Rapid construction of modular buildings using the 'Reciprocal Frame'

O. Popovic[a], J.C. Chilton[a], B.S. Choo[b]
[a]*School of Architecture, University of Nottingham, Nottingham NG7 2RD, UK*
[b]*Civil Engineering Department, University of Nottingham, Nottingham NG7 2RD, UK*

Abstract

The paper describes the use of the 'Reciprocal Frame' roof structure (RF) for modular buildings. Advantages, such as rapid construction and the variety of possible internal functions are demonstrated. The construction process both of temporary and permanent RF industrialised buildings is described, together with the principal advantages and disadvantages of the system. Finally, some examples of existing buildings are presented.

1. Introduction

When rapid construction of buildings is necessary then one of the main criteria is to have a system which consists of as few easily assembled modular elements as possible. Very often architects argue that industrialised design is by its very nature monotonous and of no real architectural value because most of the elements used to form the buildings are identical. On the other hand, as Nissen[16] stated "...most of nature's forms are composed of identical elements, and yet the effects are far from monotonous...". If the Reciprocal Frame structural system is to be used for rapid construction of buildings, it could provide a greater variety of forms than any other conventional industrialised system. The result would, therefore, be buildings of greater architectural qualities.

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2. The Reciprocal Frame

The Reciprocal Frame is the patented name for a three-dimensional grillage roof structure. It consists of sloping beams which, at the outer end, could rest on a wall or column, and at the inner end rest on each other (Fig 1). The number of beams, the sizes of the inner and outer polygons and material (timber, glulam, steel, reinforced concrete etc.) can vary depending on the function which needs to be accommodated in the building. For short span structures, the beam cross sections need not change over their lengths however, for long span structures, members with varying cross sections, bow-string beams, or trusses can be used. The resistance to vertical loads is by bending and shear rather than axial forces, as reported by Chilton and Choo[5]. Both the maximum moment and shear force are most likely to occur at or near the point where the adjacent beam rests on the beam under consideration. Therefore, if tapered beams are to be used, the best solution would be to have the deepest cross section where the beams rest on each other, whilst it gradually decreases towards both ends of the beams.

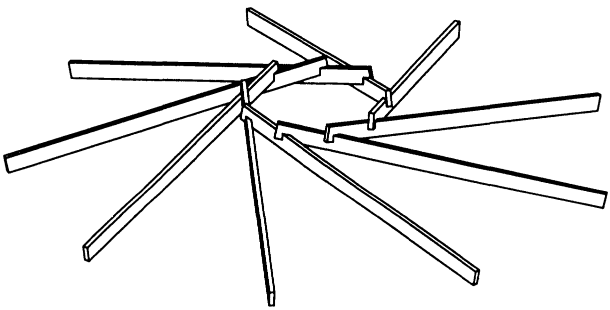

Figure 1: The Reciprocal Frame roof structure

3. Modular design of buildings using the RF

The idea of industrialisation in construction is to increase efficiency by use of standardised modular elements, but at the same time to maintain the personal and individualistic elements of the design. Ehrenkrantz[7] states that "...buildings need to be designed for people and not the other way round - people who will fit in the buildings...". This is often very difficult to achieve by industrialised construction. Unfortunately, the modular industrialised systems employed in the construction of blocks of flats in Eastern Europe through the fifties and sixties do themselves no favours. Most of these buildings, have neither personal nor architectural values.

On the other hand, if one looks at buildings constructed of lightweight modular elements, especially by using timber or steel posts and beams, or frame systems, the results are more pleasing. Lightweight industrialised systems give the possibility of having partly or fully glazed elevations and open plan

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organisation of the function. Rapid construction of buildings using the RF can be achieved because for regular plan forms all the structural elements (columns and beams) will be identical. The structure can be classified as a special type of modular lightweight system which employs regular polygonal or circular rather than the commonly used rectilinear modules. Construction of temporary and permanent buildings can be achieved using the RF system with only differences in the building materials, details used and way of construction.

Zuk and Clark[19] stated that "...architecture had often been called 'frozen music', considered as permanent expression of an age, the petrifaction of an idea or the recording in stone of an isolated fragment of history...". On the other hand if we look at nature it is more than obvious that every single cell evolves and changes over time. Life itself is in permanent motion. If the motion would cease life would cease, too. Therefore, as Rowan[17] stated "... the main task is to unfreeze architecture - to make it a fluid, vibrating, changeable backdrop for the varied and constantly changing modes of life...". Temporary RF buildings would have these qualities - they could create architecture which would be capable of kinetic movement, changing as life itself changes. These buildings could be a form of contemporary marquees, having the enclosure formed by a membrane, which would be hung from the beams of the RF structure. They could be used as temporary structures for shelter, concerts, exhibitions, village fairs, travelling circuses etc. They could be very rapidly erected (exploded) and disassembled when they are no longer needed. Although there are no such RF tents built to date, there is no reason why the idea could not become reality in the near future.

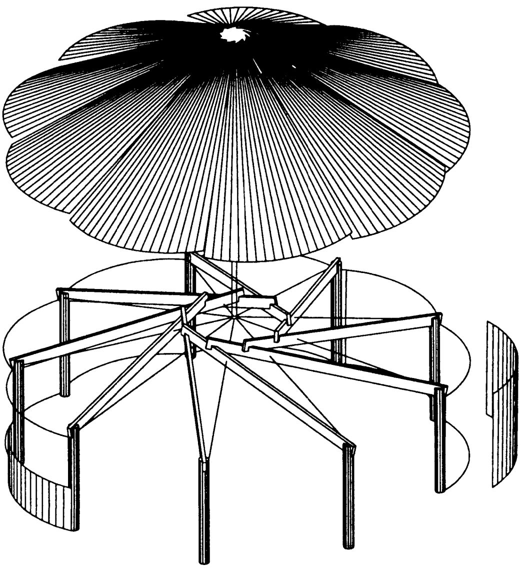

Figure 2: A temporary RF building - tent

On the other hand, permanent RF buildings need to be constructed of suitable materials which enable easy transportation and rapid construction. One of the main characteristics of the RF system is that no internal supports are needed to support the main elements of the roof structure. Consequently, it opens up the possibility of designing free and flexible architectural spaces required by assembly buildings such as exhibition and community halls, restaurants, kindergartens and hospitals. It can also be used for buildings which need subdivided spaces, but it favours an offset radial division of space, with walls descending from the beams. This results in the formation of segmental spaces and the consequent difficulty of fitting furniture within them.

The most appropriate span for RF modular buildings is in the range 6-15 m. The RF is also applicable for much longer spans, but the increased size and weight both of the panels and main structural elements makes the construction more complicated in that transportation to the site is more difficult, a crane becomes necessary for lifting etc.

Although, the 3-d geometry and, therefore, the construction details are more complicated than for other conventional industrialised systems, once designed they can be repeated as many times as necessary. Although the more complicated 3-d geometry of the buildings will increase the cost it will undoubtedly contribute to their architectural qualities, due to the infinite variety of plan forms which can be achieved. The comparison used by Ehrenkrantz [7] "...in the textile industry, one sees how different patterns of cloth are standardised, and then how the individual can have the cloth sewn to fit his own needs..." can be adequately applied to RF modular buildings. The variety of forms is a result of the possibility to vary the number of beams (and vertical supports) and in that way create basic modules of regular polygons comprising three to any number of sides. Another variation of the system could be the formation of a cluster of RFs within a building or clusters of RF buildings. This could be used instead of longer span structures. This would make the transportation and construction easier (because of the smaller sizes and weights of the elements). Some possibilities of clustered RF buildings are presented on Fig. 3.

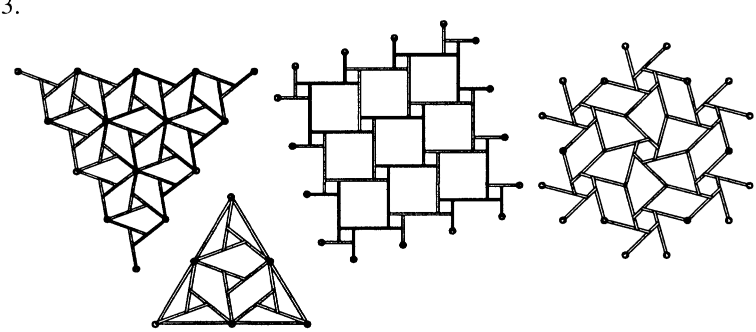

Figure 3: Some possibilities of RF clustered modular buildings

4. Construction of RF buildings

The construction of the RF modular buildings would differ depending on whether they are to be temporary (RF tents) or to accommodate a more permanent function.

Temporary RF buildings need to be

- constructed rapidly (several minutes to several hours)
- of lightweight materials (for easy transportation)
- of reversible construction process (for disassembly and transportation to another site).

Although, RF tents have not been constructed to date, some preliminary research for small scale buildings has been done by Chilton[4] . He looked at the possibility of joining each column with an associated beam with a hinge which allows the beam to be folded parallel to the column for transportation to site, where they would be unfolded, the columns erected and all the beams joined at their inner ends so that they support each other. This would be an easy and fast way of forming the structure. Similarly, the envelope needs to be designed for simple and fast construction.

Another possibility of creating kinetic architecture would be to design an expandable the RF system. The research on expandable structures goes back to the sixties, as reported by Escrig[8] , when Emilio Peres Piñero, designed his foldable trusses. More recently, as reported by Fong[9], Levane and Cecilia[15], and Blaser[3], Santiago Calatrava designed a number of buildings which employ movement. The closest to the idea of the RF tent, is his design for a restaurant roof structure in Zurich which is composed of nine metal and glass trees 12 metres high. They are operated mechanically to provide shelter for the restaurant underneath and each of them folds and unfolds in a sequence with the others. The small scale RF structures could be designed in a similar way, so that the whole assembly of beams and columns is brought and simply unfolded on the site.

The idea of expandable structures has thoroughly been researched by Hoberman in the last few years, see Hoberman[10, 11], Wick[18]. His main interest are "structures which are at the same time mechanisms" capable of complete transformation in three-dimensions, as reported in Architecture[2]. The objects range from collapsible luggage boxes and portable storm shelters to stadium roofs which open and close like the iris of an eye. He has also designed the expandable sphere displayed in the atrium of the New Jersey's Liberty Science Centre. The expansion in Hoberman's structures is achieved by the scissorslike movements of hinged elements relative to one another. It may be that such techniques or similar can be found to make RF structures expandable along similar lines.

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The construction techniques employed in other forms of deployable structures such as temporary military bridges, self-erecting camping devices and emergency shelters could be applied to RF structures.

Experience to date has shown that the construction of permanent modular RF buildings can be very fast and fairly simple. All the elements which form the structure can be prefabricated in a workshop before being brought on site for assembly. If the envelope of the building is also prefabricated in a workshop, then the entire construction process can be completed in only few days.

The construction starts with the casting of foundations on site and the assembly of the columns, RF beams, wall and roof panels. The materials used will determine both the sizes of the structural elements as well as the details. To date RF buildings have been constructed of timber columns which support the timber or glulam RF beams, the enclosure of the buildings being achieved by well insulated lightweight panels. Also, a combination of different materials for the structure (exposed concrete round columns or steel columns with glulam beams) could contribute to the final architectural image of the building. All the column-beam, and beam-beam joints and construction details need to be very carefully designed, because otherwise it would be impossible to assemble the elements. This is especially important for the sloping beams, which when made of timber, are notched in order to form the roof structure. For the roof to be constructed a prop is needed to support the RF beams, at their inner end, until they can form a full circle (polygon) and are able to support each other.

A ring beam is not needed either at the outer or at the inner end of the RF beams, since the beams are primarily in bending and shear, rather than axial forces. A typical RF modular building is presented on Fig. 4.

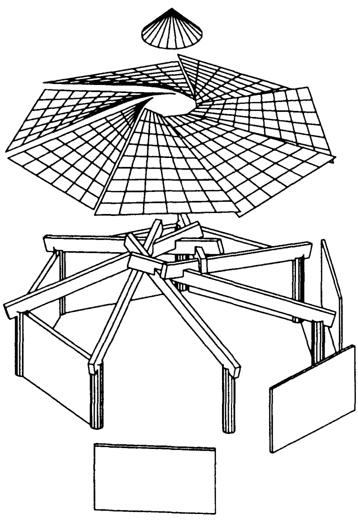

Figure 4: Modular RF building

5. Built examples

The "movement-orientated architectural space" is a concept that has been used in traditional Japanese architecture, as Inoue[12] reported. Therefore, it is not surpassing that, most probably the first idea for the "spiralling beam structure" came from Japan as early as the 12th Century, as stated in the Japan Architect[1]. Since then the dynamic forms in Japanese timber construction have evolved considerably. Contemporary examples of Japanese RF buildings demonstrate a traditional and sophisticated use of timber in both design and construction.

The private house of the engineer Youchi Kan, designed in 1992, uses an 8 beam RF structure over a square plan, with a span of about 8 metres. The steep roof beams are connected to the timber columns with traditional Japanese joints, without any metal connectors, as reported by Chilton, Choo and Popovic[6].

The contemporary Japanese architect Kazuhiro Ishii used the structure on several of his buildings, such as: the Seiwa Bunraku Puppet Theatre, near Kumamoto on the island of Kyushu in southern Japan, the Yu house, in Sukiya style and on the Enomoto residence (Spinning house) in Tokyo. Inspired by the Buddhist tradition of spiralling beams, Ishii[14] designed the 12 beam RF roof structure over the exhibition hall of the theatre. It actually consists of two, very low-pitched interwoven RFs which support the 7 metre diameter RF over them. The parlour of the Yu house, also has a RF structure which is interwoven clockwise and anticlockwise and over a span of 8 m supports a lamella dome. Both RF structures provide very good earthquake resistance, having many energy dissipating joints and, at the same time, overcoming the danger of progressive collapse by use of a double spiralling system of beams. The RF structure in the Enomoto residence, as reported by Ishii[15], is composed of steel Vierendeel trusses.

Another good example of an exposed RF structure in contemporary Japanese architecture is the Stonemason Museum, designed by Yusufi Kijima. The woven effect of the timber RF beams considerably enhances the quality of the interior spaces of the museum.

Because of lack of information it is very hard to make definitive statements about the construction of these buildings. On the other hand, it is very likely that the roof elements of the above described buildings have been previously prefabricated in a workshop and assembled on the site.

There are also examples of modular RF buildings in the UK built since 1988. They all have regular plan forms (polygonal or circular) and are all constructed from timber elements. The spans range from 4.2 to 13 metres. For the shorter spans plain timber beams, and for the longer spans glulam members, have been used, as reported by Chilton[4]. The smallest RF buildings, no more than gazebos, at 4.2 m. in diameter possess only one space and are utilised for meditation spaces. There are several built in the UK (in Findhorn Bay,

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Oxfordshire, Nottingham etc.) The interior space is well proportioned and the oak finish makes them pleasant to be in. All the building parts were prefabricated and assembled on site.

The Findhorn spiritual community has built two RF roofs over recycled whisky barrels (6m diameter) and both buildings are used as dwellings. Both buildings have open plan organised spaces with a bath in the middle and a sleeping loft over it.

An 11 metres diameter, 2 bedroom house was constructed in Ferryhill, Forres, Morayshire in 1993. It has a gallery over the bedrooms which are formed using partitions which follow the beam lines. As a result of this, the rooms have irregular forms without right angles. This is one of the main disadvantages of partitioned RF modular buildings. The house has a sky light over the main hall which lets in sunlight into the house. It is constructed of timber panels which incorporate columns supporting 405 mm deep by 115 mm wide glulam beams. The outer timber frame "breathing" walls are externally clad with lapped larch boarding and insulated with 14.5 mm Warmcel cellulose insulation. All the structural elements for this building were prefabricated in a workshop and the construction was completed in only one day.

The longest span RF modular building is an unfinished 13 metres diameter house at Saorsa, Ardlach, Nairn, Scotland. In plan it is a regular 10 sided polygon, and the main structure, as in the previous house, has timber columns, supporting ten 450 mm deep by 140 mm wide glulam beams. The enclosure is made of breathing insulated walls and roof panels finished with cedar shingles. Due to the magnitude of the shear forces, at the notches, the glulam beams needed to be strengthened by metal fixings. Again, the construction took only three days because all the beams, wall and roof panels were prefabricated in a workshop.

6. Conclusions and future development

This paper described the modular construction of RF based systems which have been used for permanent functions and the possible use for temporary buildings. Preliminary ideas for RF expandable structures have been presented with directions for future research. Various construction methods as well as the built examples of RF modular buildings have been described. The existing RF buildings in the UK were rapidly constructed resulting in open plan layout, with roof light and, sometimes, a gallery. Even though these buildings were easy to build, their design was not straight forward (fitting a function in a polygonal plan and complicated 3-d construction details). Open plan functions were easier to organise then functions which required internal divisions of the spaces.

The system provides some advantages, but also some disadvantages, when compared to other more conventional industrialised systems of construction. The main advantages of the RF modular system are:

- a greater variety of plan forms can be achieved

- open plan functions can be easily accommodated
- higher spaces, galleries and roof lights are possible
- the exposed RF structure contributes to the qualities of the interior spaces.

Some of the disadvantages of the RF modular system are:
- the details are complicated to design
- partitioned spaces need to be well designed.

The main advantage of the RF system is the greater spatial qualities which it provides. The speed of construction of RF permanent modular buildings is comparable to that of other lightweight industrialised systems. On the other hand, temporary RF buildings can be erected in a relatively short period of time (minutes) if appropriate expanding mechanisms are developed. Therefore, future research should be directed to achieve this aim.

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