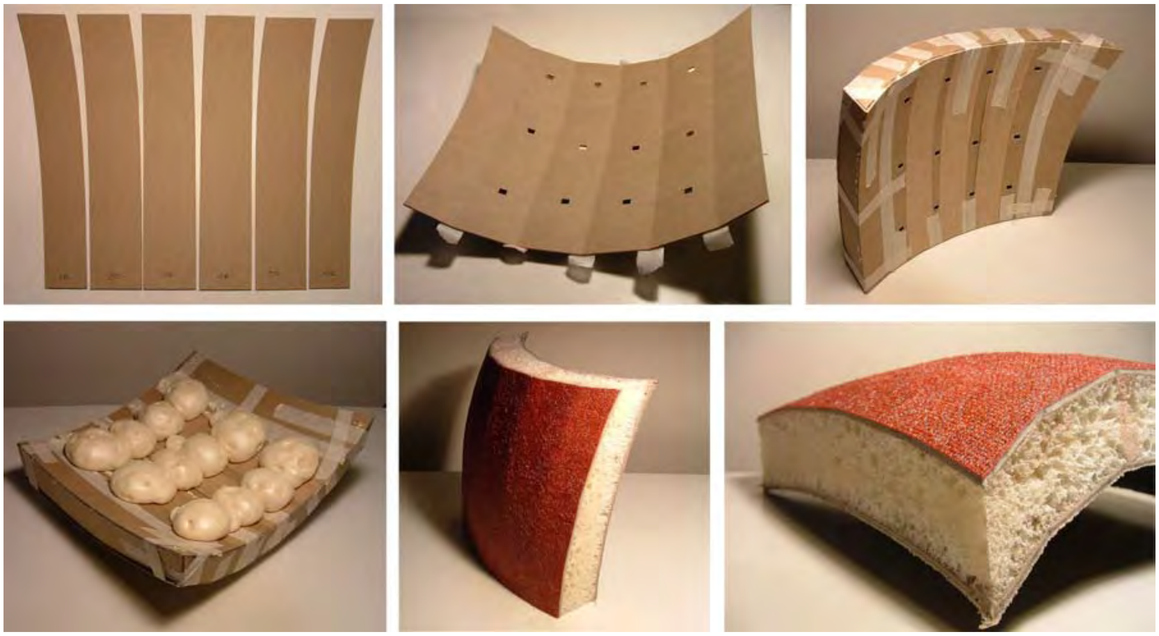


Figure 9.10 Compound curved sandwich assembly.

While generally successful, this method relied on the inextensible nature of the surface skin material, as well as maintaining gap-free joints between each strip. As with the initial experiments with expanding foam in a closed cavity, both the volume of liquid as well as properly placed bleeder holes were crucial for success. The large number of surface joints were vulnerable to the pressure placed against them from the expandable foam. However, with proper foaming technique the fabrication method was successful, with little to no distortion caused by expansion, and allowed fast realization of complex sandwich forms. (Fig 9.11) The use of standard sheet products to generate a cavity for foam placement resulted in a rapid fabrication technique.

Figure 9.11 Compound curved sandwich assembly.

9.2 *Research Synthesis*

The knowledge gained during these bottom-up investigations of materials and fabrication methods was reconsidered vis-à-vis the larger framework of the complete set of stated criteria, and the research that had been executed within each of these areas. This synthesis allowed the convergence of the focused and specific bottom-up investigations with the breadth of the top-down overview, resulting in a narrowing of the design space.

It was such a convergence that resulted in the early rejection of manufacturing methods that relied on unique molds, as it was judged to be inadequate to meet the needs of some criteria categories, such as those requiring a flexibility of architectural form-making. The expense incurred with the tooling cost of molds also has the distinct disadvantage of requiring a large enough production run of identical products to amortize this investment. A manufacturing method that could allow the realization of multiple unique designs from a single tooling investment could thus be advantageous.

The focus on moldless fabrication methods indicated two possible alternative directions; a subtractive process such as the shaping of core material, or an additive process of combining elements of some type. As the shaping of core material generally results in a large quantity of waste material and is time intensive, the latter was chosen as the primary trajectory for this research. Furthermore, the ability to bond bond together multiple and disparate types of components is an intrinsic advantage of working with liquid polymers, and one that is rarely utilized with molds.

Of the case study examples, the SpaceBox was the only one not to use dedicated and unique molds for its realization. Although all of the built examples of the SpaceBox are identical, the manufacturing method of edge-bonding planar components is perhaps the most flexible. With modification to the method of orienting and clamping these components in place during the bonding phase, other building morphologies based on the language of planar faces could easily be realized. Adjustable fixtures could potentially allow a wide range of formal expression within a conceptually simple system.

The experiments in this research with in-situ foaming were also based on such an assembly of components, and utilized flat sheets of facing material. Like the SpaceBox, there existed a method of constraining these components in position during the assembly (foaming) process. This assembly from standardized elements, in addition to being suited to an adjustable manufacturing method, could also lend itself to a rules based system that links design methodologies to a manufacturing process. Such a rules based technique could also have an associative relationship to building code regulations and be managed with computational tools. Such were the origins of the proposed system presented here.

9.3 *Proposed Construction System*

The proposed construction system is based on a common set of governing rules that encompass design and engineering methodologies as well as a manufacturing process and a structural scheme. The conceptual packaging of these multiple domains into a single rules driven framework, with distinct boundaries, is an inherently prescriptive and codified method, which lends itself to ease of compliance with building code requirements.

9.3.1 Manufacturing Principle

The manufacturing process is based on the placement of a series of parallel ribs, cut from flat sheet stock of rigid foam material. (Figs. 9.12, 9.13) These ribs are clamped in their desired spatial locations by use of an adjustable fixture. Against these clamped ribs, strips of thin sheet material can be further clamped, resulting in a cavity that spans between adjacent ribs and can be injected with expandable rigid foam. The result is a monolithic foam core in the configuration of a continuous surface with integral ribs. The outer surface of this assembly will then be fully laminated with composite facing material, resulting in a complete sandwich assembly.

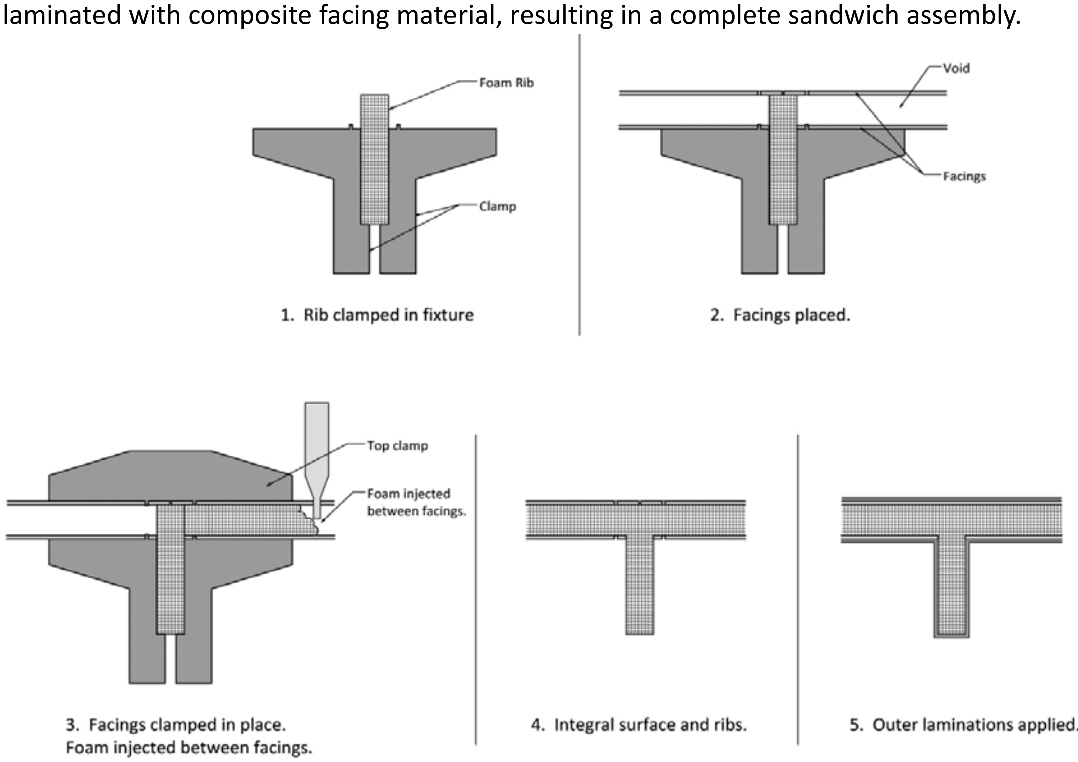


Figure 9.12 Manufacturing process.

The sheet material that is used to form the cavity in step 2 can be cut from a thin laminate of the same natural fiber reinforced composite as the final facing. Thus, as these surfaces become embedded and encapsulated in the overall assembly, they compose the first ply, or series of plies, within the face laminates. The injection of liquid foam either could occur through the face of these surfaces, or via an apparatus traveling through the length of the cavity. A resin infusion method with vacuum bag could be used for the application of the outer lamination.

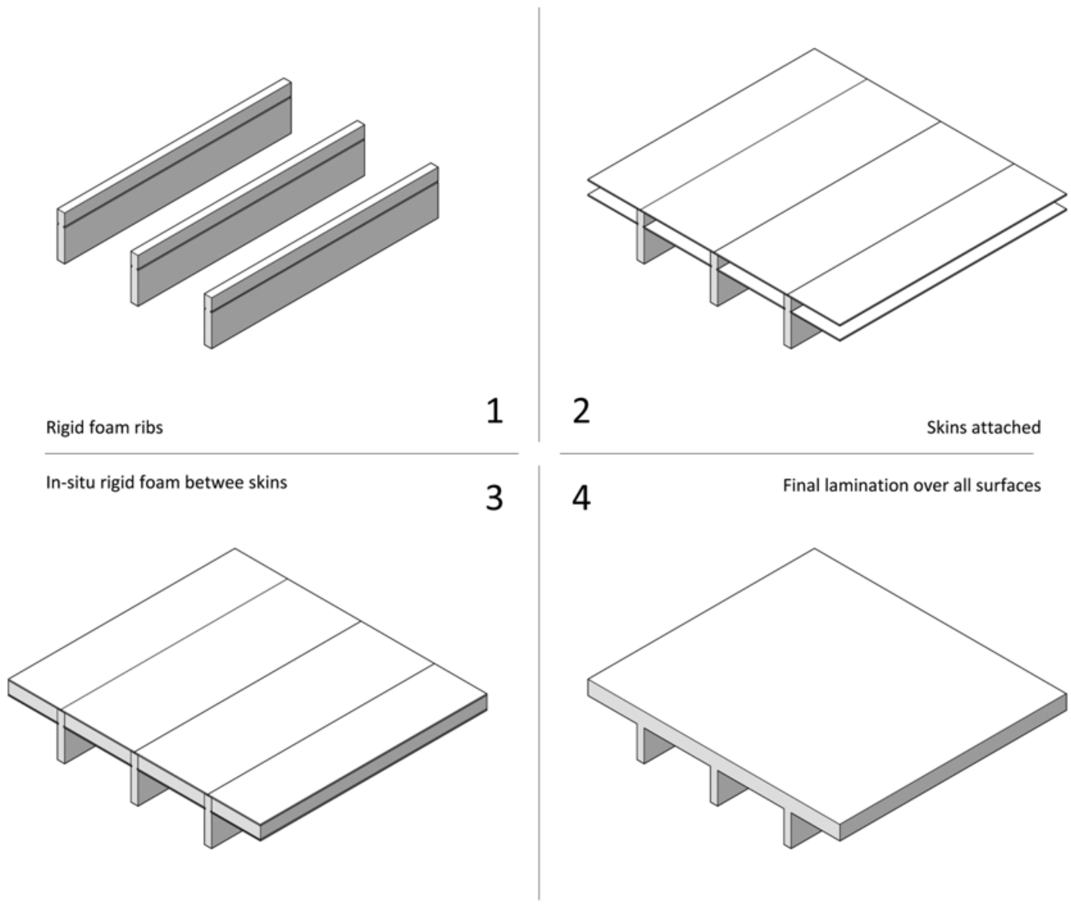
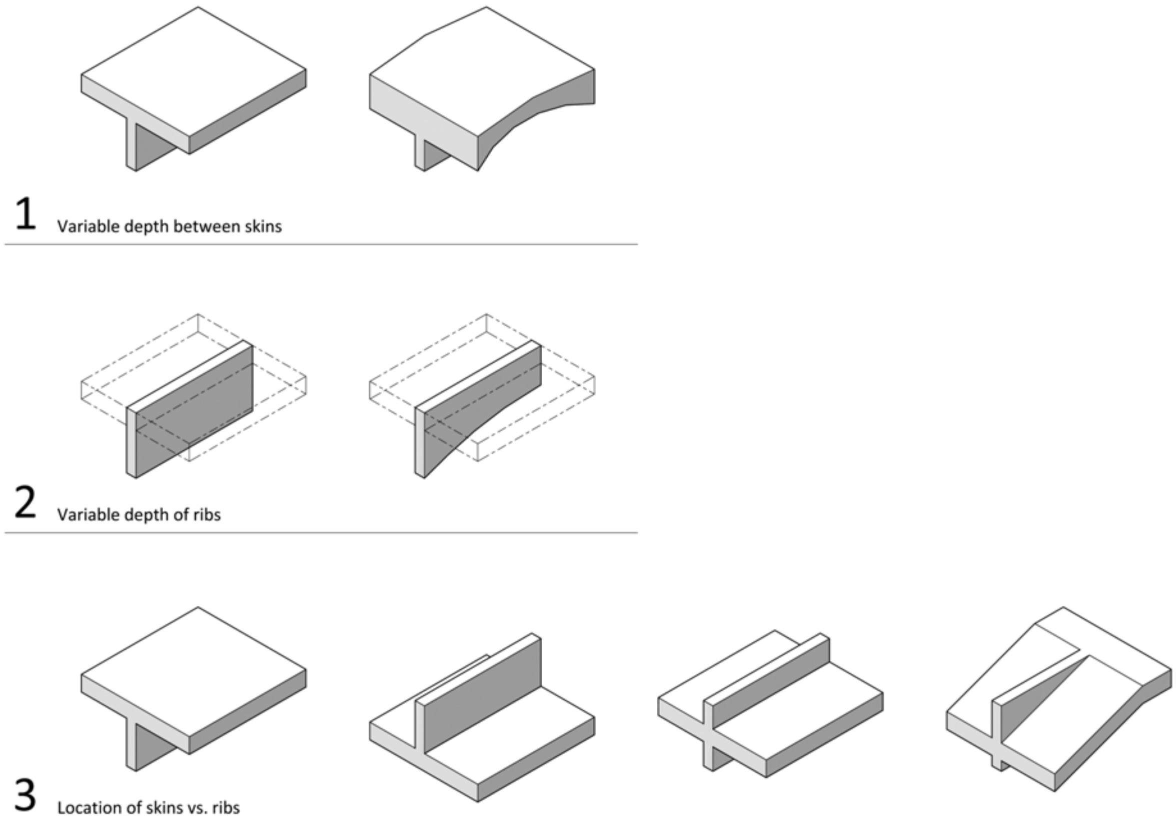


Figure 9.13 Manufacturing process. Fabrication of surface with integral ribs.

The overall morphology of such an assembly can be characterized as a continuous surface with integral parallel ribs.   Such as system could accommodate a range of variation in



the rib to surface relationship, which could be executed through adjustable fixtures. (Fig. 9.14) The distance between skins, the depth of ribs, and the location of the skins relative to the ribs are all variable conditions. Furthermore, these variables do not have to remain globally consistent across all ribs, but rather are conditions which can change locally. This adaptability can work in concert with an assembly's structural needs, and allow for significant flexibility in surface forms and expressions.

Figure 9.14 Variation in skin:rib condition.

As each rib can assume nearly any desired profile along its length, a wide range of surface geometries can be realized. These may range from simple planar surfaces, when identical straight ribs are employed, to expressive shell-like forms from curved ribs. (Fig. 9.15) Like the compound curved sandwich assembly experiments described earlier, these shell-like surfaces would be composed of strips of developable surfaces, which would approximate true geometries of double curvature. The closer the spacing of the ribs, the tighter the curvatures could be, without assuming an excessively faceted condition.

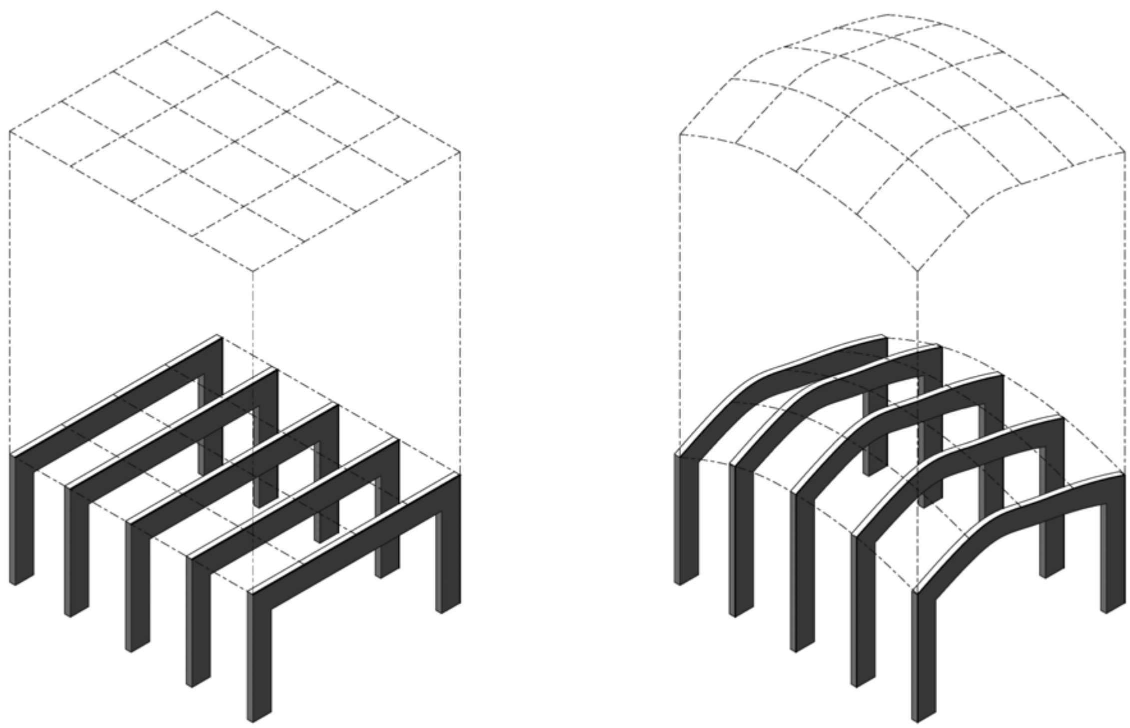


Figure 9.15 Flat vs. compound curvature from same system.

The general method of holding various components in relation to each other while either injecting foam between them to create a core condition, or bonding them together with an encapsulating skin, can also accommodate other potential types of elements. As long as a fixturing method can be devised to hold them in the proper orientation, elements such as transverse ribs, core segments of milled foam, and even pultruded components could be integrated.

9.3.2 Structural Principle

Conceptually, the system is based on a hybrid structural scheme that combines surface structure and one-way spanning frame structure. By allowing a combination of two non-optimal solutions to work in concert, a wide range of surface forms can be accommodated. If the desired surface geometry is such that it acts efficiently as a shell structure, then the integral rib elements can be minimally sized, being just large enough to fulfill their role during the manufacturing process. However, if the surface geometry is structurally inefficient, the rib depth would be increased to become the primary load bearing element, acting as integral beams, with the surface merely spanning transversely between these ribs. If there are local variations in surface geometry, transitioning from flat to compound curved for instance, the rib depth could also vary locally, with increased depth occurring only where needed.

To maintain structural continuity between surface segments, as well as maintain continuous laminate webs between top and bottom "flanges" of the ribs, the laminate would need to pass through the core foam as shown in figure 9.16. One precedent for this type of manufacturing method is the Rabin Center by Moshe Safdie. Reinforcing fibers were placed between the milled foam segments that composed the core of the sandwich assembly, reaching from top to bottom surface. A resin infusion method was used for wet-out of the facing laminates, which simultaneously delivered resin to these fibers oriented normal to the surface. This resulted in a series of embedded internal diaphragms to transmit shear forces between the two outer skins.

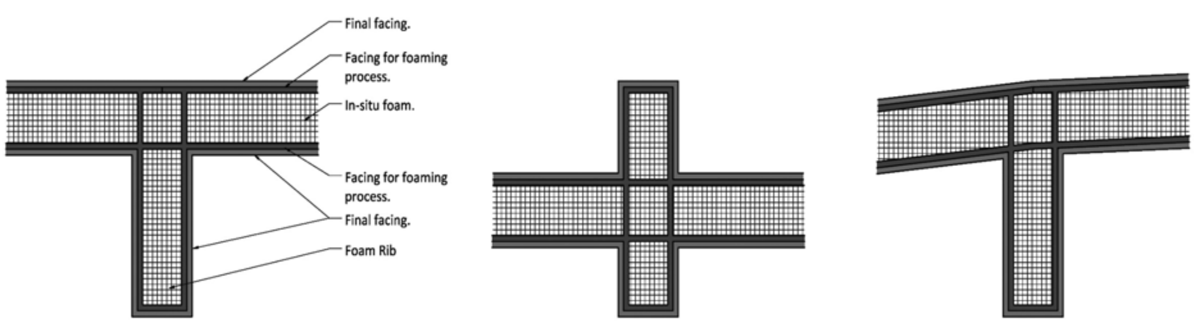


Figure 9.16 Structural continuity of ribs and surface components.

9.3.3 Design and Structural Analysis Methodology

Designing with composite materials in structural sandwich assemblies is an inherently complex task due to the large number of variables, such as number of laminae, reinforcement ply orientation, degree of material consolidation, core material properties, and overall geometry. With this proposed manufacturing process, the wide variation in possible geometry serves to accentuate this problem. Thus, within an overall design and structural analysis method there becomes a need to prioritize these variables, resulting in a hierarchy and series of procedural design steps.

To this end, a design methodology is proposed that prioritizes the surface geometry of the system. The parallel ribs that are the foundational elements in the manufacturing process will thus serve as generating elements within the design methodology as well. The final surface geometry can ultimately be reduced to a series of lines that exist on parallel planes, defining the profile of each rib. (Fig. 9.17) It is the spatial layering of these rib profile lines that result in a continuous and apparently fluid surface.

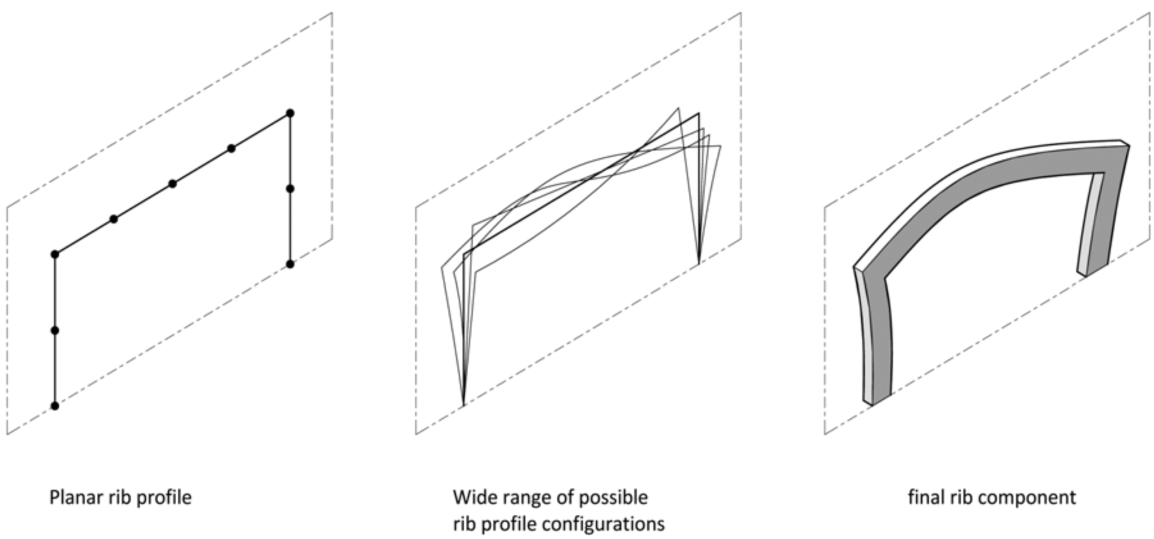


Figure 9.17 Rib profiles.

A specific digital design environment could be created that is based around the generation of surface geometries from such a series of planar profiles. (Fig. 9.18) By having an integral Finite Element Method tool, those prioritized structural factors could then be solved in a step-wise manner. The remaining geometry variables, such as rib depth and surface thickness could be solved first. Integral Classical Laminate Theory tools could then be utilized to determine local laminate thicknesses, ply orientations, core densities, etc. By being based on a fixed set of rules , such an integrated design and structural analysis environment could solve for load cases based on governing building code requirements.

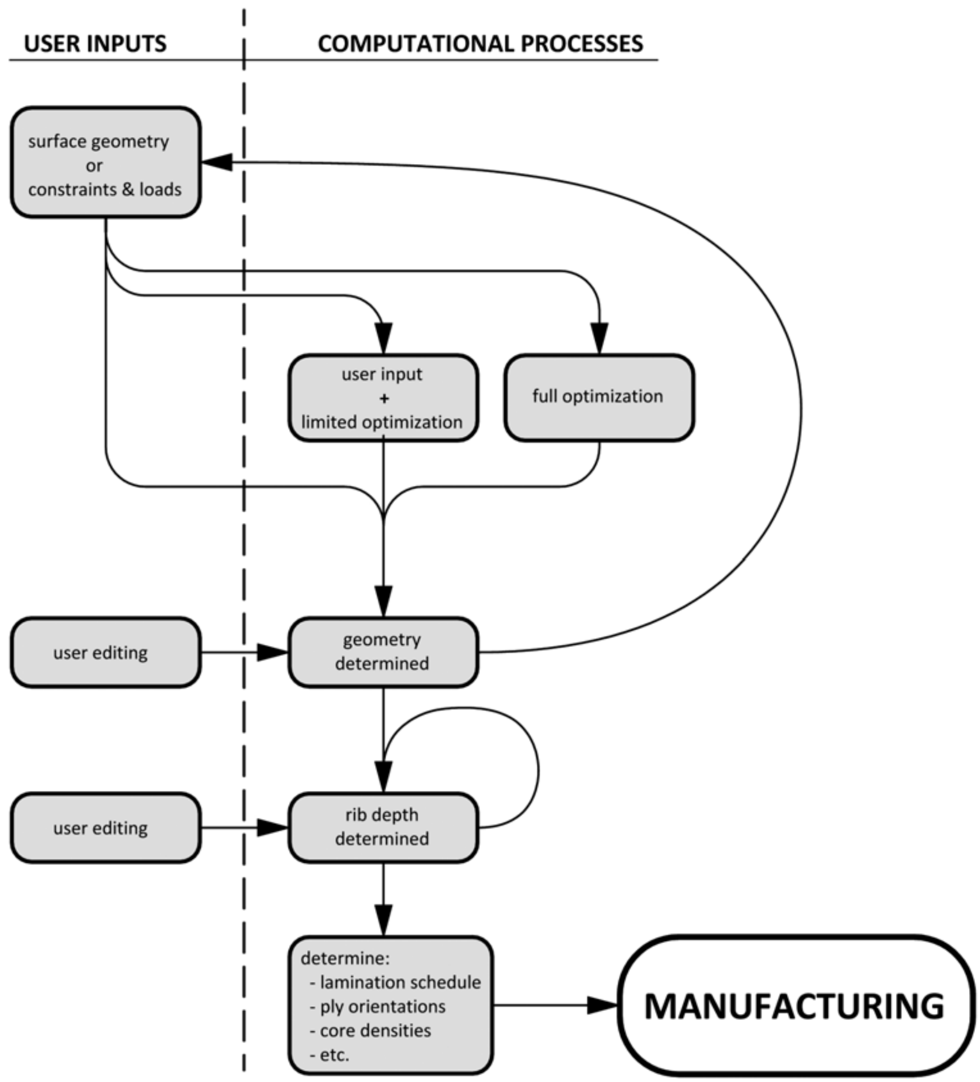


Figure 9.18 Design/Analysis environment flowchart.

The initial process of defining of surface geometry could be handled in several ways. A designer could input the desired form, and then the software would determine the remaining factors as outlined above. This would allow non-optimal forms to be realized. However, methods could also be incorporated to arrive at more optimal surface geometries. Optimization methods could be used either to modify a geometry that was input by a user, or could generate an optimal solution from boundary, constraint, and load case conditions. With the former approach, a range of variation from the original input geometry could be specified. This would result in a geometry with an improved structural performance, yet with minimal deviation from what was originally intended. This could be used to improve performance while minimally modifying important geometrical features as required for needs of program, formal expression, or strategies such as daylighting. The full optimization strategy would result in a geometry of the highest structural performance, yet may not necessarily satisfy other architectural requirements.

By using integral Classical Laminate Theory tools as part of the structural solution, information would automatically be generated for the manufacturing process. This data could be exported for scheduling number of laminate plies, ply orientations, and fiber placement would be integral to the design solution.

9.3.4 Joint Considerations.

Joint design considerations need to be taken into account, and are not yet developed in this current proposal. Several material properties indicate that monolithic assemblies are desirable, however, this would not realistically allow for ease of transport except for the very smallest of structures. Hence, an entire building would need to be produced in segments, requiring decisions and strategies of how and where a design is subdivided.

While geometrical transitions, such as from vertical to horizontal surfaces, could be manufactured as one piece, building components that are entire building cross sections would again be too large. Both of these scenarios require development of joint details and a method of integrating these nodes into the design method.

9.3.5 Environmental Factors

Such an integrated digital design and structural analysis environment could have beneficial environmental impacts by providing feedback to the designer. With a design methodology based on the same underlying geometrical rules as the physical manufacturing process, numerous types of quantifiable data could be presented to the user. Information such as total volume of materials used, energy and carbon footprint of those materials, manufacturing energy required and amount of waste produced could all be graphically presented so that various design options could be compared. Total amount of surface area, core thicknesses, and building orientation information could be used to calculate thermal performance.

9.3.6 Range of Formal Expression

The inherent adaptability of the proposed construction system allows for a wide range of tectonic expression. Figure 9.19 illustrates a collection of models that were 3-axis milled from foam as an exploration of potential variations. Figure 9.20 further illustrates a range of potential formal expressions.

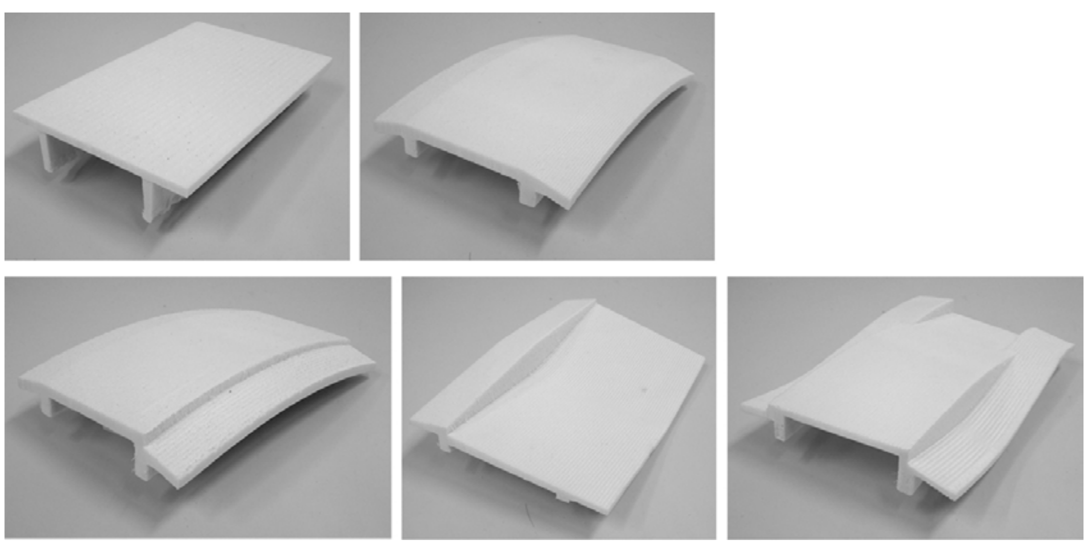


Figure 9.19 Formal variations of construction system.

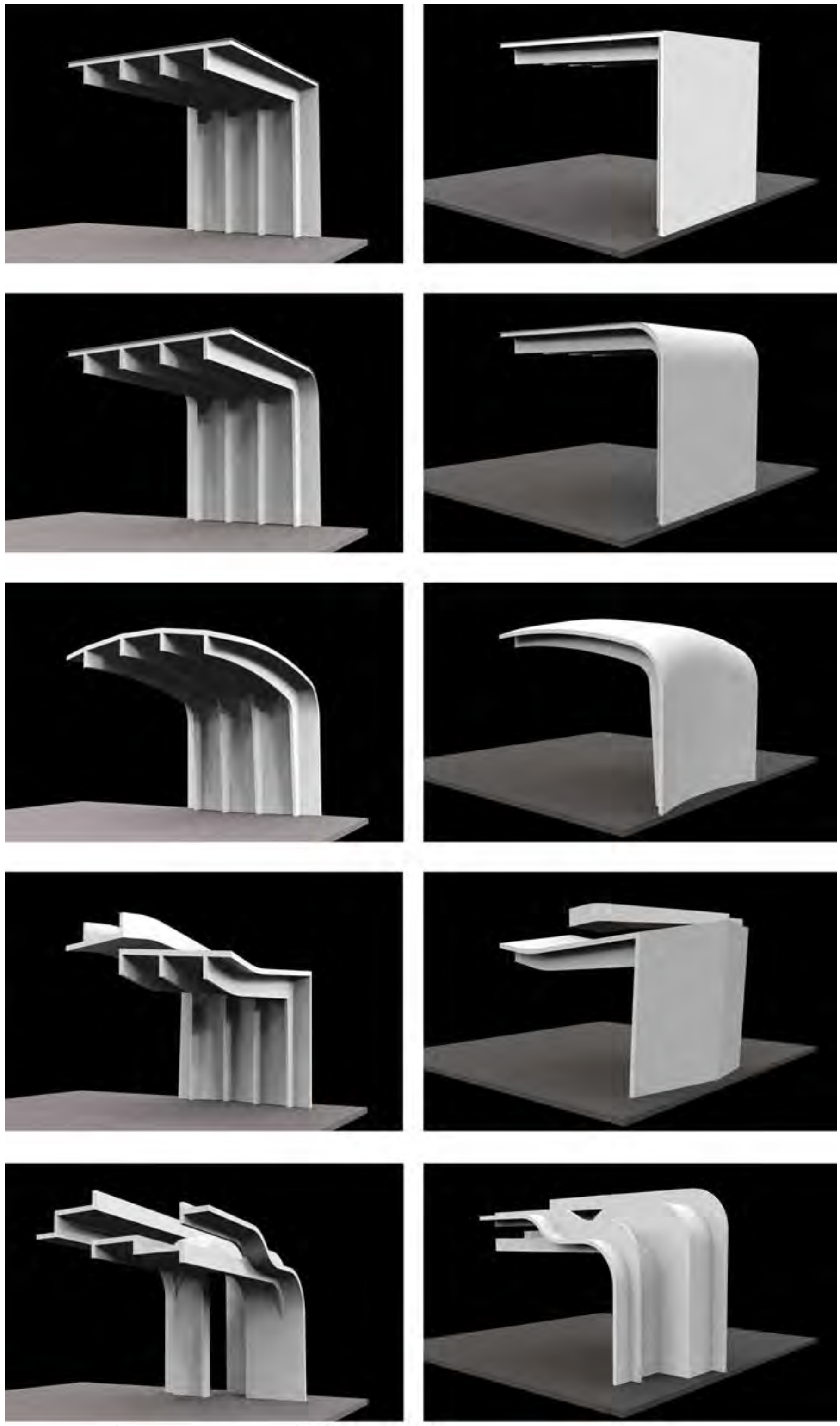


Figure 9.20 Formal variations of construction system.

9.4 Prototype Fabrication

As proof of concept, a half-size prototype was fabricated utilizing the proposed construction system. (Fig. 9.21) Measuring approximately 4' x 4', it was constructed in two segments, to serve as a starting point for future development of joint conditions. The chosen surface geometry is of a non-uniform compound curvature, which is difficult to realize through most conventional construction systems. This geometry was constructed in 3d modeling software, and the digital model was used to generate the cutting information for components such as the rib cores and the sheet materials that act as foaming surfaces.

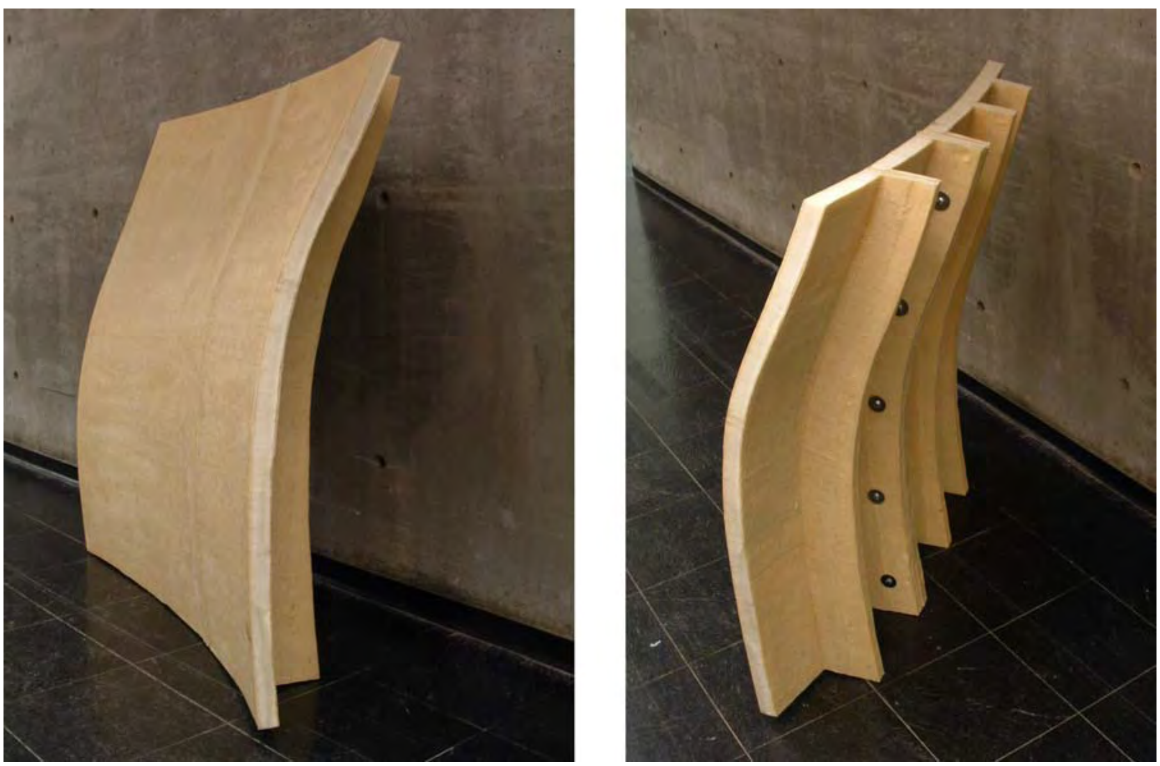


Figure 9.21 Prototype building component.

A plywood fixture was fabricated to orient and hold the components during the sandwich assembly phase. (Fig. 9.22) As it was anticipated that only one prototype design would be constructed, this fixture was not designed to be adjustable. Nor did this fixture accommodate any clamping action, rather it served as a simple cradle into which the individual components were held by a light pressure fit.

Figure 9.22 Foam ribs placed in fixture.

Rib profiles were cut from bio-based rigid foam that was cast into sheets of the required thickness. The ribs were installed in their respective slots in the plywood fixture. The next step consisted of placement of the foaming surfaces. While the intended method is to utilize thin sheets of laminate material, due to time constraints these could not be prepared. In their place, thin sheets with a non-stick release surface were used. (Fig. 9.23) After foaming, these were removed, leaving a monolithic foam core in the configuration of surface with integral ribs. (Fig. 9.24)

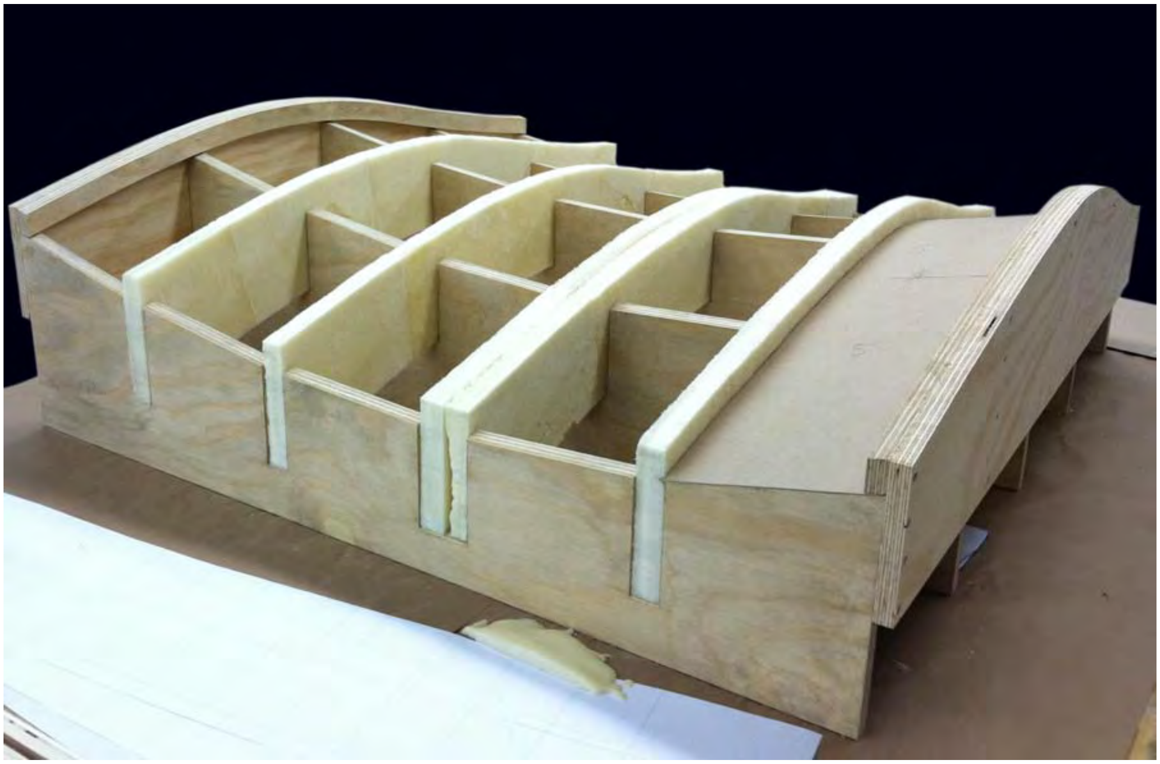


Figure 9.23 Foam ribs placed in fixture.

Figure 9.24 Foam surface.

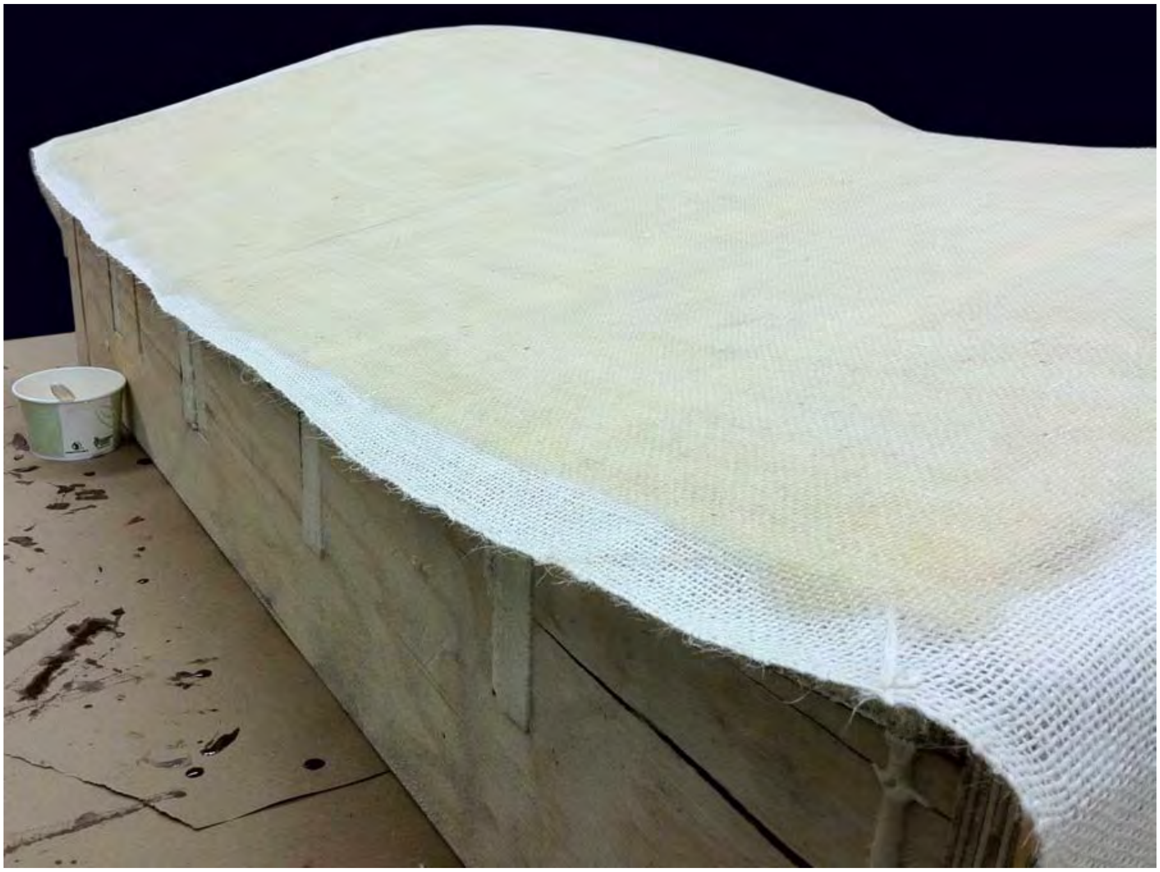


Figure 9.25 Lamination of foam surface.

This raw foam surface was laminated with bio-based epoxy resin, which was reinforced with plain weave jute textile. (Fig. 9.25) The fabric was hand-laid and wet-out, and consolidated and cured in a vacuum bag. (Fig. 9.26)   The front surface was laminated while the two segments were held together in the fixture. The rear ribs and flange areas were laminated and vacuum bagged after removing the assembly from the fixture and splitting the segments apart. A thin sheet material with a non-stick release surface was placed between the mating flanges of the two segments to prevent them from bonding together.

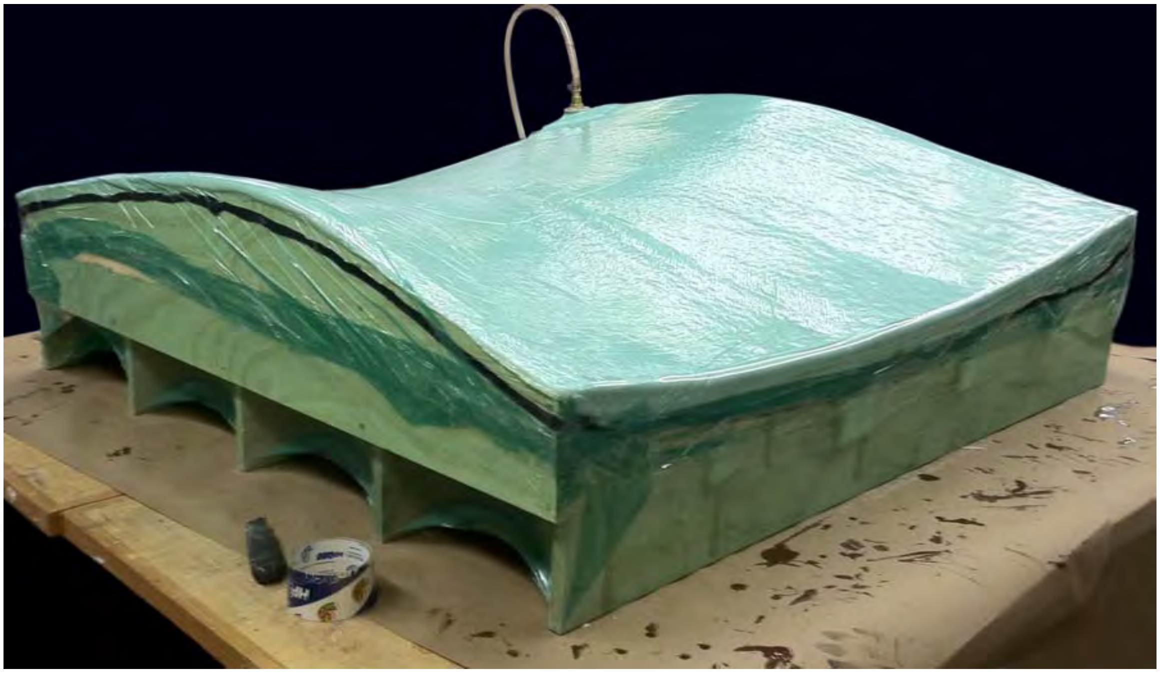


Figure 9.26 Vacuum bag consolidation of front lamination.

Figure 9.27 Vacuum bag consolidation of rear lamination.

After removal from the vacuum bag, holes were drilled in the mating flanges of the two completed prototype segments. A simple bolted connection was employed, with plate washers to distribute the load over a larger area of the flange laminate.

Figure 9.28 Two segments of prototype assembly.

Figure 9.29 Surface of sandwich laminate.

10. CONCLUSION

This research investigates the design methodologies necessary for the development of novel construction systems utilizing bio-based polymer composite materials. A construction system was herein defined as being driven by a codified conceptual framework, whose rules allow consistency and predictability in the domains of design, engineering, and construction. By adhering to such an underlying set of rules, a construction system can operate within the boundaries of accepted practices, yet still allow for a wide range of configurations and architectural expression. In answering the question of how this particular material is best deployed within a method of construction, it was discovered that any proposal must satisfy a wide range of governing criteria in order to potentially be successful. It was also witnessed that prior attempts at developing construction systems utilizing petroleum based plastics typically failed due to satisfying a set of criteria that were too narrow, preventing widespread adoption. Thus, the bulk of this research was executed withe purpose of illuminating and making visible these criteria, which could then serve as a guide in developing a viable construction system.

These governing criteria were parsed out of the entire field of information and considerations that are relevant to this particular material at this particular point in time. The process employed was one of current literature review, case studies of prior art, and direct physical experimentation with the material and methods of fabrication. It was discovered that the criteria that are necessary for consideration extend beyond the immediately obvious categories such as the engineering and technical requirements of materials, manufacturing processes, and governing building codes. They also encompass domains that are either difficult to comprehensively analyze, such as environmental issues, or those that are less tangible and quantifiable, such as the current cultural context and design methodologies and workflows.

With such a framework of governing criteria in place, a construction system was developed. This development intentionally encompassed two modes of investigation, a “bottom-up” experimentation that focused strictly on materials and methods of fabrication, and a “top-down” search for a solution that would holistically satisfy all criteria simultaneously. The former served to provide unique insights and suggest possibilities of how to deploy such a material, while the latter provided a means of synthesizing this knowledge with that which pertains to the full range of criteria.

The proposed construction system can be characterized as a hybrid between a surface structure and a one-way spanning structure, that provides a flexible platform for a wide range of realizable forms and architectural expression. The integration of beam-like rib elements into a structural surface is also foundational to the proposed corresponding manufacturing process and the methodologies of design and engineering analysis. Each of these domains is organized around the same organizing set of design rules, which thus allow design and analysis to be embedded within a digital environment that relies on computational tools. Therefore, this research proposes that a novel construction system can incorporate a proprietary computational and design environment as an integral and inseparable component. This digital environment can also allow for an integration of quantifiable building code compliance requirements into the design process.

This research concludes that by identifying and adhering to a comprehensive set of governing criteria, a novel, and viable, construction system utilizing bio-based polymer composites can be successfully developed. To this end, a system is here proposed as an example of how such criteria might be revealed and satisfied. This occurs through a formal configuration of the material that corresponds to a common rules-based organizational strategy that encompasses all domains, from design, to manufacture, and building code compliance.

10.1 Future Research

Recommendations for future work fall into three general categories:

Firstly, better inventorying of environmental impacts of this class of materials, such as embodied energy and carbon footprint. Current data is typically contradictory or incomplete, and does not analyze these materials with consideration of the environmental boundary conditions that are unique to building components, such as repair, replacement, and contribution to energy performance of the building during its lifetime.

Secondly, a continuing investigation of a wider range of bio-based polymer materials as their chemistries are improved through further materials science research. Materials that are currently under development, such as reinforcing fibers drawn from bio-based polymers, and alternative matrix materials, may have advantages over the materials used in this study.

Lastly, further development and refinement of the proposed construction system. While conceptually sound, many details still require design resolution, such as methods of maintaining structural continuity at rib to surface interfaces, strategies of subdividing global geometries into segments, joint conditions between such segments, and the potential integration of other types of elements such as pultruded sections or local areas of milled foam core. Most important, however, is the further development of a design environment, as it is here that all of the guiding criteria and subsystems are linked together in an integrated manner, providing the point of contact with the user of such a construction system.

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