Project Nervi: Aesthetics and Technology

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ABSTRACT:

Project Nervi: Aesthetics and Technology in Building Pier Luigi Nervi questioned the nature and physical impact of the relationship between aesthetics and technology from the viewpoint of architecture, engineering and construction; this question remains vital for both academy and profession. Project Nervi, a collaboration of the CMU School of Architecture and the Carnegie Museum of Natural History, was formed to extend the engineers proposition of the relationship of aesthetics and technology by undertaking an empiric research project to characterize the relationship between material placement and aesthetics in architecture with reference to the correlation of material placement and performance found in nature. The tools of Processing and Grasshopper combined with physical modelling are used to better understand Nervi's structural/visual thinking of the cast concrete floor plates at the Palace of Labour (1961), the Gatti Wool Factory (1951) and the Palazzetto dello Sport (1957) and to morphologically further these prospects. In the second part of this study, we apply the pattern research to two relatively new building materials, plywood and carbon fiber for lightweight stressed skin construction based on force trajectories.

KEYWORDS: Nervi, pattern, structure, nature

> *"The form […] of any portion of matter, whether it be living or dead, and the changes of form which are apparent in its movements and in its growth, may in all cases alike be described as due to the action of force. In short, the form of an object is a 'diagram of forces' in this sense, at least, that from it we can judge or deduce the forces that are acting or have acted upon it."*
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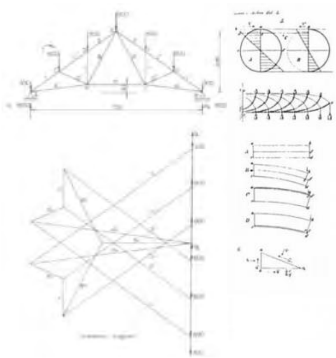
> *D'Arcy Wentworth Thompson, On Growth and Form*

1.0 INTRODUCTION_PATTERN RECOGNITION AND KNOWLEDGE TRANSFER ACROSS FIELDS

Structural patterning is of significant interest to many fields, including chemistry, biology, materials science, medicine, engineering and architecture. The deeper we look, the more we find that geometric arrangement is responsible for chemical and material properties and our sensorial perception of their qualities. This condition operates at a range of scales and forms the base inquiry of nanotechnology, the orchestration of matter at the atomic and molecular scale to construct materials with new behaviors. Increasingly, one field is contributing to the knowledge base of another and boundaries that have historically shaped disciplines are becoming porous, enabling the exchange of experience and information productive to each. A classic example is the relationship between engineering and medicine, when Karl Culmann (1821-1881), professor of Engineering Science at the ETH in Zurich, and Julius Wolff (1836-1902), the German anatomist and surgeon, as they shared insight into each other's work. Culmann had recently developed the method of analysis known as 'graphical statics,' a means of visual/structural analysis based on vector scaling that was to become a standard within the engineering community for force calculation (Figure 1). It was from Cullman's drawings that Wolff predicated his hypothesis known as Wolff's Law [1]. His observations characterized the relationship of trabecular force trajectories within cancellous bone (interior structure) and bone loading. It was the visual nature of Culmann's work that enabled the transfer of knowledge from engineering to medicine. Our study is also based in the visual comprehension of the forces that generate patterns in architecture and nature.

Both Culmann and Wolff understood the relationship between material patterning, function and performance. Similarly, the work and thinking of Pier Luigi Nervi, (1891-1979) is rooted in the conceptual, creative and pragmatic understanding of material properties and their visual and structural patterning. Nervi's technical innovation and demonstration of the correlation of aesthetics and technology was due to familiarity and keen insight into the nature of materials, craftsmanship and methods of assembly. In his hands, the ordinary material of concrete became extraordinary. In his buildings, there exists a union of material, form, structure and pattern, and in these terms his buildings approach the organic. Masterful at making the flow of forces visual, Nervi called to question the similarities between artist, architect and engineer. While his structural patterns convey clarity of mind and a sound logic of construction, they are not the inevitable conclusions of formulaic thinking. Reason, emotion, decision-making, authorship convenes in Nervi's work. It is this agreement that was causal to Nervi becoming known, during and after the 1930's, as a technical artist.



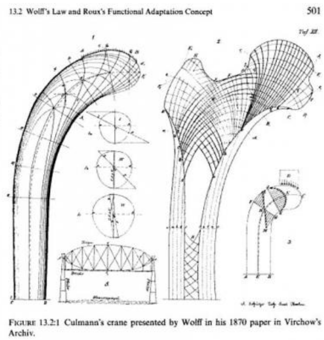


Figure 1 (left): is a Cremona diagram, a graphic system developed by Luigi Cremona based on the vector analysis work of Culmann.

Figure 2 (right): is a visual description of Wolff's Law that traces bone growth along principle stress trajectories compared to a cross section of a human femur, at right.

2.0 DESCRIPTION OF STUDY_NERVI'S PATTERNS

The intent of this research, as was Nervi's, is to study the balance of material properties, structure, available technologies, intuition and aesthetics. In this survey, it was (re)discovered that Nervi's patterns, while aesthetically compelling, are not based entirely on structural optimization. By working in a similar vein as Nervi, and by addressing the relationship of technology and aesthetics, this project seeks to look through his eyes with our hands. The question was how to gain insight into the spirit of Nervi's own working method to further current design thinking with contemporary computational tools and knowledge of pattern formation in nature. As a point of departure, three of Nervi's works were chosen for study: the concrete floor slabs of the Palazzo dello Sport, Rome, 1956 (figure 3a) and the Gatti Wool Factory, Rome, 1951 (figure 3b + c) and the rib patterns of the Palazzetto dello Sport, Rome, 1958 (figure 6). Evidence of Nervi's interest in the relationship of aesthetics and technology is present in these works.

During reconstruction of Nervi's slabs questions arose concerning the diversity of geometry found in Nervi's work. In the slab of the Palazzo dello Sport mezzanine (figure 3a + 4) the rib patterns concentrate on the center of the beam, a placement that increases moment and results in a higher quantity of material required for the given loading condition. Certainly Nervi was aware of this condition and made the conscious choice not to have structural optimization be the sole design determinant.

Figure 3 a,b,c: Nervi's work demonstrates a strong correlation between aesthetics, statics, materials and construction technology. This is evidenced in the mezzanine slab in the Palazzo dello Sport and the Gatti Wool factory. These have been studied to gain tangible insight into Nervi's intuition and working method.

Figure 4: Process of slab casting (Palazzo): 1) Finished plaster slab, 2) Silicon mold, and 3) CNC milled wax positive.

Figure 5: Example of the Gatti Wool Factory slab geometry with Voronoi patterning.

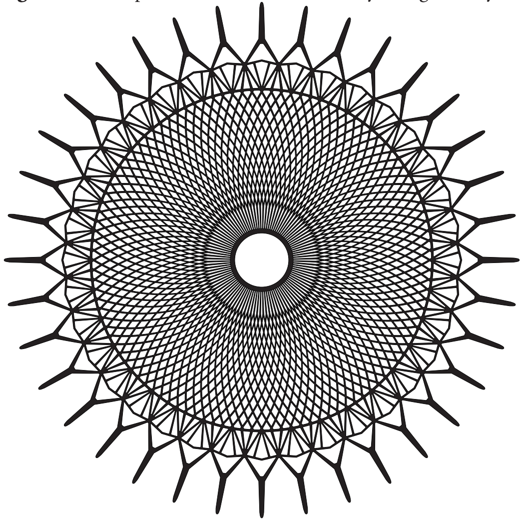


Figure 6: Reflected plan of the Palazzetto dello Sport. The radiating pattern was used as a generator for the morphological study on Michell patterning.

In Phase 1 we established a process to reinterpret Nervi's work by making drawings and scale models of the Palazzo and Gatti Wool slabs. Phase 2 is a morphological extension of Nervi's radiating rib pattern of the Palazzetto dello Sport as a generator and subject to the mathematics of Michell's Theorem {2} for optimal structural networks. Phase 3 was to morphologically extend Nervi's structural patterns with the Gatti slab as a generator and subject to the mathematical constraints of Voronoi patterning {3}. Both systems are found in the structural patterning of natural systems as diverse as the cross-helical patterning of sunflower seeds to the construction constraints of soap froth.

Figure 7: Construction photo of the Palazzo dello Sport, Rome. An array of precast elements form the dome.

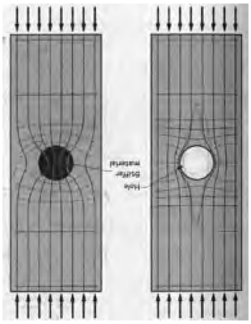
3.0 PRINCIPLES_ FORCE TRAJECTORIES

The guiding principle of Nervi's work, and by extension, this study is the supposition that force follows stiffness, illustrated in figure 8. The image to the right describes the force trajectories through a homogenous material with a hole. The image to the left describes force trajectories through an anisotropic material with trajectories 'attracted' to regions of increased density. Figure 9, a project by Professor Horacio Caminos, demonstrates the application force trajectories as the ribs are in closer proximity in regions of concentrated stress. The ribs collect force, as they are stiffer than the surrounding shell. In the last phase of this project, we apply these principles to the materials of carbon fiber and plywood and each are recognized to hold inherent properties implicit to their fabrication, the strength of weaving and lamination, respectively. Plywood was chosen for its relative low cost and ease of workmanship, carbon fiber was specified for its high tensile strength and capability to bond with plywood. Both materials are used frequently in boatbuilding to make lightweight and resilient hulls of complex curvature.

3.1. GROWTH AND NATURE

A tie to nature mentioned above is Wollf's theory on cancellous bone growth, positing that material deposition occurs along principle stress trajectories. According to Wollf's theory, greater and increased loading patterns result in denser regions of bone; the converse has also been observed, that light and infrequent loading results in more porous bone tissue. The orthopedic surgeon and researcher of bone biology, Harold Frost [1], observed that adaptive bone regeneration, known as remodelling, does not occur simply according to static loading but requires flexure, as a result of dynamic mechanical forces. He went further, with observed data from empiric experimentation; to describe the stimulus activated mechanical signaling that triggers biological response.

In 'On Growth and Form,' mathematical biologist D'Arcy Thompson states that form of an organism is a result of intrinsic and extrinsic forces, a plastic and regenerative medium that is a transaction of genetic coding and environmental conditions. He observes that gravitational forces are significant for terrestrial animals, yet for aquatic animals, buoyancy prevails over gravity and pressure, as current and nutrient supply are principle determinates of size and shape. The structural lines of Nervi's architectural work bears similarity to patterns recurrent in natural systems and strikes an orchestrated balance of intrinsic (material properties, construction technique, economy and Nervi's authorship) and extrinsic forces (gravity). The intrinsic forces are fluid, fluctuating with advances in the imagination, materials science and construction technology, the extrinsic force of gravity is relatively constant. There is no explicit reference for Nervi looking at nature, though his work approximates nature's constructive technology in principle – that of effective material distribution.



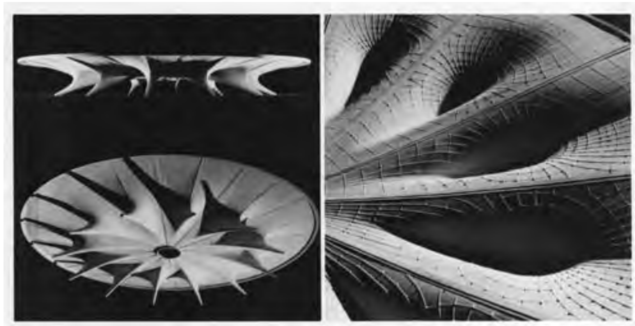


Figure 8 (left): Image from 'Form and Forces', by Edward Allen and Waclaw Zalewski, illustrating the principle lines of stress within a material subject to compressive loading. The image to the left graphically describes the isostatic lines around a hole; the image to the right describes influence on force distribution as the result the insertion of a region of denser material. An interesting note is the similarity of the isostatic lines of image with the hole to fluid flow around a circular impediment. **Figure 9 (right):** Roof structure designed by Professor Horacio Caminos that economically distributes material along principle stress trajectories. The local thickening of the shell is designed to prevent buckling by collecting and distributing forces.

When observing nature's materials and methods of assembly where the structural patterning bears geometric similarity to Nervi's work there are two key conditions that are recurrent: 1) the principle of material placement according to stress trajectories and 2) that complexity is an emergent property based on these simple rule sets. The simple rules sets chosen for this study are Voronoi and Michell conditions for pattern formation.

4.0 SPECULATION

The following project is speculative and has been undertaken to more clearly understand the peripheral influences on Nervi's thought process combined with the teams' interest in drivers of pattern formation. Described below are the procedural processes used to replicate Nervi's slabs at model scale and to computationally extend the patterns he designed. In each phase of the project there is an aesthetic outcome derived from technological underpinnings. The ongoing goal is to uncover why Nervi worked the way he did, and why there has been relatively work since that is similar.

4.1 (RE)DRAWING AND (RE)CASTING

Our steps included 1) making accurate drawings from photographs of the built work, 2) transferring drawings to 3-D models, 3) cnc milling a wax positive, 4) pouring a flexible silicon negative, and 5) pouring a plaster positive (figure 4). Digital technologies expedited the process of mold making and enable the team to make multiple iterations of each slab. Although we were able to work more quickly, some knowledge was lost, as we did not think directly through the material itself, focusing more on the technological process of making. The team recast several of slab designs, with effort place on accurate geometric reproduction and attention to surface finish. The mezzanine slab of the Palazzetto is shown in figure 4.

4.2 MICHELL'S THEOREM

The second series of drawings and models were made according to Michell's Theorem that describes the optimal distribution of material for a given support and loading pattern. Of interest is that Michell's theorem leads to structural patterning where members act in 'pure' tension or compression. In nature, even though we assume efficient structural patterning, many systems, especially plants subject wind load effectively use bending as a structural strategy. This is partly due to the desired attribute of resiliency in organisms and the properties of the soft and pliant materials organic life uses for construction. The rib patterning of the Palazzetto approximates Michell's Theorem of optimal structural frameworks, and this mathematical filter was used to develop new structural patterns in the matrix (figure 11). The variables that define each iterative pattern are number of ribs and rib curvature.

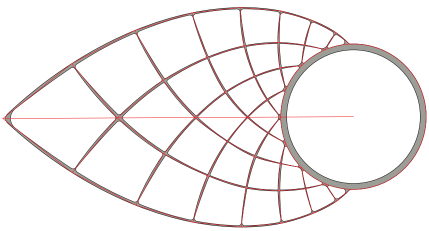


Figure 10: Pattern constructed according the Michell's Theorem for optimal material placement. In the cantilever above, the loading is downward at the point with support connections at the ring. The geometric patterning eliminates bending from the members and resolves forces to 'pure' tension and compression. If the diagram were to be of higher accuracy, the members would be straight lines.

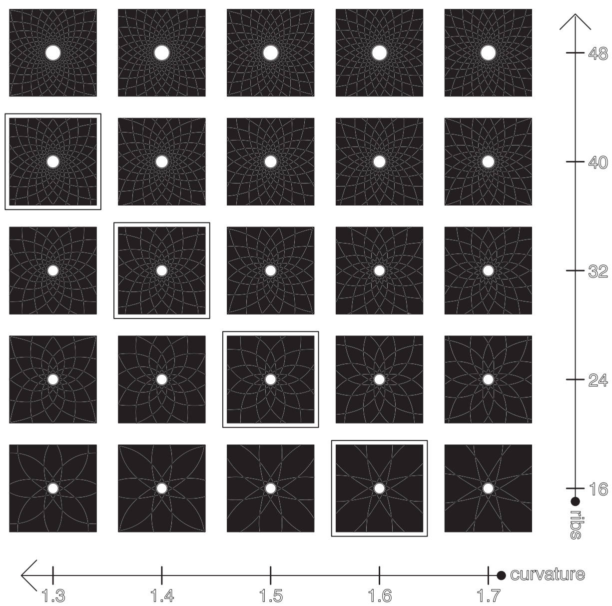


Figure 11: Image of a partial Michell matrix generated from the geometry of the Palazzetto dello Sport. The bordered diagonal series have been physically modeled.

4.3 VORONOI PATTERNING

A Voronoi pattern is determined by a line equidistant between two points and perpendicular to the shortest line connecting those two points. Voronoi patterning is a principle determinant in the material coding of both organic and inorganic natural systems. In the case of honeycomb construction the Voronoi pattern is a metabolically advantageous means of material distribution for the wasp, filling effectively with regular hexagons. The pattern emerges also in the choice of material placement of the sea sponge as shown in the micrograph in figure 14. In organic nature, as in our study, for a given loading condition, as cell number increases, cell size decreases and cell wall thickness decreases. This strategy makes an organic structure more versatile with the advantageous properties of lightness, strength and resiliency. Correspondingly a structure will be of higher 'frequency' and will either be lighter in weight or capable greater mechanical stress or be capable of longer span. R. B. Fuller demonstrated this principle in the design of lightweight and long span geodesic domes (figure 15).

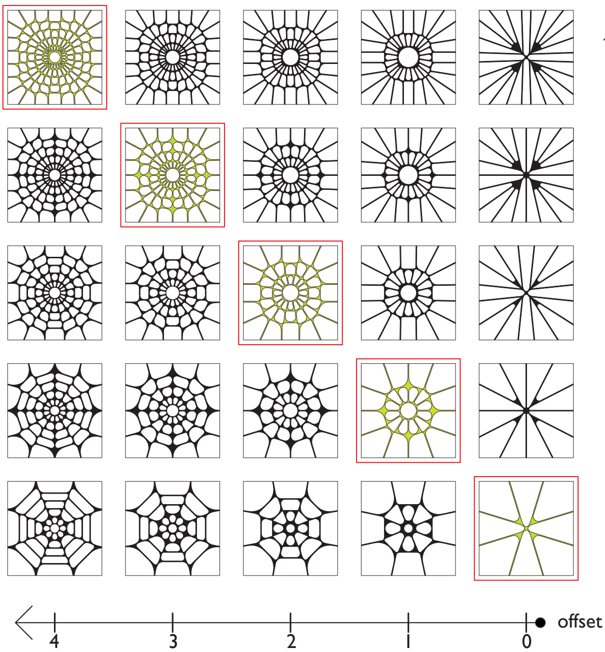


Figure 12: Image of a partial Voronoi matrix generated from the geometry of the Gatti Wool Slab. The bordered diagonal series have been physically modeled.

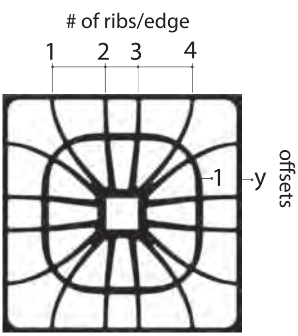


Figure 13: Diagram of the method for viewing the Gatti Wool Slab. The number of ribs and number of offsets are the variables in the matrix above.

The slab pattern was simplified with the variables being the number of edge points and the number of divisions along a radiating rib (figure 5 + 13). Each slab pattern was then constructed according to a Voronoi rule set (fig 12). The cellular patterns of Voronoi tessellations were chosen as the resultant patterns are aesthetically interesting and touch upon the relation of aesthetics or ornament and structure. This is relative, as Nervi did not operate wholly according to structural optimization but also relied upon economic and technological constraints and intuition to derive slab patterns. The relationship between aesthetic interests in Voronoi patterns is not random, and example can be taken from honeycombs, soap froths or the structural ribbing of insect wings. In the soap froth, the eye recognizes the natural beauty of a three-dimensional structure in equilibrium. The homogenous and elastic material of the soap film is unable to concentrate force and therefore equilibrates regardless of cell size or number.

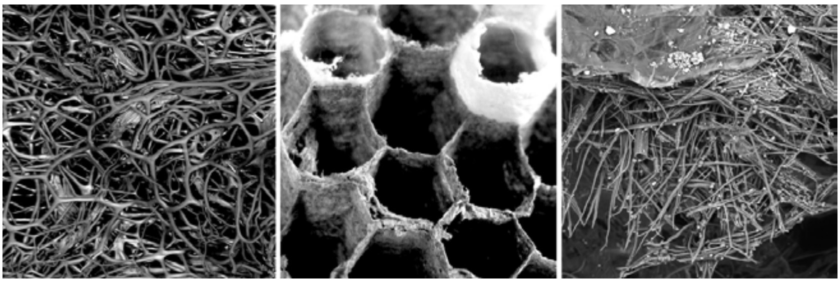


Figure 14: Scanning electron micrograph (SEM) of a sea sponge (1500x) of growth patterns according to Voronoi patterning. Close photograph of the nest of a paper wasp (center). The SEM at right is taken from a sample of the nest at center at 2500x magnification. The Voronoi patterns become less apparent at this magnification and we begin to see the mechanics of material distribution taken by the wasp.

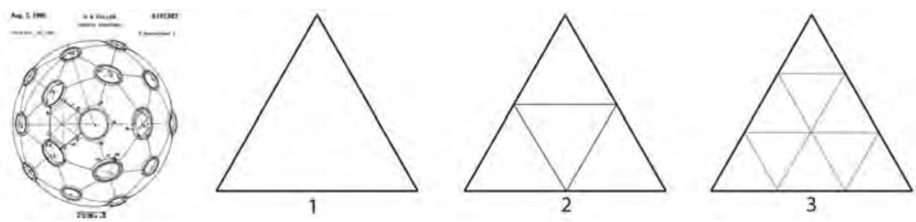


Figure 15: Frequency change in a triangle as demonstrated by R.B. Fuller in Synergetics.

5.0 MATERIALS, PROCESSES + FUTURE STUDY

The above geometric study will feed directly to a future material based study to construct medium span prefabricated construction panels from plywood. The fist, constructed from plywood and carbon fiber and derived from isostatic lines, is described below.

5.1 PROCESS_ WEAVING + LAMINATING

The impulse to redistribute natural fibers to gain utility and strength has a long history in the development human technology. Basketry is one of the oldest crafts and engages human ingenuity to extend the structural propensities of natural fibers through patterning. The relatively weak singular reed is woven into a resilient composition that distributes load to a multiplicity of components and is therefore capable of withstanding significant load and wear. The structural key in the non-rigid system of the basket is load dispersal through effective patterning and redundancy, similar to the frequency change in the triangle above. The basket is certainly utilitarian, and as with all finely crafted artifacts, bestows status to the maker and owner in proportion to societal value placed on the artifact. A basket made by a craftsperson embodies the wisdom of pragmatic and artistic values and displays a history of innovation derived form variations in use, materials and methods of construction. The field of wooden shipbuilding advanced in much the same manner; the artifact was subject to continual qualitative field-testing and feedback loops, over time.

5.2 MATERIAL_ PLYWOOD

Wood gains structural ability most importantly from cellulose. The 'ose' in cellulose refers to its classification as a sugar, and its long linear polymer chain has much in common with sucrose. Cellulose is polymerized glucose, long molecule chains that form polysaccharides (many sugars). The long molecule chains assemble into micro fibrils to form a resilient network, giving the cell wall form and strength. In reference to Nervi's slab patterns, it is our intent to replace concrete with plywood in to construct medium span structural panels. As plywood, even loaded parallel to the grain, cannot compare with the compressive strength of concrete, the spans and loading will be commensurate. Plywood was chosen for its availability, low cost and ease of workmanship. It is a common material that, after studying Nervi's approach to design, we plan to use in an uncommon way; by increasing it's current span potential and visually expressing the load paths via isostatic lines. It is here that we hope to enter Nervi's territory – the space between engineering, architecture and art.

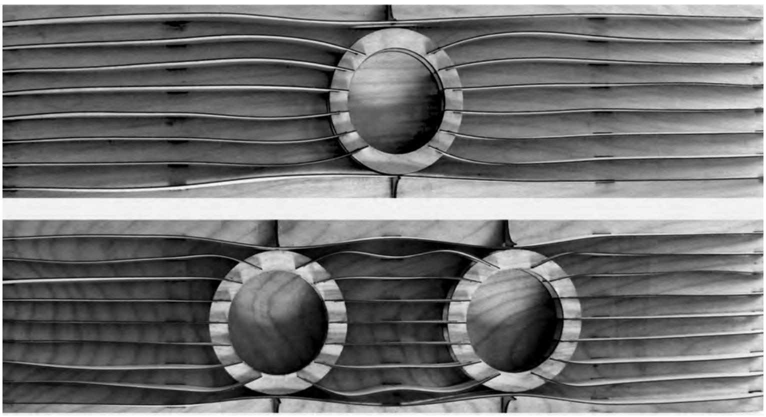


Figure 16: Initial plywood study derived from isostatic diagrams. The model is constructed at 1:10 scale and measures 6" x 24". It is expected that the hole could be removed from the plate as the stiffened plywood ring removes load from the inner region. Thin strands of carbon fiber are bonded to the tensile side of the 'beam.'

5.3 MATERIAL_ CARBON FIBER

Carbon fiber was chosen as a material of study as the material demonstrates the state-of-the-art in fiber technology in terms of tensile strength-to-weight ratio. A potential drawback of the material is that it does not yield resulting in sudden and catastrophic failure as the breaking point is exceeded. This combined with the materials high cost were reasons to reconsider the applicability of the material for architectural applications. The material has found contemporary architectural applications as externally bonded carbon fiber fabric and plate is used to reinforce existing concrete/masonry structural systems. The carbon fiber fabric is directly bonded to the concrete in this application as a means of noninvasive structural and earthquake retrofitting. The fibers, through the matrix of epoxy resin, also bond well with plywood. In our study, we expect carbon fiber of fiberglass to replace the steel of Nervi's reinforced concrete structures.

5.4 PLY/CARBON PROTOTYPE

Figure 16 describes the initial models constructed from plywood and carbon fiber based on isostatic lines. The first of a series, the models are thought of as 'anisotropic' materials. First the 'holes' were placed, then the stiffening rings added. The introduction of a hole weakens the material causing stress trajectories to flow around the weakness. The introduction of the stiff ring around the hole increases the density of the material causing stress trajectories to seek regions of greater stiffness. With this phenomenon, the team plans to influence the physical and visual flow of forces through materials by selectively introducing regions of varying stiffness. Figure 17 is the first prototype from the Michell morphology made with a panelized plywood/carbon fiber system. The model is constructed at 15" x 15" at ½"=1' for a full-scale panel of 30'x30'. The ribs are epoxy resin with prestressed carbon fiber filaments bonded to the outer rib edge.

Figure 17: Resin/carbon fiber/plywood prototype generated from the Michell morphology. The prestressed carbon fiber strands are shown in the image at left.

6.0 CONCLUSION: AESTHETICS AND INTUITION

This study has sought to further Nervi's intuitive structural patterns through the prospect of morphology. In terms of aesthetics our ply/carbon prototype has a certain beauty. Perhaps this is because it references patterns found in nature that our eye recognizes as interesting. Specifically in the prototype references the patterning of the sunflower, which is not a structural reference. The ply/carbon model was also subject to many subjective decisions in its making including color, translucency and proportion, all of which are not the inevitable outcome of formulaic thinking. These decisions rely on an integrated emotive and rational process, which is advanced through the feedback making.

Nervi speaks of the "the mysterious affinity between physical laws and the human senses,' calling to question the relationship of structural principles and aesthetics. It is assumed that intuition and structural constraints coupled with an awareness of the sensorial impact of material patterns played a substantial role in Nervi's own design thinking. Stanford Anderson reminds us that 'Tektonic referred not just to the activity of making the materially requisite construction . . . but rather to the activity that raises this construction to an art form . . . The functionally adequate form must be adapted so as to give expression to it's function. The sense of bearing provided by the entasis of Greek columns became the touchstone for this concept of Tektonic.' Larger questions emerge concerning the ability of the eye to detect performative characteristics, in the case of Nervi, the effective patterning of material for structural purposes. Is there an optical interest in purposeful embellishment that augments a structural characteristic? If the Greek column were optimally shaped would the eye appreciate the entasis? According to Anderson's observation Nervi's work is strongly tectonic, elevating the functional deposition of material to an art form, positing him as a structural artist.

The question arose during this study of the bearing of Nervi's work on contemporary architectural thinking. The benefits in learning from Nervi are relevant today, as many designers have a strong interest in the relationship of aesthetics and performance tempered by material properties, construction technology and economics. Accordingly, this team aims to further the tangible relationship of aesthetics, material deposition, and technology – relationships that Nervi masterfully engaged.

ACKNOWLEDGMENT

This ongoing project would not have been possible without the close collaboration and creative insight of Joseph Koon and Aaron Chenault. Thank you to Rohan Rathod for his analysis and drawing of the Palazzetto dello Sport.

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END NOTES

1. Wolff's Law developed the theory that bone grows in response to stress or put another way, the internal patterning of bone is transformable and responsive to external loading from the environment. The converse is also true, that bone will degenerate if not subject to loading. The phenomenon is known as remodeling. In terms of an energy expenditure, it is not metabolically advantageous for an organism to maintain support where is not effective for survival. It is on this point that engineers and nature usually agree. More current research has shown the loading pattern is required to be a continuous series of impact loads, such as applied to the le during walking, rather than constant.

2. Michell's Theorem mathematically describes optimal material placement for a given loading condition.

3. A Voronoi pattern is determined by a line equidistant between two points and perpendicular to the shortest line connecting those two points. Our reference has been to two-dimensional networks with three-fold and four-fold vertices.

IMAGE CREDITS

Figure 1	Luigi Cremona
Figure 2	Julius Wolff
Figure 3+6+7	Pier Luigi Nervi
Figures 4+5	CMU Bio_Logic Lab
Figure 8	Ed Allen, Waclaw Zalewski
Figure 9	Horacio Caminos
Figures 10-17	CMU Bio_Logic Lab