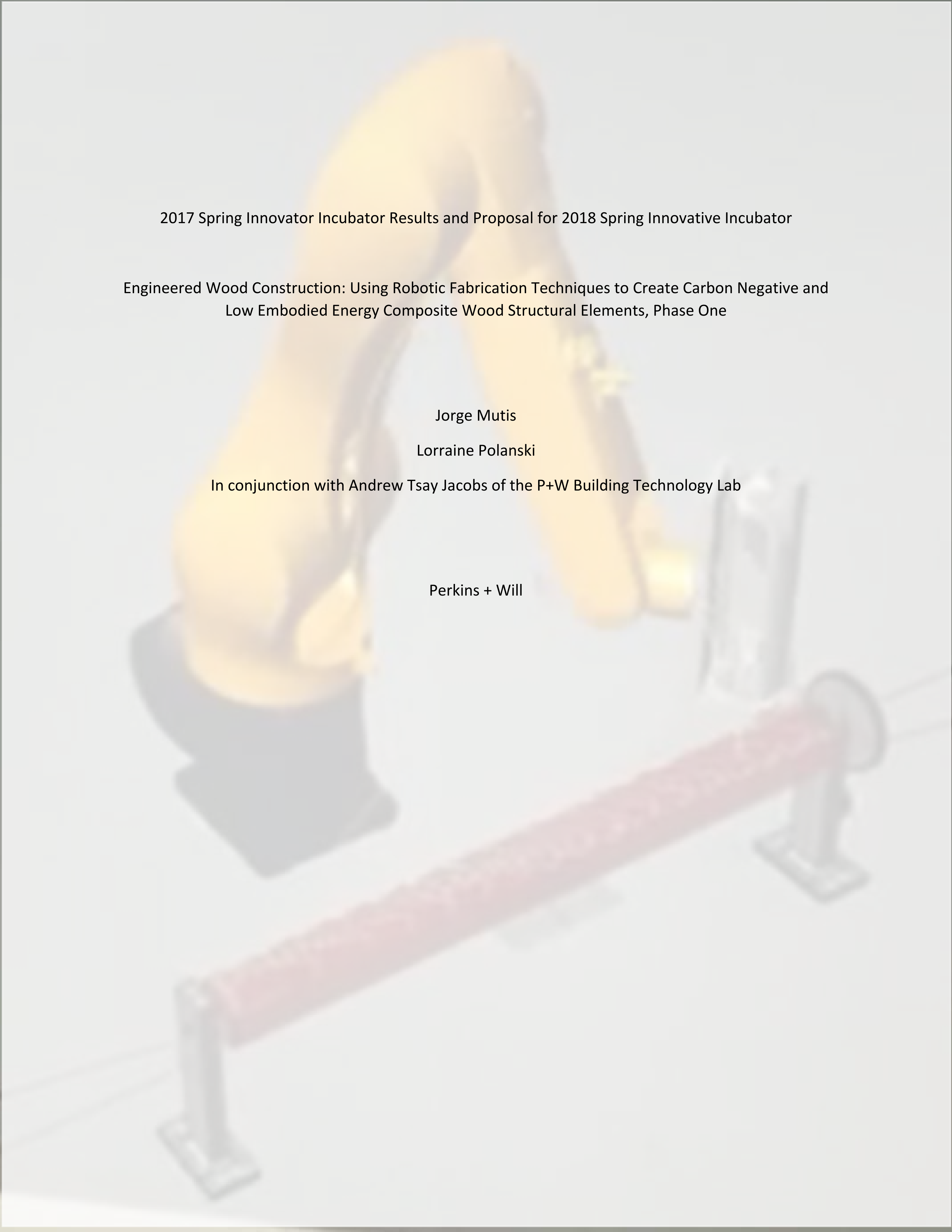

2017 Spring Innovator Incubator Results and Proposal for 2018 Spring Innovative Incubator

Engineered Wood Construction: Using Robotic Fabrication Techniques to Create Carbon Negative and Low Embodied Energy Composite Wood Structural Elements, Phase One

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ABSTRACT

The 2017 Spring Innovation Incubator project proposed to develop the next generation of net carbon negative, low embodied energy wood composite structural elements. The interest in mass timber construction is what brought a resource librarian, and two project designers together to work on this project.

We presented three phases in our initial submission. Phase one and two were to be completed in the 2017 Spring Incubator; phase three is slated for the 2018 Spring Incubator. In phase one we created composite fibers composed of a bio-based thermosetting plastic and fiber additives (carbon, aramid, and two types of wood fiber), and evaluated their sustainability and began the process of tensile strength testing at the University of Southern California's Material Testing Lab. We were unable to complete our second phase due to the lack of access to a robotic arm. Instead we have used the time to further develop the method and model of our composite structural element.

In the 2018 Spring Innovation incubator, we will construct our element, and test it for strength.

BACKGROUND

To develop an alternative method for fabricating laminated wood elements, such as beams and columns, it is important to understand the existing methods for binding lam stock together. Glued-laminated (glulam) structural elements are formed by combining lam stock using adhesives, heat and pressure in a mold. Nail-laminated structural elements secure lams together with nails. Dowel-laminated elements use extremely dry hardwood dowels fitted into holes in the lamellas to connect the lamellas. Swelling of the hardwood dowels under ambient moisture secures the dowels in place.

Our proposed wood element would most directly compete with the glulam structural elements. Glulam is "manufactured by finger-jointing dimensional lumbar and then planning and face bonding the lumber elements into a beam with pressure and one or more of several different resins."[1] To allow more flexibility in the form of the structural elements (beams, columns, etc.) without requiring custom hydraulic presses, nails or wooden dowels, we devised a system of 'lashing' lamellas together using automated processes for wrapping the beam with fiber-reinforced plastic.

While the LCA of glulam beams indicates a sustainable product, the adhesives used to bond the layers are not. From the EPD of glulam timbers by the AWC:

[1] AWC. "Environmental Product Declaration Glulam" http://www.awc.org.

"One cubic meter of average North American glulam weighs 533.97 kg. excluding the variable moisture content. The product composition is presented below and represents the weighted average of the various resin types that are used by different manufacturers:

Wood: 525.97 oven dry kg (98.50%)
Phenol resorcinol formaldehyde resin: 6.69kg (1.25)
Melamine urea formaldehyde resin: 0.79 kg (0.15%)
Polyurethane resin: 0.35 kg (0.15%)
Resorcinol formaldehyde resin: 0.12kg (0.15%)
Melamine formaldehyde resin: 0.05 kg (0.01%)"[2]

Although the percentages of the adhesives are small, they are hazardous chemicals. For example, phenol resorcinol formaldehyde resin; taken from the MSDS of Cascophen, which is the trade name for phenol resorcinol formaldehyde resin:

"Signal word: WARNING! Hazard statements: COMBUSTIBLE LIQUID AND VAPOR. MAY FORM EXPLOSIVE MIXTURES WITH AIR. INHALATION CAUSES HEADACHES, DIZZINESS, DROWSINESS AND NAUSEA AND MAY LEAD TO UNCONSCIOUSNESS. CAUSES EYE IRRITATION. MAY CAUSE RESPIRATORY TRACT AND SKIN IRRITATION. CONTAINS MATERIAL THAT CAN CAUSE TARGET ORGAN DAMAGE. CANCER HAZARD"[3]

The intent to conduct an LCA of the fibers used in our incubator as proposed in our original submission proved to be harder to accomplish than we originally anticipated. Without access to software such as GaBi or SimaPro, it was impossible to access databases that provide the various measurements required in order to model a LCA of each fiber. To model an LCA, information regarding raw material extraction, transport of raw materials to the manufacturing site, manufacturing, transportation to the site of use, use phase and end-of life scenario is required. The published LCAs that we found were based on fiber composites; however, most of these addressed an entire assembly, such as ship's hulls, automobile parts and parts made for wind turbines.

Still needing to identify which of our proposed fibers: carbon, glass and Aramid, (steel fiber was eliminated), would be the most sustainable and most likely to perform the best in our incubator project, we looked at the properties of each fiber which helped to determine the pros and cons of each.

[2] AWC. "Environmental Product Declaration Glulam" http://www.awc.org.
[3] Hexion. "MSDS Cascophen (TN), LT-5210Q" http://www.anthonyforest.com/assets/pdf/msds/msds-hexion-cascophen-lt-5210Q.pdf

FIBER MATERIALS RESEARCH

Life Cycle Analysis of Carbon, Kevlar, Glass and Wood Fiber Reinforcements

Carbon Fiber

Carbon fiber has high tensile strength, high stiffness and low weight and is a synthetic fiber. With the proper mix of resins/thermoplastic binders, carbon fiber composites are 10 x stronger than steel yet 5x lighter, in comparison to aluminum, carbon fiber composites are 8 x stronger, 2 x stiffer yet 1.5 x lighter. Most notable is the fact that carbon fibers are one of the most corrosive resistant composite materials. There are two ways to manufacture carbon fiber: pan-based and pitch-based.[4]
The table below shows properties of pan-based and pitch-based carbon fiber[5]

Property	Units	Thornell P-55 Pitch-based Carbon Fiber	Thornell T-300 Pan-based Carbon Fiber
Density	g/cc	1.90	1.76
Tensile Strength	GPa	1.9	3.75
Young's Modulus	GPa	379	231
Thermal Conductivity	W/m-K	120	8
Strength to Weight	kN.m/kg	N/A	2457

90% of the carbon fiber manufactured today is pan-based having a high tensile strength. The pitch-based fibers have a high stiffness and thermal conductivity. For our project, we are working with pan-based carbon fiber.[6]

Pros of Carbon Fiber

- Strength to weight ratio
- Superior fatigue properties
- High stiffness to weight ratio
- High heat tolerances and resistance
- Moisture resistance
- Exceptional durability
- Can be recycled

[4] P. Joyce. https://www.usna.edu/Users/mecheng/pjoyce/composites/Short_Course_2003/1_PAX_Short_Course_Composite-Technology.pdf
[5] P. Joyce
[6] P. Joyce

Cons of Carbon Fiber

- Price—higher than most fibers
- Carbon fiber does not yield; under a load, carbon fiber bends but once the ultimate strength is reached, carbon fiber exhibits a shattering plastic failure mode.
- Energy intensive to manufacture, although the durability of products made of carbon fiber should offset this by some degree
- Recycled by pyrolysis, an energy intensive process. The product to be recycled is heated in an oxygen-free environment to 390-570 degrees and the composite material is burned away leaving the carbon fiber.[7]

Aramid Fiber

Originally manufactured by Dupont as Kevlar, this material is processed in a way that produces a high strength and high modulus fiber. Kevlar is 5x stronger than steel on an equal weight basis and the density of Kevlar is approximately half that of glass.[8] There are three grades of Kevlar; Kevlar 49 is manufactured specifically as a reinforcement in polymers and is what we are working on our project. The table below shows properties of Kevlar[9]

Property	Units	Kevlar 49
Density	g/cc	1.44
Tensile Strength	GPa	3.6
Young's Modulus	GPa	131
Thermal Conductivity	W/m-K	0.2
Strength to Weight	kN.m/kg	2514

Pros of Aramid Fiber

- Strength to weight ratio
- Resistant to impact and abrasion
- High stiffness to weight ratio
- Resistance to chemicals
- Recyclable

Cons of Aramid Fiber

- Absorbs moisture
- Low compressive properties

[7] http://www.hj3.com/the-benefits-of-carbon-fiber/

[8] P. Joyce
[9] P. Joyce

- Difficult to cut or grind
- Large environmental impact. One of the main substances used in the manufacture of aramid is sulfuric acid, which is a highly corrosive chemical. Sulfuric acid enters the air during production, use and transport. It exist as particles or droplets when released to the atmosphere, which may dissolve in clouds, fog, rain, dew, or snow, resulting in very dilute acid solutions. In clouds and moist air it will travel along the air currents until it is deposited as acid rain, acid fog, etc.[10]

Glass Fiber (not yet used in our project, but proposed to be used in the future)

There are 4 types of glass fiber manufactured: A-glass, E-glass, C-glass and S-glass. Of these, E-glass is most commonly used in glass fiber composites. E-glass or electrical glass is a low alkali glass that was originally developed for stand-off insulators for electrical wiring and is now used almost exclusively as the reinforcement most commonly used in fiberglass. This is the glass fiber we are working with on our incubator[11]

The table below shows properties of glass fiber[12]

Property	Units	E-Glass Fiber
Density	g/cc	2.55
Tensile Strength	GPa	2.0
Young's Modulus	GPa	80
Thermal Conductivity	W/m-K	1.2
Strength to Weight	kN.m/kg	1307

Pros of Glass Fiber

- Low cost
- High strength
- High stiffness
- Non-flammable
- Resistant to Heat
- Good chemical resistance
- Able to maintain strength properties over a wide range of conditions

Cons of Glass Fiber

[10] https://www.azom.com/article.aspx?ArticleID=764

[11] P. Joyce
[12] P. Joyce

- Low modulus
- Self-abrasiveness if not treated appropriately leading to reduced strength
- Low fatigue resistance
- Higher density compared to carbon fiber and aramid fiber
- Can be recycled only as a composite. It is used as filler in the manufacture of a new composite[13]

Wood Fiber

We used Steico Zell air injected wood fiber insulation as the wood fiber for our project. This is manufactured from timber from FSC certified sustainable forests. Steico has published an EPD for this product online. The LCA interpretation indicates three environmental impacts of the production of this product.[14]

Global Warning Potential, (GWP)
72% of the total emissions of the global warming relevant gases are attributed to the wood fiber insulation production on site
27% of the total emissions is caused by the provision of raw materials and preliminary product production
1% is attributed to transportation of raw materials to the factory

Acidification Potential, (AP)
82% of the acidification potential results from the production of the wood fiber insulation materials. 17 % is caused by the provision of the raw materials and preliminary products. Transportation contributes only 1 % to the AP. With 52 % of total emissions in the production phase, the drying of the fibers and of the pressed wood material and with 7% the provision of heat to boil the fibers are the main contributors to the AP.

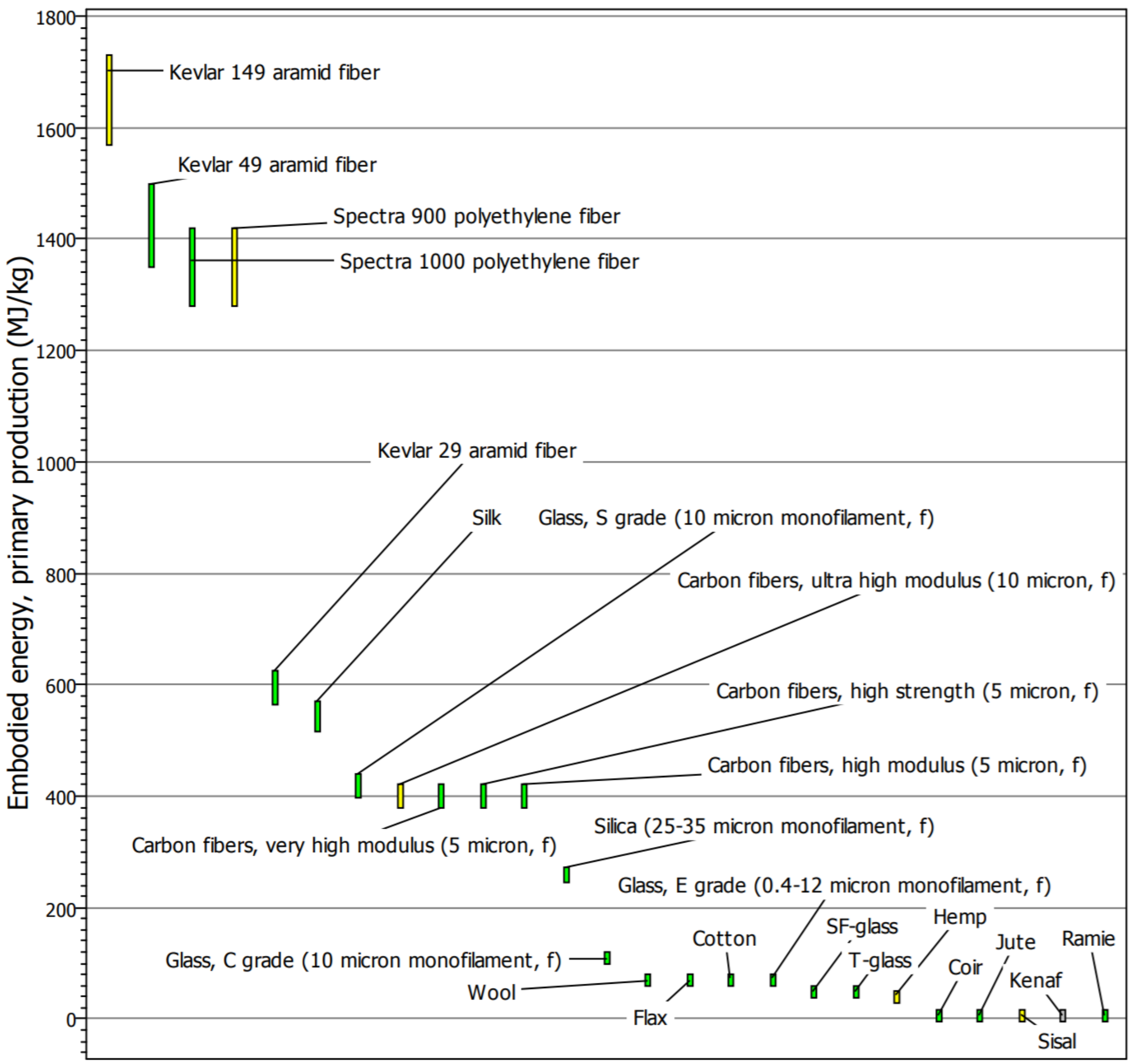
Photochemical Ozone Creation Potential, (POCPP)
Production at the location (Module A1) is responsible for 86 % of ozone creation-relevant emissions, 0.3 % is caused by transportation (A2), and a further 14 % by the production of the raw materials and semi-finished goods (A3). At the factory location, the ozone creation analysis is dominated by the setting of the adhesives and of the additives (52 % of total emissions in Modules A1-A3) as well as the provision of heat for the drying processes (22 %). [15]

Although the findings above may seem to indicate sustainability issues, it is difficult to make a comparison when we do not have and EPD or LCA on the other fibers. Weighed against the pros and

[13] P. Joyce
[14] Steico SE. Environmental Product Declaration Air Injected Wood Fiber Insulation. http://www.steico.com/fileadmin/steico/content/pdf/Certificates_-_Documents/English__multiple_markets_/STEICO_EPD-STE-20150327-IBD1-EN.pdf
[15] Steico SE

cons of the other fibers, we believe that the wood fiber is the most sustainable, followed by glass fiber, carbon and aramid. In a study published by the University of Bath, Natural Fiber Composites and Their Role in Engineering; they created a table of the embedded energy of both plant and synthetic fibers.[16]

Embodied Energy For Synthetic and Plant Fibres[17]



[16] Martin Ansell. Natural Fibre Composites and Their Role in Engineering. http://staff.bath.ac.uk/mssmpa/index/PAPERS%20&%20PRESENTATIONS/Ansell%20natural%20fibres%20BRE%20Sept%2011.pdf
[17] Martin Ansell.

STRUCTURAL APPROACH

The goal of using FRP to wrap wood lamellas is to achieve composite action. Without composite action, three lamellas stacked on top of one another provide three (3) times the strength of one lamella when acting in bending. However, because strength varies as the square of the depth of the structure, if these three lamellas are bound to one another in a manner that achieves composite action, they provide nine (9) times the strength of one lamella. To achieve composite action, slipping must be eliminated at the shear plane between lamellas.

To eliminate the slipping, our FRP wrapping technique uses two methods:

1. Dowel action. FRP deployed in grooves that are oriented vertically are engaged in a transverse shearing mode tat restrains the lamellas from slipping at the shear plane.
2. Tension straps. FRP deployed in groves that are oriented longitudinally are engaged in a tensile mode that restrains the lamellas from slipping at the shear plane.

In addition to achieving composite action by addressing the shear plane between laminations, the orientation of the FRP strands could assist with beam bending and shear.

1. Bending forces: To resist moment forces induced by bending, orienting the FRP deposits longitudinally in the bottom 1/3 of the wood elements could assist with tensile forces acting in the bottom of the composite beam. This is similar to steel tensioning tendons used in precast beams.
2. Shear forces: Vertically oriented FRP deposits could be concentrated toward the ends of the beam to assist with shear forces. This is similar to steel reinforcing 'straps' used in concrete beams.

PRODUCTION

Materials Used

1. Fiber reinforced plastic.

The fiber-reinforced plastic was produced by mixing high-strength with plastic pellets and feeding the mix through a Strooder machine. We set the feed rate and heating temperature of the Strooder based on the melting point and viscosity of the plastic being used. The Strooder melted the plastic and extruded a cylindrical filament, suitable for 3D printing or use with an industrial plastic extrusion gun.

We produced aramid-fiber reinforced plastic, carbon-fiber reinforced plastic and wood-fiber reinforced plastic through this process. Determining the appropriate ratios to achieve optimal stiffness and strength was beyond the scope of the work performed.

Challenges:

When developing the wood-fiber reinforced plastic, we initially used a polylactic acid (PLA) plastic, commonly used for 3D printing. However, we discovered upon inspection that the filament produced expressed ashen color signatures. The melting point of the plastic is 200 degrees C, which is above the charring temperature of wood (120 degrees C). Hence, the wood fibers were being structurally compromised through charring during the filament creation process. To maintain the strength of the wood fiber, we selected an alternate plastic with a lower melting point, Polycaprolactone (PCL), at 60 degrees C. We were able to eliminate the charring through by use of this alternate plastic.

We initially planned to use a plastic extrusion gun mounted to the robot arm to deposit the plastic. Consequently, our initial fiber-reinforced plastic filament production was calibrated to the extrusion gun requirements. However, without the robot arm, we shifted to a smaller diameter filament that could fit in the Makerbot 3D printer and be used to print tensile test specimens.

2. Wood lamellas

The wood stock used for the laminated wood beam element was 2x1 pine with square edges in 30" lengths. Stacking three lams, we developed a profile 2.25" tall and 1.5" wide.

Fabrication of the Jig

1. With a goal of robotically milling grooves into wood lamellas and robotically extruding plastic into the grooves, we needed to develop a jig that would hold the wood in place and also rotate it into position for the robotic arm to execute the milling and plastic depositing routines.
2. We designed a jig that secures the wood beam and rotates it using an Arduino controller. We 3D printed all of the parts we designed using ABS plastic and the LAO Stratsys printer. Drive shafts outfitted with ball bearings were secured to the ends of the wood beam and rest in vertical supports secured to the wooden base. We modified a servo to allow continuous rotation of the wood. A drive belt connected to the servo spindle drives a shaft attached to one end of the wood elements.

Fabrication of the Composite Beam

1. Though not yet tested, the method for fabrication is as follows:
    a. Secure lamellas in jig.
    b. Use robotic arm with spindle mill end effector to cut grooves into top, bottom and side faces of the beam layup.
    c. Use robotic arm with plastic extrusion gun end effector to deposit fiber-reinforced plastic into the grooves.

We have developed the jig and a script for deploying any FRP lashing 'pattern' onto the geometry of the beam. When we have secured access to the robot arm, we will begin the fabrication process.

TESTING/RESULTS

To determine the validity of fiber-reinforcement in our plastics, we wanted to execute tensile tests of the fiber-reinforced plastic. We collaborated with the University of Southern California and the Cal Poly San Luis Obispo material testing labs to develop protocols for testing. It was agreed that we would use ASTM D638-02a, 'Standard Test Method for Tensile Properties of Plastics'. USC provided a cheaper quote so we elected to use their facility.

To develop the specimens required for this test, we consulted with the Institute for Computational Design and Construction (ICD) in Stuttgart, which has done extensive work with robotic assemblies for wood and carbon fiber structures. They advised against our initial concept of casting the tensile test specimens into a mold because it would result in anisotropic fiber orientation. They advised that we 3D print the specimens to achieve alignment of the fibers parallel to the length of the tensile test specimens.

We have begun 3D printing the specimens and testing is ongoing. We provided two specimens to USC which they have tested to failure: 1. Unreinforced ABS plastic, and 2. Carbon-fiber reinforced plastic made from commercially available filament. We will soon submit for testing specimens made from fiber-reinforced filament produced in-house using the Strooder.

CONCLUSION / FUTURE WORK

With our jig complete and having confirmed the feasibility of producing our own fiber-reinforced plastics, we are ready to begin use of the robotic arm for plastic deposition.

We will apply for the Spring 2018 Innovation Incubator with a proposal to use the robotic arm to complete Phase One of the initial proposal as well as the structural testing proposed for Phase Two.

In the meanwhile, we will continue working with USC to test the strength of our fiber reinforced plastic types to determine the strength impacts of the use of fiber reinforcement.

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