Design Robot-enabling Architectural Elements For Roof and Facade Retrofits

A Major Qualifying Project Report
Submitted to the Faulty of
WORCESTER POLYTECHNIC INSTITUTE
In partial fulfillment of the requirements for the
Degree of Bachelor of Science

by
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Abstract

This project integrated current retrofitting methods with newly-developed robotic technology. A shingle system was designed that may be robotically or manually installed to improve the building envelope of existing structures. The design is based on classic shingle installation, as shingles have historically proven to be a cheap and practical aspect of residential facades. To modernize traditional shingle design, an insulated shingle was developed, which can interface with an inchworm robot to provide an automated installation process. By utilizing Therm analysis, structural testing with an Instron, and experimental water tightness tests, many designs were created before recommending a final design and recommendations for material research, cost analysis, and mass fabrication processes.

Capstone Design Statement

The Design Robot-enabling Architectural Elements For Roof and Facade Retrofits Major Qualifying Project (MQP) satisfies the Worcester Polytechnic Institute Civil and Architectural Engineering Capstone Design requirement for a Bachelor of Science degree. This team was composed of both civil and architectural engineering students, so both requirements were taken into consideration.

The architectural design process was considered for aspects of building enclosure such as thermal performance and watertightness. Therm software was utilized to simulate heat flux and heat transfer analysis to determine the necessary insulation thickness to achieve various R-values in the facade or roof construction. The team developed a watertightness procedure based on International Organization for Standards (ISO) tests.

Solidworks and AutoCAD softwares were employed for both two- and three-dimensional drawings and renderings for each iteration of the design process. Each design iteration was first sketched by hand, then drawn in both Solidworks and AutoCAD softwares for 2D and 3D renderings. Designing in Solidworks also allowed for 3D printing of multiple iterations of the shingle design, in conjunction with 3DPrinterOS software. The 3D printing process provided physical prototypes necessary for watertightness testing.

Multiple design and building codes were consulted to ensure the design remained within current standards. The International Building Code (IBC), the The National Design Specification for Wood Construction (NDS), and The American Society of Civil Engineers (ASCE) Section 7 (Minimum design loads for buildings and other structures) were utilized for various structural calculations to ensure the design met the necessary specifications as stated in each code.

The Accreditation Board for Engineering and Technology (ABET) is a nonprofit and non-governmental organization that accredits university programs in engineering, among other science and technology disciplines. ABET states that engineering students must address various categories in project development. The constraints are as follows: economic, environmental health and safety, social, political, ethical, and manufacturability.

Economic:

A major implementation of this project was for the use of retrofitting houses, and this strategy aims to be cheaper than a total replacement of a facade, cost analysis was heavily considered in the process of this research. The cost of composite materials, as well as of magnets, RFID chips, and insulation was considered when creating design iterations.

Environmental Health and Safety:

Sustainable materials were thoroughly researched for recommendations and implementation. Additionally, the ultimate goal of this project aimed to provide a long term solution to improve energy efficiency and reduce energy waste in residential buildings. Energy leakage from residential homes is a major contributor to the climate crisis faced across the country. This project aims to address current building enclosures that leak significant energy, by retrofitting existing buildings and improving overall insulation abilities to promote energy efficiency of existing buildings. This goal was an important focus throughout the duration of the project.

Social:

The goals of this project aimed to address building envelopes and facades, specifically those of residential houses throughout the country. By improving the longevity and overall performance of these buildings, housing and living conditions of millions of people can last significantly longer while not contributing negatively to the climate crisis.

Political:

The initial draft of this project proposal was presented to the U.S. Department of Energy as part of an Advanced Building Construction research grant. Universities and other research institutions must comply with regulations stated when applying for, receiving, and reporting on the results of federal research grants. This documentation and research paper serves as a way to report on the progress of this research.

Ethical:

The objective of the robotic aspect of this project as a means of installation aims to decrease the need for human labor on job sites and thereby increase worker safety. By looking to mitigate human risk and improve safety, ethical considerations were valued during this project.

Manufacturability:

Ease of manufacturability was considered heavily as the design is part of an eight year plan to bring to the commercial market. Instead of producing one product, the team is essentially producing multiple products for one house. Ease of manufacturability was a crucial concept and has direct relations to cost of implementation.

Professional Licensure Statement

The National Society of Professional Engineers is a professional association in the United States whose overall goal is to:

> "create an inclusive, nontechnical organization dedicated to the interests of licensed professional engineers, regardless of practice area, that would protect engineers (and the public) from unqualified practitioners, build public recognition for the profession, and stand against unethical practices and inadequate compensation" ("Who we are," n.d.)

As the governing organization for Professional Engineers (PE), the NSPE defines the necessary criteria for obtaining a PE certification. To successfully become a PE, an individual must:

1. Earn a four-year college degree from an accredited engineering program
2. Pass the Fundamentals of Engineering (FE) exam, thereby becoming an Engineer in Training (EIT)
3. Complete four years of progressive engineering experience under direct supervision of a PE. Individuals must develop a portfolio showcasing their work over the course of these four years, to be submitted to the board for approval.
4. Upon receiving portfolio approval, an individual must pass the Principles and Practice of Engineering (PE) exam to obtain their license

Becoming a PE provides a variety of benefits and assets as opposed to an unlicensed engineer. In order to ensure public safety, each state now regulates that only PEs may have authority to sign and seal engineering plans. Licensure is a legal requirement for those who are in charge of work, regardless of principal or employee status. Most higher-level engineering positions must be filled by PEs, and many states also require that teaching engineering must also be done by PEs. A PE license signifies an ability to take on a higher level of responsibility, while maintaining high ethical standards. PEs are expected to improve and maintain their skills over the course of their careers, by fulfilling continuing education requirements based on which state(s) they are licensed in.

Authorship

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1. Introduction

Trends show that 75% of buildings in the United States will be renewed or renovated by 2035 (Harvard Environmental and Energy Law Program, 2019). Retrofitting the exterior of existing buildings by adding another layer of insulation is one way to have a more energy efficient building. To execute this is rather difficult because every building envelope is different. The dimensions, material, structural support systems, and other architectural aspects like windows, trim, and doors and more must be taken into account to build the system. The elements also have varying thermal properties. This raises the difficulty to effectively increase the thermal efficiency because thermal bridging can occur. Thermal bridging is the movement of heat across an object that is more conductive than the materials around it, and the conductive material creates a path of least resistance for heat. Thermal bridging can be a major source of energy loss, and can occur due to improper insulation, material choice, building design and/or conductive components of a buildings facade allow heat to transfer into the building.

On site cutting and construction of current facade and roofing retrofits by human labor undermines the goal of increasing thermal performance and decreasing cost of retrofitting. Due to convoluted fabrications and on site processes, air leakage and allowance of moisture to seep into the building is commonly found in typical retrofitting efforts. One way to mitigate this human error and increase worker safety, energy efficiency, and overall performance of retrofitting is the use of robotics. Current robotic construction systems include drone and wheeled based robots, however these methods can be problematic due to short battery life and an inability to withstand varying conditions (Fallahi et al., n.d.).

This project is a part of a multi-year project to develop a roofing system intending to improve upon these existing solutions of building retrofits, and furthermore, to assist the United States Department of Energy in addressing the energy crisis in regards to existing buildings in the country. A preliminary shingle system was designed that included two parts; a cup and a ball joint to which the shingle is attached to the latter. This system is meant for robotic installation of the cups to the building's facade first, followed by emplacement of the shingle with ball joints into the cups. Holes in the shingle and cup allow for spray foam insulation to be dispersed into the cup and cavity allowing for increased thermal performance. This system proved to be too costly, and increased the opportunity for robotic error. Using principles of civil and architectural engineering, this cup and ball joint system was modified, culminating in a final design of a simple, one-part shingle system. The system consists of interlocking blocks, and is designed in such a way that a lower shingle fits onto the underside of a block that sits higher on the facade or roof. The shingles are to be manufactured with foam board insulation inside of each block for the added value of thermal performance. Magnets and RFID chips are placed under the top surface for ease of robotic installation. The design was 3D modeled and printed and tested for watertightness, structural capability, and energy efficiency.

2. Background

2.1 Energy Crisis

Over 150 million homes have been built since 1900, though energy efficiency was not considered in construction until the 1950s. Millions of homes still in use today are therefore contributing to the significant problem regarding the overuse of energy resources throughout the United States. Specifically, heat loss and gains throughout building enclosures pose a large source of energy leakage. It has been found that adding thermal insulation to these existing building envelopes is an effective method to combat this problem while preserving the millions of structures and homes that are still in use. However, this process of retrofitting existing buildings has proven to be challenging when considering the various aspects that can make up facades, including windows, doors, and corners, as these all impact thermal performance. These current methods are commonly time-consuming and costly installations.

2.2 Roofing Systems

In order to develop an integrated shingle system that can be robotically installed, traditional roofing procedures and materials were researched. This ensured that any design alterations the team pursued were rooted in established processes that have proven to be successful and serve as industry standards. To grasp a firm understanding of these systems, the history of shingles and roofing such as asphalt and composite roofing were examined. This allowed the team to make informed decisions regarding shingle design.

2.2.1 Asphalt Shingles

Asphalt shingles are one of the most popular types of shingles used in the United States. They are extremely cost effective to manufacture, buy, and install, they are widely available, straightforward to work with, and are relatively durable. They have served as an industry standard since their development in 1893. Original asphalt shingles were referred to as “asphalt prepared roofing,” but were missing a key aspect of surface granules that were later developed. Asphalt shingles were first introduced in the United States in 1901, and by 1939, over 10 million shingles were being produced in the country. Initially, cotton felt was used as the organic base material for the shingles, though cotton became too expensive as the Great Depression hit, and new materials needed to be used as a substitute. Jute and wood pulp were used as substitutes, and by 1926 the Research Institute with the National Bureau of Standards tested 22 different kinds of experimental felt materials. This research concluded that there were no substantial differences in performance. By this point, single-tab and multi-tab shingles cut from strips were being developed and widely produced; these are the same shapes and styles used today. By the 1950s, adhesives were being integrated into the design of asphalt shingles to prevent wind damage commonly found in shingle roofs. Ultimately, a standard was set for the self-sealing strips of adhesives to ensure the shingles' durability. Another iteration during this time was the introduction of ¾" staples (as opposed to nails); six staples performed as well as four nails, and staples are still widely used today. The 1960s brought fiberglass mat bases, but were not found to be successful as they were too lightweight and susceptible to wind damage. The material composition of asphalt shingles was changed in 1987, where slate granules were added to the surface to increase durability. Other granules tested included oyster shells, mica, fly-ash, clay, and silica. These are essentially the same shingles widely used today (The History of Asphalt Roofing Shingles - Central Roofing, 2020)

Over the past century, asphalt shingles saw many iterations and improvements. Today's shingles are more durable and protective than ever, thanks to the development of modern roofing systems that utilize multiple components, such as leak barriers and ventilation. These components help avoid moisture penetration from rain and ice damming from snow. Today's shingles also meet high performance standards for fire, wind, and impact resistance. Importantly, asphalt shingles are now more environmentally friendly than ever; computerized equipment allows for improved production efficiencies which results in less material waste. Furthermore, shingles from roof tear-offs are commonly recycled to use for paving roads across the country. Innovative designs include solar reflective shingles, which can help reduce energy use. Current shingles also come in a variety of formats, including single-layer shingles with no cutouts, single-layer shingles with multiple cutouts, standard laminated shingles of multiple thicknesses, and open tab designer shingles. Each format offers different architectural elements, though all are effective and durable. Even shingle colors can also now be changed to match any design. Typical current asphalt shingles usually come in stacks, sheets or rolls, and are fairly uniform in design and composition. Shingles now have a ceramic granular upper surface, and smooth asphalt layering over a fiberglass base. They are then nailed into wooden frames for roofing structures, and are layered and staggered upwards beginning with the lowest point on a pitched roof. Modern asphalt shingle technology offers the same ease of manufacturing seen over the past decade, with added enhancements to keep asphalt as a viable material as newer technology advances (Advances in Asphalt Shingle Technology – Asphalt Roofing Manufacturers Association (ARMA), 2015).

As with any material or system, there are a variety of pros and cons to asphalt shingles. Materials and manufacturing costs are inexpensive, and serve as an economical option for construction (as well as replacement when necessary). Additionally, they are simple to install, which reduces cost as well since specialized instruction or training is not required for any contractor doing the work. These shingles are typically between $2-6 per square foot, and are not extremely susceptible to cost fluctuations. Asphalt shingles are also very easy to come by; most shingles on the market are comparably priced and constructed. Maintenance is relatively easy, with a benefit of being able to replace individual shingles as needed. Furthermore, they have a lifespan of about 40-50 years, extended by regular maintenance. Asphalt shingled structures also have a tendency to be warmer overall, which can help reduce heating costs in colder climates. There are some drawbacks to asphalt shingles, as compared to other systems on the market today. Shingles are prone to slipping, disintegration, and possibly falling off due to wear from the elements. They can weather quickly (relative to other materials), especially due to precipitation and wind. Accumulation of snow and rain can be detrimental to shingles. Additionally, since structures with asphalt shingles tend to run warmer, cooling costs in the summer and in warmer climates may increase. Asphalt shingles have both pros and cons, but it is evident in their widespread and historic use that they prove to serve as relatively effective roofing materials (Metal Roof Vs. Shingles: Pros & Cons 2022, n.d.)

2.2.2 Composite Roofing

Composite roofing is defined as a synthetic roofing material made of several commonly used roofing materials such as fiberglass, recycled paper products, and asphalt (Composite Roofing FAQs, n.d.). Much of the focus and research of composite roofing systems regards recycling materials or using green materials, being cost-effective, and making roofing more accessible in developing countries. Composites are found in a variety of industries, throughout technology, the automobile industry, and construction. Composite materials provide a large variety of properties with many different materials to choose from. Each mixture of materials provides different rates of production, material strength, ductility, thermal properties, cost and other variable properties.

Polymer composites provide a useful option for composite roofing as there are a wide variety of properties to select. Thermoplastic elastomers (TPE) are highly processable in their rubber and thermoplastic phases. There are two different types of thermoplastic elastomers; thermoplastic elastomer olefin (TPO) and thermoplastic elastomer vulcanizate (TPV) with two different chemical makeups. Despite their excellent properties and high processability, TPEs are not commercially utilized as roofing system composites. When producing these varying composites, for comparison, it is vital to look at properties such as strength, thermal characteristics, water absorption, hardness, and ductility among others. TPEs include polymers like polypropylene, polystyrene, polyethylene, polyvinyl chlorides, and other synthetic and natural polymers. TPOs are an attractive option for composites as they have a low density, can be produced at low prices and have a transparent structure. TPVs have higher tensile strength, hardness, and tear strength than the TPOs as well as having lower values for absorption and swelling. Due to its properties, TPVs are a more suitable option for application as a composite roofing system (Wickramaarachchi et al., 2019). Of the TPVs, a composite mixture of high-density polyethylene and natural rubber displayed the best overall properties. These composite mixtures could be further improved through additives.

Commercial composites that are currently used in the roofing industry are cost effective and affordable, with the averaging between $9.50 to $10.50 per square foot (Boesky, 2021). Composite roofing systems are an attractive option as they can be easily customized to match a desired aesthetic appearance as well as the material properties can be adjusted based on climate and application. Composites are typically more durable than asphalt shingles, are highly recommended for their fire-resistant properties, are often highly impact resistant, and are lightweight, with their weight ranging from 175 to 350 pounds per square, roughly equal to that of asphalt shingles. In addition to material properties, composite roofing systems currently utilized in commercial operations typically require little maintenance and can be easily installed. Similar to the metal composites, in comparison to the asphalt shingles, they are an eco-friendly option as most of the composite mixtures used are from recycled material.

2.2.3 Installation of Current Roofing Systems

The International Building Code (IBC) states that asphalt shingles must comply with section 1507.1, which states that the roofing shingles must comply with the manufacturer's installation instructions. Therefore, the primary instructions for installation are not explicitly stated in the IBC, but instead come from individual manufacturers of each product (International Code Council, 2015).

In order to gauge and understand current industry standards, the largest roofing manufacturer in North America, GAF Materials Corporation, was investigated (Asphalt Shingle & Roofing Manufacturers | ARMA, 2017). Requirements for roof and installation instructions of both the underlayment and shingles were listed on GAF's website. They stated that roofs are required to have a slope greater than 2:12 (or 17 degrees), meaning a 2" rise every 12" across, which results in a 17° slope. plywood roofing greater than ⅜", and for fasteners to be made of either aluminum coated steel or zinc. These fasteners are commonly nails, and must be between 10 to 12 gauge, have a $^{7}/_{16}$" or ⅜" head and penetrate ¾" into or go through the plywood (GAF Timberline Series Application Instructions (Trilingual), 2011).

The manufacturer GAF produces a standard asphalt shingle measuring 39 ⅜" by 13 ¼". For this standard shingle, there is a four-row pattern, repeated over the entirety of the roof. For the first course, there is no cut on the shingle. The rest of the row is placed with full shingles. For the second course, the shingle has a 6" cut and the rest of the row is placed with full shingles as seen in Figure 1. The third course's first shingle has a 11" cut and the fourth course has a 17" cut. For the fifth course, the process begins again and the first shingle is a full one. Keeping all the first shingles in each row creates a stair pattern. To fasten a full-sized shingle, four nails are used, each nail being 6" apart (GAF Timberline Series Application Instructions (Trilingual), 2011). The number of fasteners needed decreases as size of each shingle decreases.

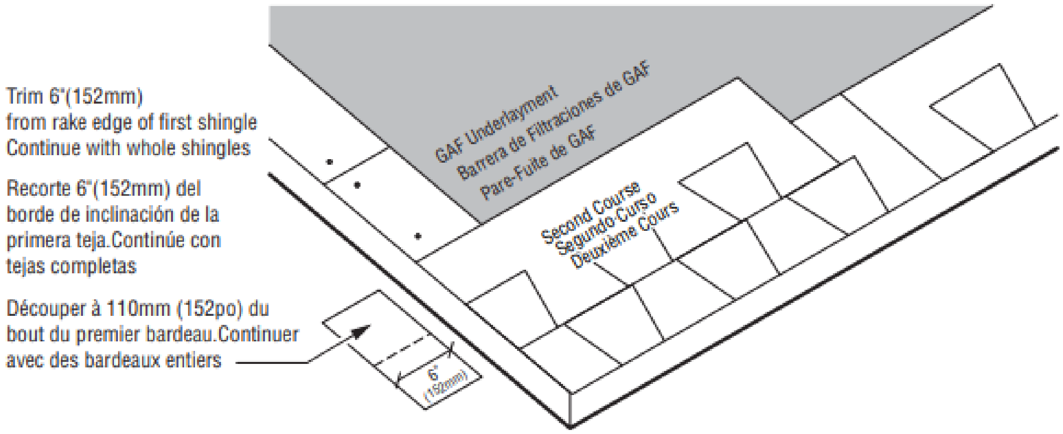


Figure 1: The installation of the second course of shingles (GAF Timberline Series Application Instructions (Trilingual), 2011)

GAF is just one of the many asphalt shingle manufacturers in the United States. However, there are several other traditional roofing systems, such as metal. There are several different requirements for installation of a metal roof, one of which is the slope. For lapped, non-soldered seam metal roof panels without sealant, the minimum slope must be 3:12. With sealant, the minimum slope must be ½:12, meaning there is a ½" rise every 12" across. The lowest minimum slope for metal roof panels is standing seam panels at ¼:12. The type of fastener used must be approved by the manufacturer. If no fastener material is specified, stainless steel can be used for all metal roofs, and commonly, galvanized metal is used for steel roofs. Furthermore, for copper sheet roofs, copper, copper alloys, bronze, brass or 300 series stainless-steel fasteners must be used for installing the sheets. Aluminum panels require aluminum screws, and additionally require supports made from aluminum. To install metal roofing, 1x4" wood strips, known as furring strips, should be applied on top of the underlayment material. They should be installed vertically, be 24" on center and fastened to the roof deck. Horizontal strips should then be laid on top of the vertical ones to create a square grid. This cavity allows condensation forming on the side of the metal to drip down the underlayment, out of the roof and not into the building.

2.3 Cavity Walls and Insulation

To further understand methods to improve building envelope, current industry efforts to improve insulation and air-tightness were examined. One design strategy proven to be effective is a cavity wall. A cavity wall is a double wall consisting of two vertical layers of masonry separated by an airspace and joined together by ties (*Cavity Wall | Architecture | Britannica*, n.d.).

Cavity walls have a heat flow rate that is 50% that of a solid wall; they are typically utilized in colder climates as a result. Cavities also allow moisture that penetrates the exterior wall to drain. They are commonly used as either non-load bearing infill for framed buildings, or for bearing-wall construction. If used as a non-load bearing cavity wall, the two sides (also known as leaves) of the structure are of equal thickness, or the internal leaf is thicker. Cavity size is typically between 4-10 cm, and the internal and external leaves should have at least 10mm thickness. These designs provide better thermal insulation than solid walls, because the cavity is full of air and thereby reduces heat transmission into the building from the exterior. Furthermore, moisture content from the atmosphere cannot penetrate the envelope because of the hollow space between the leaves, thereby preventing dampness. While current cavity walls are intended for masonry design, the team investigated the possibility of implementing the mechanics behind cavity walls into the design to provide effective insulation in retrofitting existing structures (Anupoju, 2016).

One of the most significant advancements of insulation technologies is the development of spray foam insulation. Spray foam is particularly of interest, as it can increase the insulation level of an existing structure without sacrificing interior space or need to install insulation in the interior of the building. One common method for utilizing spray foam insulation includes installing 2x4 studs over the existing siding, which are held slightly away from the wall via metal clips so when the spray foam is applied to fill these cavities, it will also fill in between the 2x4s and the existing walls. This method reduces thermal bridging or transfer of heat through the existing wall studs, while also creating a vented rain screen assembly to ensure the foam dries and solidifies (Spray Foam Insulation Applied Over the Siding of Existing Exterior Walls, 2015). A detailed drawing of the process of adding spray foam insulation can be found below.

Figure 2: Deep energy retrofit showing insulation sprayed on exterior of walls over existing siding (Spray Foam Insulation Applied Over the Siding of Existing Exterior Walls, 2015)

There are three primary densities of spray foam:

1. High Density: 3 lbs/ft^3; closed cell foam; R-values start at 5.5 per inch
   a. Used for exterior and roofing applications
2. Medium Density: 2 lbs/ft^3; closed cell foam; R-values start at 5.7 per inch
   a. Used for continuous insulation, interior wall cavity fill; and unvented attic applications
3. Low Density: 0.5 lbs/ft^3; open cell foam; R-values start at 3.6 per inch
   a. Used for interior wall cavity fill and unvented attic applications

For the purposes and goals of this project, the focus was more on high and medium density spray foam, as they have the greatest insulation potential and are better suited for our application. Closed and open cell foam are the two types of spray foam; closed cell foam is made up of cells that are pressed together so air and moisture are unable to penetrate the foam. This makes closed cell foam more rigid and stable than open cell foam, whose cells are not fully encapsulated. Open cells are deliberately left open, making the foam a softer, more flexible material. One notable difference between the two is their expansion properties; closed cell foam is designed to expand about 1” of thickness when sprayed. Open cell foam can expand to 3” of thickness; each should be chosen based on design considerations to ensure there is sufficient room for expansion. If space is a hindering factor, closed cell foam would be most appropriate as it can achieve 2x the R-Value of an open cell inside a standard wall. Closed cell foam also serves as a vapor barrier so water and moisture are more unlikely to enter the home, as well as the foam itself is protected from water damage (Open Cell Vs Closed Cell, n.d.).

2.4 Robotic Construction

All aspects of the construction field are constantly being researched and innovated. One important consideration in this field specifically is the development of robotic construction, and the implication it has on the field. In an age some define as "post-digital," in other words a blurring of digital and analogue worlds where real experiences become interchangeable with virtual ones, it is a natural step that fields that were historically dominated by manual labor may soon become replaced with automated aspects or systems. Architecture and construction is no exception (Hopkins, 2018). Robotic aspects of construction are more frequently arising; one new example of this is the Polibot, a prototype cable construction robot developed by Mamou-Mani architects, based in England. This technology allows architects to design in code, which is fed directly to the robot. Architectural drawings can be translated into lines of code, read and interpreted by the robot, which can then pick and place construction blocks to build the design. The cable robots are portable, easy to hoist, and can handle various construction materials. A sensor helps the robot differentiate between modules, and a constant flow of information between the machine and a computer ensures that every piece is laid exactly where it should be. The robot can also autonomously assemble or disassemble modular structures, following the digital blueprint. (Volpicelli, 2018). Though the Polibot is currently doing small scale work, the designers have plans for full skyscraper construction with this technology within the next few years. Similar technologies are popping up across the globe, and serve as powerful pioneers for what the future of the construction industry may look like in the near future.

3. Methodology

Our project goal is to design a shingle system that is able to be robotically installed (or manually) that is watertight, structurally sound in various weather situations, and improves energy efficiency of existing buildings. Three objectives were developed to achieve the goal of this project:

1. Develop a shingle system with the robotics team, that may also be manually installed, while optimizing RFID chips and magnetic connections.
2. Model all loading scenarios during the placement process by the robot for screw installation and Velcro installation.
3. Test water tightness and thermal performance of the system to detect leaks and verify the quality of assembly utilizing Therm simulations.

Our research team began with a preliminary 3D design developed in Rhino that included a cup and ball joint. This became one of 5 shingle system designs that were explored and tested; four being slight modifications of the “cup and ball” system and the fifth being a shingle block. The designs were then tested in compliance with ASTM (formerly known as American Society for Testing and Materials) for water tightness, structural capabilities, and energy efficiency. The data was analyzed and modified to be in compliance with IBC (international building code), IRC (international residential code), the IEBC (international existing building code), and the ASCE (American Society of Civil Engineering) 7. Having achieved these three objectives, the shingle system is able to be robotically installed and increases energy efficiency of a building's facade.

3.1 Development of Shingle System Design

Several different modifications were made to the existing cup and ball design, as well developed a new shingle system design dictated by the name “shingle block system.” To help guide the design process, criteria were made. These design criteria came from both teams of the project. On the (architectural engineering (AREN) & civil engineering (CE) side, the design had to be energy efficient, structurally sound, watertight, cost effective and aesthetically pleasing. From the robotics engineering (RBE) team, their goal for the team was the design to be easily movable by a robot, simple installation and to be traversable by robot.

First, the design of the cup and ball system (the original design given to us) was researched and tested. The original cup and ball system was printed in PLA material. However, the material was too rigid to allow the cup to deform enough for the ball joint to be inserted. To solve this problem, the team researched a number of different 3D printing materials and sorted their pros and cons. TPU (thermoplastic polyurethane) has a rubber-like elasticity, resilience, and durability and is an available material in the prototyping lab located at Worcester Polytechnic Institute. This material allowed for the cup and ball system to fit together and increased elasticity the system material needed for the design to work (TPU's shore hardness is 60A - 55D) (Chen, 2020).

There were several limitations of the cup and ball system. The entirety of the ball joint was not able to fit inside of the cup. This was solved by two modifications: increasing the notches on the side of the cup from 0.5 inches to 0.75 inches long and decreasing the wall thickness by 0.1 inches as seen in figure 3. Both designs changed the force required to push the ball into the cup and were considered because they addressed the RBE requirement of easy installation. In the preliminary design, the base that the ball sat on held a triangular shape, which created the opportunity for tilting caused by wind uplift. To combat this, the base of the ball joint was extended and made flat. With this modification, any wind uplift force applied to the shingle would not cause tilting, as the shingle, which lay directly in contact with the ball, now laid flat on the upper surface of the cup as well.

The cup in the original system had only one screw for means of installation. This could create possible rotation around this singular screw, and thus, misalignment when a shingle is being installed. Furthermore, the ball's spherical geometry also allowed for rotation while inside the cup which could also create potential misalignment of shingles. One solution to mitigate this potential issue was to add spikes to the design on the bottom of the cup as shown in Figure 5a. These spikes were designed to penetrate the roof deck to prevent rotation. Furthermore, to address the issue of the rotating of the ball inside the cup, a cube was added on the end of the ball joint as seen in figure 4. A cube would better resist the moment and torque applied to the shingle, thereby increasing stability in the design. Shown in figure 5b, it was also considered to add a clipping mechanism, similar to a clip found on a backpack, on the end ball joint that would connect to the cup. This would increase the capacity of the uplift force on the shingle, intending to create a more secure connection between the cup and ball. This design would also mitigate rotation.

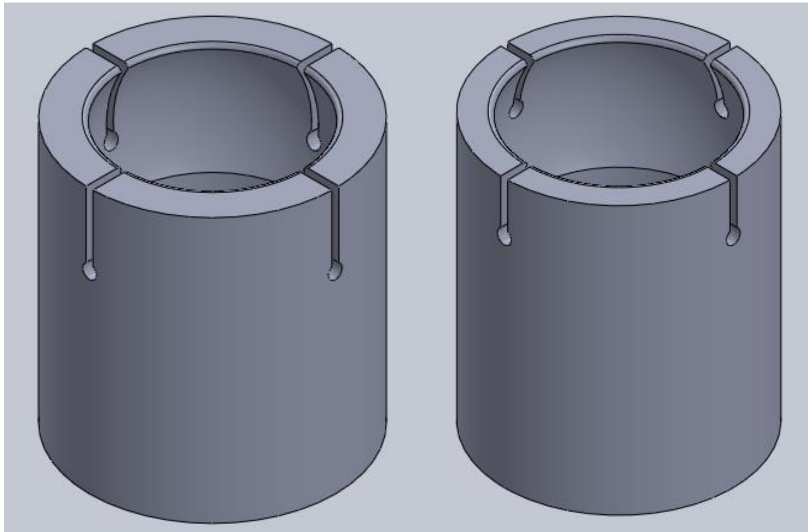


Figure 3: Cup and ball redesign with 0.75 in notches (left), and 0.1 in thinner walls (right).

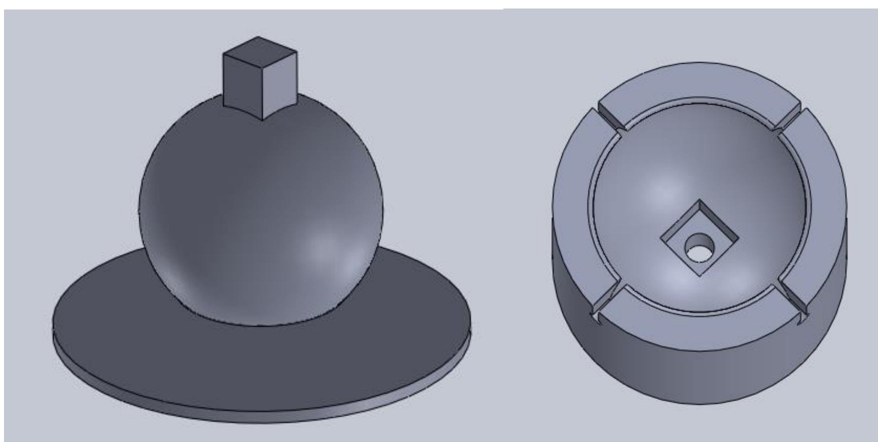


Figure 4: Cup and ball redesign with square end ball joint (left) and square end cup (right).

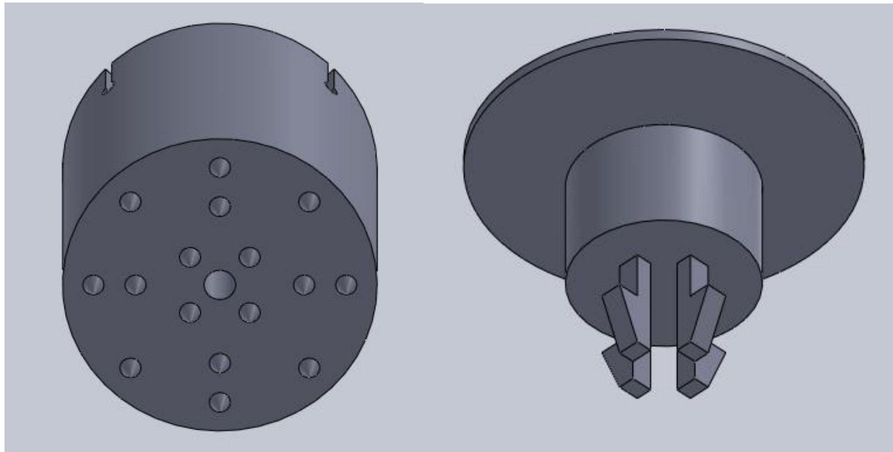


Figure 5: Cup and ball redesign of cup with spikes on the bottom (left) and Cup and ball redesign with added clipping mechanism (right)

There were still potential structural issues with the proposed design, so further iterations were considered to try to improve the system. A singular part system was also explored, to where the cup was disregarded and the shingle with a cube backing was installed directly into the roof or wall. This design created an opportunity to look at more simplified designs. It also still allowed the use of spray foam insulation, as a cavity would exist between the shingle and the wall or roof surface.

The two part system of having a cup and ball was thoroughly researched and tested. However, this system proved to be too complex, over-used materials, and the structure of the design was fundamentally flawed. A new design was developed that became known as the "block design," or "shingle block." This composite design mimicked the look of traditional wood or slate shingles in its rectangular design as seen in Figure 6. However, this version was much thicker than an ordinary shingle. This had the purpose of holding insulation inside of the shingle shell as opposed to using spray foam in a cavity. This system also was more cost efficient as it used less material. The cup and ball system designs required about 50.67 in^3 [830.33 cm^3] of material, while the block system utilized 21.87 in^3 [358.39 cm^3]. When converted to cost, the cup and ball system was 47 cents of plastic per pair of cup and ball. On the other hand, the block design was 19.87 cents of plastic per singular shingle for a similar size (*Post-Consumer Plastic Bale Prices Jump - Plastics Recycling Update*, 2021). The shingle block also provides an opportunity for a simplified robot interface. The robot only has to surmount traversing one component (just shingle) as opposed to two (both cup and shingle). Furthermore, installation by robotic means can be streamlined due to simplified shape; a rectangular shape can be stacked and stored on the robot for more systematic storage and placement. Finally, foam insulation was placed in the shell of the shingle block and therefore, the thermal performance was integrated into the system. This differed from the cup and ball system, where a cavity was created for spray foam insulation to be inserted. An integrated thermal system eliminated the need for complex robotic function, and decreased the installment time.

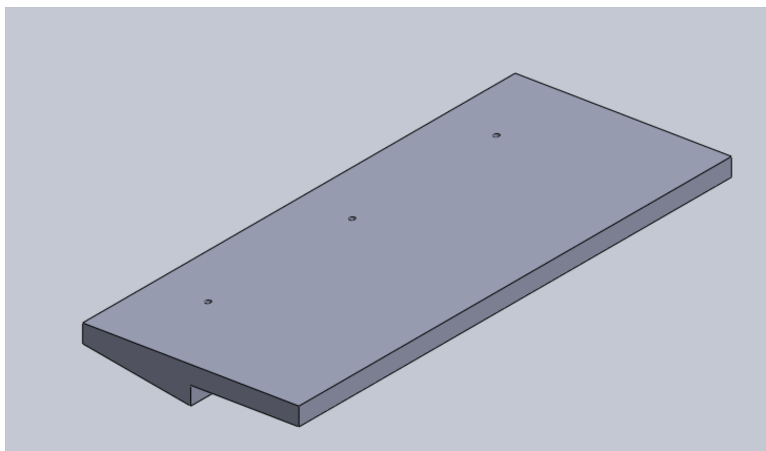


Figure 6: Shingle block shingle design with screw holes

Two fastening methods of the shingle block, one with screw holes and one with Velcro as means of installation. Screws can be drilled into pre-manufactured holes in the shingle and then further into the roof deck. The advantage of a screw is there are design provisions in the NDS. Finding the capacities of the roof deck and screw are a known process. The disadvantage is the installation time. Screws cannot be drilled quickly by the robot and may require storage on the robot. The second method is to secure the shingle with Velcro. Velcro would be adhered, in a lattice form, to the bottom of the shingle as well as the roof deck. The shingle would then be installed on the roof deck via compressive forces from the robot. The advantage of Velcro is the ease of installation and the elimination of robot processes such as drilling and screw storage. The robot only has to apply force and ensure the connection between the shingle and the roof. However, there are more components involved with the connection such as adhesion of Velcro and more surface area to account for proper distributed force while installing. There are also no design provisions available for Velcro. This makes determining the capacity of the shingle more challenging.

There existed several solutions for the interface of the block design and robot in regard to transportation of shingles and robotic traversing of the shingles. A main concept brought to the table is use of magnets and radio frequency identification (RFID) chips. RFID chips use radio waves to transfer information from microelectronic tags to an object, in this case the receiver on the robotic end-effector (Ajami & Rajabzadeh, 2013). The size and placement of the magnets rely on the size and shape of the robotic end-effector. Weekly meetings with the robotics team were conducted to discuss its latest design. First iterations of magnet placement with screw hole design can be seen in figure 7. Foam insulation is placed inside of the shingle shell and magnets are placed on corners of the top face of the shingle. The corner magnets serve the purpose of alignment of shingles as well robotic manipulation.

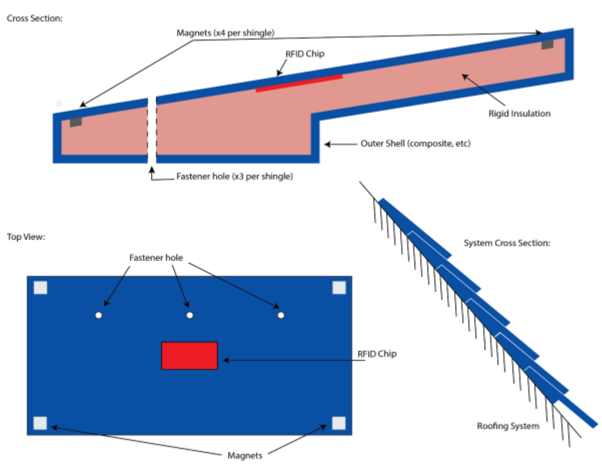


Figure 7: First iteration of Shingle block with screw installation

However, magnet placement in the does not create a balanced distribution of weight and thus the design is inefficient. Cost was also considered when designing the size and placement of magnets. Simply, the more volume of magnets, and more magnets placed on the top surface, the increased manufacturing cost. The circular end effector of the robot prompted a redesign of three magnets placed in a triangular formation centered in the bottom half of the top surface, as seen in figure 8. This design was then tested in terms of its dimensions, the Velcro was tested for the minimum force needed for installation, and physically tested with the robot.

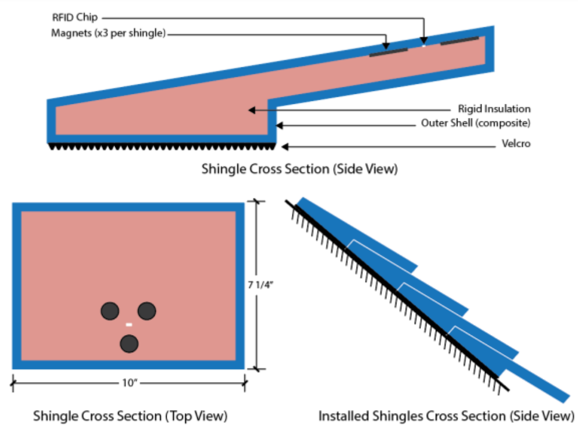


Figure 8: Second iteration of shingle block with Velcro design

3.2 Data Organization

To collect the information, Google Doc folders were used. This was especially helpful for the Solidworks designs. Every design and change were documented. The designs were in a folder and the changes, as well as the procedure to make the change. The same was done for the testing and manual calculations for each of the designs.

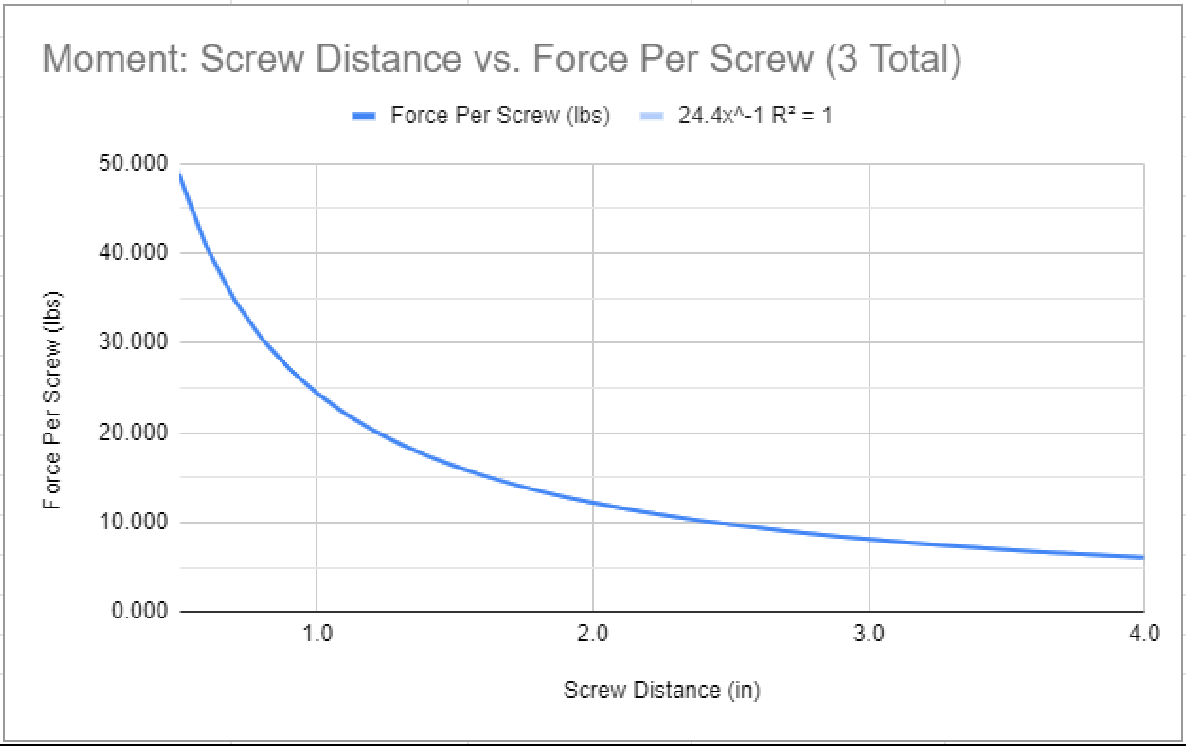
Stress vs. strain curves taken from the Instron tests were used to compare each design to each other and the design criteria. For example, if a design required less force to push the ball into the cup, then that design was more favorable. In addition, the designs were compared to requirements, from both our team and the RBE team. If the more favorable design did not meet the design requirements, then both designs were not considered. This caused a modification of the system. If all feasible designs were tested and none met the design requirements, then a modification to the design was made. This same method was applied to the structural analysis calculations. Each design was compared to each other, and the design requirements based on the calculations. The most favorable design was used, if it met the design criteria.

3.3 Structural Methods

To begin with the structural analysis of the shingle, a free body diagram was constructed. The free body diagram was a two-dimensional cross section of the shingle. The load applied to the system was the robot's weight and the weight of the shingle the robot would be carrying. The reactions of the system would be the pivot point of the shingle and the screw resisting the moment. The goal of the structural analysis was to find the forces subjected to the screw, if the shingle could withstand the shear forces and what size screw and material of plywood was necessary for the withdrawal loads in the plywood.

After constructing the free body diagram, the moment loads of the system had to be summed. The total moment of the robot-shingle system equaled the moments from the robot and the carried shingle. Those moments were calculated by multiplying the weight of each by their respective distances from their center of mass to the attachment point of the robot to the installed shingle. Once the total applied moment was known, the moment equilibrium equation was used to isolate the load and the screw's reaction. From here, the load on the screw was found. It was assumed the load was evenly distributed between the screws.

After understanding the forces on the screw and calculating them, dimensions of the shingle and the weights of the robot and shingle were changed to find the effects on the screw load. The graphs were created in sheets. The general equation was found by solving for the force on the screw in the moment equation with only variables. Graphs were then created to show the effects of each of the variables. The first graph created was the change in roof angle. This would affect the amount of moment being applied to the installed shingle. As the angle became closer to vertical, the higher the moment was and the more force the screw had to resist. The second variable change was the distance from the pivot point to the screw. As the distance became smaller more force was applied to the screw. In this load case, the roof angle was assumed to be 90 degrees, so the maximum amount of force was applied. This would also be the same for the rest of the graphs. Figure 9 shows the screw distance versus load graph. The remaining graphs can be found in the Appendix A.



Load Angle (Degrees)	Robot Length (inch)	Robot Weight (lbs)	Shingle Weight (lbs)	Number of Screws
90	22	2.646	2.000	3

Figure 9: The screw distance versus force per screw graph with the load case

The third variable was the robot weight. As the robot's weight increased, the load applied to the screw increased linearly. The last variable was the carried shingle weight. As the shingle's weight increased, the load applied to the screw also increased linearly.

The next step was to find the available combinations of plywood materials and wood screws that can support the system. In the NDS table for withdrawal wood screws, there are capacities for every wood screw size and material. The capacities are in lbs per inch of thread in plywood. To find the capacity of the plywood, first, a load case was taken from the graphs. Then a 1.5 factor of safety was applied. To get the factored load into lbs/inch of thread, the load had to be divided by the plywood thickness. In this case, ⅜" plywood was used because it is the thinnest common plywood.

The last aspect of the analysis was to find if the shingle could withstand the shear forces applied. The first step was to find the capacity of PLA. To calculate the shear capacity of the shingle, the area under loading would be multiplied by the shear capacity of the material. The area was calculated through multiplying the distance from the screw center to the edge of the base away from the pivot point by the screw's shank. This product was then subtracted by half the screw's area because that area does not contribute to resisting shear. The area was then multiplied by the shear capacity of the material and divided by a 1.5 factor of safety. This number is then compared to the shear load applied to the shingle. If the capacity is greater than the load, then the shingle will not fail.

For wind loads, ASCE-7 helped the team understand the wind forces being applied to the shingles. To get the design wind speed, the hazard tool from ASCE.org/ ASCE-7 was utilized. The Risk Category was then selected, which was Type II for a small residential example. To find the wind speed, a location had to be picked. For this instance, Worcester was chosen for the location of the building and the wind speed was found to be 117 mph. This was then converted to wind pressure. From there, the worst-case scenario was assumed where the wind would blow parallel with the roof deck, causing an uplift force. This was the capacity for the design.

3.4 System Testing

3.4.1 Water Tightness Testing

3.4.1.1 Setup

Additive manufacturing processes were utilized, in the form of 3D printing, to produce enough shingles to install on half a 2' x 2' acrylic board. 18 full sized shingles, four ⅔ sized shingles, four ⅓ sized shingles, and six ½ sized shingles were printed to test which step pattern would be most effective in preventing water infiltration. An acrylic board would be most effective during the water tightness tests, as it would enable the observation of the system underside system to check for any water infiltration. Using the same type of Velcro the tests were conducted on (see appendix B), the hook side was placed in vertical Velcro strips at 1.5" increments along the span of the board. Then, the loop side of the Velcro was placed horizontally across the base of each shingle. Each strip was measured to fit across the given shingle (using different strips for full, ½, ⅓, and ⅔ sized shingles). Next, the shingles were installed on the board, row by row to cover the necessary area, creating a lattice pattern as shown in Figure 10.

Utilizing Duct Tape, the system was sealed at each side of the installation, emulating the seal that would be found at edges of a building enclosure.

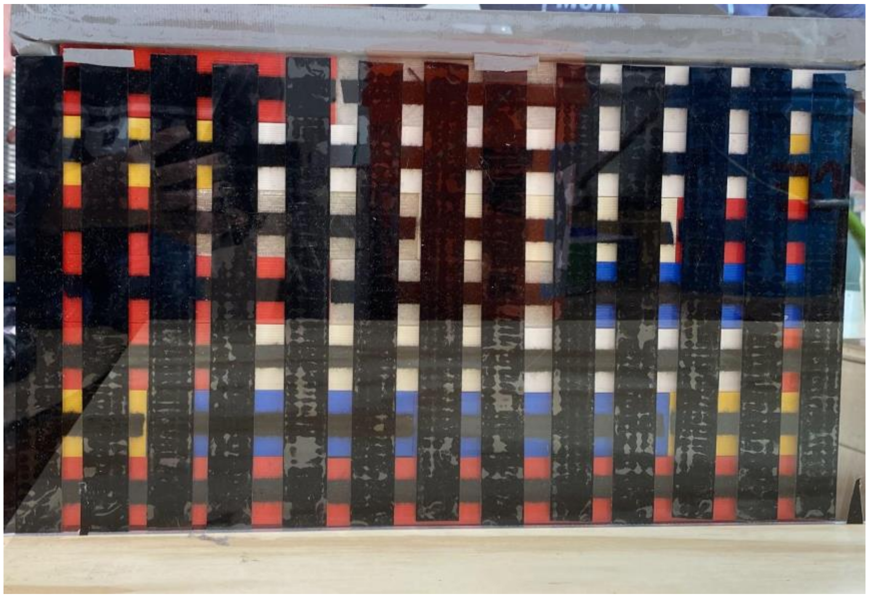


Figure 10: The backside of the watertightness roofing system showing the lattice pattern of Velcro

The acrylic board was attached to a 2’ x 4’ piece of plywood using a strip of heavy-duty Duct Tape. This would allow the team to change the angle of the shingle system, to test water-tightness at a variety of angles, as the design is intended to be used on roofs as well as facades. After the shingles and sealing were in place, a 3D printed trough was installed at the bottom of the acrylic board. This trough was designed to catch any water that might penetrate the system, which would later be measured to quantify the water leakage. A 5 L container was utilized to catch the water that would pass over the system. This was placed underneath the system, similar to the trough. Appendix B details an in-depth description of this procedure.

3.4.1.2 Conducting the Experiment

16 total trials were conducted to ensure the results were reproducible. For one set of trials, the ⅓ step shingle pattern was used, and another set of trials utilized the ½ step shingle pattern. For each trial, the water tightness of the system was tested at 45 degrees, 60 degrees, and 90 degrees, emulating various angles these shingles may be installed at for both roof and wall

construction. Simple trigonometric equations were used to determine the distance at which to place the support board, as the angle of the board was known. A 2' x 2' piece of plywood was used as a base to support the wood and acrylic board.

To conduct the experiment, a watering can was filled up with 2 liters of water. A timer was set for one minute and the water was poured the entire top layer of shingles for this amount of time. The water was then measured from both the trough and container and the results were recorded.

3.4.2 Thermal Testing

To define the scope of testing, research was conducted to determine the average residential housing wall and roof construction in the United States. According to Building Science Corporation, the typical wall construction consists of gypsum board, a vapor control layer, fiberglass, exterior sheathing, and house wrap (*ETW: Walls*, 2015). Typical roof construction was determined to consist of batt insulation, roof sheathing, roofing paper, and ultimately shingles (Lstiburek, 2004). Using Therm, a computer program developed at Lawrence Berkeley National Laboratory (LBNL), two-dimensional heat transfer was modeled for both wall and roof construction. The determined wall and constructions were each drawn in the program. Each layer's thickness was determined and subsequently drawn, then each layer's material properties were defined. This process was repeated for both wall and roof sections. The cross section of the shingle block was then drawn in the program. Copies of each shingle block were made, and drawn similarly to how they would be installed in a roof or wall construction. The figure below diagrams the wall construction with the shingles attached in the software. Material properties were defined for the shingles. As the scope of this project did not allow for focus on various types of insulation materials, the shingle material was defined as expanded polystyrene (EPS) insulation, as this is a common, widely accessible, and cost effective material. A drawing created in the Therm software can be seen below.

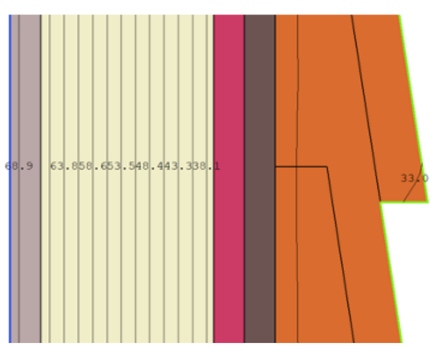


Figure 11: Wall construction with added shingles drawn in Therm simulation software

The goal of this simulation was to determine the necessary thickness of the shingle composed of EPS insulation. Interior and exterior temperature conditions were set, and two trials were conducted. One trial simulated summer conditions, the other simulated winter conditions. Average exterior summer and winter temperatures were found from Climate Consultant, which is a computer program designed to help architects understand their local climate. Climate Consultant utilizes ASHRAE Standards to display regional climate data. The average summer temperature was found to be 77°F, while the average winter temperature was found to be 33°F. These temperatures were used as outdoor temperatures for summer and winter simulations, respectively. The indoor temperature used was 68°F for both sets of simulations. After all materials and temperatures were defined, simulations were run. Six simulations were run for both summer and winter; with each trial, thickness of the shingle insulation was changed. The heat transfer across the wall and roof constructions were considered. Data was collected and results were recorded.

3.4.3 Velcro Testing

3.4.3.1 Setup

To determine the minimum force needed for the robot to push a block into place as well as remove a shingle from its place, testing was required. The material used was Velcro Brand Industrial Tape, Hook 88, 1” by 75’, Adhesive: PS72 and Velcro Brand Industrial Tape, Loop 1000, 1” by 75, Adhesive: PS72. The equipment used was the Instron machine. An Instron is a stand-alone, fully digital, single-axis controller that is packaged as a tower, and uses a motor encoder and load cell to collect data during tension, compression, and 3-point bend tests (Noren, n.d.). By gluing two ‘L’ brackets together, a ‘T’ bracket was formed and 4” inches of either the hook or loop Velcro was epoxied to the top, flat, portion of the ‘T’. Appendix C details an in-depth description of this procedure.

3.4.3.2 Conducting the Experiment

Three different tests were conducted: compression, tension, and shear. For the compression test, the method was created in BlueHill. For the first test, the specimen would be compressed up to 400 N and released. The loading rate was defined at 5.08 mm/min. The Instron was then calibrated for weight and the compression plates were attached via the hook. PVC pipes were used to transfer the load from the T bar to the compression plates. They were installed at the center of the circular plate. The hook T bar was then installed by placing it inside the PVC pipe. Then the loop Velcro was installed by lightly placing it onto the hook Velcro, so the hook and loop sides were in contact. A PVC was then placed on top of the loop T bar, so that it mirrors the hook side. Two more PVC pipes were placed on top of the loop T bar, surrounding the first PVC pipe placed on the loop T bar, as seen in figure 11. Lower the Instron so it is just touching the PVC. Zero the Instron and begin the test. Once the test ended, the T bars were carefully removed and laid them on the table for the later tensile tests. This process was repeated for 500, 600 and 700 N limits. Lastly, the compression plates were removed. The resulting stress strain graph was saved and moved onto a flash drive.

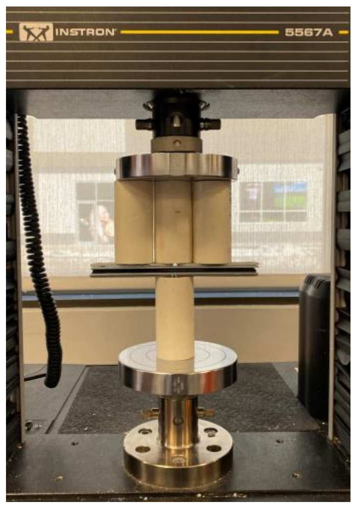


Figure 12: Set up procedure for compression test.

For the tensile tests, the method was created in BlueHill. For the tests, the specimen would be pulled apart until the present load was 80% of the peak load. The loading rate was defined at 5.08 mm/min. Then the tension clamps were installed through metal dowels. Then Instron was calibrated. The T bar was then positioned into the clamps and tightened as shown in figure 12. The Instron was zeroed and the test was started. The resulting stress strain graph was saved and moved onto a flash drive.

Figure 13: Set up procedure for tension test

For the shear test, the method was created in BlueHill. The Instron was calibrated before the clamps were attached. For the tests, the specimen would have shear forces induced until the present load was 80% of the peak load. The loading rate was defined at 5.08 mm/min. Using the tensile clamps, the T bars were pushed together with half of the hook and loops in contact with each other as seen in figure 13. The T bars were then placed into the clamps and tightened. The Instron was then zeroed and the test began.


Figure 14: Set up procedure for shear test

4. Results and Discussion

The preliminary results concluded that alterations needed to be made to the initial cup and ball design for it to be a feasible system. After completing a 3-D printed prototype with PLA material, the ball did not fit into the cup. Design criteria was established so changes could be made to this design to ultimately result in a feasible system. These criteria included: changing printing material, adjusting the diameter of cup/ball, changing wall thickness, and changing the length of the notches in the cup to provide more flexibility. Ultimately, printing the design with TPU material proved to be a significant improvement, and the ball was able to securely fit into the cup. This material was considered in future iterations of the design if chosen to move forward with this system.

We determined that the cup and ball system (or any two-part system) may not be the most effective, easy, or informed solution. This design was initially developed with the idea of a robotic interface in mind, though in discussion with the RBE team, this design would in fact be quite challenging for them to implement. Additionally, while discussing structural properties and calculations with Professor Sakulich, the team concluded that a two-part system leads to possible structural failures more than a single component system would. Speaking with both CEE/AREN advisors as well as RBE advisors, the idea was further developed to consider a system that did not require two separate pieces to install. Thus, the shingle block idea emerged as a possible system design. Conceptually, there are many benefits to this single-component design. It would be a much more cost-effective system to prototype (or ultimately manufacture), there is opportunity to enclose insulation within the thickness of the shingles themselves, it is an easier interface for the RBE team to work with, and could ultimately create a stronger and more structurally durable system than the cup-ball system would.

4.1 Structural Results

One of the important aspects of the shingle geometry is the exposed area. The exposed area is what the robot interfaces with. It also helps determine how watertight the system is. If the exposed area is much larger than the unexposed or base area, then there is sufficient water tightness, but too much material is used for little improvement in watertightness. If there is too little exposed area to base, then the tripoint of the shingles below is exposed, allowing water to seep below the shingles. The tripoint is where the overhang of two adjacent shingles begins. This point is where water can seep below the upper row of shingles through the seam and penetrate under the lower shingles by moving down the backside. The balance is where the exposed area is just small enough where the overhang of the next row covers the tripoint but does not waste material by making a very long overhang.

Using the methods mentioned in the structural section, it was determined the screw had to be #6 sizes or larger. The roof deck material must have a specific gravity of 0.35 or greater to have enough capacity to hold the screws. This was found through the vertical load roof case. The load on each screw would be 12.184 lbs [54.19 N] and from the 1.5 factor of safety, 18.276 lbs [81.29 N]. This number was divided by the plywood thickness of ⅜” [9.53 mm] to get the capacity of the plywood. To have sufficient shear capacity, the screw holes had to be positioned 1.5 in [38.1 mm] from the edge in which the screw loads the shingle. This is because the shear capacity of the material is 37.8 psi [0.26 MPa].

For wind, a 117 mph [52.2 m/s] gust would induce a force of 38.02 lbs [169.12 N] on the shingle. This would result in a moment of 52.81 in-lbs [6.55 N*m] and a force of 38.10 lbs [169.47 N] on the fasteners. A ⅜” [9.53 mm] deck do not have adequate capacity to withstand this force with screws installed. This point load was 1.58 pounds per linear inch [276.7 N/m] if distributed over velcro. This was sufficient for both the Velcros capacity and the roof decks capacity.

4.2 Thermal Results

By simulating an average wall construction and roof construction, then experimenting with necessary thickness of rigid EPS insulation to be added to the shingle, it was determined that a thickness of 1.2 inches was required to reach an overall R-1 value, 1.3 inches was required for R-2 value, and 1.5 inches was required to reach an overall R-3 value. Additionally, taking into consideration the RBE team’s limitations and optimal size and thickness of a shingle that the inchworm robot could effectively interface with, it was suggested that a shingle thickness of 1.3 inches would be most effective in terms of insulation capacity and robotic interface.

4.3 Water Tightness and Velcro Results

From the water tightness test, it was determined both patterns were sufficiently water tight. However, the ⅓ step performed better than the ½ step pattern. For the ⅓ step, 0.001% of water was able to penetrate the shingle system while 0.005% of water for the ½ step pattern. For the velcro tests, all specimens reached at least 150 N [33.72 lbs] of tension. This converts to 25,000 N/m^2 [3.63 psi]. For shear, all specimens reached at least 400 N [89.92 lbs]. This converts to 66,666 N [9.66 lbs]. Resulting graphs from the Velcro tensile tests can be found in Appendix D.

5. Recommendations

At the onset of our project, our team developed various goals and objectives to accomplish over the course of the three academic terms. It therefore was necessary to define a detailed scope of our project, and focus efforts on realistic and accomplishable objectives. As the scope was defined and worked towards our project goals, other aspects of this project were recorded that were deemed to be valuable. As this project was initially designed to be completed over the course of multiple years (and multiple different MQP teams), this team proposes these aspects be continued in future iterations of this work. Our recommendations for future project teams are as follows

1. Investigate materials properties for various component of current design
    a. Shell material, insulation material, fastener options
    b. Different thermal conditions impacting Velcro performance, and how thermal conditions effect R values of phase change materials
2. Research mass fabrication processes for shingle production
3. Expand upon current robotics demonstrations to develop real-world demonstrations in industry
    a. We suggest this include developing shingle prototypes fitted with magnets and RFID chips for robotic interface
4. Invite members of the WPI Business School to conduct market research and cost analysis on robotic and shingle system
    a. Consider what changes need to be implemented to the current design on both RBE/CS and CEAE sides to make the system more marketable for potential product commercialization

5.1 Recommendation 1

The current shingle design proposes two distinct components: an outer hard shell, and an inner insulation component to improve thermal performance of existing structures. It is recommended research be conducted on material to use for the hard outer shell. This material should optimally accomplish three goals: minimize thermal bridging that may occur between each shingle, be composed of a sustainable material so as to not further contribute to pollution and waste, and be cost-efficient as to maintain a low production cost for each shingle. Furthermore, teams should consider the versatility of the shingles for both roofing and facades, and determine if one shell material could be utilized for both roofing and wall systems, or if two different materials would be necessary in keeping with traditional architectural styles. It is also recommended research be conducted on material to use for the inner insulation layer, considering thermal properties, cost, and overall weight added to the system as to keep the shingle system compatible with the robot's capabilities. Specifically, phase-change materials are suggested (PCMs) to be considered as they are an emerging industry that would enhance the thermal performance of the system, while incorporating innovative technology to the design. PCMs can store and release heat within a certain temperature range, which can raise the building inertia and stabilize indoor climates. This is a relatively new industry, so it is suggested future teams follow the developments in phase-change technology as a possible material that would benefit the system. Another recommendation is researching how various thermal conditions would impact the R-value of PCMs. Furthermore, our team narrowed our scope to focus on Velcro as a possible fastener method to meet the needs of the RBE team's design. It is suggested that further investigation into other fastener methods be taken, as well as how various thermal conditions impact Velcro performance if chosen as a viable fastener option.

5.2 Recommendation 2

After material research has been conducted and viable material options are chosen, the second recommendation is researching ways to mass produce shingles, and what best practices would be for creating low-waste production. Additive manufacturing was used over the course of this project, and it was determined that 3D printing was a costly and time-consuming method of producing shingles, even at a smaller scale for the purposes of prototyping and watertightness testing. As the overarching goal is to develop a system that would positively contribute to the building industry as a waste-minimizing product, ultimate mass production for commercial use should be as low-waste as possible. Research should be conducted to determine best practices for production, and ways to keep costs low while developing an efficient system.

5.3 Recommendation 3

At the culmination of the first CEAE project year, the RBE/CS ultimately developed a working inchworm robot prototype to demonstrate shingle installation using the proposed shingle design. As both teams further amend their respective designs, it is recommended upon the current robotic demonstration to showcase new iterations and improvements. Specifically, once applicable shingle materials have been decided upon, prototypes should be made utilizing the chosen shell and insulation, and fitted with the necessary magnets and RFID chips for robotic interface (or any decided upon interface points in future RBE designs). Architectural and aesthetic considerations should be made regarding the shell material, while keeping in mind how the robot's end-effectors need access to magnets and RFID chips. The current shingle prototype reveals the shingle's magnet and RFID chip to the robot, though would not be an optimized design for architectural and aesthetic purposes. Future teams should take these aspects into consideration.

5.4 Recommendation 4

As future iterations are developed and materials and manufacturing are decided upon, students and faculty of the WPI Business School should be consulted to conduct market research and cost analysis on both the RBE and CEAE designs. As the goal would be to introduce this system to real industry applications, a business plan and strategy should be developed to feasibly bring this system to market. A cost-benefit analysis should ultimately be conducted to present homeowners with data on why using this system would be beneficial to them in the long term by reducing energy costs. Research would also need to be conducted to determine the cost of manufacturing shingles and robots, as well as the physical installation of the retrofits, which data CEAE and RBE/CS students could utilize to alter designs to reduce costs. Ultimately, a market strategy and business plan should be developed to present to potential investors, clients, and companies reflecting the benefits of using the final system.

6. Conclusion

Adding insulation to a building's exterior surfaces can improve a buildings thermal performance and in turn lower energy costs considerably. Typical retrofitting solutions for buildings involve on site cut and construction, leading to a decreased potential for energy efficiency and inordinate cost. Systems that do not work at potential show air leakage, absorption of moisture, and disruption of consistent indoor air temperature. Our research team sought a solution to improve the energy performance and durability of facade and roofing retrofits by use of robotics. First, the team was given a preliminary 3D design developed in Rhino that included a cup and ball joint. This shingle system included two parts; the cups are distanced at one foot apart to be installed first. A rectangular shingle with dimensions 2 by 1 feet with a ball joint attached is then to be placed into the cups. Spray foam insulation would be dispersed through a hole in the shingle and several holes on the side of the cup to hold the system in place and add a level of energy efficiency. However, this system proved to be too costly and convoluted when it came to opportunities for robotic inaccuracies. A much simpler 'shingle block' design was adapted, where the top portion of a shingle is designed to fit onto the lower portion of another, essentially creating a fitted overlap. The shingle is manufactured with insulation inside of the block for increased thermal performance and robotic manipulation is eased using magnets and an RFID chip embedded under the surface.

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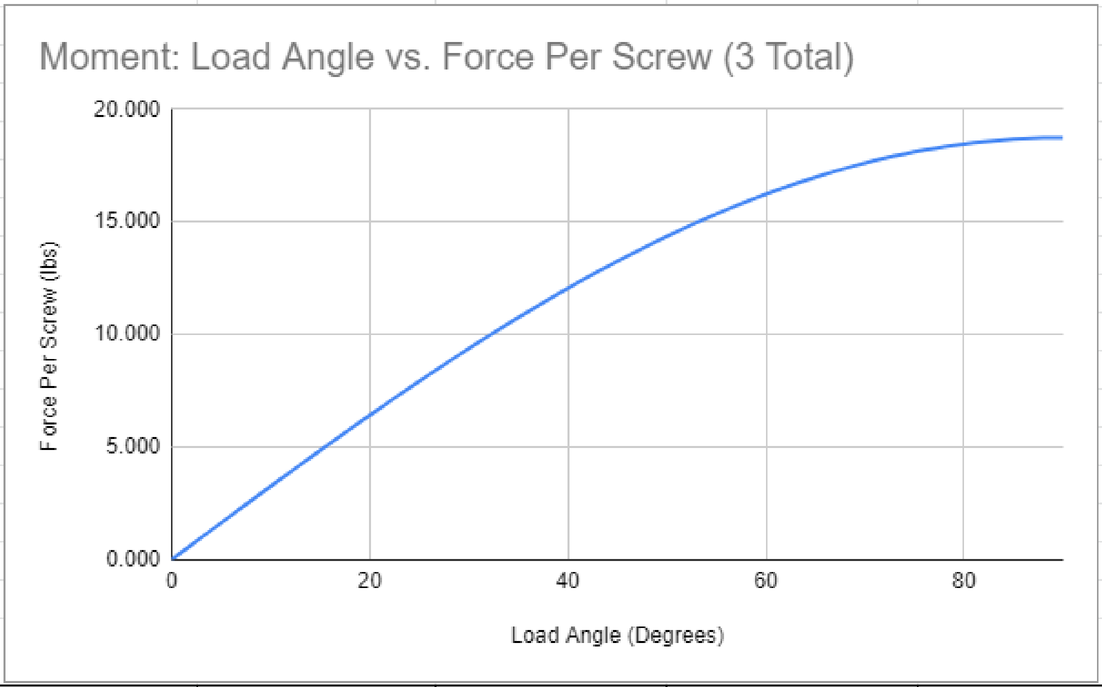
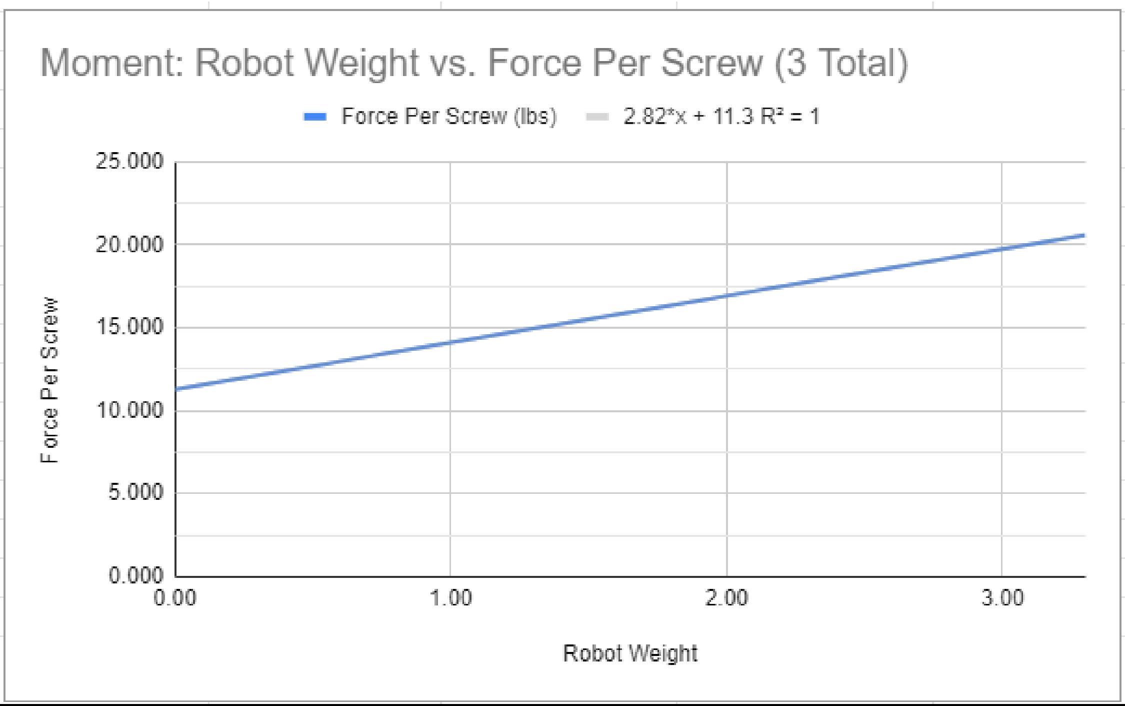
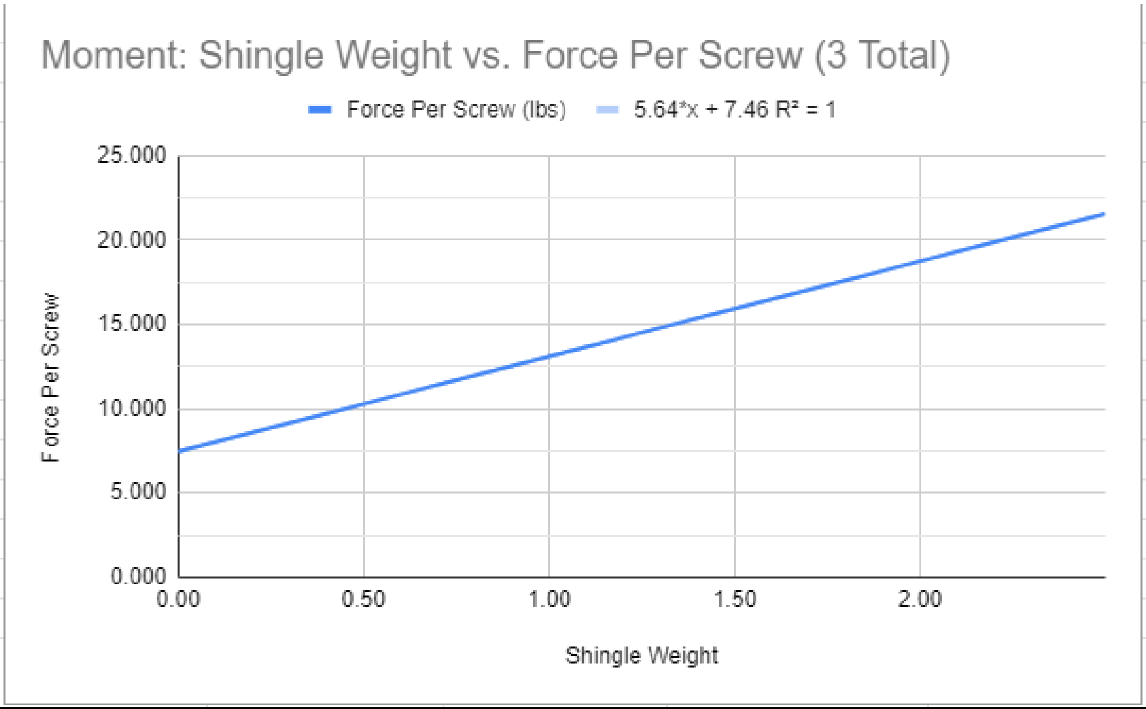
Appendix A: Structural Analysis Graphs.



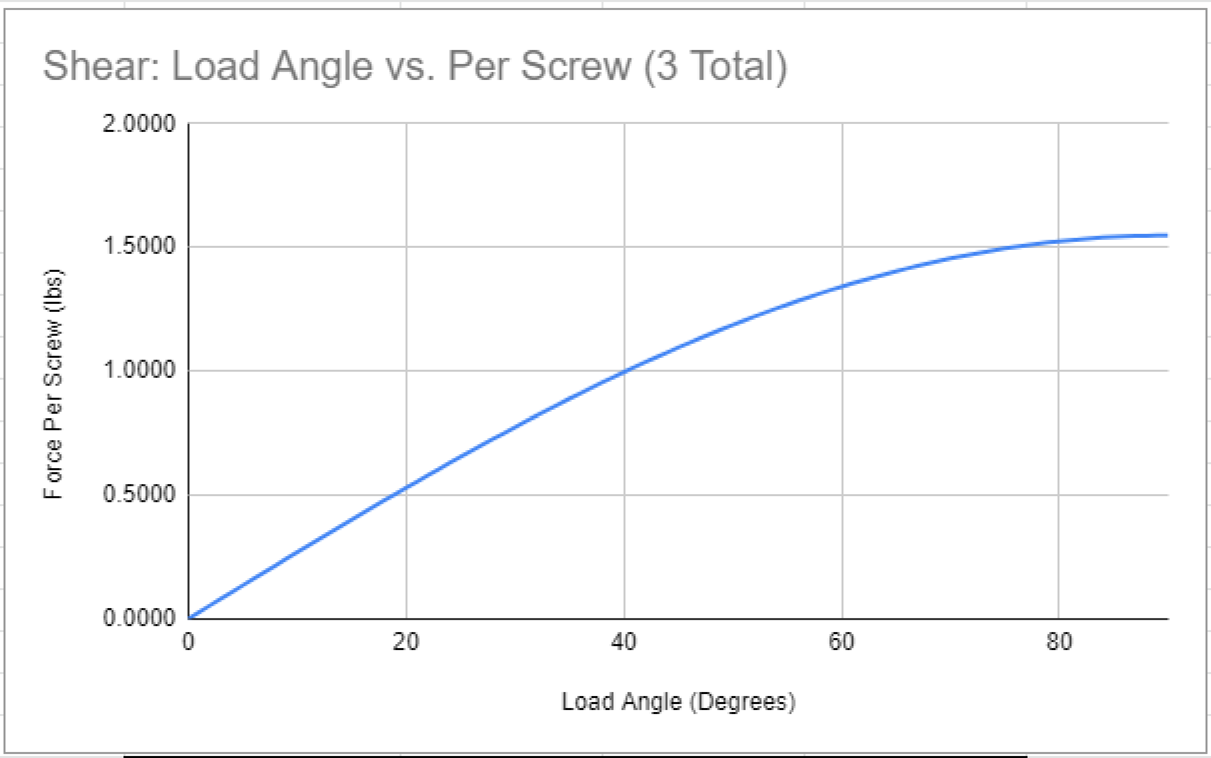
Robot Length (inch)	Robot Weight (lbs)	Shingle Weight (lbs)	Screw Distance (inch)	Number of Screws
22	2.646	2.000	1.3	3



Load Angle (Degrees)	Robot Length (inch)	Shingle Weight (lbs)	Screw Distance (inch)	Number of Screws
90	22	2.000	1.3	3



Load Angle Degrees)	Robot Length (inch)	Robot Weight (lbs)	Screw Distance (inch)	Number of Screws
90	22	2.646	1.3	3



Weight Robot + Shingle (lbs)	4.6460	Screws	3.00

Appendix B: Procedure for Water Tightness Testing

The purpose of this research is to design a shingle system that increases a building's energy efficiency. This experiment will test the effectiveness of the shingle design, shingle offset pattern, and the use of velcro or screws for installation.

Materials:

- 18 - six inch length shingles (full sized)
- 6 - three inch length shingles (half sized)
- 4 - four inch length shingles (⅔ sized)
- 4 - two inch length shingles (⅓ sized)
- Two feet by four feet acrylic material board and Two feet by four feet piece of plywood
- Screws/Velcro

Procedure for ½ offset:

1. Starting with the bottom most row (row one), left to right, install three full shingles.
2. For the next row up, from left to right, install the half shingle then proceed to install two full shingles followed by one half shingle.
3. Install row three similarly to the pattern in step 2.
4. Install row four similarly to the pattern in step 3.
5. Repeat steps 2 and 3 until there are seven rows of shingles.
6. Place one continuous piece of duct tape across the top portion of the top row of shingles as well as one piece vertically on each outer portion of the finished product to act as flashing.

Procedure for ⅓ offset:

1. Starting with the bottom most row (row one), left to right, install three full six inch shingles
2. For the next row up, from left to right, install one ⅔ sized shingle and proceed to install with two more full sized shingles followed by one ⅓ sized shingle
3. For the next row up, from left to right, install one ⅓ sized shingle and proceed to install with two more full sized shingles followed by one ⅔ sized shingle
4. Repeat steps one through three until there are seven rows of shingles.
5. Install row seven similarly to row one.
6. Place one continuous piece of duct tape across the top portion of the top row of shingles as well as one piece vertically on each outer portion of the finished product to act as flashing.

Procedure for Water Tightness Test:

1. On the short side of the plywood, create four markings at lengths 7.5 in, 13 in, 13.875 in, and 15 in.
2. Place the correct support at its corresponding length location, and place the acrylic board (with shingles installed) at the short most edge. Lower the acrylic until it meets the support and fasten with duct tape.
3. Cut two 19 in pieces of duct tape and adhere them to each other, this will be the "trough". Then, align and duct tape the trough to the underside of shingle row "1," so that one inch is covered by this row.
4. Install, with duct tape, the two 3d printed supports to the trough separated by 7 inches.
5. Pour one half gallon of water into the gardening container. Place at row 7 and distribute water evenly until all water is expelled. Making sure no water flows off the sides.

Appendix C: Procedure for Velcro Structural Tests

The purpose of this experiment is to test the material properties of the selected velcro, and to retrieve the maximum efficiency needed from the robot to install shingles using the velcro system.

Materials:

- Velcro Brand Industrial Tape, Hook 88, 1” by 75’, Adhesive: PS72
- Velcro Brand Industrial Tape, Loop 1000, 1” by 75, Adhesive: PS72
- Scissors
- Epoxy adhesion
- 16 - ‘L’ brackets.

Equipment:

- Instron

For push - used compression test press press until load reaches some value starting with 50N rate of 2.54 mm or 1/10 in per min. Calibrated it making sure no load is on the load cell.

Procedure for Compression Test:

1. Using epoxy, glue two L brackets together and form a ‘T’. Continue until all L brackets are used.
2. Cut one piece of hook at length 4” and one piece of loop velcro at lengths 4”.
3. Attach one hook velcro onto the flat, top portion of one glued ‘T’ bracket and attach one loop velcro onto the flat, top portion of one glued ‘T’ bracket.
4. Place the lower portion of the hook ‘T’ bracket into the clamp of the instron. Place the lower portion of the loop ‘T’ bracket into the PVC piping and place this on the lower anvil of the Instron.
5. Place the two other PVC on the lower anvil and under the top portion of the ‘T’ bracket for support.
6. Lower the upper anvil until the two ‘T’ brackets are almost touching and in alignment. See figure 7 for reference.
7. Conduct a compression test and stop the load when the hook and loops are completely free of each other
8. Save the stress, strain graph and record the load of failure.

Procedure for Tension Test:

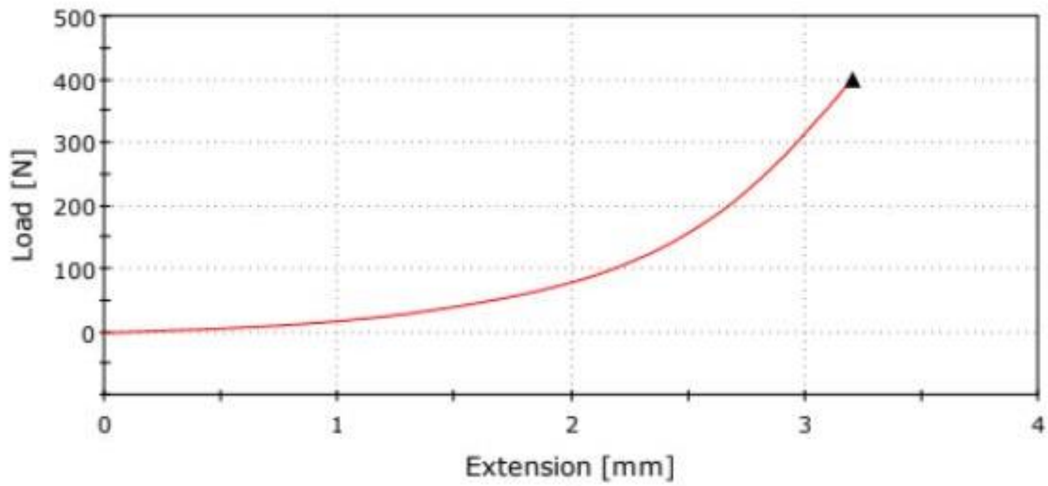
Using epoxy, glue two L brackets together and form a ‘T’. Continue until all L brackets are used.
Cut one piece of hook at length 4” and one piece of loop velcro at lengths 4”.
Attach one hook velcro onto the flat, top portion of one glued ‘T’ bracket and attach one loop velcro onto the flat, top portion of one glued ‘T’ bracket.
Place the lower portion of the hook ‘T’ bracket into the clamp of the instron. Place the lower portion of the loop ‘T’ bracket into the PVC piping and place this on the lower anvil of the Instron.
Place the two other PVC on the lower anvil and under the top portion of the ‘T’ bracket for support.
Lower the upper anvil until the two ‘T’ brackets are almost touching and in alignment.See figure 8 for reference.
Conduct a tension test and stop the load when the hook and loops are completely free of each other
Save the stress, strain graph and record the load of failure.

Procedure for Shear Test:

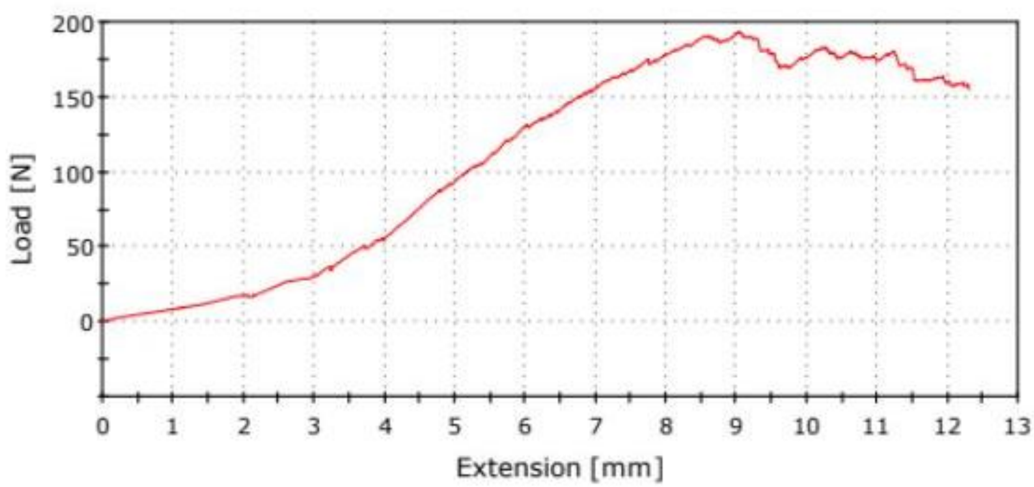
Using epoxy, glue two L brackets together and form a ‘T’. Continue until all L brackets are used.
Cut one piece of hook at length 4” and one piece of loop velcro at lengths 4”.
Attach one hook velcro onto the flat, top portion of one glued ‘T’ bracket and attach one loop velcro onto the flat, top portion of one glued ‘T’ bracket.
Push the two ‘T’ brackets together so that the hook and loop are interconnected and in such a way that there is one inch of unconnected velcro on each bracket.
Place one side of the top portion of the ‘T’ bracket into the lower clamp so that one inch is being held.
Lower the upper clamp and place one side of the top portion of the ‘T’ bracket into the upper clamp so that one inch is being held. See figure 9 for reference.
Conduct a shear test and stop the load when the hook and loops are completely free of each other
Save the stress, strain graph and record the load of failure.

Appendix D: Resulting Graphs from the Velcro Testing.

400 N Compression



400 N Tension



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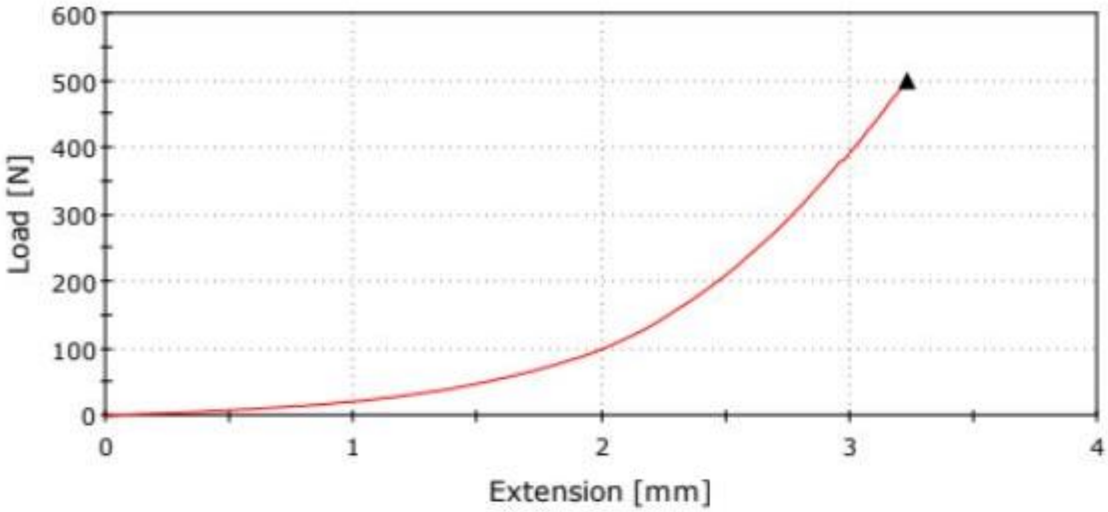
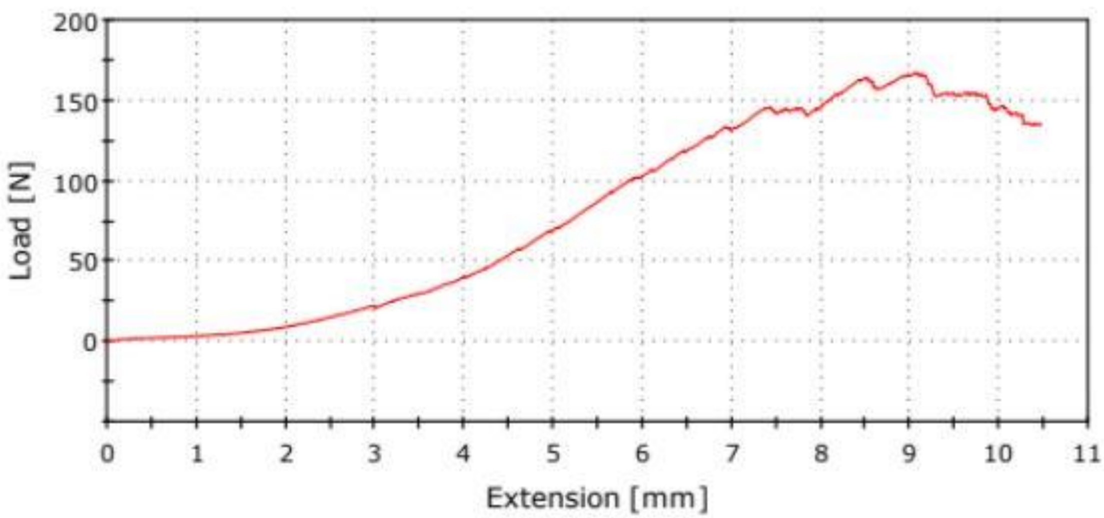


500 N Tension



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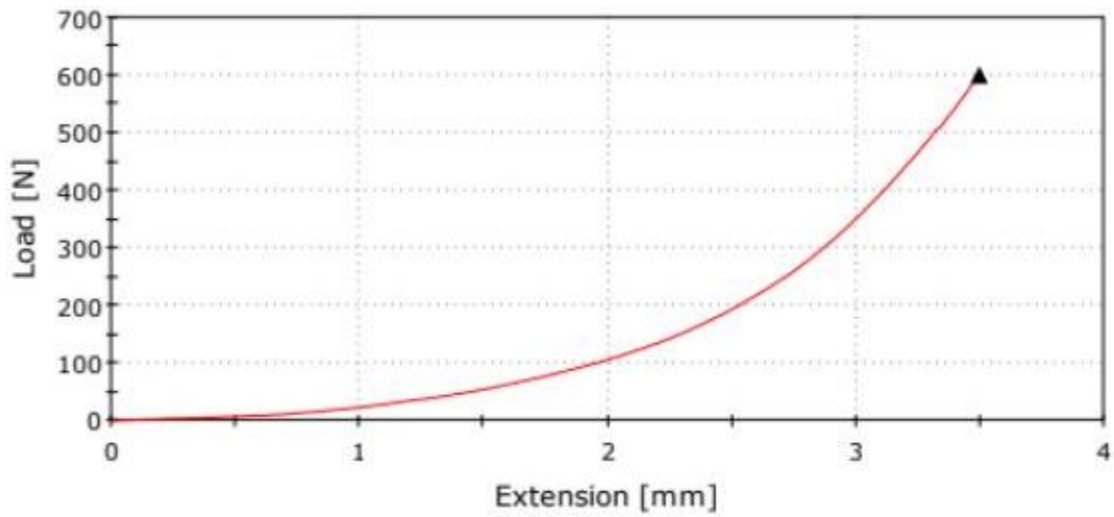
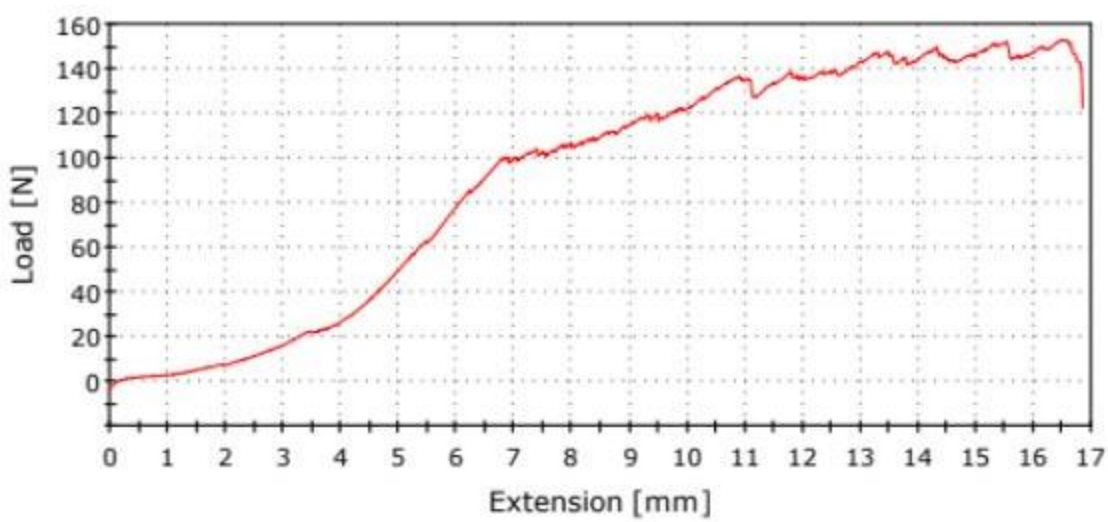


600 N Tension



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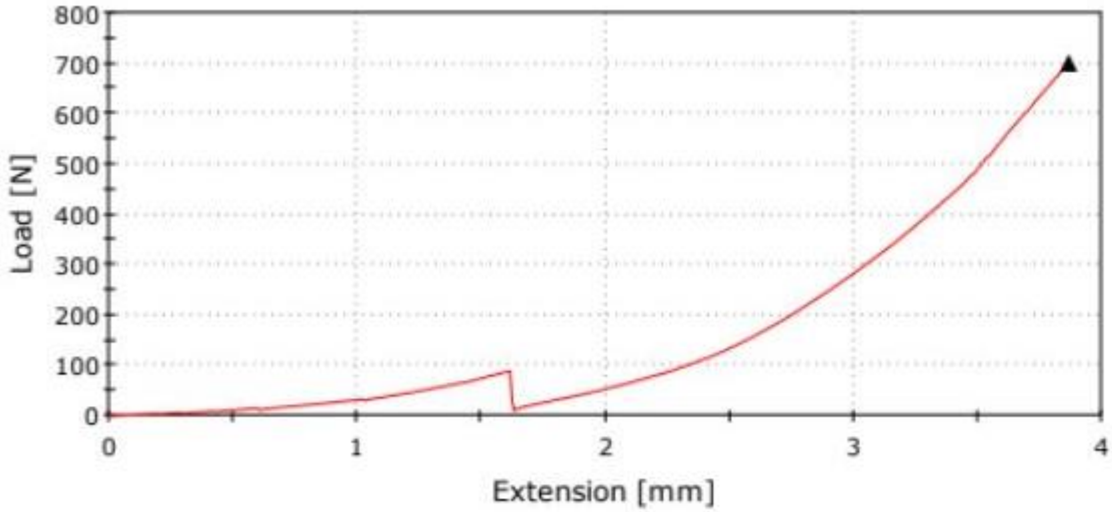

700 N Tension