New Materials in Architecture: A Pedagogical Approach to Materials by Design

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In recent years, materials have emerged as a focus of architectural pedagogy. Beyond teaching students to think of materials in architecture as part of the design process, the ambition here is bolder: to design architecture means to design materials. Conversely, materials in architecture should not be thought of as a matter of choice, as from a catalog, but rather as an explicit design objective. This paper examines a Framework for a Pedagogical Approach to Materials by Design.

While we explore the idea that we design material as we design form, we shouldn't have to choose between the two. It does not have to be the one way relationship of form to material. This relationship has been disrupted by recent advances. In Materials Science, the term Materials by Design refers to "computational materials prediction approaches, corresponding advanced synthesis and characterization methods" for the purpose of accelerating material innovation. However, this approach is limited to optimization at small scales. Here we expand the term to approach the design of materials through a multi-scalar evaluation framed by their structural, energetic, ecological, social and cultural performances..

Composite materials have caught the attention of designers and scientists alike as a paradigmatic counter-example to industrial production of assemblies for the built environment. The efficiency in the use of materials, economy of production and the reduction of CO2 emissions have become common place discussions among practitioners of architecture. Composites seem to promise a viable way forward. Composites also present unique formal and performative potentials for architecture. Moreover, they tend to require design of new fabrication methods. As such, composites are the focal, but not the exclusive, effort of the framework.

The Materials by Design Framework is taught through our Materials Systems and Production class. Four successive engagements with materials, from their cultural positioning, to their ecological and scientific characterization, culminate in the design and fabrication of functional composites for architecture.

Material Cultures: Beginning with the history of materials, students develop timelines exploring the feedback loop of culture and materials.

Material Selections: Using CES EduPack software, students encounter a vast expansion of materials available to architecture paired with workflows to select specific materials for given functions.

Material Ecologies: Circular economies and the emerging role of waste in design are presented. Students develop lifecycle and embodied energy analyses of emerging materials.

Materials by Design: Students develop a parametric sensibility of materials, providing inspiration and precedent for later invention. A literature review of existing technological and biological composites is performed. Students design material library "cards" for all researched examples generating their own taxonomic system and a basis for their own designs. Then, through the virtual "cross breeding" of material properties, students rigorously evaluate materials by compatibility and difference. The pairings of performances such as opacity and transparency, structure and insulation pose challenges and opportunities for fabrication and design. Composite samples, which we term Materials by Design, are fabricated in a consistent format, a "core sample", to test and compare design hypotheses.

INTRODUCTION

The pressing challenges of the present moment require a synthetic approach in architectural pedagogy that accounts for an ecology of concerns. The sustained rise in CO2 levels threatens to accelerate through population growth and rapid urbanization. The built environment and, consequently, materials are central climate challenges. How can the materials we build with perform well culturally, structurally, thermally and ecologically? Here we present a Framework for a Pedagogical Approach to Materials by Design that addresses this question through four engagements: Material Cultures, Material Selections, Material Ecologies and Materials by Design. Taught in our Material Systems and Production class, the successive engagements are interdependent, interdisciplinary and multi-scalar. The framework can be thought of both as a network and hierarchy as shown in the diagram in Figure 1.

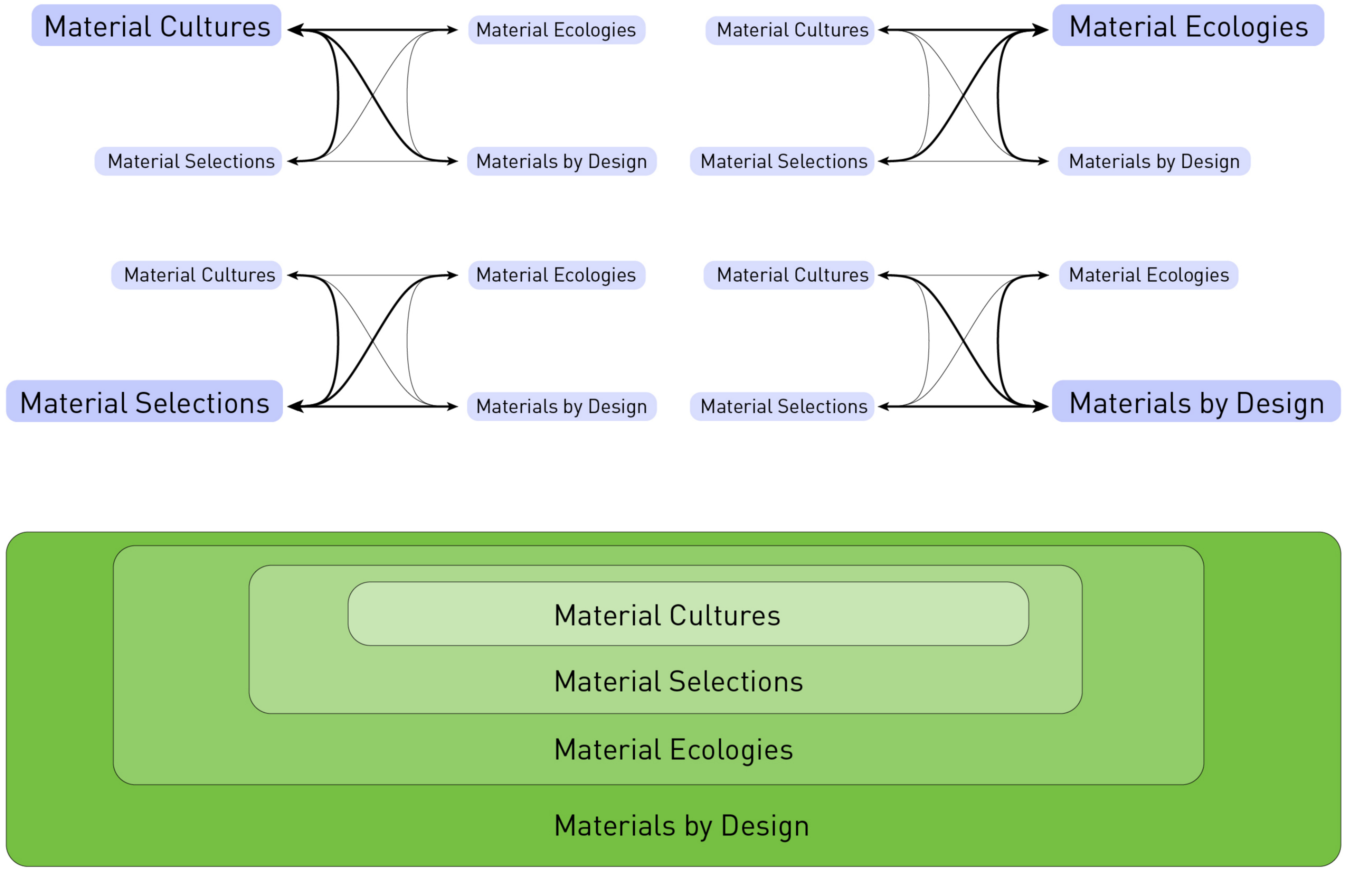


Figure 1. A Pedagogical Approach to Materials by Design: Network and Hierarchical diagrams. Image credit: CASE

Framework as network (Figure 1, top): In any given engagement with materials, whether we are concerned with the cultural, structural, thermal or ecological performances of a material, no performance is excluded. Rather, the model is a network of performances, of interrelated concerns, where a node of the network can be emphasized but its connections to the others remain. This approach encourages learning pathways that are active across the range of engagements which, in turn, activate the network.

Framework as Hierarchy (Figure 1, bottom): While students are initially introduced to the network of engagements, we begin with fewer constraints and more familiarity in "Material Cultures". The process becomes more complex as each engagement subsumes the last. The initial engagements are less constrained, the final ones more so, developing rigor in the work progressively. The networked and hierarchical qualities of the Framework operate in tandem. Interdependence and sequence are symbiotic, reinforcing and deepening the Frameworks goals.

MATERIAL CULTURES:

> We live in a world of materials; it is materials that give substance to everything we see and touch. Our species - homo sapiens - differs from others most significantly, perhaps, through the ability to design - to make things out of materials - and in the ability to see more in an object than merely its external form. Objects can have meaning, carry associations, or be symbols of more abstract ideas. Designed objects, symbolic as well as utilitarian, predate any recorded language - they provide the earliest evidence of a cultural society and of symbolic reasoning. Some of these objects had a predominantly functional purpose: the water wheel, the steam engine, the gas turbine. Others were (and are) purely symbolic or decorative: the cave paintings of Lascaux, the wooden masks of Peru, the marble sculptures of Attica. But most significantly, there are objects that combine the functional with the symbolic and decorative. The combination is perhaps most obvious in architecture - great architects have, for thousands of years, sought to create structures that served a practical purpose while also expressing the vision and stature of their client or culture: the Coliseum of Rome...the Pompidou Centre of Paris, each an example of blending the technical and the aesthetic.
>
> - Michael Ashby and Kara Johnson, *Materials and Design (Third Edition)*

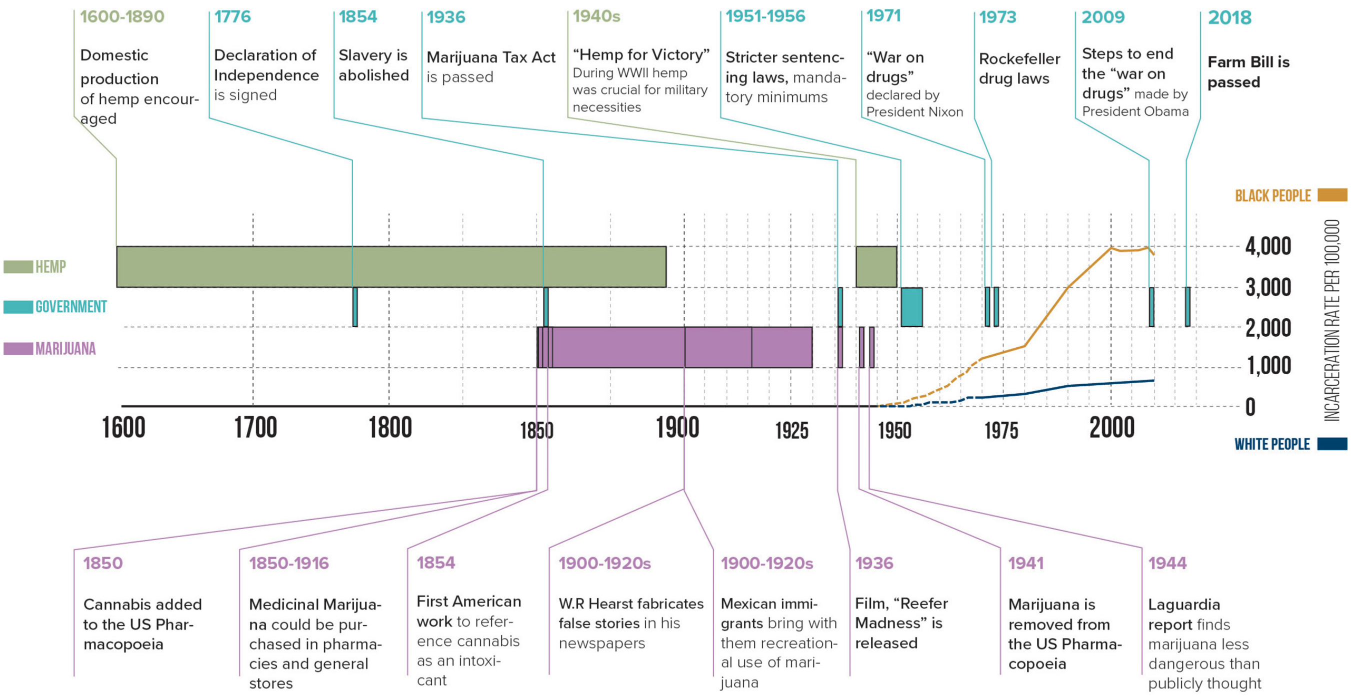


Figure 2. Material Cultures: United States History of Cannabis Timeline. Image credit: CASE

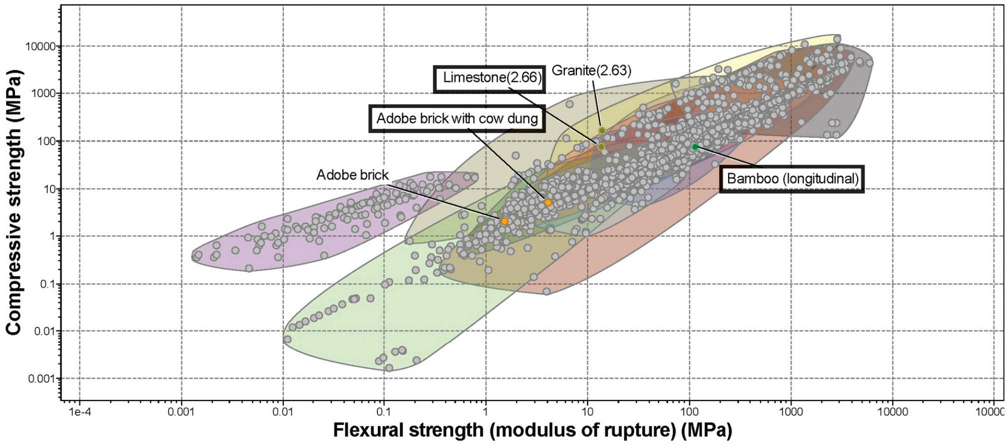
Ashby and Johnson's positioning of materials as the basis of design, the historical substrate and differentiator of the human species and a primary vessel of meaning, aesthetics and function, supports the choice of materials as the center of a culturally engaged and interdisciplinary architectural pedagogy. However, while the history of materials is the material of history itself - "Materials have enabled the advance of mankind from its earliest beginnings – indeed the ages of man are named after dominant material of the day: the Stone Age, Copper Age, the Bronze Age, the Iron Age." - the current moment is one of an explosion of available materials. "This is not the age of one material; it is the age of an immense range of materials. There has never been an era in which their evolution was faster and the range of their properties more varied." How do we choose where to begin? The parallel trend to the growth of available materials is their progressive non-renewability. "We don't just use materials; we are totally dependent on them. Over time this dependence has progressively changed from a reliance on renewable materials - the way mankind existed thousands of years – to one that relies on materials that consume resources that cannot be replaced." Ecological concerns can provide focus for our choices. An historical analysis of renewable materials may re-surface their meanings, aesthetics and functions for design while provoking a discussion on biases for and against materials. How do we characterize the ideologies that make certain materials desirable and others not?

In the Material Cultures engagement, students begin by researching and producing timelines of renewable materials. Figure 2, "Material Cultures: United States History of Cannabis", examines an outstanding example of a renewable material, hemp, with rich historical uses for architecture that was also effectively exiled. Hemp and marijuana were conflated and both made illegal. However, the "Hemp Farming Act of 2018" legalized "industrial hemp that has a tetrahydrocannabinol (THC, the psychoactive component of marijuana) concentration of no more than 0.3% by removing it from schedule I of the Controlled Substances Act." The United States market for industrial hemp, closed down since about 1950 , is now growing rapidly. This student researched the cultural and legal status of hemp over time, the uses of hemp both within and without architecture and its structural, thermal and ecological performance. Figure 2 tracks the entanglement of hemp and marijuana, which are both types of cannabis, and the cultural, legal and penal causes and consequences of that entanglement. The visualization of conflicting and resolving ideologies surrounding hemp helps structure and motivate successive engagements in the framework as different modes of persuasion for materials that, while they may possess important and useful architectural performances, are perceived with implicit biases.

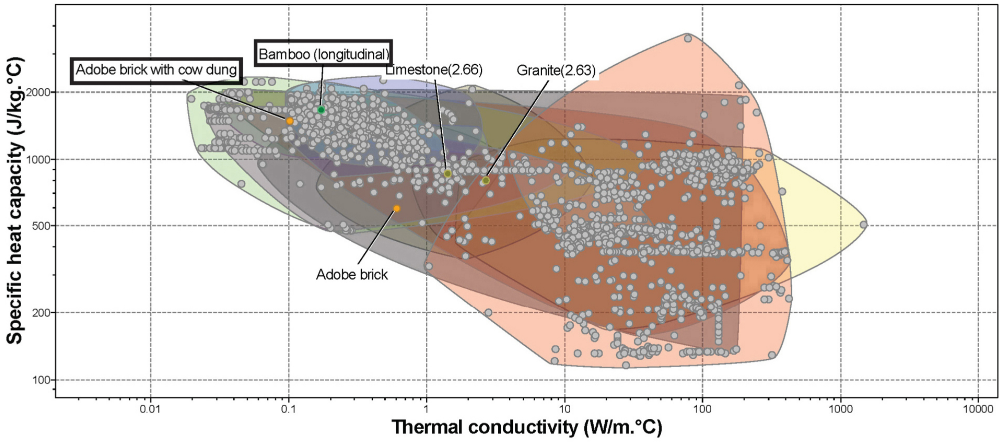
MATERIAL SELECTIONS

> Asking if two colors are "similar" can be answered by comparing their wavelengths. But if by "similar" you mean a larger set of properties, you are asking for something more difficult: recognition of a pattern of behavior. The brain is better at pattern recognition when the input is visual rather than text-based. So: how can we make technical attributes visible?
>
> — Ashby and Johnson, *Materials and Design (Third Edition)*

🟥 **Compressive Strength**
Flexural Strength



🟦 **Specific Heat Capacity**
Thermal Conductivity



		ADOBE BRICKS	COWDUNG STABILIZED ADOBE	COMPRESSED CEMENT STABILIZED EARTH BLOCKS	RICE HUSK ASH STABILIZED BLOCK	ENGINEERING BRICK	HOLLOW CEMENT BLOCKS	CES CHARTS
PHYSICAL	APPEARANCE							
	DENSITY (Kg/m^3)	1.55e3	1.88e3	1.75e3	1.77e3	2.29e3	1.67e3	🟪 🟨
PERFORMANCE	COMPRESSIVE STRENGTH (MPa)	2.1	5.16	3.2	6.5	82.2	17.8	🟥 🟪
	FLEXURAL STRENGTH (MPa)	1.5	4.02	4.35	4.2	8.66	1.9	🟥
	SPECIFIC HEAT CAPACITY (J/Kg.°C)	600	1.5e3	1.32e3	1.63e3	798	973	🟦
	WATER ABSORPTION	12.3%				1%	14%	
	THERMAL CONDUCTIVITY (W/m.°C)	0.6	0.1	0.72	0.2	0.89	0.62	🟦
	WEAR RESISTANCE	Unacceptable	Unacceptable	Limited Use	Limited Use	Limited Use	Limited Use	🟨
ECONOMIC	PRICE (INR/UNIT)	10	10	25	25	10	22	🟩
ECOLOGY	EMBODIED ENERGY (MJ/Kg)	0.9		2.2		4.5	2.98	
	RECYCLE	✓	✓	✗	✗	✗	✓	
	DOWNCYCLE	✓	✓	✗	✗	✓	✓	
	LANDFILL	✓	✓	✓	✓	✓	✓	

Figure 3.Material Selection and Ecologies: Comparative Analysis towards a Contemporary Indian Vernacular. Image Credit: CASE

CES EduPack is the primary software and interdisciplinary foundation of the Framework. Both science and design-led, its linked databases of materials and processes are structured as trees in five levels of hierarchy: Universe, Family, Class, Member and Attributes. Each field name for a material record is linked to pages of notes explaining the property, how it is measured and the Materials Science behind the property. This depth and connectivity, culminates in charts that "condense a large body of information into a compact but accessible form…reveal correlations between material properties that aid in checking and estimating data and…become tools for materials selection, for exploring the effect of processing on properties, for demonstrating how shape can enhance structural efficiency, and for suggesting directions for further material development"

CLASSIFICATION AND COMPARISON

We begin broadly, exploring the Material and Process Universes in CES through its generated charts, understanding Materials Selection as the visual and quantitative assessment of "combinations of properties that matter: the need for stiffness at low weight, for thermal conduction coupled with corrosion resistance, or for strength combined with toughness, for example." In parallel, continuing the examination of "exiled materials" from Material Cultures, students contrast CES's technical hierarchy with one proposed by Cardwell et.al in their article New Materials for Construction from the Arup Journal. This epistemologically-based materials classification system is organized by the degree to which a material is familiar, contemptible or known. The five material categories are Unfamiliar, Familiar, Contemptible, Unknown and Unknowable. "If we can visualise this way of looking at 'unfamiliar' and 'familiar' materials, and use our new materials science understanding to benefit, what of the materials we no longer use - the overly familiar discarded or contemptible materials? By applying our understanding, can we relearn or re-use 'contemptible' materials?" This sets the stage for the assessment of the viability of waste and vernacular materials for construction through technical analyses.

SELECTING MATERIALS

In Figure 3, a student examined vernacular building traditions in her home country of India through the lens of CES. Two CES charts (Figure 3, top) situate "Adobe brick with cow dung" vs. its vernacular peers, limestone, bamboo and granite, over and against the background of the Material Universe of CES which includes normative, contemporary materials of construction. This selection process foregrounds the superior thermal performance of these bricks while recommending them structurally as infill.

Production of these charts, visualizing pairs of material performances, are valuable storytelling elements for architecture students in an overall analysis of a material.

MATERIAL ECOLOGIES

The linear 'take, make, dispose' model, the dominant economic model of our time, relies on large quantities of easily accessible resources and energy, and as such is increasingly unfit for the reality in which it operates. Working towards efficiency – a reduction of resources and fossil energy consumed per unit of economic output – will not alter the finite nature of their stocks but can only delay the inevitable. A deeper change of the operating system is necessary.

The notion of the circular economy has attracted attention in recent years. The concept is characterised, more than defined, as an economy that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles. It is conceived as a continuous positive development cycle that preserves and enhances natural capital, optimises resource yields, and minimises system risks by managing finite stocks and renewable flows. It works effectively at every scale.

- Ellen MacArthur Foundation, *DELIVERING THE CIRCULAR ECONOMY: A TOOLKIT FOR POLICYMAKERS*

The well-known butterfly diagram of the prototypical circular economy by the Ellen MacArthur foundation , described in the above quote, helps to locate the Framework's ecological engagement. The Framework privileges materials that can oscillate between the technical and biological cycles of a circular economy of construction (such as agricultural waste e.g. cow dung) vs. non-renewable ones. To proceed, this first requires a reevaluation of current linear construction systems and their potential as circular ones.

DIAGRAMMING CONSTRUCTION SYSTEMS

Beginning the Ecological engagement of the Framework, students research and produce system diagrams of normative linear and proposed circular construction systems tracking flows of material, energy and information. Understanding diagrams as topologically malleable mental models, students manipulate linear construction system diagrams, re-connecting and hybridizing their flows into circular systems. These ecologically oriented circular construction system diagrams act both as an aspiration for and check on the student's proposal, guiding the technical storytelling done with CES charts.

The Framework requires students to interrogate and represent the different material systems they discover in their research. The needed research and system diagramming skills are taught in our "Research Design" class. The synthetic, integrated character of this Framework is a sort of microcosm of our overall curriculum and pedagogy which has the same characteristics. An important outcome is the reflection that students inevitably perform on their own methods through the evaluation of the methods of others. They are encouraged to "design how they design".

ECOLOGICAL TOOLS IN CES

Developing from system diagrams, students characterize materials ecologically in CES through its suite of ecological tools. Eco-Audit, a "fast Life Cycle Analysis tool", draws on the eco-attributes in material records. These include the attributes of the material itself such as global reserves, CO2 footprint and embodied energy; Processing attributes and End of Life (EoL) including recycling and the fraction of recycling in current supply. Eco-audit expands and situates materials within their actual flows characterizing their Life-energy including Transport which depends on where the material is sourced from and its destined site. The six Eco-Audit categories: Material, Manufacture, Transport, Use, Disposal and EoL credit quickly demonstrate if a material assembly's embodied energy is material-dominated or use-dominated, providing guidance and targets for improved efficiencies. Expanding further, Enhanced Eco Audit provides cost information and flags restricted or critical materials risk. Very recently, CES has rolled out a Social Lifecycle Analysis Tool (S-LCA) that expands on Eco-Audit providing an integrated analysis of the three "sustainability capitals" – Manufacture Capital, Social Capital and Human and Social Capital. While Eco-Audit provides a quick overview of the first two capitals, the S-LCA presents all three linking materials to the international social and political conditions of their sourcing and manufacture.

EXTENDING CES WITH RESEARCH

While finding appropriate architectural roles for vernacular materials through these kinds of analyses can begin to relocate them in architectural practice, "Adobe brick with cow dung" did not initially exist as a record in CES. However, with its ability to add well-structured records, students can gather research on target materials and their testing results adding them as new materials to CES. This is another important aspect of interdisciplinarity in the Framework as the desired research tends to be authored by Material and Environmental Scientists. Students generate matrices of research (Figure 3, bottom) that extend and complete the data of materials under consideration. In addition to mechanical and thermal performance, ecological and economic parameters are added to complete the picture.

ASSESSING COMPREHENSIVE ARCHITECTURAL PERFORMANCE

The overall analysis of cow dung stabilized adobe bricks supports their assessment as an appropriate, contemporary infill material based on their structural, thermal ecological and economic performances in a lower density, Indian urban condition. More generally, this is a vital tool in an effort to reintroduce the vernacular in a contemporary context. As Indian practitioners Seema M Burele and Sheeba Valson note in their evaluation of mud-based construction techniques in Vidarbha, a central Indian region, vernacular materials can face significant cultural barriers to deployment:

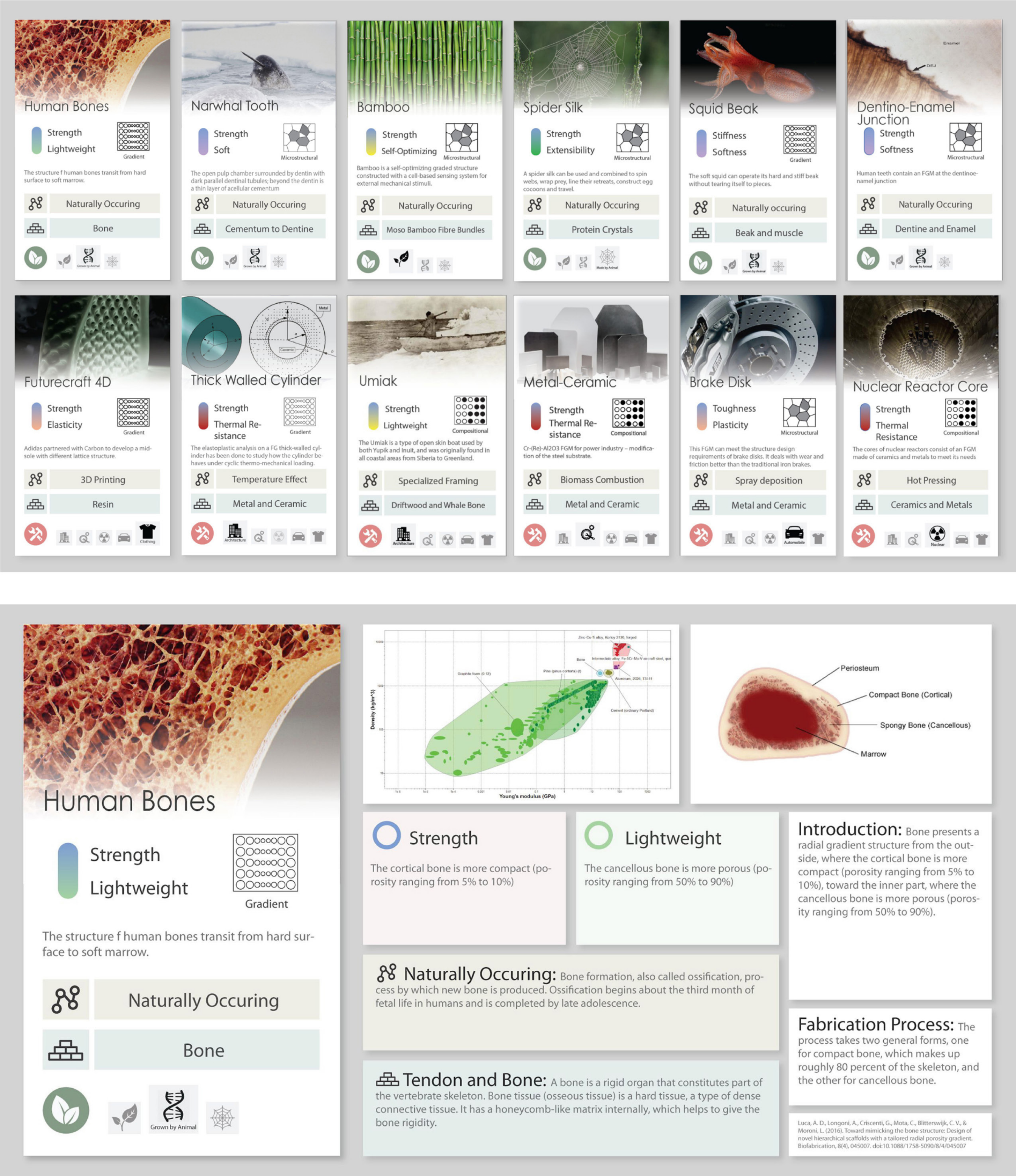
> The vernacular architecture of Vidarbha is evolved out of social needs, response to the climate, availability of resources, and through the local craftsmanship, which are all the important elements contributing to the sustainability.
>
> In today's scenario people don't want to build in mud. It is considered as the material of the poor. Even the rural areas are deteriorating their fabric by switching over to the newer material which is more harmful to the environment. Here also our role starts as an architect - the concept of sustainability and eco-friendly architecture can be introduced by designing certain modules as per the requirements and can be introduced to them at the rural as well as urban level. Many well-known architects are experimenting with mud in modern contexts. Other ways for the revival of vernacular mud construction techniques should be focused on.
>
> - Seema M. Burele and Sheeba Valsson, *Vernacular Mud Construction Techniques of Vidarbha Region-A Sustainable Approach*

The notion of mud as a "material of the poor" illuminates its "contemptible" character. The efforts to return vernacular materials to contemporary use are not merely technical. However, making the technical case for vernacular materials can be an important "other way" to argue for a reconsideration of both their cultural position and biases can be an important "other way" to argue for a reconsideration of both their cultural position and biases.

MATERIALS BY DESIGN

Structure, infill, window, wall, insulation, ornament, etc. would be dealt with within a piece's variable material properties. We can always substitute the notion of structure and surface with the equivalent structural and non-structural body, the notion of the window and the wall with a relationship between transparent and non-transparent areas, changing the point of view from parts to properties. This endeavor would entail a new more open dialog between architects, computer and material scientists, robotic and structural engineers, hearkening back to Violletle-Duc and his desire to see engineering inform architecture and vice versa. A dialog that is very present in the discipline today.

The multi-dimensional material-property space is only part-filled by monolithic materials The basic families of Metals, Ceramics, Glasses, Elastomers and Polymers combine to create Composites, the focus of this inquiry, which, combining properties of different materials, can occupy unclaimed territory. The Materials by Design engagement, the final one of this Framework, pursues gaps in the cultural, scientific, ecological and technological material-property space through Composites. Materials by Design are composites which blend properties and functions through the continuous blending of their constituent materials and geometries. They exist at the cutting edge of materials development in a range of disciplines because they achieve breakthrough performance but are usually produced at smaller size and scale (nano or microstructural) and expensive energetically and economically to produce. This engagement investigates Materials by Design for architecture that are larger in scale and energetically and economically "cheaper". The work proceeds in three phases: Research, Design and Fabrication culminating in an original material library.



Human Bones
Strength
Lightweight
The structure f human bones transit from hard surface to soft marrow.
Naturally Occuring
Bone

Narwhal Tooth
Strength
Soft
The open pulp chamber surrounded by dentin with dark parallel dentinal tubules; beyond the dentin is a thin layer of acellular cementum
Naturally Occuring
Cementum to Dentine

Bamboo
Strength
Self-Optimizing
Bamboo is a self-optimizing graded structure constructed with a cell-based sensing system for external mechanical stimuli.
Naturally Occuring
Moso Bamboo Fibre Bundles

Spider Silk
Strength
Extensibility
A spider silk can be used and combined to spin webs, wrap prey, line their retreats, construct egg cocoons and travel.
Naturally Occuring
Protein Crystals

Squid Beak
Stiffness
Softness
The soft squid can operate its hard and stiff beak without tearing itself to pieces.
Naturally occuring
Beak and muscle

Dentino-Enamel Junction
Strength
Softness
Human teeth contain an FGM at the dentinoe-namel junction
Naturally Occuring
Dentine and Enamel

Futurecraft 4D
Strength
Elasticity
Adidas partnered with Carbon to develop a mid-sole with different lattice structure.
3D Printing
Resin

Thick Walled Cylinder
Strength
Thermal Resistance
The elastoplastic analysis on a FG thick-walled cylinder has been done to study how the cylinder behaves under cyclic thermo-mechanical loading.
Temperature Effect
Metal and Ceramic

Umiak
Strength
Lightweight
The Umiak is a type of open skin boat used by both Yupik and Inuit, and was originally found in all coastal areas from Siberia to Greenland.
Specialized Framing
Driftwood and Whale Bone

Metal-Ceramic
Strength
Thermal Resistance
Cr-(Re)-Al2O3 FGM for power industry – modification of the steel substrate.
Biomass Combustion
Metal and Ceramic

Brake Disk
Toughness
Plasticity
This FGM can meet the structure design requirements of brake disks. It deals with wear and friction better than the traditional iron brakes.
Spray deposition
Metal and Ceramic

Nuclear Reactor Core
Strength
Thermal Resistance
The cores of nuclear reactors consist of an FGM made of ceramics and metals to meet its needs
Hot Pressing
Ceramics and Metals

Human Bones
Strength
Lightweight
The structure f human bones transit from hard surface to soft marrow.
Naturally Occuring
Bone

Strength The cortical bone is more compact (porosity ranging from 5% to 10%)

Lightweight The cancellous bone is more porous (porosity ranging from 50% to 90%)

Introduction: Bone presents a radial gradient structure from the outside, where the cortical bone is more compact (porosity ranging from 5% to 10%), toward the inner part, where the cancellous bone is more porous (porosity ranging from 50% to 90%).

Naturally Occuring: Bone formation, also called ossification, process by which new bone is produced. Ossification begins about the third month of fetal life in humans and is completed by late adolescence.

Fabrication Process: The process takes two general forms, one for compact bone, which makes up roughly 80 percent of the skeleton, and the other for cancellous bone.

Tendon and Bone: A bone is a rigid organ that constitutes part of the vertebrate skeleton. Bone tissue (osseous tissue) is a hard tissue, a type of dense connective tissue. It has a honeycomb-like matrix internally, which helps to give the bone rigidity.

Luca, A. D., Longoni, A., Criscenti, G., Mota, C., Blitterswijk, C. V., & Moroni, L. (2016). Toward mimicking the bone structure: Design of novel hierarchical scaffolds with a tailored radial porosity gradient. Biofabrication, 8(4), 045007. doi:10.1088/1758-5090/8/4/045007

Figure 4.Materials by Design: Biological and Technological Composites Precedent Matrix. Image credit: CASE

RESEARCH

Students begin by performing a literature review of existing technological and biological Materials by Design. Having visited and studied the offerings of a professional material library early in the course, students design their own material library “cards” (Figure 4) for their own Materials by Design examples generating a taxonomic system which, in turn, acts as an inspiration and context for their own designs.

The biological spectrum of Materials by Design inspires and aligns with the aims of the Framework. Nature’s highest performing materials are Materials by Design. This research leads to bio-inspired design. The technical spectrum of Materials by Design outside of architecture provides a palette of performances and techniques promoting a process where scale, performance, application, industry and discipline must be identified, compared, and understood in order to activate the examples for architectural research.

The Materials by Design Matrix in Figure 3 incorporates the previous Framework engagements. Material cultures, selection and ecologies become parts of an interactive prototype material library through literature reviews, CES charts and performance analyses.

DESIGN

A common form factor of a “core sample”, a cylinder 8cm in diameter by 20cm in height, was chosen for design and fabrication. The conceit of the core sample evokes the scientific extraction and analysis of geological and ecological Materials by Design: core samples of composite rock, produced layer by layer over millennia and core samples of ice in which the composite conditions of the history of atmospheric CO2 levels are deciphered. Practically, they providing a consistent module for comparison.

Figure 5 shows fabricated Materials by Design core samples for architecture and their “material cards” which extend and refine the classification system of the previous Materials by Design Matrix. The samples shown are three of nine samples that were exhibited in 2019. Several of the core samples accompanied larger, more elaborate studies that jumped in scale to architectural system prototypes.

FABRICATION

The production of Materials by Design tends to require the design of their fabrication. The Framework organizes fabrication under the concepts of Self-Organization, Hylomorphism and the spectrum of their hybrids. As Levi R. Bryant explains: “The term hylomorphism comes from the Greek hyle signifying ‘matter’ and morphe denoting ‘form’. Under this model of fabrication, the artisan first has a sort of blueprint of what he wants to produce in his mind (the form), and then imposes that model on matter giving it form. I first have a mental model of the knife I wish to produce in my mind and then set about fashioning the materials of the world about me into that form.” The hylomorphic paradigm of imposed form finds its counterpart in the emergent form of self-organizing material processes: “In essence, self-organized systems are autonomously shaped units resulting from their inner determination under the influence of environmental conditions. It is important to recognize ordered structures and interpret them as self-organized with respect to their (external) environment and their (inner) components and properties in order to understand their genesis. Conversely, self-organized geological systems that have ordered structures contain valuable information about their genesis that is preserved within the structure.”

Within the spectrum of hylomorphic/self-organized hybridity, we first note that the normative conditions of material production are never purely hylomorphic. Bryant continues “The problem with hylomorphic models of how artifacts are produced is that they forget both the time of production and engagement with the materials of the world. What attentiveness to the time of production and engagement with matter reveals is that the production of any artifact is much closer to a negotiation than the simple imposition of a form upon a passive matter. And as is the case with all negotiations, the final outcome or product of the negotiation cannot be said to be the result of a pre-existent and well-defined plan.” The essence of this negotiation is perhaps the feedback loop between the plan of the maker and the self-organizing character of the material being worked with. Hylomorphic methods require self-organizing material processes. They are already hybrids. Conversely, the Framework asks: how can self-organizing material effects become design goals in themselves? How can they be manipulated? How can we control the uncontrollable? The previous geologically-oriented definition of self-organization is helpful: self-organization emerges in the interaction between the inner properties of material and its external environment. Instead of imposing form we manipulate the material’s environment – its energies and boundaries - to yield a range of self-organized effects. While a material’s sensitivity to initial conditions may ultimately determine its non-linear form generation, the designer can nevertheless induce formal and performative direction through the manipulation of higher-level system parameters within the material: its energy states such as temperature and humidity; the forces operating on the material (as in, for example, a centrifuge); its overall spatial configurations. Furthermore, self-organization tends to occur through minimal energy processes. Complex shapes and systems may emerge which are “expensive” geometrically but “cheap” energetically and, in turn, possess important architectural performance characteristics. This is a hallmark of Materials by Design in the natural world: the particular grading of materials minimize energy and maximize strength, resilience and sometimes formal complexity.

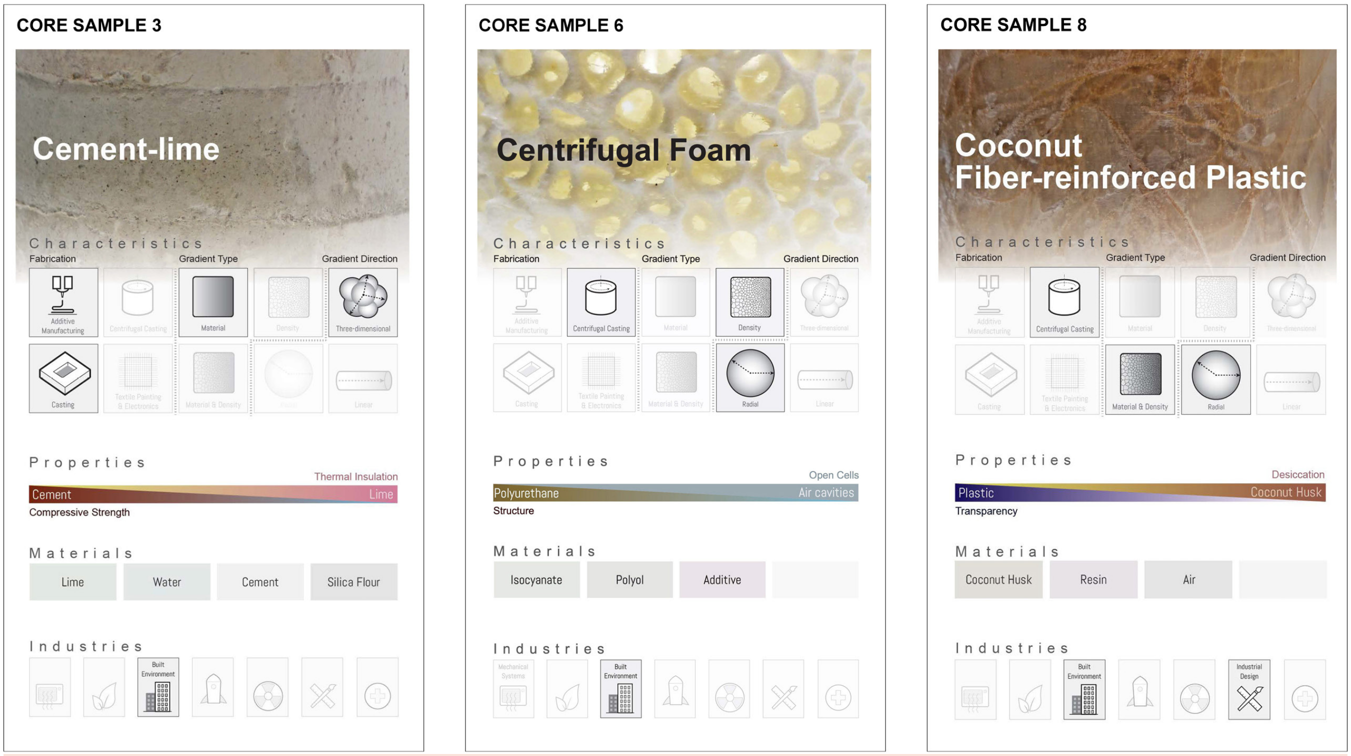


Figure 4.Materials by Design: Materials by Design: Composite Core Samples and Parametric Framework. Image credit: CASE

Core Sample 3 | Hylomorphic: In order to reduce Greenhouse Gas emissions from cement, the most ubiquitous construction material in the planet, this proposal aims to reduce the consumption of cement in envelopes through the use of Additive Manufacturing (AM). The mass-manufacturing capability of AM allows for the implementation of Materials by Design in the realm of construction without extra costs. Materials by Design allow for buildings to be designed and constructed in a way that is tailored to their context.

Using a gradient between cement and lime allows for envelopes to take advantage of the compressive strength and toughness of cement and transition into thermally insulative lime wherever it is needed. This could allow for a reduction in the solar heat gain or heat loss of buildings and reducing the need for extra assemblies which would, while at the same time, help reduce the need for mechanical systems in the interior of the building for thermal comfort.

This core sample has been conceptually extracted from a wall whose design consists of a cement-predominant structural space frame that grades outwards into a lime-predominant, thermally insulative material. Two layers of cement-predominant material enclose the fragile lime insulative infill.

The student team used Grasshopper to produce a custom definition which delivered pseudo G-code to fabricate the "Cement-lime" core sample (Figure 5, left). A "multi-extruder" casting mechanism was developed to execute the volumetric printing of this Material by Design. Future steps include the broad effort to deliver Materials by Design for architecture through AM.

Core Sample 6 | Self-Organizing: Exploring the collapse of fabrication, force and form, "Centrifugal foam" (Figure 5, center) is a simulation of a large, open cell foam under centrifugal force in a centrifuge. The increasing centrifugal forces from the sample's center to perimeter produce a gradient of lattice density from insulative to structural. It mimics the structural section of human bone.

The student team produced a custom Grasshopper definition to simulate centrifugal forces at a range of RPMs and simulate an open cell lattice under those forces. The geometry output was 3d printed using a high-durometer rubber. This sample is the only "simulated" one in the core sample library. Future steps include the development of a digitally controlled centrifuge to produce gradient porosity foam and a process to couple the simulative and empirical methods of lattice generation.

Core Sample 8 | Self-Organizing: The "Coconut Fiber-reinforced Plastic" core sample (Figure 5, right) uses coconut coir, a mutli-performance agricultural waste product that acts as the matrix of a structural tube whose binder is a bio-resin. Coconut coir can sorp moisture from humid air that would pass through the tube's "furry center", off-loading moisture load from HVAC systems. This is particularly applicable in the hot/humid belt of the planet where thermal comfort requirements and the CO2 footprint of HVAC systems collide.

Exhibiting a gradient of sorptive to structural performance, "Coconut Fiber-reinforced Plastic" was produced by a centrifuge at lower RPMs. Future steps include the scaling up of the sample to column size, a study of the effect of centrifugal force on the density and structural performance of the bio-resin/coconut coir composite and a study of the sorption efficiency of the unbound coir at the column's center.

Within the spectrum of hylomorphic/self-organized hybridity, we first note that the normative conditions of material production are never purely hylomorphic. Bryant continues "The problem with hylomorphic models of how artifacts are produced is that they forget both the time of production and engagement with the materials of the world. What attentiveness to the time of production and engagement with matter reveals is that the production of any artifact is much closer to a negotiation than the simple imposition of a form upon a passive matter. And as is the case with all negotiations, the final outcome or product of the negotiation cannot be said to be the result of a pre-existent and well-defined plan." The essence of this negotiation is perhaps the feedback loop between the plan of the maker and the self-organizing character of the material being worked with. Hylomorphic methods require self-organizing material processes. They are already hybrids. Conversely, the Framework asks: how can self-organizing material effects become design goals in themselves? How can they be manipulated? How can we control the uncontrollable? The previous geologically-oriented definition of self-organization is helpful: self-organization emerges in the interaction between the inner properties of material and its external environment. Instead of imposing form we manipulate the material's environment – its energies and boundaries - to yield a range of self-organized effects. While a material's sensitivity to initial conditions may ultimately determine its non-linear form generation, the designer can nevertheless induce formal and performative direction through the manipulation of higher-level system parameters within the material: its energy states such as temperature and humidity; the forces operating on the material (as in, for example, a centrifuge); its overall spatial configurations. Furthermore, self-organization tends to occur through minimal energy processes. Complex shapes and systems may emerge which are "expensive" geometrically but "cheap" energetically and, in turn, possess important architectural performance characteristics. This is a hallmark of Materials by Design in the natural world: the particular grading of materials minimize energy and maximize strength, resilience and sometimes formal complexity.

CONCLUSION

Research in architecture and its array of associated disciplines have…changed dramatically from the time of the emerging manufacturing and technical production of the industrial revolution to the current firewall between much of technology research and design work…Clear and strong divisions between design and technology (and, by the way, criticism, history and visual studies and others) have resulted in both productive and debilitating shifts away from the generalist center of design. In some contexts, this has created the disciplinary equivalent of "gated communities"

- John Fernandez, *Material Architecture*

The ambition of our Framework for a Pedagogical Approach to Materials by Design is to position materials at the center of architectural pedagogy: to design architecture means to design materials. Materials may obtain this central position because they intrinsically support and engage ecology of cultural, scientific, ecological and technological concerns that address our challenges and aspirations. Likewise, the phases of design demonstrate "material by design" at all scales. We claim that its disciplinary impact is also significant. Interdisciplinarity, crucial to this Framework, places students in a parallel ecology of disciplinary concerns that align with and generate the Framework's content. Likewise, interdisciplinarity germinates the ecological character of the architectural pedagogy itself. If the complex problems of the 21st century require complex teams to solve them, then we see this Framework as a way to drive toward Fernandez's "generalist center of design" positioning architects as active and central in the network of disciplines forming those teams, proposing solutions through the lens of Materials by Design.

ENDNOTES

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