The Journal of Architecture

ISSN: 1360-2365 (Print) 1466-4410 (Online) Journal homepage: http://www.tandfonline.com/loi/rjar20

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The Journal
of Architecture
Volume 21
Number 1

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Aluminium is a widely used material offering many advantages when employed 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 aluminium in buildings. This paper reviews innovative aluminium developments by the Japanese architect Toyo Ito and the structural engineer Masato Araya. With strong industry support, the two professionals designed and built five free-standing aluminium 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 final outcome the structures the two professionals built remain unique.

As common as a cola can, aluminium, while widely used for window frames and curtain-wall construction, is still struggling fully to expand into its ideal architectural market in Japan. Between a quarter and a third of all aluminium consumed globally is used in building construction—but only 13.2% of Japan's aluminium is so used.[1] The soft metal is widely available, strong for its weight, corrosion-resistant and very versatile: but it is not without disadvantages for 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 aluminium will also creep over time, with up to 12% elongation under tensile loading.

For more than half a century, aluminium 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 aluminium pipe structurally: it was subsidised 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 aluminium waned, leaving the experimental buildings that

1360-2365 http://dx.doi.org/10.1080/13602365.2016.1138137

emerged in these eras as unusual architectural landmarks.

From the 1950s through to the early 1970s, industry again pushed this novel material's architectural promise. A handsome two-volume promotional publication of 1956 by the Reynolds Metal Company featured proposals for the structural use of aluminium offered 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 aluminium, 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 metre space frame erected in only twenty-seven hours.[3] More prosaically, fabricators in Japan and the USA produced aluminium 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.

During this period, Japan's aluminium 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 aluminium failed to gain traction, Japanese architects readily embraced it as a finish, in curtain walls and for window frames.

The profession's enthusiasm for aluminium 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 aluminium throughout the early years of his career. In the 1978 exhibition 'A New Wave of Japanese Architecture', 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 aluminium panels. Airy perforated-aluminium 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 aluminium. As a young architect, he was limited by cost and what was available off the shelf. Nonetheless, his architecture became identified with aluminium, used as an engagingly fluid skin or screen. By the late 1990s, Ito's reputation would lead the

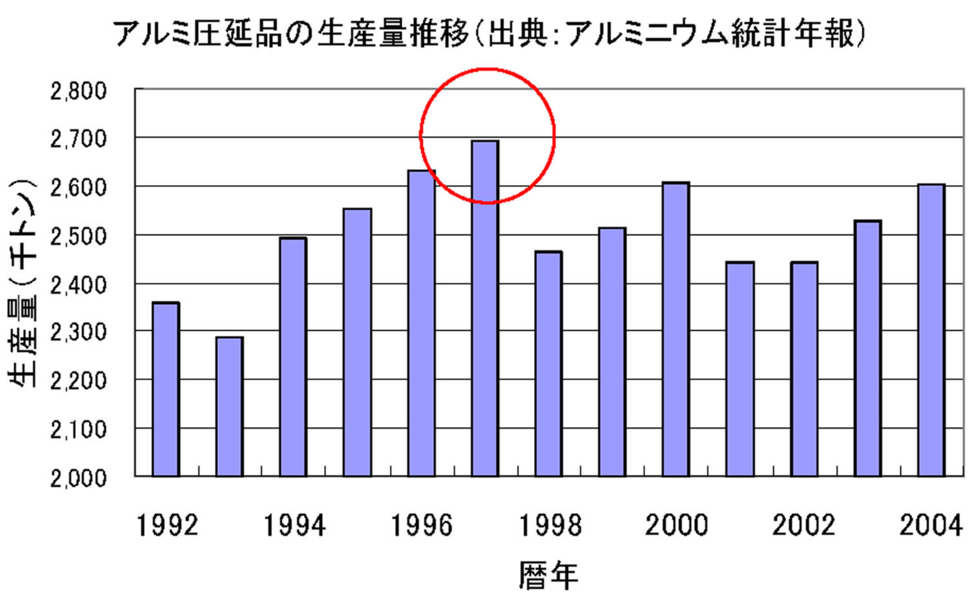

Figure 1. Aluminium extrusions reached a production peak in 1997—27 million tons, up from 23 million tons in 1993. (Government documents of this sort are not covered by copyright in Japan: the original can be found at: http://www.meti.go.jp/policy/nonferrous_metal/strategy/aluminium02.pdf).

aluminium industry to engage him in a series of unusual prototypes, advancing the structural use of aluminium.

As with many globally available commodities, the price of aluminium 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 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 aluminium increased dramatically, growing from 23-million metric tons in 1993 to 27-million in 1997 (Fig. 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 its market for aluminum. This led to the establishment in 1994 of the Aluminium Architectural Structures Association (アルミニウム建築構造推進協議会).

At the beginning of 1998, a number of well-regarded architectural professionals were invited by the Japan Aluminium Association (日本アルミニウム協会) to discuss new strategies for aluminium in buildings.[8] Toyo Ito chaired the group, the 'Home and Aluminium Study Group' (住まいとアルミ研究会), which would come to advocate aluminium 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 Organisation) offered subsidies for the development of a demonstration house developed by the Home and Aluminium Study Group under the title 'Eco Building Material House Technology Development' (エコ素材住宅の技術開発).[9] Reference to ecology may seem odd to Westerners aware of the embodied energy in aluminium 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 the light of the two- to three-decade lifespan of most Japanese houses.

With NEDO support, two prototype structures were built out of aluminium for research purposes only. These were then quickly followed by the first fully aluminium structure built for long-term residential use—with exterior finishes, floor and roof slabs, shear walls, columns and beams all aluminium—designed in the late 1990s by Toyo Ito and the structural engineer Masato Araya, consulting closely with the Building Centre of Japan (日本建築センター), a

Figure 2. Sakurajōsui House (© *Tomio Ohashi*).

quasi-governmental organisation. The house was completed in January, 2000.

'Aluminum House' or 'House in Sakurajōsui' (桜上水の家 or K邸)

This trailblazing all-aluminium 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 黒の回帰 ; Fig. 2).[10] Sakurajōsui is a neighburhood 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 older and more affluent parents after their children had grown—and, more importantly, Ito was at the peak of his career, creating the Sendai Mediathéque.

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

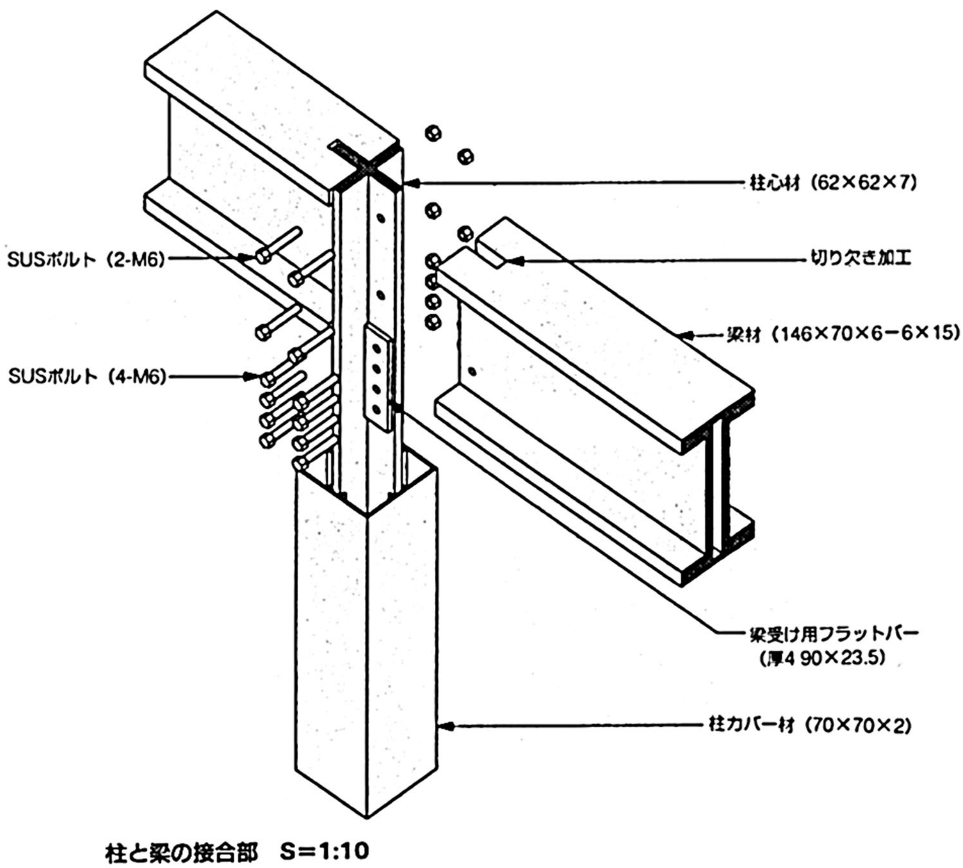

Figure 3. Double-web beam and cruciform column connection (© *Toyo Ito & Associates*).

while they were still working in Kimura's office. The architect's close collaborations with structural engineers usually exploit their own proclivities and passions. For example, his 2002 Serpentine Gallery was a response to Cecil Balmond's passion for number theory; Sendai Mediathéque, 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]

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. 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 aluminium, 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 aluminium structure and forty days for interior work.[13] It is worth noting that there were many novel 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's and Ito's overall approach. The shape was an innovation that Araya proposed, in the light of Ito's general inclination towards thinness. It was stiffer than a single-web beam, addressing aluminium's greater ductility (Fig. 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 is a watchmaker's detailing, fully highlighting 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 aluminium components. This reduced the need for trim, but expanded the number of specialised 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 aluminium buildings that followed, as reflecting the fundamental character of aluminium—but at a cost, in both time and money.

At the time this house was built, aluminium was not officially accepted as a structural material under Japanese building codes. It was not until 2002 that 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 aluminium's poor performance in fires.

Figure 4. Aluminium components were lightweight and easy to handle on site (© *Toyo Ito & Associates*).

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 (Fig. 4). The house has an 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-storey 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-metre (925-square-foot) house is only 4.2 metres (13 feet 9 inches), which significantly reduced the depth of the roof slab (Fig. 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

Figure 5. Plan organisation yielded short structural spans (© *Photograph by Shinkenchiku-sha*).

walls and floors and the effective thermal conductivity of aluminium were the source of this discomfort. Thermal breaks, it should be noted, are not yet used in Japanese aluminium 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 aluminium, seismic forces were addressed with diagonal bracing. However, Araya instead complemented the framework of columns and beams with aluminium 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 realise over time that when aluminium is welded, its strength is compromised; late projects would rely more on bolted connections. But in this first permanent application of an all-alu-

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Figure 6. On-site welds were intended to create a water-resistant surface (© *Toyo Ito & Associates*).

minium structural system, channel ribs at wall and roof were welded together on site (figs 6, 7). Since the aluminium 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 aluminium were resolved in the house through a rich collaboration between architect, engineer and industry. Araya and Ito both shared an interest in exploring an unusual structural material 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 for 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


Figure 7. Neatly integrated components (© *Toyo Ito & Associates*).

practical to explore such unique extrusions for what was, after all, a relatively small house; 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 observations, the aluminium industry initiated this effort not simply to produce a unique residential prototype by two influential professionals, but to encourage broader demand for aluminium by fostering new structural uses for the product. Ito and Araya were able to demonstrate innovative techniques to overcome the inherent challenges of aluminium, incorporating short beam spans and new structural forms (a double-web beam and tube-encased cruciform column) to address aluminium'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 the fact that aluminium 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 state that this first experience caused the architect and engineer to remain interested in the structural use of aluminium, but aware of drawbacks in their initial approach.

The Bruges (*Brugge*) pavilion

The second aluminium structure Ito and Araya designed together was a small, temporary structure in Bruges, Belgium, completed in 2002 (Fig. 8). A cathedral once sat where Burg Square is today, the site of Ito's and Araya's pavilion. French Republicans destroyed the church in 1799; important archaeological remains exist only a metre below ground, inspiring the designers again to propose aluminium, due to its light weight.[18] The aethereal structure nonetheless totalled 8 metric tons (17,637 pounds)—but the load at the wall was a relatively acceptable

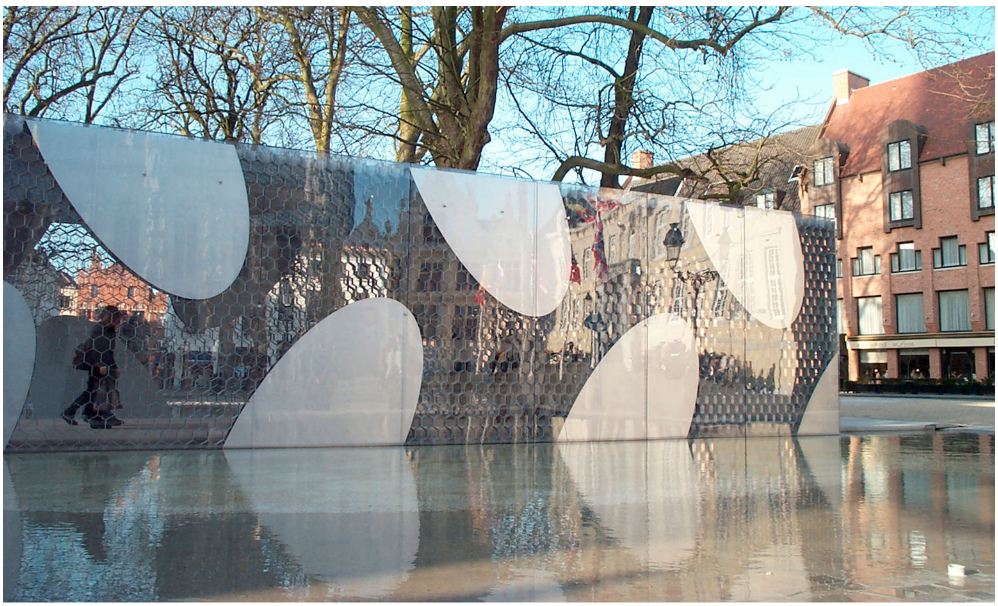

Figure 8. Bruges (*Brugge*) pavilion (© *Stefaan Ysenbrandt*).

250 kilos per linear metre (400 pounds per linear foot).

Araya has pointed out that aluminium 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 aluminium being used, increasing the weight compared to a post-and-beam structure.

The pavilion took a considerably different approach from the building 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) aluminium strips, folded into shape and welded. The original proposal was for a tunnel-like structure 8 metres (26 feet) wide and 28 metres (nearly 92 feet) long, but due to cautious structural testing, the size was reduced to about 85% of the original, a tube 6.75 metres (roughly 22 feet) wide and 16 metres (just over 52-1/2 feet) long. It was 3.75 metres (just over 12 feet) tall.

With the exception of the Belgian building, all of the aluminium 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, the 'House in Sakurajōsui' (as well as the other Japa-

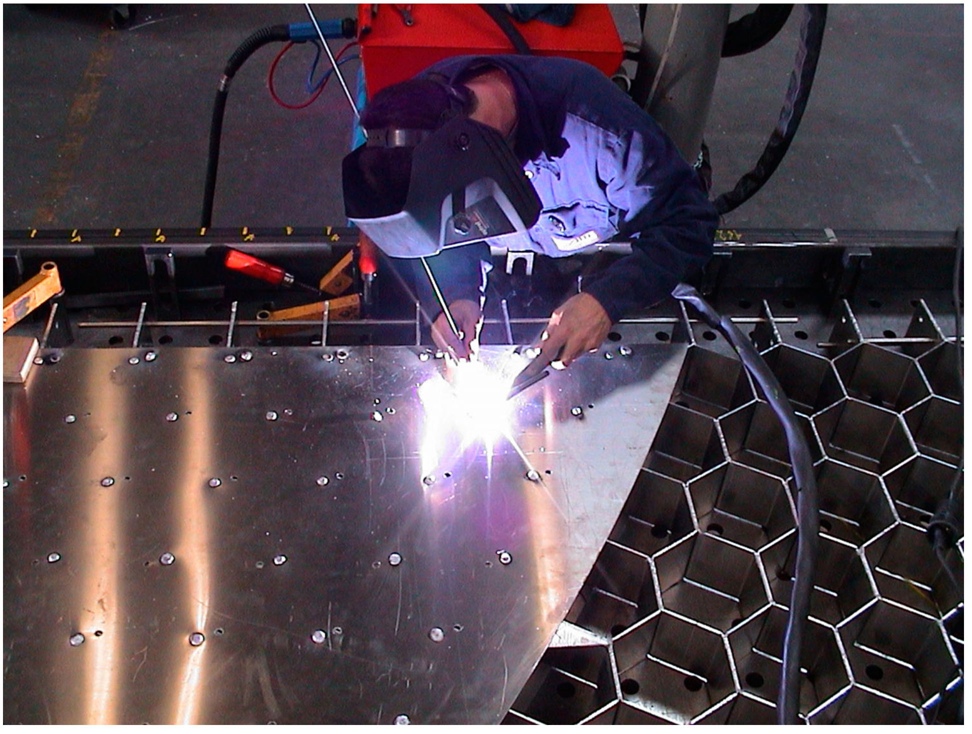

Figure 9. Aluminium welding (© *Toyo Ito & Associates*).

nese projects that were to follow) benefited from strong industry support, which reduced the cost of developing these customised aluminium extrusions significantly and gave the architect and engineer an unusual level of technical support. The parts for every one of their jointly designed aluminium structures were fabricated in Japan—except for the Bruges pavilion.

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

Thus the honeycomb panels for the Bruges pavilion were handcrafted; Araya wrote that this level

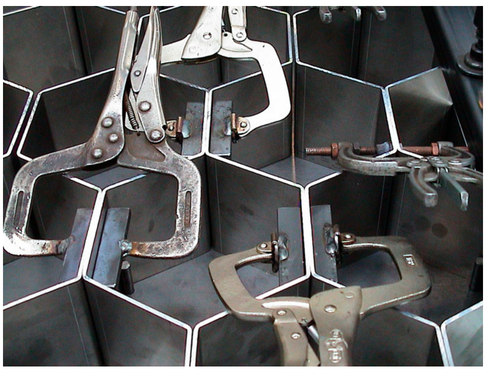

Figure 10. Assembling the honeycomb from aluminium strips (© *Toyo Ito & Associates*).

of aluminium 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 7,500 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 aluminium 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 (Fig. 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 through-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 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 the Sakurajōsui House was completed), Araya realised that 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 (Fig. 12). In a draft version of Araya's essay about this experience for the Japanese magazine *Shinkenchiku* (新建築), he repeated two adages that 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 the 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

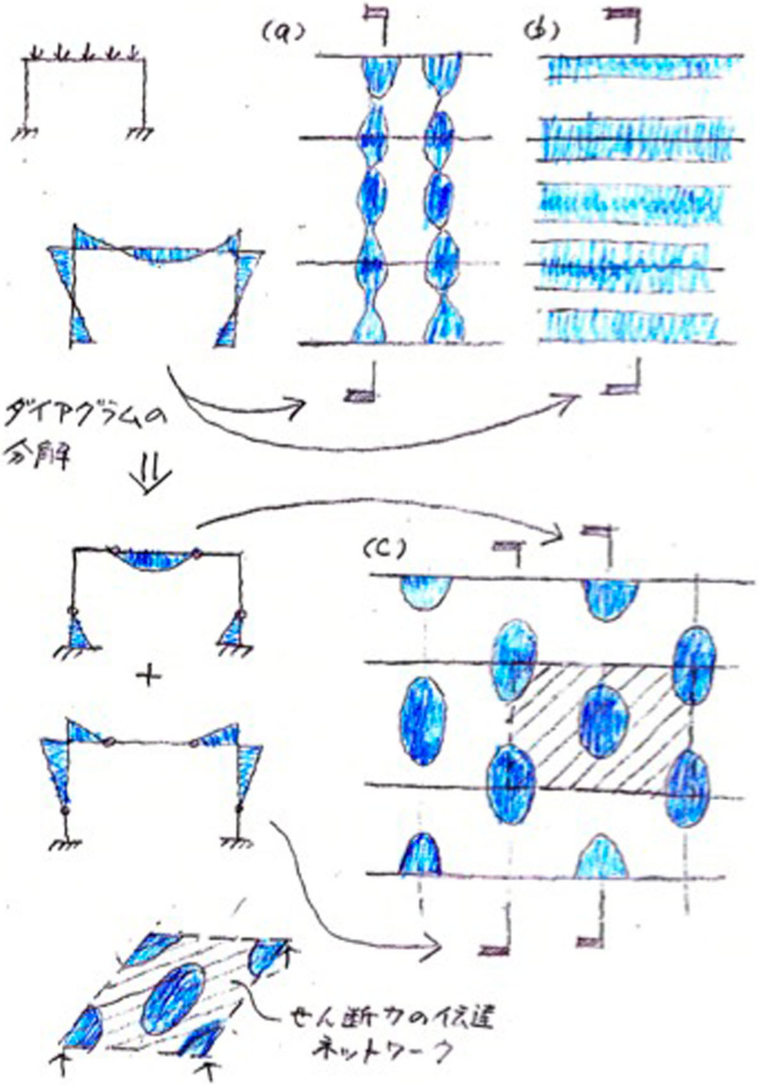

Figure 11. An early sketch shows how the 'ornamental' ovals were deployed at locations where moment was highest (© *Masato Araya, Oak Structure Design Office*).

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Figure 12. Deflection of honeycomb was tested through full-scale mock-ups (© *Toyo Ito & Associates*).

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 Aluminium House at Sakurajōsui, extensive prefabrication in the shop considerably sped up work on site, a particular benefit considering the cultural significance of Burg Square (Fig. 13). 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; aluminium 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 Bruges 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 Mayor of Bruges approved the popular pavilion for

Figure 13. Prefabricated panels were slipped into place on site (© *Toyo Ito & Associates*).

continuing 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 aluminium remained sound; it was cut into smaller sections with a torch (not following the 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 aluminium structures Araya and Ito designed together, a 490-square-metre (5275-square-feet) dormitory, was completed five years after the House in Sakurajōsui. Their earlier buildings used aluminium in a linear arrangement of right angles; here the designers created gently curving

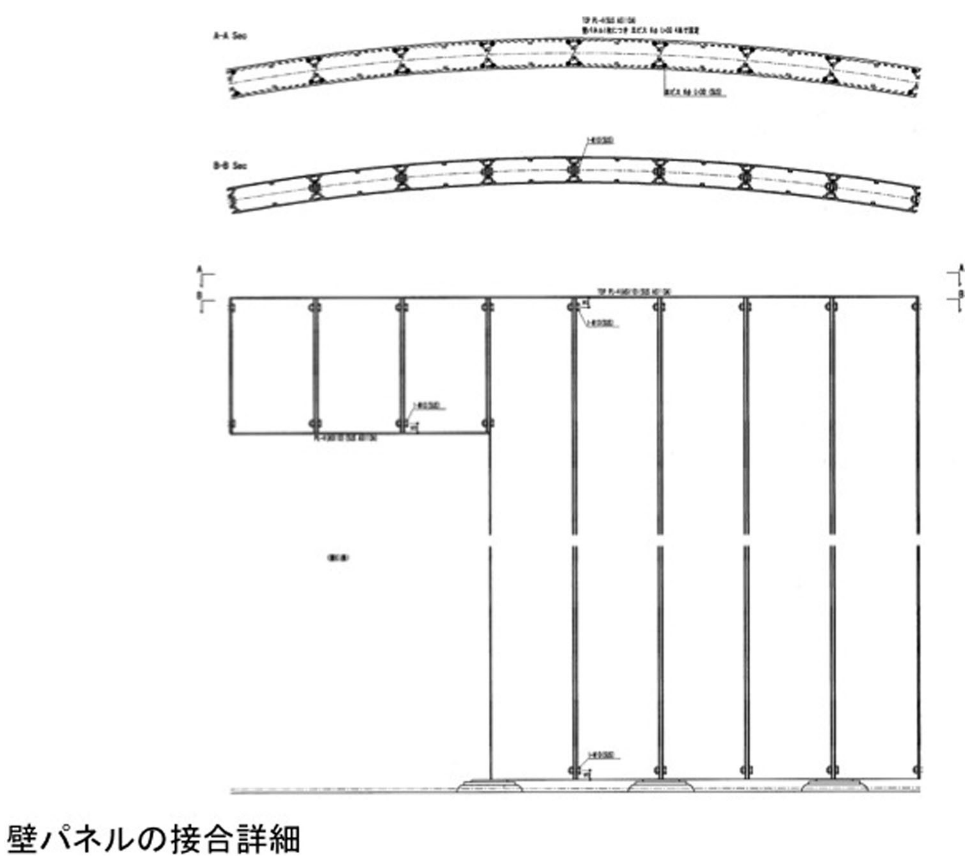

Figure 14. Panels with two radii were used to produce the gentle curves (© *Toyo Ito & Associates).*

walls of extruded planks (250 mm/9-7/8″ wide) only 70 mm (2″) thick. With only two die shapes—radii at 5.4 metres (17 feet, 9-1/2 inches) and 13.5 metres (44 feet, 3-1/2 inches)—the walls were laid out in loosely undulating lines (Fig. 14). A closed-box plank rather than a channel, the components carried both gravity load and lateral stresses caused by earthquakes (Fig. 15). 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.

Figure 15. Setting the slim walls (© *Toyo Ito & Associates*).

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 aluminium 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 (Fig. 16). And while architects in Japan did not at this time customarily insulate buildings, care was taken to enclose the interior thermally; 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 (figs 17, 18).

Figure 16. The plan shows how the dormitory-room layout takes into account sound transmission and fire safety by applying an open, cellular structure (© *Toyo Ito & Associates*).

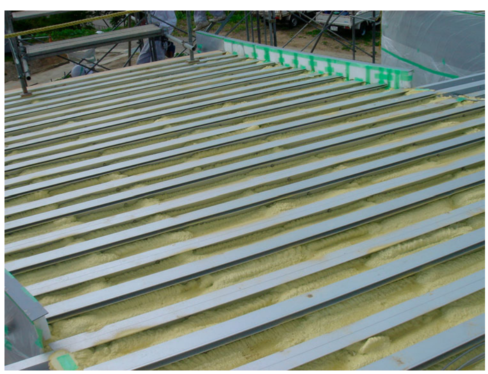

Figure 17. An interior layer of wall insulation addressed thermal bridging (© *Toda Kensetsu*).

Figure 18. Roof insulation (© Toda Kensetsu).

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 the light of the industry partners with which the designers were working. Mass production, it can be argued, is a more logical approach to using aluminium extrusions than small one-off buildings, since the cost of dies used to make unique shapes could be spread across greater use. Ito and Araya developed the aluminium cottage from June, 2002 to August, 2004, with the oldest Japanese aluminium producer, the Nippon Light Metal Company (日本軽金属); the aluminium 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 aluminium in novel ways, but only Ito and Araya, clear leaders, were able to collaborate with more than one aluminium-industry 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—aluminium, after all, resists decay and mould. The structure was built out of channel-shaped panels and cruciform columns, complemented by aluminium cross braces and an internal layer of structural plywood that enhanced rigidity and, it was hoped, acted as a thermal break. In August, 2003, Nippon Light Metal applied for four patents to protect its intellection property, naming Ito as a co-applicant and inventor (Fig. 19). 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.

As with the other aluminium 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 metres—less than 10 feet—apart, so did not require much foundation work.) Five unique extrusions were utilised, but instead of using an extruded profile to transfer stress between panels (inefficient since the profiles did not fit tightly), the cottage incorporated a special paint on the abutting faces of channels to increase friction.[25]

In the Autumn, 2004, Nippon Light Metal announced that it would bring the cottage to market in April, 2005. The 75-square-metre (800-square-foot) prototype had a stated cost about thirty million yen (US$330,000). This came to a fairly pricey $4400 per square metre ($408 per square foot) without land costs and soft costs such as 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' (加工費). 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 reach the market. The prototype, however, was still in its original setting in 2008 and in use promotionally (Fig. 20).[27]

The Journal
of Architecture
Volume 21
Number 1

JP 2005-68994 A 2005.3.17

(19) **日本国特許庁(JP)**　　(12) **公 開 特 許 公 報(A)**　　(11) 特許出願公開番号
特開2005-68994
(P2005-68994A)
(43) 公開日　**平成17年3月17日(2005. 3. 17)**

(51) Int.Cl.⁷	F I	テーマコード（参考）
E04B 1/343	E04B 1/343 K	

審査請求 未請求　請求項の数 19　ＯＬ　（全 27 頁）

(21) 出願番号	特願2004-245250 (P2004-245250)	(71) 出願人	502255818 株式会社伊東豊雄建築設計事務所 東京都渋谷区渋谷１丁目１９番４号
(22) 出願日	平成16年8月25日 (2004. 8. 25)	(71) 出願人	000004743 日本軽金属株式会社 東京都品川区東品川二丁目２番２０号
(62) 分割の表示	特願2003-208901 (P2003-208901)の分割	(74) 代理人	100064414 弁理士　磯野　道造
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最終頁に続く

(54) 【発明の名称】 建物

(57)【要約】
【課題】　構造材が外装材を兼ねた建物であって、プレファブ構法の利点を活かしながらも、斬新で洗練されたデザインを採用することができ、且つ、容易に組み立てることができる建物を提供することを課題とし、さらには、屋根勾配を有しながらも床と壁との接合構造と屋根と壁との接合構造とを同一にすることができる建物を提供することを課題とする。
【解決手段】　枠状に形成された複数のユニットＵ１を奥行方向に連接して建物を構成する。また、ユニットＵ１を、等脚台形を呈する一対の壁構成材１０，１０と、壁構成材１０，１０の上辺間に架設された等脚台形を呈する屋根構成材２０と、壁構成材１０，１０の下辺間に配設された床構成材３０とで構成する。
【選択図】　図４

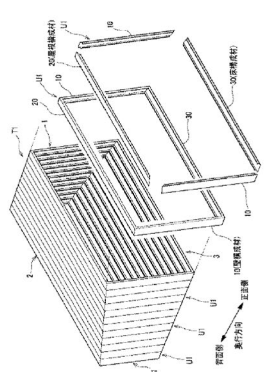

Figure 19. Patent document depicts the aluminium cottage's wall construction.

Figure 20. Aluminium cottage prototype (© *Tsuneho Asada*).

The container's prototype constituted 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 (Fig. 21). 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 aluminium cottage took twenty-one months to develop.

The column-free space within the container was 2.78 metres (9 feet 1-1/2 inches) tall and 3.7 metres (12 feet 1-1/2 inches) wide; it was 6 metres (19 feet 6-1/4 inches) long.[28] Its name, 'sudare' (簾), referred to traditional Japanese blinds. Ninety-two extruded plank-like components

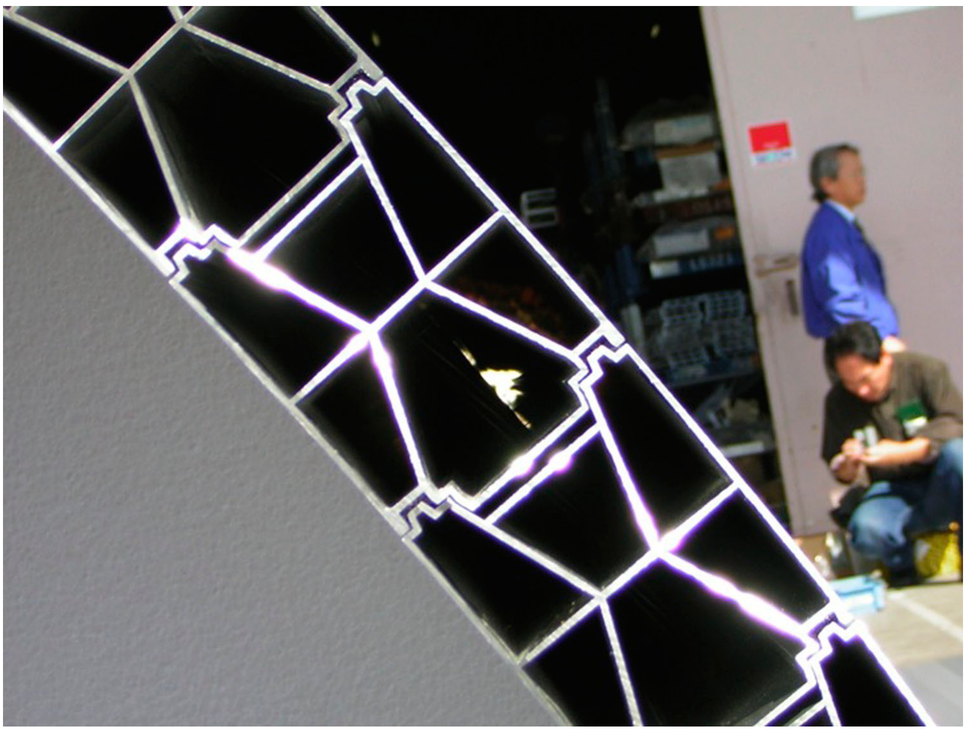

Figure 21. Aluminium container, extrusion detail (© *Masato Araya, Oak Structure Design Office*).

were assembled into a flexible sheet at the plant, strung like beads along cables spaced half a metre (20 inches) apart (Fig. 22). On site, they were pulled into shape over template-like false-work. 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 (Fig. 23). Even though aluminium was employed, the container weighed 2 tons—roughly the same as a similarly-sized steel shipping container.[29] This is probably due to the additional material making up the cellular structure of each extrusion. The result, whilst 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.

Figure 22. Aluminium container, showing cable connections (© *Masato Araya, Oak Structure Design Office*).

Finally, Ito and Araya's 'aluminium brick' screen, a façade that tied together a new structure and an 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 aluminium structures (Fig. 24). 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 (日本軽金属) and Shinnikkei (新日軽), and shipped to Holland for assembly. As built the screen 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 in which the small units connected. The aluminium 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 where major earthquakes occur, as in Japan.

The end of another aluminum age

Together, Ito and Araya designed six aluminium 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 lavatories 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.

In addition to these two designers, who played the largest role in exploring new uses of aluminium, suppliers worked with other respected architects during this period, including Riken Yamamoto, Kazuhiro Nanba, Mikan Gumi and Coelacanth K&H (the last working with Araya on a model house built with off-the-shelf parts). One other engineering office, the considerably larger Iljima 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 lavatories erected in southern Japan.

Most of these structures were produced with subsidies and industry R+D support, outside the normal regulatory oversight within which architects and engineers generally work. Some were inhabitable, but not strictly considered to be buildings. Some—the Bruges pavilion, *sudare*—benefited from the greater freedom allowed temporary works. The House at Sakurajōsui complied with earlier prescriptive building codes that had not anticipated the lower yield point of aluminium, essentially conforming to the letter of the law, but skirting its intentions.

Figure 23. Aluminium container, with plank size evident (© *Masato Araya, Oak Structure Design Office*).

But later regulatory changes did permit the use of aluminium; the dormitory was built with conventional oversight and the aluminium cottage was planned within regulations, though it did not undergo building approvals.

Japanese professionals, especially those of the stature of 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 aluminium industry and these building design professionals were able to develop an experimental body of work that fell between their conventional territories to test whether aluminium could be economically adapted to new structural uses. Whilst the body of work they developed did not establish new markets, they were able to make discoveries about its potential which will probably trigger later investigations into aluminium as a structural material.

Figure 24. Aluminium brick façade (© *Wim te Brake*).

And Ito and Araya benefited professionally from these endeavours. 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 aluminium, recognising the first house again, the two overseas projects and an aluminium mudsill in another project not included here. The aluminium-related collaborations between Ito and Araya were also widely published at home and abroad.

Suppliers aggressively promoted this work. A subsidiary of SUS, *ecoms*, began publishing a quarterly magazine under the same name in January, 2003, featuring a variety of works using aluminium 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; the grand prize was a million yen (roughly $8,500 in 2003). In the first year, with Ito chairing the jury, there were over 450 entries.[30] Design professionals who had employed aluminium in novel ways were not only jurors, but also paid speakers at various professional events.

The market response to these aggressive efforts to advance new uses of aluminium in architecture was, however, modest. In retrospect, the close collaborations with industry, and the unusual extrusions that were central to each Japanese project, probably discouraged broader acceptance of aluminium 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 aluminium, starting with the Sakurajōsui house by Ito and Araya. Although there were still proposals in development, the monograph covers all the novel aluminium structures designed with industry support; no more were built. Another 'Age of Aluminium' was coming to an end.

It might be said that the final curtain of this era of experimentation occurred on 11th

March, 2011. The SUS dormitory Ito and Araya is located in Fukushima Prefecture, not far from the nuclear plants that melted down following a severe earthquake. Affordable aluminium production, even when involving recycled aluminium, requires cheap electricity to accomplish—in the mid-twentieth century Reynolds Metals proudly referred to the material as 'solid electricity'.[31] Production usually occurs in the context 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 aluminium's light weight, durability and recyclability, became far less practical.

Araya continued to pursue more limited research on aluminium in his Waseda University laboratory. 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, analysed the structural performance of challenging new forms (eg, curved honeycomb) and tested as-yet unsuccessful proposals to address the low melting point of aluminium with water-filled structural sections. But in Spring, 2014, he reached mandatory retirement age at his university, and lost the use of its intellectual and physical resources. Without a research laboratory or research assistants, Araya's aluminium experiments thus came to an end.

Japan offers architects and engineers the rare opportunities to develop unusual prototypes through collaboration with industry. But in the case of aluminium, this collaboration may also have prevented broader adoption by building professionals who did not have access to similar levels of subsidy and industry support. In fact, the attention and awards that Ito and Araya received for their work on aluminium were due to its groundbreaking applications of hard-to-access technologies. Other designers who followed would, ironically, have been perceived as less innovative unless they were able also to 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 Aluminium', conflicts between the goals of professional and production communities, left unresolved, had already created the reasons for its end.

Acknowledgements

The Author is grateful to both Masato Araya and Toyo Ito for their time and support (including the interviews conducted with them in Tokyo during December, 2013 and January, 2014).

Work on the structural innovations of Toyo Ito and Masato Araya 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);

'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);

'Structural Innovations in Japanese Architecture', University of California Humanities Grant for translation support (2000–1) and University of California Academic Senate Junior Faculty Research Grant (2000–1).

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4. I am grateful to Shimizu Construction's Toshiyuki Yamada for bringing the Japanese materials to my attention many years ago.
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9. 「アルミの家ができるまで」['Aluminium House to Completion'], 室内 [*Shitsu Nai*] (November,1999), p. 149; NEDO 「エコ素材住宅の技術開発にかんする研究」: 'Development of Ecology Housing Technology', # 98Z33-018.
10. My interviews and informal discussions with Toyo Ito about his work have taken place over a period of seventeen years, starting with my weekly visits to Sendai Mediathéque 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.
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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*. I have written more on how Ito and Sasaki, working closely with steel fabricators, built Sendai Mediathéque: see my *Japanese Architecture as a Collaborative Process: Opportunities in a flexible construction culture* (London, Spon Press, 2001).

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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 her 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*.
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