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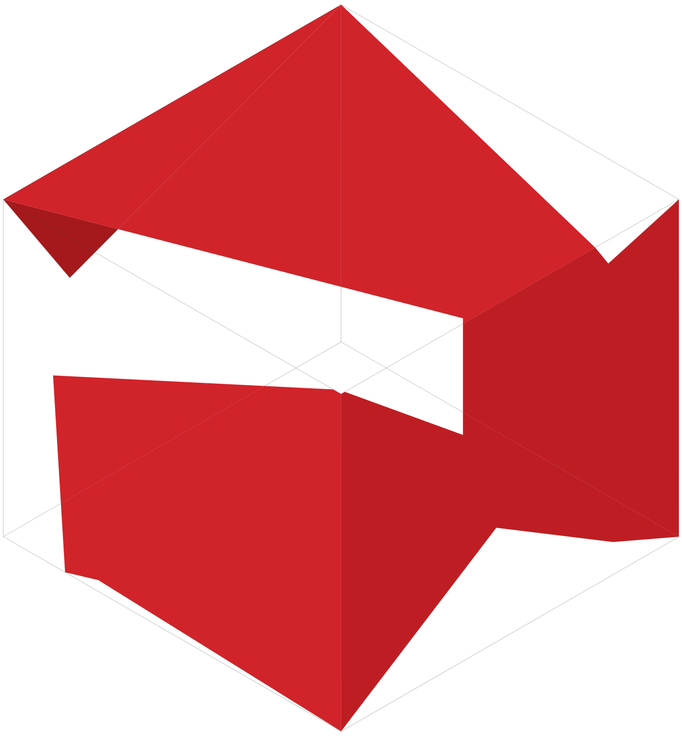

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Knitting Moves:
Bio-inspired Transformable Textiles for knitted Architecture

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Abstract: This paper reports on postgraduate research exploring the use of biomimetic design principles in the design and development of responsive knitted textiles for architecture. Central to the investigation is the relationship between the inherent properties of natural materials and weft knit structure. The research suggests that it is through the manipulation of these elements that innovation in responsive design can occur. This research sits at the intersection of materials innovation and smart textile design. Whilst current research remains speculative in terms of architectural application, conclusions discuss the potential impact of the work.

Keywords: Knit, biomimetics, responsive materials, architecture, smart textiles, participatory

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Introduction

Nature has always provided inspiration for pattern and form in design, however biomimetics is emerging as an important method for design research. Based on analysis of natural forms, processes and systems, biomimicry considers function as essential to determine form (Benyus, 1997). Current biomimetic research within architecture includes *Protocell Architecture*; the development of materials which mimic the natural processes of growth and self repair (Spiller & Armstrong, 2011), and Philip Beesley's biomimetic responsive architectures based on a framework of lightweight textile materials which move in response to activity (Beesley, 2005).

This paper reports on experimental knit design work for architecture based on biomimetic principles which test the potential of natural materials as sensors and actuators within weft knit fabric structures. The paper outlines the specific properties of knit which provide transformative qualities for innovation.

Context

Textiles are intrinsically linked to the relationship between people and the environment, providing protection for individuals through clothing and shelter. Historically natural materials were used to construct primitive shelters; natural fibres woven into simple enclosures or animal hides for insulation. Textiles had the ability to maintain a comfortable environment even in extreme weather conditions (Kruger, 2009). It is this inherent responsiveness that is of particular interest in the development of knit fabrics for architecture.

Textile architecture has traditionally been associated with tensile structures (Kruger, 2009), however new materials and a search for responsiveness and flexibility within buildings have made knit structure appropriate for investigation. The emerging field of knitted architecture explores the use of environmentally responsive fabric to define spatial conditions beyond the scale of the individual human body. This field is developing principally through work by architect Mette Ramsgaard Thompson. *Slow Furl and Vivisection* are gallery-sized knitted installations which move in response to activity (Ramsgaard Thompson in Quinn, 2011, p202-4).

Research Questions

- 1: How can the structure of knitted fabric be engineered using biomimetic models to design environmentally responsive textiles for architecture?
- 2: How can biomimetic models inform the design of knitted structures?
- 3: How can the inherent properties of natural fibres be exploited to engineer responsive behaviour?

Biomimetic Model

In order to determine a suitable biomimetic model for investigation, a broad overview was conducted into the mechanisms used by plants to actuate modifications in size and shape.

Plants are able to modify their shape or move in response to a number of stimuli, for a variety of different reasons. The majority of plant movements are so slow that it is difficult to observe them in real time. Such movements include twisting stems, tendrils attaching themselves to other plants, and the movement towards and following sunlight (Martone et al, 2010). Rapid motion can also be observed in many plants for specific functions such as seed dispersal (White Mulberry), defence (Sensitive Mimosa) and nutrition (Venus Fly trap) (Martone et al, 2010). Plant Movements respond to a variety of stimuli, including light, moisture and touch. (Fratzl & Barth, 2009). Responses can be described as nastic, independent of the spatial direction of stimulus, and tropic directly influenced by the direction of stimulus (Fratzl, Elbaum, & Burgert, 2008). These movements can also be distinguished as either active or passive. Active systems are based on living cells that activate and control responses through chemical and physical changes within the organism (Fratzl, Elbaum, & Burgert, 2008). Passive systems rely on dead tissues which are designed to go through specific movements when environmental conditions change. These systems do not require further control or energy supply for actuation. (Fratzl, Elbaum, & Burgert, 2008).

Plants have evolved a variety of mechanisms to actuate modifications in size and shape; slow movements rely on changing pressure within either the cell vacuole or cell wall, however elastic instability is required for fast movements (Martone et al, 2010). Mapping these movements against reversibility illustrates that changes to cells and cell walls are reversible in many cases including the pine cone model, although irreversible within growth tropism. Elastic instabilities can also be both reversible (snapping motion of Venus Flytrap) and irreversible (seed expulsion, White Mulberry) (Fratzl & Barth, 2009).

The aim of this research was to design and develop fabrics that can change in shape in response to environmental conditions without any external control mechanism. The pine cone hygromorph was identified as a suitable model to study in order to identify how a reversible, moisture responsive process can occur in nature.

Pine Cone Hygromorph

Many passive movements in plants have the common feature that the movement is caused by differential swelling and shrinking of specific parts of the tissue. The mechanism that controls the swelling is the architecture of the secondary cell wall (Vincent, Dawson & Rocca, 1997). In the example of the pine cone, the scales move towards the base of the cone in high humidity and away from the base of the cone as it dries out to reveal the seeds inside. This can be observed while the cone is on the tree or once is has fallen from the tree (Vincent, Dawson & Rocca, 1997).

The mechanism is controlled by swelling and shrinking within cell walls. The cell walls contain a combination of cellulose, hemicelluloses, the starches in which cellulose is embedded and lignin a woody and rigid material (Martone et al, 2010). The scale is made up of differently structured tissue on the upper and lower sides. Fibres on the upper part of the scale run parallel to the cell axis, as these cells dry out the shrinkage is pronounced perpendicular to the cell axis but minimal along the cell axis. In cells on the bottom of the scale cellulose mibrofibrils lie perpendicular to the cell axis (Vincent, Dawson & Rocca, 1997). As these cells lose moisture they shrink in the axial direction. The combined action of the tissue layers leads to a bending of the scale, opening the cone (Fratzl, Elbaum & Burgert, 2008).

It is the orientation of fibres within the scale that allows the two materials to behave differently; one which swells along the length of the scale in the presence of moisture; and one which resists swelling - this causes the bending movement in the cone (Vincent, Dawson & Rocca, 1997). The geometry of the individual scale allows the swelling and shrinking effect within the central area of the scale to act over the whole scale, amplifying the movement (Vincent, Dawson & Rocca, 1997).

This biomimetic model has been explored within knit design using highly swellable natural materials. Investigation into appropriate materials and knit techniques is outlined below. In terms of a biomimetic principle for development within fabric design there are three key areas of investigation:

- 1: A composite of more than one material, one that swells and one that resists swelling, forcing the material to distort.
- 2: The orientation of fibres determines movement; either by controlling potential shrinkage or allowing swelling and shrinking.
- 3: Deformation within a small area of a scale is amplified throughout the structure geometrically.

Materials

To create responsive materials some method of sensing and actuation is required. Within smart textiles this has traditionally been achieved through embedding electronic systems within textile materials (Braddock Clarke & O'Mahony, 2005). Recent developments in material science use nanotechnology to manipulate the physical properties of fibres at a molecular level. This allows specific smart functionalities to become inherent within the fibre. Innovations include *Smartcel*, a heat regulating yarn developed by Smart Fiber, and *Luxilon* a thermoformable monofilament produced by Luxilon Industries.

An alternative approach for developing environmentally responsive textiles is through the manipulation of inherent properties in natural fibres. These materials have surprising properties that have been underexploited within smart textiles.

The ability for natural fibres to absorb moisture is taken for granted; it is this property that allows clothing to absorb moisture from the skin, and is fundamental to traditional laundering processes (Morton & Hearle, 1986). However there is great potential to exploit this characteristic beyond these conventional applications. Historically the ability of fibres to absorb changing amounts of moisture from the air led to early indicators of changing weather. Leonardo da Vinci experimented using cotton fibres to predict rain; as moisture levels in the air increased the weight of the cotton fibres set against wax on a balance increased, and tipped the scales to indicate potential showers (Morton & Hearle, 1986).

Cellulosic fibres, both natural and regenerated, have dynamic moisture absorption properties; fibres swell and increase in volume and density in the presence of moisture. Changes in fibre properties have a direct impact on the yarns made from them; changes in size, shape, stiffness, and permeability occur. This has direct impact on mechanical properties (Morton & Hearle, 1986). In cotton fibres, the cellulose network is penetrated by water molecules; water makes its way into the capillaries, forcing the molecules apart and reducing the rigidity of the cellulose molecules. Fibres become more plastic and are easily deformed (Cook, 1968).

In regenerated cellulose fibres such as viscose the effect is even more pronounced. As a result of processing, regenerated cellulose has less crystallinity within the fibre structure. Although the molecules are aligned through processing there is a reduced amount of ordered, crystalline regions, and an increase in the quantity of amorphous regions within the fibre. Viscose has twice the moisture absorption of cotton; when saturated viscose will swell to double its original volume (Cook, 1968).

Synthetic fibres have very low moisture absorbency and do not swell appreciably; nylon 66 filaments only increase by one fiftieth in water (Cook, 1968). These fibres remain dimensionally stable in the presence of moisture due to their molecular composition which does not attract water molecules.

Veneer

Wood, composed of 40-50% cellulose is easily penetrated by water. The mechanical and physical properties of wood are changed through varying levels of water within bound water in the cell walls (Hon & Shirashi, 2001). Wood swells and shrinks in different directions by different amounts; the greatest shrinkage occurring in the tangential direction (8%) (Tsoumis, 1991). Water is absorbed most rapidly in the longitudinal direction however the least shrinkage occurs in this direction (0.1%) (Tsoumis, 1991). Veneer will bend or warp due to differential shrinking in the radial and tangential directions (Tsoumis, 1991). If water is absorbed through one surface of a veneer it will bend. The direction of bending can be attributed to the cut of the wood in relation to the direction of the grain. The bending movement of veneer can therefore be programmed through the direction of cut.

Knitted Fabrics

Weft Knitted fabrics are composed of loops of yarn; the properties of the knitted structure are largely determined by the interdependence of each knitted loop with the loops on either side, and above and below it (Spencer, 2001). Under tension weft knitted loops can easily distort, loops will stretch both horizontally and vertically as the yarn is robbed back by adjoining loops (Spencer, 2001). This characteristic provides knitted fabrics with exceptional levels of extensibility, deformation and recovery compared to other textiles (Spencer, 2001).

Fabrics can be produced as flat shaped pieces or as three-dimensional nets, ideal for the construction of complex shapes and forms. Their mechanical properties can be altered through yarn, fabric structure and by manipulating the parameters of loop length and stitch density.

This research examines single bed fabrics, which naturally curl due to the unbalanced nature of the structures. Single bed fabrics are composed of loops of yarns constructed in the same direction. The loops are always created by drawing a new loop through the old loop, from the technical back to the technical front of the fabric. At the point of intersection between the old and new loop there are two thickness of yarn controlling a single stitch. This holds the loop in position at both the head and the foot of the loop and causes the sides of the loop to curl upwards. Fabrics curl towards the technical front (TF) at the top and bottom and towards the technical back (TB) at the sides (Spencer, 2001).

Plated fabrics have been incorporated into the investigation to test whether physical properties of yarns can overcome the mechanical properties of the fabrics. Plated fabrics are composed of two or more yarns, one of which lies on TF of the fabric, and the other lies on the TB of the fabric (Spencer, 2001). Within this research this has allowed use of yarns with opposing moisture absorption characteristics to be incorporated within a single bed fabric in a uniform manner. As the fabric inherently curls towards the TB at the sides, the changing physical properties of the yarns acting on the TF and TB restricts and exaggerates the inherent curl of the fabric.

Rib structures are balanced structures with an equal number of face and reverse loops on each side of the fabric. These fabrics are constructed using two sets of needles alternatively set on opposing needle beds. By combining the balanced structure of a rib fabric with the unbalanced nature of a plain fabric pleats can be achieved within the fabric. Where a single wale of plain fabric is spaced within a rib structure diagonal pleats are formed.

Design Practice: Research Methods

To test the biomimetic principles a series of fabrics have been developed. These technical samples explore potential movements and changes in form achieved by exploiting the inherent curl of the knitted fabric. In order to form composites a combination of natural moisture absorbing materials and synthetic hydrophobic materials have been used to develop knitted fabrics. Different approaches have been considered to analyse how natural materials can be used to manipulate fabric structure.

- 1: The first series of samples use viscose ground yarn plated with synthetic materials; monofilament or elastane, to test whether the changing physical and mechanical properties of viscose in the presence of increased moisture could alter the shape of the fabric.

- 2: A second series of samples explore the use of nylon monofilament and elastane within a variety of single and double bed fabrics in combination with viscose and embedded wood veneer. These samples test the potential to create smart responses in textiles when subjected to increased moisture levels.

Samples were produced using different manufacturing methods including Dubied knitting machines (5gg), domestic knitting machines (6gg) and Shima Seiki Power machine (10gg). Samples were actuated from a relaxed state using steam introduced from above. Steam was continually blown at the sample until actuation occurred. Samples were tested in a domestic environment with the actuation recorded on video. Where possible both the initial actuation and the return to a relaxed state were recorded.

Design Practice: Outcomes

Series 1

In this set of simple fabrics viscose was plated with synthetic materials. In a relaxed state the single bed fabrics curl towards the TB. The viscose appears on the TB of the fabrics. The aim of these developments was that as the material was actuated the fibres in the yarn would swell forcing the fabric into a flat form. As the fabric dried the fabric should curl again. This was investigated as an all over effect and within stripes and links/links fabrics. The success of these fabrics depended on the synthetic material that was combined with the viscose.

In several samples using monofilaments the resistance provided by the monofilament was too strong for the viscose to overcome when actuated and the samples remained in their original form. Where links/links was incorporated into the structure the patterning was critical to the success of achieving movement, with bold structure within large areas of plain achieving the most dramatic effects.

Series 2

A series of fabrics have been developed with strips of veneer embedded into a tubular knit structure composed of elastane on the TB and monofilament on the TF. The elastane is under tension within the structure to encourage the veneer to bend, the monofilament resists tension and supports the return to the original form. These tubular knit sections have been incorporated into a variety of single and double bed structures including; shaped panels (Figures 1,2), box and knife pleated structures (Figures 3,4), and within pocket formations (Figures 5,6).

Sample 1: Fibre orientation determines movement

This example illustrates how changing the direction of the knit using shaped panels of single bed fabric can achieve a three dimensional form after actuation. The fabric begins as a series of plain knit triangular segments interspersed with strips of veneer embedded into pockets of tubular elastane (Figure 1). The veneer used for this sample was cut perpendicular to the grain. In a relaxed state the material sits flat in a semi circular shape. However as the material is actuated sections curl towards the technical back, and the form of the fabric is altered (Figure 2).

The most dramatic form is observed at the top and bottom of the fabric where the veneer is controlled in only one direction by the knit fabric, here spiralling of the veneer is supported in a complete twisting of the fabric. As the fabric dried a partial return to the original form was observed, and on re-actuating the spiral form was recovered.

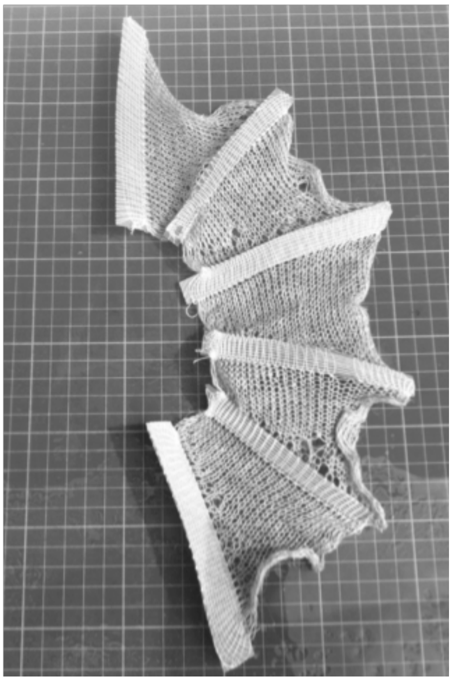

Figure 1. Sample 1 in relaxed state

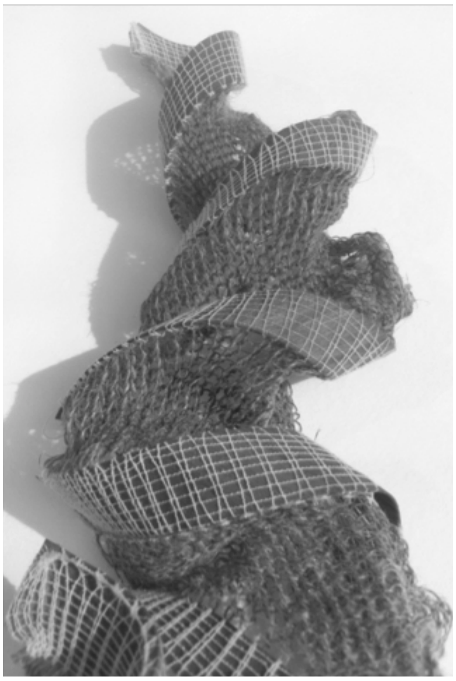

Figure 2. Sample 1 after actuation

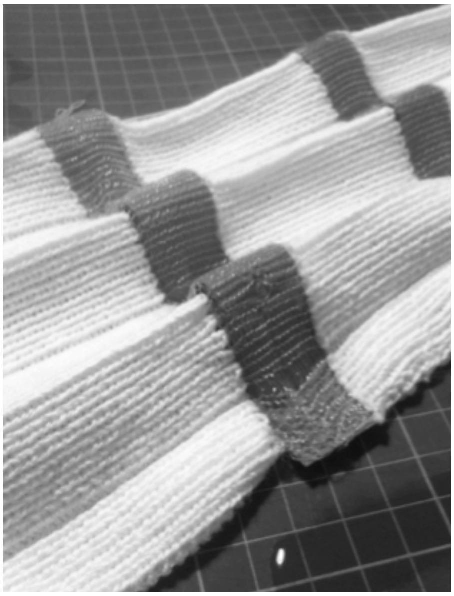

Figure 3. Sample 2 - Knife pleat (actuated)

Figure 4. Sample 3 - Box pleat (actuated)

Figure 3 shows a knife pleat form, Figure 4 demonstrates a box pleat outcome. In each example the fabric width is reduced and the fabric increases its three dimensional profile. Although the pleat form is programmed into the fabric during construction, in a relaxed state the veneer holds the fabric flat. The transformation caused by actuation of the veneer produces a pronounced effect across the whole of the fabric despite only directly acting on a small area. Like the biomimetic example, this demonstrates that by deforming a small area, the impact can be translated throughout the fabric as a whole.

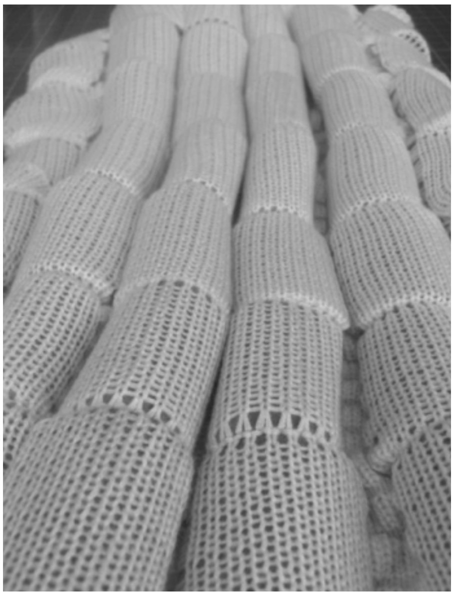

Figure 5. Sample 4-Pockets with straight cut veneer (actuated)

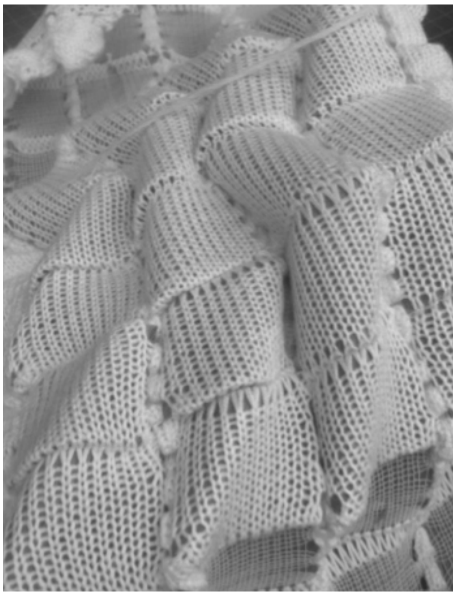

Figure 6. Sample 5 - Pockets with diagonal cut veneer (actuated)

Samples 4 & 5: Further Developments

Further fabric development investigated the use of individual pieces of veneer embedded within a pocket structure. This work considered the impact of individual pieces of veneer to test whether the pieces would act in a uniform manner within the fabrics. Samples were constructed from viscose (TF) and elastane (TB).Different cuts of veneer were explored; straight cut veneer curled in a very consistent way within the fabric.

This resulted in the fabric shrinking width-wise and developing a pronounced three dimensional profile of corrugated columns of bent veneer (Figure 5). Depending on how closely together the vertical rows of pockets were constructed along the width of the fabric the veneer bent to a greater or lesser degree.

When a diagonal cut of veneer was incorporated into the structure, the actuated fabric skewed diagonally, producing a three dimensional zigzag effect along the length of the fabric (Figure 6). The effect of the diagonal cut was particularly interesting as individual pieces did not curl in a uniform manner across the fabrics. Instead the position of the veneer within the fabric form determined the degree of movement.

Conclusion

This work has required both an understanding of material properties and knitted fabric techniques. Analysis of materials identified key properties for exploitation, and analysis of knit structure has provided appropriate fabrics for investigation. The changes in both the physical and mechanical properties of natural fibres after exposure to moisture has been explored as a way to actuate knitted textiles and achieve changes in shape and form.

By distilling key ideas from the pine cone hygromorph into clear technical concepts interpreted within fabric design, it has been possible to focus design work achieving specific functional outcomes. Technical samples interpreted three key concepts as a starting point for innovation. The outcome of the work is not, however, a knitted pine cone, the fabrics respond with different transformations in shape and form. Although each form is different the general characteristics observed are; a reduction in the width of the fabric combined with an increase the three dimensional profile. Although the shapes and forms vary throughout the work it is the same key principles that underpin all design work.

Creating simple composite fabrics using materials with different moisture absorption properties has allowed the inherent characteristics of natural fibres and materials to be used in a smart way. By combining natural materials with synthetics, the swelling that occurs as a result of moisture absorption has been used to actuate fabrics and create controlled changes in shape and form. The properties of synthetic materials have also been carefully applied to control the structures combining materials with excellent stretch and recovery (elastane) with materials that demonstrate very limited extensibility (nylon monofilament).

In terms of application development of this work is aimed at an architectural context where low impact passive systems could automatically respond to changing environmental conditions. Speculative ideas include passive ventilation systems and exterior awnings. The passive ventilation system would respond to changes in the moisture content of a room. The fabric could change in form when warm moist air builds up inside a space to allow the moisture to escape, and then return to the original form as the moisture levels are reduced. As an exterior awning the textiles could provide responsive shelters which transform from decorative shading to provide areas of shelter against showers whilst channeling water away for reuse.

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