BIO-REINFORCED LIGHTWEIGHT REVERSIBLE PANEL CONSTRUCTION FOR LOW-RISE BUILDING

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ABSTRACT

Light-weighting that results from the substitution of fibre-reinforced flowed composites has long been part of aerospace and nautical engineering. (Heuss et al, 2012) Building construction can benefit from this approach as a way to reduce material intensity and embodied energy, and to gain performance efficiency and formal possibilities. The opportunity to apply current research in bio-based flowed matrices and fibre reinforcing is particularly high in building construction because of the relative predictability, stability and scale of the loads to which it is subjected. Another potential benefit we identify is increased reusability of construction materials.

A thin shell construction can advantageously unify the functions of moisture, air, shear and lateral loading resistance, which are assumed by no fewer than three different layers in conventional construction. By eliminating the need for lamination among layers, thin shell construction increases the opportunities to harvest and reuse materials. Whereas moisture and air resistance is inherent to the material, such other properties as stability are best achieved by geometric manipulations. For example, by moving material out of the axis of inertia, thin shell panels can be given appropriate stiffness where resistance is needed while preserving local flexibility to facilitate installation, repair or de-installation. Our work focused on the use of local geometric manipulation to create panel joinery and calibrate panel flex.

Our work identified a series of joint and panel typologies and applied an empirical methodology relying upon the generation of physical models. Using hand-making in concert with PLA/3-D printing technology, we undertook to optimize panel-to-panel connections and to develop panel types uniquely suited to the implementation of the joints we identified. Our outcomes hold promise for a next series of design iterations and testing at large scale.

Keywords: light-weighting, bio-based materials, joinery, planar geometry

INTRODUCTION

Our research concerns the potential application of fibre reinforced, engineered composite materials for built environment applications. Favoured for use in transportation design, including aerospace, automotive and ship building, ‘composites’ have proved invaluable to light-weighting, an approach in which traditional metal alloys are replaced with equally high performing carbon or graphite-reinforced epoxy composites. Reduced weight greatly reduces the amount of energy needed to propel these vessels at the high speeds desired. The trade-off, however, is that these materials are typically extremely high in embodied energy, especially from fibre production. (Kara and Manmek, 2009) This downside has in turn spurred increasing research in the use of natural vegetable fibres such as hennequin, flax, pineapple and hemp for reinforcing. (Westman et al, 2010; Van Vuure, 2008) The resulting vegetable-reinforced materials, often captured in bio-based epoxy flows, offer much greater environmental benefit but because their performance is less easily engineered, they are less appropriate to transportation applications. We foresee in this class of materials an invaluable opportunity to introduce lightweighting into an architectural context. Our on-going work (Ko, Widder, 2013) has focused on the design of panels realized in bio-reinforced, bio-based epoxy flowed, that fulfil many of the complex demands placed on an exterior wall – waterproofing, structural stability, air-tightness – while also being inherently de-mountable and reusable. Panel to panel joinery can be integral to the panel shape, taking advantage of extruded or pulltruded composite production techniques and variable stranded reinforcing to give greater strength at the points required.

Our current research has developed a typology of joints categorized by the way in which they relate the two meeting panels: interlock, overlap, involution, friction and clip. Each type was mapped against eight salient properties, resulting in visual tools to immediately identify affinities and trade-offs among these types. The joints were then associated with a design for self-stabilizing panels. The most promising joint/panel types and characteristics were then systematically transferred into a 3-D modelling environment (Rhino and AutoCAD) and prototyped as a 3-D printed form. Through analogy to US standard wood frame, low-rise construction, a series of performance criteria were derived for panel to panel and panel to foundation junctures. The resulting artefacts explore a variety of geometric configurations for each juncture. Value was given to the reversibility of each connection. Material failure due to stress or fatigue at model scale was taken as an indication of where reinforcing mesh could be engineered once full-scale prototyping in bio-based composite material can commence.

METHOD

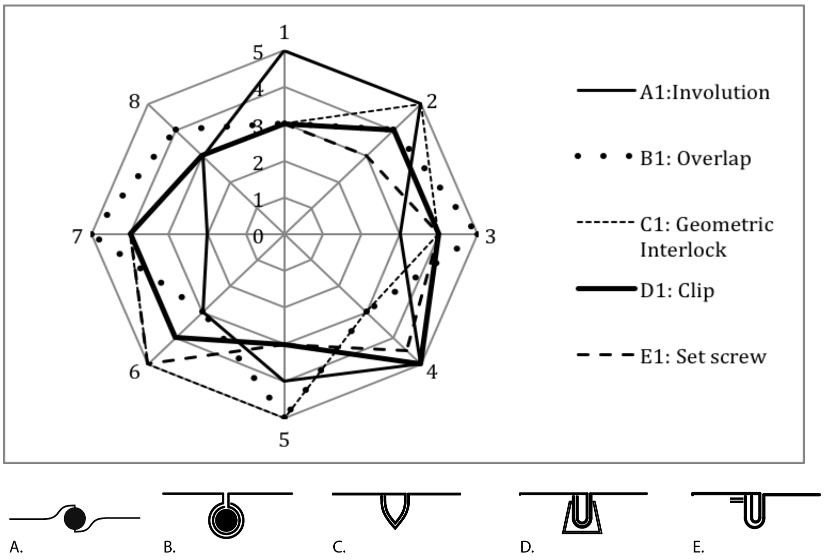
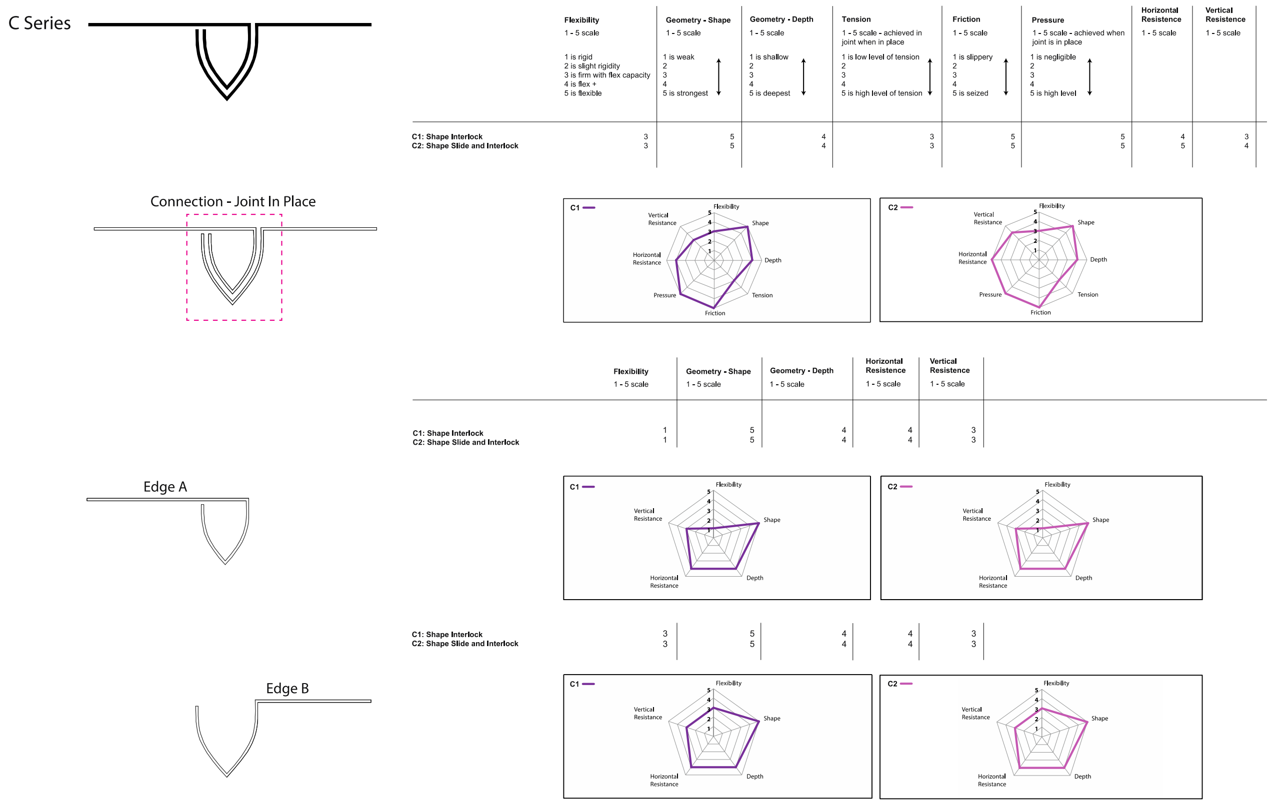


Fig. 1: Typologies A-D with a 'Spider' graph comparing the performance of the five different basic typologies; criteria 1) Flexibility 2) Strength of Shape 3) Depth of Shape 4) Tension 5) Friction 6) Pressure 7) Resistance to Horizontal Forces 8) Resistance to Vertical Forces (See Fig. 2 also)

Our project adapted the use of performance criteria to capture properties of materials and manufacturing processes, already a validated method (Ashby, 2010). We undertook an initial typological characterization of promising joinery methods: involution, overlap/interlock, snap-in configuration and two different friction connections, one using a set screw for punctual pressure and the other using a linear clip along the joint's full length. Each type was evaluated relative to significant criteria that affect in-situ structural performance as well as those that affect construction through ease of use and potential for reversibility. These properties include flexibility, reliance upon geometry, tension, friction, pressure and resistance to horizontal or vertical forces. By normalizing values for each criterion on a unitless, common scale of 0-5, we generated visualizations that allow quick comparison in performance of joint typologies across a range of materials and fabricational methods.



	Flexibility 1 - 5 scale 1 is rigid 2 is slight rigidity 3 is firm with flex capacity 4 is flex + 5 is flexible	Geometry - Shape 1 - 5 scale 1 is weak 2 3 4 5 is strongest	Geometry - Depth 1 - 5 scale 1 is shallow 2 3 4 5 is deepest	Tension 1 - 5 scale - achieved in joint when in place 1 is low level of tension 2 3 4 5 is high level of tension	Friction 1 - 5 scale 1 is slippery 2 3 4 5 is seized	Pressure 1 - 5 scale - achieved when joint is in place 1 is negligible 2 3 4 5 is high level	Horizontal Resistence 1 - 5 scale	Vertical Resistence 1 - 5 scale
C1: Shape Interlock	3	5	4	3	5	5	4	3
C2: Shape Slide and Interlock	3	5	4	3	5	5	5	4

	Flexibility 1 - 5 scale	Geometry - Shape 1 - 5 scale	Geometry - Depth 1 - 5 scale	Horizontal Resistence 1 - 5 scale	Vertical Resistence 1 - 5 scale
C1: Shape Interlock	1	5	4	4	3
C2: Shape Slide and Interlock	1	5	4	4	3

C1: Shape Interlock	3	5	4	4	3
C2: Shape Slide and Interlock	3	5	4	4	3

Fig. 2: Type C 'Geometric Interlock', a sample typological analysis. Each radius on the spider graphs represents a quality that is valuable for any joints' capacity to be set in place, and to withstand forces once completed. Those characteristics considered here as methods to create joinery are: the capacity for flex; geometric configuration; and a tensile, compressive or frictional connection between parts. The spider graph also indicates on a scale of 1 to 5 the resulting joint's capacity to resist horizontal/lateral or vertical/gravitational force.

In a multidisciplinary team drawing from diverse areas of architecture, sustainability management, design computation and rapid manufacture, this type of data capture and analysis has become a critical part of our collaborative workflow. Especially in the initial stages of design and prototyping, this analysis allows for a common awareness of relevant parameters affecting performance as well as potential trade-offs resulting from making adjustments. In the subsequent stage of prototype formulation and development, we employed an iterative design process, in which each idea progressed with the application of both hand-drawn and rapid prototyping techniques. Any failings and potentials then informed our subsequent design iterations.

PROTOTYPE FORMULATION AND DEVELOPMENT

To stay within the scope of our current fabrication capacity, we began by pursuing type B 'overlap' and C 'geometric interlock. Beginning with simple clip forms and evolving the joint form so that it could stand when set on a flat surface, we focused the design and fabrication on two basic joint classes. One was based on a triangular interlocking joint and the other on a cylindrical overlap joint. The base geometries of circle and triangle exploit these figures' inherent geometric stability to lend the overall construction bearing capacity in analogy to wood framing. Various joint iterations were in turn tested for reversibility and adequate resistance to lateral stresses when in place. The joints were first printed as flat pieces to test their interlock mechanisms; later iterations depicted the full height of an 8ft wall panel at scale. For the purpose of testing the joints, the panels were simplified and modelled only as flat planes.

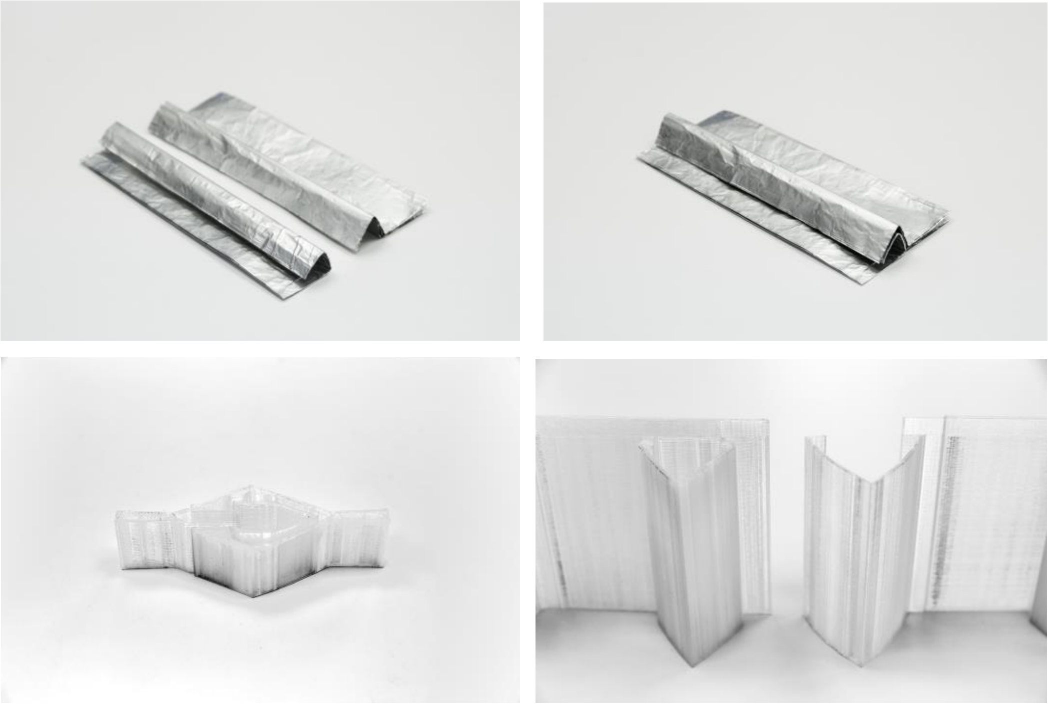


Fig. 3: Iterative models of triangle/ogee-shaped male-female joint in metal and PLA

After studying these two joints, we moved to the design of their associated panels. Here, we sought stability at the panel's centre and adequate flexibility at its ends to ensure the ability to implement and reverse the joint to the next panel. The PLA 3-D printed flat panels showed significant warping, which we took to be indicative at scale of the likely panel performance in any synthetic material. For this reason, panel stabilization became our focus as the project continued. Initially, we used struts positioned in an X configuration for stabilization. Although these struts offset warping and instability, they interfered with the snap-in joint and the required flexibility at the panel's end. We recognized that the struts functioned in two ways: by moving material to the points of instability at the panel's centre; and by creating geometry, which tied the sides together. These two strategies were used as the basis for further iterations of panel designs, one associated with the triangular joint and the other with the cylindrical overlap joint.

JOINT/PANEL ITERATIONS

The triangular/ogee-shaped male/female snap-in joint, integrated directly along the panel's edge, provides excellent vertical stability with little material intensity. A closed, hollow triangle at the 'male' end was slightly offset from the surface of the panel, creating a depression into which the female element would clip. The 'female' portion comprised two legs of an ogee, which fit on top of the 'male' element, as well as an additional edge to complete the clip. It is not difficult to imagine how these linear elements might clip into place on the construction site using a simple tool to slide along the length of the 'female' element, moving it out of plane and into the grove along the 'male' element behind it.

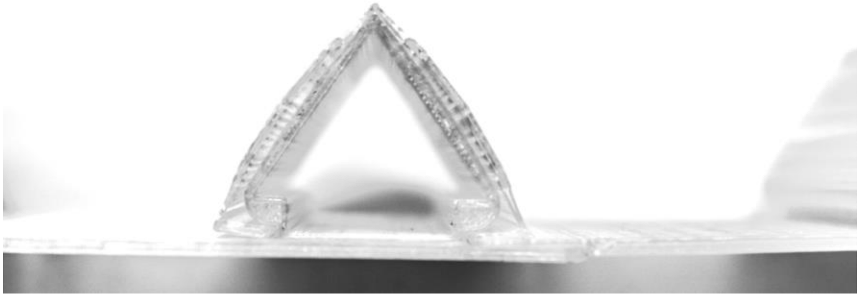


Fig. 4 Triangular/Ogee joint

Construction systems require much more than panel-to-panel connections. We therefore explored several variants to account for the way panels could attach to a sill plate or foundation while retaining reversibility. Another challenge was maintaining clearances that facilitate the placement and snap-in of panels while creating an overhanging edge on the panel, which can waterproof the gap between sill plate, foundation and wall. We devised three distinct iterations of a fuller wall construction system:

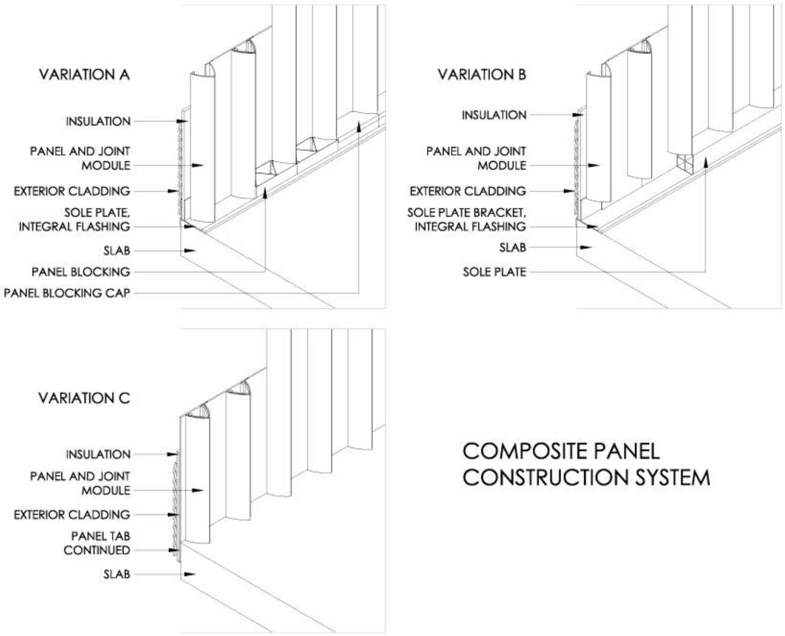


Fig. 4: Three variations on panel/sill plate connection and exterior finish

We tested each iteration, especially the customized sill plate and the friction connection designed to hold the wall stable. Models indicated the challenges of overturning and the limitations of a friction-only connection. Some potential remedies at building scale include using fasteners in holes that are provided in the panels during the fabrication process or weak adhesives that can temporarily hold elements in place while construction is completed.

Refocusing our efforts on the panel, we pursued strategies for the triangular joint panel type, which considered the displacement of material from the neutral axis as its means of stabilization. Three-dimensional corrugation-like deflections along the surface of the panel were fine-tuned through multiple model iterations to balance adequate rigidity in place with flex at the panel's ends. Within the limitations of the PLA material, we were able to achieve appropriate stability at the panel centre while maintaining flex at the edges using an egg crate corrugation pattern displaced symmetrically about the neutral axis.

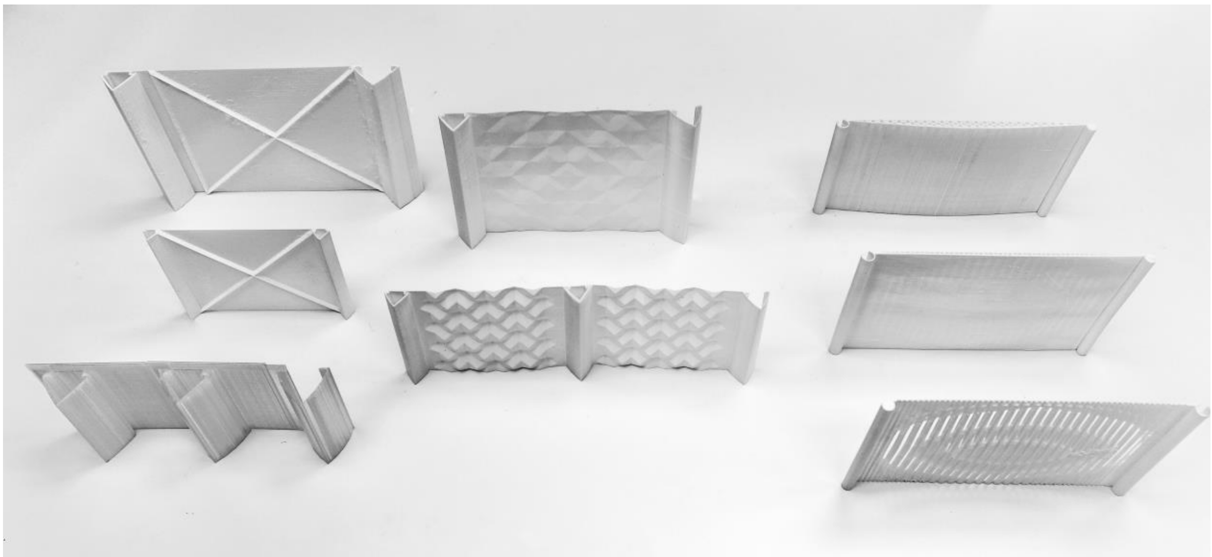


Fig. 5: Panel iterations with struts, egg crate corrugation and honeycomb

The cylindrical joint with overlapping 3/4 round concave component had an interesting capacity to hinge, and to form interior corners. Its disadvantages in comparison to the triangular configuration were its greater material intensity, required to give stability to the much smaller cross-sectional area at the joint; and the difficulty of increasing the size of the joint's cross-section. While the depth and geometry of the triangular piece can be almost endlessly varied in comparison to the equilateral triangle we chose, the circle can only be manipulated based on diameter.

In developing a strategy through which to stabilize this panel, we chose to explore a different approach, which we believed to be more formally compatible with the round joint geometry. We adapted interior honeycomb geometry, typically used in lightweight panel construction to form a diaphragm between the two exterior sheathing members. After several iterations, we discovered that thickening the panel towards its geometric centre – as if the panel had been intersected by a sphere – and retaining only the exterior sheathing provided an appropriate balance between flexibility at the ends and stability elsewhere.

CONCLUSION

The outcomes argue persuasively for the potentials of lightweight, panelized construction that unifies the three primary functions of a wall in one. The families of joints and panels in their 3-D printed forms at 1:20 scale demonstrate how effective simple geometric manipulations can be, even when prototyped in an unreinforced, isotropic material. Next steps include a fuller engineering stress analysis and the prototyping at full scale of joinery systems in vegetable fibre reinforced bio-based composite material.

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