LIGHTWEIGHT MATERIAL PROTOTYPES USING DENSE BUNDLED SYSTEMS TO EMULATE AN AMBIENT ENVIRONMENT

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Abstract. This paper describes and reflects upon a computational design and digital fabrication research project that was developed and implemented over 2014-2015, with subsequent development continuing for applications at present. The aim of the research was to develop methods of modelling, analysis, and fabrication that facilitate integrative approaches to architectural design and construction. In this context, the development of material prototypes, digital simulations, and parametric frameworks were pursued in parallel in order to inform and reform successive iterations throughout the process, leading to a refined workflow for engineering, production, and speculation upon future directions of the work.

Keywords. Digital fabrication; biomimicry; ambient environments; grasshopper; computational design.

1. Introduction

While the use of plastics in architecture is undoubtedly commonplace, applications overwhelmingly tend toward the utilitarian or emulation of natural materials (Brownell, 2015), in contrast to the consumer goods industry where the functional and aesthetic characteristics of polymers are used to their full advantage. One reason for this may be that many well-known fabrication methods with plastics typically require a high degree of skill (plastic welding, fiberglass moulding) or highly application-specific equipment
(blow-moulding, thermoforming) and are not suited to the one-off nature of building projects. Yet with the wide availability of many plastic products, specifically in sheet form, and the relative ease of processing with increasingly common equipment such as CNC routers, plastics can be seen as fertile ground for architectural experimentation.

The goal of this project from a research standpoint is to begin to bridge the aesthetic and structural properties of widely available polymer materials at an architectural scale and level of formal and structural complexity which is outside their normal functional domain. By employing generative and parametric design techniques, increasingly fabrication techniques, and assembly methods requiring little or no skill it is possible to effectively make use of the advantages of the unique material characteristics of plastics; its isometric structure, strength to density ratio, inherent flexibility, yet sidestep the aforementioned fabrication disadvantages, while also maintaining the ability to produce highly customised architectural artefacts.

2. Early development

Conceptually, Arclight is conceived from a biomimetic basis – namely, to emulate dense bundled systems of fibres or branching structures found in the natural environment e.g. the Mangrove or Strangler Fig tree, as a paradigm for structural and formal qualities. Like most fibrous systems in nature, the research investigated bundling at multiple scales in order to build up strength.

The project was initiated with students in an undergraduate research seminar at Bond University School of Architecture in September 2014. At this point the authors were in discussions with several external groups about the
possible installations for public events in Gold Coast and Sydney, Australia. Since these installations were not confirmed at the start of the seminar, the seminar was structured in a way that several different research projects could be developed and prototyped in parallel with the goal of at least one of the topics being more fully developed for a larger scale installation. This structure allowed the authors and their students to conduct a broad range of research while iteratively integrating new constraints and parameters related to the potential larger commissions into the research.

One of the initial research trajectories focused on the potential of using thin-sheet materials to construct volumetric structural elements. The research aims of this trajectory are as follows:

- Produce a strong, yet lightweight structural member fabricated from sheet materials.
- As several of the possible commissions were for light festivals, produce a translucent element that had the capacity to transmit LED light.
- Develop a fabrication workflow that takes advantage of the available digital fabrication tools at the Bond University School of Architecture while expanding the capacity of the equipment and the diversity of its output.
- Produce a parametric system composed of a singular component logic that can be differentiated to produce a range of effects and performances, and allows for continuity throughout the design process.

The authors and students pursued these research aims over the course of the semester through the iterative development of digital and physical prototypes. This process began with simple physical prototypes of box beams made from HDPE as these prototypes collapsed many of the aims into one testable framework. Each of these prototypes were tested for their structural capacity and stability, ability to transmit interior LED light, and various fabrication and assembly criteria such as ability to unroll the box beam’s sides into flat patterns and the specific joint details connecting each side to its neighbour.

After several rounds of testing, an initial design direction was determined that rested on the use of a box-beam component with a semi-triangular cross-section. The faces of the beam were made from CNC-milled HDPE sheets that were then attached using standard aluminium pop-rivets. Across the length of the beam (or column if positioned vertically), the cross-section could change in size, position, and rotation. This transformation produced a global curvature to the beam that allowed bundles of them to form areas of loose or close aggregation. This variable aggregation allowed the bundle to both have widely spaced support points when loosely aggregated and increased stiffness when closely aggregated.
Furthermore, each strand’s stiffness was increased through the curvature induced through the riveted connection. Although digitally modelled as an idealised triangular cross-section, each edge of the triangle was closer to an arc than a line due to the surface-to-surface contact made by the riveted connection. Thus, not only was the beam curving along its length, but along its cross-section. This curvature made each beam incredibly stiff in comparison with the relatively weak and thin HDPE material (Figure 2).

![Figure 2. Prototypes in the process. (Left to right) A beam failure due to buckling, testing light transmission; and finally, a successful aggregation of strands.](image)

3. Prototyping

*Arclight* underwent considerable prototyping over a short timeframe to resolve a number of issues concerning materiality, fabrication, assembly, and structural efficacy. As stated, a major goal in this research was the full integration of skin and structure, and as such at the prototyping stage this centred largely on the interaction of HDPE skin and the connection methods between elements.

Multiple options for connecting skin/structure elements though many these were dismissed as either not attractive (zip ties) requiring too much skill (plastic welding), too expensive (Chicago Screws), or unreliable (industrial staples and chemical bonding). Aluminium rivets, with washers to prevent tear-out, were eventually chosen as they fit all expected criteria, and integrated material fastening tabs with pre-drilled holes were developed to facilitate quick installation.

During this stage it was discovered that while very strong, HDPE is quite flexible and tends to bend not only in the longitudinal direction, but in order to allow the exterior tabs to be riveted together, it also bends transversely...
causing material distortion and tends to create openings at vertical seams, exposing the LED lighting inside. This aspect made the distance between rivets critical in order to reduce unwanted openings. Due to the overall strength of the aluminium rivets the spacing had little overall structural effect on the installation the spacing, and thus total quantity, of rivets greatly increased assembly time, which was a real concern (Figure 3).

Further it was found that tab generation at an early stage in the computational process, ie. when the overall forms were being generated was too imprecise to be of value during fabrication as the tabs and rivet holes tended to not line up accurately and deform slightly while unrolling. It was discovered that generating the fastening tabs and pre-drilled rivet holes after unrolling surfaces was much more accurate and not only reduced the tolerance required for fabrication (+/- 1mm) but saved significant computation time while fine-tuning the parameters for the overall design. While 1mm tolerance is significant in terms of manufacturing precision – the equipment used is capable of +/- 0.05mm - as noted by Kolarevic, “‘zero tolerance’ is an oxymoron in the context of the building industry,” - although digital fabrication would suggest such a goal is achievable – he continues that “tight tolerances (which should not be mistaken for no- or zero tolerances) are tied to the kinds of materials used. Good designers and engineers plan for precision and tolerance issues, allowing size variations and imperfections in interfaces.”

4. Engineering workflow and optimisation

For the purposes of structural engineering, the Arclight structure is composed out of a bundle of 6 individual shaped triangular HDPE pipes. Different criteria have an influence on the final layout and geometry of the installation, including orientation, material thickness and behaviour, topology, fabrication processes, and external forces.
Those factors can be utilised as a design driver to change the overall geometry of each individual tree like structure. An integral workflow of shape making and structural behaviour was one part of the investigation that helped to understand the material behaviour to push the design to the material limits. The workflow can be described as a loop where the design was developed in the modelling environment Rhino / Grasshopper. The parametric logic allowed fluent changes of the shape and material thickness of each tree. Within Grasshopper a structural analyses with the plug-in KARAMBA was set out to gain real-time feedback of any change of the design.

The iterative analyses started to look at the smallest tree with a height of 2.6m and a simple extrusion body to understand the boundary conditions of the material, since HDPE is not a conventional building material that is used for structural purposes. The structural analyses had the following parameters as input: Wind speed of 80 km/h or 30.5 kg/sqm; Material properties of HDPE. The results show that the tree has a deflection of 9.6cm and is almost 70% utilised. The surface area of the tree is 13.24sqm.

The optimisation of the structure went through multiple steps and included twisting and tapering the individual branches of every single tree. The results of the manipulated geometry show that the deflection went up to approximately 10cm but the utilisation of the material could be reduced to 34%. The surface area are could be reduced to 10.5sqm (Figure 4).

![Figure 4. Arrows indicate deformation. Colour mapping indicate utilisation (red compression/blue tension). Left: first simulation, Right: surface area reduced.](image)

The results for the tallest of the trees showed that the same optimisation approach was also effective. The deformation of the tree could be kept within a maximum of 40cm for an overall height of 6.8m. This is for the worst
case wind speed. Still the utilisation of the material was in the allowable range. The maximum utilisation of the material of the tall tree was only reaching 66.5%. As a result the optimisation could reduce the material usage but maintain a similar result for the deflection.

Since the structure could not be connected to a regular concrete foundation due to its temporary nature, 300mm high concrete footings were casted in the hollow cross section of the triangular branches of the tree. To ensure the sliding and overturning of each structure under horizontal wind loads, it was necessary to provide laminar footings e.g. plywood sheets as shown in the layout. The resulting forces for the support system were designed by a simple structural logic to divide the forces and to reach equilibrium with the least amount of additional structural elements (Figure 5).

![Figure 5. Left: Arrangement of trees with shared footing system to reduce and counterbalance the overall system with the least amount of additional weight to ground the structure (Yellow area indicates position of ballast and connection). Right: Horizontal forces create an uplifting and a counter force. The forces are being balanced, reducing the overall ballast required.](image)

5. Fabrication and assembly

Though HDPE is relatively soft and can be cut rapidly on CNC equipment with good quality, the necessity of cutting approximately 1800 self-similar yet unique parts requires an efficient strategy for CNC cutting and part differentiation. A simple numbering system that systematically isolated a part location using an impromptu taxonomy, in this case Bundle-Strand-Length-Side, was developed and routed into each piece during fabrication to bypass human error.

While this had the disadvantage of increasing routing time significantly – it actually took longer to number the parts than to cut them out – small efficiencies were gained with minor adjustments such as rounding out inside corners, as routers tend to slow down during sharp direction changes, which
made up for a portion of the extra time. The parts were also nested in order so that assembly and fabrication could occur simultaneously and labourers were not waiting for parts to be cut.

The strands were manufactured from 3mm HDPE which was chosen for its translucence, high strength, isotropic composition, durability, recyclability, and value. In order to maximise material efficiency, it was necessary to dissect strands into multiple parts along their length and each strand was separated into its 3 constituent sides and further divided so that pieces fit neatly within the material bounds, which had the benefits of lowering material waste due to increased part nesting efficiency and increasing the number of lap joints to aid in load transfer and reduce the risk of buckling.

Assembly into subcomponents was carried out over a two week period with unskilled and mainly volunteer labour who were available at irregular intervals. For many projects this would be difficult or impossible to complete as the reliance on skilled labour is often critical to success. However, due to the simple logic designed into the structural and assembly strategies it was possible to train productive team members in only a few minutes and without the need for images or written instructions.

The entire project uses approximately 1.3 tons of sheet HDPE with a material efficiency yield of about 68%, approximately 12,000 aluminium pop rivets, and nearly 500m of LED lighting. The resultant strands vary in total length from 2.4m to 8.5m and are light enough to be carried and positioned comfortably by one person.

6. Installation

Logistics provide the biggest challenges for installing a project such as Arclight in the public domain. Additionally, the project site is more than 1000kms from the facility where the project is fabricated. Freight combined with remote assembly were both factored in as part of the strategy, resulting in branch segments of approximately 1200mm each – making parts both easy to handle and easy to pack into a shipping container. On site, parts can be easily laid out and prepared for joining; however this creates the need for an on-site compressor to run a rivet gun, as each section of the branches must be lapped and fixed before standing up into the tree clusters.

Due to the scale of the trees, mechanical assist in the form of a scissor lift is required to get up to a working height of ~3 to 4m above ground to make the attachment of each bundle. Attachment of individual strands to form a bundle is made simply with zip ties, which are concealed from view and allow rapid disassembly.
Additional logistical hurdles include fixing shallow 300mm star pickets to the ground surface in combination with the ballast. 800kg of ballast was required, which also needed to be hired and delivered to site. While mundane and pragmatic, these issues are often overlooked in the context of digital fabrication projects, but they are an inherent reality for consideration. An on-site team of 2-3 skilled and knowledgeable team leaders run a construction site over 3 days, guiding a volunteer team of 6-8 people per day working 14 hour days to prepare all the trees and associated lighting (Figure 6).

![Figure 6. Site installation showing fully assembled elements and subcomponents.](image)

7. Conclusions

As with architectural projects that are contextually situated between pure research and built outcome for public use, Arclight was subject to the demands and rigour required from both extremes, which are at times opposed and at others compounding. Issues of budget, robustness both from climactic and human factors, transport and assembly/disassembly logistics, and maintenance and repair are typically addressed in the realm of built outcome. Conversely, issues of computational craft, geometric rationalisation, and design intent can be thought to reside chiefly on the research end of the spectrum, as the latter issues can be resolved with small scale prototypes and simulations.

As this work illustrates through successive iterations, managing complexity is fundamental to the task of architectural fabrication, and this can be managed effectively through key strategies. The projects here achieve this through the use of associative modelling strategies, reductions in material variety, separation of fabrication processes for employment of the appropriate tools, and assembly that relies upon awareness of tolerance and precision implications. The project presented here is ultimately limited – and optimized – for material properties. Through a feedback loop that runs from
conception to modelling to testing, and finally, to complete assembly, the prototyping feedback loop plays a central role in facilitating progress and efficacy in the work, resulting in the final piece which manifests an ambient environment of bundled light.

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