Digital Material Skins: For Reversible Reusable Pressure Vessels

by
Sarah Hovsepian

B.S. Architecture
California Polytechnic University of Pomona, 2010

SUBMITTED TO THE DEPARTMENT OF ARCHITECTURE IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTERS OF SCIENCE IN ARCHITECTURE STUDIES

AT THE

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2012

Signature of Author:_
Department of Architecture, Design & Computation
May 18, 2012

Certified by:____
Terry Knight, Professor of Design & Computation

Certified by:___ _________________________
Neil Gershenfeld, Professor of Media Arts & Sciences

Certified by:__ _________________________
Takehiko Nagakura, Chair of the Department Committee on Graduate Students

Terry Knight
Professor of Design & Computation
Thesis Supervisor

Neil Gershenfeld
Professor of Media Arts & Sciences
Thesis Supervisor

Jeffrey Hoffman
Professor of Aeronautics & Astronautics
Thesis Reader

Digital Material Skins: For Reversible Reusable Pressure Vessels

by

Sarah Hovsepian

SUBMITTED TO THE DEPARTMENT OF ARCHITECTURE ON MAY 18, 2012
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTERS OF SCIENCE IN ARCHITECTURE STUDIES

ABSTRACT

Spacecraft missions have traditionally sacrificed fully functional hardware and entire vehicles to achieve mission objectives.Propellant tanks are typically jettisoned at different stages in a spacecraft mission and left to burn in the atmosphere after one use, creating a substantial amount of waste and redundancy which leads to high operational costs.Spaceflight programs cannot continue to rely on current methods of discarding hardware, since the cost to transport materials from Earth is extremely high. Significant improvements need to be made in recovery and reuse of valuable hardware, to be able to lower costs per mission and increase the number of missions. Strategies need to focus on avoiding complete loss of hardware. This thesis proposes a new class of materials called digital material skins, that will revolutionize the fabrication and assembly of everyday functional objects to spacecraft structural applications, by embedding the intelligence not in the fabrication tools but in the materials themselves, to create reusable and recyclable materials.A workflow for digital material skins is also demonstrated, based on existing fabrication tools to rethink the entire lifecycle of functional skins from design to fabrication to disassembly.When a child builds a structure out of legos, precision lies not in the human assembler but in the material, component geometry,and linking mechanism to dictate how and where each material interlocks within the larger material system.

A digital material skin is made of discrete units with a finite set of parts and joints used to construct a functional structural skin for airtight,waterproof, high or low pressure applications.The surface is enclosed or the surface is open. Digital material skins are used to construct any shape or interior volume that is regular or amorphous. A digital material skin is an exterior structure which relies on an interior digital material structure for support, or a digital material skin is self-supported with few or no interior support.Parts and links are arranged and configured in a regular pattern to create a surface larger than the units themselves. The skin is part of a larger assembly or part of a single unitary structure of any size or shape. The skin may have a thickness that is smaller or larger than any dimension. The skin is made of one or more layers of one material or multi-material units.The joints are reversible, allowing transfer of forces from one unit to adjacent units to create a continuous bulk material. The work will develop a prototype of a digital material skin concept for pressure vessel skins, and adumbrate a new design methodology that considers the entire lifecycle of digital material skins.

Thesis Supervisor:Terry Knight
Title: Professor of Design & Computation

Thesis Supervisor:Neil Gershenfeld
Title:Professor of Media Arts & Sciences

Acknowledgements

First, I thank God for the wonderful gift of life He's given me for without it I would cease to exist and cease to have a purpose in life.

I thank Mom, for encouragement, support, and love. For teaching me the impossible is possible, and for always believing I could do it. I dedicate this thesis to you.

I thank Terry Knight, a truly amazing advisor who was ready to listen and help every step of the way.

I thank Neil Gershenfeld, for accepting me into the Center for Bits and Atoms family, a true Renaissance man, walking encyclopedia, fab guru.

I thank Jeffrey Hoffman for introducing me to the world of outerspace(not literally but maybe one day), and it is truly a marvel to know somebody who has been to the ISS.

I thank Alex Slocum, for the greatest conversations about high heels and fashion.

I thank John Vickers & NASA's Office of the Chief Technologist for my fellowship.

I thank the entire crew at CBA, Nadya, Prashant, Kenny, Matt, Ara, Amy, Joe, Patty, Sherry, John D, and Tom L.

Authors Note

A refined comprehensive understanding rather than a narrow specialization of reality is continuously needed to reorient, and to carefully examine our own experiences in order to intuitively grasp the fundamental behaviors and relationships. Unbeknownst is the larger picture but man is able to first experience and then comprehend phenomena through repeated encounters with reality, only able to grasp but a mere pinhead of information, a split second out of the entire day else the information is lost at the signal and left to interpret and rediscover by another. The physical world is entropic but mind anti- entropic, or is it the other way around? And it is only through engaging ones metaphysical capabilities, that we each pave way to our discovering new experiences or refine contradictory pre-catalogued experiences which previously were held to be true. The information, specialized and tagged within esoteric taxonomies, levels, classes, kinds, types, lists, orders, the art of classification, inhibits further inquisition, discovery deferred and the book closed, simplicity to explain complexity. An onerous task to comprehend and reconsider, not an overconcentration on a flashing moment, or a specific chapter in our body of knowledge, but a good thorough survey of previously accepted notions and even more so, daring to challenge popular belief. It is by free will, and choice, that man has been given or endowed with these capabilities, which makes it of the highest order of all living things, to program and reprogram. Each one of us has his/her own paradigm, which is affected by an aggregation of a lifetime of unique experiences, interactions and relationships. The paradigms portray reality as we each see it, not as it really is, never objectively but always with a degree of subjective perception. For a more objective description of reality, we must continuously examine and take responsibility of our own paradigms, examine what and whom they are based upon and continuously test them against reality. We want to make sure we have the correct map, or at least that we are aware of the map or the model of the world we have created for ourselves, a foundation, a set of principles we want to think and live and create by in order to expand upon and continue the creation, addition, subtraction of our map, of an unsettled reality.

In what follows, I present to you a piece of my own.

Table of Contents

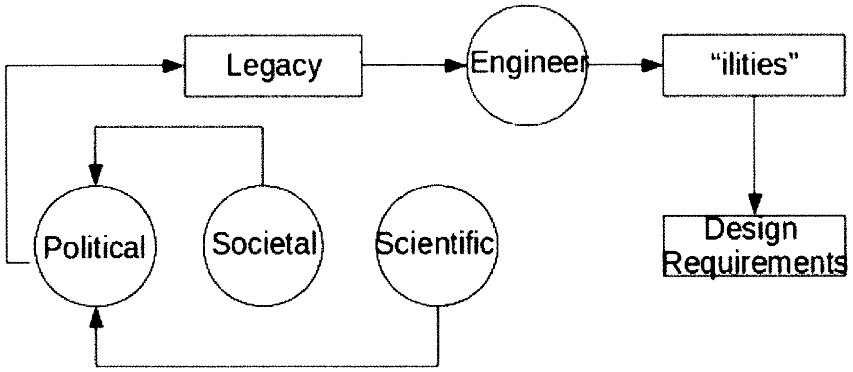
1 Introduction

This section introduces the larger problem, and adumbrates the expected outcome and application of a digital material skin.

1.1 Scenario: Spacecraft Mission Profile

Remaining on the lunar surface longer, is synonymous with creating sustainable, recyclable, reusable, and reversible capabilities. Every system, whether engineered or natural, acts as a whole and it is not until these interactions are well understood, will humans be able to create manageable systems with predictable outcomes. This very notion of the interaction of the whole unpredictable from its' parts is called synergism. Any human space flight mission, such as Apollo, establishes the most important and inherent synergism between scientists and engineers. Science seeks to answer the 'why' questions, and what our motivations are for any particular mission at the highest level. Engineers answer the 'how' questions, and the method to go about creating and providing a technology to enable scientific exploration and discovery.

At the height of the Apollo mission, 400,000 people worked on this highly technical project, to be able to deliver a valuable tool that would allow humans to explore or to search systematically for that which has not been found and to discover or to obtain for the first time sight of the Moon and Earth from outer space. Apollo's legacy is permanent: man's first step on the Moon. There have been a plethora of programs at NASA since the Apollo, to further lunar or other space destination exploration, such as the Constellation Program established in 2005. NASA proposed working on two spacecraft, two launch vehicles and finally surface support systems to establish a lunar outpost. Altair's first landing on the moon was scheduled for 2020, but the program was cancelled altogether in 2010.Constellation's and other Spaceflight Programs Legacy: It never happened.



Government, society, scientists, engineers will all have a different view of what the legacy of a mission will be.

Figure 1.1 Factors that affect the legacy of a mission from the highest level down to design and operation

Any spacecraft lifecycle begins with a legacy or mission statement, which is then translated into a set of “ilities” as illustrated in figure 1.1, to be evaluated according to some criteria. Next, a trade analysis of many architecture’s occurs until a concept is synthesized, refined, assessed and finally selected. Preliminary design follows concept selection, with in depth detail design of all subsystems. It is not until manufacturing, where material and manufacturing engineers begin the process of material search, selection, manufacturing, assembly, verification and finally operation. Most spaceflight lifecycles are considered in this phase, and reusability has been an after thought either omitted from a project or not pursued in rigor because of schedule, cost, and risk. In addition to eliminating reusability from the lifecycle, high development and operational costs have had a history of necessitating the retirement of spaceflight programs. All spaceflight programs established thus far sacrifice fully functional hardware in order to achieve mission objectives.

The Constellation Program for example, consisted of roughly 16 different stages depicted in figure 1.2, starting with pre-launch operations and ending with completed disposal of Altair. Each mission would have resulted in the abandonment of the lunar lander descent module, complete destruction of the ascent module and the majority of the Orion Vehicle used to return the human crew back to Earth.If humans are to incorporate sustainable building solutions, then the spacecraft lifecycle should not be a byproduct of the legacy, but rather the legacy itself and what it comes to be known for. This will affect the architectures employed at the highest level, because instead of discarding a vehicle in LLO for example, the vehicle can be designed for reusability for another application at another stage of the mission, thereby changing the overall architecture entirely and simultaneously expanding mission capabilities.

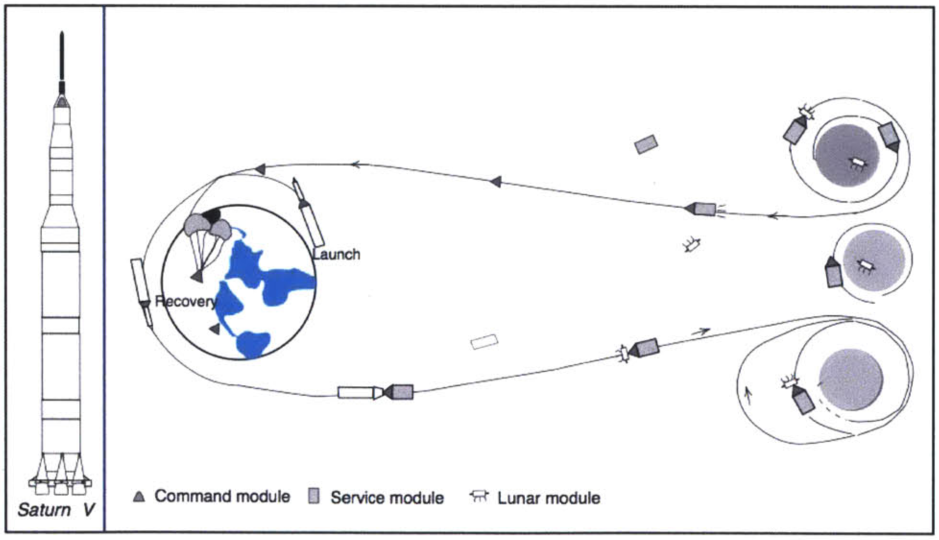


Figure 1.2 Altair mission profile 16 different stages

The difference with the proposed Digital Material Skin Lifecycle for a spacecraft pressure vessel skins vs. past and current models has to do with material selection. Instead of selecting a material, engineers will design a new material based on geometry, scale, attachment, properties, and arrangement of discrete multimaterial units within a larger structure. Future building, aircraft, and spacecraft skins will not be fabricated as large unitized structures, but as thousands of small standardized parts, and assembled in a factory as easily and quickly as lego pieces are snap-fit together, contributing to lowered fabrication and assembly costs, new multi-material combinations with specific properties for high strength to weight ratios, greater payload mass, improved performance, lower risks, fuel savings and recyclability and reuse of materials at the end of the product lifecycle.

1.3 Solution: Digital Material Infrastructure

This thesis presents digital material skins as the future materials for industries creating reusable, recyclable and reversible materials and methods for structural skins. Digital material skins will transform industries and the future of fabrication, to rethink our current material choices and methods for fabricating materials selected. It proposes not only a new way to think about our functional structures, but a new way to manufacture and assemble a skin.Many relevant applications of skins are seen in the following industries: aerospace such as aircraft wing skins, boilers and pressure vessels such as storage and processing of liquid in water tanks, space and spacecraft fuel tanks, high pressure tanks for power storage, manufacturing such as everyday household items, transportation such as automobile structural frames and skins, building and construction such as building facades, and countless other industries and applications all relying on creating three dimensional objects as distinct enclosures.A pressure vessel is the object of inquiry because they are some of the most ubiquitous applications across societies for hundreds of years. Pressure vessels can be generalized towards any application that requires an airtight and waterproof skin, and represents the most challenging of applications. Vessels are also typically jettisoned in the atmosphere for every space mission profile. If we can think about how to reuse and recycle the material units like we can with legos, then we don't end up discarding the material, but disassembling the system and rebuilding another one. Section 5 illustrates prior work completed by the author on digital material solids, and section 6 the work developed for digital material skins. The objective is twofold: to present a digital material skin design methodology and to produce a digital material skin prototype for a pressure vessel skin.

2 Materials

This section introduces the difference between current analog materials used in digital fabrication and future applications for the use of digital materials as the material and process to revolutionize the way we build and design from everyday functional objects to highly technical aerospace applications.

Materials are ubiquitous and we have a plethora of material choices when it comes to selecting the best material for the application. All materials and all matter are made up of atoms that are held together by atomic forces between it and adjacent atoms in the material. What results from these atomic forces are inter-atomic bonds, and depending on the material considered, the bond strength varies accordingly. From Newton's third law of motion, we know that every action has a reaction that is equal and opposite in nature. When a force is applied to some solid material, then the solid deflects enough to be able to counter the force applied. Not only can the atoms in a material change position, but the interatomic bonds will also experience some movement. It is this property we are interested in, and depending on bond strength, we can predict how a material might behave under various design parameters. Material bonds are even more complex than the analogy of tiny atomic spheres connected with springs. Some materials can fail before these atomic bonds have been broken. Most failure modes though, are introduced when the material is being produced in bulk during the fabrication and assembly stage.*Let us consider several relevant material categories before introducing digital materials.*

2.1 Analog Materials

At the highest level, all materials are inherently analog, considering two or more atoms are connected irreversibly in the system.The term analog refers to information or physical matter that is represented as a continuous quantity. Digital refers to information or physical matter that is represented as discrete quantities or values, depending on the user-defined representation of the system. The term 'digital' in digital fabrication is not to be confused with this definition. Digital fabrication refers to the use of tools and manufacturing processes which allow us to take parts as initial CAD representations, and to create prototypes which are closer to the final product by using analog materials. Analog materials can refer to thermoplastics deposited continuously or to a solid block of wax; anything continuous to create a bulk material with special properties.All additive manufacturing processes use materials to create 2D, 2.5D and 3D models that are analog in nature.

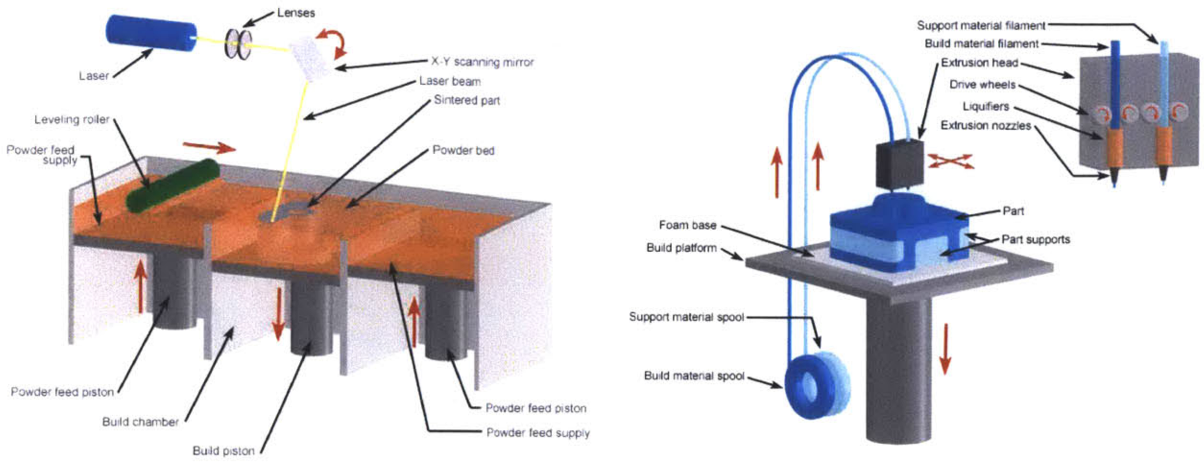


Figure 2.1(Image Left): Selective Laser Sintering Process, (Image Right): Fused Deposition Modeling Process, www.custompart.net.com

Selective laser sintering(SLS) uses high power lasers to fuse powders such as glass, metal or thermoplastics, creating forms that are irreversible. The powders are not analog but are initially formless particles discrete and separate.Upon fusing a particle to another, we suddenly have a new analog material that is continuous and attached to adjacent particles to form the larger object. Another additive method which creates a final analog material, is fused deposition modeling(FDM). FDM takes a coil of thermoplastic or metal wire and deposits material from an extruder by heating and melting the material. Stereolithography(SLA) is similar to SLS but instead of using powder, uses a vat of liquid with a high power laser to create the part in cured layers[Bourell 2009]. Electron beam melting(EBM) for example is another additive process prevalent in the aerospace industry, which uses an electron beam to melt metals such as titanium in powder form. Similar to previous processes, each part is built one layer at a time, solidified and a subsequent layer is built. Current additive manufacturing technologies may utilize the same materials used in manufacturing processes, but the final products rarely behave per materia specification, always depend on the machine for surface resolution, and any error in the part generates wasted material.

Subtractive manufacturing processes take solid blocks or sheets of material and machine out material by drilling or milling from the existing material to create the final part. The initial material is analog in nature, but often these discrete parts are combined within larger assemblies using irreversible joining and bonding methods which again, render the assemblies irreversible, with surface resolution depending on the machine tools used, and any error in the part means waste of the entire assembly of materials. For any given additive or subtractive process, representation of the initial model and translation from initial design to final product requires greater integration than the tools currently offer. Digital fabrication is currently only great at rapid prototyping and not for creating reliable, robust functional structural components yet. *Can we combine analog materials to create stronger and lighter materials for structural applications?*

2.2 Composite Materials

Composite materials describe any two materials which are combined together in a single bulk material to obtain the best properties from both materials. Many industries are shifting towards the use of more composite materials because they display the single most significant consideration for any application: low weight. The material properties of composites are unlike any material thus far, because it combines the properties of a high modulus and high tensile strength fiber for flexibility and strength, with a low modulus stiff matrix which transfers forces from one fiber to the next, creating essentially a continuous analog bulk material.

Composites are still problematic as the material of choice hindering widespread use for many reasons. First, composites vary in fibers, resins, and weaves from one manufacturer to the next, with strength and weight dependent on layup and direction of weave. Second, composites require an energy intensive process. Highly skilled technicians are never really able to have complete control over the application of pressure and heat to allow for proper curing and even distribution of heat over the entire surface[Dorworth 2010]. Third, any flaw detected in a composite skin renders the entire material a complete waste, or makes repair difficult since creating the exact conditions to maintain bond strength is close to impossible to reinact. Fourth, not only is the composite surface designed, but the tooling and moulding for the composite is just as intensive as the final part. In the process of mitigating stress concentration, composite skins are ultimately labor intensive, time intensive, and expensive *What about nature, are there examples of seamless integration of material and structure, such that the properties of the final form are both strong and light?*

2.3 Cellular Materials

Nature displays the ultimate integration of material and structure, with the properties we seek embedded at the very microstructure of matter. How is information about material and structure embedded at the material level, and infinitely reproducible?

DNA and proteins, illustrate how discrete and aligned building blocks create infinitely larger continuous structures. The human cell contains a nucleus, and inside every nucleus are 46 chromosomes arranged in identical pairs. The chromosomes contain tightly packed coils attached to a scaffolding system. The coils are made up of two strands which twist around one another connected by tiny bars or base pairs, A,T, G, C. These base pairs are spaced evenly along the scaffold. Each strand base pair corresponds to the other side and these four letters are called codons, a four letter code in the DNA. The codons form genes, with an average gene containing up to 30,000 letters. Genes are arranged as chapters in a novel in the individual chromosomes. The genome, or the genetic information of any biological organism can be described completely in 23 chromosomes.

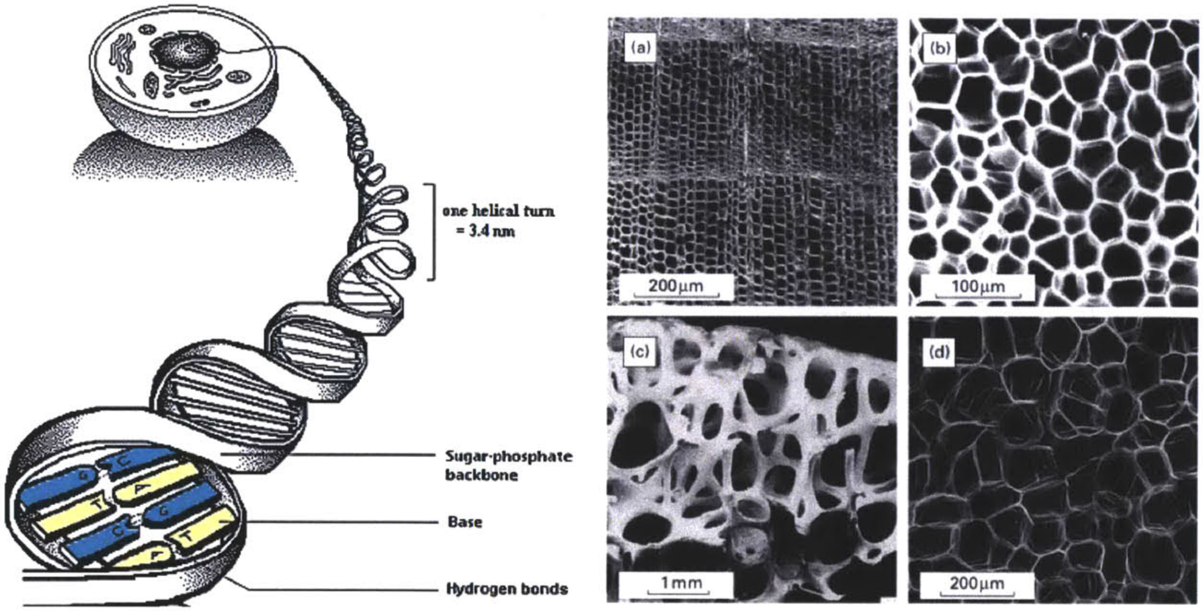


Figure 2.3 (Image Left): DNA Scaffolding with base pairs (Image Right): Cellular materials (a) cedar (b) cork (c) trabecular bone (d) carrot parenchyma (Image from Cellular Materials in Nature and Medicine by Lorna J. Gibson, Michael F. Ashby, Brendan A. Harley, page 5.

The genome is a 'very clever book, because in the right conditions, it can both photocopy itself and read itself"[Ridley 2000]. How is this information then used? Enzymes function as molecular machines, moving around to attach to strands of DNA, copying the same genetic information, replicating and producing new copies of strands simultaneously. Code lies in the material, and by accessing this code, the machines can copy and reproduce the same genetic material forever. The instructions in the DNA are discrete, illustrating the very digital nature of the human genome and what makes you and I look the way we do.

Like the material in the human cell, one step above are the cellular materials which make-up the structure and scaffolding that give organisms their shape[Gibson 2010]. Cellular materials refers to the material structure of any living or nonliving matter, typically described as anisotropic and unidirectional or isotropic and having the same properties in all directions. Cellular materials can fill space in two-dimensions as extruded honeycomb or prismatic cells or three-dimensions as space filling polyhedra in various lattice formations.Cellular materials have been mimicked in engineered foam core structures used in construction, aerospace and medical industries. These man made materials can be designed as highly porous scaffolds or fully dense structures which can be mechanically tuneable for a specific performance.

Everything in nature is a sandwich structure, that is a skin with an exterior and interior contents to support the skin. Depending on the mass of the matter or structure, the moment of inertia is an important property which we can derive from the cross section of any structure, dictating whether the material is strong and able to resist bending and buckling forces. The moment of inertia increases as the cross section of any given shape such as a tube also increases, provided that the radius divided by the tube thickness ratio also increases. By preserving these concepts and translating them to other materials such as metals, plastics or composites, we can create structural skins with the best resistance to bending and buckling, with specific tuneable properties. There are many similarities between a digital material and a cellular material. *What properties do digital materials display, that make it the material of choice, taking cellular materials to the next level?*

2.4 Digital Materials

Like cellular skins and solids in nature, the future of digital fabrication of functional objects will be revolutionized with digital material skins and digital material solids. Digital materials have been defined in prior work by Popescu as having three main properties at the highest level of description: a finite set of components or discrete parts, a finite set of discreteized joints of all components in a digital material, and finally complete control of assembly and placement of discrete interlocking components[Popescu 2006]. The beauty of a digital system is the ability to achieve precision within some threshold, out of an initial noisy system, as demonstrated by Shannon, Von Neumann, and Nyquist. Just as digital communication and computation have moved from analog to digital, and are discrete in code space, digital materials are inherently discrete in physical space.

In 1927, Vannevar Bush constructed one of the first analog computer that could solve differential equations with 18 independent variables. Analog computers use physical phenomena, electrical, mechanical quantities to model problems being solved. This development led to the digital computers of today. Each person now owns a personal computer that computes by representing varying data incrementally. Finally we can have data be precise within some specified threshold, as demonstrated in Shannon's master's thesis at MIT. In parallel, the history of digital fabrication started in 1953, where the first CNC machine was connected to a computer at MIT. Today, we have personal desktop printers where machines make materials, with the next shift from digital fabrication to digital materials, where code and intelligence and the very instructions to make the material lies not in the machine or software, but at the material level, as is demonstrated with the example of DNA.

A digital material desktop printer was the first application constructed entirely out of discrete, snap-fit, reversible digital materials. This printer was designed and fabricated by Jonathan Ward, and the machine is now called the MTM Snap. The entire structure for the MTM Snap is made up of a finite set of discrete parts, with built-in flexural connections and slots that are all milled as one CAD file on any cnc shop bot machine. The parts for the machine are currently made of high density polyethylene which as a material demonstrates great potential to create robust and stiff flexural connections, although it could have been made out of another material. The entire machine can be fabricated within a day, with additional motors and tool heads installed depending on the fabrication method desired. These digital material printers can print or mill its own parts eventually, to replicate and build more machines, larger machines like itself for infinite replication. Current work at MIT's Center for Bits and Atoms is taking the digital material printer to the next level, by incorporating a pick and place mechanism called a digital material assembler, a machine which like a child assembling and snapping legos together, would pick and place each newly fabricated piece to create the final form. The properties of digital materials are endless, and they can be designed out of any material using existing fabrication technologies and tools to build cellular structures for any application. The difference is that digital materials, compared to analog materials, are completely reversible, eliminating waste completely by allowing for individual parts no matter how large the assembly, to be reused and recycled at any point in the product lifecycle. In a future section titled Digital Material Solids, we will consider the next application of digital materials , which is being demonstrated with the first aircraft wing wedge structure constructed entirely out of a digital material solid structure that is fully reversible for assembly and disassembly. Assembly and disassembly algorithms digital material assembler are not within the scope of this work. All the structures and models are currently fabricated by human assemblers. *How though do we design structures with the property of reversibility in the material structure?*

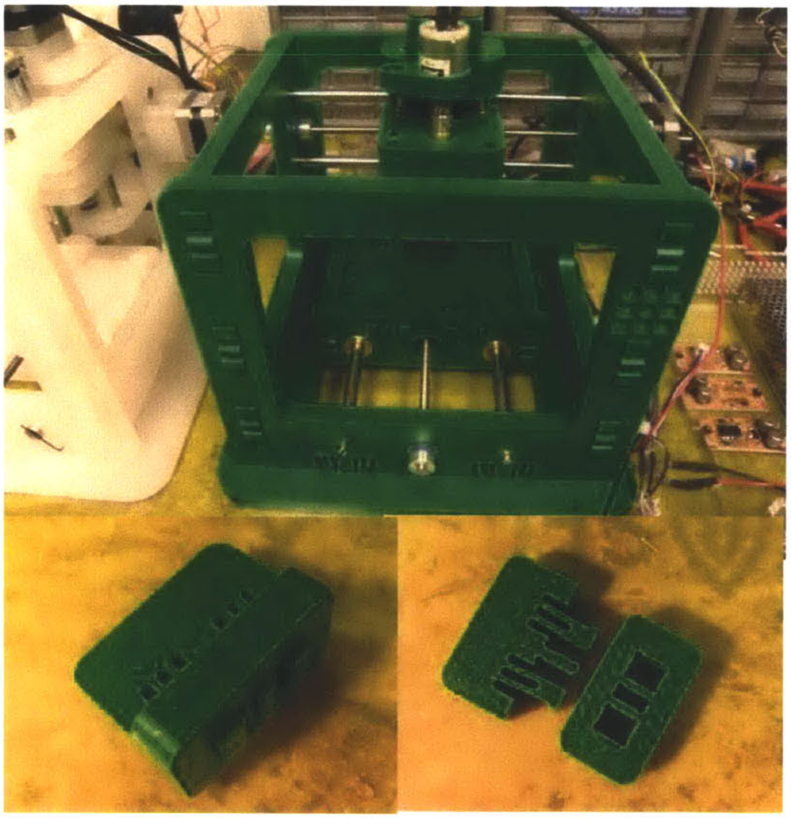


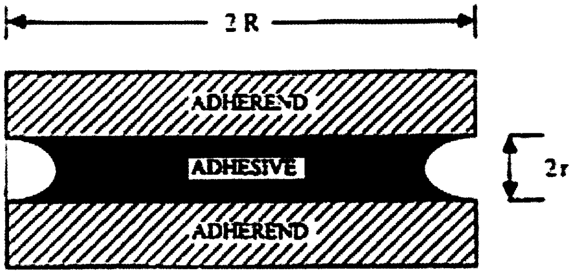
Figure 2.4 (Image Top): MTM Snap by Jonathan Ward, developed at MIT's Center for Bits & Atoms (Image Bottom): HDPE material cnc'd and illustrating a flexural connection of two digital material pieces part of the MTM Snap structure.

3 Reversible Joining Methods

This section introduces a small selection of joining methods that can be reversible for the application of disassembly and assembly, reuse, and recyclability.

3.1 Adhesives

Although adhesives are generally non-reversible, they demonstrate great potential in composite applications which require thin and flexible joints to adhere two or more materials together such as mylar film or composite laminates. Any adhesive is made up of a highly viscous fluid which fills the pores of the surface to which it bonds. The best applications use adhesives with high surface area to low volume bonding, which creates stronger interatomic bonding. Imagine a sheet of paper that adheres to another sheet of paper. It is more difficult to peel the sheet with the adhesive away because the forces are distributed over a larger area, creating less stress concentration and a stronger joint.



$$P_L - P_A = \gamma_{LV}\left(\frac{1}{R} - \frac{1}{r}\right)$$

Figure 3.1 Calculating the Ideal Adhesive Joint

The idealized adhesive joint is illustrated in the figure 3.1. The adhesive that wets two material forms a concave edge at it's interface with the atmosphere. If this is the case, then the radius of the circle R with a thickness 2r can be used to calculate the difference in pressure between the air and the pressure in the liquid. As long as r is less than R, then the difference in pressure is negative, which means the pressure in the air is greater allowing greater compression and adhesion in the joint.

3.2 Fasteners

Fasteners are fully reversible in most applications where two or more materials are being joined. Fasteners can be used to join any kind of material of any shape. Fasteners are also inexpensive because parts can be ordered off the shelf since there are standard established sizes for any manufacturing application. While fasteners are great for these reasons, they do not necessarily deliver in terms of strength compared to other bonding methods such as welding. Fasteners may also require extra parts and may be difficult to automate for high volume production. There are several factors to considers when using fasteners including the following: high stress concentration because of over-tightening a screw or rivet, threads can get ruined as the screw is inserted, and burring on the screw head or on the nut can also create stress and failure in the system.

3.3 Press-Fit Joints

Press-fit joints commonly use intereference to allow parts to maintain a certain level of stress, without loosening the connection or creating an excess of stress in the joint. They are held together by friction, where pressure from both materials act on the contact surfaces. In figure 3.3, a press-fit GIK digital material joint is demonstrated for parts lasercut out of baltic birch wood.

Figure 3.3 Press Fit GIK components laser cut and assembled by hand

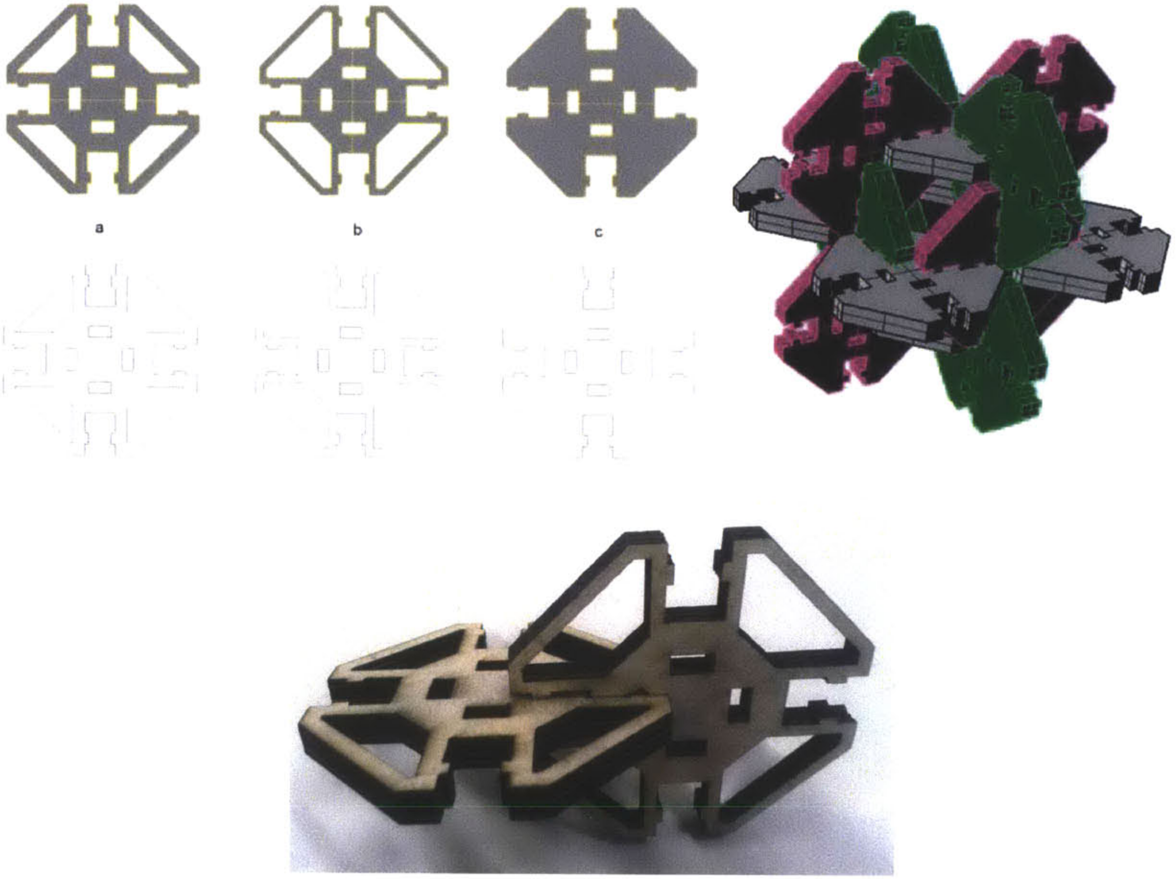


Figure 3.4 Snap-Fit Joints from an earlier version of the aircraft wing wedge design

3.4 Snap-Fit Joints

Snap-Fit joints can be made out of any material, but usually work with plastics. Figure 3.4 illustrates a simple lasercut digital material geometry with a built in snap-fit joint. When designing this joint, two parts are engaged and under stress until an undercut relieves the interference. During interference, the joints should not go above their linear portion of the stress strain curve. Once both parts have joined, the load should continue to keep the parts engaged, without any additional stress. The design in figure 3.4 is of a digital material solid, and joints are built in and the same for every unit. The very end of each joint features an extrusion which extends from both sides to be able to catch the mating material to snap in place.

This section introduces two traditional fabrication methods for continuous pressure vessel skins.To achieve reduction in weight, increase in strength, and reduction in cost, then engineering design, materials of construction and methods of fabrication must all be considered for the results desired.

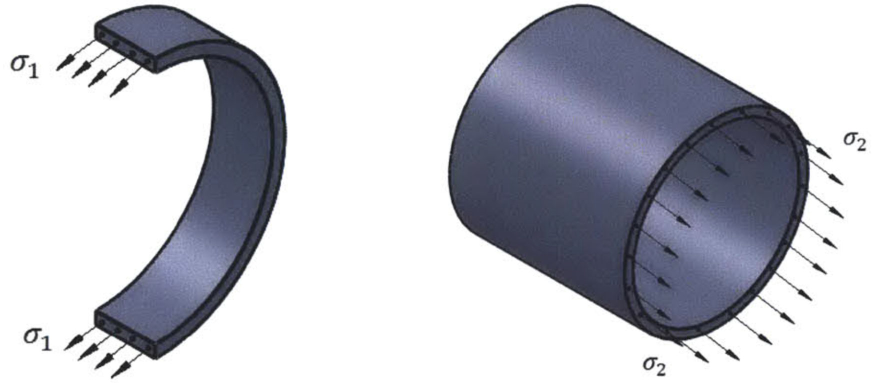


Figure 4.1 Hoop and longitudinal stresses in pressure vessel skins,www.sbainvent.com

4.1 Pressure Vessel Stresses

Pressure vessels are leak proof containers to contain any matter such as solid, liquid or gas. Pressure vessels can have any combination of geometries based on cylinder, ellipsoids or spheres. Many materials, tools and processes can be chosen, each displaying significant advantages for different metrics such as cost, mass, strength, and vessel life. Traditionally, pressure vessels have been manufactured with welding, forging, and brazing techniques.

An axis-symmetrical shell cross section with some internal pressure is subject to radial forces which distribute along the circumference of any cross-section considered. Internal forces translate to hoop stress, which act tangentially in plane with the vessel skin. Spherical pressure vessels are stronger than cylindrical pressure vessels, because stress is uniformly distributed at every point, but are more difficult and expensive to manufacture. The mass of a vessel is proportional to the pressure and volume it contains. To determine stresses resulting from loads, the relationship between stress and strain from an applied static or dynamic load needs to be quantified for a given material, pressure, and vessel thickness. A spherical pressure vessel considered for any given circumference along the cross-section contains two types of stresses: radial and hoop[Harvey 1991]. Hoop stresses occur at every point, in a direction tangential to the plane the point lies on. The vessel skin will try to expand or contract, depending on what direction the radial forces are pointing. To understand the force along a given cross- sectional cut of the spherical vessel with a small thickness (in comparison to other dimensions of the vessel), the vessel must achieve equilibrium of forces for the exterior and interior pressure values.

4.2 Pressure Vessel Fabrication

The design and fabrication process identifies 1) final vessel requirements based on matter to be contained 2) likely failure modes 3) stress analysis for failure modes identified, 4) material selection and behavior, 5) fabrication and finally 6) testing. Most pressure vessels are made of two or more parts that have been previously fabricated as segments of a cylinder or hemisphere, which are then joined to form the base vessel with additional attachment and openings. ASME Section VIII, Division I present three types of processes currently used for vessel fabrication: welding, forging, and brazing. Take welding for example. The general welding technique for welding two parallel parts with no overlap is called a butt-weld, used in in conjunction with any of the following pressure welding processes: explosive, flash, thermit, induction, continuous drive friction, inertia, resistance, and gas pressure.

No matter what the weld process, any one of those mentioned creates a non-precise fabrication process increasing stress factors or potential failure modes in the vessel. Let us consider potential failure modes during the welding process. The first area where failure can be introduced is with the structure of the metal being welded when compared to the parent metal, which may or may not have a similar structure. The second is that failure can be introduced is during the welding process creating local deformities in the form of porosity, lack of fusion, slag inclusions and shrinkage cracks. The third is due to local stress concentration as a result of misalignment of the two vessel halves, which have been prefabricated as separate segments.

The fourth area is with the weld geometry and surface finish, whereby deformities arise from less than perfect welding techniques. The fourth area has to do with repair of welded vessel joints, which often cost more than just using an existing method to remove and re-weld the two halves. Repairing welds is also risky, because one never knows with all the tests whether the weld has produced in some cases a less than desirable result, compared to the original surface of the vessel skin.

All methods from casting of metals, multilayer construction, wire wrapped construction or filament wound vessels, the part production and the joints and their associated processes create flaws which affect the entire assembly or piece. Through these local discontinuities, entire structures eventually undergo global failure. The same failure modes for aircraft skins generally apply to pressure vessel skins and for other skin applications.

4.3 Composite Pressure Vessels

Structural composites for pressure vessel applications will soon replace steel tanks, since composite vessels are demonstrating a 60% weight reduction, less corrosion, require low maintenance, and normally do not need coating for UV protection.

NASA has also recently begun a project with Boeing to develop one of the first composite

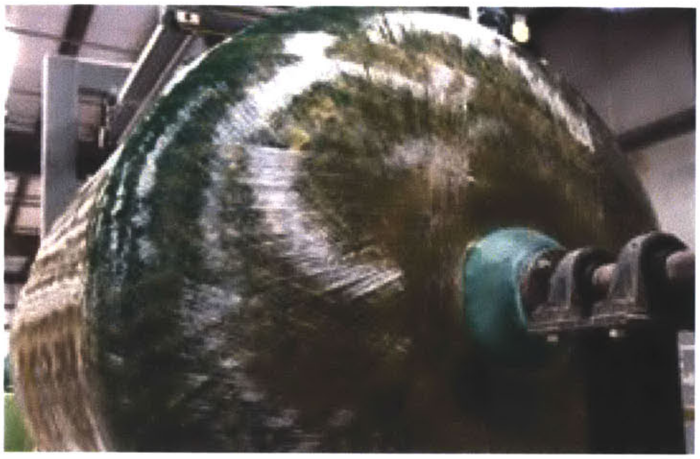


Figure 4.4 Filament Wound Vessel

cryogenic propellant tanks which will use the latest composite materials alongside new fabrication and assembly technologies to develop lightweight low cost tanks. This will result in an increase in upmass capability through the advancement in materials, manufacturing and structures for use in heavy lift vehicles, in-space propellant depots, and any other space exploration architectures. The goal of this project is to develop these disruptive technologies by coupling affordability with performance.Cryogenic Propellant Storage and Transfer(CPST) is another project led by NASA's Office of the Chief Technologist, which aims to develop a Space Launch System(SLS) to be able to deliver fuel for deep space exploration, along with logistics of creating orbiting fuel depots to contain fuel and new technologies needed to mitigate or prevent boil-off in orbit.

4.4 Filament Wound Vessels

A permanent or removable mandrel in the shape and size of the final pressure vessel is wound continuously with a filament as seen in figure x. The carbon fiber matrix is applied with a wrapping system oriented in the principal direction of stress incurred in the system. Also, if the longitudinal stress is three times the hoop stress, then the mandrel is filament wound three times the thickness of the hoop direction in the longitudinal direction, to maintain the same stress throughout the skin. The advantages of filament wound vessels include high strength to low weight material properties, high corrosion resistance due to material properties of the resin, and lower notch sensitivity since broken filaments do not affect neighboring filaments.

4.5 Multi-Layer Construction

Multi-layer construction of pressure vessels is another common fabrication method, where the tank system contains an inner shell between 1/4”-1/2” thick, wrapped and welded in order to incur the membrane stresses. It is created as a concentric layered skin system, with attachments and holes drilled in different layers to be able to montior leakage. The advantages of multi-layer construction include lower costs since each layer can be a different material, the inner compatible with the matter contained and the outer can be a cheaper material used to hold the tank walls in place. Disadvantages include local stress concentration since layers are not attached, and thermal gradients created by heating and cooling of different layers at different rates.Now that we have briefly considered several pressure vessel fabrication methods, let us consider one of the first applications of digital material solids for an aircraft wing wedge.

5 Digital Material Solids

This section demonstrates the first application of digital material solids towards the design of an aircraft wing wedge structure. Related to a cellular material, this digital material, or digital material solid is designed to replace the interior structure of a wing wedge, and ultimately any aircraft load bearing interior structure. The design and fabrication was completed at MIT's Center for Bits & Atoms, by Kenny Cheung and Sarah Hovsepian.

5.1 Requirements for an Aircraft Wing Wedge

Digital material solids have previously been applied towards the design of a desktop printer out of discrete reversible parts. The aircraft wing is the first application to consider the design of a digital material solid out of composite materials, similar to a cellular solid, with constraints that the structure be extremely strong and lightweight. The major requirement for an aircraft skin, is its' resistance to compressive stresses, in order to prevent the entire structure from buckling. Buckling is mitigated by providing a stiff but lightweight material core connected to an exterior skin which performs aerodynamically. The skin may or may not be load bearing depending on loading requirements. Aircraft core construction is analogous an I beam , with the skin of a core functioning the same way the top and bottom flange would on a beam, and the inner core in a sandwich similar to the web of a beam.

The interior of the wing wedge is designed as a cellular solid, a repetitive lattice with standard elongated shapes which interlock with a reversible insert in each joint, to allow for easy assembly and disassembly for ultimate reusability, recyclability and repairability. Another objective was to design a hierarchical geometric space filling shape, such that it would be scalable to allow for greater surface resolution of the final structure. If not scalable, there could also be different variations of the initial part geometry, such as half shapes or quarter shapes of the original. Also, the parts had to be milled out of flat sheets of material utilizing subtractive fabrication methods to allow for quick, easy and greater control over the fabrication process. Finally, the goal was to create an isotropic structure, such that the properties of the geometry and material would be the same in every direction of the bulk material. The ultimate goal was to create a lightweight and highly porous structure for a wing with a stiff cross-sectional core analogous to spars in a wing or fuselage.

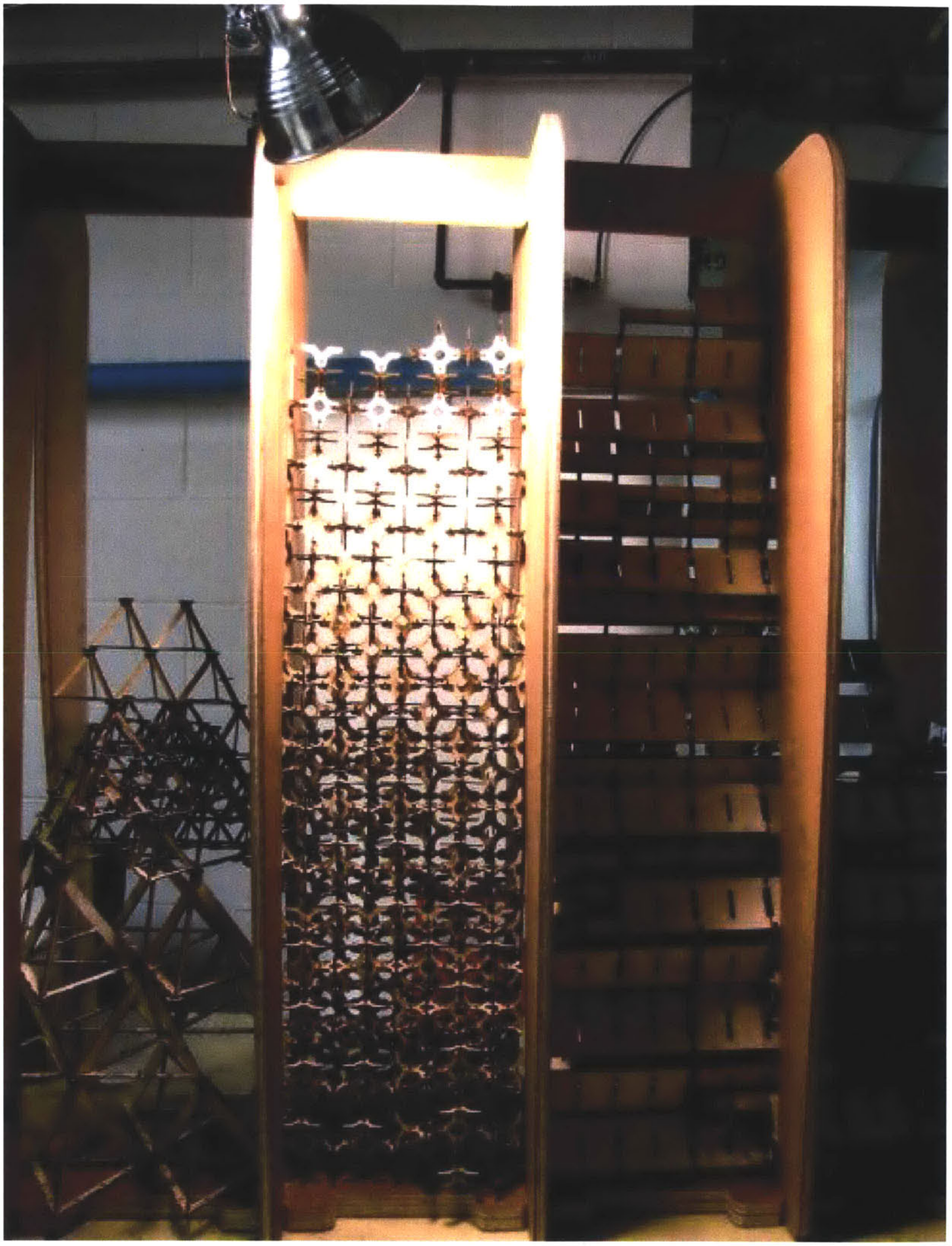


Figure 5.2A Three design strategies developed for the aircraft wing prototype, contained within an outer structural frame of an actual wing.

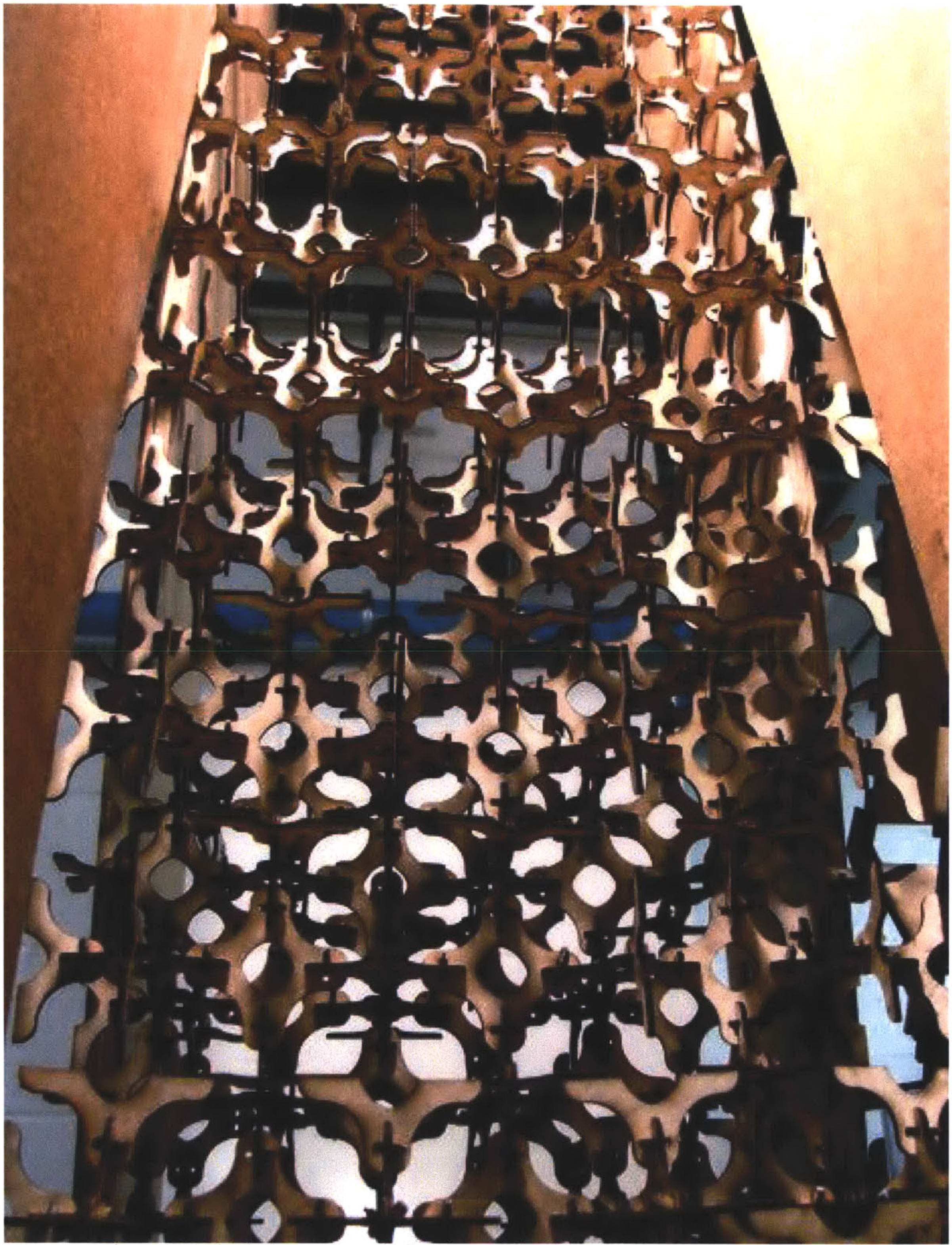


Figure 5.2B The design strategy of a digital material solid, chosen for further development

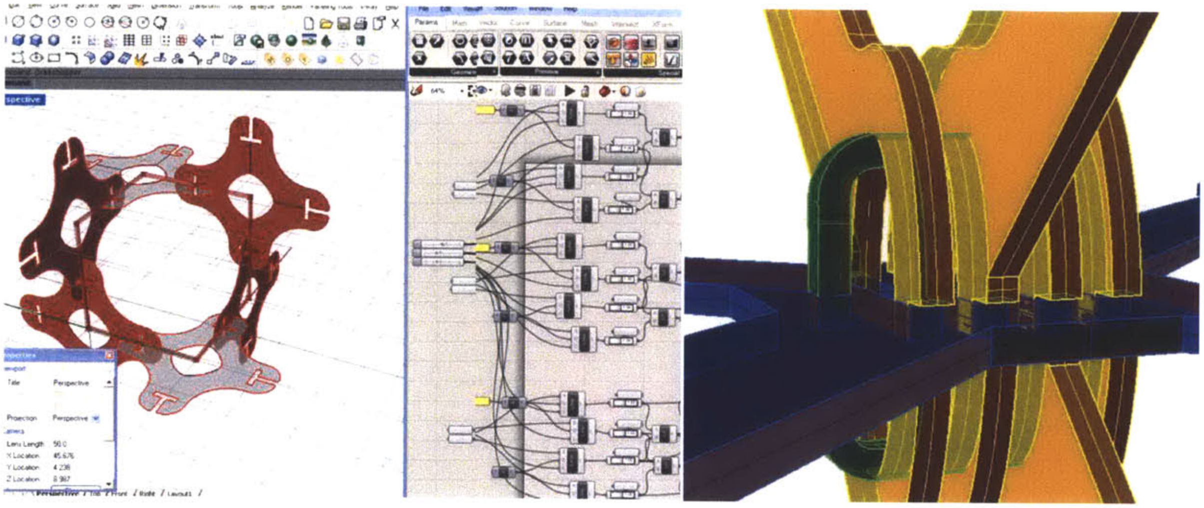


Figure 5.2C (Image Left): 3D model of digital material geometry and actuation of adjacent digital materials for bulk material actuation and elongation studies (Image Right) Earlier press fit joint design

5.2 Design studies for an Aircraft Wing Wedge

The first step involved a series of design studies for a proof of concept lattice structure to fill three dimensional space. In two dimensions, there are five different lattice configurations: square, hexagonal, parallelogrammic, rectangular and rhombic. In three dimensions, there are 14 different lattice shapes, commonly referred to as Bravais lattices. The model illustrated in figure 3.1 illustrates three design studies of space filling geometries. The design typically begins by choosing a lattice type and then proceeds with a geometry which repeats across the entire lattice in all directions. Figure 3.2A illustrate design strategy 1, 2, & 3 from left to right.

Design strategy 1(left most structure in figure 5.2A) is a space filling polyhedron also known as a tetrahedron.It is hierarchical and scalable because it features three different tetrahedron sizes. The disadvantage with this proof of concept lies in the weak connections between adjacent interlocked 2D parts. Each 2D geometry meets at a plate connection, and the plates hold in compression while the diagonal members serve to hold in tension. The connection between the diagonal members and plates requires a better strategy for stiffening the joints.Design strategy 2 is a space filling geometry based on a body centered lattice with t shaped members. This strategy does not fulfill a hierarchical system in the sense that the model only features half shapes of the original. The strategy needs to incorporate three or more different sizes of the same component scaled up with the same connections. Structurally, the system relies on stiff joints acting in tension and compression. This strategy demonstrates the greatest potential because of its joining system, and the next iteration would feature snap fit or press-fit joints for a stronger connection. Design strategy 3 is a space filling geometry which fulfills the hierarchical

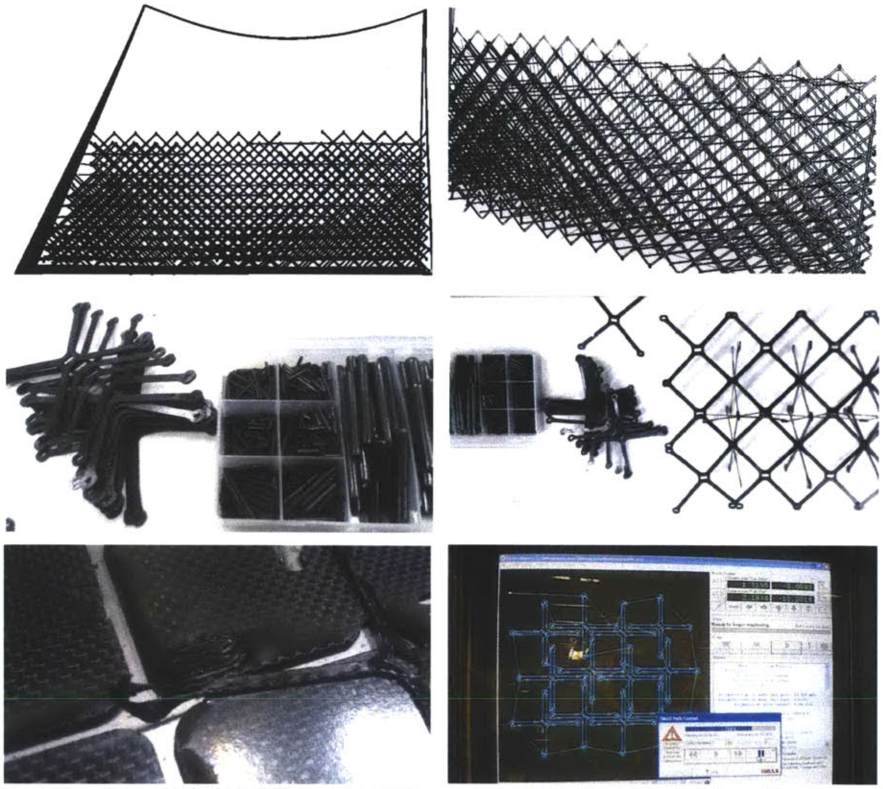


Figure 5.3 (Image Top Row): 3d digital model of all the pieces within the aircraft wing, (Image Middle Row) Laser-cut pieces of carbon fiber laminated sheets (Image Bottom Row) Process of trial and error of finding the best settings

requirement but works as an anisotropic structure which fails the requirement of isotropy. Furthermore, the joining system relies on press-fit joints which are weak and direction dependent. Since strategy 2 demonstrates the greatest potential, it was further developed in the next phase of design and fabrication of the wing.

5.3 Fabrication and Assembly of Aircraft Wing Wedge

The next phase of the wing wedge prototype is made of 12"x24" laminated sheets of carbon fiber composites. In Figure 3.2 C, the images in the third row illustrate earlier test pieces of the laminated sheets using a 500W laser cutter, along with several experiments on a shopbot and a waterjet. The shopbot shows the most potential, when used with a 1/32" diamond carbide end mill. Although the shopbot creates the best cuts, it also required a lot of time to change endmills, especially since the endmills are prone to break after two or less pieces are milled. The laser cutter was eventually the machine selected because of rapid part production. Over a 1000 pieces of the digital material shapes were lasercut in 6 days and assembled by hand in 4 days(see figure 5.3A).

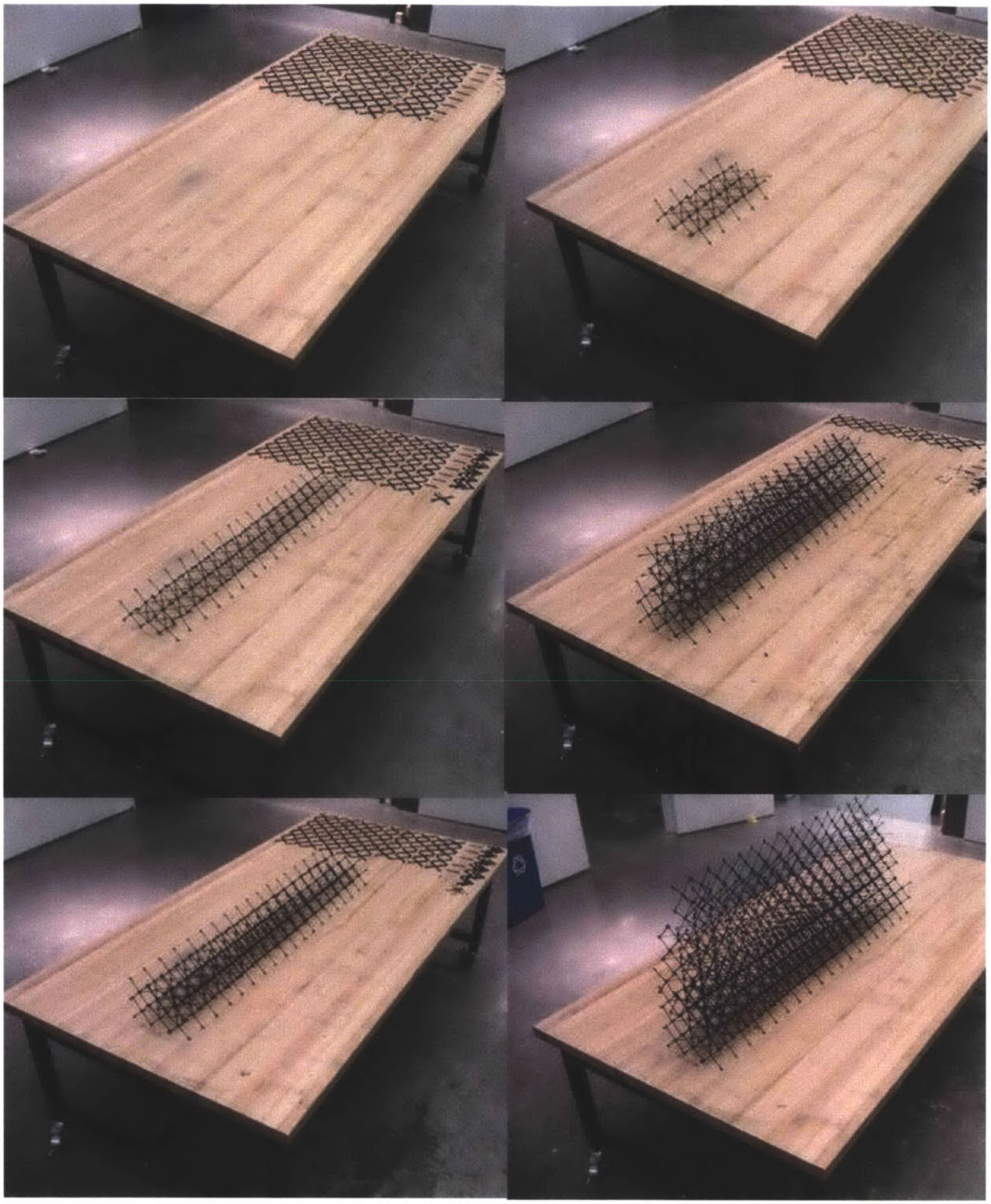


Figure 5.3A Digital material assembly featuring the parts, links, and inserts

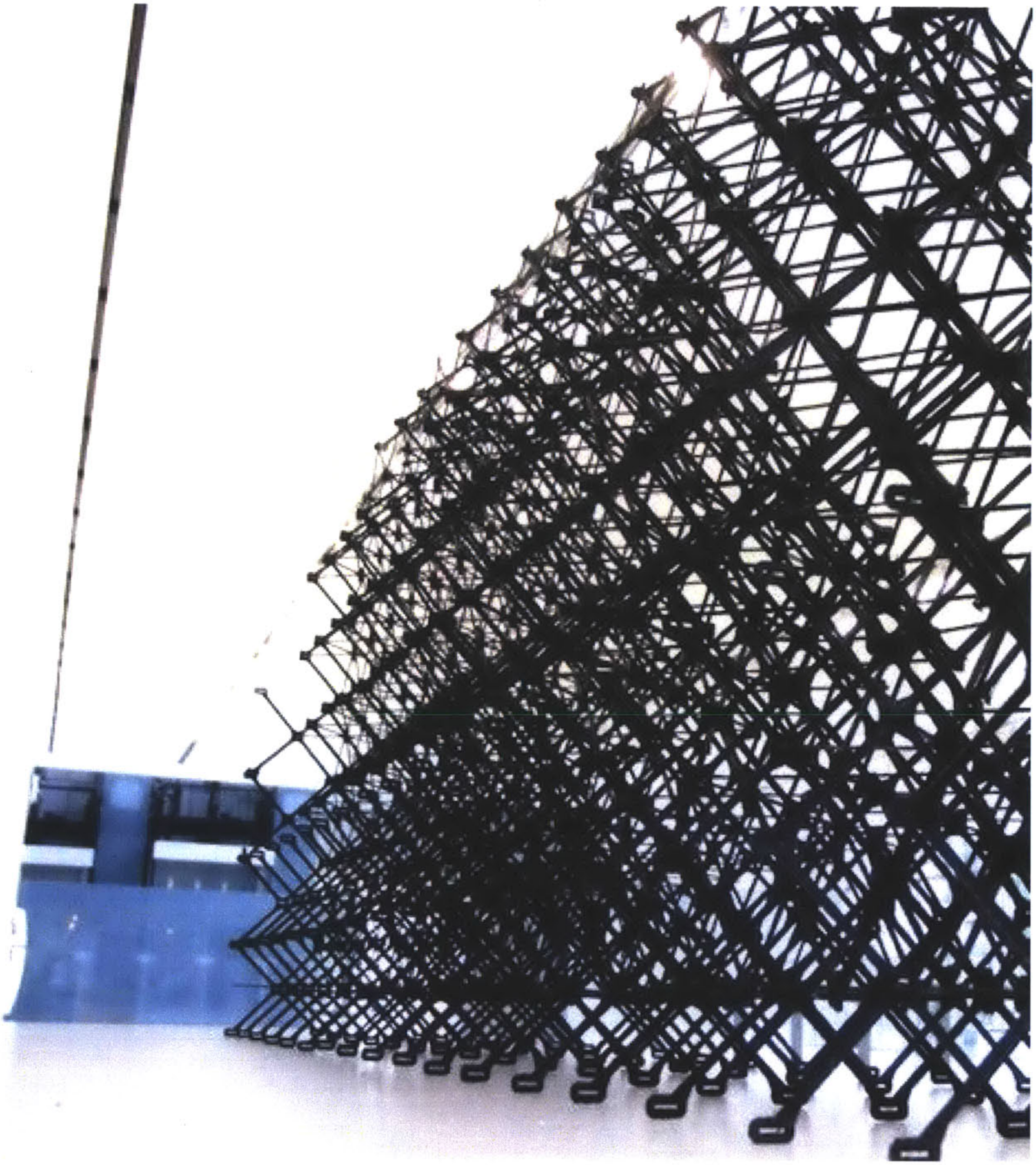


Figure 5.3B Final aircraft wing wedge model

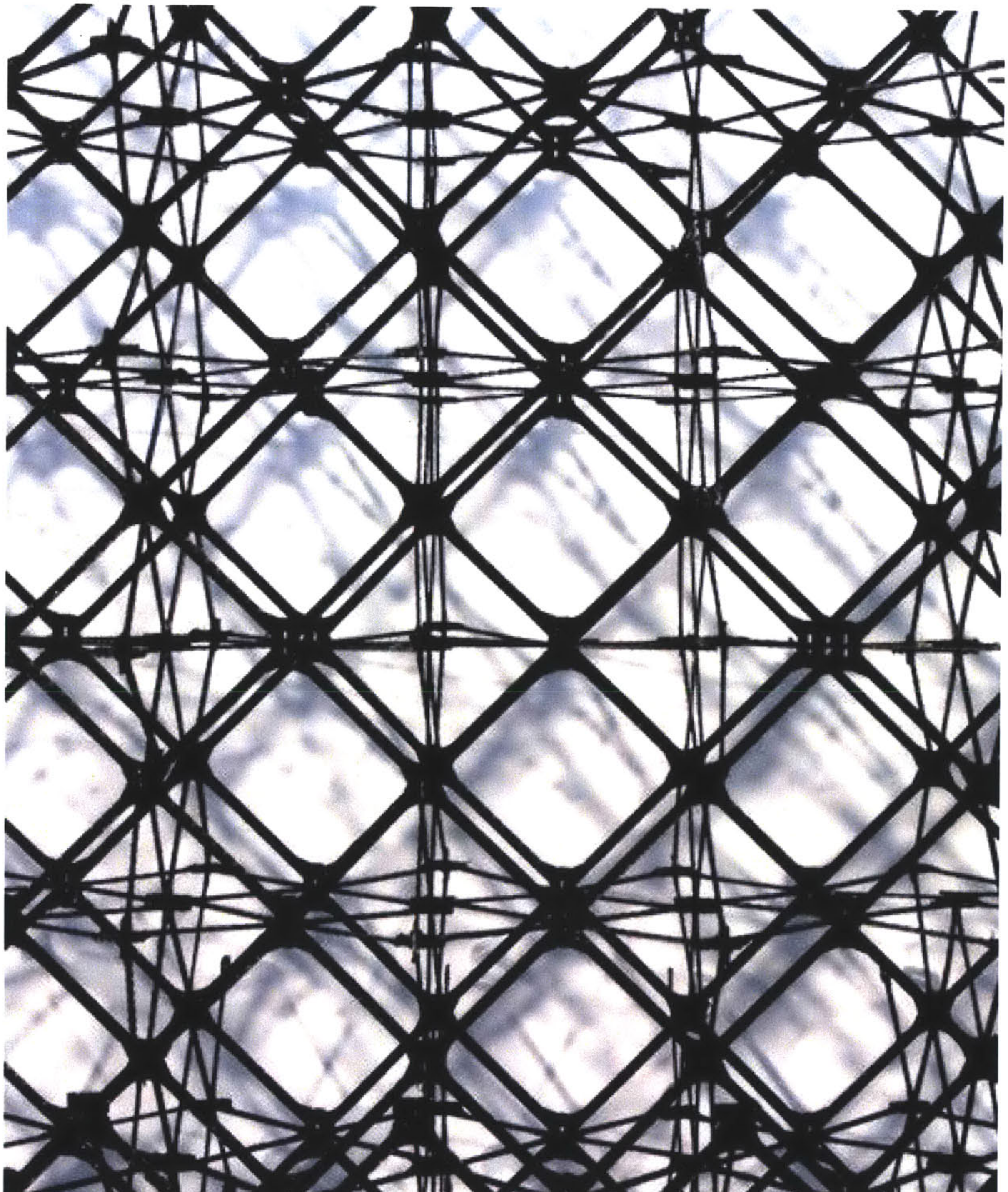


Figure 5.3C Final aircraft wing wedge model

This section describes the first digital material skin prototype designed and fabricated for pressure vessel applications.This work was funded by NASA, and design and fabrication of digital material skins was conducted by Sarah Hovsepian at the Center for Bits and Atoms.

A digital material skin is made of discrete units with a finite set of parts and joints used to construct a functional structural skin for airtight,waterproof, high or low pressure applications.The surface is enclosed or the surface is open. Digital material skins are used to construct any shape or interior volume that is regular or amorphous. A digital material skin is an exterior structure which relies on an interior digital material structure for support, or a digital material skin is self-supported with few or no interior support.Parts and links are arranged and configured in a regular pattern to create a surface larger than the units. The skin is part of a larger assembly or part of a single unitary structure of any size or shape. The skin may have a thickness that is smaller or larger than any dimension. The skin is made of one or more layers of one material or multi-material units.The joints are reversible, allowing transfer of forces from one unit to adjacent units.

6.1 Strategies for Pressure Vessel Digital Material Skins

The pressure vessel application can have any of the following scenarios pertaining to the diagram in figure 6.1A. Scenario A depicts equal pressure on both sides of the adjacent

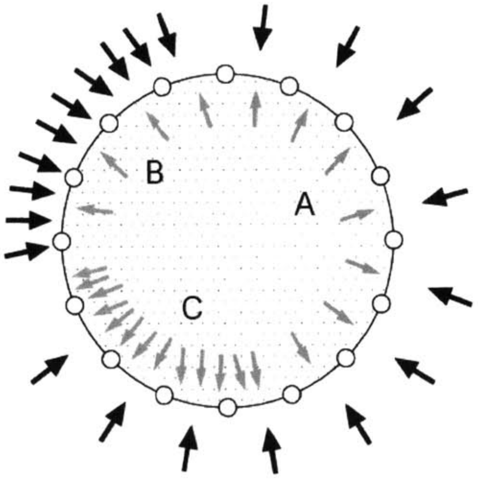


Figure 6.1A High Low pressure scenarios , (A) equal pressure interior and exterior (B) low pressure interior and high pressure exterior (C) high pressure interior and low pressure exterior

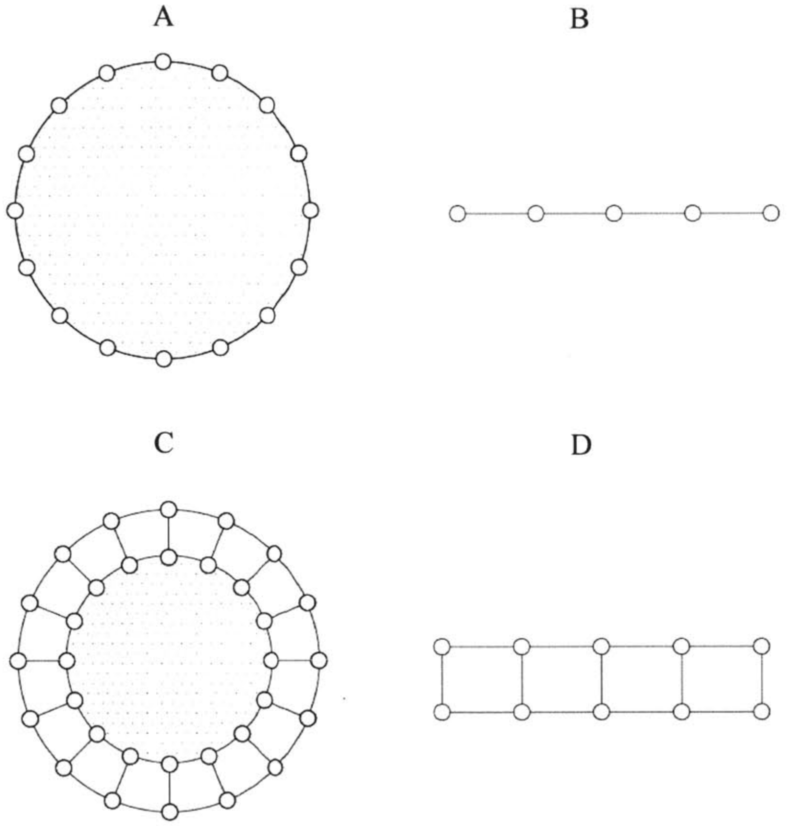


Figure 6.1B Digital Material Skin Strategies, one layer and two or more layer of an open or enclosed self supporting skin system.

pressure vessel wall. Either side may have high-high pressure or low-low pressure. Scenario B depicts a low pressure interior, and higher pressure exterior skin. Finally, scenario C depicts a high pressure interior and lower pressure exterior.

In figure 6.1B, A depicts the first type of skin strategy. It is comprised of a single layer system of an enclosed free-form digital material skin with some differential internal and external pressure. Image B in the same figure depicts a single layer system of an open free-form digital material skin with some differential internal and external pressure. In C, the diagram depicts a two or more layer system of an enclosed free-form digital material skin with some differential internal and external pressure. Image D is a two or more layer system of an open free-form digital material skin with some differential internal and external pressure.

Figure 6.1C illustrates the second strategy of digital material skins. In image E, we see a single layer system of an enclosed free-form digital material skin with some differential internal and external pressure supported by an internal structural core or digital material solid(indicated by dotted lines). Image F is a single layer system of an open free-form digital material skin with some differential internal and external pressure supported by an internal structural core or digital material solid(indicated by dotted lines).In image G, we first encounter a two or more layer system of an enclosed free-form digital material skin with some differential internal and external pressure supported by an internal structural core or digital material solid(indicated by dotted lines). In H, we see a two or more layer system of an open free-form digital material skin supported by an internal structural core or digital material solid on one side(indicated by dotted lines). Finally, in I, we see a two or more layer system of an open free-form digital material skin on one or both sides, supported by an internal structural core or digital material solid(indicated by dotted lines).

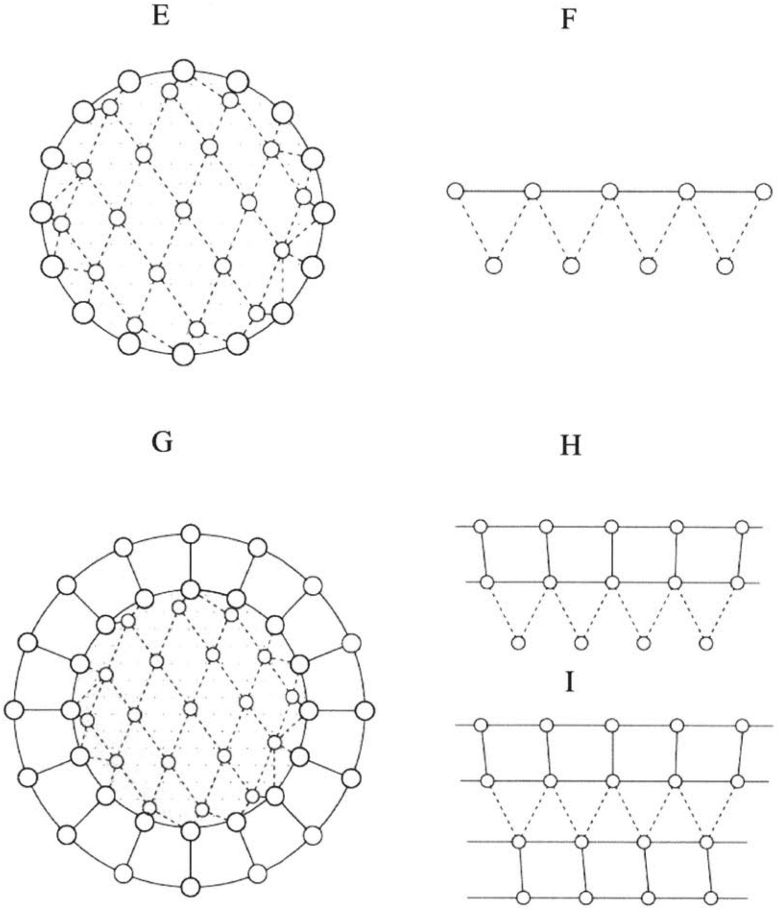


Figure 6.1C Digital Material Skin Strategies, one layer and two or more layer of an open or enclosed skin system supported by an interior digital material solid core

6.2 Design Methodology for Digital Material Skins

The design methodology for digital material skins begins by determining what global form or geometry is desired. Once the form is determined, it is then subdivided. Given some configuration, subdivision and panelization of the surface is created, to populate the interior with 2-3 scales of a digital material skin used to achieve some resolution of the final form. Since each part is inherently discrete and 2D, the design is then translated to GCode. Each unique 2D element is translated to numerically controlled machine code depending on the tool used.The designs are then created as individual components using either an additive or subtractive manufacturing method, also greatly influenced by the material to be used. The next step would include assembly of the digital material skins by a digital material printer, which uses a pick and place mechanism to interlock components in the structure. Once the structure is built, then material testing of the substructure and larger bulk structure takes place to characterize properties of the bulk material skin system. When the structure is no longer needed, it is then disassembled by the same digital material assembler.

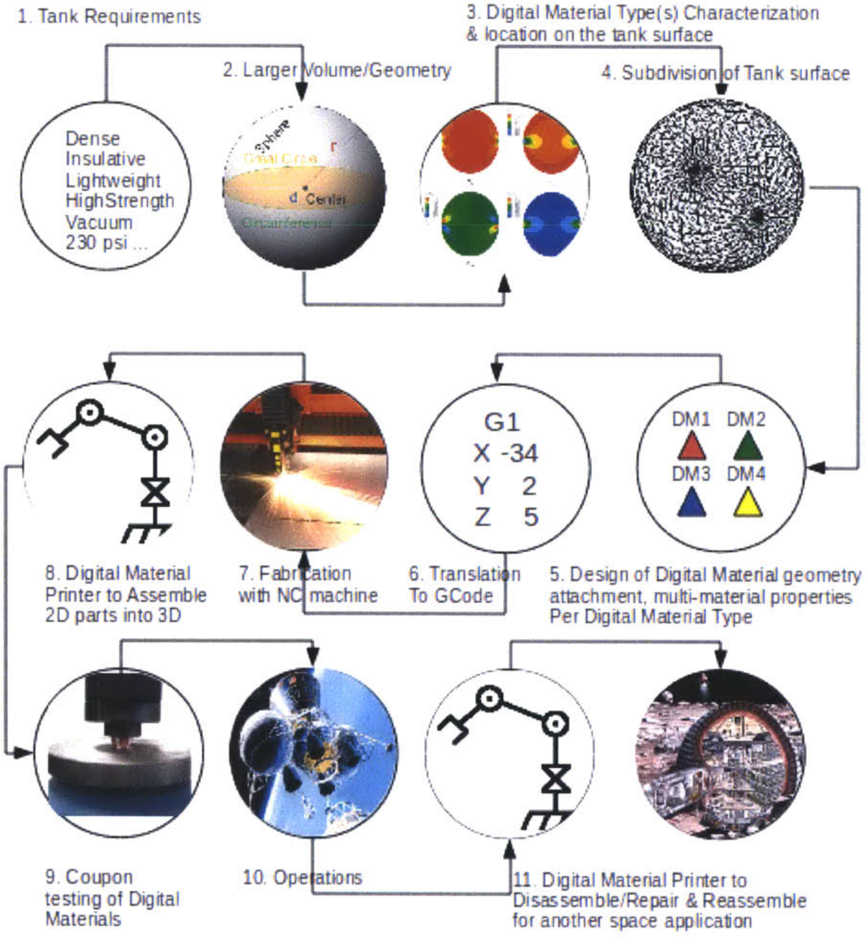


Figure 6.2 Pressure Vessel Design methodology

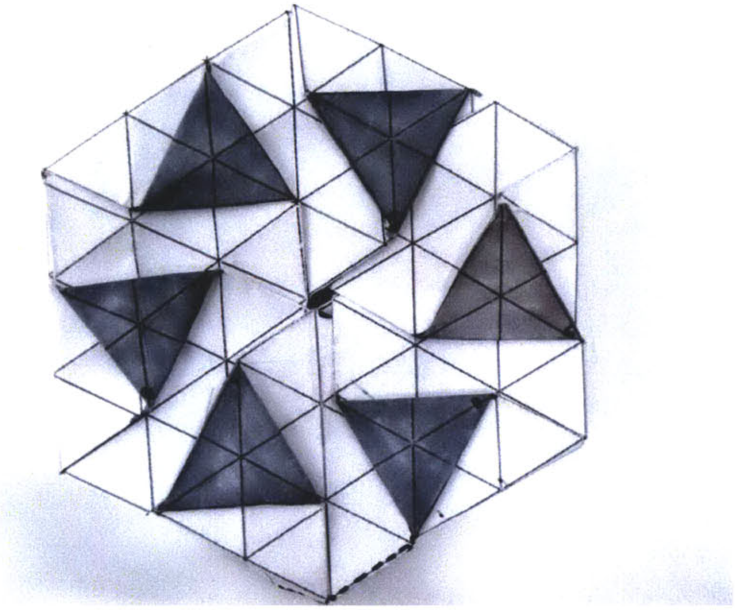


Figure 6.3A 2D flat digital material skin system made of 6 repeating and interlocking components

6.3 Design Studies for Pressure Vessel Digital Material Skins

The final skin conguration can be traced back to the initial subdivision of the spherical surface. To simplify, I use an icosahedron with 20 identical equilateral triangles which make up the faces, and begin to develop a new strategy for the self-supporting skin, based on origami tessellation. All tessellation patterns are based on repetitive geometries which tile two-dimensionally without creating any gaps or overlapping in the system. These properties are ideal for thinking about how to approach and develop a repetitive standard material unit and geometry that tiles in two (figure 6.3A) and eventually three dimensional space.The pattern must fit without gaps, but it must simultaneously provide overlap to constantly redirect matter from one point to another. Ideally, the overlaps are such that they decrease in elevation and direct matter in one continuous direction, allowing liquid to flow perpendicular to the edges of overlap.

There are three tiling systems, grids or tessellation patterns: squares, equilateral triangles or hexagons. Since these tilings are two dimensional with no gap and no overlapping patterns, there must be a method to go about including overlapping into the tessellation, for the application to function as a sealed skin. We looked towards origami tessellations, a

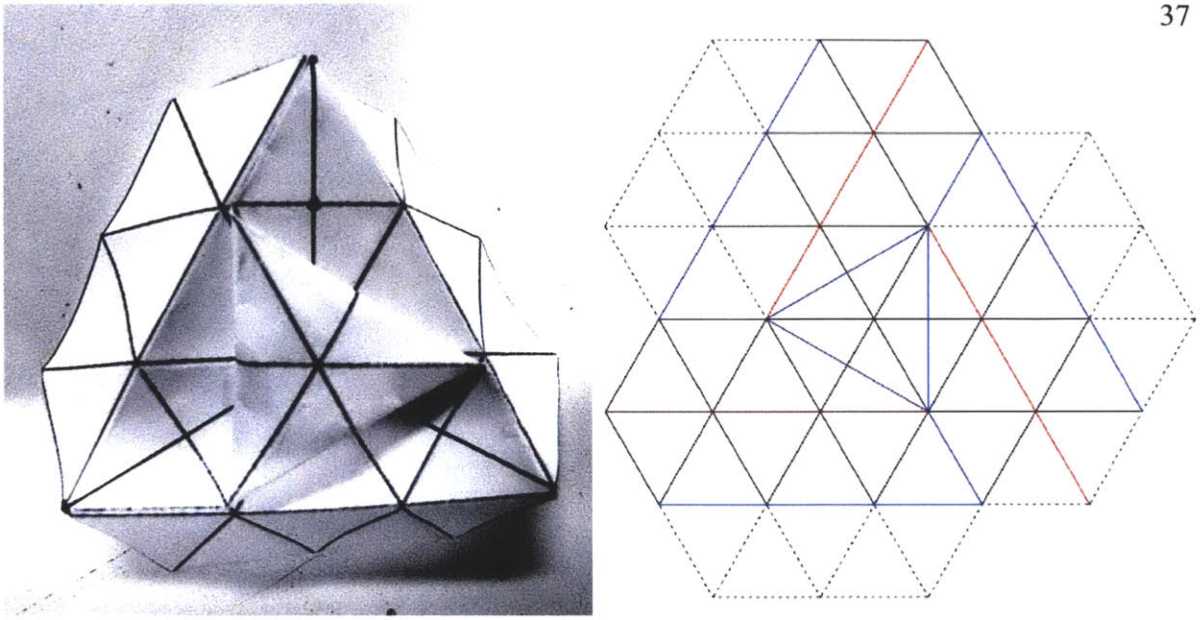


Figure 6.3B (Image Left) Digital material skin unit (Image Right) Origami Tesselation mountain-valley fold pattern

subset of tessellations which create repetitive geometric designs by folding a single sheet of paper. Depending on the grid, the final folded design can either stack and propogate, or expand homogeneously throughout the paper.

Origami tessellations do not typically involve cutting any part of the paper being folded, and patterns use the full sheet to propogate the design by folding. A pattern first is developed by choosing the grid type and then pre-creasing the grid on a sheet of paper. The difference with origami tessellation and what the research has proposed, is to use origami tessellation to identify repeating overlapping components, to cut these identical components out of that already folded pattern, and to evolve the design of the part such that each component has areas along the edges of the outer triangle or hexagon perimeter, which fold and slide under adjacent overlapped areas.

Once the overlapped geometries are identied, the next step is to translate the paper model into a physical model made of everyday materials. Paper folds easily, but the challenge is to evolve the component such that they can eventually translate to discrete components. One can achieve the same objective in later models of the component constructed out of wood, metal or carbon fiber composites.The origami tessellation for the digital material skin system was initially folded and based on a triangular grid creating a repetitive triangle twist pattern. A triangle twist and a hexagonal twist are the two simplest origami folds one can create.

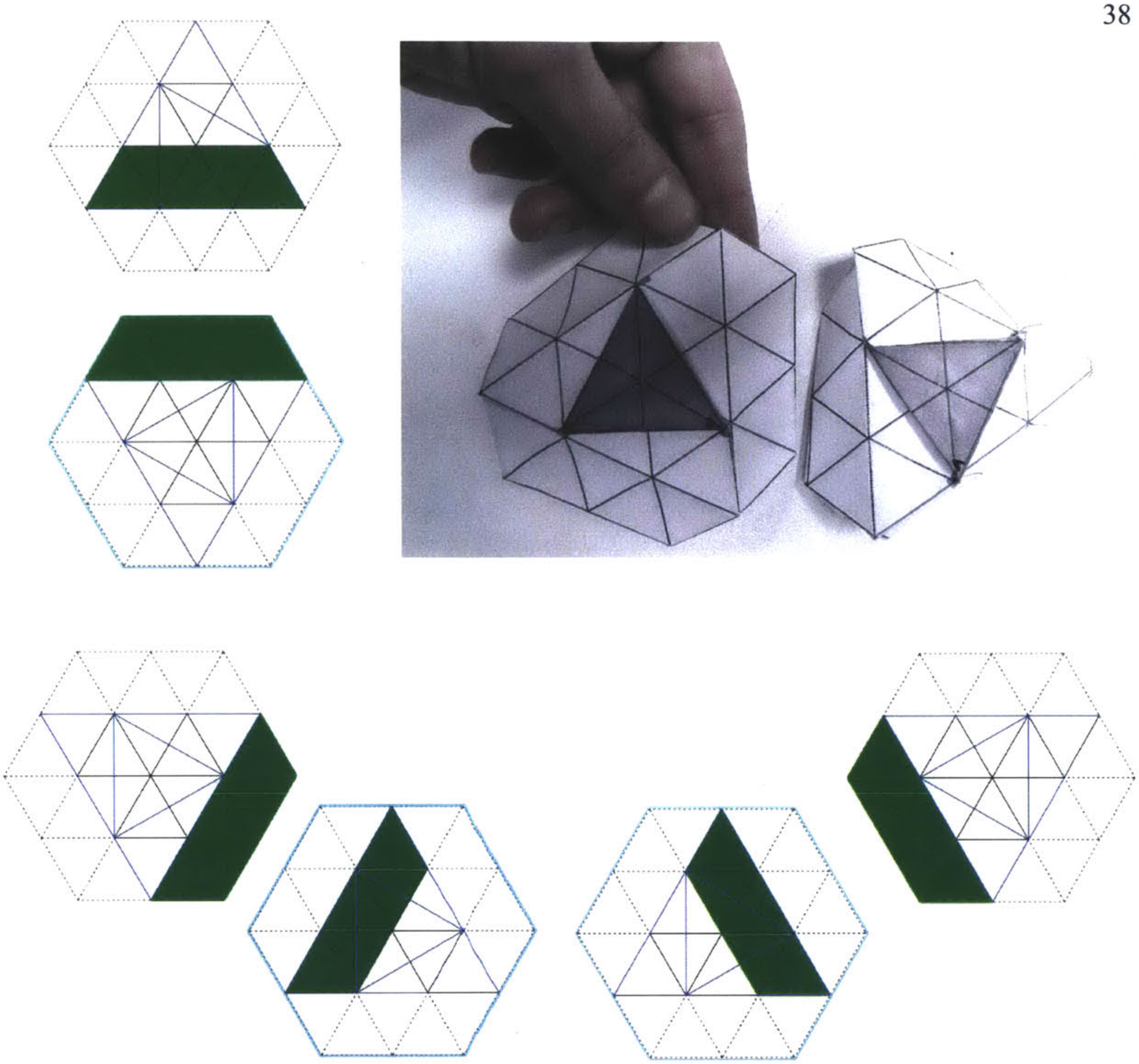


Figure 6.3C Each green flap illustrates where the adjacent unit interlocks

The triangle twist for example, creates 3 overlapped areas that share a common point. These three areas or strips are then mirrored along their outer triangular edge to create flaps on three sides of the trianglular base(figure 6.3B). The triangle twist could also have been superimposed on a hexagonal shaped panel for the outer edge, but for convenience of the icosahedron faces, the triangle remained. To further clarify, whether you create a triangle twist or a hexagonal twist, the base of paper under the fold can be conceived as any geometry or shape the designer chooses, depending on the system and shape of the subdivided geometry.

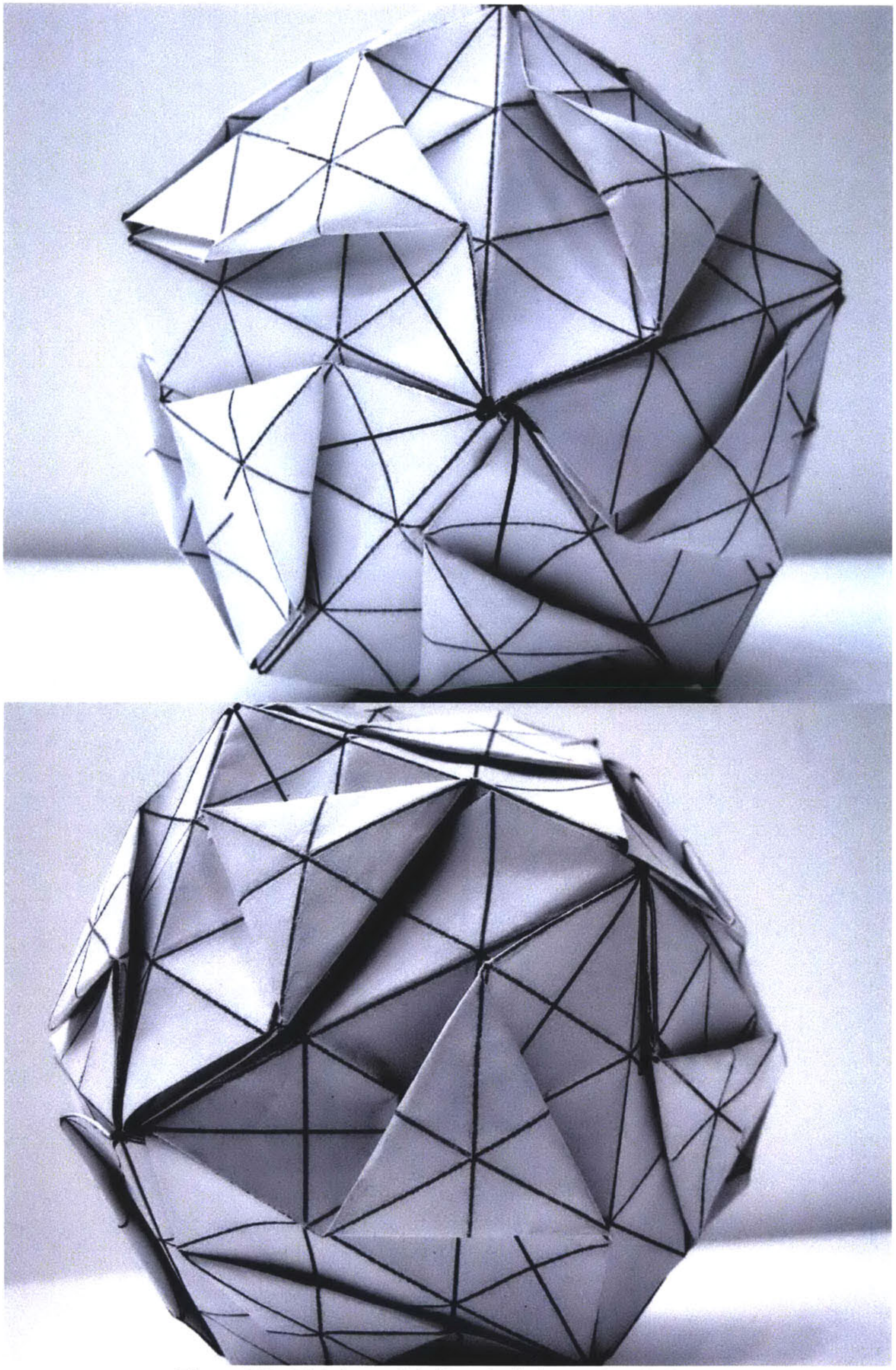


Figure 6.3D Digital material skin unit tiled on an icosahedron

Now that each digital material component features a triangle twist and three flaps, one could imagine tiling this component infinitely by sliding the flaps of every component under the adjacent components overlapped sections. The digital material skin component consists of a pleated area and aps. Each equilateral triangular face on the icosahedron is now made up of 3 identical overlapped strips which are the digital material units. They are then combined from adjacent triangular units to create double strips folded along every edge of the icosahedron.This creates a seal by covering all the edges of the icosahedron. It is also important to mention that the outer and innermost layers of the skin both display similar overlapping patterns to further create barriers for leakage in the system. The next goal is to then design a bistable rigid and high strength joint which penetrates in cross-section through two or more digital material components to link the structural skin together.

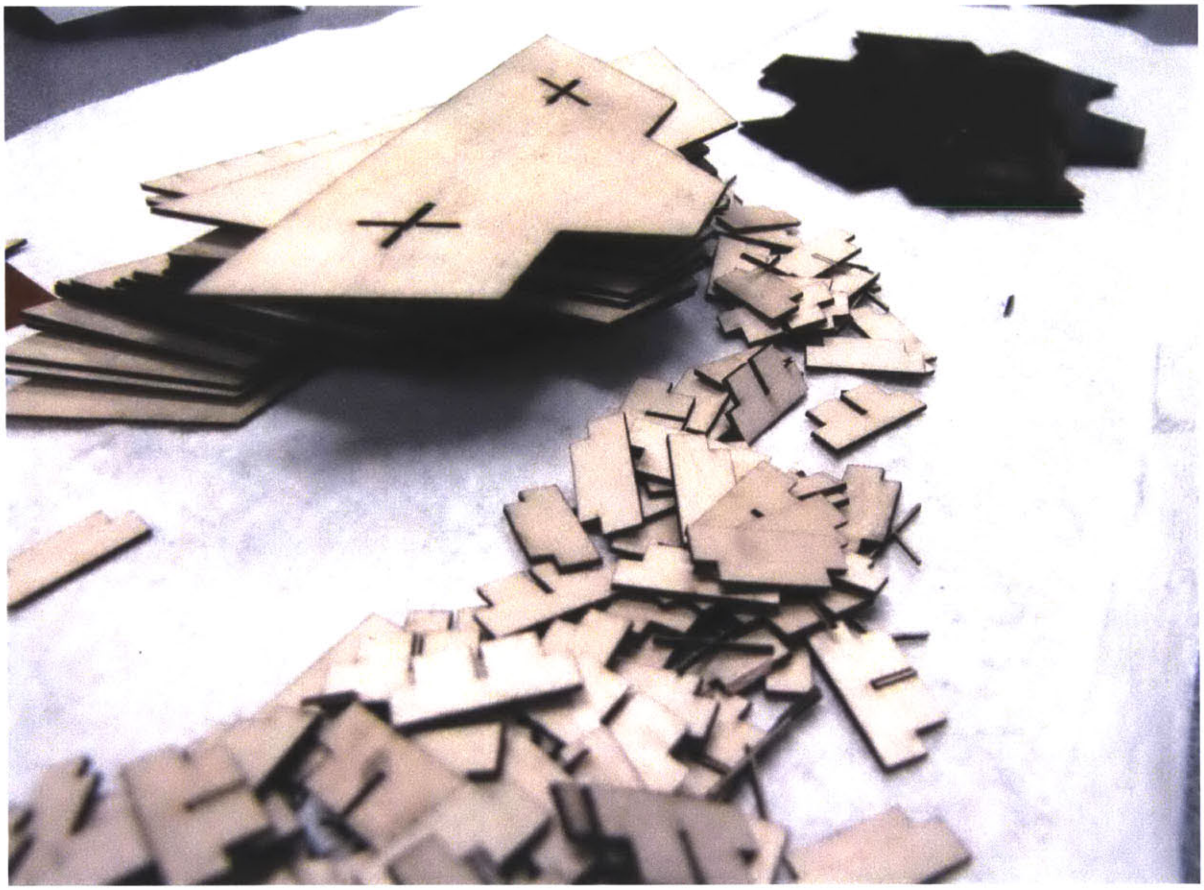


Figure 6.4 Joint inserts and rigid components for the outermost layer of the pressure vessel prototype

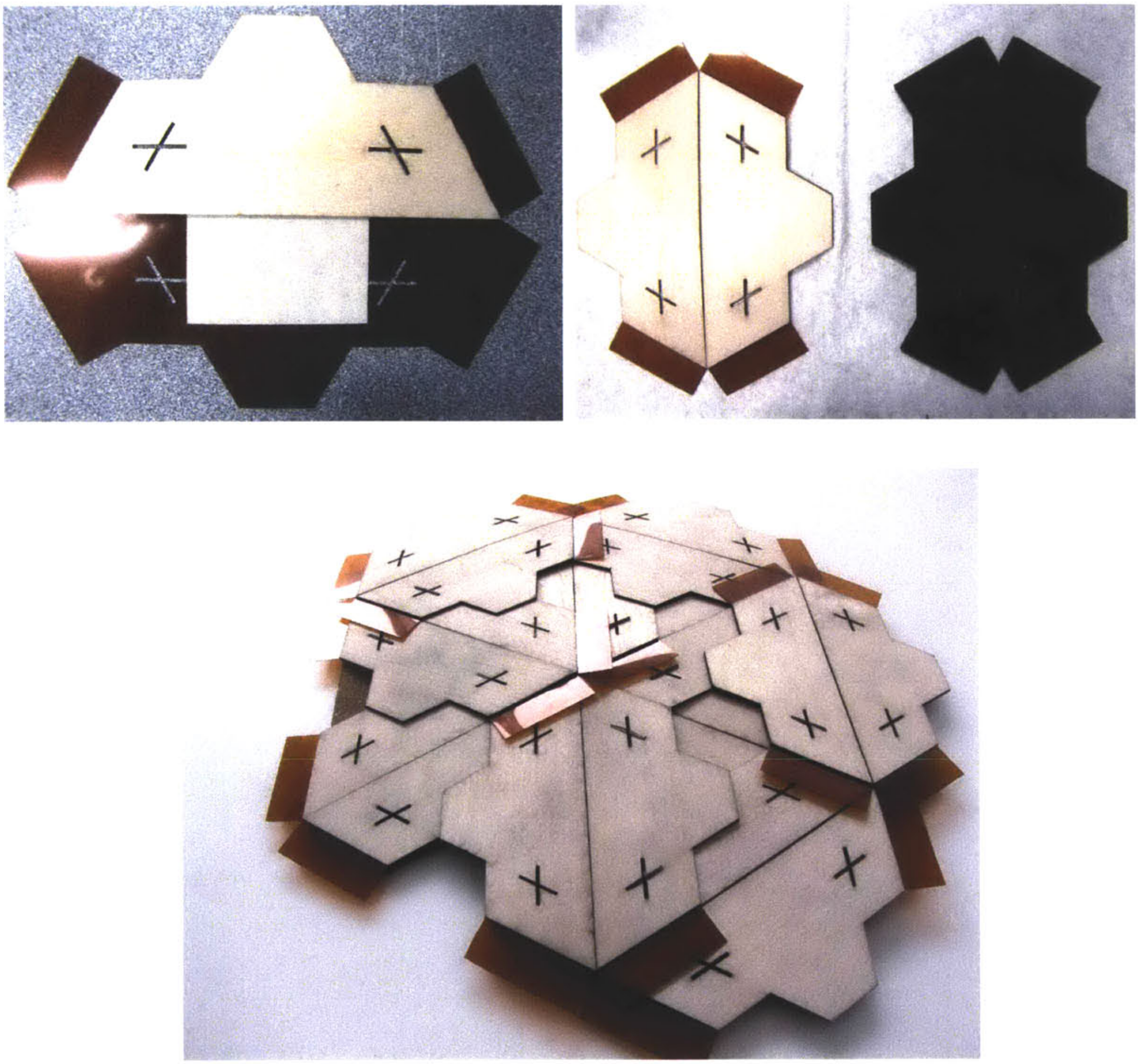
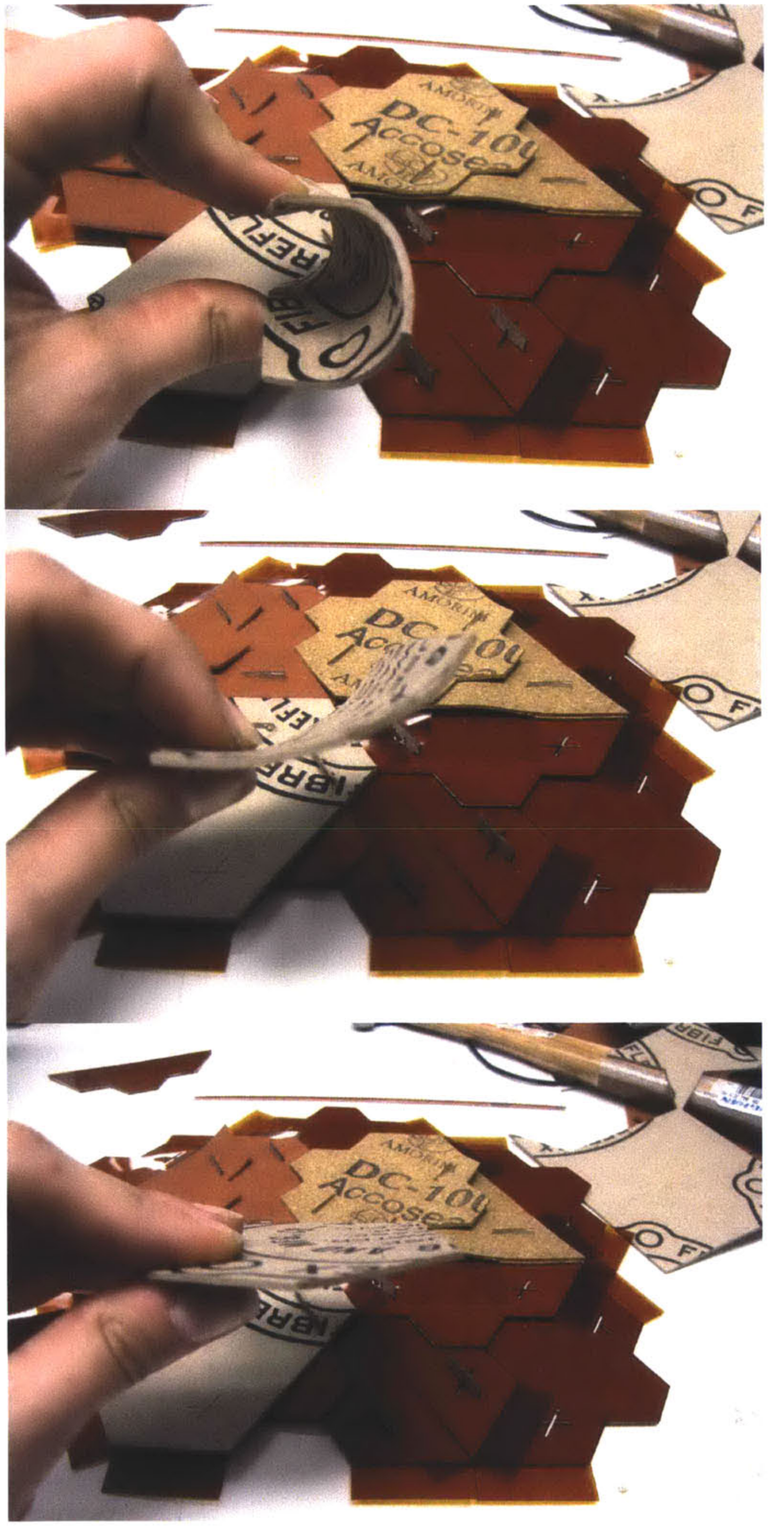


Figure 6.4B Rigid exterior , and flexible interior with inserts penetrating through several skin layers

6.4 Fabrication and Assembly of a Pressure Vessel Digital Material Skin

The surface is designed as a multi-layer composite skin system, with every layer completing one or more important functions. The concept of multi-layered and multi-material composite skin is demonstrated in the work of the Harvard Monolithic Bee(Mobee), which uses folding and pop-up microfabrication with lasercut patterns of 8 different layers com-



6.4C Gasket experiments, vegetable fiber gasket part of digital material skin composite layer

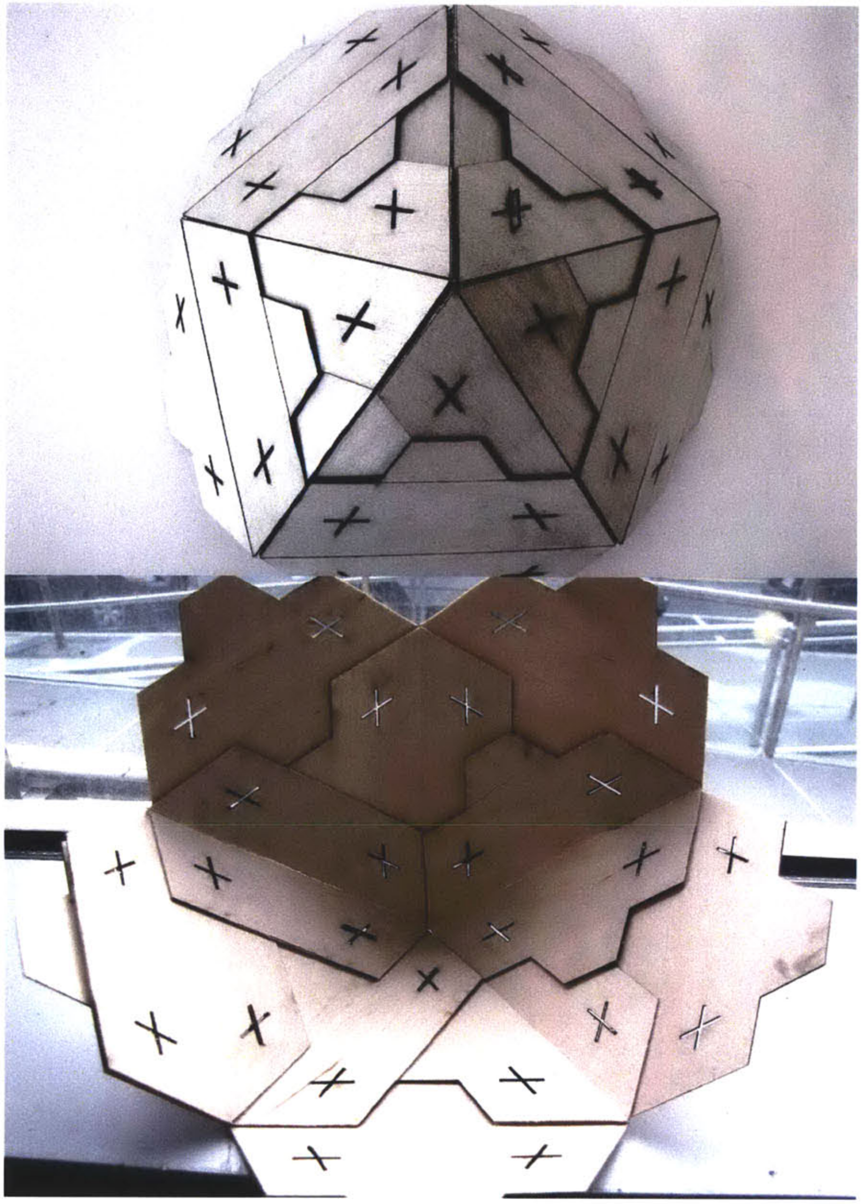


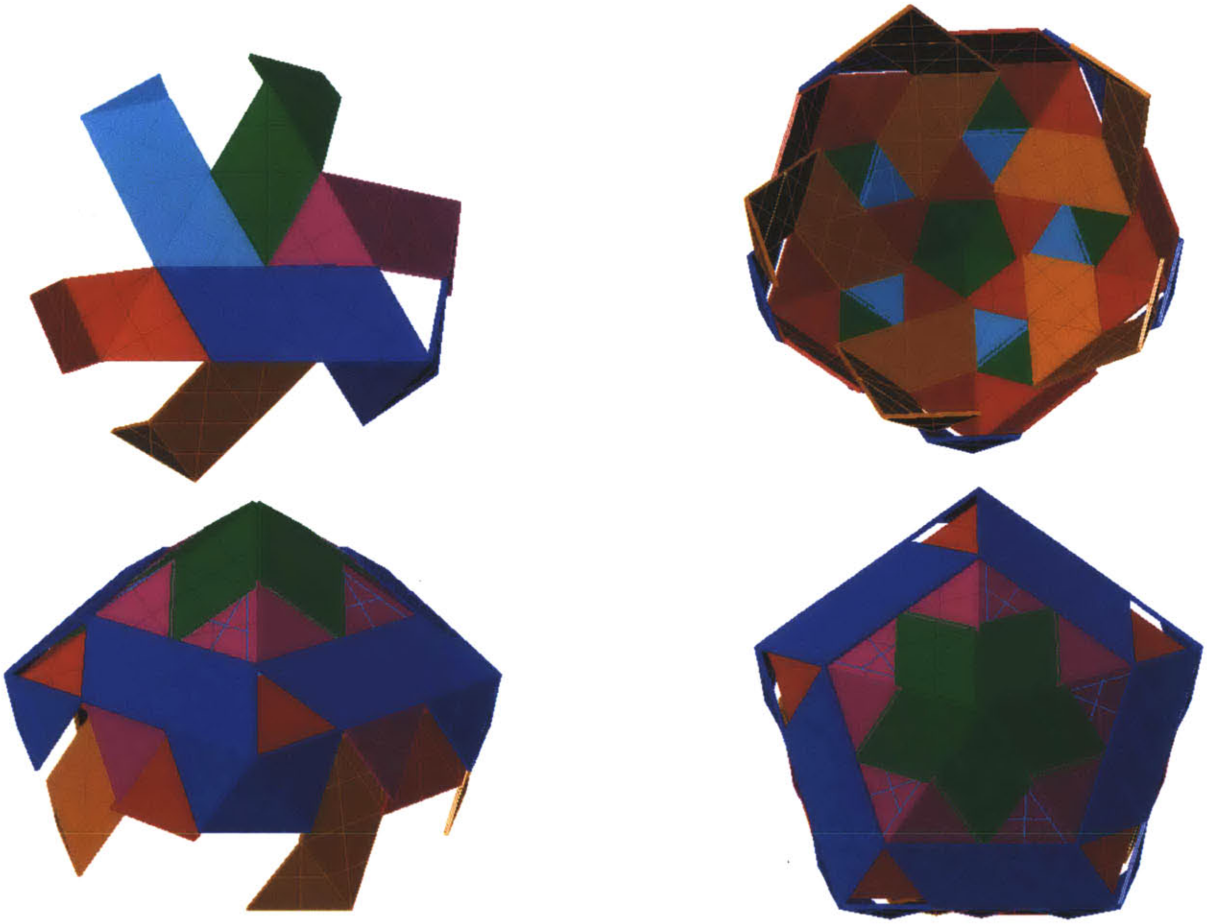
Figure 6.4D Digital material skin, rigid exterior layer

bining both rigid and flexible materials that function as beams and joints in the system. A diagram of the digital material skin system is illustrated below. The layer on the exterior is a stiff and high strength material which defines the part geometry and shields the interior contents from the exterior. The next layer is kapton film, which provides flexibility and strength in tension. The third and final layer on the interior is a thin gasket sheet.

For the construction of the physical prototype which initially is just a flat skin, several ma-

Figure 6.4E Final composite digital material skin system

terials were tested for each layer. The outer most layer was made of 1/32" birch plywood that was lasercut with a line etched along the center of two adjacent components to allow the units to bend together. This layer would eventually become a carbon fiber material. This second layer is HN kapton polyimide film at 100FPC, providing flexibility along with a thermal barrier for applications up to 400C. The ultimate tensile strength of this film type is 139MPa, an elongation of 83% and a density of 1.42 g/cc. This is currently used as a flexible joint in the model applied with an adhesive backing, but eventually would only function as a thermal barrier. The third layer is the gasket layer, and several gasket and rubber materials were tested in the first physical prototype. Vegetable fiber gaskets are impregnated with a compound which protects against water and oil, and although this demonstrated good absorption, the exterior side of the fiber was also wet after the initial test. The red gasket in the image is SBR Rubber, while the brown is a cork and rubber blend. Additional gasket materials to look at include high temperature carbon and graphite gaskets, corrosion resistant gaskets, and ultra high temperature gaskets made of alumina ceramic fibers that can withstand up to 2600F. Adhesives are only used to secure the kapton layer to the wood, while the press fit pin secures all layers in cross-section.



6.5B An icosahedron with 20 equilateral shapes using the most current digital material geometry which tiles by creating 3 or more overlapped areas per face.

The current physical prototype has inserts that press fit from the exterior and shift and lock on the interior. This is the key property which allows for reversibility of the structure. The pins are pushed and locked in place by hand, but one could imagine a digital material assembler which would pick and place each joint quickly and easily speeding up fabrication time. A square foot of this composite digital material skin was tested by pouring water on the gasket side of the model. After a few minutes, there was leakage on the exterior side of the model.

6.3 Future Design Studies of Pressure Vessel Digital Material Skins

The problem with this model is that the inserts for the joints are exposed on both sides, and it is believed that if the skin is designed such that the rubber gaskets also overlap on another layer to cover each joint on the interior, then there should be no way for the water to permeate the skin.This design solution is illustrated in the figure above. Each color represents a different layer in the skin system. The design for the part geometry is in the

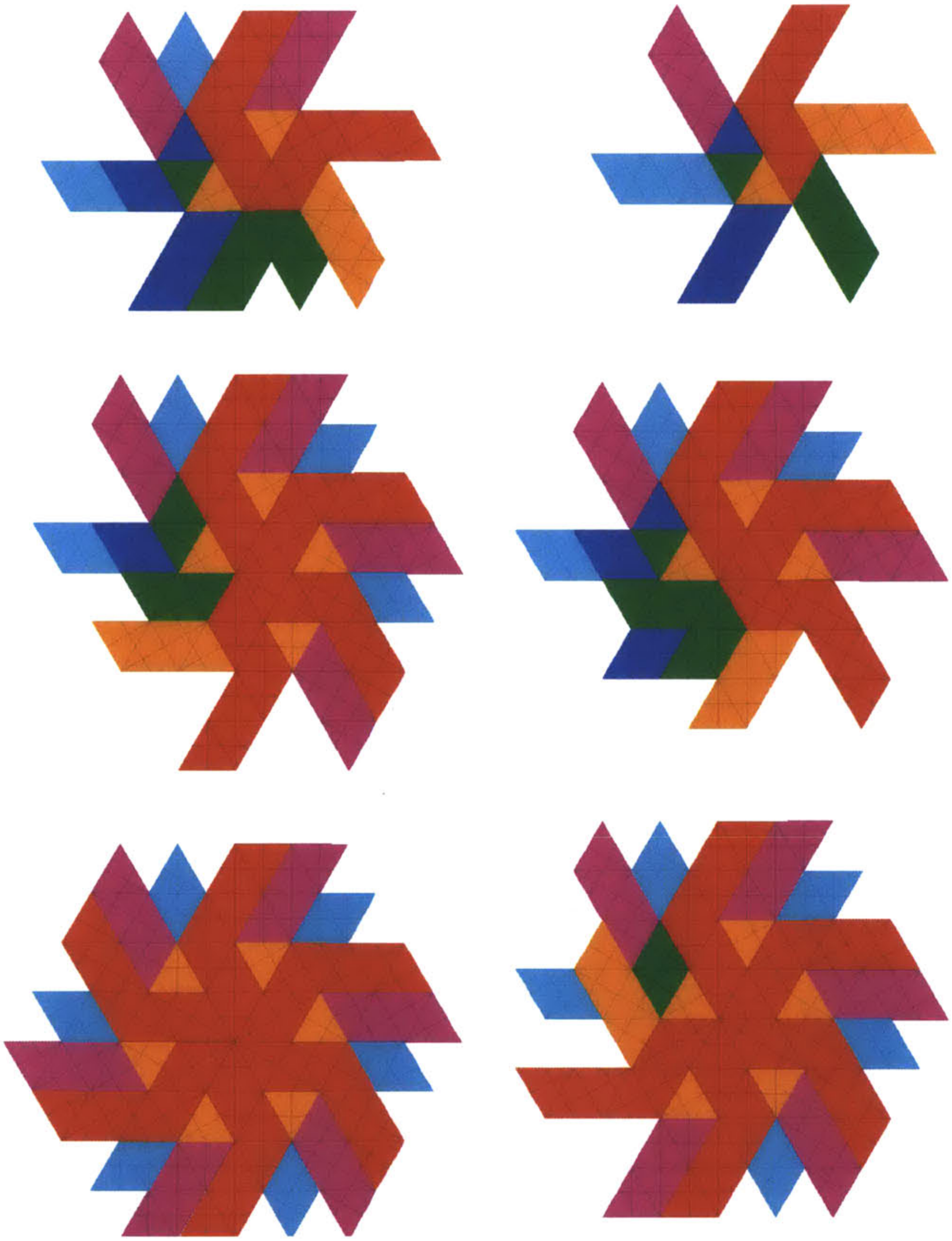


Figure 6.5C Close packed configuration of an overlapping digital material skin system

shape of an L, confined at one end into the skin while the other end is a loose flap which covers an existing joint directly below. In figure 6.5A, we see the same shape forming one flap of an icosahedron face or equilateral triangle by simply rotate the same geometry. Six strips form one face. Figure 6.5C shows the geometry tessellated and closely packed, while figure 6.5D shows the strips spread out. Future work will identify how the joints and number of layers change depending on the configuration of the tiles. Future work will also identify how this system can be used to tesselate a sphere(figure 6.5B) as well as other polyhedral shapes.

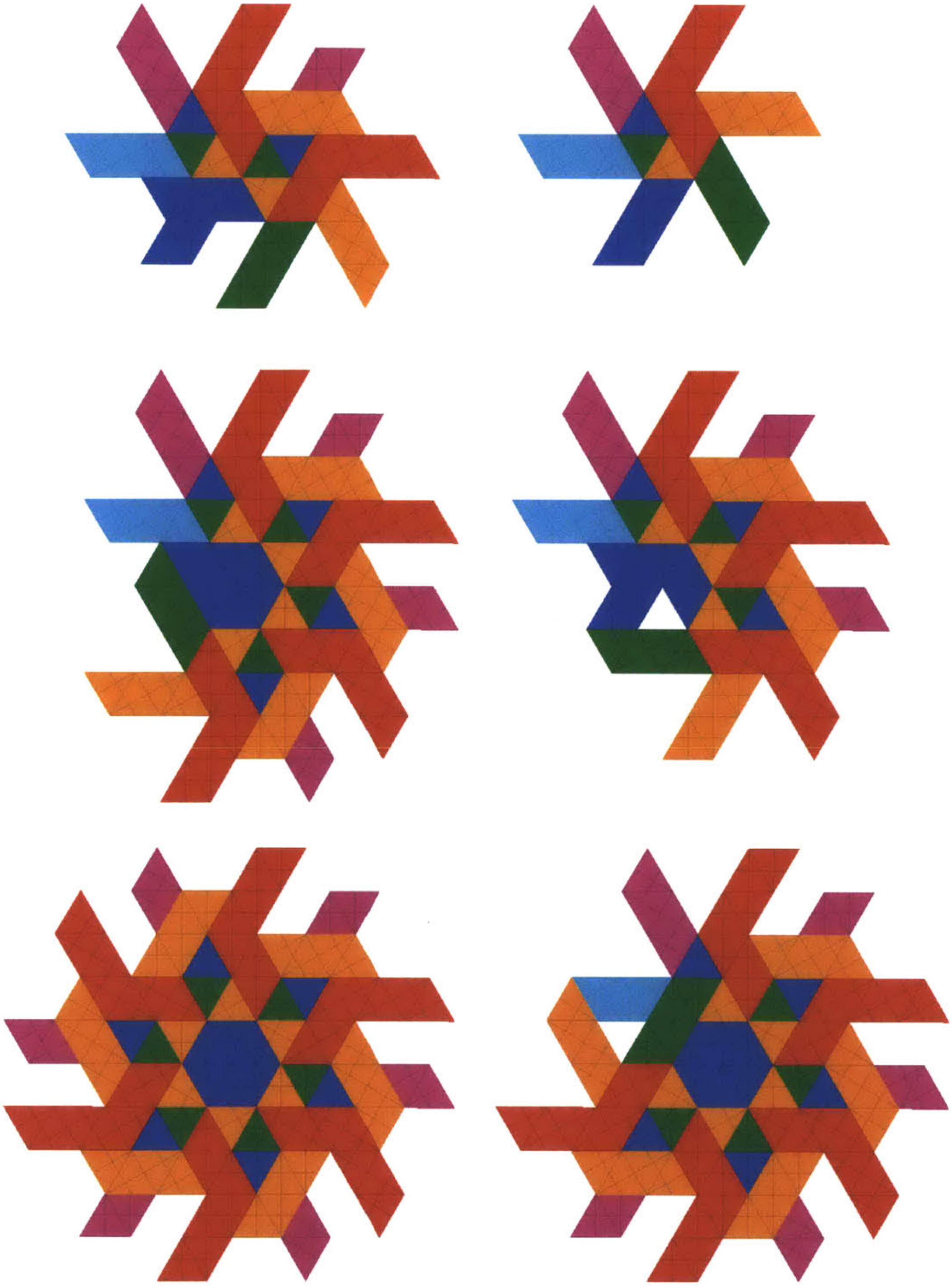


Figure6.5D Second configuration of an overlapping digital material skin system

7 Conclusion

7.1 Relevance to NASA

This work has been funded by NASA's Office of the Chief Technologist. Digital Material Skins for space applications delivers a new space capability which is fundamentally based on reversibility, reusability, and recyclability. To be able to build long term self-sustaining permanent infrastructure, reuse and recyclability must be incorporated in every design aspect as early in the lifecycle as possible. Current infrastructure and technologies for high risk environments rely on redundancy and waste, where valuable hardware is discarded after one time use. To be able to colonize planetary surfaces, one must build self-sufficient closed looped systems which are able to expand capabilities from initial seed technologies. This work has great potential application for Tab 07 of the 14 Space Technology Roadmaps: Human Exploration Destination Systems, specifically Section 2.2.1.4-Manufacturing and Infrastructure Emplacement. This section is comprised of three subcategories including: In-Situ Infrastructure, In-Situ Manufacturing and In-Situ Derived Structures. The primary goal of ISRU is to reduce the need to launch items from Earth, by creating technologies that are sustainable, to produce and reuse materials onsite to build permanent infrastructure for long term exploration. NASA has also recently begun a project with Boeing to develop one of the first composite cryogenic propellant tanks which will use the latest composite materials alongside new fabrication and assembly technologies to develop lightweight and low cost tanks. This will create an increase in upmass capability through the advancement in materials, manufacturing and structures for use in heavy lift vehicles, in-space propellant depots, and any other space exploration architectures. The goal of this project is to develop these disruptive technologies by coupling affordability with performance.Cryogenic Propellant Storage and Transfer(CPST) is another project led by NASA's Oce of the Chief Technologist, which aims at developing a Space Launch System(SLS) to be able to deliver fuel for deep space exploration, along with logistics of creating orbiting fuel depots to contain fuel and new technologies needed to mitigate or prevent boil-off in orbit. Future space technology strategies need to focus on avoiding complete loss of harware by creating a workflow that is able to repair and reuse parts at different stages in a mission.The research has proposed ditial materials as a starting point for the design of systems that will be easily reconfigured for scavenging and reuse at the component level in in-situ repair and fabrication.

7.2 Contributions

The work has demonstrated that traditionally continuous pressure vessel materials discarded at the end of the tank lifecycle can be constructed out of a new material and new design methodology that allows for reuse and recyclability. The work contributions include: a) new design workflow for tank skins and many other space applications,b)two high level strategies for digital material skin applications, one for a self-supporting skin such as ballons, thin walled tanks and another for a supported skin analogous to a foam core sandwich used in aircraft skin structures,c)origami tessellations as the approach to create overlapping digital material skins geometries for airtight and waterproof skins, d) a composite digital material skin made of multiple layers incorporating a rigid and flexible system both functioning as a skin and joining method to transfer loads within the structure, e) joints based on two inserts that interlock using a press-fit connection, penetrating one or more layers f) the first structural skin application with components that are reversible, reusable and recyclable g)the first skin design to be part of a future material library of digital material skins. The larger goal includes developing a useful material fabrication method that may be used by all industries, and also for the average person interested in designing their own functional kit of skins. Not only will digital material skins expand our current applications and material selections, but it will greatly enhance our understanding of future waste retrieval of everyday commodities and have a great impact on our future environment.

Bibliography

Bourell, D. L., Leu, M. C. & Rosen, D. W. (Eds.) Roadmap for Additive Manufacturing: Identifying the Future of Freeform Processing, Austin, TX, The University of Texas at Austin Laboratory for Free- form Fabrication. (2009)

Chamberlain, P.G., Taylor,L.A, Podnieks, E.R., Miller, R.J., "A Review of Possible Mining Applications in Space", Resources of near-earth space. Edited by John S. Lewis, Mildred S. (1993)

Dorworth, C. Louis, Gardiner L. Ginger, Mellema M. Greg, "Essentials of Advanced Composite Fabrication and Repair", (2010)

Eager W. Thomas. "Processes of Joining Materials" (2001)

Matthews, and Mary L. Guerrieri. Space Science Series. Tucson, London: The University of Arizona Press, p.51 (1993)

Gershenfeld, Neil. (2005), "Bits and atoms", IS&T's NIP21: International Conference on Digital Printing Tech- nologies, Baltimore, MD, September, p. 2.

Gibson, J. Lorna. Ashby, F. Michael. Harley, A. Brendan. "Cellular Materials in Nature and Medicine" Cambridge University Press; 1 edition (2010)

Gilbroath, W., P."Adhesion, or Cold Welding, of Materials in Space Environments" ASTM STP 431 (1967)

Harvey R. John, "Theory and Design of Pressure Vessels"Springer; 2nd edition (September 19, 1991)

Hiller, J., Lipson, H. (2009) "Fully Recyclable Multi-Material Printing" Solid Freeform Fabrication Sympo- sium (SFF'09), Aug 3-5 2009, Austin, TX, USA HILLER, J. & LIPSON, H. (2009b) Tunable Digital Material Properties for 3D Voxel Printers Rapid Prototyp- ing Journal.

Hilty, L. M. Electronic waste--an emerging risk? Environmental Impact Assessment Review, 25, 431-435. (2005)

Larson J. Wiley, Pranke K. Linda. "Human Spaceflight: Mission Analysis and Design(Space Technology Series). McGraw-Hill Companies; 1 edition (1999)

Moss R. Dennis, Basic M. Michael. "Pressure Vessel Design Manual, Third Edition" Gulf Professional Publishing; 3 edition (2004)

Oeftering, R., Struk, P.(2010), "A Lunar Surface System Supportability Technology Development Road- map", paper presented at AIAA SPACE 2010 Conference & Exposition, Anaheim, CA,August.

Oeftering, R., Struk, P., “The Impact on Flight Hardware Scavenging on Space Logistics”, paper presented at AIAA SPACE 2010-8700 Conference & Exposition, Anaheim, CA,August. (2010)

Pettegrew, R., Easton, J. “In-Flight Manual Electronics Repair for Deep-Space Missions”, National Center for Space Exploration Research. (2007)

Pham, D. T. & Gault, R. S. A comparison of rapid prototyping technologies. International Journal of Machine Tools and Manufacture, 38, 1257-1287. (1998)

Popescu, G., Gershenfeld, N. and Marhale, T.“Digital Materials For Digital Printing”, paper presented at International Conference on Digital Fabrication Technologies, Denver, CO, September. (2006a)

Ridley Matt. “ Genome: The Autobiography of a Species in 23 Chapters”. Harper (2000)

Robert, K. T., Hafley, R. A. & Dicus, D. L. Solid Freeform Fabrication: An Enabling Technology for Future Space Missions. 2002 International Conference on Metal Powder Deposition for Rapid Manufac- turing. San Antonio, TX. (2002)

Smith, Zeke. “Understanding Aircraft Composite Construction”. (1996)

Sodhi, M. & Knight, W. A. Product Design for Disassembly and Bulk Recycling. CIRP Annals - Manufacturing Technology, 47, 115-118. (1998)

Steitz, E. David. Newton, Kim. “NASA Picks Boeing For Composite Cryogenic Propellant Tank Tests” www.nasa.gov/home/hqnews/2011/sep/HQ_11-305_Cryotanks.html (2011)

Yanchun, L., Zhiming, J., Leu, M. C. & Caudill, R. Environmental performance analysis of solid freedom fabrication processes. Electronics and the Environment, 1999. ISEE -1999. Proceedings of the 1999 IEEE International Symposium on. (1999)