

Reciprocal Frame Architecture in Japan

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Abstract

Reciprocal Frame Structures (RF) are a form of a three-dimensional grillage structure. In their simplest configuration they are formed by placing beams in a closed circuit in which each beam is supported by the preceding beam at the inner end, and by an external wall or ring beam on the outer end. In their more complex configurations gridshell-like structures with a double curvature can be formed. Although RFs have been used in many countries throughout history and are known under different names: Serlio-type ceiling; Reciprocal frames, Svastica structures, Nexorades, Lever-arch structures etc., they are not widely known and used in buildings. The most beautiful contemporary examples have been built in Japan. This paper describes and analyses the contemporary Japanese RF examples from the point of view of structural behaviour, geometry, configuration, detailing, materials used and architectural qualities of the buildings.

Keywords: Reciprocal Frames, Advanced Structures, Structural Morphology, Architecture

1. Introduction

One can make the case that RFs are an example of an advanced structure because they have a role beyond the traditional one to carry and transfer the loads. To a great degree RFs are part of the architectural expression and contribute to the qualities of the spaces they enclose, Popovic Larsen [1]. RFs have been used in different countries throughout history and appear in different forms and under different names such as ‘Serlio-type ceiling; Reciprocal frames, Svastica structures, Nexorades, Lever-arch structures etc. One must however start by posing the obvious question: “What is a Reciprocal Frame?”

The reciprocal frame is a three dimensional grillage structure mainly used as a roof structure consisting of mutually supporting sloping beams placed in a closed circuit. The inner end of each beam rests and is supported by the adjacent beam. At the outer end the beams are supported by an external wall, ring beam or by columns. The mutually supporting radiating beams placed tangentially around a central point of symmetry form an inner polygon. The outer ends of the beams form an outer polygon or a circle. If the RF is used as a roof structure the inner polygon gives an opportunity of having a roof light.

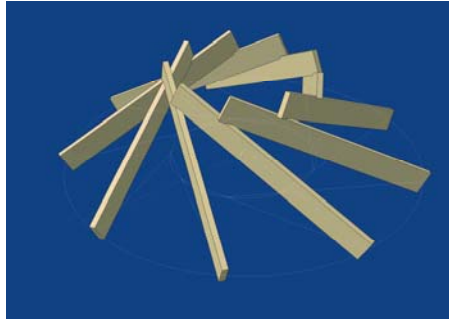


Figure 1 Typical RF structure

The RF principle in the form of a flat configuration has been used throughout history, the main difference to the RF being that in the flat structures the beams were connected in the same plane instead of being inclined as in the case of the RF. Flat grillages have typically been used for forming ceilings and floors when timbers of sufficient length were not available. Examples are the structures developed by Serlio, da Vinci, Honecourt and others.

The geometrical characteristics of the structure offer a great number of possibilities for it to be used on both regular and irregular plan forms and also, to be constructed out of different materials. Although most of the RF buildings constructed to date are regular, the RF can be used to cover almost any form in plan. This versatility of the structure makes it possible for the RF to be used on buildings with very different functions, indeed, for any function.

2. Reciprocal Frames in Japan

It is very difficult, if not impossible to establish where the first RFs were built. Although examples of RFs and similar structures appear in many cultures sometimes simultaneously, as these structures have not had a common name over the centuries of their development, one cannot establish where the structure originated.

However, it is evident that the most sophisticated both architecturally and structurally are the contemporary examples built in Japan by designers Kazuhiro Ishii, Yasufumi Kijima and Yoichi Kan. Before going into detail of their RF work, it is important to present the Japanese context that has probably influenced the sophisticated RF designs.

2.1. The Japanese context

There are many reasons why RFs of such architectural merit have been designed and built in Japan. It is interesting that all RFs, but one, in Japan have been constructed out of timber and that the “old” and the “new” influences of history are interlaced in their designs. The ‘Sukiya’ concept can be traced in the work of Architect Kazuhiro Ishii.

This is not unusual because Japan is renowned for the use of timber in construction. Throughout Japanese tradition, trees were objects of worship and the ‘godly nature of trees has been raised to an art which can be felt in the architecture of wood’. The main use of timber construction was a ‘post and beam’ structure, most probably as a protection against earthquake. Timber construction in Japan has been developed to perfection, especially in the details of timber joints which are a very sophisticated method of dissipating earthquake energy.

The other most important influence, on the other hand, the ‘Sukiya’ is a style used mainly for residential architecture and was developed in the 15th century. As Itoh stated, ‘it evokes a world of associations with buildings in which the traditional fondness for natural materials, simplicity, and closeness to nature dominates every detail of the composition’. Sukiya developed as a result of consideration of the aesthetics of a house, the search for its own beauty, so that the ‘sakui’ (the creative will) of the individual had the highest priority. The Sukiya concept is very important because it stresses the importance of individualism and creativity of design for the first time in Japanese architectural history.

The word ‘Sukiya’ means teahouse in its basic sense, but, in its broadest sense it is any structure built with the architectural techniques of the teahouse. Both the use of timber in a sophisticated way and the influence of ‘Sukiya’, especially in the work of Ishii, can be easily traced in the contemporary RF designs.

2.2. Kazuhiro Ishii

The work of architect Kazuhiro Ishii is of great sophistication and artistic depth incorporating the influences of the “new” but deeply connecting it with the “old” and rooting it into the Japanese context. It is therefore not surprising that Ishii’s RF designs are of such architectural merit, too.

One of his first RF projects, was the ‘Spinning’ house, the only RF structure in Japan that has been designed in steel. All other examples in Japan have been built in timber. The ‘Spinning’ house was designed in 1985 by Ishii for the Enomoto family and is situated in the residential district Tamagawa Gauken in Tokyo. It is a steel framed house with spiralling steel Vierendeel trusses, externally clad with exposed prefabricated concrete panels. It is on a small hill on a tight urban site and is organised over three levels with bedrooms radially arranged on the ground floor around a central hall. The living room area is on the second floor and there is a study on the third floor. The longest span is about 5 metres. The steel RF structure, made of Vierendeel trusses, is the only part of the building that can be seen from a distance. As one comes very close, the rest of the house becomes visible too.



Figure 2: The Spinning House

The client wanted a different house, one that would have a lot of light inside the building. Ishii came up with the idea of using a RF structure. Inspired by the method of holding hands where there is no support for the load at the cross points of an arm and a hand, support being given at the outer end, by Islamic drawings as well as by the spinning of the planets in the cosmos, Ishii created this unusual house.

Another example of a RF design by Ishii is the Sukiya Yu house where the RF structure creates the roof of the guest-entertaining building. The house was built in 1990 in Asakuchi-gun, in Okayama Prefecture. The wealthy client Mrs Yasuda had commissioned Ishii to design her a retirement home because she had seen and was impressed by the cultural centre, school and swimming pool buildings that Ishii designed at the nearby Naoshima Island. There was a long process of negotiation between her and Ishii. The design of the Sukiya Yu house took nearly two and a half years and the building took another year and a half to construct. Over this time the design was changed more than ten times and it was only because of the mutual understanding, respect, trust and the patience of the architect and client that the house was built to the satisfaction of all.



Figure 3 Interior view to Sukiya Yu showing the RF structure

The house is positioned on a relatively big plot of land in beautifully landscaped gardens in a residential area in the small town of 5000-6000 inhabitants, Asakuchi-gun, in Okayama Prefecture. It is a particularly generous site for Japanese conditions, where houses are closely built together and hardly have any garden. Sukiya Yu's entrance is on the densely populated side of the residential district. At the back the house is surrounded by beautiful

countryside planted with berries, bamboo shoots and other indigenous plants arranged in a way to complement the design of the house.

Sukiya Yu is an unusual house in that it is not built into one volume as most houses would be. Instead the house is organised in several small buildings, some of which are interconnected with corridors and some of which are free standing. It forms a small hamlet, a village consisting of several very distinct buildings. Thus, the name for this house, 'Yu', which means 'village consisting of different houses'.

'Sukiya', has been used in residential Japanese architecture and is closely connected to the sensual and spiritual experiences of tea ceremony houses. In architectural terms Sukiya is a calm and refined style used in the past by wealthy people in Japan for building their residences. The spaces in Sukiya are usually organised as a number of separate spaces attached to a central space. They create a community of their own. The calmness is achieved by refined detailing and use of timber. There is hardly any decoration, especially not any golden decoration. Everything is just calm and refined.

The building in which the RF structure is used is an entertaining space, seven metres in span, named Yu-an. The horizontally overlapping timber RF beams support the wooden dome. The circular plan, the door openings, the interior with the folding shrines and the construction details are all traditional. With addition of the wooden geodesic dome, the building becomes an interesting combination of old and new. It is a free-standing building positioned away from the main house overlooking the beautiful garden. The main space of the building has a roof structure in the form of a Buckminster Fuller dome which is held up by a double opposite direction spiralling RF structure. The whole building is enclosed by sliding panels that are formed in the traditional Japanese way.

The detailing is very precise and refined. To make sure that all the geometry was right the contractors first built 1:5 models of the interlocking joints. When they were sure that the geometry was correct they scaled up the notched timber interlocking beams and constructed the roof. Untreated Canadian pine for the roof was used because it was cheaper than to build the roof from local timber.

It is worth mentioning that all the timber beams are pre-cut to high precision so that the members slot into each other, just like a 3D puzzle or a Meccano set. They had to fit perfectly to make the whole structure fit together, especially because there are no metal connectors used in any of the joints. They are held in position because they all slot into each other perfectly. The RF structure in this building is in the form of interlocking beams that form a ring which supports the geodesic dome forming the roof. There are two RF structures in this roof: one with RF beams spiralling clockwise, interlocked with another RF structure consisting of beams spiralling anti-clockwise. In this building it is clear that the architect and the engineer have worked closely together. The double spiral of RF beams

overcomes the risk of progressive collapse. In the event of an earthquake, if one set of spiralling RF beams loses a member the other spiral will take over and provide structural stability. In addition the complex joints, based on traditional Japanese joints with no metal connectors, also help in the event of dynamic loading. They allow for movement so that if there was an earthquake, the whole building would sway and move with it. Thus the energy is dissipated, making this an earthquake-resistant structure. Apart from being a stable and earthquake-resistant structure, it is also a very beautiful structure, one whose presence enhances the architect's aspiration to create a new, contemporary, Sukiya style.

The Bunraku Puppet Theatre designed by Kazahiro Ishii is set in the town of Seiwa in Kumamoto Prefecture, Southern Japan. It is set in the landscape surrounded by dramatic high hills which form a backdrop and a natural border to the site. It is a complex of four distinct buildings, each distinct but brought together through the use of a common architectural language. All the buildings use timber for their structure and all of them except the newly built restaurant use an RF structure in some form. The structures are very much part of the overall architectural language, and to a great degree contribute in creating its particular architectural expression. The structures used are all different and define each space in a very sophisticated way.



Figure 4 Seiwa Bunraku Puppet Theatre complex

The complex consists of four free standing buildings in the landscape: a Puppet Theatre with auditorium; an exhibition hall building; and the shop and cafe in a separate building. A recent addition to the complex is the new building that houses the restaurant.

Inspired by writings about a Buddhist Monk called Chogen who lived in Nara in the 12th century and who had used spiral layering of timber to create structures Ishii created the RF structure for the exhibition building. The RF in the exhibition building is probably the most impressive of all the RFs on the site. It forms a thirteen metre high space which is flooded in light from the windows and the roof light.

Part of the architectural expression is achieved by using a RF structure for the roof which is left exposed and is visible in the space. The twelve RF beams that form the roof structure

are supported by a woven structure which consists of two flat RFs spiralling in opposite directions and supporting each other. The RF structure is only apparent when entering the exhibition hall, because externally the roof is clad with ceramic tiles laid on rafters concentrically. The exposure of the RF only in the interior of the exhibition hall adds to a visitor's astonishment when noticing the roof for the first time after entering the space.

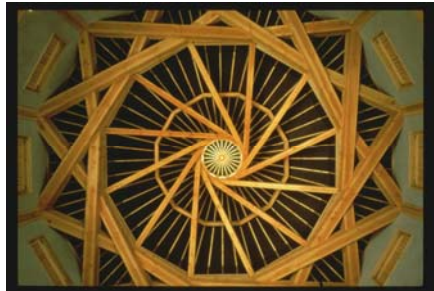


Figure 5 Seiwa exhibition hall RF structure

The detailing in this building is done by using carpentry joints that are based on traditional Japanese 'Vatariago' joints. None of them use any metal connectors. The architect, Ishii, and the engineer, Tadashi Hamauzu, worked very closely to develop the structure that fits and complements the architectural expression envisaged by Ishii. This can be seen by looking closely at the building design. The technical necessities are resolved so that they are part of the architecture. The buckling protection of the columns is clearly part of the overall architectural expression. Also, the ring of opposite direction spiralling RF beams that support the RF roof structure is relatively heavy, which helps against wind uplift but at the same time mirrors old, traditional Japanese roof structures. It is both utilitarian and beautiful. And, as for the most amazing pieces of architecture, it is difficult to decide what came first: the need for a particular architectural expression or the necessity to resolve it in a technically viable way. The two are part of one inseparable whole, a very refined piece of architecture.

The other building on the site is the auditorium building which is connected to the exhibition building via a covered but open walkway. Inside the auditorium building the architect has used a planner grillage structure (in Japan referred to as 'chop stick structure') to create the roof and the ceiling. One could describe it as a flat type of RF structure, consisting of relatively short timbers that are interlocked and create a woven effect.

The atmosphere and the feeling in the auditorium are very different to the exhibition space. It is a very dark and oppressive space. The roof structure which is left exposed in the space adds to the feeling of weight. It is a very heavy interlocked grillage consisting of timber beams that overlap each other to form the roof structure. At the points where the timber

beams cross each other and interlock, the overall section (of all three members) exceeds one metre in depth. It is a heavy weight hanging over our heads, making us feel the oppressiveness of the space almost physically. The structure mirrors the stories that are told in the theatre: they are sad ones that tell us about the hardship of people who suffered from the Samurai. They are stories about love, money, loss, etc. but they are always sad stories.



Figure 6 The Auditorium building in Seiwa

The other two buildings on the site, although different, are equally successful. The shop and café are housed in an elongated and curved-in plan building whose roof truss uses RF principles. It is a truss where interlocking beams that are shorter than the span are used which, although different to a RF structure, has some resemblance to it. In a way it is similar to the temporary bridges that Leonardo da Vinci designed.

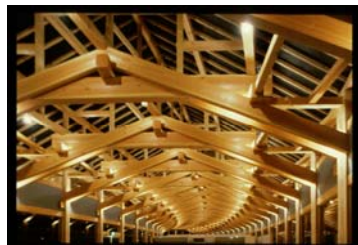


Figure 7 The shop and café building's roof structure

The last building on the site, the restaurant, was erected in 2004. Although very different to the three buildings described so far, it is interesting how Ishii has been able to work with the same theme of grillage structures and develop it a stage further. And although the restaurant structure does not work like a RF, it takes the idea of the RF to another level of development, one that complements the architect's vision.

2.3. Yasufumi Kijima

The late architect Yasufumi Kijima designed the Toyoson Stonemason Museum using a complex RF structure. The building with an area of approximately 800 m² consists of three distinct cylindrical volumes: the exhibition building and the multi-purpose hall, both of

which have shallow metal-clad conical surface roofs, are linked by the administration building which has a flat roof. The exhibition building houses all the changing exhibitions as well as the permanent exhibit, a 10m long replica of a stone arch bridge. The administration building consists of an entrance hall, an office and a cafe. The multi-purpose hall is used for meetings, lectures and some other functions. When looking at the building externally one cannot tell that the two main volumes, the exhibition building and the multi-purpose hall, have been formed by the use of multiple roof structures. The complex reciprocal frames are only visible to the visitors when they enter the spaces.



Figure 8 The roof under construction

The RF structures that are used on this building are truly unique. At first view the exposed round-wood cypress poles look as if they have been arranged in a chaotic way: there are poles pointing in the most unexpected directions. Yet after just a few moments studying the roof it is obvious that there is a clear hierarchy and that the pattern formed by the roof poles creates a very regular overlapping star-shape arrangement. At the centre, the apex of the roof is a regular hexagonal RF unit which is supported by a combination of three-member single RF units combined with hexagonal RF units. Due to the geometrical characteristics of the multiple reciprocal frames, the 'in-between' units are four sided regular polygons in the shape of rhomboids that interlace between the triangles and the hexagons.

Kijima was an architect who strongly believed in the integration of structure and architecture. He had a great interest in how things are put together and how one can, as an architect, create structural forms that complement the overall design. During his working life he was both a practitioner at the practice Keikaku-Inc he established in Tokyo and an academic: he was a professor at Kumamoto University where he taught for over twenty years until his death. In addition he was always at the cutting edge of architectural and engineering research. Just after his graduation at Waseda University in 1962 he went for six months to the Eduardo Torroja Research Institute in Madrid to research and study concrete shell structures and their application in architecture. Later in life he became a member of the International Association of Shell and Spatial Structures (IASS) and attended all the conferences where he often talked about his cutting edge design projects. He was a person with many interests and someone who could create most amazing structural forms as part of his architecture.

2.4. Yoichi Kan

Yoichi Kan, a structural engineer and the Managing Director of Pal Corporation Group, a building design consultancy that employs about 65 people grew up in a family of carpenters in the countryside of the island of Shikoku. He designed the Life Sciences Laboratory—Torikabuto, which is an environmental research and learning centre. Mr Kan has designed and built this centre as a research laboratory of design and construction of buildings that support the environment, use natural resources such as rain water, solar energy and educate young people about these issues rooted in the Japanese context.

Within the complex he designed the New Farmhouse which has a reciprocal frame roof. The building is square in plan and, following the Japanese traditional farmhouse design, it has four rooms divided by sliding partitions but no corridors. The spaces flow into one another and are formed by closing or opening the sliding partitions. It is the reciprocal frame roof with the external walls that creates the enclosure. The greater than usual height for accommodation rooms and the lack of furniture makes the spaces feel larger than they really are. The spaces have a warm feeling because of the light that comes in and because of the use of natural materials. The beautifully detailed cedar wood used for the structure of the building adds to the feeling of warmth.

The span of the New Farmhouse building is 8 metres. The eight RF beams that form the roof structure are quite small in section. They are 15 cm wide and 30 cm deep. Mr Kan calculated the beams so that they would take their own weight and the weight of the roof including wind and snow loads. This is the only RF design which has no notches, and because of this it was possible to use extremely slender RF members for the structure.

The notched RF design used on other buildings creates a particular expression. However, it also has some disadvantages. By notching the beam at the point of highest shear stress (each beam contributes with its own weight in a point load applied to the supporting beam) the beam is weakened at the least desirable place because of which greater beam sections are required to achieve the needed load bearing capacity. Obviously this makes the structure less efficient, and although structural efficiency is not always (and should not) be the most important factor in deciding on the type of structure to be used for a particular building, one must agree that it is an important one to consider. Perhaps a more important implication is the overall architectural expression achieved when notched beams are used or not. In the first case the relatively larger sections needed for the RF beams will contribute to a heavier looking structure. This, as shown in the other examples may be fully appropriate and justified for some RF buildings and may be part of the whole aesthetic expression and narrative of the particular building. In the same way the lightness of the structure of the New Farmhouse is part of the architectural expression of this building.



Figure 9 The New Farmhouse building – internal view

Perhaps it is not only the RF New Farmhouse and its innovative design that make this place special. It is the whole context and idea behind the creation of Torikabuto that are special. In the last 20 years Yoichi Kan has shared his knowledge about life sciences by running a non-profit summer school for children here. Every year school children of 7–14 years of age from all over Japan and from abroad come and stay at Torikabuto for a few weeks. At this Life Sciences Laboratory they learn about Nature and how to be part of it, about Japanese culture and traditions, about growing herbs, fruit and vegetables, renewable power, reusing and recycling and about natural structures. Most importantly they learn about the ‘seed’ that Kan has planted by creating Torikabuto, a seed that can grow and spread and maybe become the way of life for the future generations. It can help them live in a more sustainable way and as part of Nature.

3. Conclusions

Japan is the home of the most sophisticated RFs from the point of view of architectural, spatial and aesthetic values of the spaces, but also from a structural point of view. This paper aimed at presenting a tiny segment of the Japanese contemporary architectural scene, but one that has a great importance in leading the way forwards in the field of Reciprocal Frame Architecture.

Acknowledgements

The author of this paper would like to express the gratitude to designers Kazuhiro Ishii and Yoichi Kan for their invaluable input and for supporting this research project. Without their help it would have not been possible to understand the full depth and context of the Japanese RFs. Also, great thanks go to Hiroshi Sawazaki, director of Keikaku-Inc, where deceased Yusufumi Kijima practiced, for providing information about his work.

References

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