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Infrathin – Nine Structures of Extreme Slenderness

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Abstract

R Buckminster Fuller memorably predicted that in a world of *ephemeralization* it would be possible to do "more and more with less and less until eventually you can do everything with nothing." Marcel Duchamp wrote at the same time of the '*infra-thin' (inframince)* as "fire without smoke, the warmth of a seat which has just been left, reflection from a mirror or glass, watered silk, iridescence, the people who go through (subway gates) at the very last moment, velvet trousers their whistling sound." This paper describes structures that have been designed to extreme slenderness as a means of achieving the pleasure of their optical effects, of the ideas materialized, and the ever-elusive goal of reducing consumption. We are not doing "everything with nothing" and our planet and its species are suffering. The art of structural engineering can provide delight in these trying times with material form, economy and conceptual elegance.

Keywords: folded plate, glued laminated timber, high-strength concrete, lateral torsional buckling, long-span beams, precast concrete, post-tensioning, rigid frame, roof structures, slenderness, stability, museum, steel plate, structural glass.

1. Introduction

The French artist Marcel Duchamp coined the term '*infrathin*' (*inframince*) to describe: "fire without smoke, the warmth of a seat which has just been left, reflection from a mirror or glass, watered silk, iridescence, the people who go through (subway gates) at the very last moment, velvet trousers their whistling sound is an infra-thin separation signaled" [Ref. 1]. The term refers to what is ephemeral, ultra-thin, and undecidable, and has been applied by many artists and writers since, to ambiguous and humorous ends.

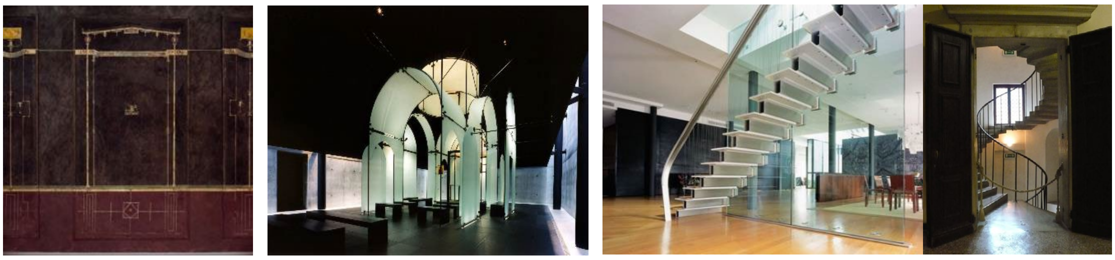


Fig 1a (left)**:** Wall painting on black ground: from the imperial villa at Boscotrecase, Roman, Pompeian (c 20 BCE – 20 CE)
1b (center left): Byzantine Fresco Chapel (1997), with architect Francois de Menil [Photo by Paul Warchol]
1c (center right)*:* Soho Cascade Stair (2000), with architects Architecture Research Office
[Photo by Paul Warchol]
1d (right) oval staircase (*scala ovata*) by Andrea Palladio at the Accademia, Venice.

Here the term is meant physically to describe structures of minimal dimensions and conceptually to designate the ideas that are embodied in those structures. A vivid example of the *infrathin* are the impossibly slender columns that appear on the *Boscotrecase* Roman wall paintings near Pompeii (Fig 1a).

The appeal of their extreme slenderness is both practical - why use more - and optical. Artists from Agnes Martin and Ad Reinhardt to Robert Irwin made works of pared lines and surfaces that nearly elude perception at times, hovering as if at its limit. Irwin, James Turrell and the Southern California "Light and Space" movement studied sensory deprivation and other psychological conditions and concepts as part of the 1960s art-technology program initiated by the Los Angeles County Museum of Art [Ref. 2]. Concept driven, pared to a *reductio ad minimum* and alert to retinal sensations, these artworks echo Duchamp's evocation of both the 'retinal shudder' he disdained, and the *infrathin* he sought. The parallels to physical structures are clear. The slender columns depicted in the *Boscotrecase* Roman wall paintings would barely stand. Yet as inspiration they are compelling: they delineate "light and space" with precision and tact.

The following brief examples from a previous publication [Ref. 3] can set the terms of this concept.

The Byzantine Fresco Chapel (1997-2012) at the Menil Collection in Houston TX incorporated two 13th century frescos originally from a chapel in Lysi, Cyprus. The frescos had been stolen and were recovered and restored by the Menil. The Orthodox Church of Cyprus allowed the frescos and the glass chapel to remain in Houston for just 15 years before their return in 2012. The temporary chapel recreated the form of the Lysi stone chapel with large laminated translucent annealed glass held in a web of pre tensioned solid steel rods (Fig 1b). The chapel was housed in a simple concrete structure and approached through a series of dark vestibules highlighting the combination of fragility and firmness of the circumstances of its brief stay.

The Soho Cascade Stair (2000) adapts the principle of interlocking stone stairs or "cantilever stair" dating to the Renaissance and before (Fig 1c). A classic example by Andrea Palladio at the Accademia in Venice (Fig 1d) dates from the 16th century. Ironically these stairs do not cantilever but act as an assembly of discrete elements supported in a "cascade" of shear and torsion, or sometimes thick shells. The Soho Stair is a homage to this long historical lineage, built of glass, metal and wood: a persistent idea made new.

Figure 2: The Museum of Modern Art Expansion (2004) [Photos by Timothy Hursley]

The 2004 expansion of The Museum of Modern Art in New York was designed by the Japanese architect Yoshio Taniguchi with KPF as executive architects. The building structure is arranged in a modular grid based on an 8:13 ratio and includes several discrete suspended structural transfers to free key galleries of columns. Only the main glass wall (Fig 2) between the entrance lobby and the Abby Aldrich Rockefeller Sculpture Garden visibly expresses the intentional qualities of the structure. This wall is 18 meters tall and supported by solid steel bars that are 6x20cm (verticals) and 6x7,5cm (horizontals). The glass panels are 2x3,6m, held in place by the slender steel bars. All but two of the verticals are propped back to the second floor by small round bars, but only for out-of-plane movements. All the vertical bars, including two that span clear, are only restrained in the plane of the wall by the frame action of the grid of steel. To form this rigid frame, the bars of this grid are connected by milled mortise and tenon joints held rigid by a bolt inserted from the outer side. Although it appears

Figure 3: Toledo Museum of Art Glass Pavilion (2006) and New Museum of Contemporary Art (2007)
[Photos by Toshi Oki (left), Hisao Suzuki (center left), Richard Anderson (right)]

that the glass wall can tie into the side wall of the adjacent Museum Tower, that connection is held by a flexible Belleville washer spring to free the newly constructed expansion from the existing tower in the event of an earthquake. The garden wall structure is in fact free standing. Viewed from the end of the garden, the thin steel is barely visible, but present.

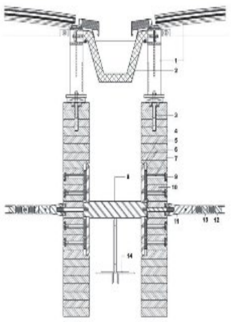
Completed shortly after The MoMA, the Toledo Museum of Art Glass Pavilion (2006) and New Museum of Contemporary Art (2007 – Fig 3), both by SANAA (Kazuo Sejima and Ryue Nishizawa) present two versions of the *infrathin.* The Glass Pavilion is a one-story structure, 60m square in plan with double glass walls delineating the exterior and interior spaces. The air conditioning and ventilation and the vertical structure inhabit this modern *poché*. Despite appearances, the glass does not support the roof but is held in inverted "shoes" that allow the roof to move independent of the panels. The roof structure, designed in collaboration with the engineer Mutsuro Sasaki, is a regular grid of 30cm deep beams spaced 2,4m apart and all rigidly connected to the girders, also 30cm deep, that meander to reach the column locations. The columns themselves are 9cm solid round bars with hinge connections at the top. The New Museum of Contemporary Art, on the other hand, is a vertical stack of shifting boxes held in place by linked belt trusses and a structural core (Fig 3). All but one of the shifting boxes overlap in three points for stable support. The second of the six boxes however is shifted diagonally and the northwest corner "floats" mysteriously above the corner skylight.

All five above projects share an affinity with the *infrathin*. The following four, presented here in more detail, explore the concept further.

2. Kimbell Art Museum Expansion (2013)

The Renzo Piano Pavilion at the Kimbell Art Museum (KAM) in Fort Worth TX is a free-standing 8300m2 addition by Renzo Piano Building Workshop (RPBW) completed in 2013 (Fig 4). As part of this expansion, the East Pavilion includes a lobby and gallery spaces above ground, divided into three 30m bays that mirror the organization of the existing 1972 building designed by Louis Kahn with engineer August Komendant. The East Pavilion roof is composed of twenty-nine long-span laminated timber twin beams (LTBs) supporting a full skylight. The twin beams are located 3m apart and span over the full 30m bays. The LTBs are supported on concrete walls and columns. Each includes two 13x20cm deep glulam beams joined by custom metal connectors with a 40cm gap. The overall section dimensions are 80x130cm overall, a golden section. The twin beams are connected to each other by

Figure 4: Kimbell Museum of Art Expansion (2013)
[Photos by Nic Lehoux (left and right) and Renzo Piano Building Workshop (center)]



1. Skylight system.
2. Gutter.
3. Steel insert for skylight support.
4. Laminated timber beam: 26 Douglas fir laminations, each 8 by 2 in.
5. Aluminum "dog bone" faceplate.
6. Neoprene pad.
7. Stainless steel pin.
8. Aluminum connector solid round bar.
9. Aluminum faceplate on Delrin pad.
10. Stainless steel pin.
11. Steel connection casting for cross bracing.
12. Steel lateral bracing pipe.
13. Steel turnbuckle.
14. Cable tray.

Figure 5: Kimbell Art Museum Expansion LTB parts diagram

horizontal struts at 3m and 1,9cm (3/4in) diameter tension-only cross bracing. The struts carry the lateral reactions at the top of the glass wall mullions of the East and West lobby walls. Since it is located at mid-depth to align with the glass mullion reactions, the horizontal bracing does not prevent the beam from twisting.

The glulam beams were made of Douglas Fir laid up in 5cm laminations by Structurlam Products LP in Canada. The choice of thicker than standard laminations required additional testing but enhanced the uniqueness of the structure. The metal connection hardware (steel, stainless steel, and aluminium) was fabricated by TriPyramid Structures in Massachusetts. These tie the two glulam beams together to form a pair and include two plates in the shape of a "dog-bone", placed against each timber beam, and connected across the gap with two 10cm diameter round bars at 1,5m spacing in plan (Fig 4). The dog-bone plates face each other on the inside face. This geometry creates discrete metal vertical H-shapes at 1.5m spacing and a horizontal ladder like a "Vierendeel" type truss. The two timber beams form a composite section with overall torsional and minor axis stiffness. The "dog-bones" are connected to the timber beams by pins, which go through the wood and are connected to smaller plates on the outside, known as "staples". This detail allows for a connection to the timber via bearing only, either on the inside face of the staple or the inside face of the dog-bone plate (Fig 5).

The LTBs are susceptible to lateral torsional buckling. Individually each beam is restrained by the dog-bone plates and round pipe but overall, the LTB could buckle. Multiple linear buckling analyses with finite element global analytical models, developed with software SAP2000 (Computers and Structures Inc), and long hand calculations were used to estimate the buckling load of a given twin beam based on an accurate representation of the stiffness contribution from the rest of the roof. Each LTB pair of glulam beam under study was modelled as shell elements, while the other beams were modelled as frame elements to estimate their stiffness contribution. The linear buckling analyses provided buckling factors at least equal to 8 under unfactored dead loads plus live loads for any twin beam. The lateral braces at mid-depth force the beams into a pure torsional buckling mode rather than a combination of lateral and torsional deformations. The buckling mode still occurs over the full span, rather than between intermediate bracing points. The rigid body rotation of the beams is prevented by a rigid connection to a continuous 10cm diameter horizontal bar at the end supports.

The detailing of the KAM beams was influenced by some properties specific to timber. Timber swells when its moisture content increases and shrinks when its moisture content decreases. The dimensional variations occur perpendicular to grain, both radially and tangentially from the tree rings. The equilibrium moisture content of timber varies based on the temperature and relative humidity of its environment. The dimensional variations of the glulam beam section were anticipated to be about 12mm in depth and 4mm in width. The variation in depth helped determine the size of the reveal around each staple and the size of the oversized holes around the pins through the wood where needed. The variation in width resulted in the addition of a spring behind the staples.

The choice of timber for the roof structure was the result of many iterative studies with RPBW. Wood seemed the right choice both in relation to RPBWs prior use but also as it resonates with Kahn's own palette and seems a noble counterpart to the exquisite concrete of both the Piano and Kahn pavilions.

The geometry and disposition of the structure with its paired LTBs, each individually supported and free spanning, also celebrates their slenderness and *élan* their kinship with the 10cm thick cycloid shells of Kahn and Komendant's structure.

3. Corning Museum of Glass Art and Design Wing (2015)

The New Contemporary Art and Design Wing at the Corning Museum of Glass, in Corning New York is a 9500m2 addition by Thomas Phifer and Partners, completed in 2015 (Fig. 6). The structure is a combination of concrete columns, slabs and walls and a perimeter steel frame and truss, with a sheer glass facade.

Figure 6: Corning Museum of Glass Art and Design Wing (2015)
[Photos by Iwan Baan (left and center) and Richard Barnes (right)]

It is adjacent to the 2001 Corning Museum of Glass expansion designed by Smith-Miller + Hawkinson (SM+H) with Nordenson and Arup. This expansion was built alongside the 1951 Glass Center designed by Wallace Harrison. As the wall of the Harrison Glass Center had been retained as part of the SM+H expansion, and as the Center was then replaced 15 years later by the Phifer Wing, the wall sliver is all that remains, sandwiched between these two new buildings, an "infra-thin separation."

The roof of the new Wing is supported by very thin precast concrete rafters. Each rafter is 9x122cm and spans in the north-south direction at a spacing of 1,05m (Fig. 6). They support a saw-tooth roof, which in northern New York can collect substantial snow drifts. All the rafters are the same cross-section, but the spans vary between 2m and 17m. They are supported at the north and south ends on the steel structure, but also on top of the curvilinear cast-in-place concrete gallery walls. These walls, hollowed to accommodate the return air flow (as is the case at the Kimbell), act as story-height deep beams supporting both the roof structure above and the concrete flat slab below, on concrete columns. (a homage in part to Komendants wall beams at the Kimbell). As a result of the meandering wall layout, many of the over 200 rafters have unique lengths. Each is simply supported and is braced at the top on a 2,9m spacing by steel roof purlins running perpendicularly. The purlins in this case provide both torsional and lateral bracing. The purlins are continuous and connect to the cast-in-place concrete shear walls by means of stiff vertical steel plate cantilever "stanchions" (Fig. 7).

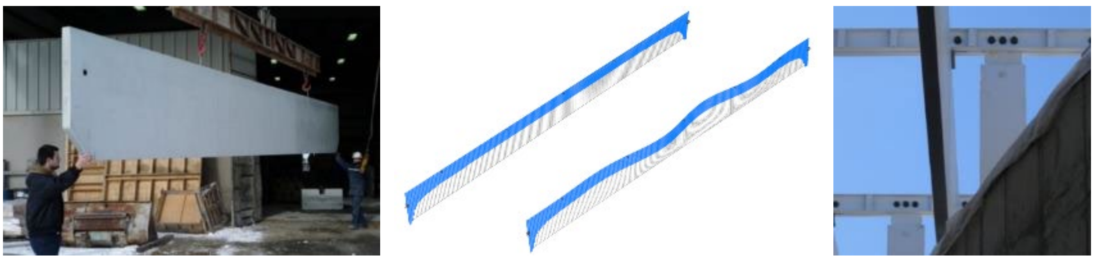


Figure 7: Corning Museum of Glass Art and Design Wing: at Béton Préfabriqué du Lac (left); analysis model (center) and "stanchions" on top of hollow concrete walls (right).

The precast elements were made by Béton Préfabriqué du Lac in Alma QC, Canada, using high-strength concrete, with a compressive strength f'c of 70MPa. The concrete mix included a minimal amount of organic fibers, not enough to be considered a fiber reinforced concrete. The reinforcement consisted of single layer of mild steel only, including longitudinal reinforcement at the top and bottom, as well as welded wire mesh shear reinforcement. Post-tensioning was not an option given the slenderness.

The stability calculations are described in detail in [Ref. 4]. The height of the effective cross section h_{eff}= kd +z was taken as the portion of the concrete that remains uncracked, where kd is the depth of the neutral axis from the compression fiber and z is the depth of uncracked concrete in tension below the neutral axis. For a simply supported beam, h_{eff} varies along the length of each beam. See Fig 7 for an example of a cracking profile for a given loading. Using $E = E_{sec}$, where E_{sec} is the secant elastic modulus [Ref. 5 and 6], a linear buckling analysis was run in a finite element model developed with SAP2000 under unfactored dead loads plus live loads. The rafter was modeled as shell elements, with the cracked concrete being omitted following the cracked profile and with lateral springs representing the purlins. In an elastic homogeneous case, the critical buckling moment would be equal to the applied moment multiplied by the buckling factor calculated for this load case. In the case of reinforced concrete, since the cracking profile is a function of the applied load and has an impact on the buckling load, the relationship between the applied moment and the critical buckling moment is not linear. To account for this, an iterative, numerical procedure was used in which successive loads were applied to the beam to find the loading and cracking profile resulting in a buckling factor equal to 1. The ratio of the critical loading, i.e. the loading resulting in a buckling factor equal to 1, to the actual loading corresponds to the true buckling factor. The minimum acceptable value for this ratio is set to 4 based on engineering judgement and by analogy with typical safety factors used for stability calculations in the American standards.

Special care was given to the detailing the roof connections since they are exposed to view in the galleries. As the joists are braced along their top surface, it was essential to prevent any negative bending from occurring. Therefore, all joist end-support connections utilize solid stainless-steel pins placed horizontally through stainless steel pipe sleeves cast into the ends of the precast joists. The pin is supported by an external “shoe plate” wrapping around the end of the joists. The shoe plate is either connected to a base plate on top of the concrete walls or directly to a steel beam. The shoe plate to curving wall relationship varies continuously.

As is the case with the Toledo Glass Pavilion, the closely spaced, thin rafters are often mistaken for non-structural light baffles, although of course this is a role they also play. The uniformity of their dimension and the geometric interplay with the meandering hollow concrete walls produces this ambiguity.

4. Menil Drawing Institute (2018)

The Menil Drawing Institute (MDI) is a 2,800m2 structure on the Menil Collection campus, designed by the Los Angeles based architects JohnstonMarklee. Beautiful old live oak trees on the site set the location of three square, open-roofed courtyards. The structure is a one-story steel structure, including a wide lobby and multi purposed space, a gallery, and a study center, with a full basement for back of house and a concrete double-wall storage vault for the drawing collection. The two exterior courtyard canopies are made of exposed thin steel folded plate, in keeping with the overall origami like forms of the architecture. The building superstructure is composed of conventional structural steel framing with concrete on metal deck roof slab. The folding architectural ceiling creates pinch points in the roof framing that meet practically at a line, though this is only indirectly apparent. Figure 9 shows the overall arrangement of the steel structure [Ref. 7].

The two exterior canopies folded plate structure is 1,6cm-thick high performance steel (HPS 50) with welded stiffeners spaced every 60cm. Each canopy is made up of four prefabricated 18,3m long by 3,66m wide sloped panels meeting at corner miters. The panels are supported on the side along the building on corbels with built in thermal breaks, and to the outside on separate steel plate walls made in the same manner, as if folded down from above.

The steel fabricator United Structures of America, Houston, built a full-scale mockup of a corner section of the folded canopy and partial-height wall, using the actual material thicknesses and welds specified on the construction documents. The purpose of the full-scale mockup was to validate the constructability, tolerance, and visual appearance of the exposed steel finish. Due to the extremely thin canopy roof profile and the limited adjustability of the thermal break connections that attached the canopy structure to the building primary structural steel frame, the coordination of the interface between the two steel structure types required a high level of precision. Both the building superstructure steel and the exposed steel canopy roofs were designed with upward cambers at specific locations. A detailed erection plan was developed by the steel fabricator to facilitate the installation of the courtyard canopy and wall sections and ensure that the correct cambers were fabricated and installed in the necessary manner and sequence to ensure proper final alignment between components.

During construction, field conditions and complications led to adjustments to the original canopy erection plan, and the field welding of the mitered corners, which induced additional stresses in the canopy. The contractor engaged an independent structural engineer to develop and oversee a load test procedure for the canopy structures to confirm its expected elastic behavior. The engineer developed an independent finite element analysis model of the two courtyard steel plate structures including the steel framing at the canopy-to-building superstructure interfaces. Expected vertical deflection results from the independent models and from our structural model were compared to establish the target deflections that were to be measured during the load test.

The load test itself was developed and conducted in accordance with the guidelines of the International Building Code. The structure was surveyed at multiple points around the interior and exterior edges of the canopy roofs prior to additional load being applied to establish a baseline elevation. Approximately 100,000kg of sandbags were then placed by hand on top of each canopy roof following an agreed upon pattern and sequence determined by the contractor's engineer (Fig. 9). Surveyed measurements of the vertical deflections at each station point were taken at regular intervals during the loading process. After the final load was in place, the structure was observed, surveyed, the weight then removed, and then the structure surveyed one final time after allowing for twenty-four hours of elastic "rebound" period.

Achieving the paper-thin folded plate structures required precision engineering and control by the fabricator. Cambering continuous, rib-stiffened plate is a three-dimensional task and the successful outcome of level and plumb lines are dependent on the slight over-camber and other optical nuances. All this relies on both the formulation of the analysis and the skilled welder's hand. The result is both abstract and material: in the direct head-on sun the steel plate walls and folded planes are flat and

Figure 8: Menil Drawing Institute (2018) [Photos by Richard Barnes (left and center) and Giulio Ghirardi (right)]

Figure 9: Menil Drawing Institute [Photo by Don Quaintance (center)]

smooth, immaterial. In the raking light the regular corrugation of the welded ribs appears, resonating with the bead blasted and stained *hinoki* cedar paneling of the building (made by Gordon Plume).

5. Day's End (2021)

In the fall of 2014 the American artist David Hammons sent a pencil drawing to the Whitney Museum of American Art titled "GORDON MATTA-CLARK MONUMENT PIER 52" (Fig 10). This followed a visit with Adam D. Weinberg, then director of the Whitney Museum of American Art in New York, to the building a year before its completion. The building was designed by Renzo Piano Building Workshop with Cooper Robertson, and the engineers Silman. During the visit the two looked out on the Hudson River from the empty galleries toward the site of the abandoned pier shed that Gordon Matta-Clark had transformed into sculpture in 1975. Matta-Clark died in 1978, and the shed was demolished by the city in 1979. Hammons' drawing registers the five loading bays of the pier shed, its proportions, and its monitor roof with double clerestory as seen in earlier photographs.

Hammons was clear that the siting of his work should match that of the original pier, but he left the investigation of the precise location to us. Although the shed and pier are gone, historic maps show they stood just offshore and south of Gansevoort Peninsula. Built in 1898–99, the pier was shortened from approximately 698 to 325 feet-long (212m to 100m) in the 1950s.

Figure 10 – Hammons' drawing, Gordon Matta-Clark's *Day's End* with bays drawn, and completed structure [Photos by Gordon Matta-Clark (center with overlay by authors) and Jason Schmidt (right)]

The original timber piles of Pier 52 remain. They extend about 40 feet down into the mud under the water and relied solely on soil friction for their support. Driven close together, they formed a kind of raft that could distribute any soil settlement caused by heavy loads on the pier above. The steel columns of *Day's End* rest on one steel pile each, so any settlement would distort and strain the slender structure. New steel piles were driven 52m down to bedrock, through the forest of old timber, to avoid any movement. The steel piles stop just above the mud line to remain submerged and prevent corrosion. Precast concrete caps were designed to be fixed to the top of the steel piles, with precast concrete columns extending above and out of the water. The new steel frame above the river is adapted from the geometry of Hammons's drawing with dimensions derived from our historical research—it is 65 feet wide by 52 feet high (20m and 16m) with five bays of 65 feet (20m) each, for a total length of 325 feet (100m). This modular (13ft or 4m) and proportioned layout fits well with the original shed's profile, matching the scale of the building when Matta-Clark approached it in 1975 (Fig 10).

The concrete pile caps and columns that join the underwater steel piles to the base of the steel columns above the river were precast upstate in Greenwich, New York, at Fort Miller. Each cap is a biscuit-shaped base 6 feet (1,8m) in diameter and 30 inch (75cm) thick, precast together with the 26 inch (66cm)-diameter concrete columns above. The column outer shaft is a hard shell made of ultra-high-performance Ductal brand concrete that was filled with steel reinforcement and normal stone aggregate concrete at the Fort Miller plant. The bottom of the Ductal shell, over the height of the tidal range, is corrugated to encourage mollusks and algae to attach. Inside the base cap, a steel "insert," designed by Danish marine engineering consultants COWI, was made to fit and wedge over the top of the 30 inch (75cm) diameter steel piles. The concrete columns extend up to the bottom of the steel frame at an elevation that should remain above tidal flows, even with projected sea-level rise (Fig 11). The use of precast and prefabricated elements and mechanical connections for the sculpture followed from environmental regulations that prohibit welding and pouring of concrete over the river, but it was also essential for quality and precision. The extreme lightness of the structure subjects it to greater impacts from natural forces, including wind, currents, ice floes, and waves during storms. A boat could accidentally strike the structure as well, and this was considered in its design.

The main force acting on the structure, however, is the wind.

Figure 11 – Corrugated concrete column base with algae, column base connection, column node and column-to-beam "coupler" connection, and completed structure as seen from the river
[Photos by Guy Nordenson and Associates (left), Richard Barnes (center) and Jason Schmidt (right)]

The thinnest possible pipes, all 8.625 inches (22cm) in diameter, make up the structural steel frame of *Day's End*. Over the 65-foot (20m) horizontal beam spans, this proportion amounts to a very slender 90 to 1 ratio. The unfolded gable's length-to-depth ratio is 105 to 1. The pipes were made from steel plate cast at Industeel in Le Creusot, France, and rolled at Rivit in Caltrano, Italy. The steel columns all have the same half-inch plate thickness. Each column was prefabricated as one piece with 3.25-foot (1m) "stubs" extending out horizontally to connect to the ends of the beams and gable pipe. The main beam pipes were made with walls of varying thicknesses—a half-inch (1,2cm) wall at the end thirds, and a three-eighths-inch (1cm) wall at the midspan. End to end, column node to column node, the beams and gables are made of multiple elements—from shaped precast node; to short, thick-walled pipe; to milled connector; to the variable pipe-wall thicknesses. The variable stiffness, ends to middle, optimized the performance. Large, prefabricated pieces—columns with stubs, straight crossbeams, eave beams, ridge beams, and gables—were assembled and welded at Mariani Metal Fabricators in Toronto, with their end "coupler" connections milled to mate in the field. The T-joints between the stubs and vertical column pipes are castings made by Electro Aço Altona S.A. in Blumenau, Brazil.

The steel used for the pipes, castings, and machined couplers is a "super duplex" stainless steel, which has a mixed microstructure that is half austenite (face-centered cubic lattice) and half ferrite (body-centered cubic lattice), providing both high strength and outstanding corrosion resistance. Avesta Ironworks (now Outokumpu) in Avesta, Sweden, first created this steel in 1930 for industrial and marine use and more recently for bridges and buildings in Europe, including the restoration of Antoni Gaudí's Sagrada Família in Barcelona. The hybrid microstructure has a distinctive iridescence that was heightened for *Day's End* by glass-bead blasting of the columns and beams after assembly.

In order to realize the abstract simplicity of Hammons's drawing at full scale, the joints of the steel lines had to disappear. The coupler connections were made to be secured in the field with just two steel 1.25-inch (3cm) diameter pins shaped to blend seamlessly to the pipe contour. The coupler fit is made with a near-zero tolerance and a sixteenth-inch reveal along the curvilinear joint line. Each horizontal and vertical line in space, though joined with little tolerance, had to fall plumb and dead level to the eye.

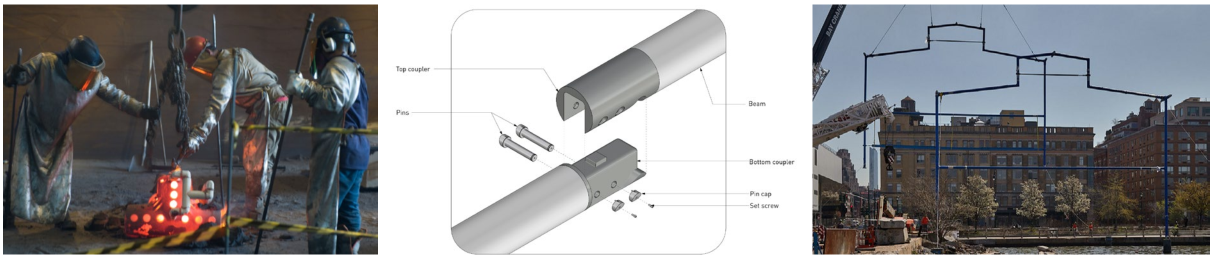


Figure 12 – Casting of the "nodes," diagram showing the "coupler" connection, erection of the steel frames
[Images by Guy Nordenson and Associates (left and center) and Richard Barnes (right)]

Each completed beam, column, and gable was cambered in the shop, sometimes in three dimensions, to counter the deflection predicted to occur once assembled in place. Any adjustments needed to correct for optical distortion could also be accounted for in the shop. Mariani's team accomplished the necessary curves by welding each piece part—the different pipe types, castings, and machined connectors—on jigs set to the prescribed segmented camber lines. The beam and gable assemblies were curved upward and the columns inward. The end gables were shaped to the calculated three-dimensional camber to counter their expected deflections as well.

The Greek word *ἐντείνω* (*enteino*, to stretch or strain tight) is the origin of the term "entasis," meaning the slight waver in a line or profile in art and architecture that is used to imply either effort or lightness. The tautness of the thin pencil lines in Hammons's *Day's End* drawing reappear in the shimmer, the slightly wavering light reflected off the frame's glass bead–blasted finish. Under certain moderate to strong wind conditions, the lines vibrate as vortices form and detach rhythmically on the leeward side of the beams. This visible "vortex-induced vibration" results from the beams' extreme slenderness, lightness, and flexibility. The welds joining the prefabricated beam elements were designed to maintain the resulting stress cycles well below the fatigue limit. Still and taut, or wavering slightly in the light and wind, the completed stainless-steel frame renders closely in the air the hard lines of Hammons's pencil drawing.

5. Conclusion

The art and craft of structural engineering is mostly hidden, sublimated in the architecture. One cannot easily admire its "performance" as one might an actor or *diva*. It is of course possible to find the art—studying photos and drawings and many great hidden works of engineering from the Sydney Opera House to the former World Trade Center will reveal their genius to the scholar. When structure is visible, however, it can play many characters as we have seen in the past half century. Here we have chosen to emphasize a conceptual strain, one where the structural form sometimes alludes and interprets historical, or nearby precedents, that will delight both the visitor and the careful reader. The idea highlighted here is both in the spirit of Duchamps' *infrathin*, and at odds with it, as it sometime seeks to produce a "retinal shudder" through the optical effect of its extreme slenderness. If there is a poetic of structures, it can range widely, allusively and at times seek to appear even immaterial, like a drawing in space. This seems appropriate in this time of excess and bland display.

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