Transparent Structures

Transparent Structures was a Design/Build course taught to two different groups of students from Stanford University, University of Tokyo, and Keio University during the spring and summer of 2015. This course asked students to investigate the use of glass as both a structural system and spatial medium. Following a methodology which we call Responsive Structures, students tested the physical and visual properties of engineered high-strength glass, and developed structural systems and spatial configurations to expand our ideas of what glass can do.

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This methodology encouraged the fluid, adaptive growth of the structures from cellular, module based models to a full scale installation. The spirit of play and investigation was realized through a series of exercises that began with small-scale modeling and the development of a structural module, which gradually grew into larger, more complex aggregations. The focus then shifted to larger scale prototyping and the refinement of the assembly tectonics, and ended with the full scale realization of the design. Through these steps, students gained a hands-on, immediate, and palpable understanding of the properties and behaviors of the glass. Visually, students explored how transparent and translucent surfaces could act as a perceptual filter, creating rich spatial experiences.

This paper will begin with a discussion of glass in its historic context, and then follow with a more detailed description of the pedagogical, structural, tectonic, experiential and spatial goals and results of the workshop. The intent was for students to test the range of spatial possibilities for specific structural combinations, and to then synthesize these findings into a singular installation.

GLASS AND THE DISAPPEARING FRAME

In 1914, German poet and writer Paul Scheerbart praised glass for its ability to transform the built environment and elevate culture through its openness and color. For him, the enclosing quality of conventional brick buildings imposed a separation between a person and society, resulting in isolation and darkness. He envisioned a new architectural world, in which light-filled spaces reconnected society, and boundaries between indoors and outdoors dissolved. A new, prismatic landscape would replace the dreary, masonry cityscapes of old Europe. Of course, this crystalline world relied on the liberation of the facade from its opaque, load-bearing function. So he described a two-part system in which iron framework is shaped to support the glass. Together, iron and glass could release buildings from an oppressive past and activate a new, free form environment and society.

As revealed in Scheerbart's descriptions, the non-structural properties of conventional glass confined its role to one of cladding and enclosure. Bruno Taut, in his celebrated glass pavilion design for the 1914 Deutscher Werkbund Exhibition in Cologne, created a prismatic dome which became a symbol for purity and openness. Although the pavilion was a milestone in the construction of glass architecture; when the structure is examined, the concrete columns at the base, and the steel diagrid frame at the cupola, figure more prominently than the glass. Earlier, Joseph Paxton's prefabricated components for the celebrated 1851 Crystal Palace, so revolutionary for its time, was realized mainly through the efficiency of its module-based iron skeleton. The glass, set within wooden frames, played a secondary, infill role in the building assembly. Despite the utopian associations carried by glass; by structural necessity, it has long remained an element which capitulates to the framework that supports it. Subsequent buildings realized by Le Corbusier and Mies, and most contemporary designers working today, continue this tradition.

These constraints, however, are breaking down with the advancement of glass technology which strives for the optimal combination of lightness, thinness and strength. Kenneth Frampton observes that "...our society has succeeded in producing glass of such different physical properties that it, as a substance, can no longer be regarded as a singular material having constant properties."[1] Indeed, technologies such as heat strengthened, thermally toughened, laminated, and/or chemically strengthened glass have come to obviate the need for glass to be hung from a structural framework because the glass itself becomes the structural framework. This has been demonstrated elegantly in projects by Peter Rice, James Carpenter, and Bohlin Cywinski Jackson.[2] As the structural capacity and behavior of glass evolves, so too can its application in practice.

At our installations, the primary materials we used were a combination of Leoflex and Dragontrail glass panels, manufactured and donated by Asahi Glass Company, which were sized from 12"x12" to 24"x24". A competitor of Gorilla Glass, both types of glass are commonly used as cover glass on cell phone displays. They are an alkali-aluminosilicate sheet glass, chemically strengthened and therefore much stronger and thinner than conventional soda lime-glass. Although they share the same material composition, the Dragontrail is slightly stronger because it is soaked longer in a salt bath, allowing a deeper ionic exchange between the silica ions. These panels were fastened together by a series of slender, bendable aluminum straps which are bolted onto the panels. Unlike conventional glass, these products are also ductile. The larger panels could flex up to 5" without breaking. The exceptional ductility, strength and lightweight nature of the panels presented a new set of design opportunities to us.

RESPONSIVE STRUCTURES METHODOLOGY

> "The informal' is opportunistic, an approach to design that seizes a local moment and makes something of it. Ignoring preconception or formal layering and repetitive rhythm, the informal keeps one guessing. Ideas are not based on principles of rigid hierarchy but on an intense exploration of the immediate. It is not ad hocism, which is collage, but a methodology of evolving start points that, by emergence, creates its own series of orders. —Cecil Balmond, "Informal"[3]

Responsive Structures is an methodology in which installations are developed to mine the structural, spatial, and experiential potential of a specific material. Inherent to the process is a spirit of flexibility and exploration as described by Cecil Balmond in his manifesto, "The Informal".[4] In the context of Design Build, structures and spaces are designed to be adaptive, mutable, and open to engaging the program, site, and human scale in a dynamic field of relationships. Specifically, structural design is used as a design catalyst, encouraging students to translate structural discovery into a tectonic language and new spatial experience. The exercises are sequenced such that students learn structural principles in an immediate and almost visceral way, because they physically experience the dynamics of their pieces through material testing, model making, prototyping, and building assembly. The process generally followed this trajectory:

MODELING

The modeling began at a cellular level and grows both in scale and in volume through an iterative process. Students began the model making session using 2"=1' scale polycarbonate sheets, which were sized to replicate the behavior of the larger glass panels; and small strips of tape to functions like the aluminum straps. Initially, students combined just a few panels in their models, but in varying configurations. As they found more stability and spatial potential in specific panel combinations, they created variations on these successes and eventually began to stack or hybridize their modules into larger assemblages. What began to emerge were specific patterns of assembly, often discovered by more than one student, which were then refined by testing the panel combinations with multiple variations.

This growth evolved in different ways at the two workshops. At Stanford, the students agreed to use a single, I-shaped module, which would be built at various angles and stacked to form of an axial vaulted passage. After the initial skeleton was built, students then reinforced the structure with panels which completed, in some cases, triangles of a polygonal truss structure. The I-shape was selected for its modularity and ability to be stacked, while still allowing for variation in depth and form.

1

Figure 1: Model Making Session

In Tokyo, students developed a few different modules and grew these nodes into more complex combinations. As students developed their ideas, distinct geometric and operational patterns began to emerge. These included stacked, polygonal, cantilevered, or arched geometries. Students then began to work together in groups, and were asked to merge their discoveries into specific elements such as a tower, arch or cantilever. Each group was forced to reconcile structural stability with spatial expression. The final model represented a hybrid structure of these various elements, merged to form a curved passage from the showroom entry.

TECTONIC DEVELOPMENT AND FUZZY NODES

A fastening and assembly system for the structure utilized aluminum straps to transfer the load from one glass panel to the next. Many of the glass panels included a ring of holes around the perimeter, spaced approximately every 6". Other panels had no holes. The holed straps were positioned on one or both sides of the glass panels and secured with a bolt and nut. The straps were fabricated in varying lengths to accommodate twisted or angled joinery. The panels without holes were clamped together using non-holed versions of the straps. These proved to be less versatile than the holed straps due to their shorter length, so students eventually decided to use only the holed straps so they could have more freedom in their form-making. Washers, separated from the glass by gaskets or glazing tape, helped spread the load from each strap onto a larger glass plane.

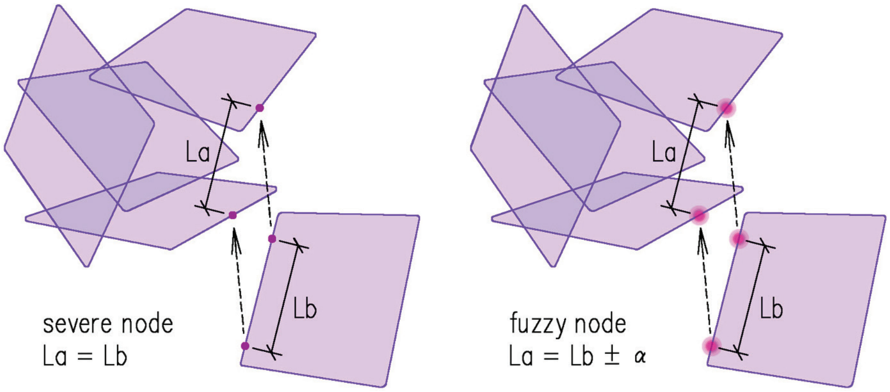
Eventually, the overall assemblage of panels began to exhibit rigidity. During the early part of the design process, it was difficult to envision such complex shapes. However, during construction, the location of panels was determined and fixed by aligning the holes in the respective panels, aided by the construction tolerance allowed by the adjustable strap system. That is, the straps could be bent or twisted to bridge the gap between the holes in adjacent panels.

In the structural analysis, some assumptions were made. The holes in the glass plates were interpreted as distinct nodes represented as dots, and the pair of holes in adjacent panels were assumed to occupy the same location. This flexible dot can be called a “fuzzy node”, as shown in Fig. 2a. In our analysis, we developed algorithms to develop the geometry of the overall form. This “fuzzy node” strap fastening is possible because the glass has notably high strength (6 to 8 times higher than conventional soda lime glass) and resistance against the bending stress, created by the gap between the center of the glass thickness and the center of the strap thickness (Fig. 2c). Also, the metal straps enhance the ductility of the overall structure. (Fig. 2b).

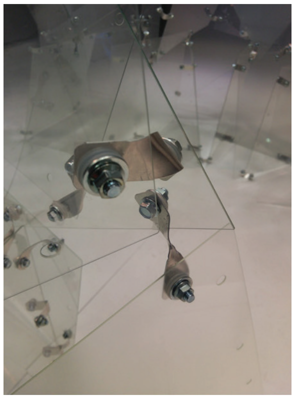
PROTOTYPING AND EXPERIMENTATION

With each iteration during prototyping, techniques and rules were developed and refined, resulting in a list of shared “best practices” which would ease and expedite the final build. One of the most important findings was the need to isolate metal from glass in all situations. Even a small amount of contact between the edge of the bolt and the edge of the opening in the 1.3 mm thick glass panel resulted in cracking. This led to a solution in which students wrapped tape around the threaded section of each bolt which would come in contact with the glass. (Fig. 2c)

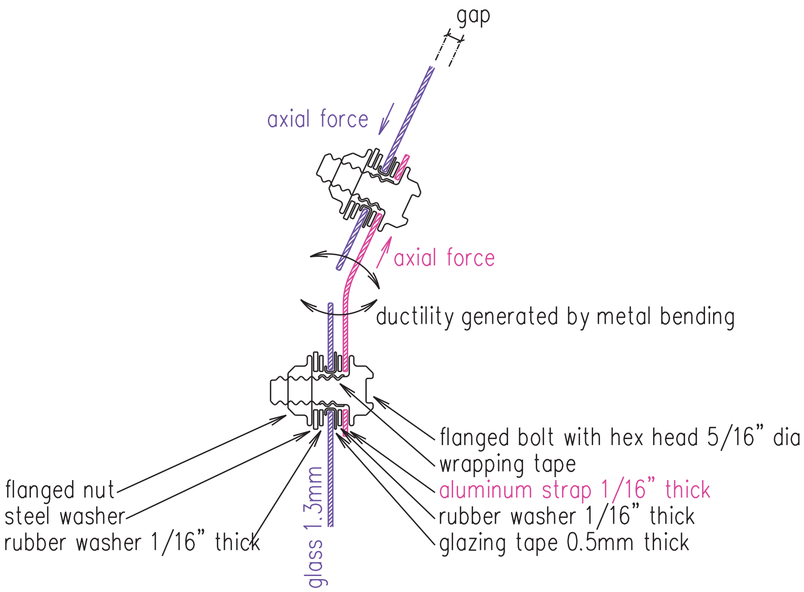
Once students began to stack and connect the modules, they were forced to confront the reality that the entire system had to withstand movement and increased loads. The assembly process required a certain amount of flexibility in order to align the straps with the pre-drilled holes in the glass. This would intensify once the structure had to resist wind loads. We changed the strap openings from round to slotted to provide a little more tolerance for the placement of the glass panels. Students found that a single layer of glazing tape was not



2a



2b



2c

Figure 2a:”Fuzzy node” assemblage

Figure 2b: Bent and twisted aluminum straps

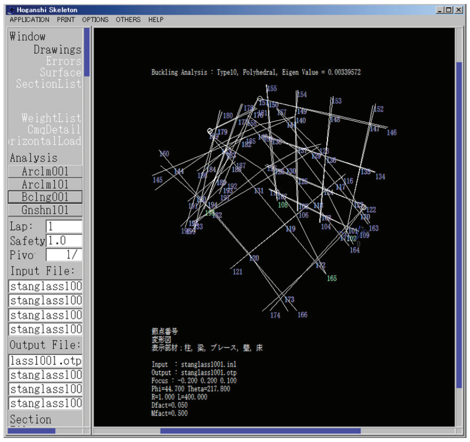
Figure 2c: Fastener assembly

enough to cushion the surface of the glass from the aluminum strap, so they used hose gaskets to create a thicker buffer. Additionally, students decided to use two panels sandwiched against each other, rather than one, at the ground layer of structure, to fortify the panels against the compressive loads from above.

The buckling strength was calculated using some prototype modules, one of which is shown in Fig. 3b. The buckling length, which can be calculated from the buckling strength, is helpful in envisioning the buckling phenomenon. We concluded that the glass panels could be assembled with a buckling length of 400mm when composing a triangulated matrix resembling a 3 dimensional truss, reciprocal compositions, or polyhedral shapes. Using this buckling strength, the safety ratio diagram shown in Fig. 3c was provided. This diagram indicates a safety ratio ranging from 0.0 to 1.0 by the gradation of blue (most stable), to green, yellow, and orange. When the safety ratio exceeds 1.0, elements appear red to announce that the element cannot resist the stress. By evaluating the diagram, the form of the entire system could be optimized by reducing the safety ratio. This diagram also enabled students to determine how the buckling length could be shortened through the addition of stiffener plates.

3a

3b



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Buckling Analysis : Type10, Polyhedral, Eigen Value = 0.00339572
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節点番号
変形図
表示部材：柱, 梁, ブレース, 壁, 床

Input  : stanglass1001.inl
Output : stanglass1001.otp
Focus : -0.200 0.200 0.100
Phi=44.700 Theta=217.800
R=1.000 L=400.000
Dfact=0.050
Mfact=0.500
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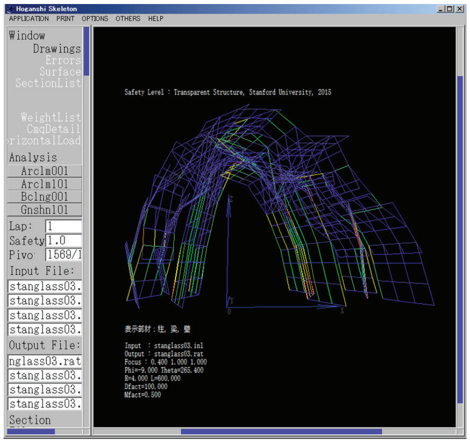
3c



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Safety Level : Transparent Structure, Stanford University, 2015
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表示部材：柱, 梁, 壁

Input  : stanglass03.inl
Output : stanglass03.rat
Focus : 0.400 1.000 1.000
Phi=-9.000 Theta=265.400
R=4.000 L=600.000
Dfact=100.000
Mfact=0.500
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Figure 3a: Prototype panel comprised of 3 panels

Figure 3b: Buckling analysis for a prototype panel

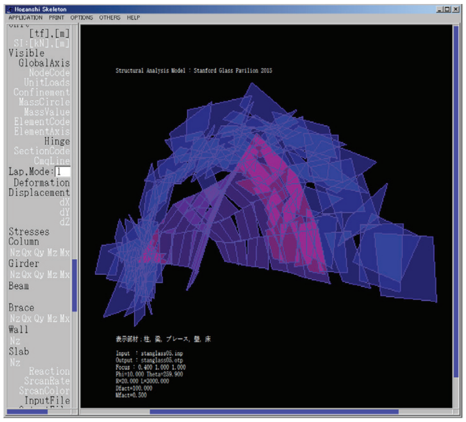
Figure 3c: Safety Ratio Diagram

Through the prototyping process, students approached the installation not as a static object, but as one which needed to accommodate movement, and could be reinforced to receive the loads of the layers of glass above. Quick decisions were made on site to strengthen weak connections. Students could feel the instability of a section of the installation, and were forced to analyze the construction and test a solution. Sometimes, this would entail the addition of a single panel to decrease buckling length, but other times, a series of panels were added to disperse or redirect the load path. Occasionally, panels were removed and reattached in order to solidify the structure. This testing and flexibility allowed students to maintain a sense of play, even at the large scale as the height of the structures approached 8’–9’.

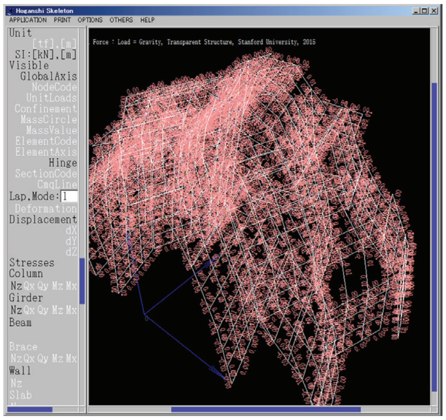
BUTTRESSED VAULT AND HYBRID STRUCTURE

At Stanford, students built a stacked arch, buttressed by two “arms” which extended from the top of the primary arch.

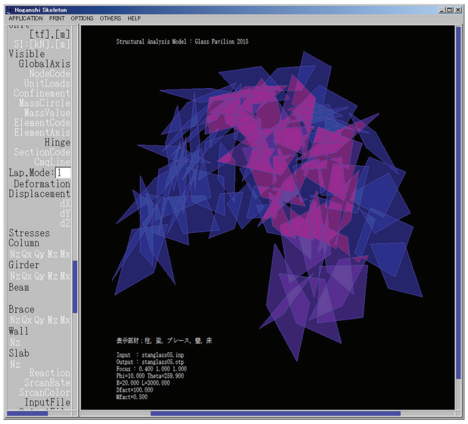
In Tokyo, the structural components were more varied, representing a hybrid of a tower, polygonal wall, arch, and cantilever within a single installation. From the static structural analysis, the axial force of the glass panels resulting from gravity and wind load was calculated. Fig.4a shows the a model of the whole shape at Stanford University. From this image, the structural analysis model shown in Fig. 4b was developed using bar elements. In this model each panel is indicated as grid plates, with each bar elements having sectional dimensions of 1.3mm x 200mm.



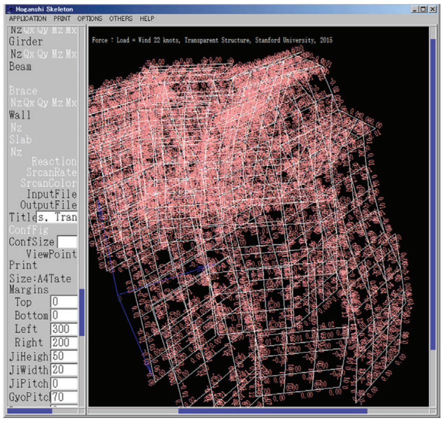
4a



4c



4b



4d

BUILD: MAINTAINING PLAY AT THE LARGE SCALE

The design build process departed from the standard of builders executing a prescribed design from a set of drawings. Our hope was that the habits of making and thinking formed during the initial loose model making would translate into the large scale. These skills became a structural necessity. As the full scale constructions grew to be more than 6' tall, the pieces became increasingly complex and in some ways, precarious.

At Stanford, the initial module-based design resembled a series stacked, polygonal units. However, after this skeleton was formed, reinforcing panels were attached to the outer layer to stiffen the structure. Lessons from model making, such as creating 3 dimensional trusses by attaching three panels, or reinforcing panels by overlapping them or tying them into the structure, established new load paths to distribute the weight more effectively. The aluminum straps became good visual markers, through which students could visually “connect the dots” to diagrammatically see how the loads were travelling.

SITING

Rather than approaching the passage as an isolated object, students were asked to situate the installations in a way that created a transition from one space to another. At Stanford, students chose to locate the passage at an oblique angle to the main east west axis through campus, an extension of Frederick Law Olmsted’s original master plan. This was angled to align with a well-used cross axis, but provided an alternate path which would alter their perception of the axial paths and the surrounding campus. Part of the Responsive Structures Methodology is to understand and analyze local conditions and alter the module system to respond to them.

Figure 4a: Modeling final forms for Stanford installation

Figure 4c: Axial force diagrams indicating gravity and wind loads for Stanford installation

Figure 4b: Modeling final forms for Tokyo installation

Figure 4d: Axial force diagrams indicating gravity and wind loads for Tokyo installation

The context in Tokyo contrasted with the formal greenery of the Stanford campus. The site was the showroom of the AGC company, located on the ground floor of a high rise, on a bustling corner of the Ginza district. Pedestrians pass this storefront throughout the day and night. Students oriented the curved passage toward the front entrance of the storefront, pulling visitors into the curved passage. The entrance of the passage featured more translucent panels, and faded to transparent as one approached the neck of the cantilevered end. The installation featured a central “tower” which supported the arched form which enclosed the passage. The experience of travelling through the installation became one of slowness and suspense.

TRANSPARENCIES AND THICKENED SPACE

The frameless tectonic of the glass modules establishes an uninterrupted dynamic visual field. No longer bound by the metal frames that tend to follow a regular grid, the module developed by the students created a layered “deep skin” rather than a singular membrane. We asked students to explore the potential of this new spatial organization. To ground the exploration, students read Robert Slutzky and Colin Rowe’s seminal essay “Transparency: Literal and Phenomenal”.[5] In this essay, the writers cite Bauhaus artist and theorist Gyorgy Kepes’s definition of the word: “Transparency, however, implies more than an optical characteristic, it implies a broader spatial order. Transparency means a simultaneous perception of different spatial locations. Space not only recedes but fluctuates in a continuous activity.”[6] Here, perception and experience, or the phenomenal aspects of transparency, elevate it from a simple material attribute to a complex interaction between elements.

Using modernist paintings as exemplars of Phenomenal Transparency, Slutzky and Rowe outline how artists such as Braque and Leger demonstrate this idea through the ambiguous and oscillating definitions of space on their canvases. They extend their concept to architectural design by discussing Le Corbusier’s Villa Garches. In the layering of glass and structure at the rear facade, they observe that “...Le Corbusier proposes the idea that, immediately behind his glazing, there lies a narrow slot of space traveling parallel to it; and, of course, in consequence of this, he implies a further idea that bounding this slot of space, and behind it, there lies a plane of which the ground floor, the free standing walls, and the inner reveals of the doors all form a part...”.[7]

A shared characteristic of the paintings and buildings used by Slutzky and Rowe was that of layering, whether it was on the compressed plane of the canvas, or rendering in 3 dimensions as a building. This principle of spatial layering, in combination with the varying translucency of the glass panels, enabled us to explore the surface of both installations beyond their physical boundaries. In Terence Riley’s introduction to “The Light Construction Reader”, he describes the potential of architecture surfaces to create “delay in architecture”, particularly in glass buildings which “hinder visual penetration, creating the greatest possible distance between the interior and exterior membranes.”[8] The slowing and blocking of light photons caused by the films/ acid etching, embed the surface of the installations with a simultaneous density and openness and creates a thickened spatial condition.

At Stanford, this began with a collage exercise, in which students assembled collages to explore the visual field created by their installation. Using a large scale photo of the site as a base image, students layered different transparencies of paper onto the image to explore compositions of the various panel types. Students decided to create bands of translucent panels which stretched over the arch diagonally. The arrangement of the panels was integral to the structural module, which was based roughly on an oblique “I” shape, in plan. Since the stacking of the modules relied on a very specific offsetting of modules, similar to a running bond brick pattern, the translucent panels followed the pattern by shifting with the modules. The four “courses” each features a shifting of the translucent panels, resulting in the stepped gradation of the bands.

At Stanford, the primary structure was shaped like a barrel vault, with buttresses that extended out to add both structural support and layers to the filter. Hence, the reinforcing structural element was integral to the resultant spatial and visual experience. The installation was illuminated by fluorescent tubes powered by a car battery. At night, turning on the lights reversed the visual effect of the glass. Previously reflective panels became transparent, while previously translucent panels appeared to materialize and project out of plane. This oscillation of the perceived space, in which different panels or spaces seemed to recede or project, was an advancement of phenomenal transparency made possible through this new tectonic. The mutability of the surfaces expands our definition of architecture from one which is permanent or massive, into one which straddles the line between the material and immaterial. Space is not defined by an absolute boundary or surface, but exists as a fluctuating zone which forms a kind of thickened space.

5a

5b

5c

5d

At Tokyo, our palette of glass was limited to two types: transparent and acid etched. Students chose to create a gradient from one end of the passage to the other: a transformation from relatively closed to mostly open and transparent. While the specific locations of transparent vs. translucent panels were ostensibly more random than the Stanford installation, the overall transition was clear. Experientially, sequence and duration became important, as the passage represented both a perceptual and physical transition from a more defined, close state, to a more open, expansive one. The viewer thus experiences a state of suspension as he/she discovers the curved space of the installation, while the surrounding city is revealed through this mutable skin.

The transparent and translucent surfaces used in these installations act as a perceptual filter, creating complex spatial experiences. Antoine Picon, in his essay Glass at the Limits",

Figure 5a and 5b: Stanford installation and detail

Figure 5c and 5d: Tokyo installation progress and final form posits that “transparency is as much about concealing as it is about revealing. To be more precise, transparency is now associated with filtering. It is not longer a passive quality; it represents a proactive behavior that is inseparable from energy and information based consideration...Glass no longer encloses but acts as a mediating skin between society and the natural world.”[9] Indeed, the impact of the glass tectonic is not confined to light: it also has the potential to regulate the passage of heat, sound, air; and in the spirit of Scheerbart, an exchange between people and society.

RESPONSIVE STRUCTURES: A NEW MODEL FOR SPATIO-STRUCTURAL THINKING

The Responsive Structures methodology synthesizes structural, spatial and visual design processes; and through its hands-on approach at a range of scales, fosters adaptive and investigative attitudes toward design. It elicits an open-ended examination of the structural and geometrical capacity of a material. At our installations, we were able to investigate the relationship between surface and structure and discover new types of space. The frameless glass structures established a thickened space which rendered a nuanced play of transparency, translucency, shadow and light. By encouraging hands-on play to explore the potentials of our material, students learned how the structural dynamics of the material could drive the growth and organic development of the design. This methodology encouraged a more holistic approach to design while also charting new architectural territory.

ENDNOTES

1. Kenneth Frampton, “Is Glass Still Glass?”, from *Engineered Transparency*, Bell and Kim, editors, Princeton Architectural Press, 2009, p. 88.
2. See La Pyramide Inversee, engineered by Peter Rice, Apple Flagship Store on 5th Avenue by BCJ
3. Cecil Balmond, Informal, Prestel, 2007, pp. 220-221.
4. Ibid.
5. Colin Rowe & Robert Slutsky, Transparency: Literal and Phenomenal, Part I, Perspecta, 1936, reprinted in *Transparenz*, B. Hoesli, ed., Birkhauser, Basel, 1968.
6. Ibid.
7. Ibid.
8. Terence Riley, Introduction, *Light Construction Reader*, Jeffrey Kipnis, Monacelli Press, 2002.

8. Antoine Picon, Glass at the Limits, from *Engineered Transparency*, Bell and Kim, editors, Princeton Architectural Press, 2009, p. 70.