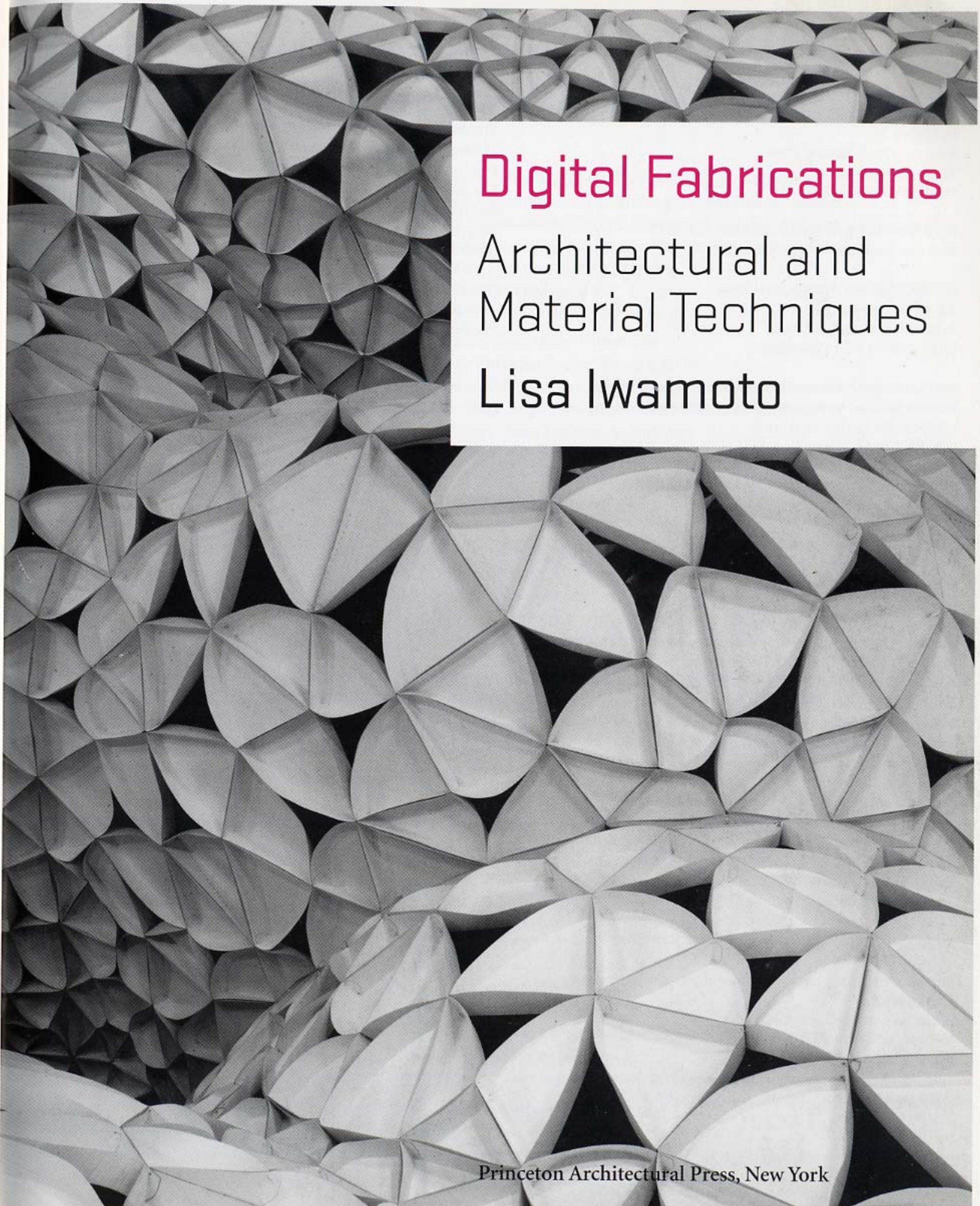

Digital Fabrications

Architectural and Material Techniques

Lisa Iwamoto

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Contents

004 Introduction

008 **Sectioning**

017 *Digital Weave*, University of California, Berkeley/Lisa Iwamoto
022 *Mafoombey*, Martti Kalliala, Esa Ruskeepää, with Martin Lukasczyk
026 *(Ply)Wood Delaminations*, Georgia Institute of Technology/Monica Ponce de Leon
028 *A Change of State*, Georgia Institute of Technology/Nader Tehrani
030 *[c]space*, Alan Dempsey and Alvin Huang
032 *BURST*.003*, SYSTEMarchitects

-rigid materials
-single units
-

034 **Tessellating**

042 *West Coast Pavilion*, Atelier Manferdini
046 *Huyghe + Le Corbusier Puppet Theater*, MOS
050 *Helios House*, Office dA and Johnston Marklee & Associates
052 *California: Stage Set for John Jasperse*, AEDS/Ammar Eloueini
054 *Airspace Tokyo*, Thom Faulders Architecture
056 *Technicolor Bloom*, Brennan Buck

060 **Folding**

069 *Dragonfly*, Tom Wiscombe/EMERGENT
074 *Nubik*, AEDS/Ammar Eloueini
076 *In-Out Curtain*, IwamotoScott
078 *Entry Paradise Pavilion*, Chris Bosse/PTW Architects
080 Aoba-tei, Atelier Hitoshi Abe
082 *Digital Origami*, University of Technology, Sydney/Chris Bosse
084 *C_Wall*, Andrew Kudless/Matsys
086 *Manifold*, Andrew Kudless/Matsys

088 **Contouring**

094 *Bone Wall*, Urban A&O
098 *Design 306*, Erwin Hauer and Enrique Rosado
100 *CNC panels*, Jeremy Ficca
101 *Door with Peephole*, WILLIAMSONWILLIAMSON
102 *Gradient Scale*, SPAN
103 *Tool-Hide*, Ruy Klein

106 **Forming**

113 *Alice*, Florencia Pita mod
118 *Prototype Pavilion*, MOS
122 *UniBodies*, PATTERNS, with Kreysler & Associates
124 *NGTV*, GNUFORM
126 "Dark Places," servo
130 "Housing in Vienna," SPAN
132 *Satin Sheet*, University of California, Los Angeles/Heather Roberge
135 *Shiatsu*, University of California, Los Angeles/Heather Roberge
138 *P_Wall*, Andrew Kudless/Matsys

140 Notes
141 Project Credits

Architecture continually informs and is informed by its modes of representation and construction, perhaps never more so than now, when digital media and emerging technologies are rapidly expanding what we conceive to be formally, spatially, and materially possible. Digital fabrication, in particular, has spurred a design revolution, yielding a wealth of architectural invention and innovation. How designs use digital fabrication and material techniques to calibrate between virtual model and physical artifact is the subject of this book.

In "Translations from Drawing to Building," Robin Evans expands on the inevitable separation architects encounter between drawing, the traditional medium of design, and building, the final outcome of their work.[1] As he describes it, great invention occurs in this gap. Like traditional drawing, digital production is a generative medium that comes with its own host of restraints and possibilities. Digital practices have the potential to narrow the gap between representation and building, affording a hypothetically seamless connection between design and making. As with any design process, however, there are invariably gaps among the modes of making. And, as with all tools of production, the very techniques that open these investigations have their own sets of constraints and gear particular ways of working. In the best cases, such as those shown in this book, innovation is born out of this fissure and advances design.

Digital Fabrications: Architectural and Material Techniques documents architecturally innovative projects realized through digital design and constructive processes. By way of several groundbreaking projects, it offers a brief and informative background to the rise of digital fabrication in architecture, providing insight into why it has sparked the imagination of a new generation of designers. It also contains practical information about the types of tools and technologies architects most frequently use for digital fabrication. The bulk of the book, however, is devoted to illustrating projects that reveal the design ingenuity that arises from digital fabrication and the material practices it has shaped and revitalized.

This book is unique because it concentrates on work designed and built by emerging and newly defined practices that, with a do-it-yourself attitude, regularly pioneer techniques and experiment with fabrication processes on a small scale. The means by which these projects were realized are within the reach of many practitioners and students. Here, the architectural project is a form of applied design research. These architects seek to leverage digital design and manufacturing for perceptual, spatial, and formal effect. The projects center on a mode of inquiry whose method of making ultimately forms the design aesthetic. Many of the practitioners teach as well and bring their interests into the classroom, offering the architecture student an opportunity to "do it" as well. For this reason, some excellent student projects have been included in the pages that follow.

The book is organized according to types of digital fabrication techniques that have emerged over the past fifteen years: sectioning, tessellating, folding, contouring, and forming. Each section introduces the basics of the featured technique through a description of pioneering case studies, after which there is a collection of projects demonstrating how architects have manipulated the tectonic method for design. Naturally, the projects overstep the chapter definitions: many combine two or three techniques. The distinctions nevertheless structure and contextualize the work, so that the projects gain specificity in light of the others.

Lastly, this book aims to show both working method and final results, documenting working drawings, templates, and material prototypes. Books on digital design tend to be highly technical, focused on documenting a few large building projects in great detail or else speculating more broadly on the implications of digital fabrication for the future of the profession. Missing from these efforts is a visually exciting collection of smaller built projects focused on design. *Digital Fabrications* does just that and will be of interest to anyone who wants to know how digital fabrication works, why architects use it, and how it promotes innovative design.

Background

It is inconceivable today to imagine designing buildings without the use of computers. They are used at every step of the architectural process, from conceptual design to construction. Three-dimensional modeling and visualization, generative form finding, scripted modulation systems, structural and thermal analyses, project management and coordination, and file-to-factory production are just some of the digital practices employed by architects and building consultants. Digital fabrication is often one of the final stages of this process, and it is very much what it sounds like: a way of making that uses digital data to control a fabrication process. Falling under the umbrella of computer-aided design and manufacturing (CAD/CAM), it relies on computer-driven machine tools to build or cut parts.

CAD/CAM has been a mainstay of industrial design and engineering and of manufacturing industries—particularly the automotive and aerospace industries—for more than a half century. Parts ranging from engine blocks to cell phones are designed and built using 3D-computer-modeling software. Scaled models are made quickly, using rapid-prototyping machines that turn out accurate physical models from the computerized data. Once the computer model is refined and completed, the data are transferred to computer-controlled machines that make full-scale parts and molds from a range of materials such as aluminum, steel, wood, and plastics. This computerized process streamlines production—effectively blending upstream and downstream processes that are typically compartmentalized, often eliminating intermediate steps between design and final production. There is the potential for architecture also to move more fluidly between design and construction. As Branko Kolarevic states, "This newfound ability to generate construction information directly from design information, and not the complex curving forms, is what defines the most profound aspect of much of the contemporary architecture."[2]

Architects have been drawing digitally for nearly thirty years. CAD programs have made two-dimensional drawing efficient, easy to edit, and, with a little practice, simple to do. Yet for many years, as the process of making drawings steadily shifted from being analog to digital, the design of buildings did not really reflect the change. CAD replaced drawing with a parallel rule and lead pointer, but buildings looked pretty much the same. This is perhaps not so surprising—one form of two-dimensional representation simply replaced another. It took three-dimensional-computer modeling and digital fabrication to energize design thinking and expand the boundaries of architectural form and construction.

In a relatively short period of time, a network of activities has grown up around digital fabrication. Inventive methods have emerged from project-specific applications developed by a handful of architects and fabricators. This inventiveness has to do in part with restructuring the very process of construction. The work of Gehry Partners and its associated firm Gehry Technologies has played a pivotal role in this regard. For them, digital integration was largely necessitated by the complexity of the building geometries.

Gehry's office began using CAD/CAM processes in 1989 to develop and then test the constructability of a building system for the Disney Concert Hall. As is usually the case in design, the process was iterative and nonlinear. Initially, physical models were reverse-engineered using a digitizer to take coordinates off a model's surface and import it into a 3D digital environment. The design subsequently moved back and forth between physical and digital surface models—physical models for aesthetics, digital models for "system fit." For this purpose Gehry's office adapted software from the aerospace industry, CATIA (Computer Aided Three Dimensional Interactive Application), to model the entire exterior of the concert hall.[3] At that time the skin was conceived as stone and glass, and the office successfully produced cut-stone mock-ups, using tool paths for computer-controlled milling machines derived from digital surface models. In other words, the digital model was translated directly into physical production by using digitally driven machines that essentially sculpted the stone surface through the cutting away of material. This building method revealed that the complexities and uniqueness of surface geometries did not significantly affect fabrication costs, and it is this realization, that one can make a series of unique pieces with nearly the same effort as it requires to mass-produce identical ones, that forms a significant aspect of the computer-aided manufacturing that has since been exploited for design effect.

In 2002, Gehry Partners created Gehry Technologies to further develop Digital Project, a version of CATIA adapted and specialized for the unique demands of complex architectural projects. Digital Project integrates numerous aspects of the construction process, including building codes, and mechanical, structural, and cost-criteria aspects. Gehry Technologies now acts as a consultant to Gehry Partners, as well as to other architects, assisting with digital construction and management. The company is revolutionary in that it expands the role of the architect to include oversight of the building and construction-management process, much as it was in the age of the master builder. In addition to Gehry's, architectural offices such as Foster & Partners, Nicholas Grimshaw, and Bernhard Franken are forging similar integrated project-delivery methods for large, complex projects. The focus of this book, however, is less on integration with the construction industry and more on another avenue of investigation taken by architects relative to digital fabrication: design-build experimentation at a one-to-one scale.

Recent Experimentation

We have experienced a fertile generation of architecture focused on the expanding possibilities of material and formal production. Digital methods have fundamentally shifted the discipline of architecture, and many paths now characterize this design arena. The architects included here are committed to employing the fluid potentials of technology to inform the design process and gear the evolution of their designs, while their experimentation is remarkable for being on a one-to-one scale. This approach recognizes what Michael Speaks has termed "design intelligence": "Making becomes knowledge or intelligence creation. In this way thinking and doing, design and fabrication, and prototype and final design become blurred, interactive, and part of a non-linear means of innovation."[4] As it does for the large-scale work of Frank Gehry and others, the digital environment allows architects to take control of the building process. Several groundbreaking projects helped instigate this avenue of design research and shape a new generation of architects.

Within a span of about five years beginning in the mid-1990s, a host of projects appeared that clearly demonstrated the aesthetic merits of using digital devices. These include, among others, William Massie's concrete formwork, Greg Lynn's waffle typologies, and Bernard Cache's surface manipulations, all of which will be discussed at greater length in the chapter introductions. In seeing these projects, one cannot deny that, in addition to the professional, industrial, and economic benefits associated with CAD/CAM, building with the computer achieves unprecedented visual, material, and formal results. While the ingenuity of the following projects goes far beyond the outward appearance, the strong visual aspect nevertheless plays a significant role in sparking the imagination of young designers. These early projects are the achievement most notably of architects with material know-how and a will to experiment—traits that have now increasingly permeated design culture.

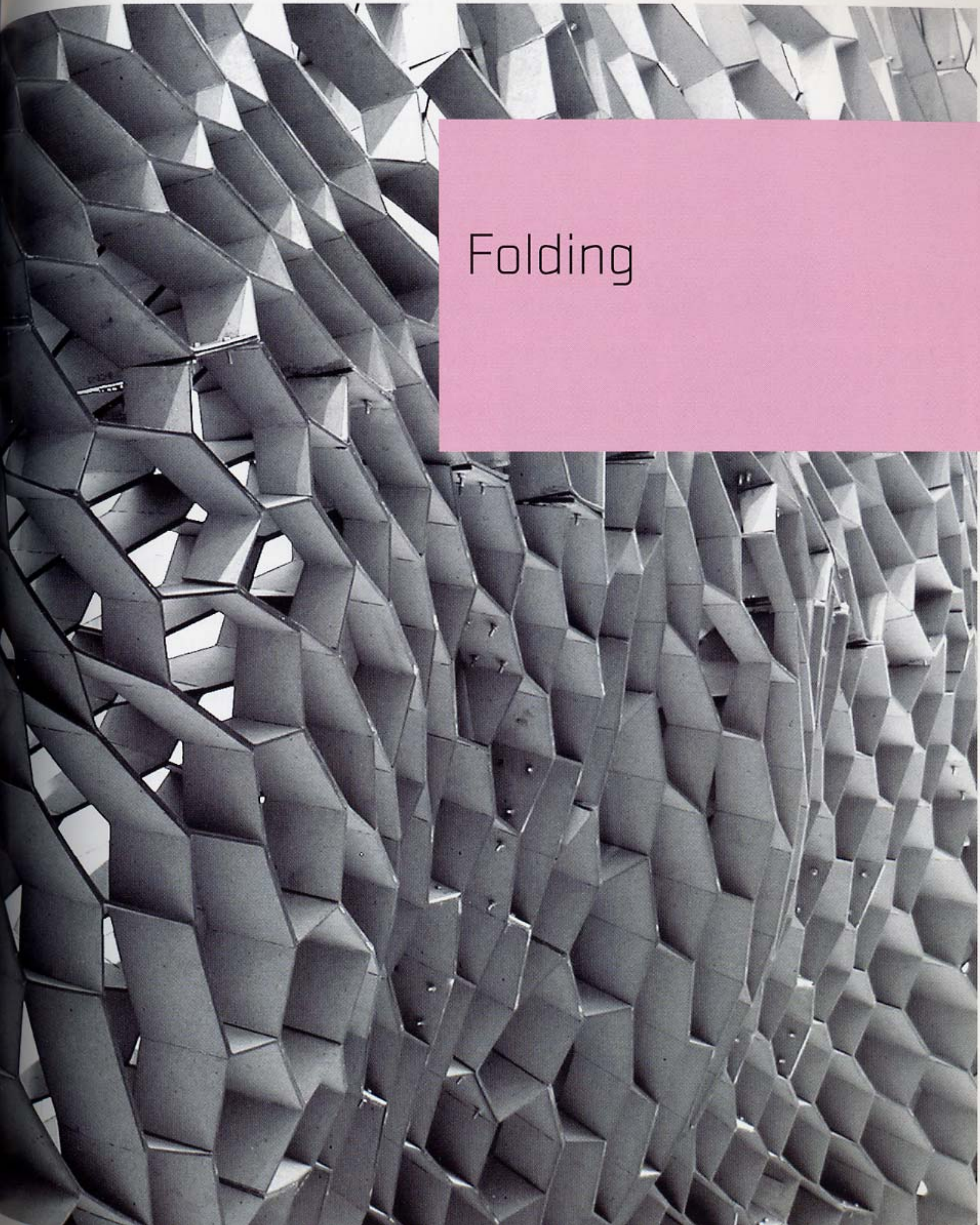
To move from design to construction, it is necessary to translate graphical data from two-dimensional drawings and three-dimensional models into digital data that a computer-numeric-controlled (CNC) machine can understand. This demands that architects essentially learn a new language. Some aspects of this translation are relatively automatic and involve using machine-specific software; others are very much in the purview of design. Decisions as to which machine and method to use must marry design intent with machine capability. It has therefore become necessary for digitally savvy architects to understand how these tools work, what materials they are best suited for, and where in the tooling process the possibilities lie.

Along these lines, architects have begun to couple form with method and revisit tectonic systems as a means to produce material effect. They seek to elevate standard building materials perceptually through nonstandard fabrication processes. Surfaces form buildings, and they can do so through smooth, undifferentiated expanses, or they can be constructed, textured, assembled, patterned, ornamented, or otherwise articulated. Digital fabrication opens onto a sea of possibilities. Punching, laser cutting, water-jet cutting, CNC routing, and die cutting are just some of the automated processes fueling this design domain.

Practically speaking, because buildings are made from a series of parts, their assembly relies on techniques of aggregating and manipulating two-dimensional materials. Computer fabrication has opened a realm for architects to perceptually heighten and make visible the nature of this accretion through constructed repetition and difference. The subtle variation of a system of elements, the transformation of recognizable materials, and the visceral response, no less, to viewing the result of intensive material accumulation—often understood to be the purview of the low arts or crafts—have been digitally redefined into a vocabulary by which architectural language is transformed. The projects shown in this book expand on these digital production techniques and capitalize on material methods as a generator for design. The architects here are concerned both with tectonics of assembly and with synthetic surface and material effect. The results are extraordinary—intricate patterns, filtered light, or evocations of abstracted images at mural scale—and all achieved through the aggregation of simple building materials.

The following chapters discuss architects who have honed digital-fabrication techniques on specific projects. Each discussion is accompanied by a detailed breakdown of the fabrication technique, providing insight into the recent projects featured in each chapter. These are projects that concentrate on the fertile realm of one-to-one-scale experimentation, which demands reciprocity between design and empirical innovation. The final outcomes hinge on the ability to reconcile the developmental shifts in material and working method. While the individual projects naturally take on different emphases, the work consistently elucidates provocative liaisons between digital production and making. Compelling design projects in and of themselves, they are both testaments to smaller-scale experimentation and the testing grounds for buildings to come.

Folding



structure through geometry

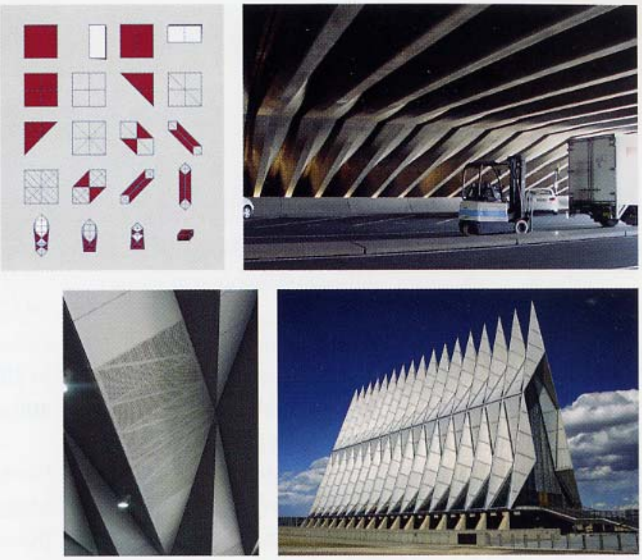
Folding turns a flat surface into a three-dimensional one. It is a powerful technique not only for making form but also for creating structure with geometry. When folds are introduced into otherwise planar materials, those materials gain stiffness and rigidity, can span distance, and can often be self-supporting. Folding is materially economical, visually appealing, and effective at multiple scales. It is not surprising that architects have expanded its use in the digital age.

In architecture, folding is theoretical concept, formal tactic, and the most literally material operation. Naturally, this chapter focuses on the material operation, but it is helpful to speak about it in the context of its other associations. In all cases, folding, or pleating, allows new spaces and territories to emerge without losing the native characteristics of what is being folded. It is already well understood that an architectural aspiration for the fold lies in its potential for manifesting cohesion and a continuity of competing spatial, cultural, social, programmatic, and contextual conditions within a single language. Greg Lynn argued in 1993 that "if there is a single effect produced in the architecture of folding, it will be the ability to integrate unrelated elements within a new continuous mixture."[1]

For roughly the past fifteen years, architects have certainly embraced the technique and progressively created continuous surfaces, spaces, and forms. Critics have rightly argued that the mere physicalization of the fold can in no way approach the complexities embedded in the concept; the fold, like all other theoretical and conceptual constructs, necessarily exceeds the formal domain of architecture. It has nevertheless produced a range of compelling work that has undeniably shaped contemporary design. Within this language, the actual folding of material is in part the simple and direct result of the process of producing a building in line with its conceptual aspirations. If floors fold to become walls and ceilings, then the material must fold as well. The examples are extensive and wide-ranging. The curved plywood walls of the Office for Metropolitan Architecture's *Educatorium*, the wrapped metal corner panels of Daniel Libeskind's Jewish Museum Berlin, and the structural cladding of Foreign Office Architects' Yokohama International Port Terminal are all instances of making the material perform in a manner consistent with the overall architecture.

As a material technique, however, folding is not limited to being a secondary system of articulating the larger building diagram. The operation of folding material is also a generative design tool that has gained currency in digital-fabrication processes. Like folding as a conceptual architectural device, it shares the aspiration to create fluidity and multifunctionality with continuous surface. Folding expands the three-dimensional vocabulary of surface by naturally producing deformation and inflection. Digital tools enable subtle and complex geometric modulations, affording the ability to both incorporate and smooth over difference. The structural stiffness produced by introducing folds into material is another significant advantage of the technique.

It is worth noting the design precedents that examined the structural potential of folding. The early and mid-twentieth century was an era of structural and architectural experimentation, fueled by engineers such as Félix Candela, Eduardo Catalano, Pier Luigi Nervi, and Eduardo Torroja. These engineer-architects strove for structural elegance and material lightness in the shaping of thin-shell concrete buildings. The projects were frequently designed around creased forms and hyperbolic curvature to create roof structures. Folded plate structures, a simpler geometric model, were also prevalent at the time. Whereas the hypar surfaces were somewhat rarified, accordion-shaped concrete roofs became quite common in many parts of the world. The relative ease of making the formwork, along with the structural potential of casting concrete into a folded form, made an efficient and popular combination. Yet, economy aside, these buildings were a new generation of architecture that used geometry to couple structural performance and enclosure.



CLOCKWISE FROM TOP LEFT:

Ballookey Klugeypop, origami instructions.

Jørn Utzon, Sydney Opera House, Sydney, Australia, 1973. Photo: Craig Scott

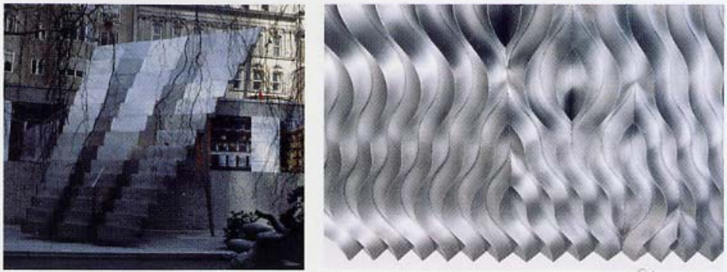
Walter Netsch/Skidmore, Owings & Merrill, Air Force Academy Cadet Chapel, 1962. Photo: Bryan Chang

FOA, Yokohama International Port Terminal, Yokohama, Japan, 2002. Photo: Georgia Ewen-Campen

A project that modifies normative reinforced-concrete structural profiles to a folded aesthetic is the underside service zone of the Sydney Opera House. A far less celebrated aspect of Jørn Utzon's masterwork, this zone is a set of undulating beams made of formed, folded concrete. What is ordinarily a hierarchical configuration of rectangular beams supporting a flat slab is transformed here into a structural ceiling landscape. In other cases, folding is the conceptual as well as the tectonic driver. The Air Force Academy Cadet Chapel, by Walter Netsch and Skidmore, Owings & Merrill, completed in 1962, merges roof and wall using prismatic folds. Smaller-scale examples also sprang from prismatic folding exercises. Heinrich Engel's book *Structure Systems* uses scaled paper models to illustrate folded-plate, two- and three-hinge frames, cross-folded surfaces, and a variety of other inventive folded structures.[2] These were often not built to full scale, but the models stimulated a range of work caught in the productive realm between architecture and industrial design.

Of course, folding is not limited to structural tectonics. Representing a method that transforms two dimensions into three, these projects describe its rich potential to make surface itself a modulated three-dimensional spatial construct. Folding has a long history in craft-based practices and product design, and it is in this context that digital tools are bridging a traditionally object-oriented practice and architecturally scaled work. With digital fabrication, folding takes on a new dimension and is extended to a method of making: building materials are literally folded into place. Of all the techniques described in this book, folding offers perhaps the greatest potential for variety because it is inherently capable of manifesting a wide range of forms. Creased surfaces, folded plates, and wrapped volumes all fall within the purview of folding. These building methods share a similar fabrication process (three-dimensional surfaces are developed—that is, unrolled or unfolded) to make two-dimensional templates for cutting.

As it has for other digital methods, software has enabled and streamlined the translation from three dimensions to two. Modeling programs such as Rhinoceros have embedded commands that efficiently unroll singly curved surfaces. There is also a group of commercially available programs



FROM LEFT:

Office dA, *Fabricating Coincidences*, Museum of Modern Art, New York, 1998. Photo: Dan Bibb

Haresh Lalvani/AlgoRhythm Technologies, InterRipples Ceiling System. Photo: Robert Wrazen; prototype: Milgo-Bufkin, courtesy Haresh Lalvani

→ software

and plug-ins (e.g., Lamina Design, Surf Master, and Pepakura Designer), as well as sheet-metal and other engineering software (SolidWorks and LITIO), that is specifically designed to turn free-form surfaces into a collection of flat pieces. These programs take material thickness into account and often offer options for jointing and labeling. The range of software available is an indication of how prevalent folding is as a material technique. Most of it is aimed at the craft, industrial-design, and sheet-metal industries, but it is equally applicable to architecture.

On the machine side, laser cutters are frequently used to make materials foldable. Unlike other three-axis machines, lasers are designed for engraving and can easily execute different line types, such as dashed, dotted, and scored. They can therefore make seams in a variety of methods without sacrificing the integrity of the material. Water-jet and plasma cutters are also widely used. These are aimed at cutting metals and do not have the ability to score, but they can readily make other types of perforations to control where the material creases.

material

As for material selection, because it must be restricted to those that are pliable and capable of bending without breaking, the materials that other industries commonly use to fold up parts—sheet metal, thick paper, and fabric—are also frequently called on by architects. Early executions of digitally fabricated folded surfaces simultaneously relied on standard sheet-metal practices and extended the aesthetic and formal possibilities of the material using digital techniques. Two good examples of these early efforts are Office dA's installation, *Fabricating Coincidences*, for MoMA's "Fabrications" exhibition in 1998 and Haresh Lalvani's sinuous metal panels and column covers for AlgoRhythm Technologies.

Although the initial design of *Fabricating Coincidences* was largely done by hand, its manufacture relied heavily on both computerized punching and laser cutting. Of particular note is the seam detail, which the architects redesigned as a "stitch." This seam is made by overlapping dashed laser cuts to minimize material at the bend and make crisp and continuous folds. Unlike typical sheet-metal bending, which uses a break and results in radiused corners, this new method takes advantage of the digital process both to cut and to perforate the panels and to obtain crisp edges. The project uses these types of folds exclusively, not only for aesthetic effect but also to unite surface and structure. The tight seams allow for the rear supports to multiply in thickness and essentially to stack as both columns and footings.

Seams are also at the cornerstone of Haresh Lalvani's research for AlgoRhythm Technologies. In his case, though, it is the geometry that departs from standard practice. Folds take on hyperbolic shapes generated by mathematical algorithms, and the seams guide the sinuous bends. These curved creases provide structural stability while dramatically redefining the sheet metal as sets of alternating convex and concave surfaces. The curved seams and internal stresses hold the dished shapes smooth. Particularly exciting is that the effectiveness of this technique depends on the elastic and plastic properties of the material, thus requiring a close affiliation between material and fabrication method.

Folding vs Sectioning

✱ Folding as
^dynamic system
-method of making

Unlike sectioning, for example, a technique that is somewhat irrespective of material in that material properties do not inherently change when cut in section, folding relies on the characteristics of the original material as it adds a new visual, spatial, and tectonic dimension.

This aspect of folding holds true at a large scale, too, where the design of the building skin has become a preoccupation of many contemporary architects. In *The Function of Ornament*, Farshid Moussavi and Michael Kubo attribute the current architectural transition toward ornament and building enclosure to affect and its sensorial and abstract communicative potential.[3] Whether this potential accounts for the fundamental shift in attention toward surface and skin, there is no doubt that there is a current obsession for work that produces material and atmospheric effect, sometimes together with functional criteria. For example, the Walker Art Center Expansion by Herzog & de Meuron, which has long been fascinated with the essential characteristics of material and its associative potential, uses a light creasing operation to create the crinkled facade. Folding is here generated largely for patternistic and ornamental purposes: the building shimmers. However, folding also serves the purpose of eliminating unanticipated oil-canning in favor of a precisely disturbed facade. Like all digital-fabrication practices, this folded skin has precedents in conventional construction. In the case of the Walker Art Center Expansion, flat-seam metal shingles and standing seam panels are standardized precursors. Yet, again, what is distinct about this new crop of work is how architects have adapted traditional methods to use folding as an operational system that manifests diversity in a highly specific and constructed manner. The projects in this chapter use such folded systems to make surface, volume, and structure.

Surface projects include *Nubik* by AEDS/Ammar Eloueini and *In-Out Curtain* by IwamotoScott: both develop a system of cuts and folds for a series of self-similar pieces that combine to create a modulated surface. *Nubik* is one of a series of projects by Ammar Eloueini that investigate the luminous, flexible, sculptural potential of pleated translucent polycarbonate. While the majority of Eloueini's work consists of fabriclike surfaces made of triangulated tessellations, this project comprises snaking linear strands. Each expresses a subtly changing rhythm of bulging "pods" and flat connectors built of the same material. The resulting aggregation locks together rigidly in a glowing cloudlike array.

IwamotoScott's *In-Out Curtain* also works to deflect direct light while it aims for a flexible end product. The design takes principles from modular origami—using folds and creases, for example, to make modules that interlock to form a collective whole—while simple material resistance generates its transformable quality. Each module is designed so that it holds two distinct shapes: in and out, which correspond to a closed/concave shape and an open/convex one. When torqued, the modules translate their individual deformations onto adjacent areas, creating a curtain of multiple shape variations. Folding, in this case, becomes a dynamic system, as well as a method of making.

While these two projects work with thickness and depth, they essentially remain surfaces. Other projects focus more specifically on achieving volume through folding. Like cardboard boxes, paper bags, and a host of other common products, folding has repeatedly proven an effective and elegant method for making three-dimensional form. The folds provide rigidity without requiring a lot of material to contain substantial areas of empty space. In other words, weight to volume, folds are highly efficient. The following projects are concerned with making volume and include Chris Bosse's *Entry Paradise Pavilion* and Hitoshi Abe's Aoba-tei restaurant. These two projects adapt parallel practices from clothing manufacturing. Folds here are soft and rely on the flexibility of the fabric or sheet metal to generate volume. Like clothes, they display the effects of draping, stretching, and seaming to arrive at the final form. Particular to both projects is the necessity of aligning material choice with the desired effect perforatras

Chris Bosse's *Entry Paradise Pavilion*, designed for an exhibition in Germany in 2006, is based on similar soap-bubble geometry, but it capitalizes on the tensile properties of lightweight Lycra fabric. Similarly to *Loop*, the design physicalizes the lines and surface tension of soap films. These seams are made tubular and expanded to form a continuous tensile framework. Bosse's pavilion, however, stands in significant contrast to *Loop*, which relies on the warped shape of the rings to introduce internal pressures and create compressive forces among adjacent cells, thereby increasing the overall structural capacity of the cellular network. The design of the *Entry Paradise Pavilion*, on the other hand, takes cues from minimal surface tent structures and expands the volumetric potential of this construction technique. Bosse used specialized sail-making software to refine the surface geometries and equalize the internal tensions of the material. The result is a taut surface, held in tension at points on the ceiling and floor. *Entry Paradise Pavilion* captures space by stitching together a pliable material into smooth yet ultimately still-folded surfaces.

The soft bend also defines the interior liner of Hitoshi Abe's Aoba-tei restaurant, which combines folding with other advanced fabrication processes—forming and perforating. The 2.3-millimeter-thick steel liner was conceived as a flat sheet folded into the space using conically curved corners. The construction process used digital shipbuilding technology to unfold this three-dimensional form into two-dimensional plates, taking into consideration the thickness and ductile properties of the material. Shipbuilders experienced in working with steel plate also assembled, formed, and welded the steel plates together. While the essence of the project relies on folding as the primary digital operation, steel clearly cannot be easily folded into place on-site. Instead, the construction team formed the steel by heating and cooling it along relevant seams.

Perforation is another automated fabrication technique, and its use here not only advances digital-fabrication processes but also pursues a powerful design thread in its abstraction and rerepresentation of elements in nature through simulated architectural affects. For this wholly interior project, dappling is made atmospheric using tree canopies as the visual metaphor. Before being bent, each panel was first perforated by a CNC turret with three differently sized holes on a fifteen-millimeter grid. This perforated liner forms a deep forestlike experience whereby the primary light source is thousands of pinpoints of light.

structure.

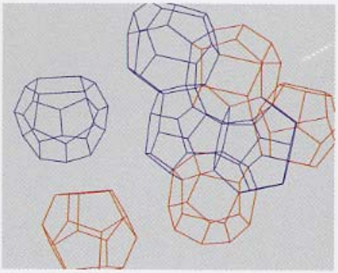
Lastly, contemporary architects, like their predecessors, have leapt on one of the great advantages of folding, which is its ability to provide structure. While the above-mentioned examples describe structures made through folded forms, a crop of new work is investigating material folding as a structural technique. Particularly compelling is the scaled-down, distributed model of structure that emerges out of material size. The following projects explore structural surface and the consequent visual and material implications: *Digital Origami* by Chris Bosse, *C_Wall* and *Manifold* by Andrew Kudless, and *Dragonfly* by EMERGENT'S Tom Wiscombe.

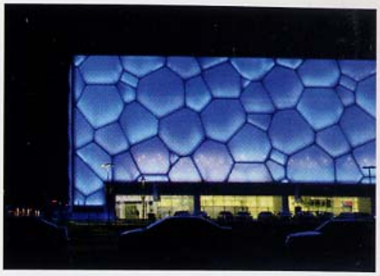
Digital Origami and *C_Wall* both transform sheet material into structural building blocks. Both laser-cut and engrave and fold paper to make stackable modules. The designs differ significantly, however, in conception and result. As the designer, for PTW Architects, of the National Aquatics Center for the 2008 Olympics in Beijing, Bosse takes efficiencies employed in the structural envelope of the building to limit the number of cells while maximizing visual difference. Also known as the *Watercube*, the design employs a cellular organization based on foam, or the Weaire-Phelan structure, reputedly the most efficient cellular partitioning arrangement. It is composed of two types of irregular polyhedra—six tetrakaidecahedra (fourteen-sided) and two dodecahedra (twelve-sided)—that nest together to form a larger interlocking unit. Yet whereas the *Watercube* shears a large block of packed cells to arrive at the final interior and exterior surfaces, *Digital Origami* allows

FROM LEFT:

Diagram of Weaire-Phelan structure. Courtesy: Nick Karklins

Chris Bosse/PTW Architects, *Watercube*, 2008. Photo: Chris Bosse





its thirty-five hundred recycled cardboard units to aggregate organically. The simplicity of the project's construction method is belied by its visual complexity. The bottom-up structural logic fosters on-site design flexibility. Cells are left out at times for porosity, the outside fringes of the installation suggest possible future growth, and the design can be infinitely reconfigured to respond to different site conditions and constraints.

The cellular units of Andrew Kudless's *C_Wall*, by contrast, are designed to fill a predetermined volume: one wythe thick. The Voronoi cells are generated using a computer script that uses points projected on the faceted surfaces of the form. Unlike the regularized eight modules of *Digital Origami*, each cell shape of *C_Wall* is unique, configured for one specific arrangement: the modular difference gives integrity to the whole. Though intricate and diverse, the units are subsumed into the larger figure of the piece. It is at once organic and constructed.

It is worth noting that *Digital Origami* and *C_Wall* outline two fundamentally different design processes: bottom-up and top-down, respectively. Both installations are laser-cut, made by unfolding and refolding building blocks, and both create distributed structure from a collection of units. The hierarchy in each of module to whole is reversed, however. Digital processes have facilitated the design of such modulated systems. Scripting, in particular, has opened the door to evolutionary design techniques that explore growth patterns and the relationships of part to whole. It is beyond the scope of this book to delve into emergent, evolutionary, morphogenetic, or biomimetic processes, but it is relevant that the type and scale of each of these projects is a valuable testing ground for this type of research.[4]

The last two projects to be discussed in this chapter, *Manifold* and *Dragonfly*, seek to synthesize the relationship of cellular configuration to overall form. As the previously described projects do, both begin by drawing from systems found in nature. *Manifold* employs a honeycomb structure, while *Dragonfly* draws from the structure of a dragonfly's wing. Rather than use pure geometric units or develop a partitioned infill, these projects work between part and whole. They are in some measure self-organizing, but both internal system and overall formation adjust to each other. Architects have turned to natural systems, as to structural models, as a way to describe this negotiation.

The honeycomb pattern of *Manifold* modulates according to specified performance criteria. Andrew Kudless developed a RhinoScript to deform the pure hexagonal geometry based on alignments and deviations of the front and back walls. The skewed hexagons maintain their topological integrity yet take on an internal dynamic governed by visual density, bearing capacity, and constructional seams in the wall structure.

Finally, EMERGENT's installation, *Dragonfly*, developed in collaboration with the engineering firm Buro Happold for the SCI-Arc Gallery in 2007, investigates the extreme structural and formal properties of the dragonfly wing. EMERGENT'S principal, Tom Wiscombe, states: "In nature, the dragonfly wing is unmatched in its structural performance and exquisite formal variation. Its morphology cannot be traced to any single bio-mathematical minima or optimum, but is rather the complex result of multiple patterning systems interweaving in response to various force flows and material properties."[5] The design process iteratively generated structural mutations based on support conditions for the extreme cantilever while using boundary conditions to interrelate overall form, cell shape, and band depth. Yet, like all good architecture, the project is not a mere reflection of structural determinism. *Dragonfly* evolved simultaneously toward structural performance and visual variation.

To achieve the cantilevered condition, EMERGENT and Buro Happold employed digital optimization routines to refine the structure, as well as to create formal variation in response to local conditions. This effort was linked to a fully parametrized fabrication process. Rather than follow the typical linear, and often laborious, progression from three-dimensional computer model to two-dimensional CAD template, the two were linked together in the modeling environment. Each member was accurately described, including material thickness, scored seams, and bolt holes, in CATIA. They were also digitally labeled with pertinent information, such as location and bending angle. The bands were then automatically unfolded as the computer model evolved structurally and formally. On final iteration, these templates were arranged with RhinoNest (a nesting program that maximizes material usage) on a four-by-eight-foot aluminum sheet and then cut using a CNC router.

As with all construction processes, realizing built form is an imprecise exercise. Digital fabrication, though highly accurate, still falls sway to material fluctuations, fabrication limitations, and other physical constraints. Building *Dragonfly* was no exception. Slight deviation in bending the angles and folds, as well as in the expansion and contraction of the aluminum, naturally created unanticipated consequences. These were dealt with in a manner consistent with both the precision of the digital model and the ductility of the material: the bands were coerced into place with the knowledge that the bolt holes were perfectly aligned. Once suspended, the final cantilevered formation acted as a single cohesive unit, a clear testament to the integrated architectural and engineering design approach.

Dragonfly uses folding for structural performance and lateral connectivity, employing the depth of the bands to span. As with all the projects mentioned in this chapter, folding is treated as an operative language that emanates throughout the schemes formally and functionally. Particular to this technique is its close affiliation to material behavior. Though limiting, it is perhaps this material constraint that makes folding so effective constructionally: it demands that design take the physical world into account from the start.

critical
to
class

- material
behavior
- steel

- part
management

vs
se framing
or
tessellation

limits
tolerance

All photos: Tom Wiscombe/EMERGENT

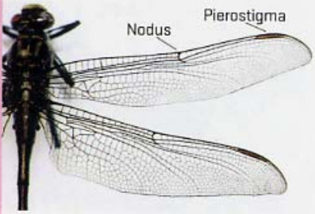
Dragonfly

Tom Wiscombe/EMERGENT, 2007

In this installation, dragonfly morphology and syntax are employed biomimetically, that is, in terms of formal and behavioral logics rather than pure aesthetics. Dragonfly wings are generated by evolutionary processes involving aerodynamics, lightness, mechanical properties, composite performance, the smooth accumulation of organic material, and the active flow of dragonfly blood. They consist of both honeycomb patterns, which are flexible and exhibit membrane behavior, and ladder-type patterns, which are stiff and exhibit beamlike behavior. *Dragonfly* is governed by a different set of parameters, including gravity and seismic loads, specific support locations and the quality of those supports, flat material increments, and buckling failure—differences that lead to an unpredictable hybrid morphology.

Dragonfly is a cooperative effort of EMERGENT and the innovative engineering firm Buro Happold. It is an experiment in the fluid feedback of design sensibility, engineering innovation, and fabrication logic in a contemporary digital environment wherein these disciplines become enmeshed like never before. This process redefines engineering—which is often about idealized problem solving and formal economy—as a messy evolutionary process closer to speciation in nature. Using boundary conditions relating to overall structural shape, individual cell morphology, vein distribution and pleating, depth, and incremental material thickness, the geometry was evolved simultaneously toward performance and wild variation.

1



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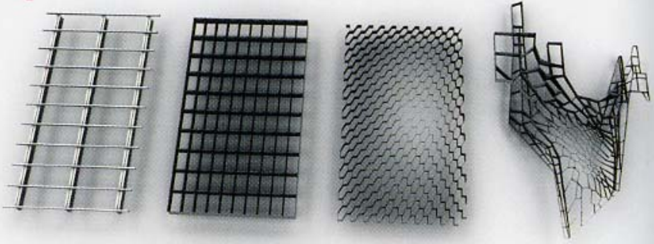

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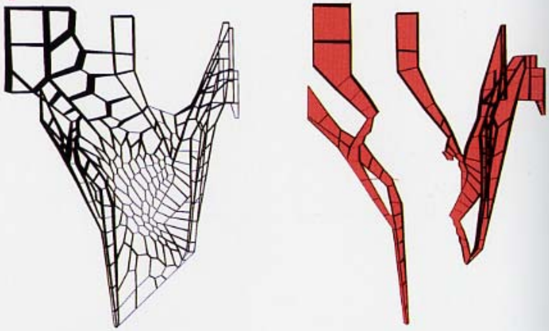
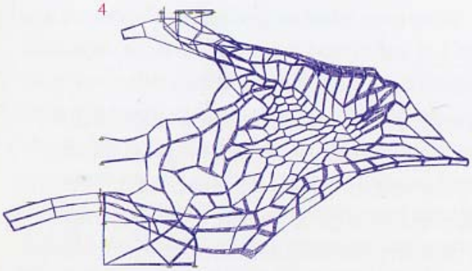


1 Dragonfly-wing structure.
2 Structural grid morphologies.
3 Final plan with projected continuous structural ribs.
4 Deformation analysis.
5 CATIA model.
6 Structural stress analysis.
7 Drawing of layered plates showing connection locations.

4



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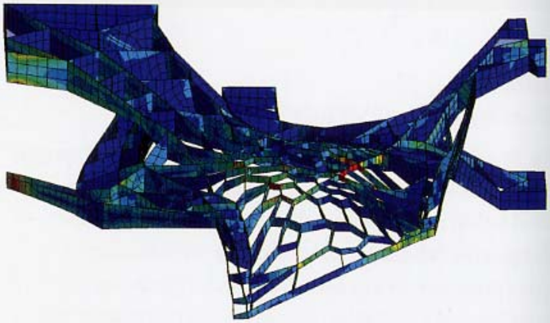

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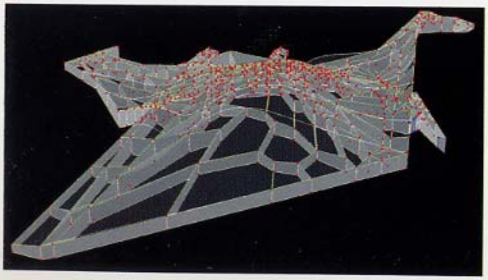

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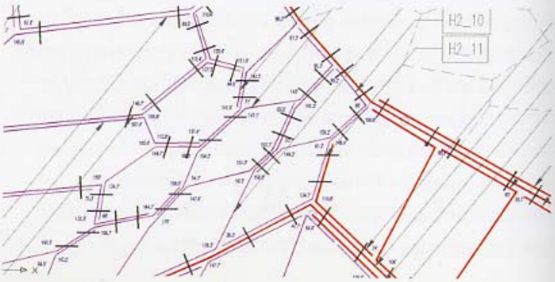

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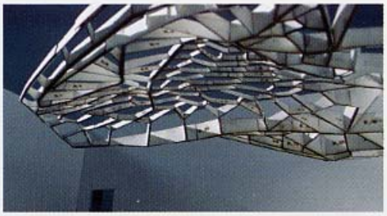

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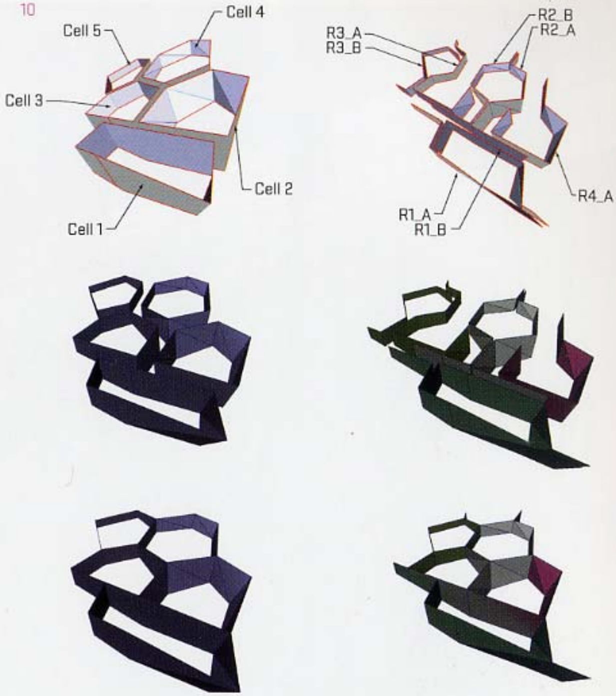
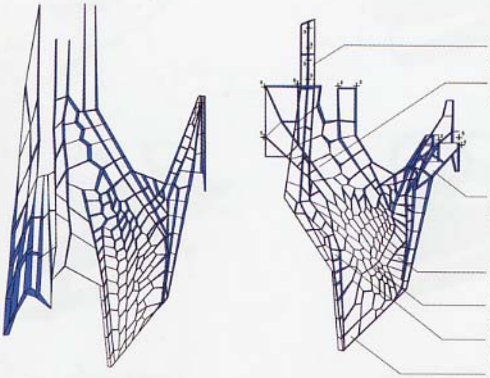


8 Laser-cut model.
9 CNC-routed ribs from aluminum plate for mock-up.
10 Digital model of test piece for mock-up.
11 Mock-up.
12 Assembly.

11

12



Vein aligns with existing steel of mezzanine and organizes into quad cells for stiffness.

Vein extends out of the honeycomb and connects to existing catwalk for stability.

Arm delaminates and pleats to connect to existing column and create beam action.

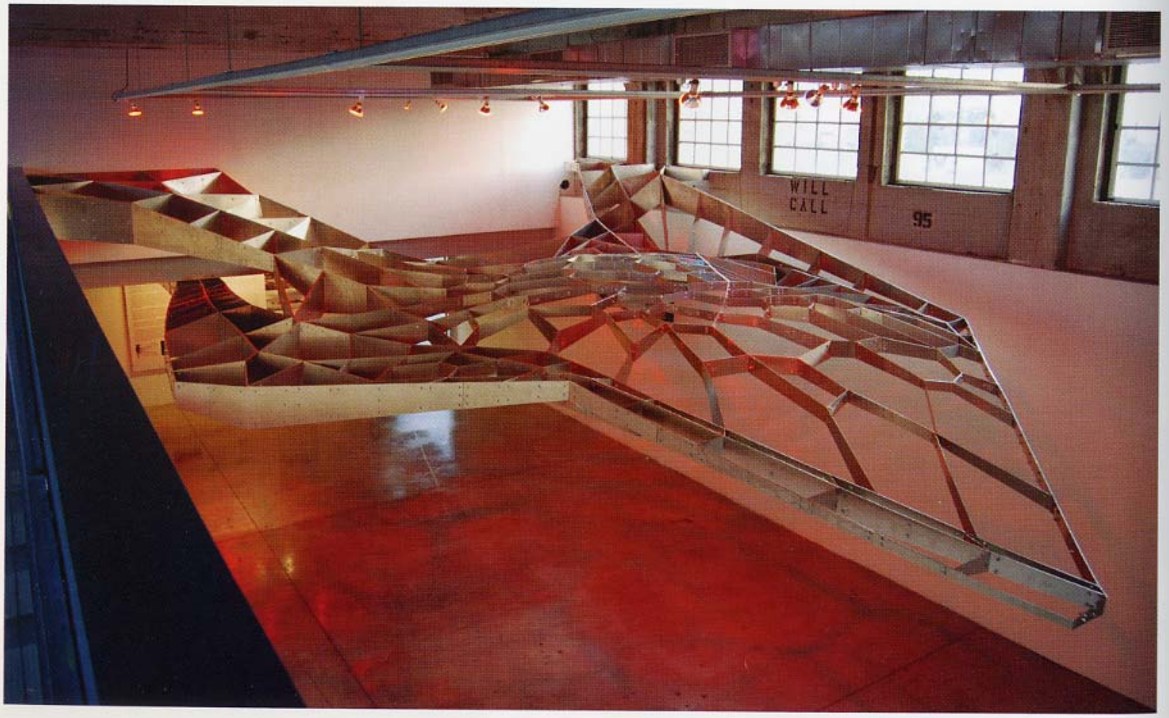
Vein splits and hybridizes with honeycomb in response to indeterminate condition.

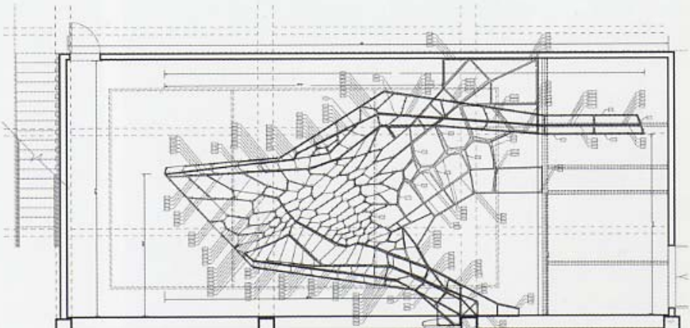
Vein emerges to create continuity through honeycomb.

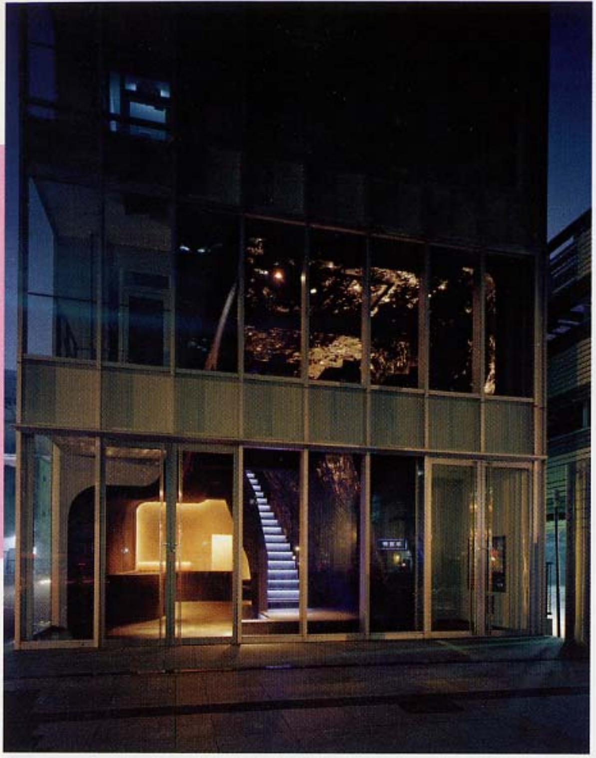
Vein emerges and pleats consolidating large loose cells into stiff beam.

Cells at end of cantilever begin to thin out to reduce material weight.

ABOVE: Plan view of structural morphology.
BELOW: Completed installation from above.
OPPOSITE ABOVE: Completed installation from below.
OPPOSITE BELOW: Plan.







All photos: DAICI ANO/FWD.INC.

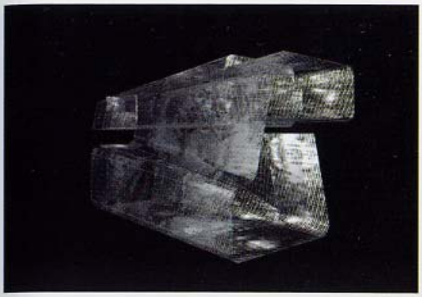
Aoba-tei
Atelier Hitoshi Abe, 2004

By inserting a wall of thin steel plates within the interior of a French restaurant in Sendai, Japan, Hitoshi Abe created for this project a soft boundary surface that spatially mediates between the first and second floors of the existing building. This soft boundary also links the inner space of the restaurant with the space defined by the famous roadside zelkova trees that symbolize the city of Sendai. Lights have been installed behind the inner wall, thereby pointillistically reconstructing the light and shade of the zelkova trees in the interior space.

The 2.3-millimeter-thick metal plates that constitute the inner wall were perforated by a numerically controlled turret with hundreds of thousands of variously sized holes. The pattern follows a digitized image of a zelkova tree that was decomposed and reassembled in Photoshop. Final adjustments to the graphic were done by hand by Atelier staff members. This process was done before the steel plates were folded into shape.

The inner wall is a monocoque structure that does not have any structural frames supporting it from behind. Therefore, the light passing through the graphic holes is not disrupted. Since there was no way to pierce graphic holes at the welded joint lines of the steel plates, the holes were marked again after assembly and welding and hand-drilled on-site.

The difficulty of welding complex shapes from thin steel plates within an existing building led to the use of shipbuilding technology for the actual manufacturing. Craftsmen who were highly experienced with the unique characteristics of steel plates were able to deform the steel freely by heating and chilling key points and thereby producing complex curved surfaces. The singular descriptive methods they used to translate a three-dimensional volume into two-dimensional surfaces were predicated on the manual craft techniques these experts used to make the curves.



ABOVE LEFT: Folded skin with perforations.
ABOVE RIGHT: Interior view.
BELOW LEFT: Unfolded skin with perforation pattern.
BELOW RIGHT: Detail of perforations.