f2f
file to factory
continuum

The
Design and Fabrication
of innovative forms in a
continuum

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London, UK

Design and Fabrication of "EmTech" Canopy at the Architectural Association

Background

The Emergent Technologies and Design programme introduces design research as a process that implements diverse analysis and design methods that continuously cross-inform each other. *Emergence is defined as that which is produced by multiple causes, but which cannot be said to be the sum of their individual effects. The programme is focused on the concepts and convergant interdisciplinary effects of Emergence on design and production technologies, and on developing these as creative inputs to new architectural design strategies*. The instruments of analysis and design in Emergent Technologies are computational processes that lead to an architectural design approach that utilizes genetic algorithms for structural optimization and generative design.

There are two main research paths that are followed. One looks at biological paradigms in order to abstract the underlying principles of their morphogenesis and function. This biomimetic approach is *looking at natural systems for inspiration and innovation*. It is a process of observation and analysis in order to abstract principles that can be applied in architectural design or engineering. The second research path focuses on the behaviour of material systems *that comprise geometric logics, material characteristics and behaviour as well as manufacturing and assembly logics*. This requires an intricate connection between design and fabrication. A strategy for the integration of all design and fabrication processes through feedback loops can lead to optimized structures that respond simultaneously to multiple performance criteria.

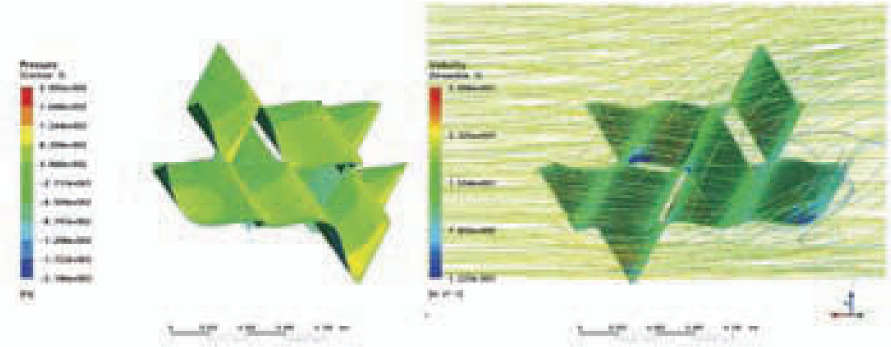
The Canopy design process created an interface where inputs from various factors were incorporated leading to an adaptive design that emerges from the negotiation of performative, fabrication and structural requirements, aiming at the generation of a system that would optimize form, function and structure.

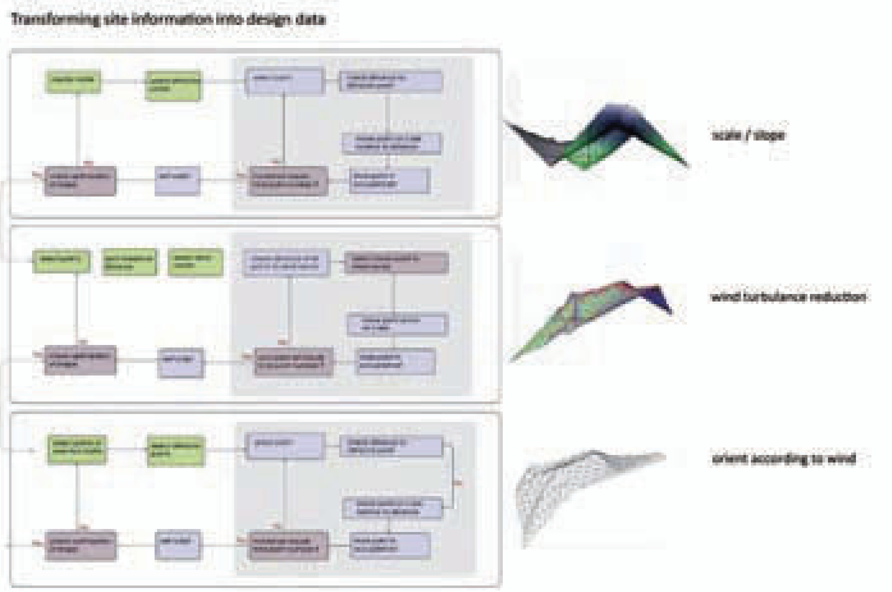
A data driven design process

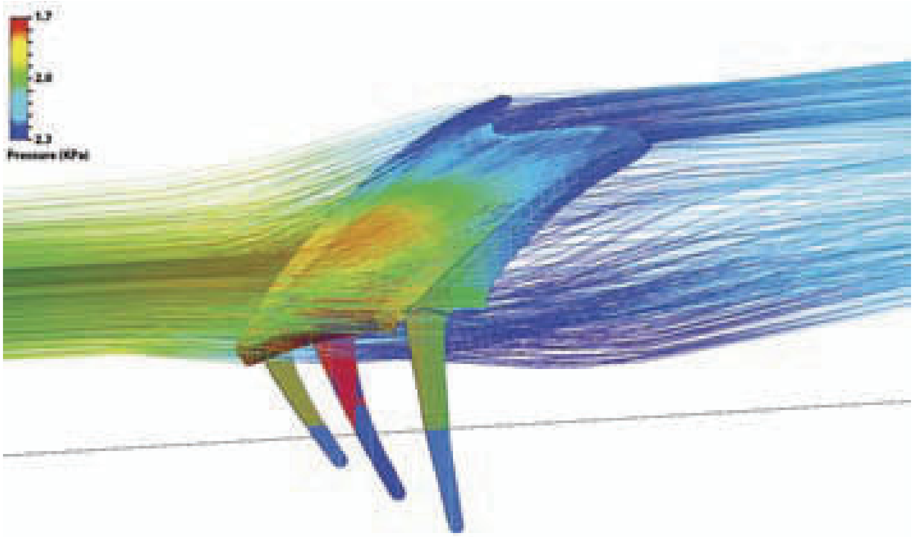
The programmatic requirements for the Canopy initiated the design process. The development of the material system was constantly informed by material constraints calibrated by physical experiments; the environmental performance and structural behaviour was continuously analyzed through Computer Fluid Dynamics (CFD) simulations in an iterative process. The brief required a Canopy that would provide shelter in one of the schools public areas, hence its environmental performance had been a key concept from the very beginning. A successful design would respond to various performance criteria, it would provide shading, protect from rain and modulate the wind.

The fabrication method was constrained by the CNC machines available, which defined a range of possible material types and sizes that could be implemented for the canopy construction. The fact that the canopy was to be constructed and assembled by students utilizing the school's facilities placed further constraints on the scale, weight and assembly logic. These constrains informed the design process at all stages. The environmental input and its influence on the structure was checked through CFD analysis that simulates wind and rain in order to inform the design process.

During the first stage of the design process, five groups of students worked on a canopy proposal. After one month of design work these five groups were reduced to three, which would further develop the ideas into a construction proposal. The final design was selected from these three proposals incorporating ideas, concepts and




Transforming site information into design data
scale / slope
wind turbulence reduction
orient according to wind


Pressure (KPa)

strategies from the rest of the design proposals. Thus a wavelike assembly of wooden strips formed the first sketch that would be further developed into the Canopy design. The overall morphology and curvature of the strips achieves water drainage at specific points in the terrace as well as channeling of the wind through the apertures created between strips.

Several physical experiments were carried out and prototypes were constructed in order to test the construction method and modify the process accordingly. The physical experiments informed the digital model of the material limitations and the radius of curvature achieved through bending. Digital and physical models constantly informed each other in an iterative fashion.

Transforming data into vectors

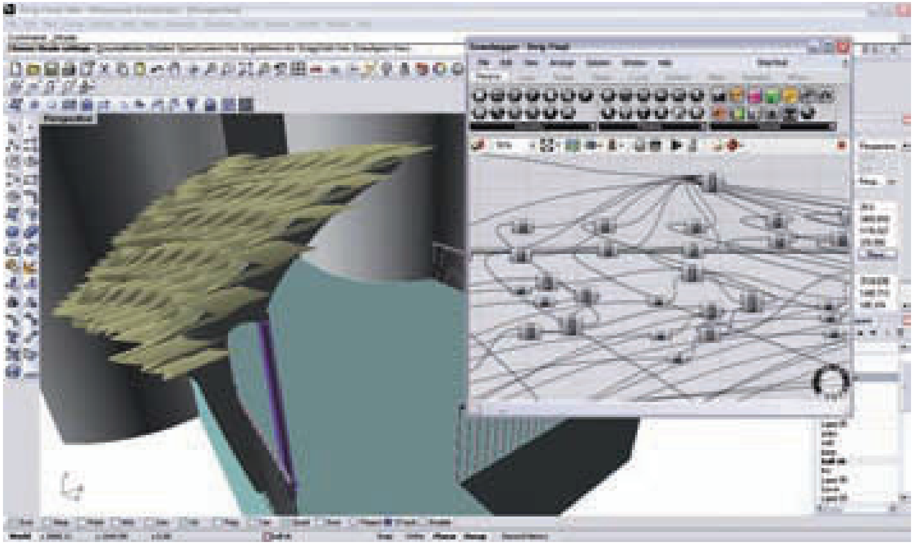
The AA terrace is located in the middle of a wind tunnel which generated very specific conditions to be taken into consideration. The aim of protecting it from the wind and rain simultaneously was a complex task, especially due to the fact that rain direction can change following changes of wind direction and velocity. This required an optimization strategy that could only be achieved through several iterations of design, analysis and evaluation. The brief had no specific requirement on the percentage of covered area, thus it was decided that the canopy would cover a part of the terrace, mainly acting as a barrier to the prevailing winds while offering protection from rain. Sunlight is not frequent in the UK which led to the decision not to prioritize the requirement for sun protection, thus shading as a fitness criterion was assigned less weight.

The input parameters of the site regarding the geometry of the terrace and the environmental conditions were transformed into data that was fed into diverse optimization algorithms that would define the overall geometry of the canopy. Thus through various iterations an initial surface was oriented according to its exposure to the wind, aiming to reduce wind turbulence under it and direct the rain water to the drainage points. An attractor based script moved the points of the surface in the z axis creating thus optimal slopes for water drainage.

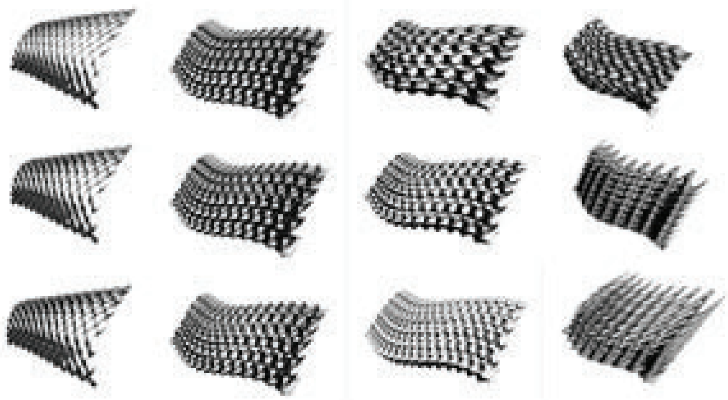
During the design process the resultant surfaces were analyzed through Computer Fluid Dynamics (CFD) simulations in order to check the effect that each geometric modification would have on the modulation of environmental conditions. The aim was to reduce turbulence under the canopy and increase laminar flows. CFD analysis of the surface highlighted the areas which are more exposed to wind pressure. Increasing the porosity of these areas would decrease the wind load and thus increase the structural stability of the canopy.

A pattern of overlapping wavelike strips proved to be an option that could channel the wind through it and at the same time direct the rain water to the drainage points of the terrace. The strip component was analyzed through CFD analysis and the simulation illustrated that the wind channeled through the apertures creates local turbulence separating thus the airflow from rain.

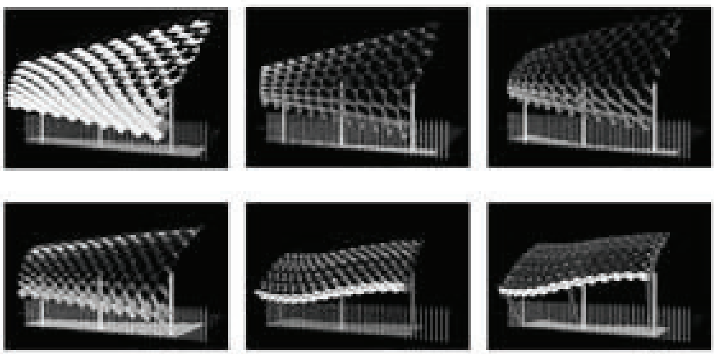
Scaled models were used in all phases of the design, ranging from the initial component exploration to the final joinery mockups. This gave an insight into the materiality of the system and informed further decisions.



Population of design variations



Parametric associative models



Engineering feedback

The collaboration with Buro Happold engineers was crucial. The initial design concept was developed so as to incorporate structural demands into the design process. The engineers were not consultants exterior to the process but played an intrinsic role in it its growth as their feedback helped the structure to evolve. There was an ongoing negotiation between the engineer's demand of the system to withstand unpredictable loads over time but also an architectural motivation to keep the system as 'pure' as possible using only one material.

Several scaled prototypes were built in order to test the structural viability of the strips and their connection to each other. Various degrees of overlap were evaluated in order to find the range needed to negotiate between structural strength and maximum angle achieved by the cantilevering of the strips outwards. A structural analysis tested the deformation of the system under load in order to inform the physical model of the axial stresses and moment stresses.

The first structural proposal consisted of two layers of 1.5mm plywood bolted together. This configuration was tested through simple load tests and proved to be too flexible and thus a number of alternatives were discussed with the engineering team. One of the options consisted of reinforcing the strips by adding a third layer of glass fibre and resin in between them. Different configurations were tested to determine the number of glass fibre layers required to provide sufficient stiffness without increasing the total weight. The use of three layers added stiffness to the system but made the strips excessively heavy. Evaluating the outputs of the physical experiments led to the conclusion that two layers of glass fibre would provide sufficient stiffness without influencing negatively the weight of the structure. In addition to the local reinforcement of the strips, the introduction of steel struts in between the strip layers would increase the overall stiffness of the system. The struts were designed as compression elements working together with the strips as a three-dimensional truss. This strategy helped to control local deformation considerably, but increased the overall weight dramatically as well as the total assembly time.

Further explorations were focused on fixing the canopy to the existing columns and investigating alternatives that would substitute the use of struts. Through the collaboration with the engineering team a new solution emerged; it was possible to achieve local stiffening of the strips and connection to the existing structure with one single element: a vertical fin that would intersect with the strips to lock their relative position and attach to the column transmitting the loads to its lower part.

Introducing vertical fins

The fins were designed as vertical beams of plywood which were slotted to accommodate the strips and act as 'stiffeners' to avoid local failure under compressive forces; they would also constitute the main travel path for any vertical loads, being the element responsible for transferring the loads onto the columns.

The structure incorporated a total of three fins, one per column; each fin consisting of three layers of plywood: 12mm for the outer layers and 18mm for the inner one.

Fabrication constraints and the standard material sizes available informed the decisions on the geometry and construction methods adopted. Plywood sheets with these thicknesses could only be provided in 1.2 x 2.4m rectangular panels. Thus, each fin was divided into two parts: top and bottom.

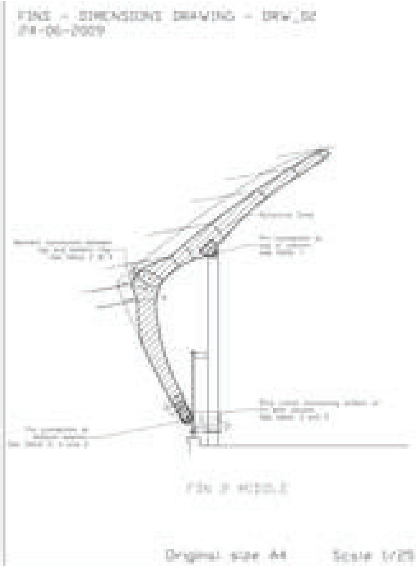
The upper fin was connected to the top plate of the existing columns through a pin connection (20mm). The existing column plate was reinforced with a steel flitch plate screwed to the inner layer. The lower fin was connected to the existing columns at the bottom using a ring clamp around the columns.

Joinery

The lower fins were positioned on the outer side of the balustrade; while only a small section of the upper fins would extend over the terrace fencing. The connection between the top and bottom fins was firstly thought to be pinned similarly to the one at the top of the column. However, providing a moment connection at this position helped with distributing the vertical load in between the top and bottom column attachment points. A connection with zero degrees of freedom was preferred over a pinned joint. This required careful consideration of the number and type of bolts used to 'form' the connection; it was necessary to ensure that it would be capable of resisting the maximum bending moment value along the fin. A ring clamp detail was developed for the connection of the fins to the bottom of the columns. It consisted of two steel layers clamped around the column section which extended over the balustrade and connected with the bottom of the fins. All steel plates were laser-cut and incorporated among the layers of the fins before assembly.

Construction Sequence

The fins' profile and the construction sequence were planned in detail to ensure that the actual construction of the



project could be made as safe and as quickly as possible. The aim was to minimize the assembly time on the terrace, considering the fact that it is one of the main public spaces of the school and was constantly occupied by students. Thus the construction sequence was aimed at the prefabrication of the biggest part of the canopy outside the terrace area, its transport on site and its assembly in place. The lack of machinery on site and the manual assembly placed further constraints on the size and weight of the prefabricated pieces. A careful consideration of the above led to the establishment of the assembly method as a sequence of discrete steps.

Phase 01: CNC milling of parts and lamination of strips.

Phase 02: Assembly of the top and bottom fins.

Phase 03: Lifting and securing of fins and bolt connection at top of column.

Phase 04: Placement of the 5m long strips from top to bottom.

Phase 05: Rotation of the complete fin and strips structure to its final position and fixing of bolted joint at lower part of column.

Parametric associative model

With numerous variables in play, there was absolute need for an associative digital model. A parametric definition was developed in order to input the changes and readapt to specific structural requirements. The curvature of the strips was informed by an attractor based script that incrementally increased the openings between components where wind drag was to be reduced. Structural requirements were also an informing factor as the structural strength needed was directly proportional to the amount of overlap between the strips. Combining the various requirements and their effects on the form created a population of forms representing various adaptations to environmental criteria; those individuals that best fitted the demands were recombined with previous adaptations and created a form that best represented a conciliation of all exterior requirements.

The parametric associative model defined the relationship between local components and global morphology. The local control of curvature of the strips through attractors allowed the development of a geometry that responded to local variations of stresses in the variable widths of the 14 strips. The strips could be fabricated from plywood sheets which would be bent and fixed in place. The fabrication logic was embedded in the design process, thus a complex geometry could be easily unfolded and translated into a flat pattern that would generate the code for the CNC machine.

CNC milling of plywood

The components of the canopy were unfolded and converted into flat patterns; they were subsequently named using an alphanumerical code and nested optimizing material using algorithmic optimization routines in Rhino. Constraints such as material thickness and CNC bed size defined the distribution of the flat geometry on the plywood sheets. Due to the parameterization of the model, any change occurring in the model, either in global or local level, it was directly translated into the flat pattern geometry, ready to be cut by a CNC milling machine. A script was used to translate the



geometry into machine code. A total of 200 sheets of 1.5 mm thickness plywood were used to fabricate the 14 strips constituting the canopy.

Lamination and finishing

The aim to achieve structural rigidity in the flexible material led to further material explorations that led to the establishment of the lamination process. Two identical pieces of wood were laminated together with polyester resin and glass fiber strand creating a much stiffer composite. Load tests and measurement of the deformations were provided with empirical data which was fed into the calculations in order to analyze the structural performance of the canopy.

The plywood was varnished before and after the lamination in order to protect the wood from humidity. Before the two sheets of plywood were laminated with resin, the strips were curved and clamped in order to verify that they acquire the correct geometry; after this verification the lamination could start. The distances between strips were measured in the digital file and verified during the bending process; thus the curvature of each strip was created with precision. The glass fiber strand would assist the bonding of the materials and prevent delamination.

Several experiments were done in order to test different finishes. The sealing and waterproofing of joints and edges would not only enhance the appearance of the finished product, but would also protect the wood in the long term.

Global form precision

The precision of the entire canopy relied on fabricating the strips as precisely as possible. In addition to the curvature of the individual waves, each strip also displayed an overall curvature. The curvature of the waves was governed by the height and length of each wave. In order to achieve the global curvature on each strip, a curved jig was carefully designed and built.

The lamination process took place on the curved jig achieving thus the overall curvature of the finished canopy. The strips were laminated with resin and glass fibre and were directly curved and bolted into place. Each strip was held in position with clamps for at least one hour until the resin was dry. Subsequent strips were constructed on top of the previous ones, securing the relative position of the two strips with bolts.

Project Logistics

The design and fabrication of the canopy was carried out by the entire EmTech group, dividing tasks appropriately in order to optimize the overall quality and construction time.

Certain works could overlap, while others had to follow a strict sequence. The design was constantly evolving incorporating the engineering input, while experiments and prototypes were carried out in parallel. There were groups investigating issues related to the geometry, digital design and translation to machine code and groups that were involved in the actual fabrication of the strips. All 14 strips were prefabricated in the school's courtyard and were transported to the terrace in clusters of three. The entire structure was assembled in two days and was completed on 2nd July 2009, one day before the opening of the annual Projects Review.

Evaluating the process

Various feedback loops had informed the design and construction throughout the whole process. This project would not have been achieved as such without an intricate connection between design and fabrication. A "file to factory continuum" was necessary in order to generate and materialize the canopy. This construction experiment explored a combination of automated and analogue tools in order to optimize the use of material, the construction time and fabrication costs, exploiting the possibilities of the available technology to create complex geometries from simple components.

Project credits

EmTech students 2008-2009:

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