

Digital Mockup: Steps into the definition of a Friction-Joined System for a Responsive ETFE Façade for Highrise Buildings

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Abstract

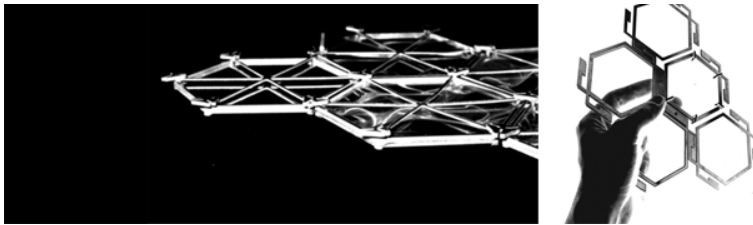


Figure 0. Waterjet Cut models of two Façade Systems

The inclusion of technological devices in the built environment may eventually have a profound influence on architecture and may lead to new design philosophies that solve tectonically the dialogue between traditional materials and computer networks; this document describes an exploration on a façade system that articulates distributed network computing and flat-cut, friction-joined architectural elements in order to improve the energy-efficiency, flexibility, and visual quality of a high rise building. The exploration takes advantage of the material properties of ETFE foil and of the processing capabilities of a micro-computer unit network in order to propose a new kind of implementation of electrochromic smart windows that allows for changing opacities of the façade elements in response to human touch.

An investigation on design tools and the role of physical representation in the design process itself, the work described in this document was developed using a variety of rapid prototyping tools and CAD software. Physical prototypes and plans of two different designs for the system are presented and discussed, followed by a 1in = 25ft scale physical representation of a larger implementation of one of the details along a verisimilar high rise building. The varied range of representations allowed for a critical evaluation of both systems at different levels, contributing to the understanding of the constraints inherent to two-dimensional friction joint assemblies, and revealing problems related to detail representation in rapid prototyping models.

While providing a review on electrochromic smart windows and distributed network computing technologies we outline the fundamental principles of a new system that uses ETFE cushions instead of glass as the base for touch-responsive electrochromic smart windows; the study presented in this document proposes a series of discussion points around the use of combined physical and virtual representation strategies in architectural design.

1 Introduction

Façade systems are to a great extent responsible for both the energy-performance and overall aesthetic qualities of a building. ETFE cushions have been largely used by architects since the 1980s as an alternative to glass because of their similar transparency, higher thermal isolation properties, and energy- and cost-efficient assembly and production processes (Robinson-Gayle 2001). Architectural applications of this material are in most cases roofs for large atria and other big-scale spaces, showing ETFE cushions to be a viable alternative to traditional glazing.

In recent years architectural thinking has been concerned with the pervasive presence of electronic devices and information networks as important components of urban space. This concern has led many architects to see the overlaying of digital technologies on buildings as a relevant design problem, and thus some have begun to seek for a deeper understanding of these technologies in order to integrate them within architectural practice (Manovich 2000). Recent works of architecture such as the *Prada Store* by Rem Koolhaas, *Jumpcuts* by Diller + Scofidio (Figure 1), and *NYSE Trade Floor* by Asymptote Architecture (Figure 2) strive for an aesthetic integration of communication networks and electronic displays within their buildings. This integration between physical space and electronic media, however, occurs only on at the surface level, as these projects use electronic devices merely as *digital fixtures* that are superimposed on a traditional architectural structure. This study examines the *tectonic* integration between computer networks and architecture through the application of ETFE cushions on the façade of a high-rise building, exploiting the soft nature of this material in order to embed an electronic network that provides functionality and touch-responsiveness in the façade.

As a first step, an architectural reading of Renzo Piano Workshop's *New York Times Headquarters* provides us with some of the main arguments that give form to our system; second, we present the design and further evaluation of two different friction-joined systems developed using different software and fabrication techniques; third, the implementation of one of these systems in a larger scale model within a verosimilar architectural context. Parallel to these, a basic review of MCU technology and of the smart windows technology allows us to assess the technical feasibility of the system. The final sections examine the generality of the results and suggest some discussion points on the implications of the work regarding two aspects:

- The touch-responsive electrochromic smart pillows as integrated elements of a high-rise building. This issue can be reduced to the following questions: a) Does the inclusion of a network of computers inform the design process with new variables and considerations? b) What are the implications of using ETFE on high-rise buildings? And c) Is it actually possible to create a touch-responsive smart ETFE pillow?
- A critical view of the design process as related to the different software and rapid prototyping tools used. This issue can be summarized in the following questions: a) How does the problem of scaling for digital fabrication affect the design process? and b) What were the major implications of using a parametric software package in

the development one of the designs and a more “traditional” CAD system in the other?

The goal of this document is to shed light on to these questions.

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Figure 2. Diller + Scofidio’s Jump Cuts in Venice California

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Figure 3. Asymptote Architecture’s New York Stock Exchange Floor, from <http://www.asymptote.net>

2 Piano Lessons

We identified some of Piano’s building most relevant attributes in terms of the visual aspects of the façade solution:

- Horizontality
- Color quality (related to thermal performance)
- Transparency

And some technical attributes as well:

- Light – Heat Performance
- Standardized small scale components

Here are some of the design considerations and learned lessons from Piano’s façade.

- The changing distance between rods throughout the façade produces a global-scale variation on the façade of the building (Figure 3). Preserving this dialogue between the local and the global conditions of the façade became one of the guiding principles of the proposal.

- The appeal of the rods as an architectural solution in Piano's building comes not only from the fact that they provide rhythm and other aesthetic qualities, but also in their creating a continuous shadow to the interior space (Figure 4). This rich solution, valuable both aesthetically and technically, is one of the great lessons of Piano's building. It is an interesting and ambitious design challenge to re-create these elements in a different key.
- Several comments by long-time employees of the New York Times have indicated that lack of variation has negatively impacted the new building's work environment as compared to the previous building (Figure 5). We decided that the driving force of our proposal is to allow for as much flexibility as the available technology can provide. Our idea of maximum flexibility consists in allowing the façade to generate different lighting conditions on the interior of the building by changing the opacity of the cushions in response to human contact.

From our reading of Renzo Piano's *New York Times Headquarters* we discuss and pose two questions: a) Can a traditionally modern architectural feature like a *brise-soleil* be reinterpreted by means of new materials and computer networks? And b) Can we design a tactile, responsive façade that changes its properties according to the desire of the users of the space while being capable of having an autonomous global behaviour?

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Figure 3. Change of density on Piano's NYTHQ façade



Figure 4. Horizontal rods providing shadow



Figure 5. Homogeneity of interior space

3 Design of the Systems

3.1 *Bottom to Top*

After adopting general guidelines on the overall geometric aspects of the façade, the first explorations on the design started at detail scale, solving the structural node of a hexagonal façade pattern. The first designs of this node included a space for hosting the MCU (Micro-Computer-Unit) and some considerations on energy transmission and cables (Figures 6-8). As will become clear below, the development of the design at this scale stopped as the representations became more and more general.

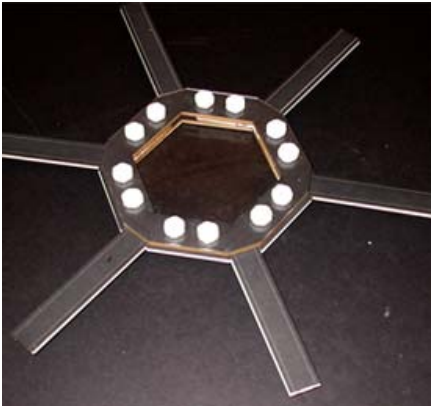
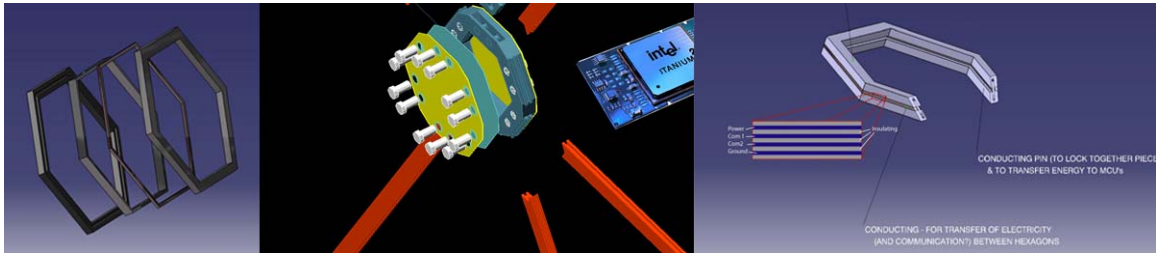


Figure 9. 1:1 Lasercut plexiglas and cardboard model of the façade element's node



Figures 6, 7 and 8. Insights into how the micro computer network becomes an architectural component

Two façade systems for ETFE foil pillows were developed to explore the architectural possibilities within flat-cut fabrication. Both are comprised of parts intended to be fabricated uniquely with two-dimensional (“flat-cut”) CNC machining techniques, assembled without bolts, nails, or glue, and that allow for the integration of micro-computer unit networking. Both systems also re-interpret existing praxis in large scale architectural and engineering design through the constraints of flat-cut fabrication technologies and friction joining. Rather than a limitation, however, these constraints become the driving mechanism in the design of the systems, as typical building components are re-designed into engineered parts for a far more precise system of assembly.

Yet, these two systems differ both in concept and in terms of assembly, and the resulting aesthetic is unequivocally affected by these differences. The following pages describe the two different approaches to the technical façade system, and an evaluation of both from the architectural standpoint, and from the perspective of critical evaluators of the implemented design procedures and tools.

3.2 System A



Figures 9. 3d image of System A

The standard steel node is here stripped of the majority of its mass, replacing size for geometry: the node first caps the diagonal members, then the hexagons, allowing for a single, optimized assembly. Completing the system, and where necessary tying the façade back to

the floor slabs, the transversal elements are finally inserted into pre-machined slots, the geometry of which is designed to allow for only the intended positioning of each member.

Thus, while this system shares both the sandwiching tectonic and perpendicular puncture (the transversal elements can be seen as a custom engineered friction bolts in a steel-frame assembly), precision of fabrication and assembly afford freedom from on-site drilling and welding, yet still allow for on-site assembly, reducing transportation costs and allowing for the assimilation of the organizational infrastructure already in place within the construction industry.

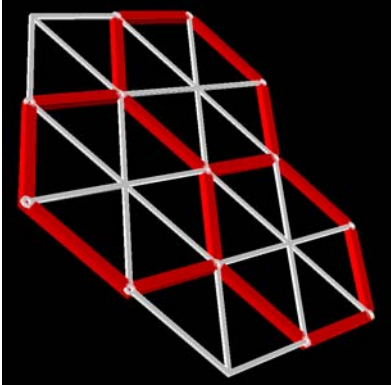


Figure 10. Early stages of the design

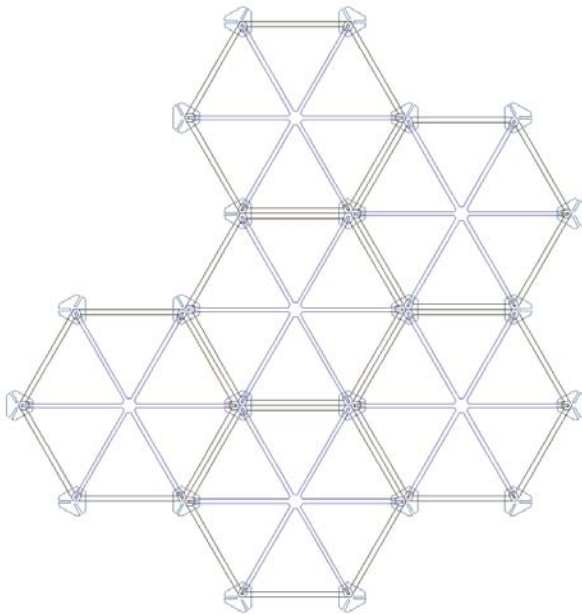


Figure 11. Image showing an arrangement of several façade hexagons

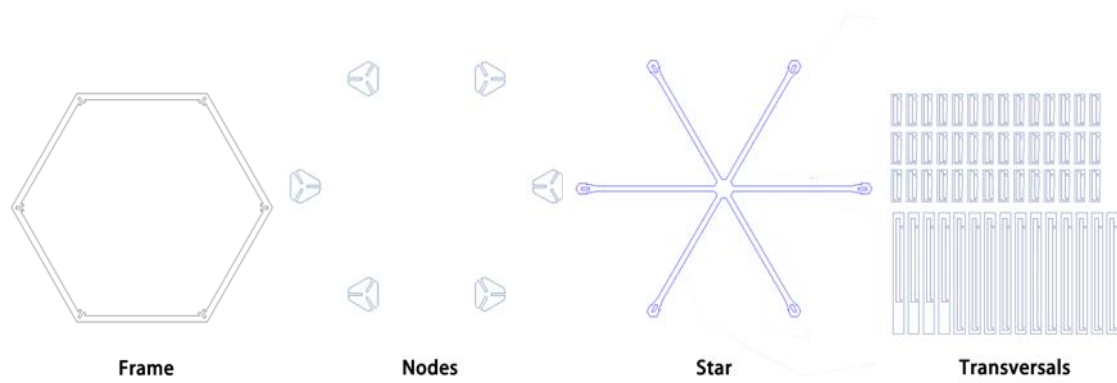


Figure 12. Pieces ready for WaterJet cutting

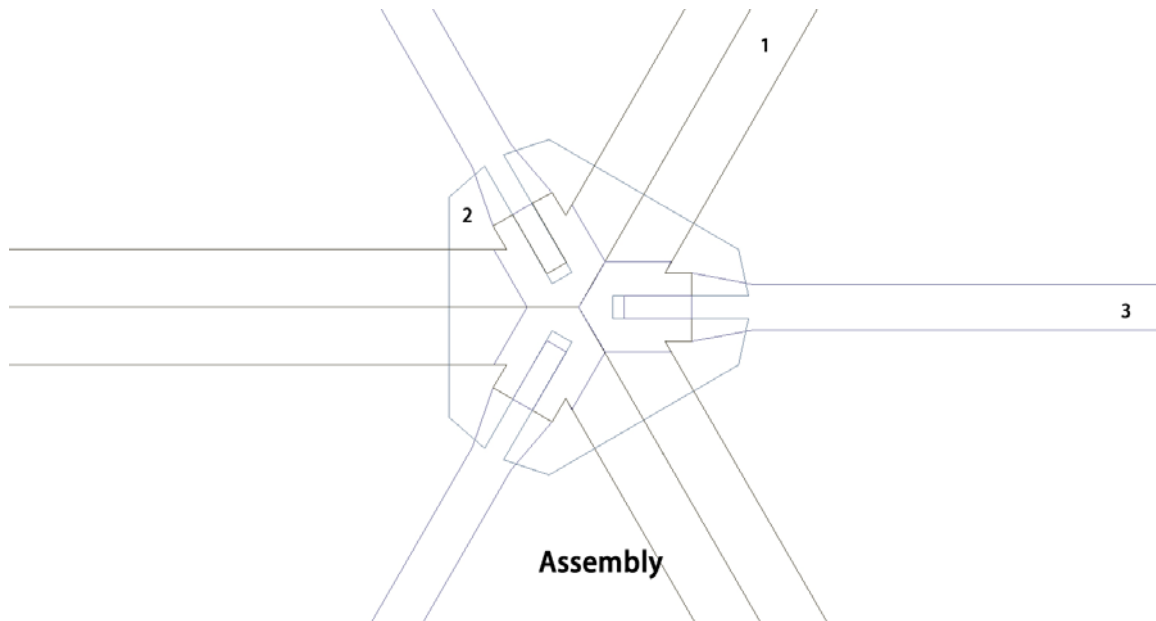


Figure 13. Detail of the assembly

- 1) Frame
- 2) Node
- 3) Star
- 4) Transversals

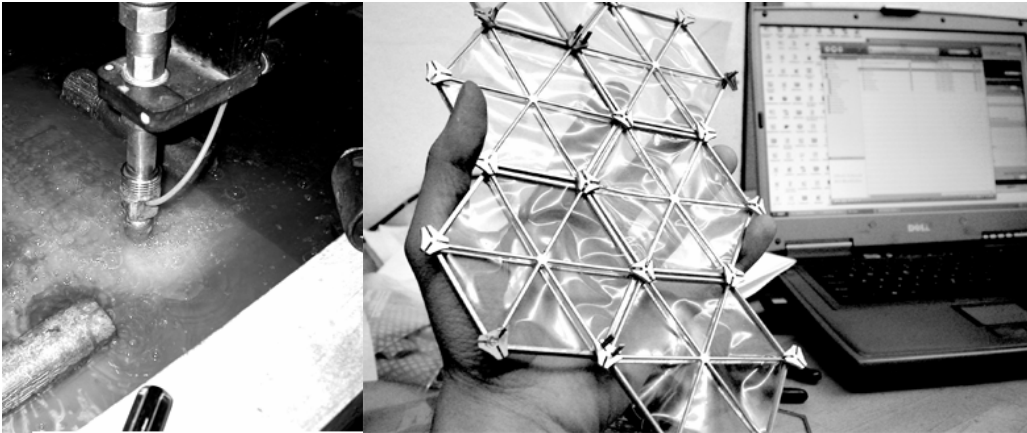


Figure 14. Waterjet cut model with plastic cushions representing ETFE

3.3 System B

The second system takes its precedence from techniques normally bound within much smaller scales: the assembly systems of the plastics industry. This provides both new potentials as well as many questions regarding the feasibility of these systems at both an architectural scale and within the extant infrastructure of the building industry. The two major differences are an almost completely flat (parallel to the façade surface) assembly and the adoption of “snap joints” within this assembly. Conceptually and geometrically, the entire system becomes a joint at multiple scales, with the addition of each part within the assembly performing both an engineered task as well as at least one additional secondary structural task that contributes to the performance of the system on the whole. However, as parts are designed to perform an increasing number of tasks, issues with potentially conflicting tolerances and material properties are fore-grounded, exacerbated concerns associated with the enormous leap in scale from proto-type to building, a problem without an analogue in the plastics industry.

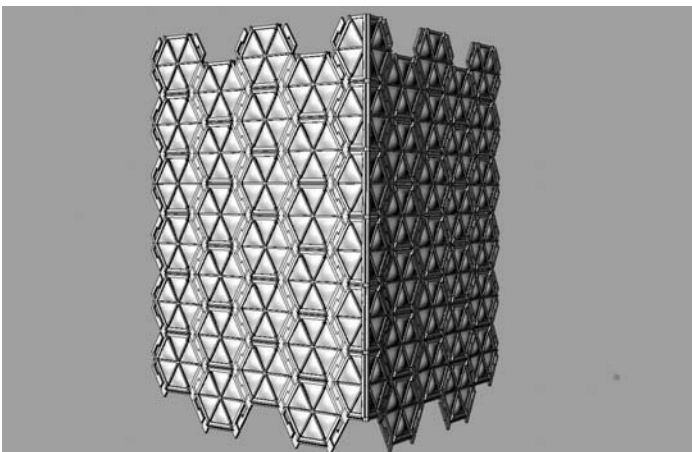


Figure 15. A 3d image of the system

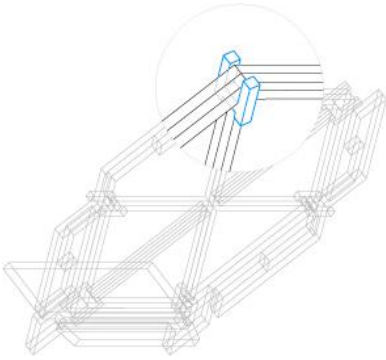


Figure 16 . Detail of the H Clip

The H-shaped Clip performs a three-fold function. It clamps the two hexagon parts together, sandwiching the two layers of each triangular ETFE foil pillow. Similarly, it clamps the diagonal members within the hexagon, thus allowing them to secure the other sides of each ETFE pillow. Finally, when assembled with these diagonal members, the clamps act as a secondary support against lateral forces in between adjacent hexagon assemblies, bolstering the friction joint system.

While relatively simple in form, the H-shaped Clip exemplifies the one of the primary goals of the façade assembly: multifarious functionality. While performing very specific engineered tasks, coalescence of the assembly surrounding the clip achieves greater strength than the sum of its parts, as the compressive force of the inserted diagonals maintains constant pressure on the clips, preventing their slippage towards the center of the hexagon (which would mitigate their efficacy as a secondary lateral support in the entire façade assembly). The form of the hexagon, which counter-balances the centrifugal force of the diagonals, inversely aids in securing the diagonals in place under windy conditions, which might otherwise surpass the point of failure in a purely friction-based joint. Further, the form of the hexagon may allow for an “elastic-fit” assembly, where the process of inserting the diagonal member is the result of a slight deformation in the hexagon part. Such an ideal situation, analogous to many typical assemblies in the plastics industry, would increase the strength of the hexagon system by maintaining an even greater constant of bilateral forces between parts.

The H-shaped Clip does however present certain questions. As it requires a tensile and compressive displacement of the hexagon and diagonal members, the scalability of this operation to full, construction scale remains to be tested. Further, the insertion of the diagonals into the clips (after they are in place on the hexagons) depends on a “snap-together” system: the diagonal piece is held parallel to the hexagon and “pressed” straight into place by one or two people, effectively “snapping” the piece into place. If it is found that the required elastic displacement necessary for this operation to be successful is not possible at full scale, the H-shaped Clip would require a modification whereby the inner “legs” of the clips are reduced in length to abate the required force for the assembly to occur. Else, the diagonal members can be redesigned as multiple pieces, rather than one star-shaped form.

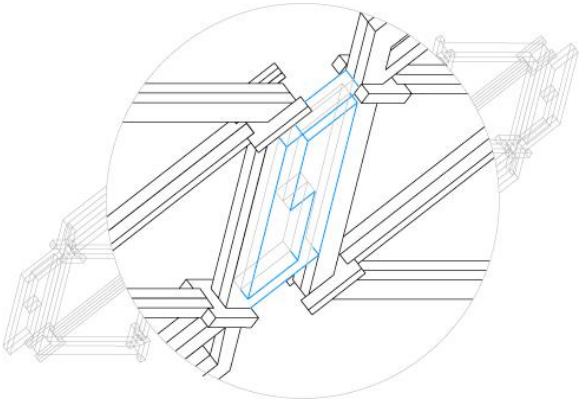


Figure 17. Detail of the ZigZag Joint

This connection drew most heavily from a the re-interpretation of plastic assembly systems for end-users, such as in model cars, remote controls, and plaster containers, while the specific geometry was developed through a series of tested laser-cut prototypes together with a parametric model that was altered in a reiterative fashion based on prototype performance. The goal was to develop a joining system that would be transparent in its on-site assembly method, physically easy to assemble, and structurally secure both as a hung curtain wall or in compression under its own weight. The specific angles chosen were developed with the idea of maximizing the joint's resistance to torsion caused by lateral forces on the façade. Thus, through geometry, assembly and structural dexterity is “built into” the system.

Further questions to explore are: How can the amount of material usage necessitated by the joint be minimized? What is the minimum amount of material, and where, that can be used while maintaining satisfactory structural performance? What tolerances, at full scale, are involved in the dimensioning of the joint for construction? Can other forms of very different “styles” be developed with comparable performance? How can more overall flexibility at all points, from design to disassembly, be afforded by the system with, perhaps, new forms?

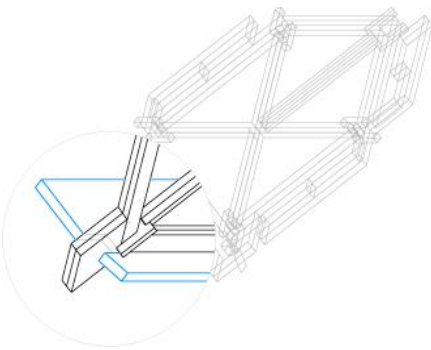


Figure 18. Detail of the Floorplate connection

The specific design of the Floor Plate Connection part (which attaches the façade to the building) was developed in response to the geometric constraints of the hexagonal system, the desire to maximize flexibility in patterning the system vis-à-vis the floor plates, and in an attempt to prevent a cacophony in the juxtapositioning of the hexagon upon the floor-plate

grid. The Floor Plate Connection is essentially built into the slabs at pre-determined positions throughout the façade, however these positions need not be regularized within a standard grid. Minimizing the interface of the floor slabs to the façade, each floor plate can be tapered on the façade ends to minimize their visual presence. Further, the façade can be placed at a certain distance from the slabs, leaving room for mechanical systems and/or maintenance workspace. Both tapering the floor plates and distancing the façade from the slabs further acts to reduce the visual presence of the slab grid on the façade, allowing for greater aesthetic flexibility in hexagon scales and patterning.

Localizing and de-standardizing the points of connection between the light-weight façade system and the floor slabs provides another means of flexibility: each hexagon does not need to be attached independently to the floor plates, as long as a sufficient number of surrounding hexagons on the same plane are mechanically attached via this detail. Thus the façade reaches a greater independence from the, typically, highly standardized and regular patterning of the floor-plates, where only those hexagons whose position coincides with the floor slabs are attached. It is important to note that in the example of the hexagon in particular, this is especially helpful when trying to negotiate hexagons sizes, visibility, patterning, and geometric consonance (e.g. a hexagon not appearing to “cut” in two at an awkward location by a floor slab).

Each hexagon attaches to the floor plates via the Arrow-Shaped piece and this connection part (where a connection to the floor plate is not made, the Arrow-Shaped piece simply does not have a slot for the connection piece). Similar to the assembly of the diagonal piece to the H-Shaped clip, the connection piece is “snapped” into the Arrow-Shaped piece, facilitated by the chamfering of the male piece, which gradually increases friction on its counterpart. This allows those mounting the façade pieces to the floor slabs to achieve a certain amount of inertia in the force that is being applied to the female piece to “snap” it into place.

This connection raises similar questions to the H-shaped clip: Can a “snapping” joint be achieved at full scale? How much material displacement can be expected given the maximum amount of force that can be asserted in the assembly process? What new assembly tools or processes might a system such as this one require or bring forth?



Figure 19. Waterjet cut model of System II with plastic cushions representing ETFE

3.4 Comparative Evaluation

Table 1 shows how the systems Type I and II compare in quantitative terms, and it shows data relating both to the technical performance of the joints (e.g. quantity of materials used, percentage of transparency, number of degrees of freedom per component) and to the design process and the performance of utilized tools (e.g. time invested in modeling and time invested in assembly) This comparison helps us to evaluate both aspects proposed by this study: as a technical proposal for a façade and as an inquiry into design methods and tools. It also allows us to determine objectively the issues involved in previous decision-making, therefore rendering conscious intuitive decisions made during the development of the design.

Table 1: Quantitative Comparison of both Systems

	System Type I	System Type II
Total Number of Part per Component	16	12
Total Number of Unique Parts per Component	5	4
Total Degrees of Freedom per Component	6	1
Total Volume of Material per Component (ft ³)	6.51	17.0
Number of Components Vertically Per Floor	1	1
Percentage of Visibility Per Component	81	50
Maximum Dimension of Component (feet)	10	10
Maximum Size Part (feet)	8.5	8.5
Maximum Size Part (by Volume (ft ³))	2.2	3.9
Minimum Size Part (inches)	6	11
Time to model	4	6
Time to Assemble Aluminium Prototype (hrs)	4	7
Software used	AUTOCAD	CATIA

The following table shows some of the major advantages and disadvantages found in both systems, summarizes the data found in Table 1, and shows the factors that weighed on our decision to privilege System II over System I. Two factors weighed most heavily on this decision: a) The smaller number of parts required for the assembly of System II, and b) The fact that there were more geometric constraints securing the elements of that system. In other words, an easier construction process due to a smaller number of parts, and structural stability, due to a larger number of geometrical constraints, were privileged as selection criteria over economy of material, transparency, and clarity of ETFE foil attachment. From the perspective of the design process, there were significant differences in time and difficulty of assembly between both systems, one of possible reasons being the fact that building the parametric model was more time consuming than the *traditional* CAD drawing for fabrication, and another that the assembly process of the model built with CATIA was much more difficult and time consuming due to the type of joint. Some more insights into the reasons and implications of these differences will be discussed in the final section.

Table 2: Summary of the Advantages and Disadvantages of both systems

	System Type I	System Type II
Major Advantages	More Transparency "Lighter" Façade Aesthetic Clearer Attachment to MCUs and ETFE Foil Less material used	Multi-Functional, Part-to-Whole Relationship More constrained (structural strength) Clarity of Fabrication Logic Smaller number of parts
Major Disadvantages	Larger number of Parts Less Constrained More Complex Fabrication Logic	Constrained to Planar Geometry Less Transparency in Façade Complexity of Tolerancing More Material required

When the two systems are compared, certain major performance differences become lucid. The most immediately recognizable difference is aesthetic. The first system generates an aesthetically light and thin façade structure, where the system itself becomes almost invisible within the context of the ETFE cushions. The second façade, by comparison, looks aesthetically much heavier, as it gives a more dominant aesthetic presence to the opaque elements of the system. While such a difference does not allow for a quantitative judgment on their relative merits, it does demonstrate that multiple, highly differing aesthetic results can be achieved within the paradigm of flat-cut, friction-joined construction systems.

Nonetheless the formal aspects of these two systems do yield performance differences with regards to transparency. The second system generates a façade with only fifty percent visibility, as half of the surface area is occluded by the metal assembly. This affects not only views from within the building, but also the amount of solar lighting and heat gain that can permeate the façade. Depending on the geographical location of the final structure, an objective judgment of the relative performance of the two systems is easily quantifiable. However, at the two hypothetical sites explored in this study (New York City and Cambridge, MA) the first, more solar-permeable façade system would be better choice with regards to climate and light.

Moreover, System II does use almost three hundred percent more material than System I, which must be considered an important variable in the decision to use this specific configuration. Somewhat paradoxically, however, the first, lighter façade is composed of a larger number of parts per hexagonal component (sixteen parts as compared to twelve in the second system). This was considered a disadvantage in assembly, as it requires more steps, increasing the potential for error in the construction process.

Further, water-jet cut aluminium prototypes of both systems revealed multiple issues of tolerance and difficulty of assembly, necessitating certain modifications prior to the applicability of these systems at architectural scale. However, while the first assembly does contain parts equaling the largest parts in the second, the prototype for System II was more

difficult to assemble, which if left unrevised would imply a proportionally larger assembly team per hexagon. Ease of assembly and the ideal of a “one-person plug-and-play” assembly can thus only be achieved after a certain amount of redesign. Difficulties in assembling the second system were more severe than those in the first, evidenced by the assembly times of the aluminium prototypes: the first system taking four hours to assemble as compared to the second, which took seven hours. Even at prototype scale, the tolerances involved in tying together the assembly with less parts performing more functions, and the use of snap-together joints requiring a relatively large amount of force during assembly, makes the system, as presently design and with existing tools and methods, nearly impossible to be assembled quickly and efficiently.

4 Processing Architecture

4.1 Electrochromic Smart Windows Technology

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Figure 20. A diagram showing a typical Electrochromic Device (C.G. Granqvist 1998)

Electrochromic Windows, also called Smart Windows, change their optical properties (transmittance and reflection) in a reversible manner when voltage is applied and a current flows through them (Heusing 2005). The material responsible for transmitting this charge needs to have thermochromic or electrochromic properties, that is, sensible to temperature or electrical charge variations (Lamper and Granqvist 1990). Most of the smart windows applications rely on a thin layer of electrochromic material, generally composed of the oxides of certain metals. The variation of radiation throughput is given by reversible shuttling of electrons and charge ions between this electrochromic thin film and a transparent counter electrode (Figure 20) (Granqvist 1998).

This technology has the potential for several different applications because of the visual variation it provides, as well as its energy-efficiency. It's calculated that in a regular building 50% of the energy enters when there's no one to look through the window. This estimate yields that by adopting smart window energy control strategies 170 kWh/m² of energy can be saved annually (Granqvist 2005). For a full case-study of the application of Smart Window technology as a remedy for solar gain in a building refer to *Smart Glazing solutions to glare and solar gain: a “sick building” case study* (James 2004). The fact that the new flexible electrochromic foils have the potential to be produced using inexpensive roll-to-roll

technology could reduce the production costs for electrochromic pillows, making this technology affordable for the construction industry. (Granqvist 2005).

Although most applications of electrochromic materials are on flat glass surfaces, there have, in fact, been some recent explorations on applying this thin film to curved surfaces, specifically to motorcycle helmet visors and car windshields. These advances on the flexibility of electrochromic materials show how quickly the technology is progressing towards a complete malleability of electrochromic surfaces with sufficient optical modulation range, dynamics, and durability (Granqvist 2005). The vision of a smart pillow is, therefore, within the margins of the extant technology.

4.2 Distributed Computing

Breakthrough research at the MIT MediaLab in the Tangible Media Group allow for inexpensive tiny microprocessors to communicate and interact without a central processing unit connecting them. This configuration creates a distributed network that is more stable and resistant to damage; the distribution of processing power allows each of the computer to act like an autonomous intelligent agent and to communicate with it's neighbours in a variety of ways. The use of MCUs (Micro Computer Units) as one technical component of the facade takes advantage of this computational power in order to act both locally as a Smart Window controller and globally as an urban scale LED display.

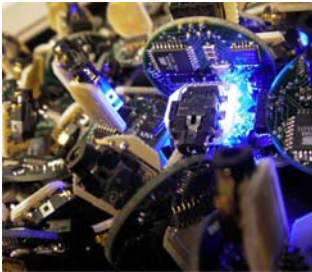


Figure 21. Micro Computer Unit

In order to allow people to interface with the facade, each MCU has an integrated air-pressure sensor that sends a signal to the processor when one of the adjacent pillows has been touched. The processor then triggers the electrical pulse used to change the opacity of the smart pillow when the cushion has been touched. This MCU also transmits a signal to the adjacent nodes such that the adjacent pillows react to the change by changing their own opacity; this reaction chain is described in the diagrams below.

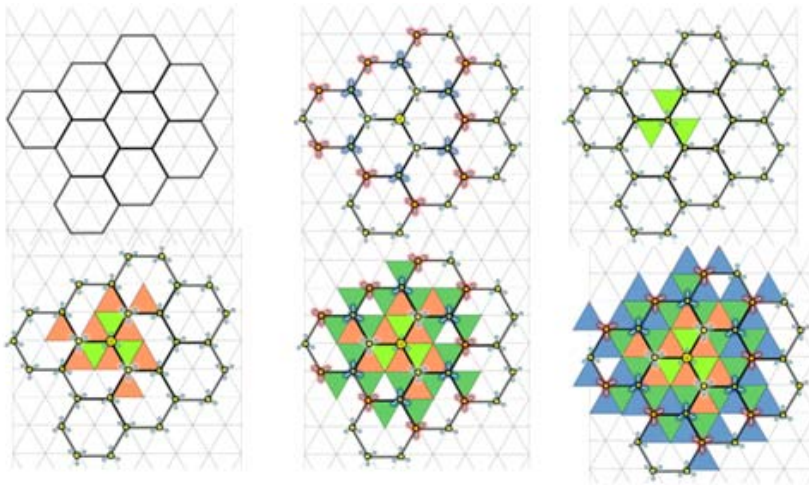


Figure 21. Colored triangles show different moments of a MCU communicating with it's neighbours

5 Implementation of System B

5.1 The context and basic architectural considerations

In order to demonstrate the possibilities for design using the developed façade system we have proposed a hypothetical tower replacing the MIT museum, on the same site. In keeping with standard practice in skyscraper design, we conceived of a general lobby form that would remain constant, while variations in the tower form could be demonstrated for the upper forty floors. The lobby, in the form of a helix, was designed to “catch” people moving along Massachusetts Avenue from MIT (Figure 23). Passer-bys are caught by the extended entrance at the terminus of the spiral, and swept into the lobby space, dominated by an obtuse L-shaped core (itself derived from the later chosen favorite tower form).

The design of the extra-large core was in response to maximum core-to-façade distances, limiting circulation and egress distances. As above implied, the selected demonstration tower form was an obtuse L-shape, derived from both the spiraling movement of the lobby and the desire to maximize façade surface along the southern side, creating a concave “light-scoop”.

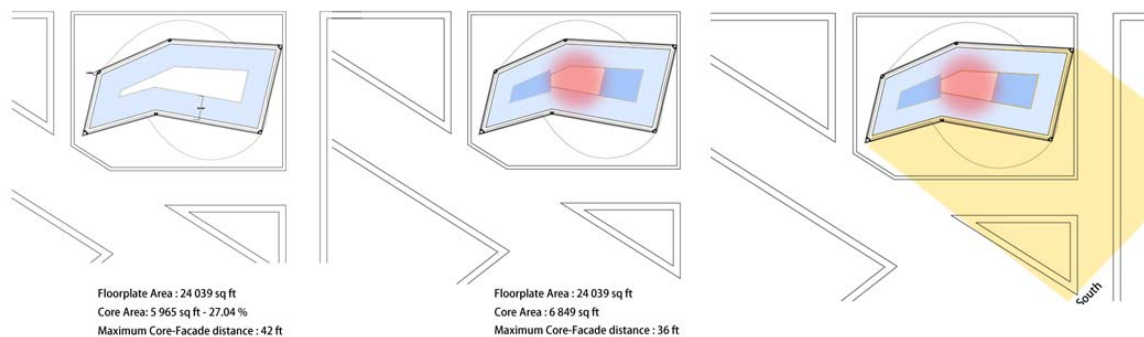


Figure 22. Diagrams showing design the principles guiding the plan of the skyscraper

The façade system was applied to the tower in a highly regularized, straight-forward manner in order to lend importance not the façade structure, but, rather, to the irregular patterns which would emerge from the internal functioning of the building, a mapping of internal functions caused by the inhabitants changing the opacity of the ETFE pillows throughout the day. Further, while local, user-directed changes of opacity would cause centrifugal propagation leading to a global, constantly reconfiguring pattern, during the evening hours the façade would be programmed to display certain patterns, images, or even text by allowing the internal security illumination to permeate the façade in certain areas at varying degrees.

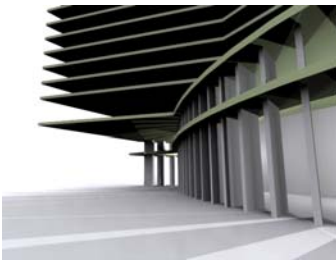


Figure 23. Rendering showing the main entrance to the building

5.2 The Fabrication of the tower

In producing the 1in : 25ft mock-up of the designed lobby and tower, the primary challenge was in discerning the level of detail to be included and what changes were needed to the system of assembly in order to produce a model with the greatest amount of information at that scale. In essence, a threshold of detail is determined based on the minimum pixel size of the ZCorp machine – which was used to prototype the lobby, floor plates, and core – and the minimum width for a piece of a given material (in this case, very thin Plexiglas) cut by a laser cutter. In regards to the constraints of the laser cutter: a piece with insufficient width (i.e. the thin members of the façade assembly) will simply be disintegrated by the heat produced in the cutting process.

Once these minimum bounds were determined, the task was to assess which details were large enough to be represented faithfully, which were too small for an accurate representation and thus could be better represented through abstraction, and finally those details which were either too small, specialized, or of lesser importance to represent at that scale. For example, the general form of the lobby and the tower were accurately represented, while the façade was abstracted into two layers: a cut-out of the hexagon pattern and an inner layer of Plexiglas scored in such a way to give the impression of the diagonal pieces in the façade. Finally, details such as the friction joints or the H-shaped clips were simply excluded. As for the attachment of the façade to the floor plates, the detail was reconfigured from the Hexagon-Arrow and Piece-Slab Connector configuration, which would have been too small to represent given the scale, into a series of notches along each column, from which the two layers of each planar façade side would be hung.

Thus, while the purpose of the 1in : 25ft mock-up was for analysis and representation of the façade system and tower, its best use is contingent upon a conceptual understanding of the limitations of scaled representation, and the subsequent concessions and alterations necessitated for a successful prototype.



Figure 24. Picture of the fabricated tower

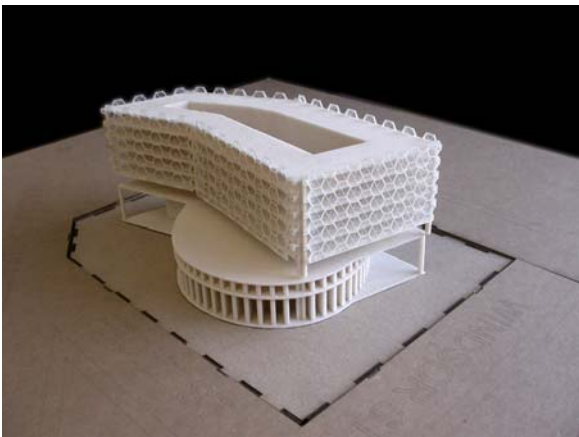


Figure 25. Picture of the fabricated tower

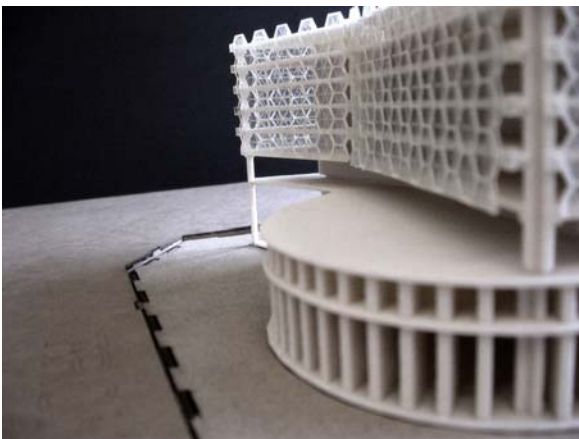


Figure 26. Picture of the fabricated tower

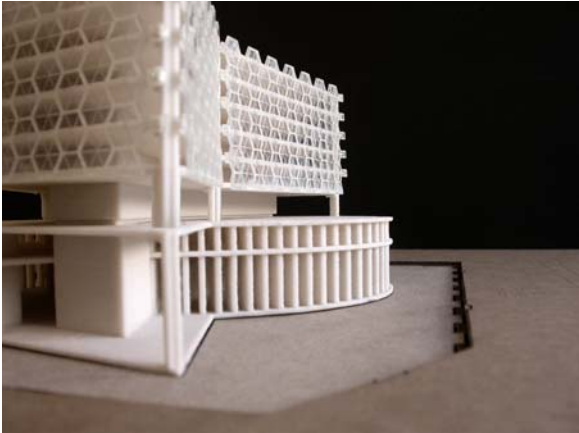


Figure 27. Picture of the fabricated tower

5.3 *Playing inside the constraints*

As in every system of construction, the two façade assemblies that were developed carry certain design implications, a set of formal constraints or rules governing the overall forms developable using the system. We take these not as limitations but rather as instigators for design, providing a certain given condition that the creativity of the designer can mold and form like clay, or cut and sample like time.

The major design constraint is that all surfaces produced using these systems must be planar. While it may be possible to produce a façade system built solely of friction joints connected flat-cut members that can approximate non-planar or even double-curved surfaces, our system does not allow for these forms as it is presently designed. This conclusion was foreshadowed in early three-dimensional computer models and later affirmed in the first laser-cut tests that preceded the aluminium prototype. Indeed, we contend that in flat-cut, friction-joined assemblies a possible inverse relationship may exist between the goals of material efficiency and simplicity of assembly (which remained our conceptual footing throughout the process) and non-planar surfaces.

While somehow presently demoted in computation-based architectural design, we found a certain liberation in the constraint of planarity. *Formal ideas became off-shoots of the constraint, propelled by the inertia of necessity.* While allowing only planar surfaces, volumes can be chiseled into a tower block or extruded from a two-dimensional plan. Planarity achieves a certain assonance within the rhythm of the hexagons, themselves a geometrically deterministic but nonetheless elegant form. And, in order to test the potential variation within the system, we generated a series of morphologies within the system.

6 Discussion Points

- Whereas the available technology seems to allow for the conjunction of ETFE pillows and Electrochromic film in order to produce smart windows, further research and prototyping needs to be done in order to assess the material feasibility of this system. This testing has yet to have been completed.

- In contrast with rendering software, digital fabrication machines provide architectural models with material properties. However it should be noted that the material properties that the prototypes inherit is usually very different from those properties that the object will have at real scale. A conscious awareness of this difference is key to any strategy of Digital Fabrication for representation and analysis. As a general approach, a careful combination of materials and prototyping techniques can help reduce this gap. Our experience demonstrated that digitally fabricated physical models were very useful in some stages of design evaluation where spatial and volumetric properties of the design needed to be tested and communicated, as well as to test designed assemblies for conflicts and collisions. However, these prototypes were unable to mimic the materiality of the full-scale system, and therefore insufficient in affirming the structural success of the assembly.
- Each physical model at different scales implies it's own set of problems related to materials, new logic of assembly, and, in sum, it's own design exploration. The definition of a *threshold of detail* for every different scale of physical representation is not a trivial process, and a great deal of time is spent making *translations* between scales in order to conform to the material limitations of each digital fabrication device. Our experience in this project shows how these translations can leave little time for design development, and sometimes become a source of design loss, where the representation becomes the principal opus of the project. A critical assessment on the purpose of scaled representation and on the design stage wherein it is best suited is fundamental to the implementation of rapid prototyping tools as design aides.
- The comparative data of the two design processes of the each system (Table 1) shows that the time required to create a parametric model using CATIA and to produce the fabrication cutsheets was larger than the time required to produce an AUTOCAD model and the consequent fabrication information. This is understandable if we consider that whereas an AUTOCAD model is relatively static, a parametric model built with CATIA is a dynamic system with an explicit set of rules that allows for geometric freedom inside a constrained design space. Setting such a system involves more variables and is generally more time-consuming than traditional CAD methods. In an interesting paradox, our experience designing with both systems on a very constrained schedule showed that System A, designed using AUTOCAD, was able to vary more than the parametric model, whereas the time invested in creating the parametric model left less time to take full advantage of it's flexibility. Far from suggesting any qualitative judgement between two very different computer aided design systems, our experience demonstrated that in order to provide greater design flexibility, parametric modeling systems require a greater understanding of the underlining logic of the design. This can be a highly advantageous component of design development but may, as in the case of this project, prove too demanding for very constrained time schedules.

7 Next Steps

- Go to detail scale in order to produce a comprehensive design solution that incorporates the technologies and materials mentioned in the previous sections into the façade elements. This design should be developed taking advantage of the lessons learned regarding digital design and fabrication and CAD software.
- The development of a 1:2 scale prototype of an electrochromic smart pillow that takes advantage of the progresses on flexible thin electrochromic foils. The objective of this first prototype is to evaluate the feasibility of the integration of these two materials.
- A second prototype that incorporates MCU Networking that senses the air pressure of the cushions and therefore controls the voltages of the electrical fields of the pillows.

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