TOYO ITO AND MASATO ARAYA'S EXPERIMENTS IN THE STRUCTURAL USE OF ALUMINUM

Dana Buntrock, Professor, University of California, Berkeley
(Corresponding author)

Department of Architecture
232 Wurster Hall
University of California, Berkeley
Berkeley, CA 94720-1800 USA
Mobile:
1-510-219-8216 (US, use after June 2015)
81-80-3449-0206 (Japan, best used until June 2015)
DanaB@Berkeley.edu

Work on Toyo Ito and Masato Araya's structural innovations has been supported by the following grants:

"Engineering Innovations in the work of Masato Araya" Committee on Research Faculty Research Grant (FRG), University of California, Berkeley (2013-4) $3000.
"Translations of an era: Toyo Ito's critical writings on the art of architecture in post-war Japan," Committee on Research Faculty Research Grant (FRG), University of California, Berkeley (2009-10) $4,500.
"Structural Innovations in Japanese Architecture," University of California Humanities Grant for translation support (2000-1) $3000 and University of California Academic Senate Junior Faculty Research Grant (2000-1) $8000.

ACKNOWLEDGEMENTS
The author is grateful to both Masato ARAYA and Toyo ITO for their time and support.

* This paper uses the Western order for Japanese names, with family name capitalized to avoid confusion.

TOYO ITO AND MASATO ARAYA'S EXPERIMENTS IN THE STRUCTURAL USE OF ALUMINUM

ABSTRACT

Aluminum is a widely used material offering many advantages when used in buildings. Supply has dramatically increased with better recycling practices. With this in mind during the 1990s, Japanese subsidies targeted exploratory development of new uses for aluminum in buildings. This paper reviews innovative aluminum developments by Japanese architect Toyo ITO and structural engineer Masato ARAYA. With strong industry support, the two professionals designed and built five free-standing aluminum structures: a house, a dormitory, a cottage, an exhibition kiosk and a pavilion. Teaming up with several different industry partners both at home and abroad, Ito and Araya explored a variety of formal approaches. Their work received numerous awards and accolades and was in some cases patented. However, in the end the structures the two professionals built remain unique.

KEYWORDS

Aluminum, Architecture, Extrusion, Collaborative design, Industry Partnerships, Japan, Masato Araya, Patents, Prototypes, Structural engineering, Toyo Ito.

* This paper uses the Western order for Japanese names, with family name capitalized to avoid confusion.

TOYO ITO AND MASATO ARAYA'S EXPERIMENTS IN THE STRUCTURAL USE OF ALUMINUM

As common as a cola can, aluminum, while widely used for window frames and curtain wall construction, is still struggling to fully expand into its ideal architectural market in Japan. Between 1/4 and 1/3 of all aluminum consumed globally is used in building construction—but only 13.2% of Japan's aluminum is used in building construction.[1] The soft metal is widely available, strong for its weight, corrosion-resistant and very versatile—but it is not without disadvantages to architects and engineers. It remains expensive to produce, process and shape. It loses its rigidity at a very low temperature (the melting point is only 660°C, or 1220°F). It has a high coefficient of thermal expansion. It will efficiently conduct sound—but like the efficient conduction of heat, that is not desirable in buildings. And aluminum will creep over time, too, with up to 12% elongation under tensile loading.

For more than half a century, aluminum supply and demand have only moved upward—and at an amazing pace. When the balance of supply and demand tips towards surplus, it seems, industry gives architecture another go, covering the construction and development costs involved in exploring new uses and aggressively promoting innovations in exhibitions and publications. In the 1930s, Albert Frey and Lawrence Kocher erected the Aluminaire House for New York City's Allied Arts and Building Products Exhibition, using aluminum pipe structurally; it was subsidized by the Aluminum Company of America.[2] In Japan at the turn of the twenty-first century, things would be little different, with industry pushing into new markets—but as I will explain, each time surpluses were satisfied, industry's incentive to nurture new uses of aluminum waned, leaving the experimental buildings that emerged in these eras as unusual architectural landmarks.

From the 1950s through the early 1970s, industry again pushed this novel material's architectural promise. A handsome 2-volume promotional set published in 1956 by the Reynolds Metal Company featured proposals for the structural use of aluminum described by leading architects such as Walter Gropius, Mies van der Rohe, Marcel Breuer and Pietro Belluschi. Federico M. Mazzolani, writing on the structural use of aluminum, focused on the value of this lightweight material in paradigmatic long-span structures such as the 1969 Interamerican Exhibition Center in Brazil, a 67,600 square meter space frame erected in only 27 hours.[3] More prosaically, fabricators in Japan and the US produced aluminum substitutes to replace wood framing in single-family homes.[4] Alcoa's Alumiframe, developed under the US Department of Housing and Urban Development's "Operation Breakthrough" was brought to market in 1971 with advertising in Life magazine. Similar systems were offered by Japan's Furukawa Aluminum around the same time.

* This paper uses the Western order for Japanese names, with family name capitalized to avoid confusion.

During this period, Japan's aluminum production also expanded, more than doubling between 1968 and 1972; there were optimistic expectations for future growth. Japan's residential market, in particular, offered an unusually high rate of housing starts each year. Although structural applications for aluminum failed to gain traction, Japanese architects readily embraced it as a finish, in curtain walls and for window frames.

The profession's enthusiasm for aluminum by this time is evident in Toyo ITO's very first building, the 1971 Aluminum House, clad in large, shiny sheets. In a recent interview, Ito recalled:

> "…the site was by the sea, and I thought metal roofing was the only possible solution. Since I couldn't have steel, I decided to use aluminum on not only the roof but the walls…The idea of the house as a closed [Metabolist] capsule and the notion of a Tokyo vernacular were both probably factors in the choice of aluminum for the exterior finish."[5]

Ito continued to explore the use of sheet aluminum throughout the early years of his career. In the 1978 show "A New Wave of Japanese Architecture," exhibited at New York's Institute for Architecture and Urban Studies, he included four buildings: one was the 1978 PMT Building, defined by a bulging façade of aluminum panels. Airy perforated-aluminum wrappers were featured in many of Ito's best buildings from the 1980s, such as Silver Hut (1984), Restaurant Bar Nomad (1986) and Tower of Winds (1986). The eye-catching finishes in this work helped launch the international careers of other young Japanese architects in his circle as well. But Ito drew distinctions:

> "Itsuko HASEGAWA also used it frequently. We used it in completely different ways. She used perforated metal in a matter-of-fact way, whereas I used it to evoke a world of fantasy of imagination."[6]

The 1970s and 1980s can be called Ito's first age of aluminum. As a young architect, he was limited by cost and what was available off the shelf. Nonetheless, his architecture became identified with aluminum, used as an engagingly fluid skin or screen. By the late 1990s, Ito's reputation would lead the aluminum industry to engage him in a series of unusual prototypes, advancing the structural use ofaluminum.

As with many globally available commodities, the price of aluminum rises and falls in response to changes affecting supply. A quick outline of the volatility of prices from the 1970s through the 1990s is found in a US governmental publication that explains:

> "…during 1974, prices rose to reflect the increased cost of energy brought about by the surge in world oil prices.
> …During the early 1980's, the aluminum industry suffered from a period of oversupply, high inventories, excess capacity, and weak demand, causing aluminum prices to tumble. By 1986, however, excess capacity had been permanently closed, inventories were low, and the worldwide demand for aluminum made a dramatic surge upward. This extremely tight supply-demand

* This paper uses the Western order for Japanese names, with family name capitalized to avoid confusion.

> situation, which continued throughout 1987 and 1988, brought about a dramatic increase in aluminum prices.
> …In the early 1990's, the major influence on aluminum prices was the dissolution of the Soviet Union. To generate hard currency, large quantities of Russian aluminum ingot entered the world market. Unfortunately, the aluminum market had just entered an economic downturn and was unable to absorb the Russian material. This period of oversupply, decreasing demand, and increasing inventories depressed world aluminum prices.
> By the mid-1990's, production cutbacks, increased demand, declining inventories, and the perceived improvement in the world market led to a dramatic rebound in aluminum prices. Prices began to cycle downward again during the late 1990's as the economic crisis in the Asian market exerted pressure on the prices of several commodities, including aluminum. Once again, the aluminum market was entering a period of oversupply."[7]

In addition to global shifts during the mid-1990s Japan's internal supply of aluminum increased dramatically, growing from 23-million metric tons in 1993 to 27-million in 1997. (FIGURE 1) Producers shifted from imported, virgin bauxite to the recycling of manufacturing waste and post-consumer materials, also using less electricity. Thus the mid- to late-1990s was a time of rising prices and increasing supply, which excited the industry's enthusiasm to expand their market for aluminum. This led to establishment in 1994 of the Aluminum Architectural Structures Association (□□□□□□□□□□□□□□□□).

At the beginning of 1998, a number of well-regarded architectural professionals were invited by the Japan Aluminum Association (□□□□□□□□□□) to discuss new strategies for aluminum in buildings.[8] Toyo ITO chaired the group, the "Home and Aluminum Study Group" (□□□□□□□□□□), which would come to advocate aluminum for structural purposes. The work that resulted, as I discuss here, uniquely reflected the context in which it was developed. With unusually high levels of industry involvement, each building was used to test purpose-driven shapes that explored the way production could influence architectural form. The dainty and highly detailed structures that resulted would have been prohibitively expensive without industry support; the resulting output was only likely to be profitable if it were broadly applied. The nature of this work differed from much of the architectural output during the 1960s and 1970s, when structural systems and finishes relied on simple flat or tubular shapes.

In the late 1990s, Japan's NEDO (New Energy and Industrial Technology Development Organization) offered subsidies for the development of a demonstration house developed by the Home and Aluminum Study Group under the title "Eco Building Material House Technology Development" (□□□□□□□□□□□).[9] Reference to ecology may seem odd to Westerners aware of the embodied energy in aluminum production (although, secondary production requires far less electricity than processing from bauxite), but the idea that building materials could be readily recycled was particularly appealing in light of the two- to three-decade lifespan of most Japanese houses.

* This paper uses the Western order for Japanese names, with family name capitalized to avoid confusion.

With NEDO support, two prototype structures were built out of aluminum for research purposes only. These were then quickly followed by the first fully aluminum structure built for long-term residential use—with exterior finishes, floor and roof slabs, shear walls, columns and beams all aluminum—designed in the late 1990s by Toyo Ito and structural engineer Masato Araya, consulting closely with the Building Center of Japan (□□□□□□□□), a quasi-governmental organization. The house was completed in January, 2000.

Aluminum House a.k.a **House in Sakurajōsui (□□□□□ /** a.k.a **K □)**

This trailblazing all-aluminum house was located next door to an earlier one Toyo Ito designed in 1975, also at times somewhat confusingly referred to in English by the same name, 'House in Sakurajōsui' (but in Japanese as □□□□).[10] (FIGURE 2.) Sakurajōsui is a neighborhood in Tokyo's Setagaya Ward; both homes were designed for the same client, but under very different circumstances. The 1975 home was Ito's third built work, designed for a young family at a time when Japan's economy was weak. A modest wood post-and-beam structure with asbestos siding, it was described in one Japanese text as "symbolic of the poor housing condition in Tokyo."[11] The later building was designed for the older and more affluent parents after their children had grown—and, more importantly, Ito was at the peak of his career, constructing Sendai Mediatheque.

Ito's most innovative work usually involves one of two Tokyo-based engineers, Mutsurō SASAKI and Masato ARAYA, both trained by the esteemed Toshihiko KIMURA. Ito first encountered each of them while they were still working in Kimura's office. The architect's close collaborations with structural engineers usually exploits their own proclivities and passions. For example, his 2002 Serpentine Gallery was a response to Cecil Balmond's passion for number theory; Sendai Mediatheque, a collaboration with Sasaki, highlighted that engineer's tendency towards bold formal gestures; Araya, by contrast, is more detail-oriented in his approach, as will become evident in the works I discuss below.[12] (I've written more on how Ito and Sasaki, working closely with steel fabricators, built Sendai Mediatheque; see my Japanese Architecture as a Collaborative Process: Opportunities in a Flexible Construction culture published in 2000.)

Design of the later 'House in Sakurajōsui' took two years, from 1997 to 1999, but construction was considerably speeded up, requiring only three winter months to build. It was a simple design, but the greater reason for quick construction was that there were few components: the structure, for example, also acted as exterior finish and waterproofing. The process of assembly was vastly simplified by the use of aluminum, parts quickly clipped together with stainless steel bolts or slipped into sleeves and tracks. Araya outlined the schedule as thirty days for the concrete foundation, twenty days to erect and weld the aluminum structure, and forty days for interior work.[13] It is worth noting that there were many novel

* This paper uses the Western order for Japanese names, with family name capitalized to avoid confusion.

aspects to the erection and no established trades to rely on for the work, thus making the three-month period even more remarkable.

The unusual double-webbed wide-flange beams used in this building illustrated Araya and Ito's overall approach. The shape was an innovation that Araya proposed, in light of Ito's general inclination towards thinness. It was stiffer than a single-web beam, addressing aluminum's greater ductility. (FIGURE 3.) Furthermore, assembly was speeded up: a gusset plate slipped into an internal slot of the web and was easily bolted to a cruciform column. But while assembly was fast, greater planning—and greater cost—were required to develop the novel shape and work out fabrication. Relying on finely tuned connections between a number of relatively simple shapes, it's a watchmaker's detail, fully hihglighting Araya's tinkerer tendencies.

Columns in this building were made up of two pieces: the central cruciform-shaped core was slipped into a square sleeve, which reduced the potential for buckling by locating more material at the periphery. This configuration has become better known over the last decade in places where earthquakes occur, a key feature in the design of 'unbonded' or 'bucking-resistant' braces. Many of Japan's leading structural engineers, including Araya, were already aware of the development of these systems in the late 1990s.

Columns and wall panels were neatly integrated with windows, thanks to the interlocking nature of aluminum components. This reduced the need for trim, but expanded the number of specialized shapes produced for the column sleeve to three and also added expense to the project that would have been impractical without industry support. Although an elegant solution, it is important to highlight the extra difficulty these careful details created during fabrication and construction, which discouraged the designers from pursuing such a tightly purpose-driven approach to component design on later projects. Araya described the Sakurajōsui House, unlike other aluminum buildings that followed, as reflecting the fundamental character of aluminum—but at a cost, in both time and money.

At the time this house was built, aluminum was not officially accepted as a structural material under Japanese building codes. It was not until 2002 when the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) released a bulletin explicitly permitting all-aluminum structural systems.[14] However, homes offered a work-around; gypsum wallboard was used as an interior finish to comply with prescriptive building codes—effectively skirting the issue of aluminum's poor performance in fires.

Japanese architects tend to celebrate delicacy in design.[15] The walls here were less than 85 mm (3-3/8") thick; floors only 156 mm (less than 6-3/8") deep. Structural panels acted also as the exterior finish. (FIGURE 4.) The house has an

* This paper uses the Western order for Japanese names, with family name capitalized to avoid confusion.

unusually neat and simple character which was well received both in Japan and abroad.[16]

The slim components were also the result of norms for Tokyo homes, which are generally quite small. Ito used a central two-story sunroom (enclosed in single-pane glass, conventional then as now) to break the house into short spans over individual rooms; the longest span in the little 86-square-meter (925-square-foot) house is only 4.2 meters (13 feet 9 inches), which significantly reduced the depth of the roof slab. (FIGURE 5.) However, even with insulation—unusual for a Tokyo home even today—the designers reported that thermal bridging and condensation caused considerable discomfort in winter. The limited cavity depth for insulation in walls and floors and the effective thermal conductivity of aluminum were the source of this discomfort. Thermal breaks, it should be noted, are not yet used in Japanese aluminum products.

This had little impact on the building's successful reception. Historically, homes in Japan were uncomfortable. However, an awareness of these issues would influence the plan of a larger residential building I will discuss below.

One important regional influence was the fact that buildings in Japan must be designed not only for gravity loading, but also for earthquakes. In earlier research prototypes built in aluminum, seismic forces were addressed with diagonal bracing. However, Araya instead complemented the framework of columns and beams with aluminum shear diaphragms built up of 30 cm wide (1 foot), channel-shaped panels welded together. The initial proposal was to make these panels wider (45 cm / 18 inches), with fewer joints welded on site; however, the wider plank would have added considerable production expense.

Araya also came to realize over time that when aluminum is welded, its strength is compromised; late projects would rely more on bolted connections. But in this first permanent application of an all-aluminum structural system, channel ribs at wall and roof were welded together on site. (FIGURES 6 and 7.) Since the aluminum was also the exterior finish, the architect and engineer neatly solved both engineering and architectural concerns with a single material, the welds also used to resist water intrusion.

The difficulties of using aluminum were resolved in the house via a rich collaboration between architect, engineer, and industry. Araya and Ito both shared an interest in exploring an unusual structural materials and in using the resulting structure as finish, too, requiring a level of tolerance more natural to architects than structural engineers. Although there was no direct application of NEDO funding on the Sakurajōsui House, the project architect Akihisa Hirata and Araya, the structural engineer, (writing in separate papers) both highlighted the importance of technical advice and materials testing by industry partners for the project.[17] Without industry support, it would not have been economically practical to explore such unique extrusions for what was, after all, a relatively small house;

* This paper uses the Western order for Japanese names, with family name capitalized to avoid confusion.

Araya estimated the costs to the client at roughly half of what it might have been without technical support.

As I noted in my opening, the aluminum industry initiated this effort not simply to produce a unique residential prototype by two influential professionals, but to encourage broader demand for aluminum by fostering new structural uses for their product. Ito and Araya were able to demonstrate innovative techniques to overcome the inherent challenges of aluminum, incorporating short beam spans and new structural forms (a double-web beam and tube-encased cruciform column) to address aluminum's ductility. Integrating skin and structure on a site with a small footprint was potentially useful in a city with many such small residential sites. The speed of construction, enhanced by the use of bolts at beam-column connections, was another desirable outcome. But their work also underscored that aluminum that was not yet market-ready for this purpose: welds, for example, created notable structural problems and the designers were aware of problems with thermal comfort, even if others were not.

It would be fair to say that this first experience caused the architect and engineer to remain interested in the structural use of aluminum, but aware of drawbacks in their initial approach.

Brugge **Pavilion**

The second aluminum structure Ito and Araya designed together was a small, temporary structure in Brugge, Belgium, completed in 2002. (FIGURE 8.) A cathedral once sat where Burg Square is today, the site of Ito and Araya's pavilion. French Republicans destroyed the church in 1799; important archaeological remains exist only a meter below grade, inspiring the designers to again propose aluminum, due to its light weight.[18] The ethereal structure nonetheless totaled 8 metric tons (17,637 pounds)—but the load at the wall was a relatively acceptable 250 kilos per linear meter (400 pounds per linear foot).

Araya has pointed out that aluminum is actually heavier than concrete when compared volumetrically; our perception of its light weight comes from the thin sections possible because of its strength.[19] But at Bruges, the wall and roof panels resulted in more aluminum being used, increasing the weight compared to a post and beam structure.

The pavilion took a considerably different approach from the one developed at Sakurajōsui. It had no columns or beams; long walls and a roof slab were made out of a 125 mm- (5-inch-) thick honeycomb produced from 3-mm (1/8-inch) aluminum strips, folded into shape and welded. The original proposal was for a tunnel-like structure 8 meters (26 feet) wide and 28 meters (nearly 92 feet) long, but due to cautious structural testing, the size was reduced to about 85% of the original, a tube 6.75 meters (roughly 22 feet) wide and 16 meters (just over 52-1/2 feet) long. It was 3.75 meters (just over 12 feet) tall.

* This paper uses the Western order for Japanese names, with family name capitalized to avoid confusion.

With the exception of the Belgian building, all of the aluminum structures Araya and Ito designed together were based on the use of extruded metal shapes, many of them unique forms custom-made for projects. As I noted earlier, 'House in Sakurajōsui' (as well as the other Japanese projects that were to follow) benefited from string industry support, which reduced the cost of developing these customized aluminum extrusions significantly and gave the architect and engineer an unusual level of technical support. The parts for every one of their jointly designed aluminum structures were fabricated in Japan—except for the *Brugge* Pavilion.

When searching for industry partners in Europe, Ito and Araya were unable to excite the same kind of support from large organizations they had enjoyed at home. Instead, a search led them to discover Aelbrecht-Maes, a Belgian metal-working organization that offered a high level of metal craft and also offered design-related consulting. The strategy they developed for the *Brugge* Pavilion reflected the artisanal metal-working traditions more common to Europe than Japan. (FIGURES 9 and 10.)

Thus the honeycomb panels for *Brugge* Pavilion were handcrafted; Araya wrote that this level of aluminum handwork would not have been possible in Japan.[20] Each of the 33,400 folds making up the half-hexagons were individually shaped in a single jig; each of the 7500 welds done by the same person, whether in the shop or on the site. (*http://www.aelbrechtmaes.be/publicatie-media_paviljoen_toyo_ito*) The fabricator Aelbrecht Maes even produced the jig used to shape the honeycomb's half-hexagons, to the surprise of the Japanese team.[21]

Formally, Araya treated the pavilion like a continuous portal frame. The roof and walls were stiffened with an external skin of 12 mm- (1/2 inch-) thick polycarbonate sheets and the strategic addition of large, 3 mm- (1/8 inch-) thick aluminum oval "sandwiches" evenly spaced along the full length of the walls and roof. Each of the full-sized ovals was 150 cm (5 feet) long and 75 cm (2-1/2 feet) wide; those at the base were cut in half at a diagonal. Along the walls, these sandwiches were strategically located to respond to the higher moment stresses arising at the roof and at the base. The wall had minimal moment stress at its mid-point, which reduced the need for added rigidity there and allowed the designers to increase the transparent character of the structure at roughly the same height as an average person's eyes. (FIGURE 11.)

Three more large oval sandwiches were located along the midpoint of the roof slab for added stiffness. All of the oval sandwiches were tied together with thru bolts.

Araya once described this structure as 'architecturally rational, but mechanically irrational.'[22] There is little in the way of established engineering practice for the

* This paper uses the Western order for Japanese names, with family name capitalized to avoid confusion.

design of honeycombs; because of the way distortion propagates through them, finite analysis was of no use. Early in the design phase (which began in April, 2000, shortly after Sakurajōsui House was completed), Araya realized computer simulations inaccurately predicted little distortion in models made of stiff paper. The team, as a result, relied heavily on testing physical models and mock-ups to predict structural performance. (FIGURE 12.) In a draft verision of Araya's essay about this experience for the Japanese magazine *Shinkenchiku* (□□□), Araya repeated two adages the team took to heart: 'Actions speak louder than words' and 'Seeing something is better than hearing it 100 times.'

But the fabricator, involved in later stages of these physical tests, at least partially blamed them for budget overruns; the final cost of 30-million Belgian francs (approximately $650,000 at the time) reported in a 2002 newspaper article was a not-insignificant five million over budget.[23] The design team may have been permitted to use a novel material structurally without the same level of regulatory oversight required for a permanent building, but the fabricator reported some delays were also due to concerns caused by the structural use of polycarbonate.

Like the Aluminum House at Sakurajōsui, extensive prefabrication in the shop considerably sped up work on site, a particular benefit considering the cultural significance of Burg Square. (FIGURES 13 and 14.) The fabricators divided the structure into nine panels (three for each side wall and three across the roof). Work on the pavilion lasted 1-1/2 months; aluminum erection, which included some minor welding on site, took only one month, and the polycarbonate envelope took about ten days.[24] Additional landscape construction took as long as the structure itself, doubling construction time.

The *Brugge* Pavilion was originally designed to last only a year. There was very little attention to weather-resistance in the design: welds connecting the honeycombs were discontinuous and allowed water between the two strips of metal; there was no gasketting where the roof met the polycarbonate cladding. At the end of 2002, however, the Bruges mayor approved the popular pavilion for on-going use; it remained in place until the end of 2013, eleven years longer than was originally anticipated. During this time, though, the pavilion fell into a period of neglect, precipitated by forklift damage to the internal plastic honeycomb bridge in 2006. The aluminum remained in good shape; it was cut into smaller sections with a torch (not following original panel lines) and stored with a stated intention to reconstruct it again one day, elsewhere—ironically following the same path as Mies van der Rohe's Barcelona Pavilion, one of Ito's key inspirations.

SUS Company Housing

The largest of the aluminum structures Araya and Ito designed together, a 490-square-meter (5275-square-foot) dormitory, was completed five years after the Aluminum House in Sakurajōsui. Their earlier buildings used aluminum in a linear arrangement of right angles; here the designers created gently curving walls of

* This paper uses the Western order for Japanese names, with family name capitalized to avoid confusion.

extruded planks (250 mm / 9-7/8” wide) only 70 mm (2”) thick. With only two die shapes—radii at 5.4 meters (17 feet, 9-1/2 inches) and 13.5 meters (44 feet, 3-1/2 inches)—the walls were laid out in loosely undulating lines. (FIGURE 15.) A closed-box plank rather than a channel, the components carried both gravity load and lateral stresses caused by earthquakes. (FIGURE 16.) This was far from simple—shear walls transfer lateral stresses best if there is a direct horizontal line for stresses to follow; a curve has a tendency to bulge out of shape instead of resisting lateral load.

Due at least in part to its larger size, there was greater attention paid here to cost control: all connections on site were done with bolts or screws. Lessons learned at the Sakurajōsui House clearly impacted planning. The tendency for aluminum to conduct sound efficiently—not desirable in places where people sleep—resulted in a plan with few common walls. This more open plan was also an advantage in terms of fire safety, establishing a very short path of travel from any interior space to the outdoors. (FIGURE 17.) And while architects in Japan did not at this time customarily insulate buildings, care was taken to thermally enclose the interior; rooms were lined with 40 mm (1-3/4 inches) of insulating foam (although again, the design did not incorporate thermal breaks). The ceiling construction included 15-20 mm (11/16 inch to 7/8 inch) sprayed urethane foam. (FIGURES 18 and 19.)

Small works

In addition to these three larger buildings, two others—a cottage and a ‘container’ for outside exhibitions—were developed by Ito and Araya as prototypes. The body of work Ito and Araya developed shifted from architecture to industry—perhaps a logical step in light of the industry partners the designers were working with. Mass production, it can be argued, is a more logical approach to using aluminum extrusions than small one-of-buildings, since the cost of dies used to make unique shapes could be spread across greater use. Ito and Araya developed the aluminum cottage from June 2002 to August 2004 with the oldest Japanese aluminum producer, the Nippon Light Metal Company (□□□□□); the aluminum container for outside exhibitions was developed with the SUS Corporation in 2005 and exhibited at Tokyo Designers Week that year. As I will discuss below, other architects were also involved in exploring the use of aluminum in novel ways, but only Ito and Araya, clear leaders, were able to collaborate with more than one aluminum industrial leader simultaneously.

The cottage was described as a ‘common-sense’ solution to problems that naturally emerge when remote wood structures are unused for much of the year in a very hot, humid climate—aluminum, after all, resists decay and mold. The structure was built out channel-shaped panels and cruciform columns, complemented by aluminum cross braces and an internal layer of structural plywood that enhanced rigidity and, it was hoped, acted as a thermal break. In August of 2003, Nippon Light Metal applied for four patents to protect its

* This paper uses the Western order for Japanese names, with family name capitalized to avoid confusion.

intellection property, naming Ito as a co-applicant and inventor. (FIGURE 20.) The patents covered not only the unique shape of the wall, but the construction method, the entire building, and alternative modular strategies. Throughout, there was a stated effort to use simple connections that were enabled by the purpose-made extrusions.

Like the other aluminum structures discussed here, erection was rapid, taking less than two months. (The building sat on a number of short supports spaced about 3-1/2 meters—less than 10 feet—apart, so did not require much foundation work.) It utilized five unique extrusions, but instead of using an extruded profile to transfer stress between panels (inefficient since the profiles did not fit tightly), the cottage incorporated an special paint on the abutting faces of channels to increase friction.[25]

In the Fall of 2004, Nippon Light Metal announced they would bring the cottage to market in April 2005. The 75-square-meter—800-square-foot—prototype had a stated cost about thirty million yen--US$330,000. This came to a fairly pricey $4400 per square meter—$408 per square foot—without land costs and soft costs like utilities hook-ups. Material costs were estimated to make up about three- to five-million of the total—and an additional five-million yen was attributed to “manufacturing/machining costs” (□□□). Roughly a third of the cost of the cottage could be attributed to the materials used.[26] The announcement stated a target of at least 10 units ordered before putting the project into construction.

The cottage did not make it to market. The prototype, however, was still in its original setting in 2008 and in use promotionally.[27] (FIGURE 21.)

The prototype for the container took a different approach, following a gently curving geometry resulting from three subtly different extruded plank shapes that could be combined in various configurations, exploiting attributes harder to accomplish in wood, steel or glass. This prototype was related to the curving sidewalls used for the SUS Company Housing discussed earlier, under construction at the time the container was designed. (FIGURE 22.) This at least in part accounts for the unusually short development period: only seven months, in spite of the complex shape of the individual parts. By contrast, the Aluminum Cottage took twenty-one months to develop.

The column-free space within the container was 2.78 meters (9 feet 1-1/2 inches) tall and 3.7 meters (12 feet 1-1/2 inches) wide; it was 6 meters (19 feet 6-1/4 inches) long.[28] Its name, “sudare” (□), referred to traditional Japanese blinds; ninety-two extruded plank-like components were assembled into a flexible sheet at the plant, strung like beads along cables spaced half a meter (20 inches) apart. (FIGURE 23.) On site, they were pulled into shape over template-like falsework. Each of the planks—70 mm (2-3/4 inches) thick and 85 mm (3-3/8 inches) wide—weighed between 13.4 and 13.6 kilograms (roughly 30 pounds each). (FIGURE 24.) Even though employing aluminum, the container weighed 2

* This paper uses the Western order for Japanese names, with family name capitalized to avoid confusion.

tons—roughly the same as a similarly-sized steel shipping container.[29] This is likely due to the additional material making up the cellular structure of each extrusion. The result, while eye-catching, did not yield any clear competitive advantages over the common steel shipping containers usually employed for this purpose.

The container, too, was patented, but did not go into production.

Finally, Ito and Araya's 'Aluminum Brick' screen, a façade that tied together a new structure and a historic building, was in development for three years; it was patented in 2002, but local code reviews caused delays and it was not completed until 2005, the last of their aluminum structures. (FIGURE 25.) Designed for the University of Groningen, its small brick-like pieces snapped together. They were produced with a great deal of technical assistance from the Nippon Light Metal Company (□□□□□) and Shinnikkei (□□□) and shipped to Holland for assembly. As built it appears quite modest. However, there were no beams or columns; the design team took advantage of the relatively low structural demands of this wall to explore the way the small units connected. The aluminum components were literally stacked like bricks, transferring the load through each extruded connection, which, because of play in the joints, transferred loads with less efficiency. This solution would have been impossible to attempt in a country with major earthquakes like Japan.

The End of Another Aluminum Age

Together, Ito and Araya designed six aluminum structures: a house, a dormitory, two small prototypical structures that never went into production, a pavilion intended for short-term use, and a façade. In addition, Ito designed a group of small public toilets in Fukuoka, a city in southern Japan, working with the engineer Mutsurō SASAKI; Araya designed a large sculptural work with one of Toyo Ito's former employees (see postscript).

In addition to these two designers, who played the largest role in exploring new uses of aluminum, suppliers worked with other respected architects during this period, including Riken YAMAMOTO, Kazuhiro NANBA, Mikan Gumi, and Coelacanth K&H (the latter working with Araya on a model house built with off-the-shelf parts). One other engineering office, the considerably larger IIjima Structural Design Office (with 35 employees in three locations), was active on many of these projects—and in fact played a key supporting role when Toyo Ito turned to Mutsurō SASAKI to design the small public toilets erected in southern Japan.

Most of these structures were produced with subsidies and industry R+D support, outside of the normal regulatory oversight within which architects and engineers generally work. Some were inhabitable, but not strictly considered buildings. Some—the *Brugge* Pavilion, *sudare*—benefited from the greater freedom

* This paper uses the Western order for Japanese names, with family name capitalized to avoid confusion.

allowed temporary works. The House at Sakurajōsui complied with earlier prescriptive building codes that had not anticipated the lower yield point of aluminum, essentially conforming to the letter of the law, but skirting its intentions. But later regulatory changes did permit the use of aluminum; the dormitory was built with conventional oversight and the aluminum cottage was planned within regulations, though it did not undergo building approvals.

Japanese professionals, especially those of stature like Toyo Ito and Masato Araya, have opportunities to work in liminal territory that many architects and engineers elsewhere tend to consider outside their scope of practice. The aluminum industry and these building design professionals were able to develop an experimental body of work that fell between their conventional territories to test whether aluminum could be economically adapted to new structural uses. While the body of work they developed did not establish new markets, they were able to make discoveries about its potential which will likely be the start of later investigations into aluminum as a structural material.

And Ito and Araya benefited professionally by doing so. Araya received two awards from the Japan Structural Consultants Association. The first, in 2001, was an Award of Excellence for the House at Sakurajōsui; the second, given two years later, was for his collective contributions to the advancement of the structural use of aluminum, recognizing the first house again, the two overseas projects, and an aluminum mudsill in another project I have not included here. The aluminum collaborations by Ito and Araya were also widely published at home and abroad.

Suppliers aggressively promoted this work. *ecoms*, a subsidiary of SUS, began publishing a quarterly magazine under the same name in January 2003, featuring a variety of works using aluminum at a scale between furniture and small buildings. Design competitions, friendly to student participation, were held annually starting in 2003, with well-known architects and engineers serving as jurors; grand prize was a million yen (roughly $8,500 in 2003). The first year, with Ito chairing the jury, there were over 450 entries.[30] Design professionals who had employed aluminum in novel ways were not only jurors, but also compensated speakers at various professional events.

Market response to these aggressive efforts to advance new uses of aluminum in architecture was, however, modest. In retrospect, the close collaborations with industry, and the unusual extrusions that were central to each Japanese project, likely discouraged broader acceptance of aluminum as a structural product. The competitions stopped in 2010; *ecoms* ceased publication in July, 2012. In 2006 *Shinkenchiku* followed up with a book of collected works in aluminum, starting with Ito and Araya's Sakurajōsui house. Although there were still proposals in development, not one of the industry-supported structures from this innovative era is missing from the monograph. Another "Age of Aluminum" was coming to an end.

* This paper uses the Western order for Japanese names, with family name capitalized to avoid confusion.

It might be said that the final curtain on this era of experimentation was drawn on March 11, 2011. Ito and Araya's SUS dormitory is located in Fukushima Prefecture, not far from the nuclear plants that melted down following a severe earthquake. Affordable aluminum production, even when involving recycled aluminum, requires cheap electricity to accomplish—in the mid-20th century, Reynolds Metals proudly referred to the material as 'solid electricity.'[31] Production usually occurs in the shadow of nuclear power or hydroelectric plants. But the 2011 disaster closed nuclear plants across Japan and cut off roughly one-third of the nation's electrical power supply. With skyrocketing costs for electricity, these experiments, earlier considered ecological because of aluminum's light weight, durability and recyclability, became far less practical.

Araya continued to pursue more limited research on aluminum in his Waseda University lab. He incorporated a refinement to the watchmaker's detail seen in Sakurajōsui as part of a small demonstration house on display in early 2014 and, with students, analyzed the structural performance of challenging new forms (e.g., curved honeycomb) and tested as-yet unsuccessful proposals to address the low melting point of aluminum with water-filled structural sections. But in the Spring of 2014, he reached mandatory retirement age at his university and forfeited its intellectual and physical resources. Without a research lab or research assistants, Araya's aluminum experiments thus came to an end.

Japan offers architects and engineers the rare opportunity to develop unusual prototypes via industry collaboration. But in the case of aluminum, this collaboration may also have prevented broader adoption by building professionals who did not have access to similar levels of subsidies and industry support. In fact, the attention and awards that Ito and Araya received for their aluminum work were due to its path-breaking applications of hard-to-access technologies. Other designers who followed would, ironically, have been perceived as less innovative unless they were able to also produce unusual results—and yet the purpose of these collaborations was to expand the product lines available to architects. Although it was a dramatic drop in available electricity in Japan that closed this Age of Aluminum, conflicts between the goals of professional and production communities, left unresolved, had already created the reasons for its end.

FIGURE CAPTIONS

(*Figures supplied are in color; it is the author's intent that the print version use only black + white*.)

FIGURE 1

Aluminum extrusions reached a production peak in 1997—27-million tons, up from 23-million tons in 1993.

* This paper uses the Western order for Japanese names, with family name capitalized to avoid confusion.

(Government documents of this sort are not covered by copyright in Japan. The original can be found at: *http://www.meti.go.jp/policy/nonferrous_metal/strategy/aluminium02.pdf*)

FIGURE 2
Sakurajōsui House
© *Tomio OHASHI*

FIGURE 3
Double-web beam and cruciform column connection
© *Toyo ITO & Associates*

FIGURE 4
Aluminum components were lightweight and easy to handle on site.
© *Toyo ITO & Associates*

FIGURE 5
Plan organization yielded short structural spans.
© *Photo by Shinkenchiku-sha*

FIGURE 6
On-site welds were intended to create a water-resistant surface.
© *Toyo ITO & Associates*

FIGURE 7
Neatly integrated components.
© *Toyo ITO & Associates*

FIGURE 8
Brugge Pavilion.
© *Stefaan Ysenbrandt*

FIGURE 9
Aluminum welding
© *Toyo ITO & Associates*

FIGURE 10
Assembling the honeycomb from aluminum strips.
© *Toyo ITO & Associates*

FIGURE 11
An early sketch shows how the “ornamental” ovals were deployed at locations where moment
was highest.
© *Masato ARAYA, Oak Structure Design Office*

FIGURE 12

* This paper uses the Western order for Japanese names, with family name capitalized to avoid confusion.

Deflection of honeycomb was tested in full- scale mock-ups.
© *Toyo ITO & Associates*

FIGURE 13
Prefabricated panels were slipped into place on site.
© *Toyo ITO & Associates*

FIGURE 14
Panels with two radii were used to produce the gentle curves.
© *Toyo ITO & Associates*

FIGURE 15
Setting the slim walls.
© *Toyo ITO & Associates*

FIGURE 16
An interior layer of wall insulation addressed thermal bridging.
© *Toda Kensetsu*

FIGURE 17
Roof insulation.
© *Toda Kensetsu*

FIGURE 18
Plan shows how the dorm room layout takes into account sound transmission and fire safety by applying an open, cellular structure.
© *Toyo ITO & Associates*

FIGURE 19
Patent document depicts the Aluminum Cottage's wall construction.

FIGURE 20
Aluminum Cottage prototype.
© *Tsuneho ASADA*

FIGURE 21
Aluminum Container, extrusion detail
© *Masato ARAYA, Oak Structure Design Office*

FIGURE 22
Aluminum Container, showing cable connections
© *Masato ARAYA, Oak Structure Design Office*

FIGURE 23
Aluminum Container, with plank size evident.
© *Masato ARAYA, Oak Structure Design Office*

* This paper uses the Western order for Japanese names, with family name capitalized to avoid confusion.

FIGURE 24

Aluminum Brick facade.

* This paper uses the Western order for Japanese names, with family name capitalized to avoid confusion.

1Notes and References
 Menzie, W.D, *et al.* “The Global Flow of Aluminum from 2006 through 2025: US Geological Survey Open-File Report 2010-1256”, p. 36, 39. Available from *http://pubs.usgs.gov/of/2010/1256/.*

2 Edwards, Clive. “Aluminum” in Sennott, Stephen. Encyclopedia of Twentieth Century Architecture (New York and London: Fitzroy Dearborn, 2004) p. 70-1 and Doordan, Dennis P. “From Precious to Persuasive: Aluminum and Architecture” in Sarah C. Nichols, Aluminum by Design: Jewelry to Jets (New York: Harry N Abrams, 2000) p 97.
3 See, for example, Mazzolani, Federico M. 'Structural Applications of Aluminium in Civil Engineering” Structural Engineering International: Reports (April 2006) p. 280-5, which includes this and other similar examples.
4 I am grateful to Shimizu Construction’s Toshiyuki Yamada for bring the Japanese materials to my attention many years ago.
5 Toyo Ito, 1971-2001 (Tokyo: Toto, 2013) p 038.
6 *Ibid,* p. 091.
7 Plunket, Patricia A. “Aluminum” in US Department of the Interior, US Geological Survey, Metal Prices in the United States Through 1998. (Washington DC: 1999).
8 The original working group of 36 companies included offices led by Toyo Ito, and by the structural engineers Mutsurō SASAKI and Toshihiko IIJIMA, and major corporate organizations such as Nippon Light Metals, Sumitomo Metals, Misawa Homes, and Tostem.
9 □□□□□□□□□□□□□□[Aluminum House to Completion] □□ [*Shitsu Nai*] (1999.11) p. 149.
10 My interviews and informal discussions with Toyo Ito on his work have gone on for a period of 17 years, starting with my weekly visits to Sendai Mediatheque during its construction. Masato Araya has been a close collaborator on this paper and presented it on my behalf at a conference in 2014.
11 Toyo Ito Space Design (September, 1986) p. 128.
12 Ito’s first building with Araya was the 1993 Matsumoto ITM Building. During the period under discussion, Araya was also the engineer on the 1995 Kasai Rinkai Park Rest House by Yoshio TANIGUCHI and the 2003 One Omotesando with Kengo KUMA, both of which demonstrate similarly notable lightness and delicacy within the architects’ *oeuvres*.
13 Araya Masato, *et al*. “Structural Design of a House with Aluminum Panel Resistant to Earthquake: New spacial (sic) expression realized by the abstracted Aluminum structure” □□□□□□□□□□□□□□□□□□□□□□□□□□□□□□—□□□□□□□□□□□□□□□□□□□□ AIJ Journal of Technology and Design / □□□□□□□□□□□□ no. 11 (2000.12) p. 116.
14 MLIT Bulletin no. 410 ‘Necessary Technical Criteria Concerning Structural Engineering Practices using Aluminum Alloys,’ □□□□□□□□ 410 □□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□. Title translation by author.
15 This is perhaps particularly true in this period. As other examples of exaggerated delicacy, see the 2003 Plum Grove House by Kazuyo SEJIMA with its 16 mm-thin structural walls or the 2009 Serpentine Pavilion she designed with partner Ryue NISHIZAWA. Kengo KUMA’s 2005 “champagne bubble” designed with Araya is one of a number of temporary teahouses enfolded in delicate membranes.
16 In addition to the publications cited here, the house was published repeatedly in Japan Architect, *Shinkenchiku*, and GA, as well as in Detail, *El Croquis*, Lotus, Monument, *Techniques et architecture*, *Tectonica*, and Title.
17 Hirata Akihisa. □□□□□□□□□□□□□□□□□□[Presenting the Realization of an Aluminum Structure] AL□ [AL *Ken*], p. 3; Araya Masato, *et al*. AIJ Journal of Technology and Design / □□□□□□□□□□□□ (2000.12) p. 116.
18 □□□□□□□□□□□□□□□□□□□□□□□□□□□□□ X □□□□□□[What kind of architecture does aluminum bring about? A Dialog between Toyo ITO and Masato ARAYA] □□□ [*Shinkenchiku*] (2004.12) p. 129.
19 *Ibid*.
20 Araya, Masato “Making Architecture: Making Architecture in Brugge” □□□ [*Shinkenchiku*] 77.5 (2002.5), p. 65.
21 *Ibid.*
22 ISHIDA Yasuo, IIjima Toshihiko, and KURIYANAGI Akio, eds. □□□□□□□□□ [*Aruminiumu no Kūkan* / Aluminum Space] (Tokyo, *Shinkenchikusha:* 2006) p 47.
23 Belgium had converted to the Euro two years earlier. It is unclear why the article only used an obsolete currency to report costs.
24 Araya Masato, *et al*. “Design of Honeycomb and Sandwitched (sic) Panel Structure With the Use of Aluminum Alloy: A new special (sic) expression realized by abstracting the structure” □□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□□—□□□□□□□□□□□□□□□□□□□□ AIJ Journal of Technology and Design / □□□□□□□□□□□□ no. 19 (2004.6) p. 140.
25 □□□□□□□□□□□□□□[Connections in Aluminum Architecture] □□□□ [*Kenchiku Gijutsu*] (2004.12) p. 116.
26 Light Metal Digest □□□ no. 1705(2004.9.27) *http://www.kallos.co.jp/member/today1705.html*. Accessed 2013.1.6.
27 *http://journal.morld.jp/2008/08/_aluminum_gate_house.html*
28 Light Metal Digest □□□ no. 1763 (2005.11.21) *http://www.kallos.co.jp/member/today1763.html*. Accessed 2013.1.6.
29 *Ibid.*
30 Light Metal Digest □□□ no. 1648 (2003.8.11) *http://www.kallos.co.jp/member/today1648.html*. Accessed 2013.1.6.
31 Reynolds. Aluminum in Modern Architecture, vol. 1 & 2 (1956). p. 9.

Other sources.

NEDO. □□□□□□□□□□□□□□□□□□□□□□ “Development of Ecology Housing Technology” # 98Z33-018.

The author also conducted interviews in Tokyo with Toyo ITO and Masato ARAYA during December 2013 and January 2014.