The Structure of Thick Space

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This paper delineates the process, prototyping and construction of two full scale outdoor installations, entitled "Fall Leaf Catcher" and "COCOON". Students followed a methodology we have developed, called Responsive Structures, in which students mine the structural, spatial, experiential and poetic potential of a specific material. The material explored for both courses was standard steel wire mesh: the type typically used for agricultural purposes. Although the methodology and material palettes were similar, the results reveal striking differences of approach structurally and spatially. We show how structural investigations and analyses merged with conceptual and visual intentions, resulting in a typology of space we call "Thick Space".

RESPONSIVE STRUCTURES INTRODUCTION

During the fall semester of 2015 and the spring semester of 2016, we co-taught Design Build workshop/courses at Rhode Island School of Design and Stanford University respectively, using a structures-driven design process for the construction of full scale outdoor installations. The material explored for both courses was standard steel wire mesh: the type typically used for agricultural purposes. Students followed a methodology we have developed, called Responsive Structures, in which students mine the structural, spatial, experiential and poetic potential of a specific material. Structures and spaces are designed to be adaptive, mutable, and open to engaging the site-specific environmental conditions, while providing spaces for introspection, contemplation and a heightened connection to nature.

In Responsive Structures, the exercises are sequenced such that students learn structural principles in a physical and immediate way. Students first conduct small scale model making and material testing. They are encouraged to push the structural boundaries of the material to the buckling point to discover the behaviors and limits of the material. These exercises also start to define the spatial character of the material. Once a range of possibilities is defined, students identify patterns and make selections to expand upon and develop the spatial potentials of their models. Their concepts evolve through this dialogue between material performance and poetic aspiration, and are further activated with a site strategy.

Figure 1: Fall Leaf Catcher Installation.

In the next phase, prototyping at full scale requires that students test and codify assembly methods. Since the final installations measure more than 10' in height and 25' in length, the pragmatics of building construction, sequencing, joinery and the development of best practices are essential steps in the realization of these ephemeral spaces. Students learn how to develop building methods and details so they strengthen the experiential, visual and poetic intentions of the pieces. These steps culminate in the full scale construction of their designs on a selected site.

BRIEF HISTORY OF WIRE MESH

We selected welded wire mesh, an offspring of the Industrial Revolution, because it is usually an "invisible" product that works behind the scenes but is seldom celebrated as a material unto itself. Wire mesh was also a relatively inexpensive material which could perform well in tension or compression when configured appropriately. Although manually woven wire mesh dates back to the 5th century, in the form of chain mail; it evolved into a manufactured sheet form, first with steam-powered looms in the 18th century, and eventually as welded sheets in the early 20th century. John Perry, a New England inventor, filed a patent for the first welded wire machine with the intent of manufacturing fences

Figures 2a and 2b: Fortune cookie-shaped Modules are then woven together. Figure 2c: “Fall Leaf Catcher” Site Model.

in 1901. However, within five years, its utility as a reinforcement for concrete was discovered. Its applications proliferated soon thereafter, intensified by the surge of manufacturing during World War I. During these waves of growth, mesh almost always worked unseen: as filters, sieves, window screens, and other utilitarian purposes. It served very pragmatic but important roles, but was seldom explored for its spatial capacities. For us, one of the goals was to broaden the applications of wire mesh as a building material, and position it in a more dynamic role in the built environment.

INSTALLATION #1: FALL LEAF CATCHER

The RISD students designed on a complex New England coastal site on Narragansett Bay that traversed beach, a restored salt marsh, grassy meadow and woodland. Prior to the workshop, the groups rigorously analyzed the site and the land with graduate Landscape Architecture faculty, including hands-on soil boring tests, water table and wind speed measurements, vegetation patterns, soil composition, and other climatic variations. This established a thorough understanding of the context and site dynamics prior to designing the installations.

Their installation, “Fall Leaf Catcher”, was inspired by the deciduous forest that defined a boundary on the site. Made entirely of 14 gauge metal mesh on a ¼” square grid, the structure was assembled during peak foliage season and was shaped to create a translucent understory canopy beneath the upper forest canopy. The mesh captured falling leaves, holding them in suspension to celebrate the season and the locale.

MODEL MAKING

On the first day of class, students received their small rolls of wire mesh, scaled at 1:10. They immediately began bending, warping, cutting and configuring these blank sheets into forms that optimized the strength and spatial expression of the elements. After a first round of models were made, we identified successful structural patterns within the models and had students develop these ideas. Students began to gather interest around modules that were folded and then bent into a form resembling a fortune cookie. (Figure 2a) They discovered that these operations dramatically strengthened the mesh along specific axes. They learned to manipulate the forms to maximize the structural capacity (both buckling length and stiffness) of the surface, and then began to make more complex configurations. Students clustered the modules together to form linear elements that performed well in compression. These elements evolved into the vertical supports, which became structural anchors in the final design. Students then discovered how to orient the modules so they could successfully span between the columns. (Figure 2c) Module by module, these preliminary studies shaped the overall concept and morphology of the structure.

Armed with their research, students selected a threshold condition between the woodland and the salt marsh, and designed a passage to mark that boundary. They designed a web of arches marking the termination of the path, where it opened to a small clearing in the woods. This marked a passage from the more enclosed, multilayered density of the woodland, to the more open and vast scale of the tidal marsh and Bay. This moment of spatial contrast caused viewers to slow down or stop to reimagine their surroundings.

PROTOTYPING

The team formed fortune cookie shapes that, when stitched together, formed larger columnar elements which would later become the primary vertical load supports for the structure. The task of connecting the modules was addressed during prototyping. Although the original intent was to use wire to bind the pieces, students decided that the joint should be subtractive rather than additive: the cut ends of the mesh were aligned and twisted with the open ends of the adjacent module. This decision stemmed from the students’ desire to create a seamless canopy to capture the leaves. Hence, the poetic drive of the piece shaped the tectonics, establishing a dialogue between the poetic and pragmatic modes of the process.

Students determined that using double layers of mesh to create the modules increased their strength, so they used these dense modules at the column bases, where the load was most intense. This began to create different gradients of transparency, where the elements near the ground were visually tight, while the structure began to dematerialize at it reached the sky. In this sense, the structural necessity and material density of the elements at the base established a desired contrast between the base and the more transparent canopy layer.

Structurally, this joint worked as reinforcement for the weak axis of the module, which caused students to align the modules in specific repeated patterns which created braid-like vertical supports (Figure 2b). These formed the base which supported the leaf-catching canopy. Again, we can see the co-evolution of the structural and poetic dimensions of the installation.

Figure 3: Fall Leaf Catcher

BUILDING

Once the modules and joinery were defined, the actual building assembly proceeded quickly. The wire mesh came in 4' wide x 100' long rolls, so students cut about (50) 4'x4' squares, which were bent and folded into shape in a makeshift assembly line. Students used their site model to help them locate the columnar bases for the installation on site. These elements supported the bulk of the weight.

As the students' prototypes grew in scale, they began to engage the rich visual potential of the mesh. New Bauhaus artist and teacher Gyorgy Kepes, In Language and Vision, described transparency as the "simultaneous perception of different spatial locations", as a fluctuating visual field." Such was the effect of layering multiple layers of mesh as the students folded and bent their modules into shape. The curved, warped forms began to absorb and reflect light in nuanced ways, creating a shifting visual tableau.

BRACKETING TIME

The basic form of Fall Leaf Catcher was a continuous ribbon loop that twisted back in on itself like a Mobius strip. The daily cycle of its presence in the woods invited a close observation of the movement of light clinging against the ground or the mesh. There were multiple layers of filtered light, first through the clouds, then through the upper canopy and then the middle canopy, and finally through the canopy of our installation, rendering a layered, multivalent play of shadows against the woodland floor. Shadows themselves started to achieve value and depth. Suddenly, the confluence of the season, the shifting light, and the unique qualities of the farm, were brought into focus, however temporarily. These evoked writer Junichiro Tanizaki's description of how the beauty of a Japanese room depends on the subtle variations of shadows layered against each other in his essay "In Praise of Shadows".

The installation, assembled in late October, marked a significant seasonal event: the profuse shedding of leaves by the oaks and maples that populate the woodland. By suspending the leaves midair, the installation suspended time briefly, bringing to light the significance of nature's cycles, while blurring the line between nature and the manmade. This bracketing of time freezes a process, disrupting and illuminating the normal flows of the season. From a distance, the entire installation resembled a group of leaves blowing in a wind current, frozen in time (Figure 3). It de-accelerated the viewer into receiving a new perspective of the surroundings. This fundamental human habit to connect ourselves to our surroundings and to the seasons was magnified through this mesh intervention on the site.

INSTALLATION #2: COCOON

The second installation was completed by a group of 10 Stanford University students in March 2016, offered by the Architectural Design program. The course was a cross-disciplinary collaboration including students from Architecture, Structural Engineering, Product Design, and Civil Engineering. Students designed "COCOON", a contemplation space that features a curved passage which terminates in a dome-like space with an oculus. The name derives from the overall form of a cocoon, but also the notion that the act of contemplation and self-reflection can lead to a sort of internal regeneration.

The installation follows the contours of an opening in the grove of trees and orients towards the sky. The procession of double layered arches provides a spatial transition from the Stanford campus into a more enclosed space, encouraging introspection and pause for students, passers-by, and visitors to the Anderson Collection.

In this course, students studied 3 different densities of steel mesh, expanding the range of structural and visual performance explored at RISD. Students used ½"x ½"square mesh, 1"x1" square mesh, and 1 ½"x1 ½" square mesh. This group used Similar to the students at RISD, the students explored how surface deformation (through warping, bending or folding) increased its strength. Unlike RISD, where the operation of folding and warping of entire sheets created a modular tectonic, the students at Stanford chose to deform the planar surface of the wire mesh sheets by warping them or stamping patterns into them (Figures 4a and 4b).

MODEL MAKING

During the model making phase, students discovered that the wire mesh surface strengthened when the surface was warped and deformed. Students built molds and stamped patterns within the surface of the mesh, shaping the slender surface in "V" and diamond forms which as a system behaved like trusses or lattices. Layering the material enabled longer span arches, while the undulating patterns create a complex visual experience from within.

PROTOTYPING

The three different densities of mesh offered the opportunity to create a gradient of transparencies across the structure. Similar to Fall Leaf Catcher, students were supplied with 4' wide x 100' long rolls of mesh. However, unlike Fall Leaf Catcher, which featured person-scaled modules, the COCOON team chose to work with long 4' wide strips, which ranged in length from 10' to 22', depending on the location.

The span limits of each mesh density was measured both as a smooth sheet, and then deformed with a stamped pattern. Students experimented with different techniques for fabricating a jig to complete the stamping, and eventually designed a laminated plywood mold with contours that fit together. Students learned how to use their body weight to effectively press the molds into place (see Fig. 4a).

Figure 4a: COCOON: Stamping the truss patterns with plywood molds

Figure 4b: COCOON: Raising the stamped panels

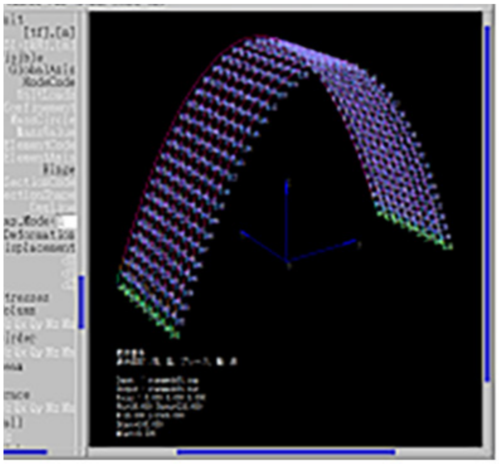
or joinery, initial attempts at using wire and metal zip ties were structurally adequate but visually disruptive. Eventually, the group decided to fasten the panels together with simple rebar ties purchased from Home Depot. These are essentially 6" long, 17 gauge wires which are looped at both ends. These rings are hooked onto a rebar tie tool and twisted together, similar to a twist tie. Their slight profiles were discreet and blended into the mesh without disrupting the effects of the undulating surfaces.

BUILDING

The panels were stamped individually and then formed into arches by the students. Students developed three different templates for folding, warping or stamping the panels. Type I embossed a truss-like pattern onto the surface of the mesh (see Fig. 4b). These were used for the double layered vault of the procession, or the "body" of COCOON. Types II and III entailed creases and folds, in order to achieve the domed curvature at the "head" of the COCOON. The non-creased areas were dimpled in order to strengthen these planar zones.

The long panel lengths required much more coordination in lifting and setting the strips into place. At the circular contemplation space, students began by stitching a few panels together to create a stable base, and worked organically from there. The passage was erected in two layers. The lower layer, comprised of denser, stronger mesh, was assembled first, and the outer layer, comprised of the more open mesh, was slid on top. This outer layer fortified the shell, while also creating an additional layer of undulating surface and enclosure.

In COCOON, one receives overlapping, layered views of the surrounding campus created by the installation. An additional layer was added by the furniture. Students designed and built benches within the contemplation space. The tighter mesh was used for this load-bearing purpose. Students applied their understanding of warping into these unique seating elements. From afar, seated users appear to levitate within the space because the mesh dematerializes (Figure 5d). The human element thus became another layer on this mutating canvas. This design process interweaves the performance-driven structural design with the pursuit of the transcendent, poetic spaces that the students envisioned.



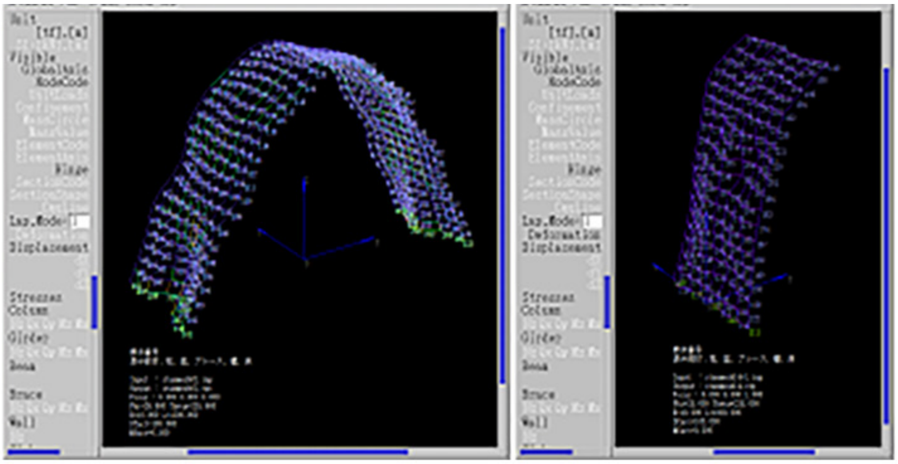


Figure 5a: COCOON Global Optimization Structural Analysis: arch results in a catenary shape

Figure 5b and 5c: COCOON: Local Optimization: Wrinkles, dimples, and grooves generate extra strength

Figure 5d: COCOON Final Installation: seated figures appear to levitate

STRUCTURAL ANALYSIS

When considering the global shape of a panel, a typological smooth shape can be achieved through the "global manipulation" of the overall geometry. A smooth vault or arch is one of the simplest manipulations of the panel unit (Figure 5a). When such a vault is optimized into a smooth catenary shape, this process can be understood as "global optimization" because the overall form is streamlined to enhance performance.

The metal mesh can be strengthened through surface deformation, through the application of wrinkles, dimples or grooves. This process of manipulating the surface at this smaller scale can be understood as "local optimization". The strength of the local area is enhanced by these small alterations. However, these smaller deformations can then work together as a system to strengthen the overall structure. In COCOON, we designed a pattern of dimples and grooves to establish an organizational system. For example, the alignments between the dimples were intentionally offset to optimize strength.

Figures 5a and 5b show how the local optimization process was applied. In the algorithm of optimization, calculating the safety ratio against the allowable stress under multiple load scenarios enables one to estimate performance. Through this process, we were able to double the strength of the arch and achieve a span that was 1.5 times the span of the smooth arch.

THICK SPACE

The processes described thus far result in spaces that share a layered, multivalent enclosure which we call "Thick Space". In 1913, Painter Robert Delaunay claimed, "Depth is the new inspiration. We live in depth...The senses are in it. And the mind is, too." . Continuing this spirit, we embrace the thickness of the architectural shell as a site for visual and experiential innovation. In these installations, the simplicity of the material palette allowed for a nuanced complexity of the visual field, setting the stage for artistic innovation. In "Fall Leaf Catcher", the structure became a suspended basket to capture leaves and mark the season. The accumulation of the leaves created an evolving density and became its own marker of time. The installation also became a framing device from which to view the surrounding landscape, inclusive of the sky and canopy above. The various transparencies of the mesh gave the whole installation an ephemeral presence, deepening its connection to the natural cycles at play.

In COCOON, the sheets of mesh transformed from relatively limp sheets to rigid shell elements through the strategic stamping and warping of the form. This process required a knowledge of the optimized structural configurations, but as importantly, a poetic understanding about how this thickened skin could define and enclose a contemplation space. Through the material exploration, students were able to explore ideas about the shift from outer to inner consciousness. The level of transparency, the filtration of light, the enclosure of a space suitable for contemplation were all tuned and calibrated to inspire this transformation.

Small areas of yellow ribbon were woven into the mesh after the panels were erected, establishing a separate yet interdependent order while providing an additional layer of enclosure. The colors fade from muted to bright yellow, mirroring a subtle transition from the natural to the manmade as one approaches the contemplation space. The ribbon was woven into the convex forms, magnifying the curved form. In different lights, these zones of ribbon either projected forward as fields of color, or blended into the surroundings, acting as a kind of camouflage. The surface of the structure began to oscillate, visually destabilizing the structure.

In Fall Leaf Catcher, the seasons and passage of time became the subject. The seamless structure and enclosure of the mesh melded the pavilion into its surroundings. In COCOON, the focus was on journey of contemplation and transformation. The mesh mirrored this process. As a visual filter, it was both present and absent. On the one hand, it allowed full visual access and transparency. One the other hand, it established a clear physical boundary between inside and out. While allowing light to penetrate, it also created a veiled screen to the surroundings, fostering the user's internal, spiritual experience.

CONCLUSION

The Responsive Structures methodology establishes a multidimensional design process and brings to light the transcendent, sublime capacity of surface and structure. It elevates design beyond pragmatics and aims to co-develop the visual, spatial and experiential potential of a material, creating a unique typology of space which we call "Thick Space". Through this methodology, we seek to develop a richer platform for spatial, experiential and structural experimentation. Optimization is expanded to include all of these realms, and the resultant projects posit a new typology of space making. We believe this cultivates a holistic understanding of design for the students; while the viewers gain awareness, slowness, and deep engagement.

ENDNOTES

1. "History of Welded Wire for Concrete Reinforcement", rebar.ecn.purdue.edu, Purdue University.
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3. Tanizaki, Jun'ichiro. *In Praise of Shadows* excerpts, Leete's Island Books, 1977.
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