"RECIPROCAL FRAME STRUCTURES"

by Olga Popovic MSc, Arch.

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If we think of defeat
that is what we get.

If we are undecided, then
nothing will happen to us.

We must just pick something
great to do - and do it.

Never think of failure.

For what we think now,
that is what we get.

Maharishi Mahesh Yogi

Acknowledgements

I would like to thank my first supervisor Dr. J. C. Chilton for his continued support and encouragement throughout this research project. At a time of doubt he introduced me to the above words of M.M.Yogi. Without his research idea the magnificent world of the Reciprocal Frame would have remained unknown to me and this project would not have been possible. I would also like to thank my second supervisor Dr. B. S. Choo from the Civil Engineering Department for his support, advice and guidance during my research. I am grateful to both my supervisors for their continued help and advice throughout my efforts to provide the necessary funding for my research and stay in this country. Without their help it would have been impossible for me to be here and have this great opportunity to read for a PhD.

The funding for my project has been obtained through a number of scholarships from the UK, USA, FYR of Macedonia, private funding and occasional tutorials at the School of Architecture, University of Nottingham. I am most grateful to all who have financially made this research possible.

At this point I would like to express my gratitude to G. Brown who came up with such an interesting idea about a pile of mutually supporting sticks. I would also like to thank him for showing me his constructed RF buildings in Scotland and for sharing with me his experiences regarding the structure.

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All the work presented in this thesis has been done using the computers at the University of Nottingham, most of it at the School of Architecture, and a part in the Engineering CAD Studio, Department of Civil Engineering, and Cripps Computing Centre. Without the use of these facilities this work would have not been possible.

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Olga Popovic

Summary

This thesis attempts an investigation of the Reciprocal Frame (RF) structure from the architectural point of view. The **Introduction (Chapter 1)** sets out the research subject and introduces the reader to the RF structure. **Chapter 2** investigates the origin of the structure and offers a survey of similar types of systems used throughout human history. Also, a review of 'kinetic' forms of architecture is presented. **Chapter 3** investigates Japanese RF construction and the possible reasons for the emergence of the system in Japan as early as the 12th century. **Chapter 4** examines the potential of the system for modular construction of both temporary and permanent RF buildings, with a review of RF modular buildings constructed in the UK. **Chapter 5** explores different RF morphologies on a student project case study, as well as their design experiences and opinions when using the RF system. More practical issues regarding the RF are presented in **Chapter 6** which investigates the parameters which define the 2-dimensional and 3-dimensional geometry of the system and their variation, methods for simplifying the CAD presentation of the structure, alternative covering systems, and the possibility of using the RF as a retractable roof. **Chapter 7** offers conclusions and aspects of future research on the system. The **Appendices** at the end include: two types of questionnaires and the complete transcribed interviews used to examine the students' design experiences and opinions, a routine in AutoLISP written by the author which simplifies the CAD presentation of the RF, and copies of the five Conference papers, published using the findings of this research project.

Contents

CHAPTER 1: Introduction

When the title "Reciprocal Frame Structures" is mentioned it hardly means anything even to people who are from the field - architects and engineers (unless they are already familiar with it for one reason or another). Therefore, they tend to ask what the research is actually about and what is a Reciprocal Frame (RF)? To ordinary people the name certainly does not mean much.

From the title one can easily get the impression that the subject belongs to the field of frame structures, but then, why 'reciprocal'? What does 'reciprocal' signify when describing a structure and what kind of quality does it add to the frame structure, if any at all?

It is obvious that it is necessary to start by defining the subject of this research: The Reciprocal Frame Structure.

1.1. Statement of the problem

The Reciprocal Frame (RF) is a 3-dimensional grillage structure constructed of a closed circuit of mutually supporting beams. *"... Each beam in the grillage is placed tangentially around a central closed curve so that it rests upon the preceding beam and this procedure is continued until the ring is complete. An* *enclosed polygon is, formed with a set of radiating beams equal in number to the sides of the polygon. The outer end of each beam rests on a perimeter support, such as column or wall, and the inner end rests on the following adjacent beam whilst in turn supporting the inner end of the preceding beam."* (Chilton,1994, p.22).

The RF, as presented on Figure 1.1, has been developed in the UK. The name 'Reciprocal Frame' was given by the patentee, Graham Brown, because of the way the beams mutually support each other.

In the Oxford Dictionary the word 'reciprocal' has several meanings:

Mathematical - so related to another that their product is unity;

Adjective - in return (e.g. I helped him and he helped me in return)

which represent the appearance and the behavior of the unified structure in which each beam supports, and in turn is supported, by all of the others.

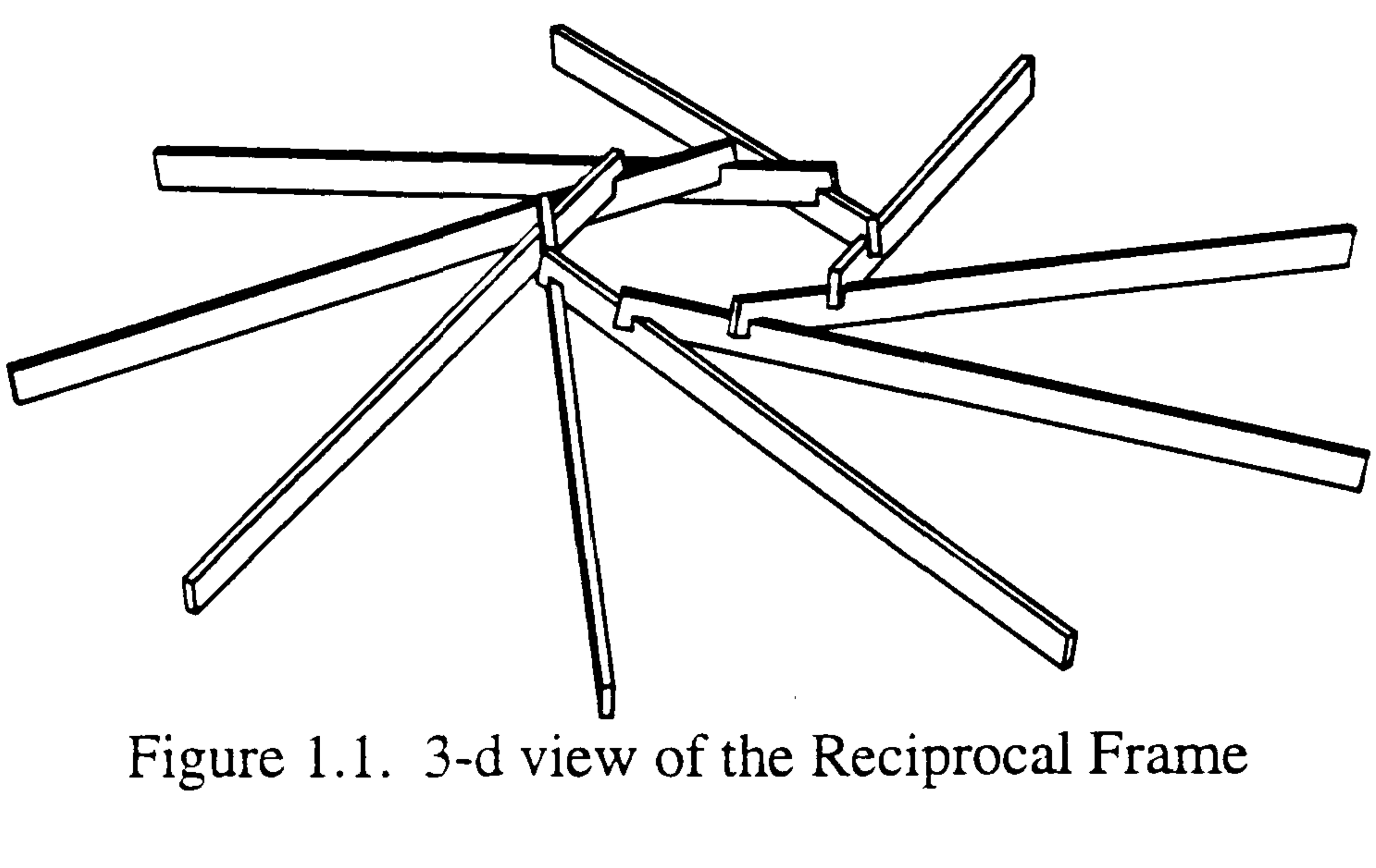


Figure 1.1. 3-d view of the Reciprocal Frame

The most appropriate forms of buildings (in plan) using the RF are circular, elliptical and regular polygonal forms. So far, most of the buildings constructed using the RF, have regular polygonal or circular plans. In the case of using regular plan forms all RF members are identical, which provides the possibility of modular RF construction. Most RF buildings constructed to date in the UK, and which are discussed in the thesis, are of modular construction.

The circular plan form is one of the first used. Many vernacular buildings throughout human history (mud huts, cave dwellings etc.) had approximately circular plan forms. They would appear to have a protective, womb-like quality. Also, circular and regular polygonal forms are typical for buildings of major significance, such as churches, concert halls, sports stadia, museums etc.

If suitable materials are used for the main RF members, such as reinforced-concrete, glued-laminated (glulam) timber, steel beams or trusses, the RF could span short and long distances with equal success. Because of the most common plan forms (polygonal, circular) the organization of the function and division of the internal spaces of the RF buildings are different from buildings with rectilinear plan forms. Since no internal supports are needed, the RF forms a very flexible architectural space. It is interesting to note that the beams which form the RF are not radial (as shown in Figure 1.1), unlike most of the roof structures over buildings with circular plan forms.

On the other hand, since the inner and the outer polygons are defined by the end points of the beams, which can have different lengths, the RF can be used to cover almost any form in plan.

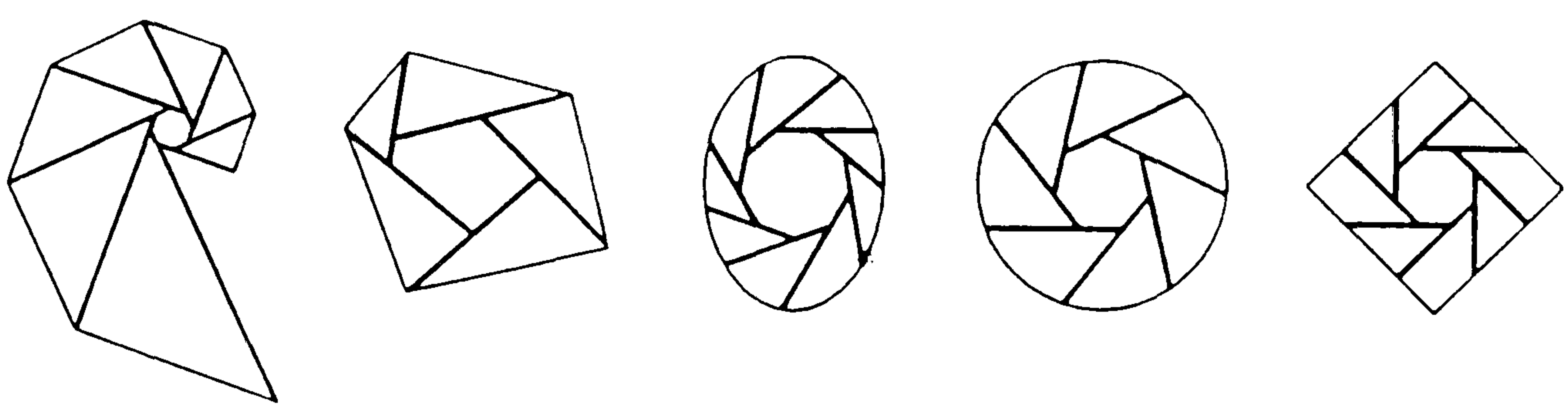


Figure 1.2. Some alternative plan forms with RF grillages

The possibility of creating an infinite variety of plan forms, and at the same time incorporating different spans, makes it possible for the structure to be used on buildings with very different functions, indeed, for any function. To date, since the structure is known to very few architects, it has been underused and its great potential remains unexplored. The contemporary use of the RF has been mostly for housing and for very few other functions. No research, so far, has been carried out on possible RF morphologies. In the context of this research project the term "morphology" has the meaning: form of the (RF) structure.

The beams of the RF, when viewed in plan, remind one very much of the iris of a camera shutter (as shown on Figure 1.3) and it is very easy to envisage the possibility of creating kinetic architecture with the RF. Retractable RF structures could be a possible solution for covering sports stadia and long-span multipurpose spaces (Chilton, Choo and Coulliete, 1994).

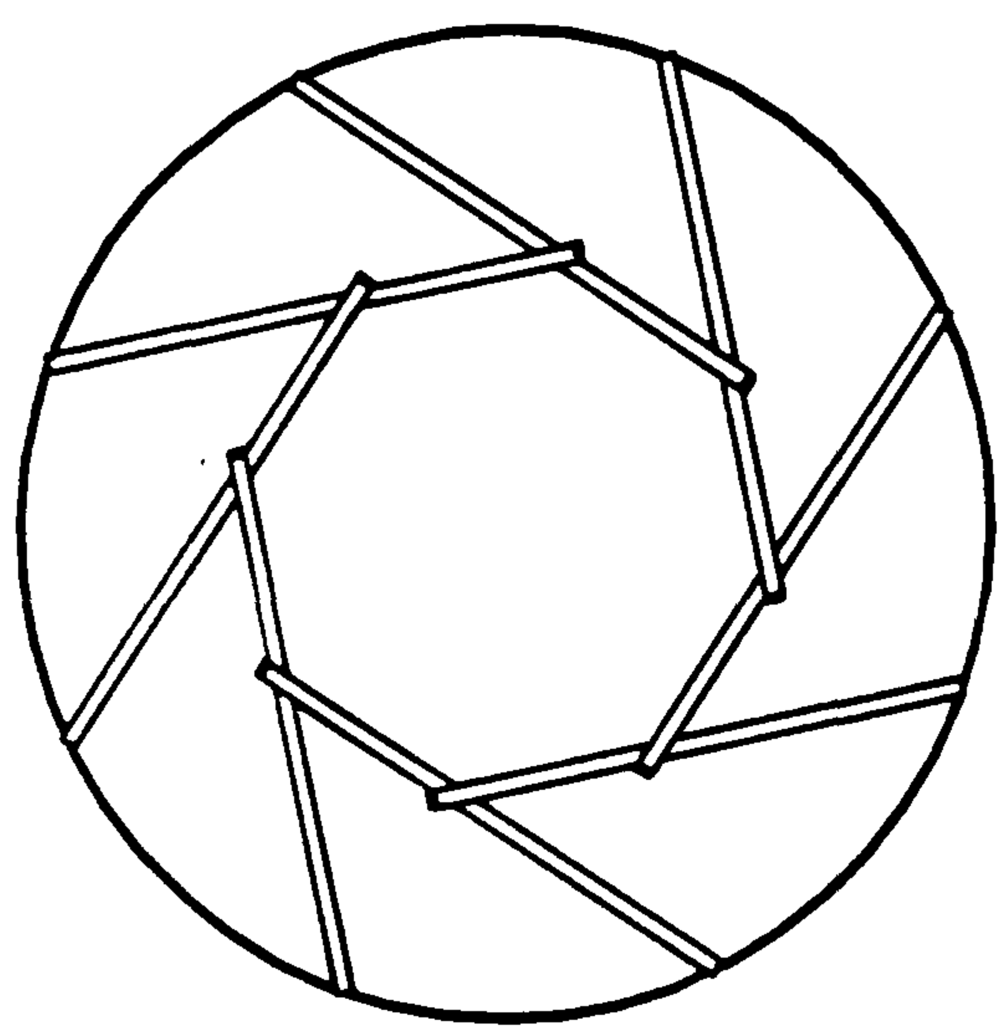


Figure 1.3 The RF in plan is very reminiscent of a camera shutter

This research project investigates all the above mentioned architectural aspects regarding the RF structure. Therefore, this Ph. D. focuses only upon the architectural and practical aspects behind the RF.

However, the architectural qualities are not the only qualities of the structure. As a beam grillage system, the RF is a form of 3-dimensional load sharing system. If load is applied on one of the beams, it is transferred and shared by all of the beams (thus being 'reciprocal'), and the deflection of one beam causes deflection of the others. The RF beams are elements of a 3-dimensional structural system, and they need to be analyzed as such. It would definitely be worth looking at the system and also exploring how roof panels would affect the structure (looking at the whole system - RF structure and roof panels together). The structural analysis of a RF structure would make an interesting research project in itself. Such an analysis has not been carried out as part of this research project, since the intention has been to explore the architectural aspects of the RF.

1.2. Objectives of the study

With regard to the problem to be examined, the overall aim of the research is to attract designers and make them aware of the potential of the RF, as well as the advantages and disadvantages of using such a structural system on different types of buildings. Possessing more information about the system will provide them, in terms of structure, with another available option when designing.

Therefore, the main aim of the research on the RF is to promote the system and to provide general guidelines for using this type of structural system in architectural design. To accomplish this aim, two main aspects of the topic have been explored:

- Architectural
- Practical

Within these two main topics, the following objectives have been identified:

a) To identify the possible origin of the RF structure.
b) To review the use of the RF and related structures in buildings throughout history, with special reference to the different functions and spans used.
c) To investigate Japanese RF buildings and the factors that influenced the emergence of the system in Japan.
d) To explore the possibility for temporary and permanent modular RF construction and to analyze the existing RF modular buildings in the UK, as well as the potential regarding sustainability
e) To investigate the applicability of the RF system to a village hall of middle span, to explore the developed RF morphologies and the quality of the architectural designs in terms of division of spaces and spatial quality.
f) To explore the RF design experiences.

g) To investigate practical issues regarding the RF such as: defining the geometry and parametric studies of the main RF variables, simplifying the 3-dimensional CAD presentation of the structure, the possibility for retractable RFs and alternative possibilities for covering the roof.
h) To identify the possible future research on the RF system.

1.3. Research methodology

In order to meet the main objectives of the research the following procedures have been undertaken:

a) Research into architectural history and theory in order to define:
    - the origin and possible reasons for the emergence of the RF system,
    - the qualities in the design of the existing RF buildings.
b) Use of a case study as part of a student project, to explore:
    - the applicability of the RF system to a village hall of middle span,
    - the developed examples of RF morphology
    - the architectural qualities of the design solutions
c) Use of questionnaires and interviews, as part of the case study, to explore:
    - the experiences of the designers (students),
    - the students' opinions about the system.
d) Use of 2-d and 3-d drawings in AutoCAD and physical models, to explore:
    - the varied RF geometry and parametric studies,
    - issues concerning retractable RFs.
e) Programming in AutoLISP, to:
    - automate and simplify the drawing process for this research project,
    - help future RF users to represent easily the RF in 3-d.

Also, other software has been used, such as: Excel for the parametric studies and Aldus Photostyler to edit the scanned images.

1.4. Expected outcome of the research

Because architecture in most respects, is a form of art, objective research is difficult. Its inherent subjectivity often changes over time, between cultures, regions and climates, making it almost impossible to prove an established research hypothesis. However, this does not apply at all to 'applied architecture'- the practical issues of buildability and detailing. This research combines the theory and philosophy concerning the design of RF buildings with the very practical issues generated. It therefore includes the research methods, often very different, which were used in dealing with both the architectural (theoretical) and applied (practical) aspects of the research project.

The expected outcome of the research is to promote a structural system - the RF (although known for a long time, not nearly used enough by designers). The research results are meant to show the potential of this structural system, and to describe the advantages and disadvantages of using it. The information presented in this dissertation should help future designers in deciding whether or not to use the RF. It should give them guidelines about the main architectural and practical issues concerning the structure. If this is successful, the main aim of the research will have been achieved.

At this stage it must be pointed out that the idea is not to prove that this is the best or most efficient structure. This is not the case. A misunderstanding of that kind must be avoided. It is simply a different structural solution which has its own advantages and disadvantages. It is its unexplored potential which makes it such an interesting research topic.

1.5. References

Chilton, J.C., 1994. Polygonal Living - Some Environment-Friendly Buildings with Reciprocal Frame Roofs, *Proceedings International Seminar on Structural Morphology in Architecture*, Stuttgart, Germany, pp. 21-29

Chilton, J.C., Choo, B.C., Coulliette, P., 1994, "Retractable Roofs Using the 'Reciprocal", Proceedings from the IABSE, Birmingham, U.K., September 1994, pp. 49-54.

1.6. List of illustrations

CHAPTER 2: Precedents

2.1. Architectural background

2.1.1. Origin of the structure

It is very difficult to tell precisely where the first idea for using a structure such as the RF originated. Although it is very likely, there is no direct evidence that the RF developed from the simple structures used by early human civilisations. Many cultures in their primary stages of evolution lived in pits, huts and similar one cell dwellings, the roofs of which were constructed by weaving branches of trees, supported by beams laid one on top of each other. *"...The hut was the basic form of architecture, and it contained major elements of shelter ..."* (Laugier, 1755, p. 3).

The roofs of some of these primitive dwellings have some similarities with the RF. Those of the Neolithic huts and pit dwellings, constructed of timber beams which meet at the top of the roof, were supported by a central pole, as shown in Figure 2.1. (Crossley, 1951). If there had been no central pole, the structure would have been very similar to a RF without an opening at the top. The central pole of the Neolitic pit dwelling is like making a RF without moving the 'temporary' support, which in this case is permanent.

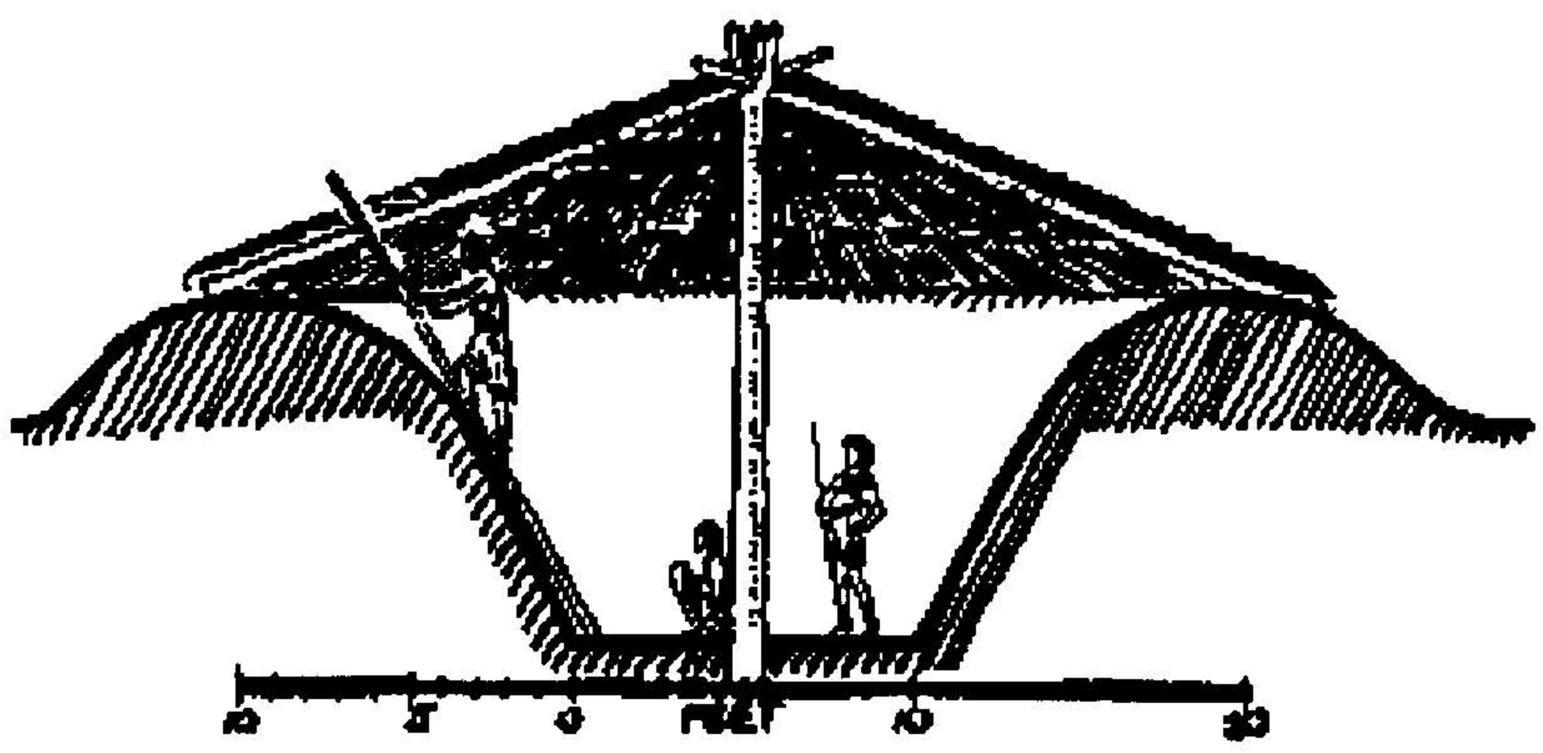
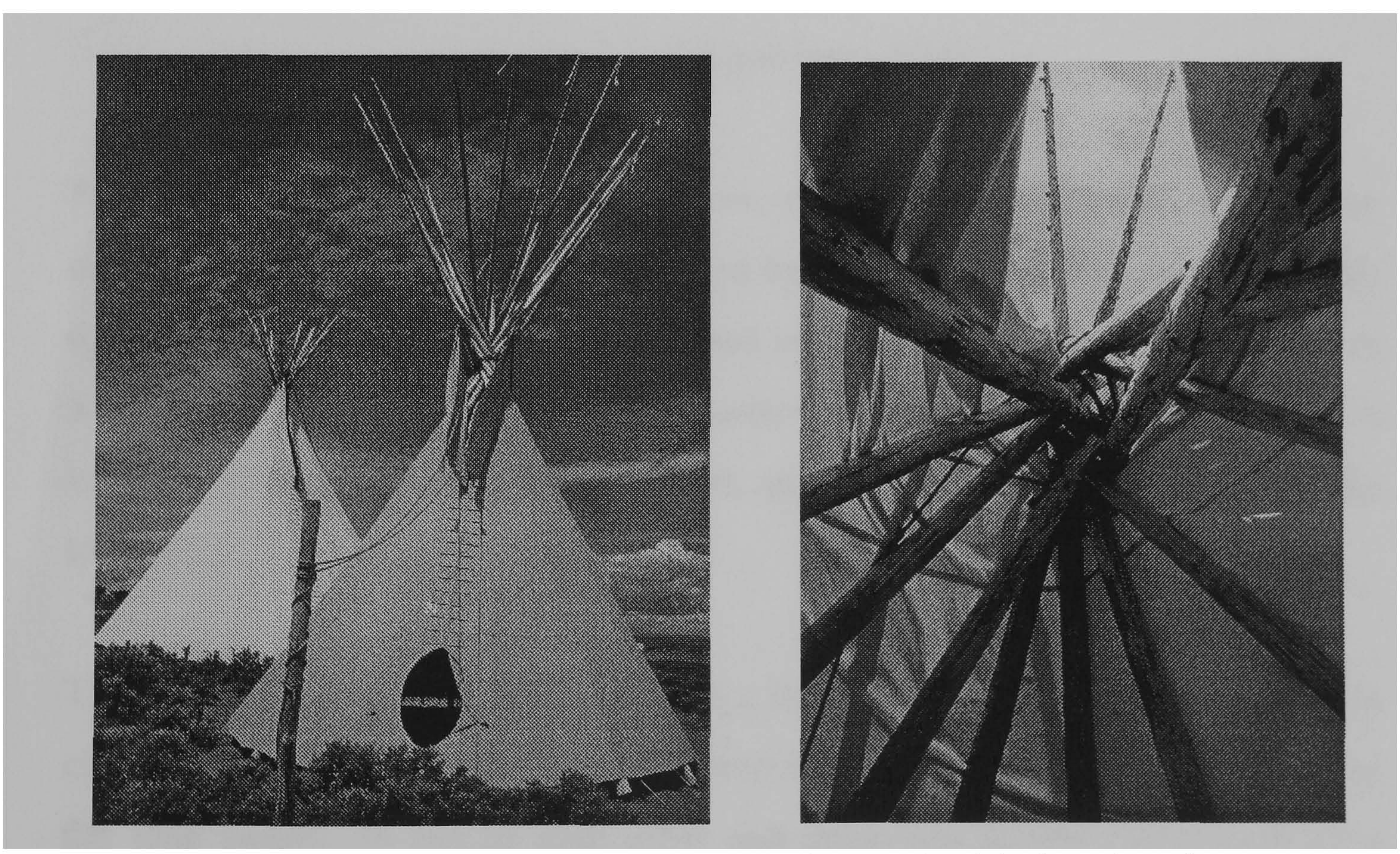


Figure 2.1. Neolithic pit dwelling

Another example of this type of structure, the Indian tent (teepee) is built of sticks, which meet at a single point at the top, with a stretched animal skin to provide the shelter (Figure 2.2). It is important to emphasise that the Indian teepee has a great similarity with the RF. In both cases, the structure consists of mutually supporting beams and a roof opening. The main differences, however, are the sizes of the structural elements, which, in the case of the teepee, are thin poles, whereas the beams of the RF are of larger cross section. In addition, the teepee members are steeply inclined, and tied to form the structure, whereas RF roofs (described in detail in Chapters 3 and 4) have specially designed notched joints.



Figures 2.2.a. Indian teepees - exterior, and 2.2.b. interior view

Similar tents, so called - *tupiqs,* were built and used by Eskimos as their summer residences. They were constructed from slender poles made of pieces of antler or willow wands lashed together. Two pairs of crossed poles formed the basic elements of the tupiq, with an arc of poles defining the back of the tent and resting on the fork of the rear crossed supports. Between the two pairs of crossed poles ran a ridge-piece and the whole frame was covered with a tight fitting membrane of seal-skin or hide (Figure 2.3) (Oliver, 1987). The similarity with the RF is small, but there is a possibility that in the evolution of some of these primitive structures the idea of the RF was born.

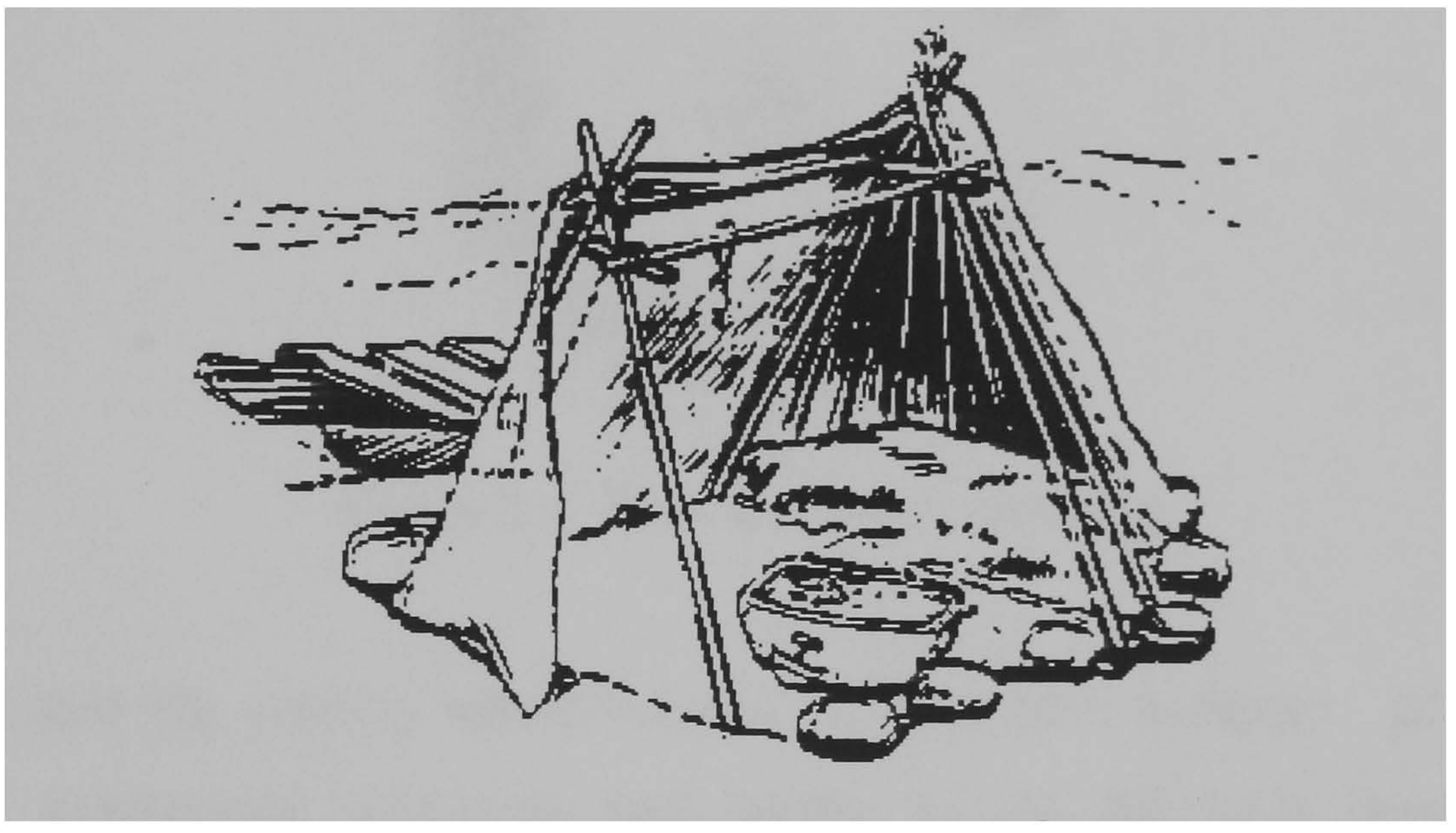


Figure 2.3. Eskimo tent - *tupiq*

Before moving on to genuine RF structures, one other primitive dwelling should be considered: the hogan. Hogans were used by Navajo Indians, and the oldest type of hogans were constructed from a tripod of forked poles against which others were laid. The pole frame was thickly plastered over with mud. Their structure is very similar to the structure of the teepees, and therefore they have some similarity to the RF.

There is also another type of hogan, with a structure covering a dwelling which is circular in plan (Figure 2.4). They are constructed by laying beams (timber logs or flat long stones) on top of each other and diagonally across the corners of a polygon. The process is repeated, so that the opening becomes smaller and when a cupola is formed the structure is covered with mud.

In this type of structure, as in the case of the RF, the beams are simply supported and are less than the full span of the building. Also, there is a similarity in the plan representations of the RF and the hogan, because of the circular form used. Apart from these common things, the RF and the hogan are, however, very different. In the case of the hogan the multiple layers of short logs are used to create a dome, whereas in the case of the RF the one layer of mutually supporting beams forms the structure.

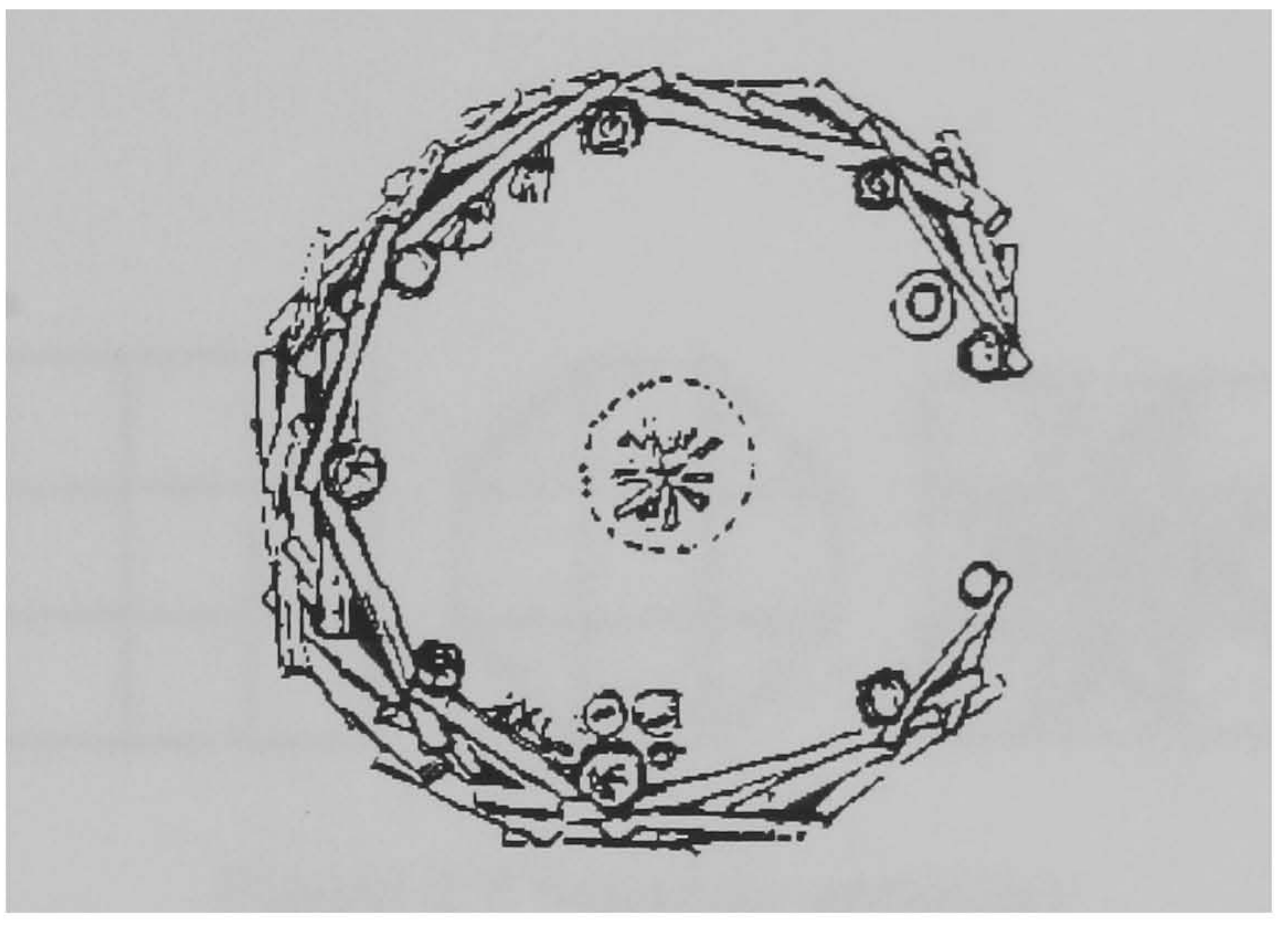


Figure 2.4. Plan of a hogan dwelling

It seems, that the country where the real RF was born is Japan. In traditional Japanese architecture structures very similar to the RF have been used for centuries. There is evidence (JA,1993-2) that in the late 12 Century the Buddhist monk Chogen (1121 -1206) established a technique of spiral layering of wood beams which was used in construction of temples and shrines. The technique which Chogen used is identical to the structural principle of the RF, and it has been used as a roof structure on other, more recent buildings in Japan. These will be presented in detail in Chapter 3.

The geometric forms of these temples in plan are reminiscent of the Mandalas used in Buddhist meditation as symbols of divinities, thus the name 'Mandala Dach' (Mandala Roof) has been used for the RF in Germany. 'Mandala' is a Sanskrit word meaning 'magic circle' (Gombrich, 1979) and it is a geometric pattern which includes circles and squares arranged to have a symbolic significance. They are one of the oldest religious symbols, and can be found as painted decoration on ceilings in religious buildings such as Tun-huang in China.

The role of the mandala in meditation is described by Auboyer, 1967, (p. 26) in the following manner: *"The one who meditates on a mandala must 'realize' through meditative effort and prayer the divinities belonging to each zone. Progress is toward the center, at which point the person meditating attains mystical union with divinity"*. On studying the form of the RF it can be noted that the beams of the structure focus towards the central polygon which frames the sky or heaven to echo the role of the mandala. Some examples of mandalas are presented in Figure 2.5.

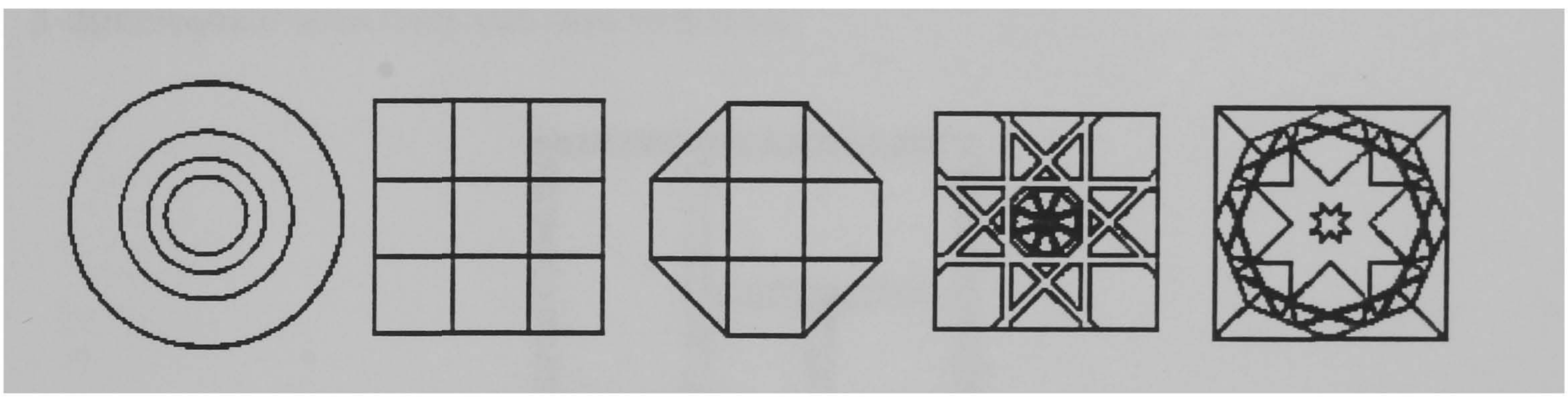


Figure 2.5 Mandala geometry

There are examples of structures that use similar structural principals to the RF in traditional Japanese architecture of the fourteenth and fifteenth century, such as the grillages used as roof structures of houses, constructed in the *sasu* system.

The two structural systems *sasu* and *odachi* used in Japan in this period affect the floor plans in a different way. They both are roof grillages, but the *odachi* system involves a row of posts placed under the beams and runs down the center line of the house. On the other hand in the case of the *sasu* system the slanting beams that form the basis of the structure are supported at their lower ends by other beams. This does not impose the necessity of installing internal structural posts and leaves the plan more unobstructed than the *odachi* system does (Itoh, 1974).

2.1.2. Historical use of the RF

Necessity has fuelled invention throughout history, nowhere more so than with beam grillages, which were devised centuries ago as a solution for spanning distances longer than the available beams. Medieval floors were sometimes supported on four beams, all shorter than the span. This was also a common configuration for the framing of stairwells, as shown on Figure 2.6. (Chilton, Choo, Yu, 1993). These structures were usually planar grillages, but examples of 3-dimensional structures can also be found.

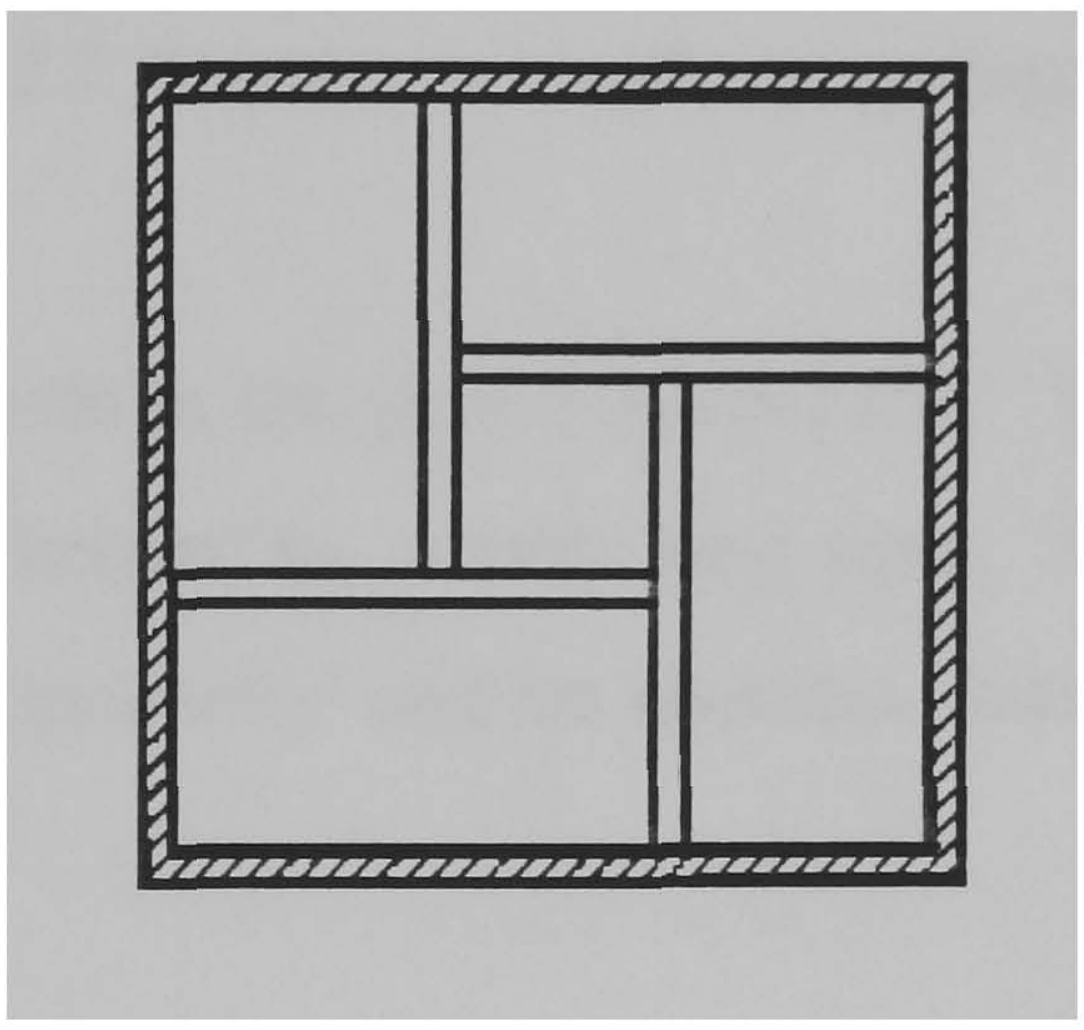


Figure 2.6. Typical medieval floor grillage configuration

The medieval architect, Villard de Honnecourt, who studied the construction of great churches such as Cambrai, Rheims and Laon, and may even have been in charge of their building, provides us with information on how to deal with the problem of beams shorter then the span, or as he puts it: "*How to work on a house or tower even if the timbers are too short*" (Bowie, 1959, p. 130).

Honnecourt gives no information on the spans he had in mind, and where this solution has been applied, but some other authors do. Plate 60 (presented in Figure 2.7), which is de Honnecourt's solution to this problem, is a planar grillage and it uses the same principle as the RF. If four beams in a RF were arranged so that they have no slope, and, instead of being placed on top of each other, if they were arranged in the same plane - we would get Honnecourt's configuration.

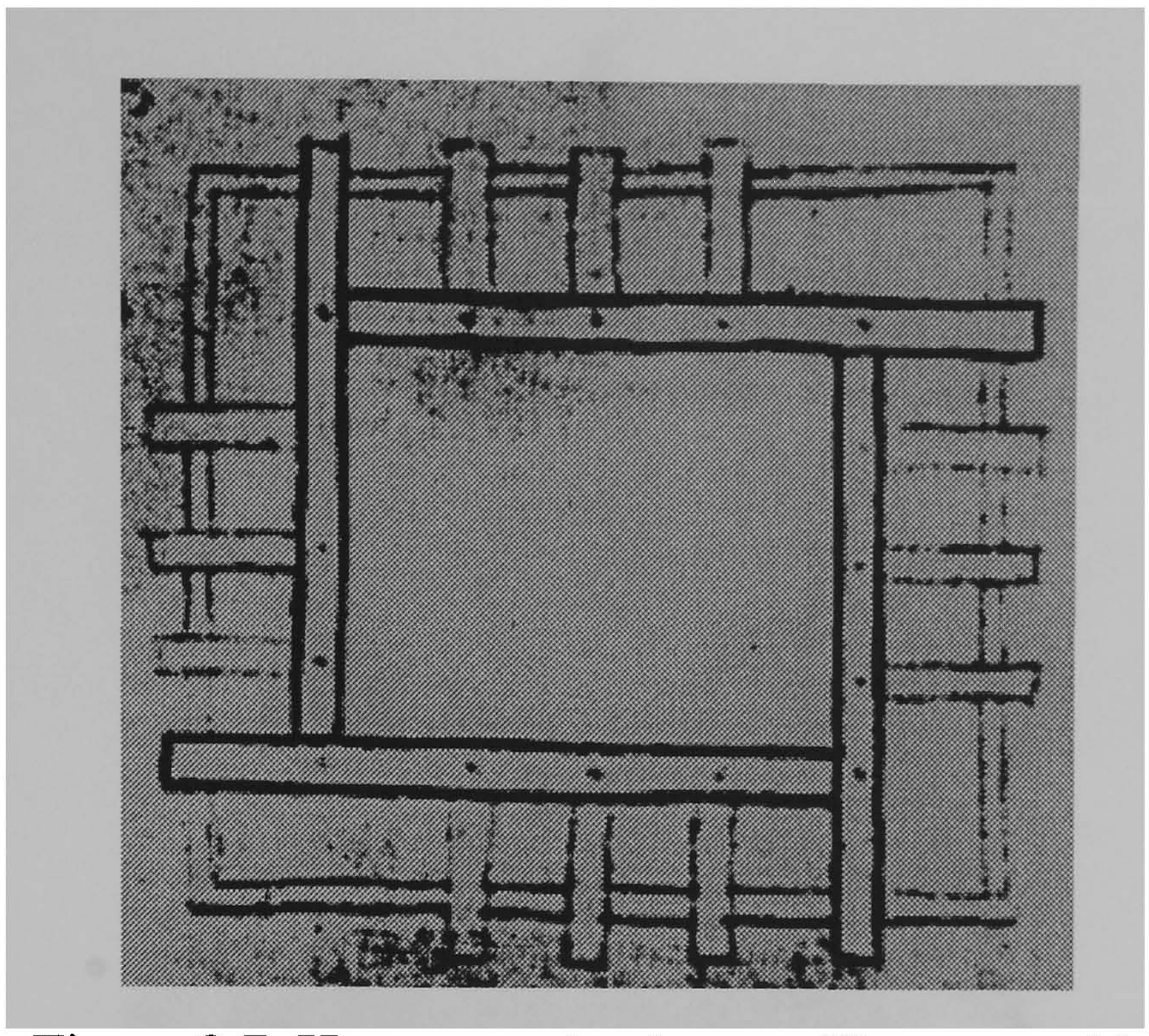


Figure 2.7. Honnecourt's planar grillage assembly

These sketches were made in the period 1225-1250. Therefore it is obvious that the principle has been known for a very long time. Honnecourt was also very interested in the 'art of geometry' and his sketches show significant understanding of the field.

Although a lot of research has been done on Cathedral architecture, there is very little data on functional carpentry. This is perhaps because *"...the roofs were normally hidden above stone vaults and only accessible with difficulty in darkness and dirt."* (Hewett, 1974, p. 9).

There is evidence that structures very similar to the RF have been used for polygonal chapter house roofing. An example of this is the chapter house at Lincoln, designed by Alexander and built between 1220-1235. The roof, which is of a puzzling complexity, encloses the ten sided regular polygonal plan of the chapter house. *"It is a real master work, which comprises of two parts - the lower a 'gambrel'-type decagonal structure, and the higher part, which restored the roof to a fully pyramidal form..."* (Hewett, 1974, p. 74), as presented on Figures 2.8. and 2.9.

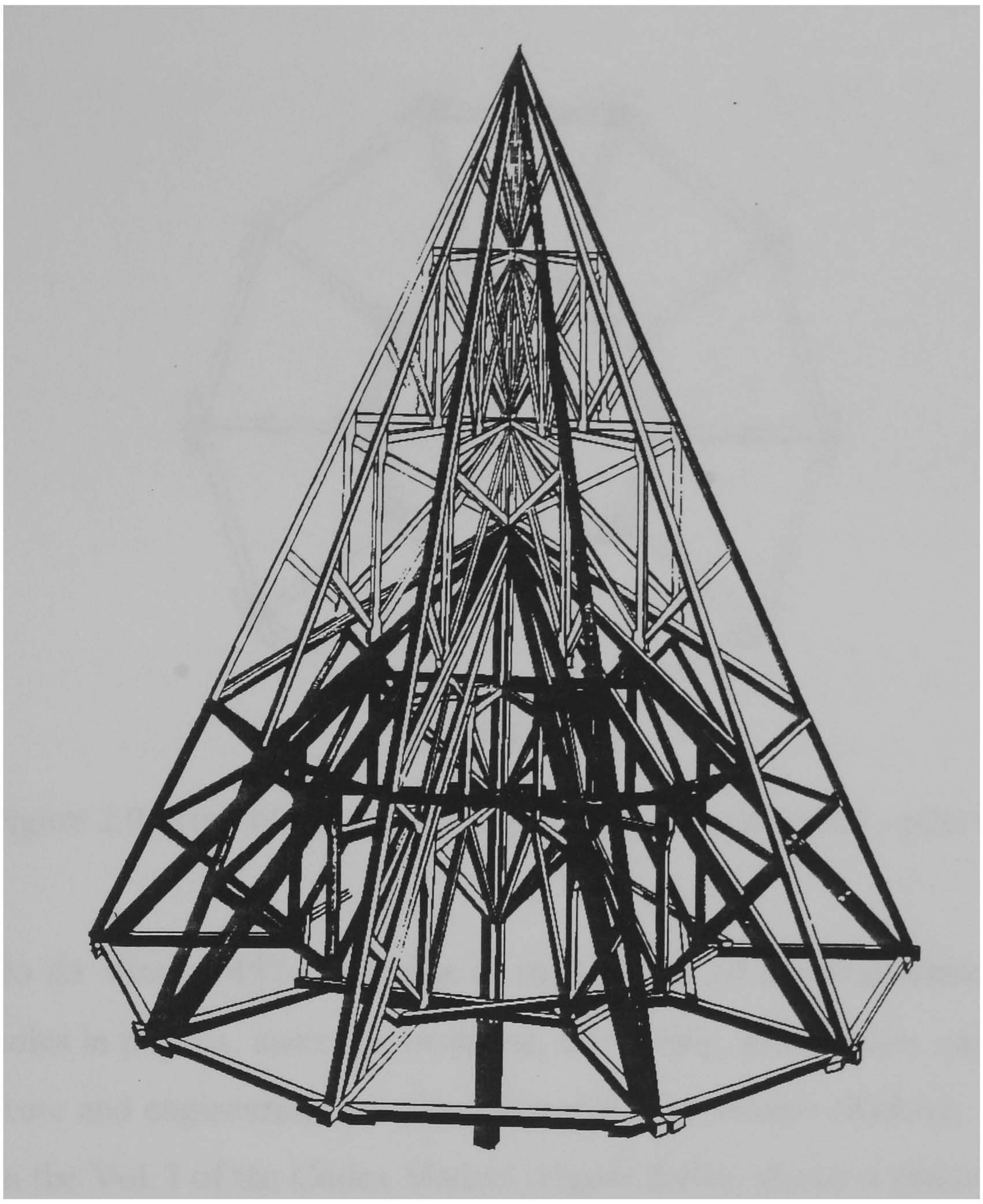


Figure 2.8. Roof of the chapter house at Lincoln cathedral - 3-d view

They are actually two superimposed queen-post assemblies set inside a pitched roof with a king post. The RF-like structure is at the base of the roof, which was built of softwood (pine) and mainly held together by ironwork and forelock-bolts. It would have been better for the radial extension and shearing stresses to which the structure is subjected had it been constructed from timber of higher quality, but it seems that cost was the reason behind this choice. This part of the roof structure is actually identical to a flat RF, and was probably was used for the first time in roofs for polygonal spaces. Therefore, it is described as 'ingenious', and it is stated that *"... the construction of the essential 'ring - beam' secures the inner ends of the ten radiating ties and it is possibly the architect's invention.."* (Hewett, 1974, p. 81). Figure 2.9. shows the plan of this structure.

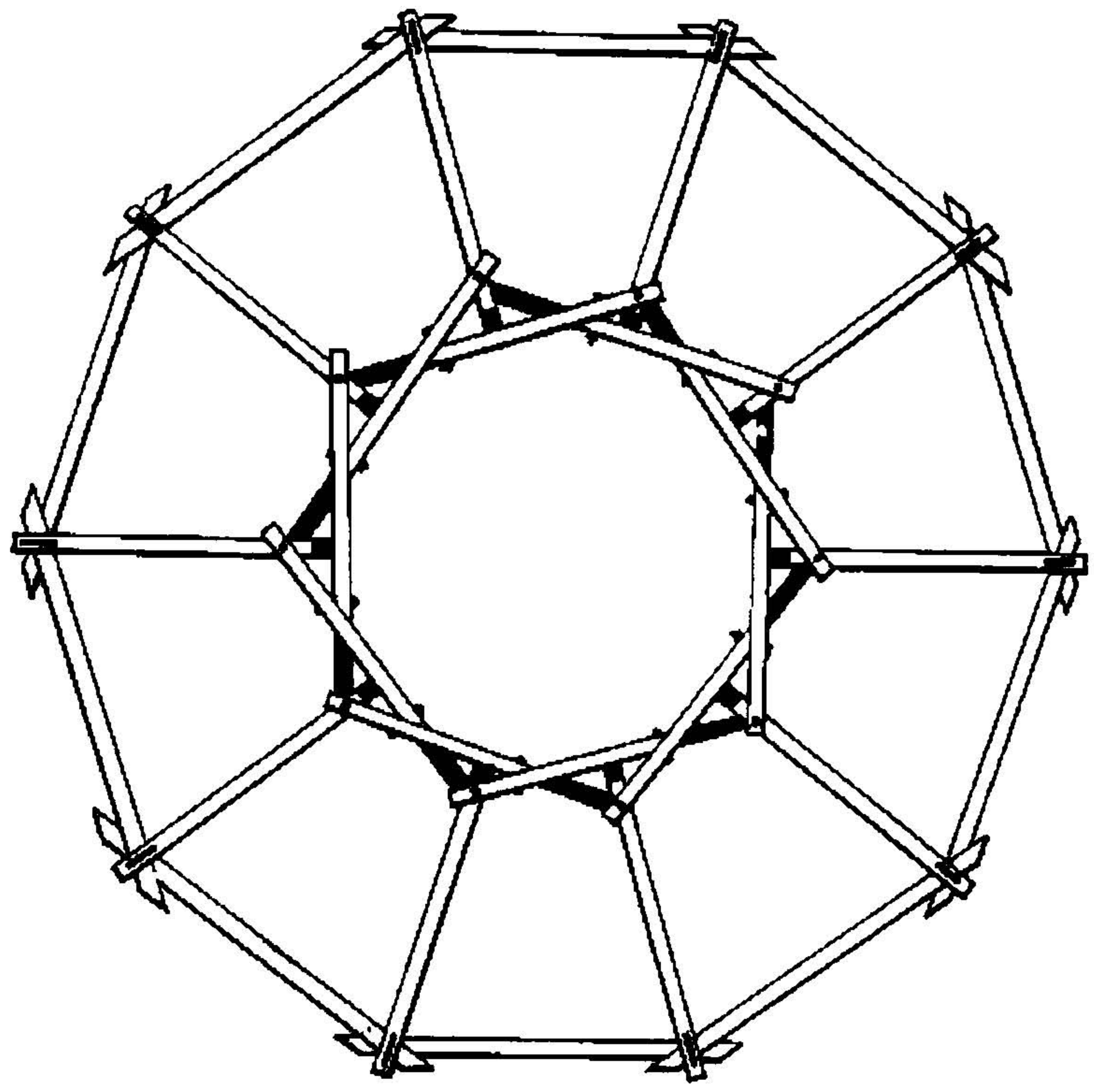


Figure 2.9. Roof of the chapter house at Lincoln cathedral - plan view

Leonardo da Vinci (1452-1519) one of the greatest of the Renaissance thinkers, with studies in physics, anatomy, medicine, astronomy, fortification, canal-making, architecture and engineering was also interested in structures (Richter, 1977). His sketch in the Vol. I of the Codex Madrid (Figure 2.10.), shows a planar grillage of four beams, identical to the main grillage structure proposed by Honnecourt (Figure 2.7.). Leonardo, also explored whole assemblies of planar grillages, which are presented in his sketches of the Codex Atlantico, as presented on Figure 2.11.

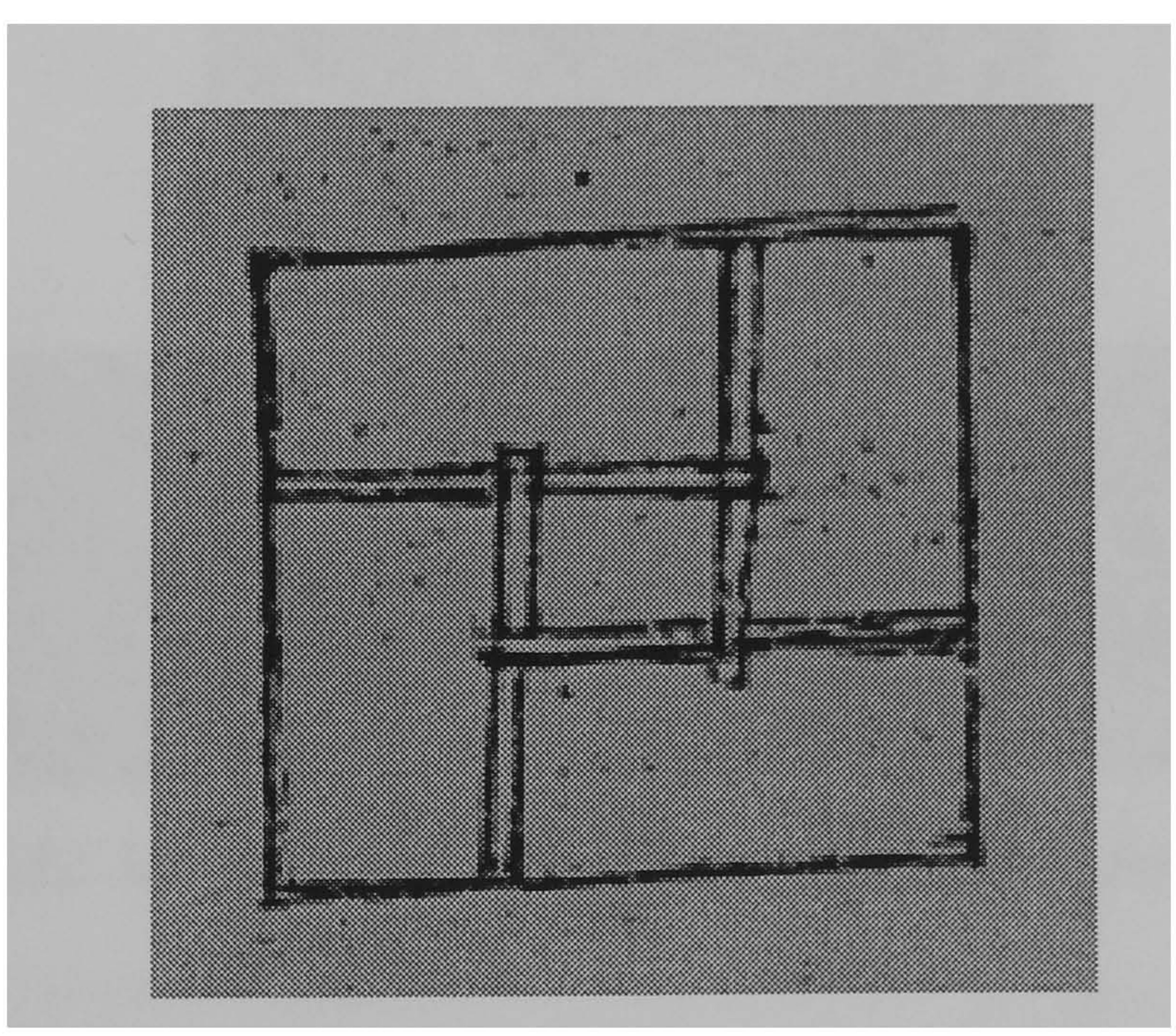


Figure 2.10. Flat beam grillage by Leonardo da Vinci

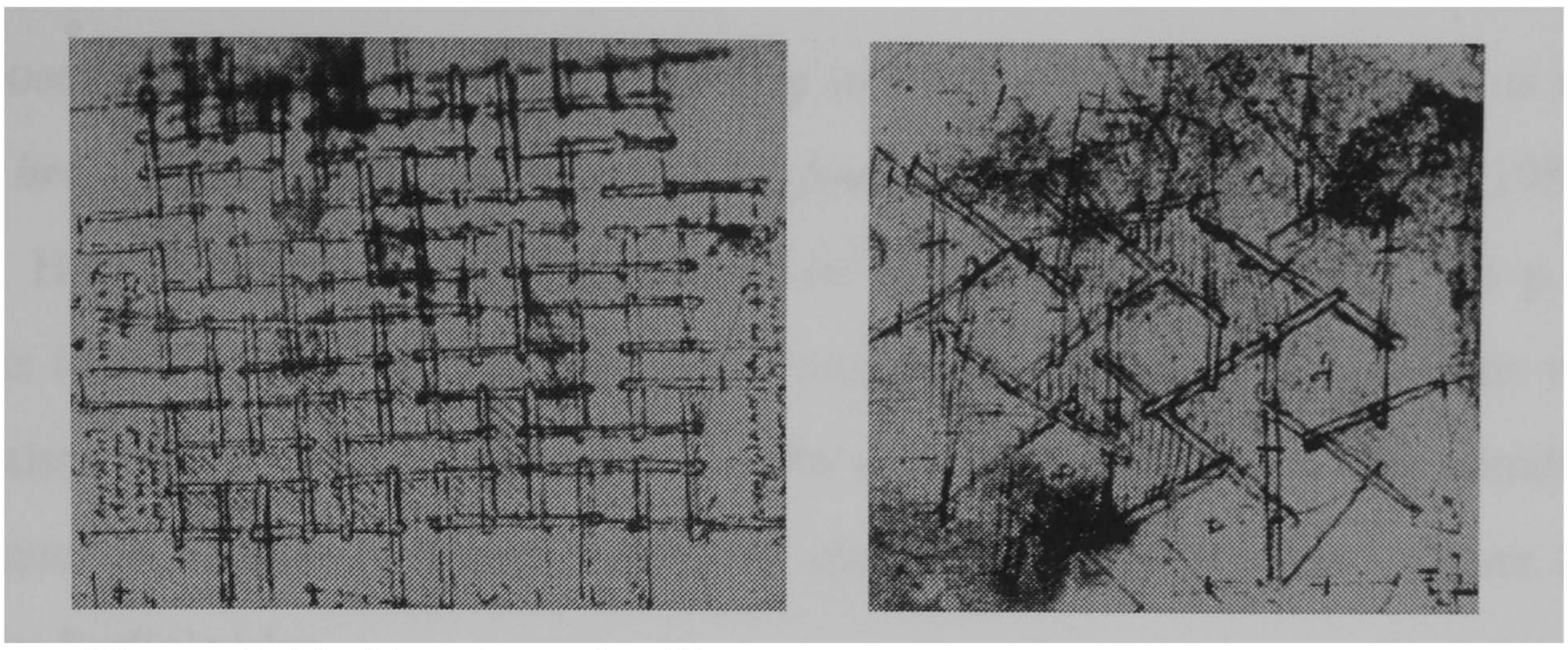


Figure 2.11. Sketches of grillage assemblies, by Leonardo da Vinci

However, it seems that Leonardo da Vinci, understood the principle of 3-dimensional grillage structures quite well, because he used them in his designs for bridges. Examples of these are the 'Temporary bridges' (Anon, 1956), originally presented in Codex Atlantico (Figure 2.12.). They are constructed from relatively short timber beams which support and are being supported by each other. The 3-dimensional structure is actually formed of two mutually connected 2-dimensional arches built from the short timber beams. When compared to the RF, although very different in form, Vinci's grillages have major similarities because they both employ the same structural principles.

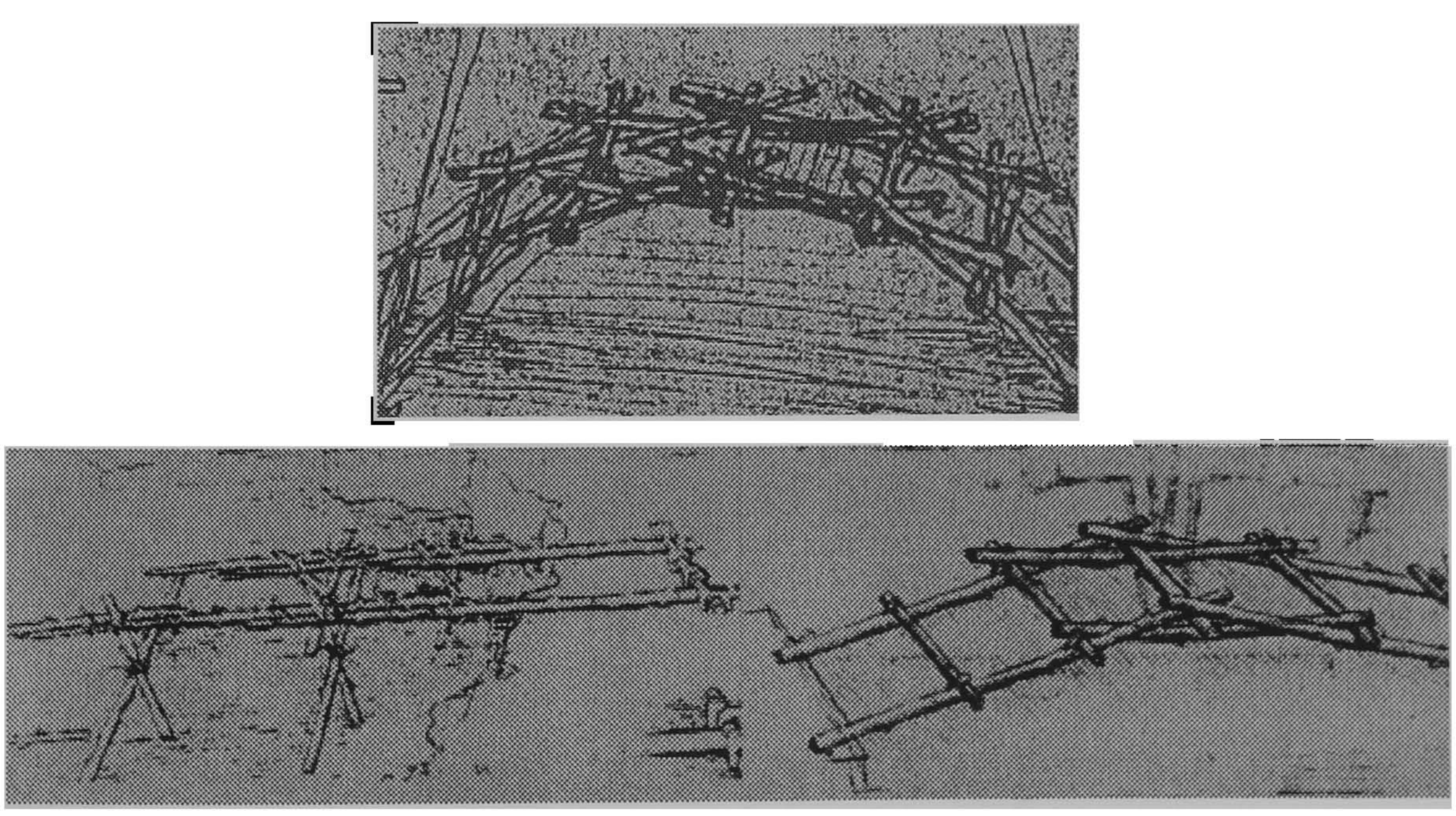


Figure 2.12. Leonardo da Vinci's proposals for temporary bridges

In the period of the Renaissance another planar grillage was proposed by the Bolognese painter and architect Sebastiano Serlio. In 1537 Serlio published a prospectus for a treatise on architecture in seven books, and in the fifth book he proposes a planar grillage for a *"...ceiling which is fifteen foot long and as many foot broad with rafters which would be fourteen feet long..."* (Murray, 1986, p. 31). He notes that *"the structure would be strong enough"* (Serlio, 1611 p. 57). In the fourth book, tenth Chapter, Serlio made two scathes for door frames which are also, planar grillage structures. Serlio's planar grillages are very similar to Honnecourt's solution for spanning long spans with shorter beams. Figure 2.13. shows Serlio's idea.

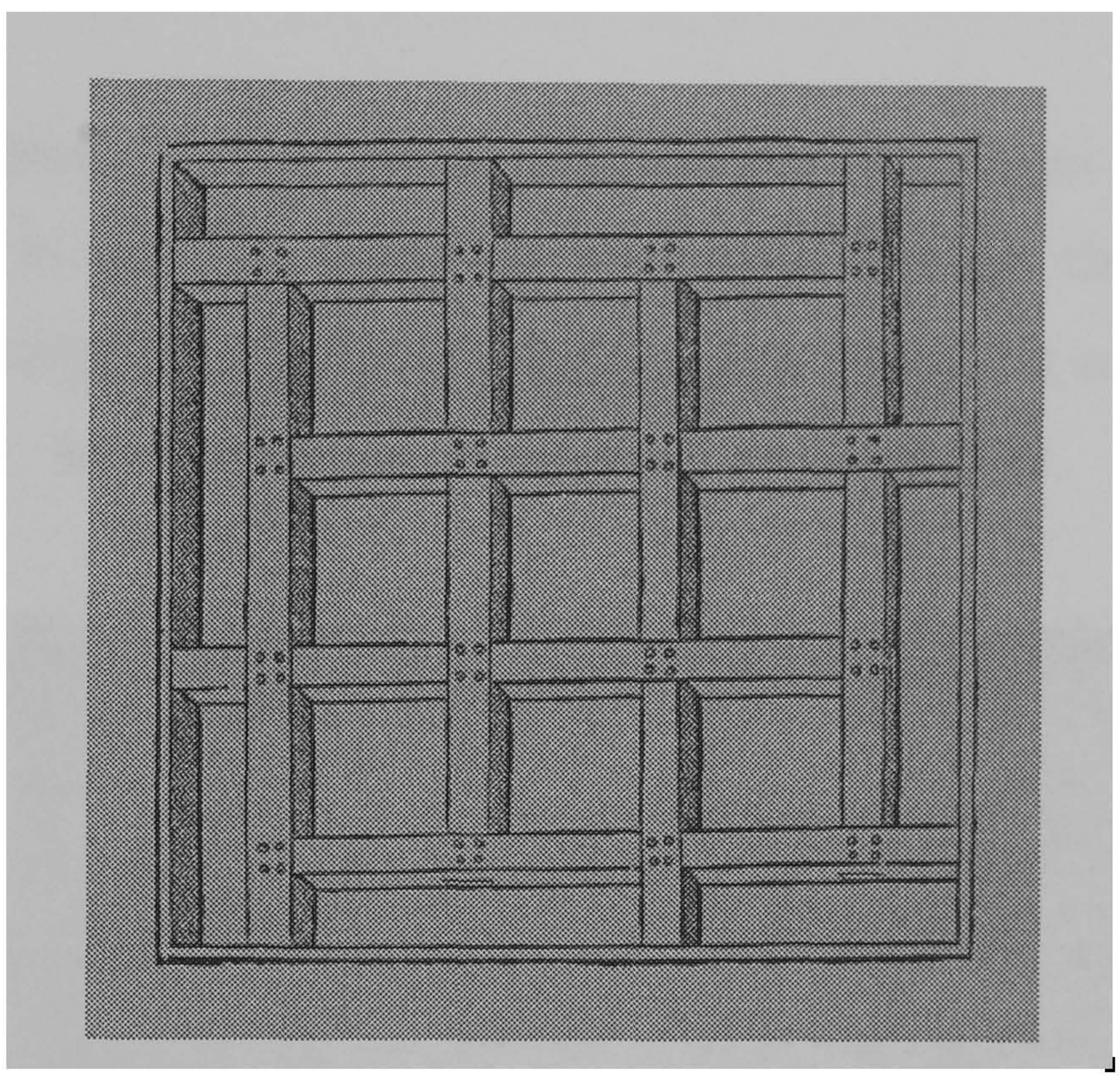


Figure 2.13. Serlio's solution for a fifteen foot ceiling

Less then a century later (1699) John Wallis wrote in Latin his Opera Matematica where he describes the planar grillage assemblies he studied. In the period 1652-1653, while lecturing at Kings College, in Cambridge, he built models of flat grillages. Wallis studied how to span longer distances with elements shorter than the span by looking at three and four-beam RF assemblies (Figure 2.14.). At this stage it is necessary to note that these structures are identical to the RF structure (thus they are refereed to as 'RF assemblies'). The only difference is that they are flat, and the RF is usually a structure referred to when sloping beams are used. However, this is only a convention which can be expanded to planar grillages, especially since the load transmission through the structure is identical in both cases.

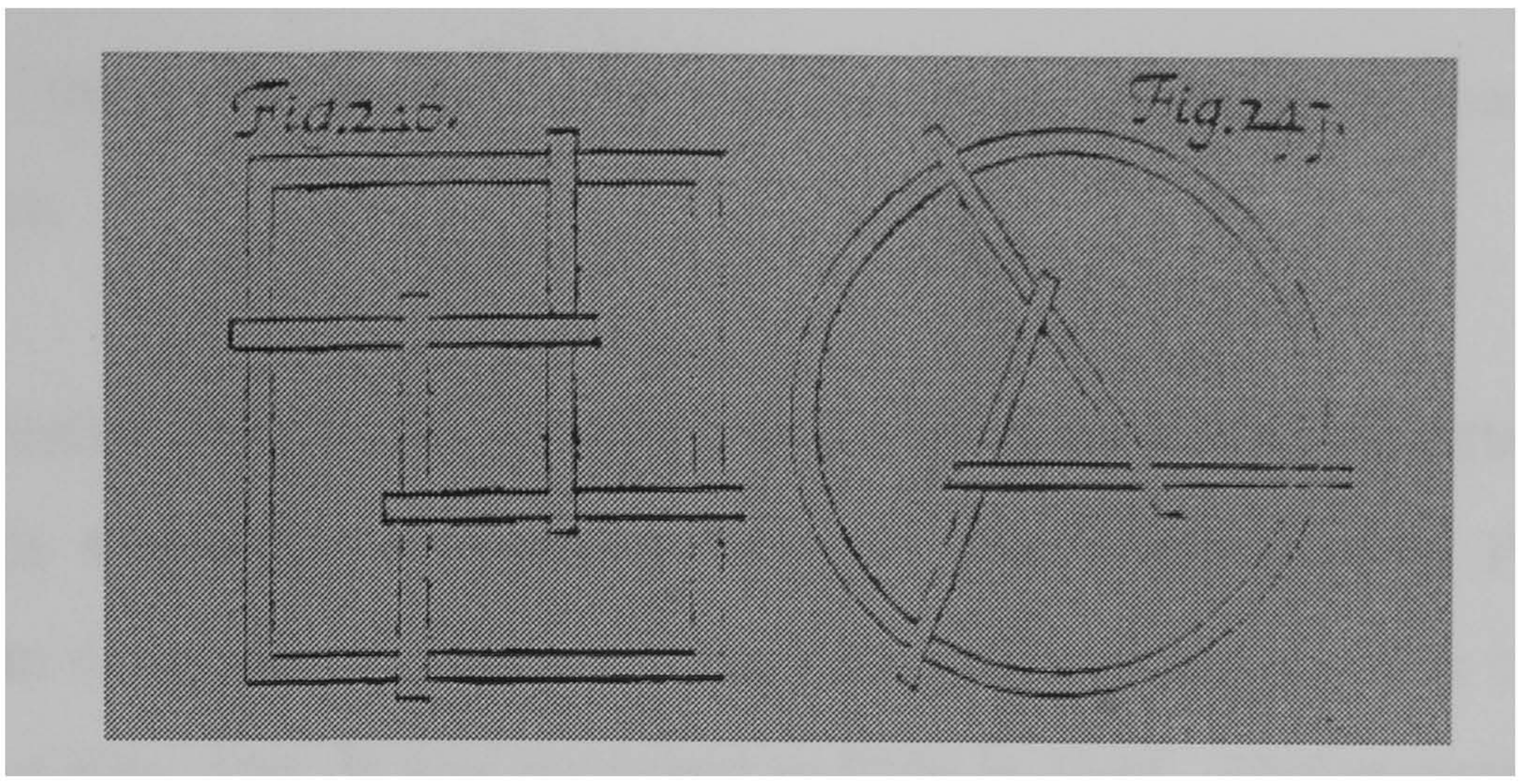


Figure 2.14. Three and four-beam RF assemblies

Wallis also explored different planar morphologies of grillages and worked out their geometry in order to study the load paths through the structure. The assemblies are constructed by connecting elements which are notched and fitted into one another. Some examples are presented on Figure 2.15.

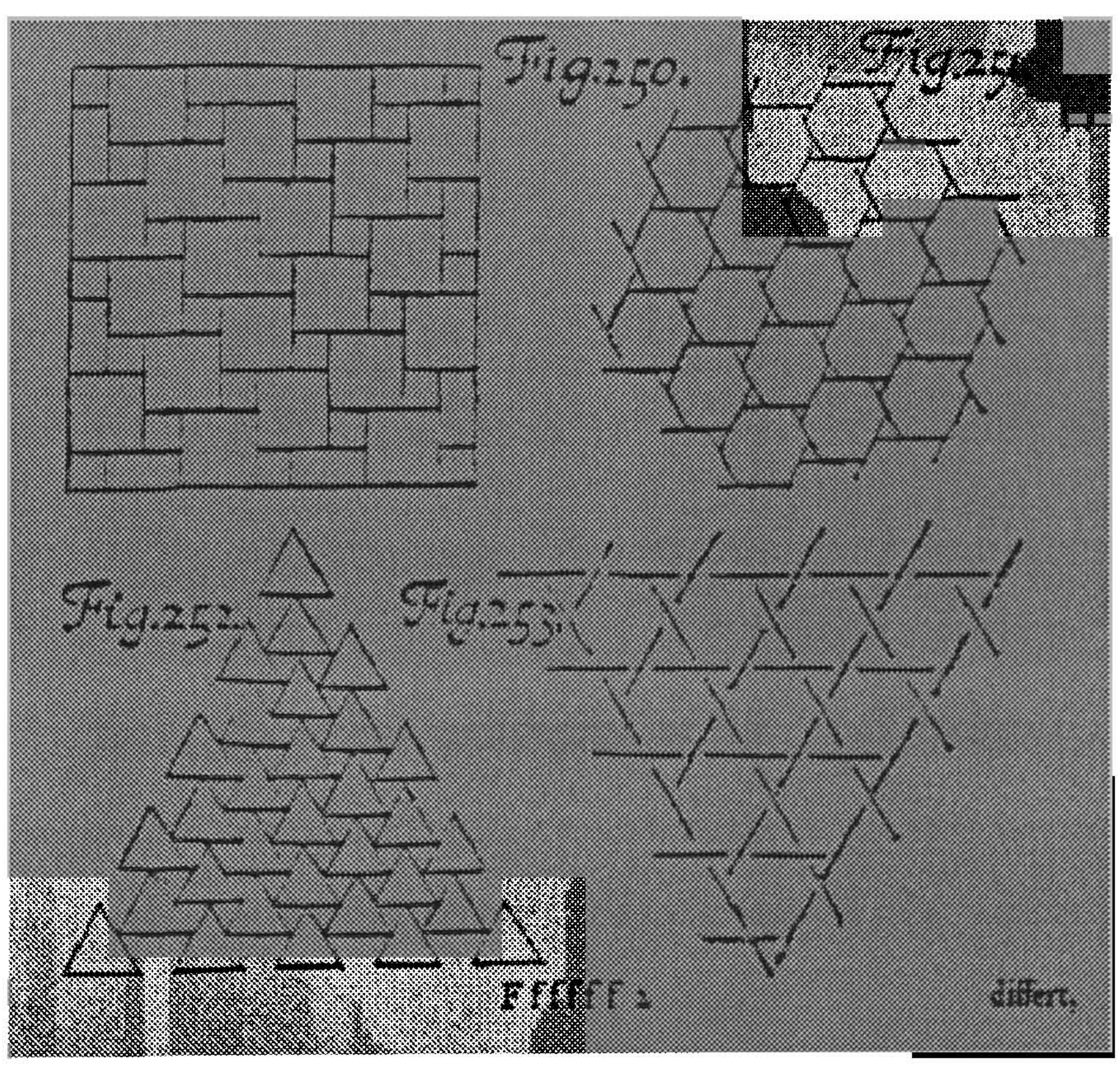


Figure 2.15. Planar morphology of grillage structures

There is no information if Wallis actually used any of his grillage assemblies on a real building. Most probably he only constructed small scale models in order to study them so that they could be applied on real buildings by architects. Although there is no information about buildings constructed using the studies Wallis did, it is evident that they provide a understanding about how the structure works. In such terms, this is the first known written document exploring the load transfer of the structure.

Other interesting examples of RF like grillages are presented in the Atlas "Traite de L'art de la Charpenterie", written by A.R. Emy, who was a Professor of Fortification of the Royal Military School Saint-Cyr, and a member of the Royal Academy of Fine Arts. It was published in Paris in 1841. Unfortunately the book gives no textual information on where these structures (presented on Figure 2.16) were used, and the spans and sizes of the elements involved. Nevertheless, it represents further evidence of the long term historical development of the structural principles behind the RF.

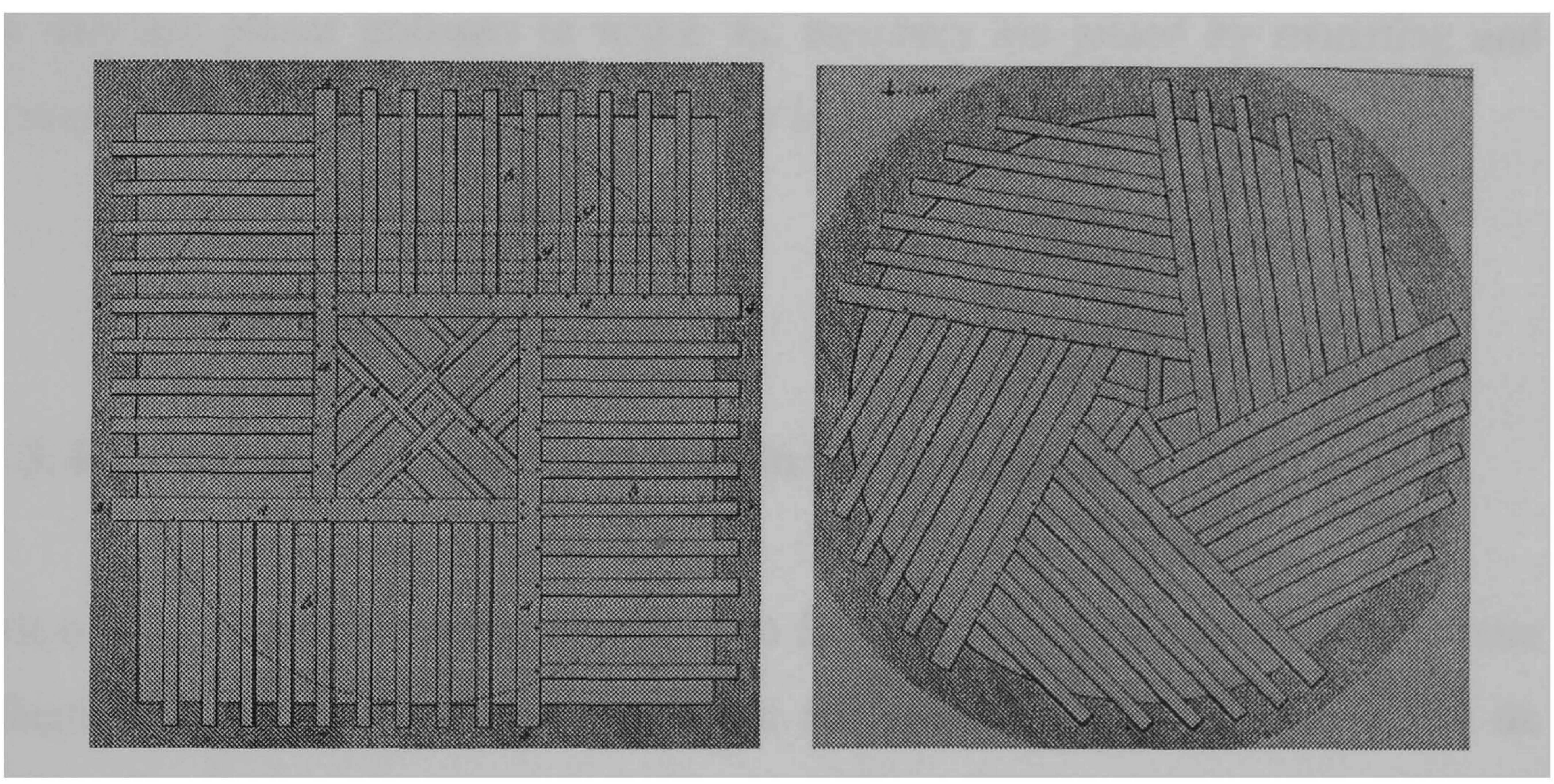


Figure 2.16. Some examples of RF-like structures

Thomas Tredgold in his book Elementary Principles of Carpentry devotes a whole section to "Floors constructed with Short Timbers". It is interesting to note that Tredgold describes these ceilings as *"...structures which can not be passed over without notice and yet are scarcely worthy of it..."* and as *"...more curious than useful..."* because they are seldom applied (Tredgold, 1890, p. 142). They are only useful when the timber is not long enough. He describes the 'Serlio-type ceiling' and gives two examples designed by Serlio (Figure 2.17.) and, also the research done by Dr. Wallis.

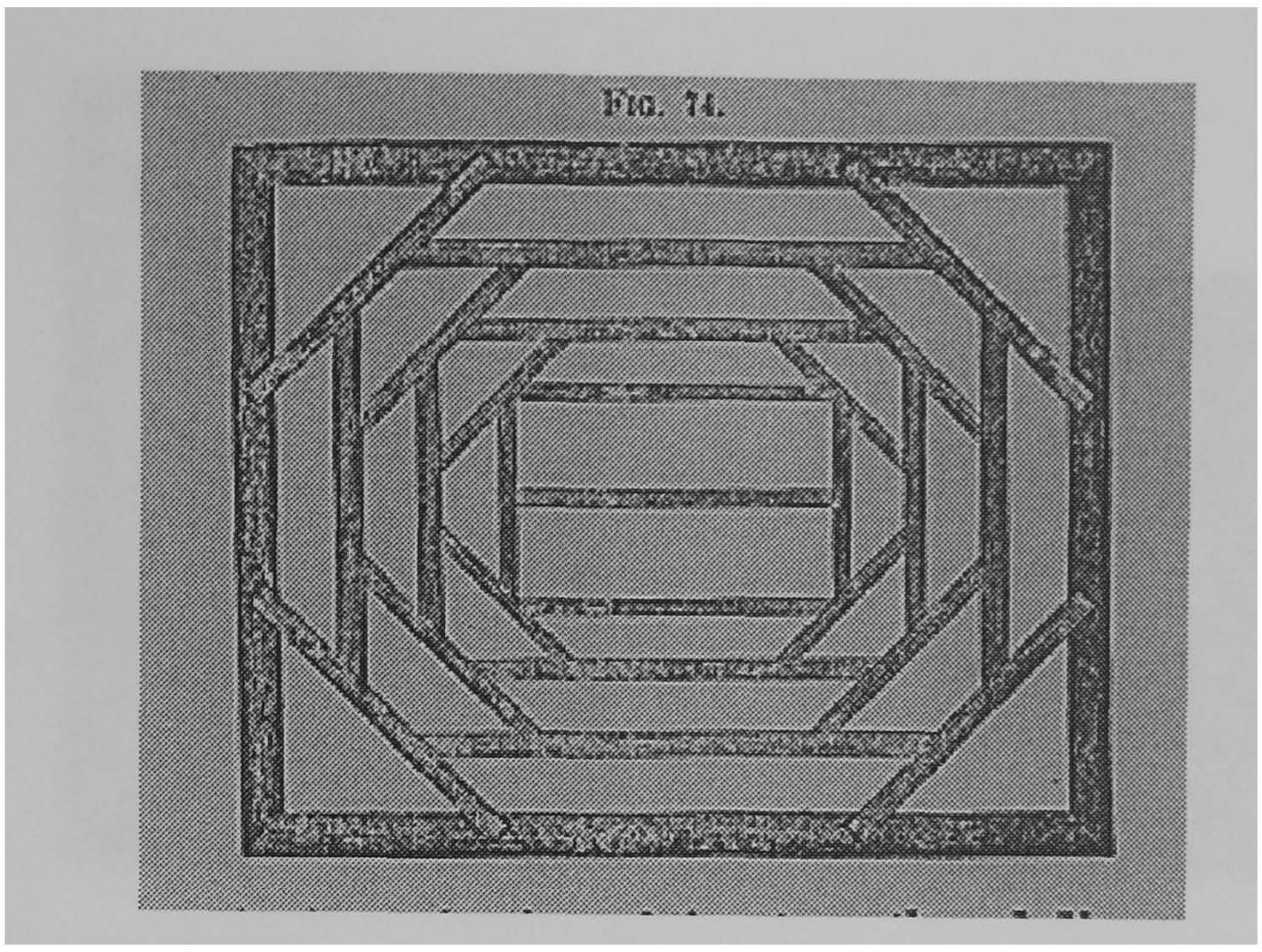


Figure 2.17. An example of a RF-like structure by Serlio

The main difference between the structures that Tredgold describes and the RF is that they are planar grillages in which the members are joined by mortising and tenoning. Still, the structural principle they both use is identical.

2.1.3. RF structures designed and built in the 20 century

Most of the grillage structures described so far have been planar or close to planar grillages (except the drawings of multiple RF assemblies done by Leonardo da Vinci). Some examples of 3-dimensional grillage structures constructed in this century are the roofs at Casa Negre, San Juan Despi, Barcelona (1915) and Casa Bofarul, Pallararesos, Tarragona (1913-1918), both designed by the Spanish architect Jose Maria Jujol (Flores, 1982). Inspired by Gaudi's architecture of spiral forms such as the ceiling of Casa Battlo and ceramic decoration, Jujol designed roof structures, of mutually supporting and spiraling beams. In both buildings the structures used are identical to the RF (Figures 2.18. a. and b.).

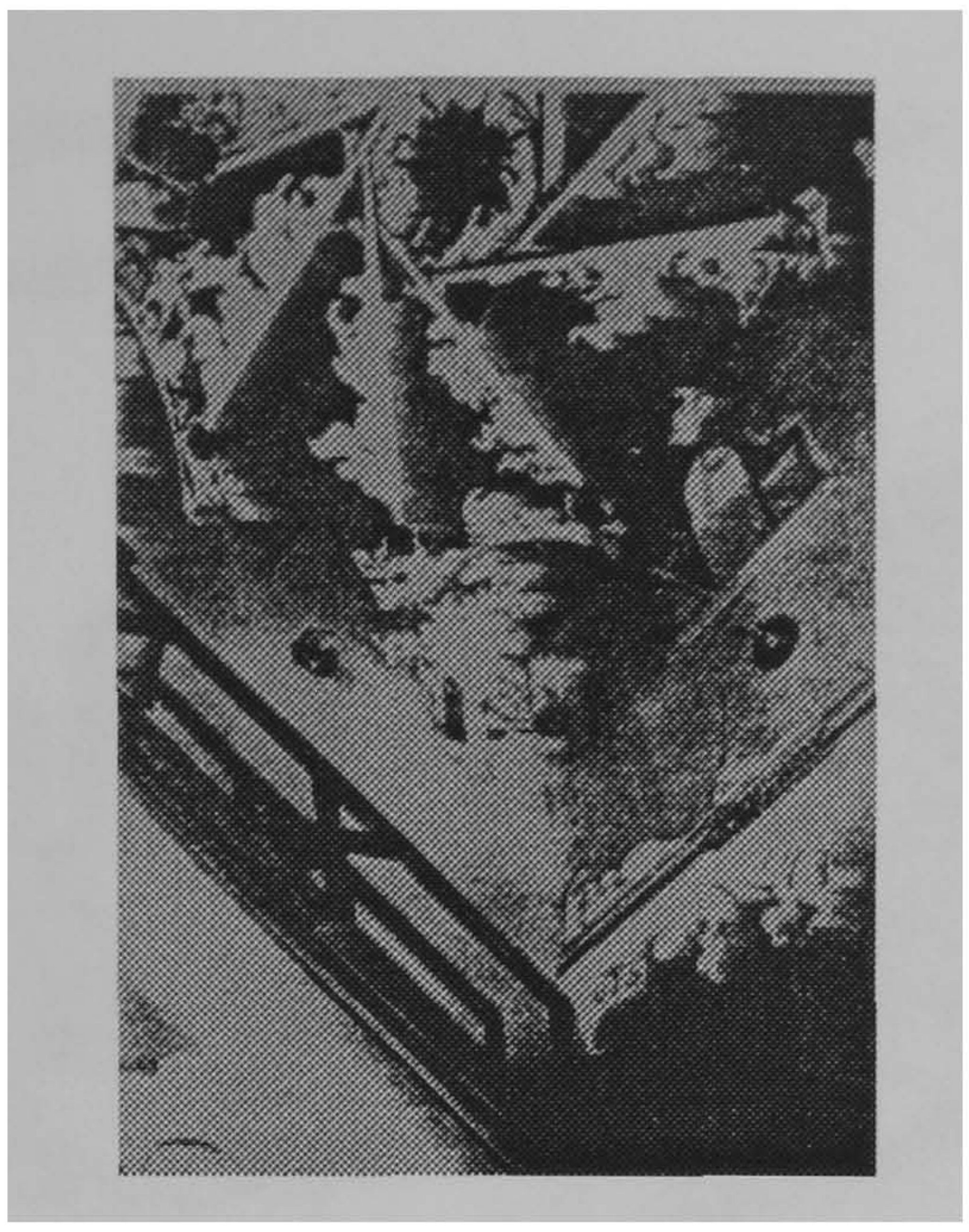
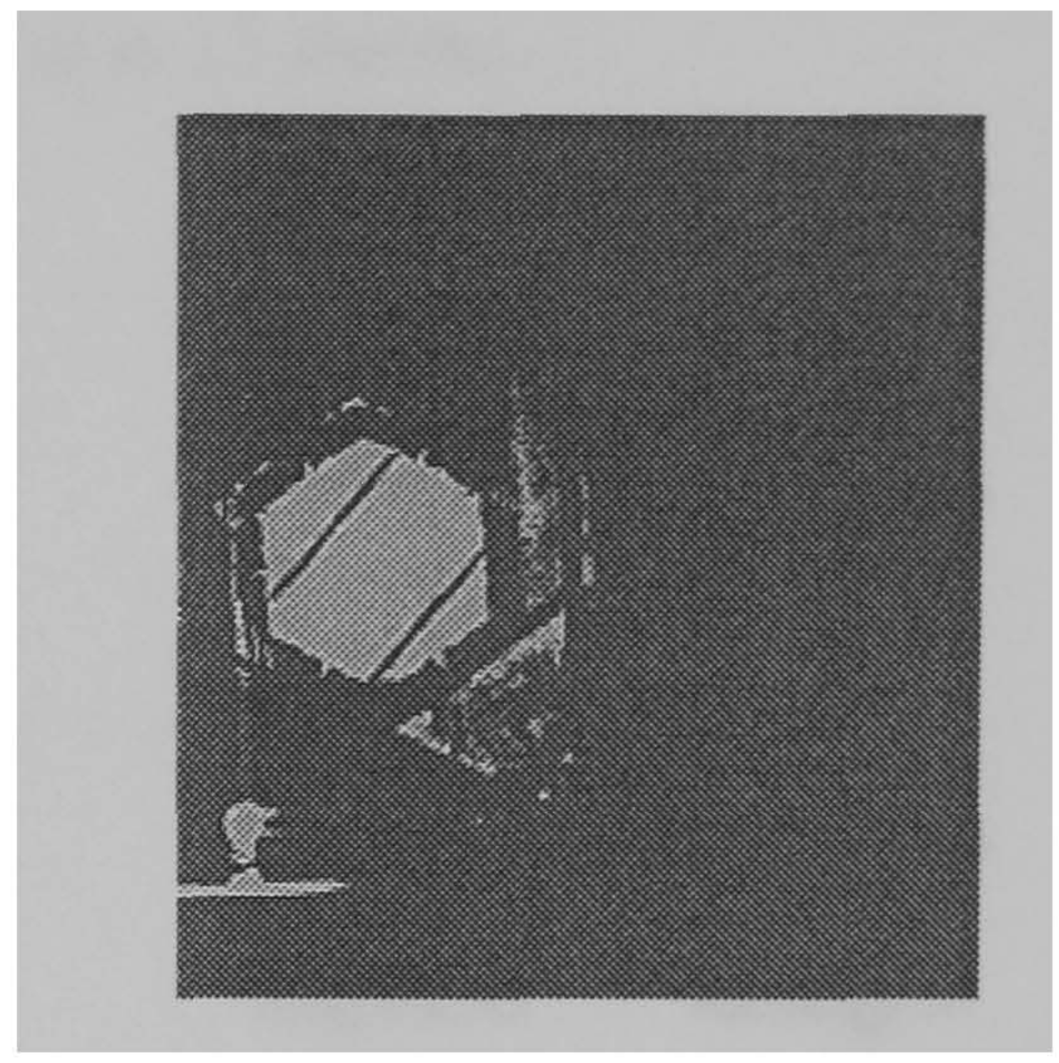



Figure 2.18.a. Casa Negre, San Juan Despi, Barcelona (1915) and 2.18. b. Casa Bofarul, Pallararesos, Tarragona (1913-1918) by Jujol

A more recent, but planar grillage structure is the roof of a salt storage building at Lausanne in Switzerland (Figure 2.19.). Eleven tapered, glulam beams are used to cover the regular polygonal plan of this building which has a span of 26 metres (Natterer, 1991).

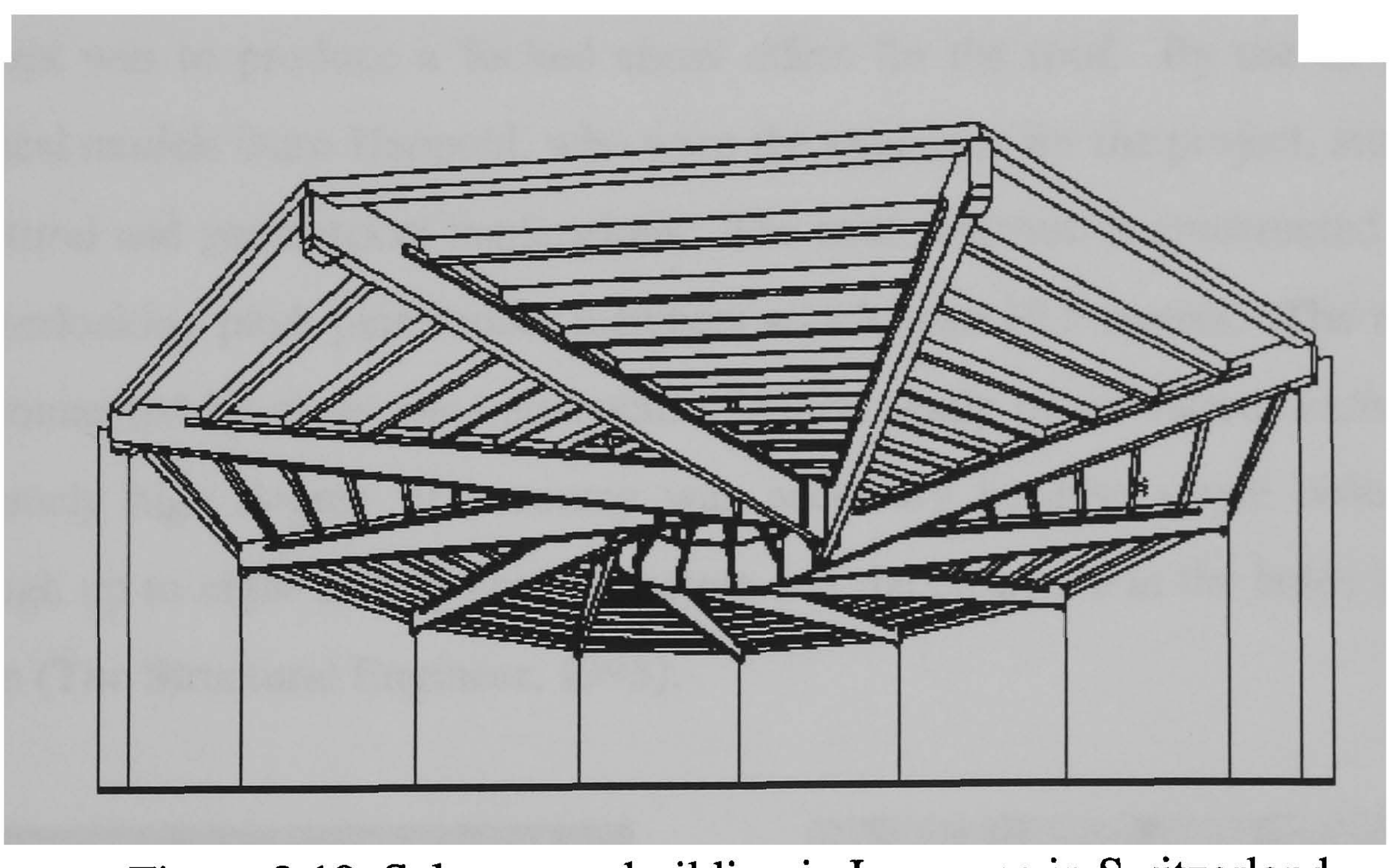


Figure 2.19. Salt storage building in Lausanne in Switzerland

The floor structure used in the Mill Creek Public Housing Project in Philadelphia in 1952-53 (Figure 2.20.), by the architect Louis Kahn, used a four beam planar grillage in the high rise buildings (Scully, 1962). The configuration is identical to Vinci's planar grillage. However, the beams used in Mill Creek were made of reinforced concrete. The main advantage of using the planar grillage, in this housing project, is the avoidance of columns within the plan, which consequently makes it easier to organise the function. The span is 15 metres.

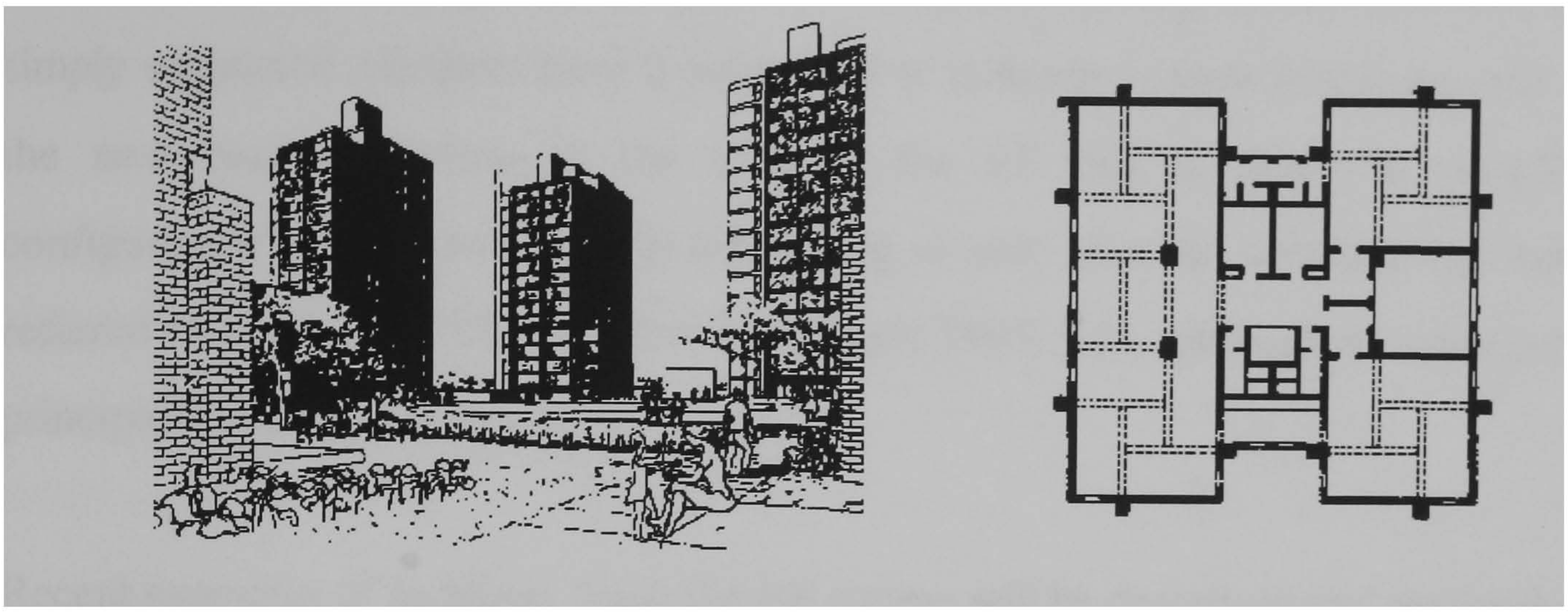


Figure 2.20. Mill Creek Public Housing Project in Philadelphia 1952-53, perspective and plan view

The most recent and similar structure to the RF, is the roof of the Langstone Sailing Centre, constructed only in April 1995 (Figure 2.21.). Influenced to a great extent by traditional ship-building technology, the Hampshire County Architect's concept was to produce a 'locked chain' effect for the roof. By use of series of physical models Buro Happold, who were the engineers for the project, studied the structural and geometrical implications. The roof structure is constructed of pairs of interlocking pitch pine timber members which span 10.5 meters. The members are connected by shear plate connectors hidden neatly by oversized washers. An extremely high degree of accuracy was necessary because single bolts passed through up to eight shear plate connectors and the clearance in the holes was only 2 mm (The Structural Engineer, 1995).

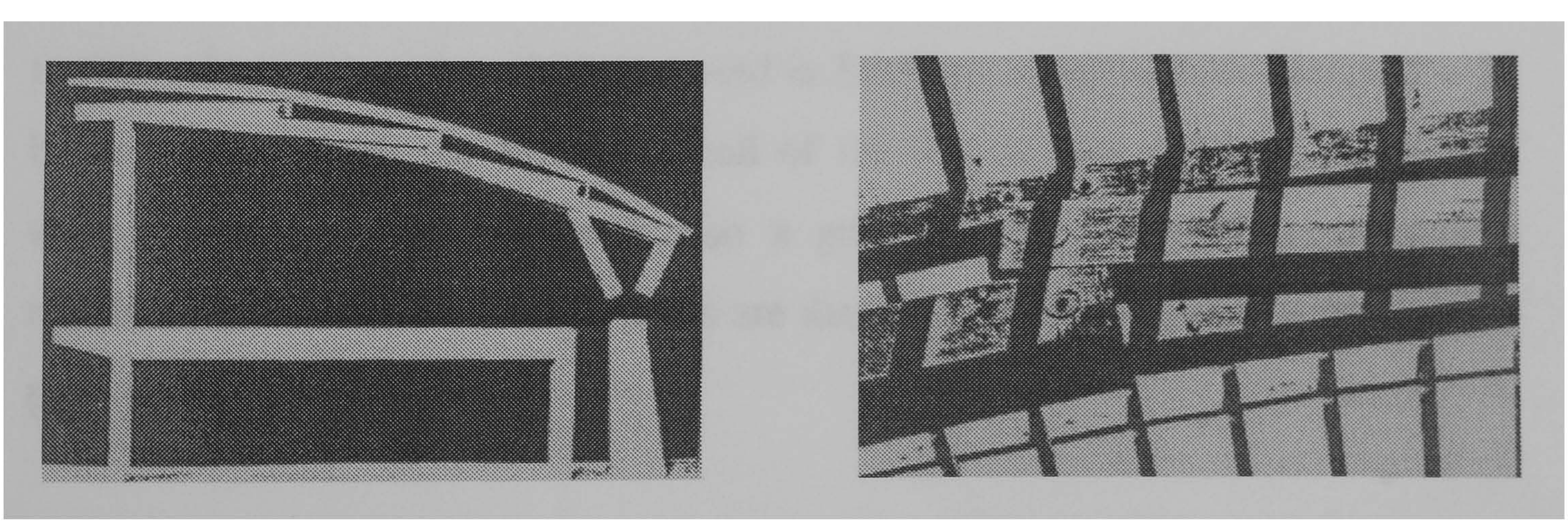


Figure 2.22. The Langstone Sailing Centre - model and detail of the structure

Both the Langstone Sailing Centre roof structure and the RF are an assembly of simply supported interlocking beams, which means in practice that both structures 'work' in the same way. In the case of the Langstone Sailing Centre structure the simply supported members have a point load at midspan (which is the reaction of the next beam), whereas in the case of the RF this is only one possible configuration (out of many). It is interesting to note that the structure has been referred to as 'unique' (The Structural Engineer, 1995, p.3), although the structural principle is identical to the RF.

Recent examples of buildings using the RF system will be described and analysed in detail in Chapters 3 and 4. However, they are mentioned here briefly to complete the survey.

Knowing that grillages are very often found in Japanese traditional Architecture, it is not surprising that there are a number of recent 3-dimensional grillage structures built in Japan. The house Yu in the Sukiya style, designed in 1990 by the Japanese architect Kazuhiro Ishii, uses a timber RF structure as a roof over the parlour and a means of support for a timber geodesic dome. The span is 8 meters (Kurokawa, 1993). The main roof structure, because of the horizontally overlapping beams, provides earthquake resistance (JA, 1990-May).

Kazuhiro Ishii used the same structure, with a 7 metre diameter, for the roof of the Seiwa Bunraku Puppet Theatre, on the island of Kyushu in southern Japan. In order to emphasize the symbolic significance of the building, and inspired by the traditional spiral layering of beams, used in Buddhist temples, Ishii designed a 12 beam RF roof over the exhibition hall of the theatre (JA, 1993-2). The roof structure over the auditorium is also a grillage, with 14 metre span over a rectilinear plan. All the wooden joints are made in a traditional way without metal parts (Detail, 1994-3).

The Spinning House (Enomoto Residence) in Tokyo, designed by Kazuhiro Ishii in 1985, is another building in which the RF structure has been used. Unlike the others described, which have a timber RF structure, the structure used in the Spinning House is an assembly of steel trusses which support each other. The structure at each level is rotated relative to its predecessor, giving the whole building a sense of motion - hence the name.

In 1992 the Japanese engineer Youchi Kan designed the timber structure for his own house in Nagasaki. The structure is a semi-rigid timber frame and wall system, with a steep 8 beam RF as a roof structure. All the column - beam connections use traditional Japanese joints with no connecting metal elements. The span is about 8 metres. Again, it is interesting to note that Kan considers the roof structure as 'an original one' (ref. to a personal correspondence). Obviously the RF is not a very well known principle, and the structure is certainly not known under the name 'Reciprocal Frame', world wide.

The Stonemason Museum in Toyoson, designed by Yasufumi Kijima, is another example of the use of the RF structure in Japan. Unlike the other Japanese examples, the Stonemason Museum uses a star-like multiple RF, and round instead of rectilinear section timber.

Since 1988, a number of small polygonal buildings have been built in the UK using the RF structure (Chilton, Wester and Yu, 1993). The spans in these buildings were in the range from 4.2 to 13 metres and in all cases timber beams were used, solid timber for the shorter spans and glulam members for the longer spans. With the exception of two buildings, which have a circular plan, all the plan forms were seven to twelve sided regular polygons. In all cases, the number of beams used for the RF structure was equal to the number of the sides of the polygons.

An 11 metre diameter RF building, a two bedroom house at Ferryhill, near Forres, Morayshire, in Scotland was completed in 1993. The biggest, but still unfinished, is the 13 metre diameter house, in Saorsa Ardlach, Nairn, Scotland. The other buildings employing the RF are used as summer houses, gazebos and meditation retreats in private gardens. Also, in 1990, RF structures were used as roofs over two 6 metre diameter whisky vats both circular in plan in order to provide living accommodation, at the Findhorn Foundation, near Forres, in Scotland. In 1995 the construction of three 8 metre RF modular pavilions designed as a Permaculture Centre in Bradford was started (Chilton, 1994).

2.1.4. Kinetic architecture

It is possible to construct movable structures using the RF. In plan, the structure strongly resembles the iris of a camera shutter and, as a result, it is not hard to envisage the possibility of creating kinetic architecture by using it as a retractable roof structure. There are no known existing buildings which employ the RF in this way, but some preliminary research has been recently carried out in this direction which is presented in Chapter 6, section 6.3.

The retraction process would be achieved by rotation of each beam about a vertical axis and a horizontal axis perpendicular to the beam at its external support. Although, the most natural plan forms when using a RF are circular and regular polygonal forms, a great advantage when using the RF as a retractable roof is the versatility of floor plans which can be achieved. *"If appropriate materials such as steel, concrete or glulam timber beams, steel or timber trusses are used for the beams it can enclose very long spans, which makes it a suitable solution for covering arenas and sport stadia"* (Chilton, Choo and Coulliette 1994, p. 50).

However, there are practical issues which need to be investigated, such as cladding materials, the changing geometry due to the retraction, design details of the hinges, the covering of the sky light, eliminating the danger of progressive collapse, drive mechanisms which will provide simultaneous retraction of the beams and the cladding, and overall construction detailing. Some of these issues have been investigated and are presented in Chapter 6, section 6.3 . However, more research will need to be carried out in the future due to the complexity of the problem.

Therefore and as part of this survey some ideas for movable structures will be presented and compared with the idea of retractable RFs.

As life itself is dynamic and changeable, it is not surprising that the wish to include movement and change in the buildings has been present throughout human history. Just as swing and lift bridges are structures that change, as the function requires, there are also examples of buildings which have made a similar attempt to include movement and allow for change.

It is very hard to say when and where the idea for creating kinetic architecture first originated. There are examples of Egyptian frescos, from as early as 1460 BC, excavated from the Senefer Tomb, with diagrams of umbrellas which open and close as the weather dictates (Escrig, 1996).

One of the first deployable structures was constructed by Buckminster Fuller. He designed *"...possibly history's first scientific dwelling to the moon..."* (Buckminster Fuller, 1965, p. 70). This geodesic structure consisted of lightweight magnesium alloy struts tightly bundled together in parallel, so that they could be transported within a rocket capsule. It could be opened and the members tensioned in only 45 seconds, by use of 200 pounds of gas pressure. The size of the geodesic dome was big enough to accommodate 2-3 cars. The only similarity of this structure to the retractable RF is that they both employ movement.

The idea of a retractable roof which operates similar to the iris of the camera lens is not the first concept of its kind. Emilio Perez Piñero in his patent of 1961 (Escrig, 1993) proposed a dome built of 3-dimensional curved segments, which retract (Figure 2.22.). The segments twist simultaneously and provide a retraction of the structure which is reminiscent, in plan, of the iris of an eye. Both this structure and the retractable RF, are similar to the camera lens. Also, both structures consist of mutually supporting cantilevers, only in the case of the RF they are linear elements, whereas in the case of Piñero's retractable dome they are curved segments.

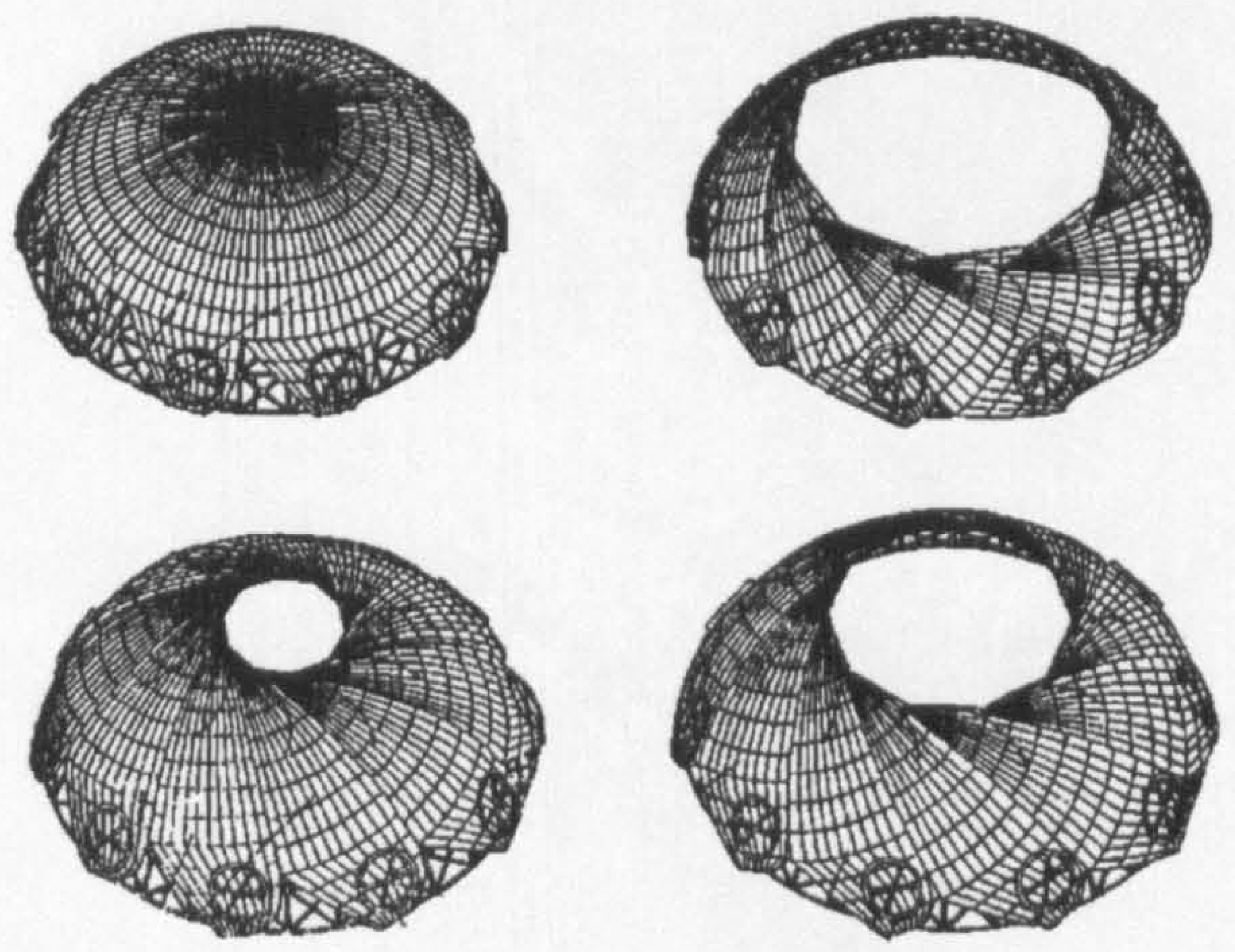


Figure 2.22. Piñero's patent of retractable dome structure

Iris-like retracting mechanisms have been used on the south façade of the Arab World Institute in Paris, for which the architect Jean Nouvel was awarded the Grand Prix of French architecture in 1987. *"The building uses leading-edge technology with a concrete structure, glazed facade and aluminum trim covering structural parts stretched like a skin"* (Boissiere and Nouvel, 1992, p. 84).

Inspired by Arab architecture of the Alhambra, in Granada, Spain, and the traditional form of the moucharabeih, Nouvel designed aluminum diaphragm panels with squares, circles, stars and polygons which generate decorative figures through rotation. The south façade is composed of these panels, which by using a photoelectric cell, to adjust the admission of natural light by opening and closing the mobile diaphragms, like the iris of the camera shutter (Figure 2.23).

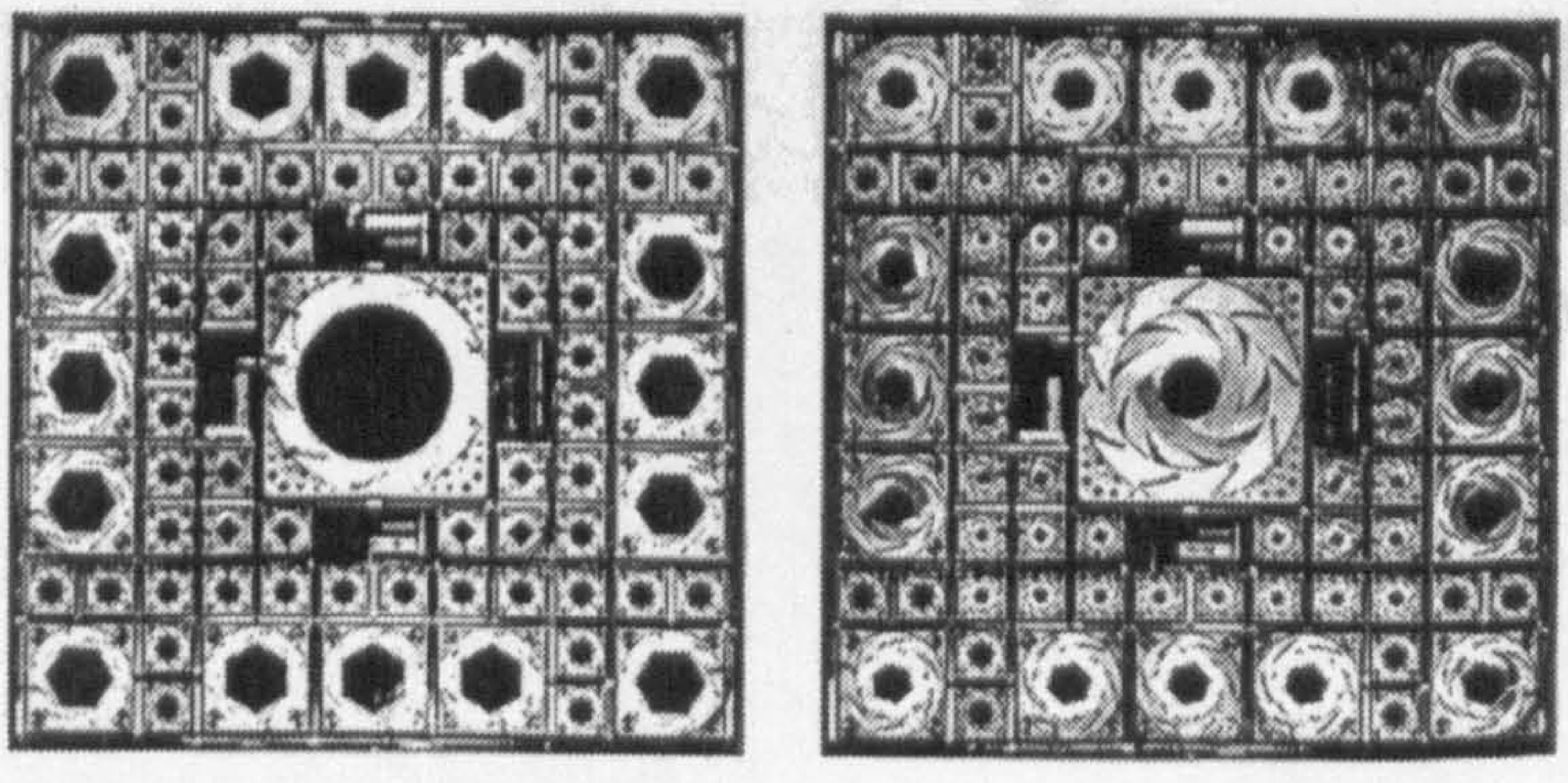


Figure 2.23. The mobile diaphragms used in the Arab Institute in Paris

Retractable roofs have been developed for use on arenas and sports stadia. All the buildings constructed so far use retractable roofs very different to the RF. Good examples are the retractable roofs for the Mukogawa high-school swimming pool, which is a 'Shell Dome' consisting of seven roof panels (four movable, and three fixed), the Ariake Colosseum with a roof which slides horizontally with a 'wire traction system', and the Fukuoka Dome which uses the 'Cantilevered Three Leaf System' constructed from three roof segments that rotate about a vertical axis at the centre of the roof (Narita, 1992). All of them were built in Japan.

However, one of the most well known retractable roofs is the Toronto Skydome (Figure 2.24.) consisting of four different roof panels, with three sliding and retracting over the fourth, fixed panel (Allen, 1992).

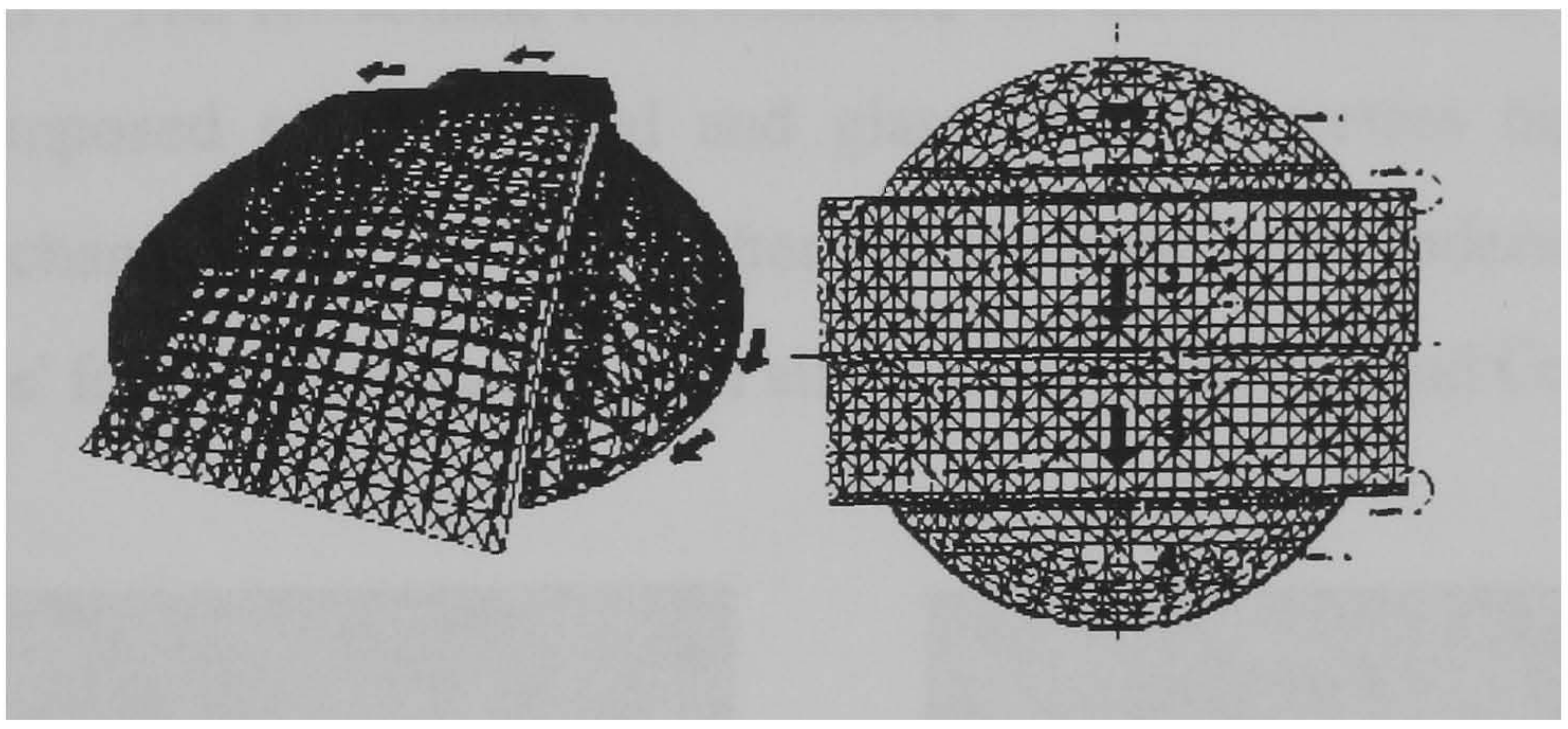


Figure 2.24. The Toronto Skydome

There have also been other solutions for retractable roof structures over arenas and sports stadia. One of the earliest examples of such long span structures is the Civic Arena in Pittsburgh, which is a retractable dome structure. When the roof is open, six separate sections of the structure pivot about a central pin and roll along curved rails before coming to rest over two cantilevered fixed sections (O'Conner, 1992).

The above mentioned are not the only built retractable roof structures which have been used for covering sports stadia, but they are the most well known. They are presented to show that the idea for using a retractable roof over such buildings is not original. However, the retractable RF and its possible use for covering sports stadia is original and very different as a solution, when compared to all of the mentioned constructed buildings. One of the main differences is that the retractable RF structure beams would allow full retraction of the structure which is not the case with the presented examples which can achieve only partial retraction.

When discussing movable structures it is impossible not to mention the renowned Spanish architect and engineer Santiago Calatrava. Calatrava, the man who managed to bridge the gap between art and science since his first designs, has been very interested in movement and has created kinetic architecture (Low, 1993). He studied the bone structures of animals, when developing kinetic forms.

Calatrava's projects for a restaurant in Zurich and the pavilions (Concrete Floating, Kuwaiti and the Swissbau) have some similarities with the principles of a retractable RF. The retractable roof structure for the restaurant in Zurich (Figure 2.25.) is composed of nine metal and glass trees 12 metres high. They are operated mechanically to provide shelter for the restaurant underneath. Each of the nine 'trees' folds in a sequence with all the others (Levane and Cecilia, 1994).

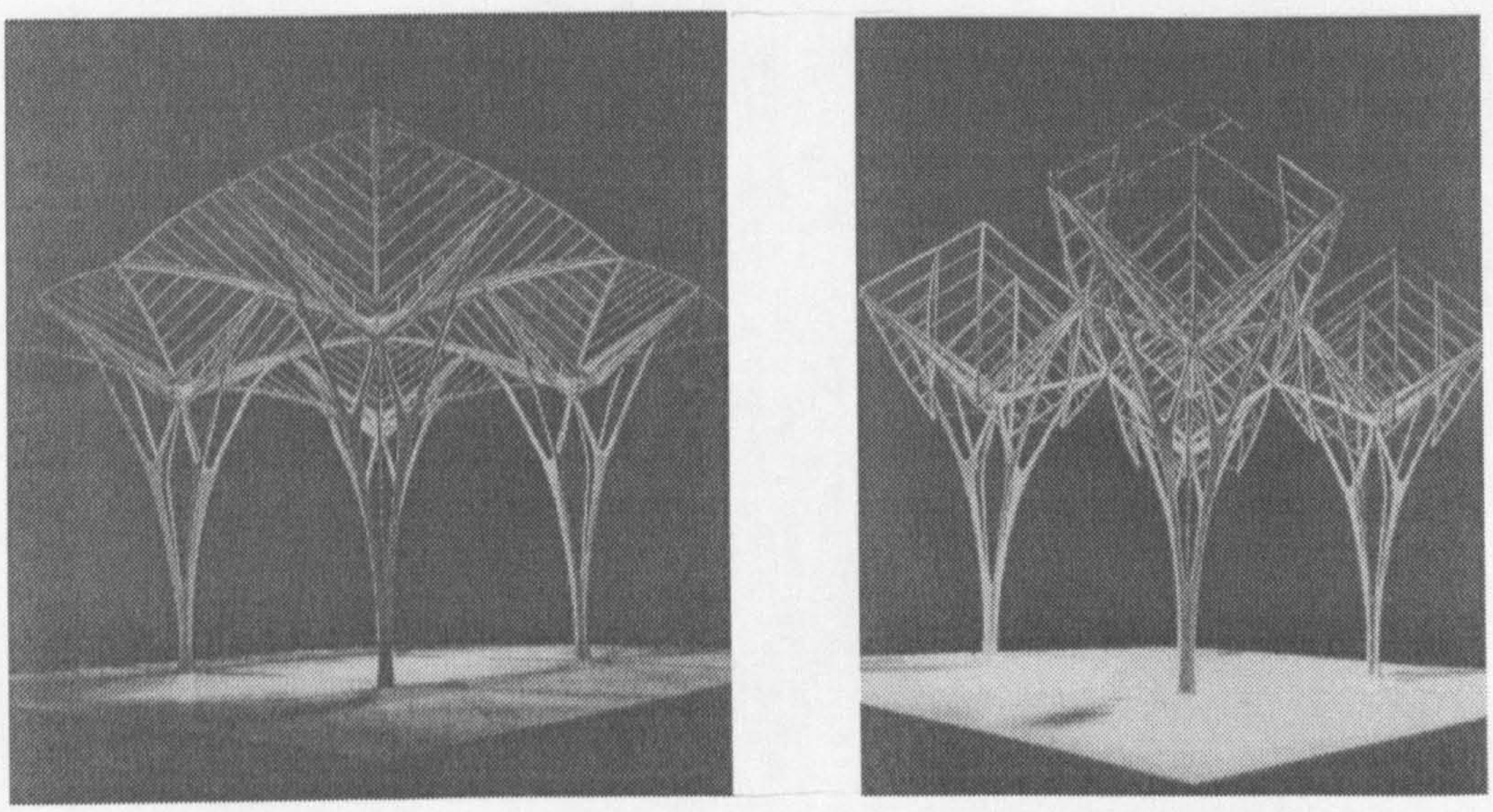


Figure 2.25. Calatrava's design for a restaurant in Zurich with a retractable roof

On the other hand, the Concrete Floating Pavilion (Figure 2.26) is constructed from twenty-four leaf-like concrete members which are arranged to form a circular plan. The opening and the closing of the roof is provided by a mechanically operated rotation of the members. This project will be built on a floating platform on the lake Vierwaldstatter, for the 700th anniversary of the Swiss Confederation.

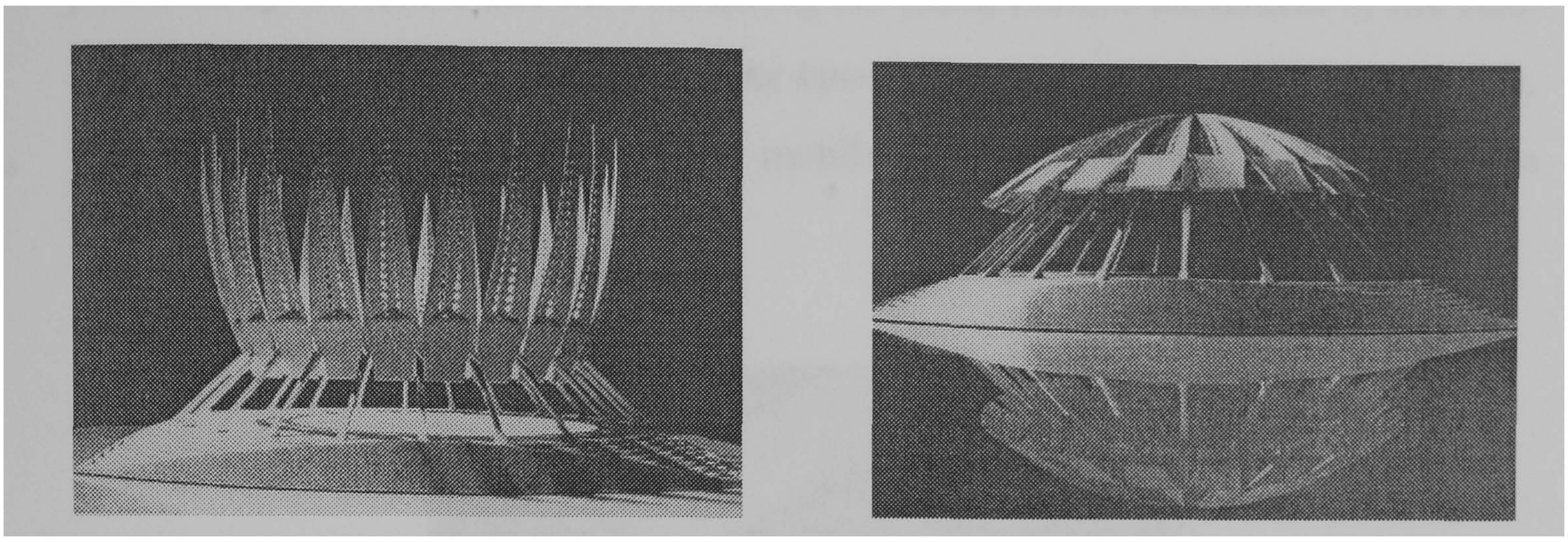


Figure 2.26. The Concrete Floating Pavilion by Santiago Calatrava

The Kuwaiti pavilion (Figure 2.27), built to capture the attention of the visitors of the '92 Expo exhibition in Sevilla, has a mobile roof which provides shade during the day. When opened, the rotating curved tapering timber ribs, which form the roof, reach a height of 25 metres. When closed they form a vault and remind one very much of a huge skeletal rib-cage. The roof ribs, supported by two rows of bone-like pillars, can be moved individually to several positions, producing a changing sinusoidal roof form. The retraction of the ribs is controlled by system of hydraulics.

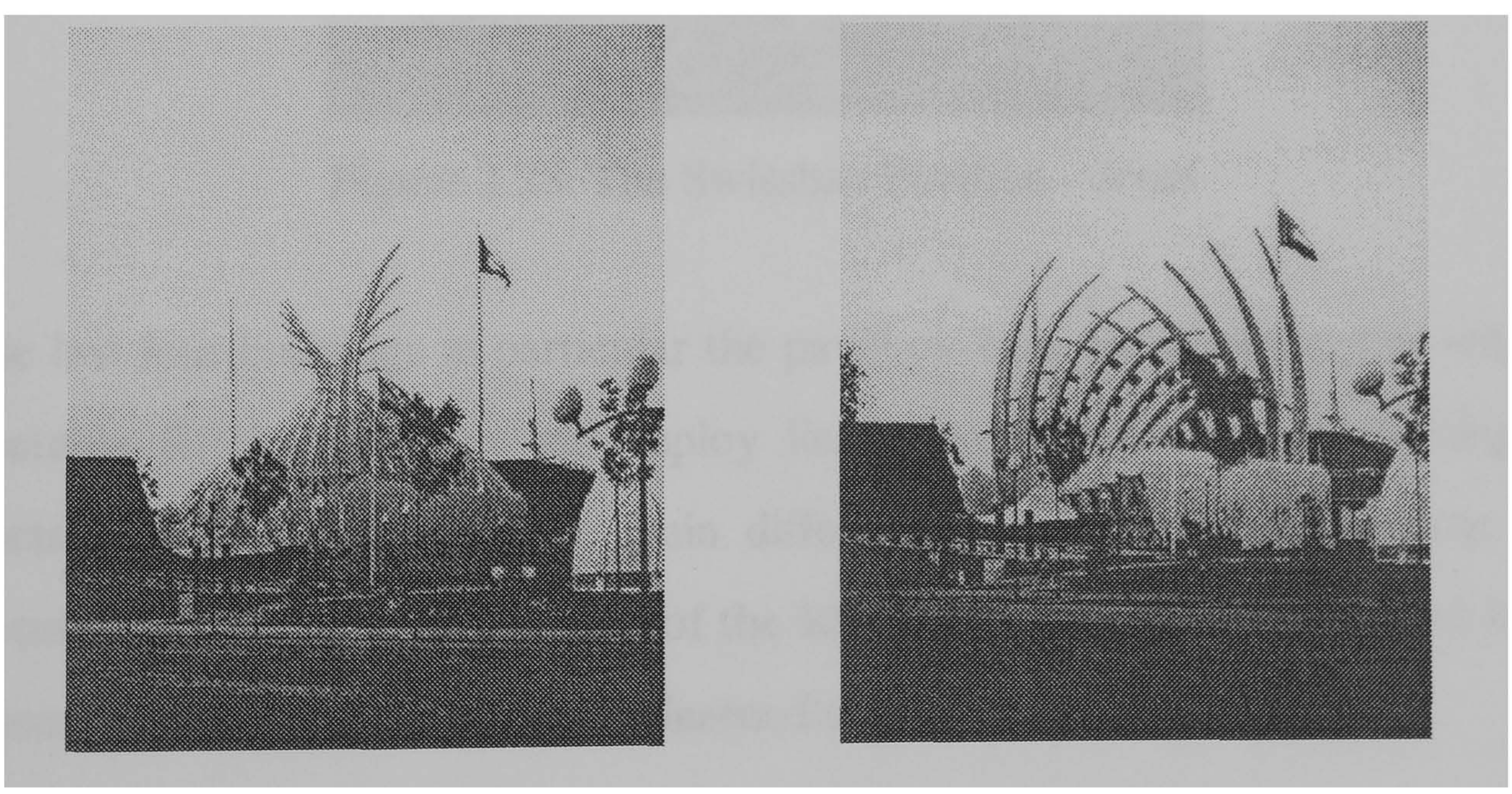


Figure 2.27. The Kuwaiti pavilion by Santiago Calatrava

The mobile structure of the Swissbau Pavilion (Figure 2.28.) consists of rows of moulded concrete ribs which are cantilevered from a concrete wall as a canopy.

The heavy ribs (each weighing more than a tonne) are moved by flat levers attached to rotating disks mounted in the concrete wall. *"The different initial positions of the levers and the rotation of the disks, creates movement of the ribs. Since, they are out of phase a wave-like kinetic structure is formed."* (Low, 1993). The opening and the closing of the mobile structure, again, is controlled by a system of hydraulics.

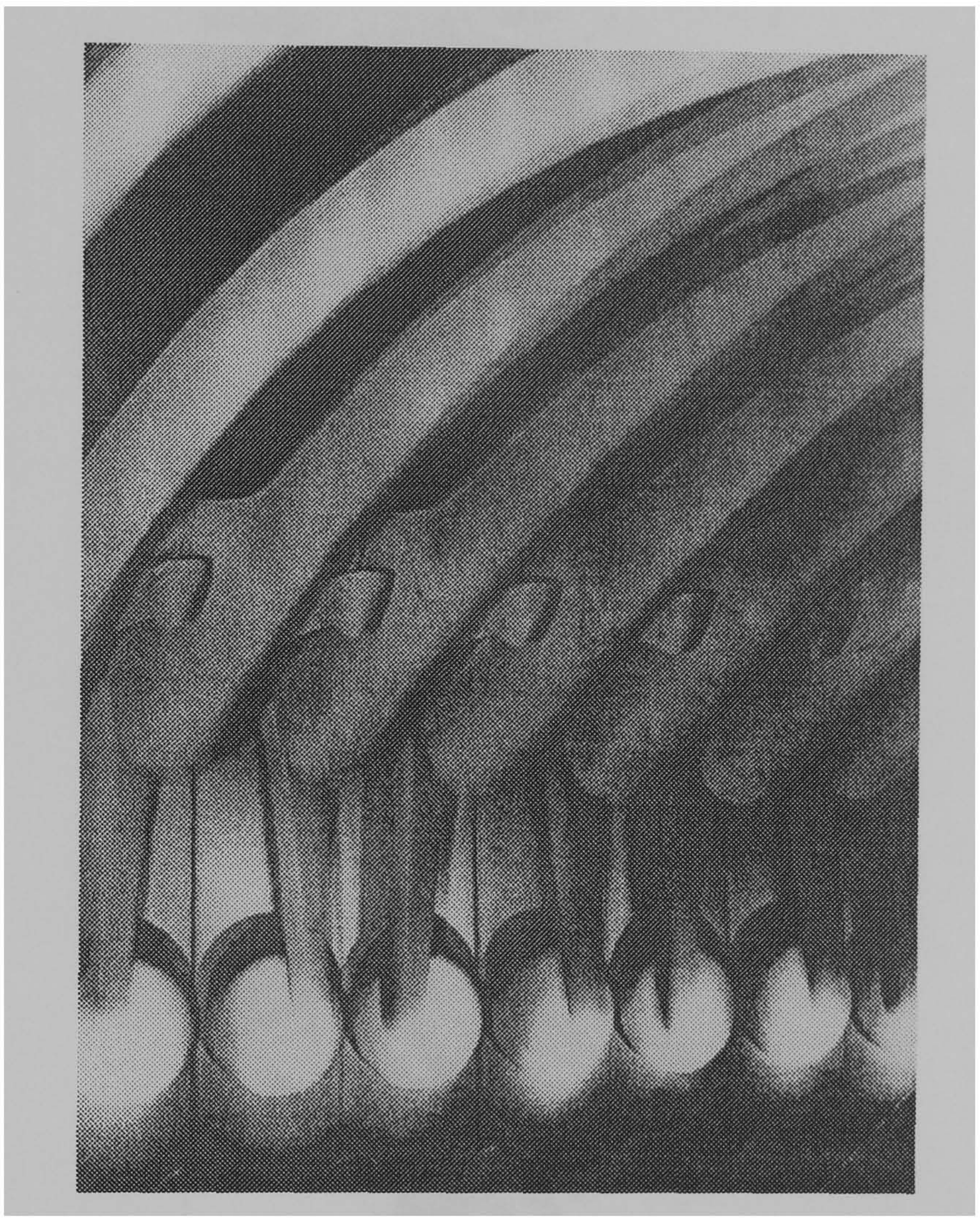


Figure 2.28. The Swissbau Pavilion - detail

These last four buildings in particular the pavilions have some similarities with the retractable RF in that they all employ linear mobile elements in forming the retractable roof structure. The main difference is in the concept of the used structural systems. Only in the case of the RF lightweight simply supported beams are used. Nevertheless, a lot can be learned from them.

Another researcher recently active in the field of mobile and folding structures is Chuck Hoberman. His special interest is structures and mechanisms and the possibility of incorporating the two into one (Waters, 1992). Trained first as an artist and then as a mechanical engineer, Hoberman, started with design of robotics and automation systems. His work soon led to the creation of two distinct families of forms known as expanding structures and iris structures (Architecture, June 1994).

The largest full Hoberman unfolding structure, built to date, is an expanding geodesic dome spanning six metres when open, and only 1.5 m when closed (Figure 2.29).

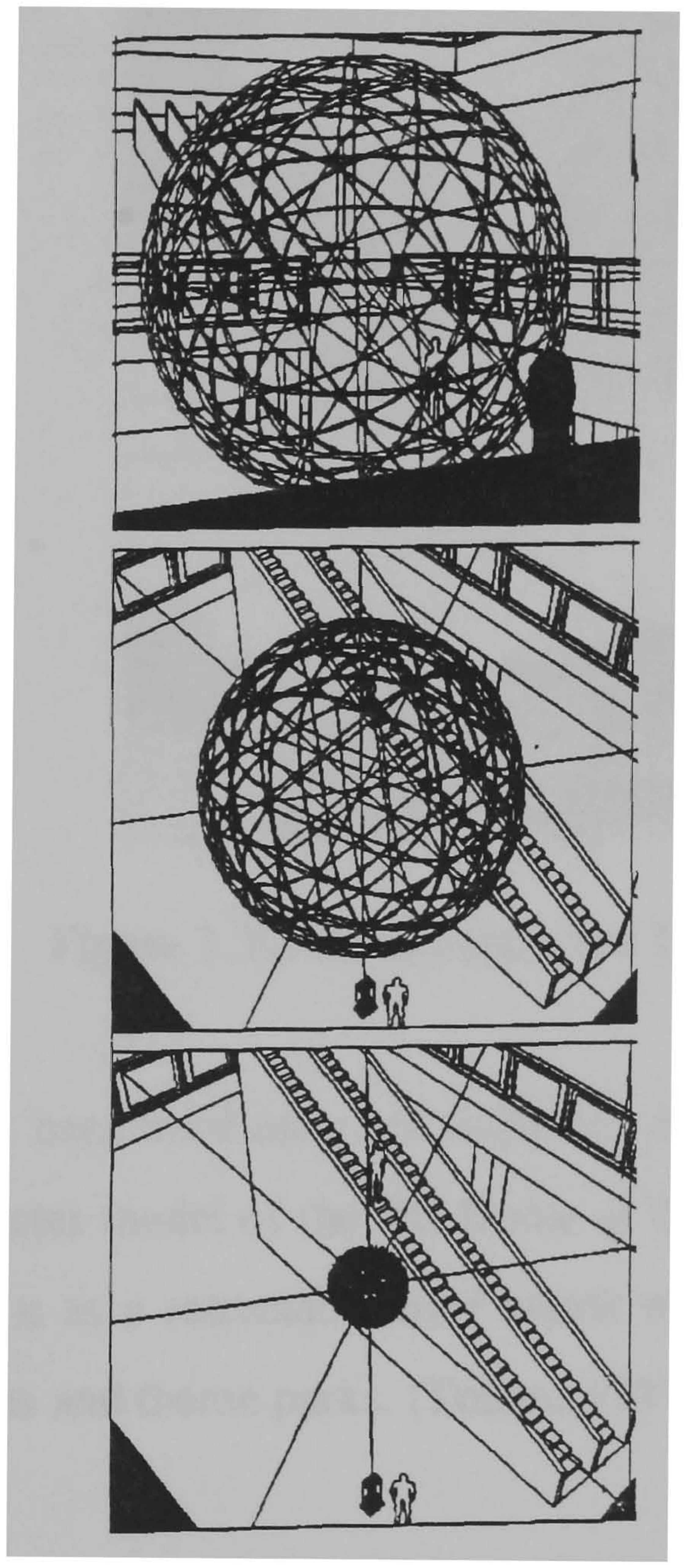


Figure 2.29. Hoberman's expanding geodesic dome

More similar to the RF, although very different at the same time, is his design for an unfolding truss dome structure. The perimeter is fixed, whilst the centre retracts in a smooth radial motion like the iris of an eye (thus the name 'Iris Dome') (Figure 2.30). In configuration the structure is a lamella dome with a geometry of interlocking spirals (Hoberman, 1993).

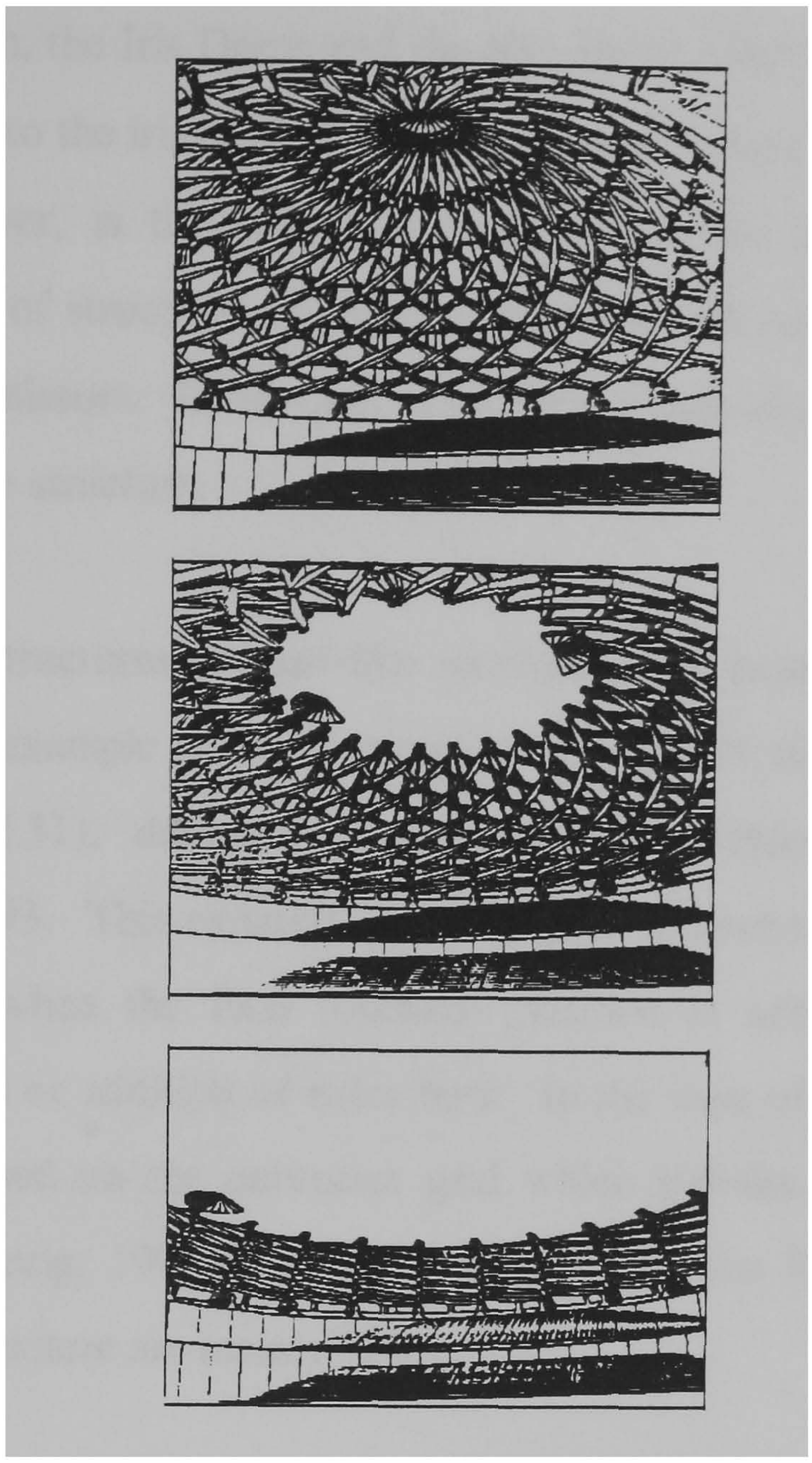


Figure 2.30. Hoberman's 'Iris Dome'

The structure has not been used on a real building. Research is being carried out on a 1.5 metres diameter model of the Iris Dome at the moment, investigating the possibilities of using it as a retractable roof which will cover large public spaces such as stadia, theatres and theme parks. (Tomei, 1993).

Unfortunately, there always is the possibility when something is built very large, that the pieces which were rigid in the small-scale model start bending and deflecting, and those pieces that were turning freely start to jam. Therefore, a large-scale (60 foot diameter) section of the Iris Dome was built, and computer models were developed, which were tested by Gay Nordenson of Ove Arup & Partners. These showed that the structure is in fact a Vierendeel grid which carries the load by bending action rather then by axial forces (Schmertz, 1994). This fact makes it similar to the retractable RF structure, which also carries load by bending action. Also, both, the Iris Dome and the RF, are in plan similar to in appearance to each other and to the iris of the eye, or to a lens adjusting to the light. The main difference, however, is that the segments which form the Iris Dome are an assembly of pairs of structural elements, connected with hinges at their midpoints which move like scissors. In the case of the RF, scissor-like movement is not used to form the mobile structure.

In several other structures, scissor-like movement has been used also to achieve movement. For example the roof structure for the Olympic swimming pool in Seville (Figure 2.31), designed by the Spanish Architect Felix Escrig and constructed in 1993. This expandable structure is a mechanism in the process of deployment and when the final (opened) position is achieved it needs to be stiffened by cables or addition of extra bars. In the case of this building diagonal bars have been used on the perimeter grid which stabilise and fix the structure (Valcarcel and Escrig, 1996). In this building, as in the RF, structure the main elements of the structure are mainly in bending.

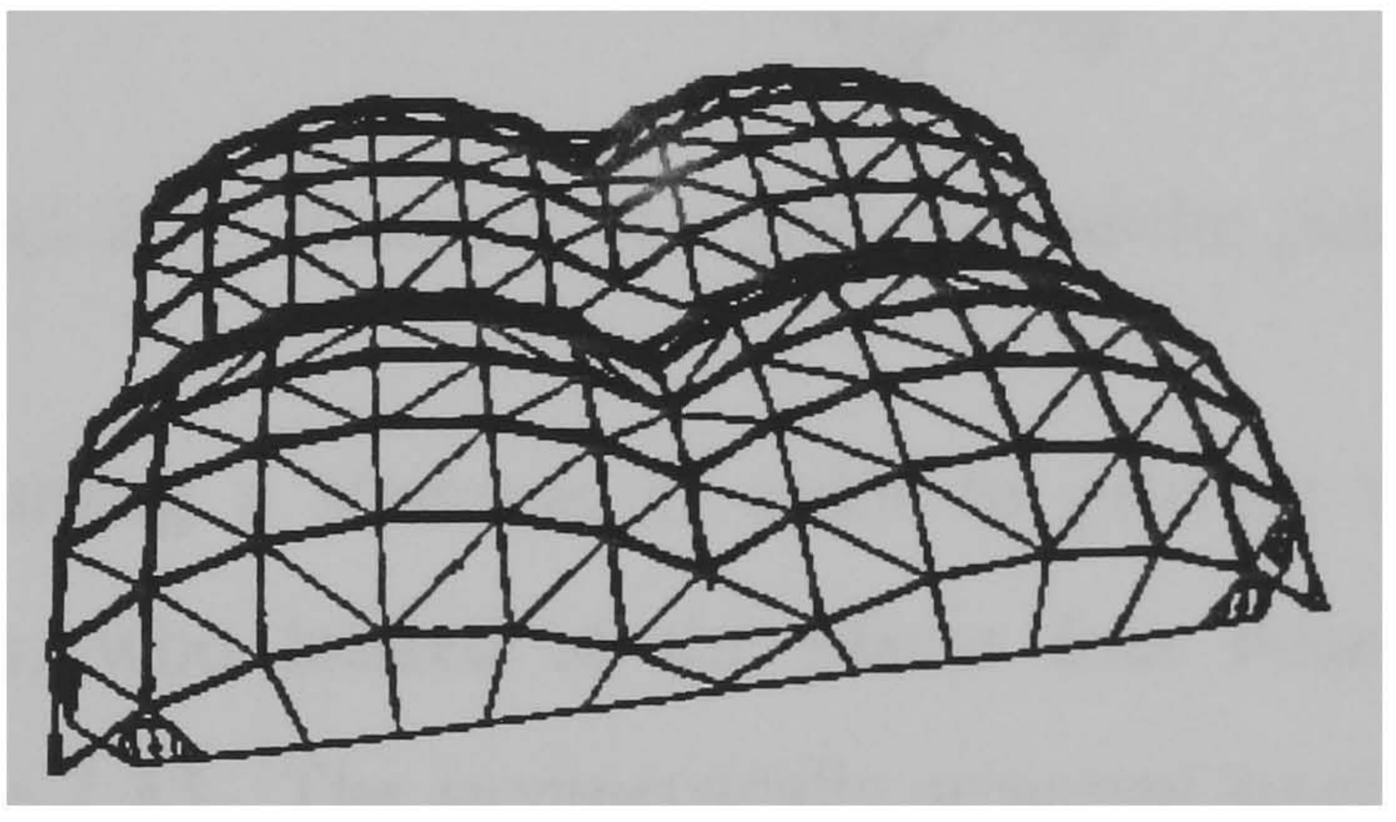


Figure 2.31. Seville Olympic swimming pool designed by Felix Escrig

The scissor-like movement and its application on mobile structures, and the mobility of structures in general, has been studied recently by Servadio, (Servadio, 1994), Pellegrino, Hernandez, Gantes, Motro (Escrig and Brebbia, 1996) and others. The mobile structures they have designed have a similarity to the RF only because of the fact that they employ movement. In all other respects they are very different to the RF. Consequently they will not be described in detail.

2.2. Structural and geometry aspects of grillage structures

The concept of a type of planar grillages, the 'Mutually Restrained, Modular Floating Platforms' , is described and analysed by Gat (1992). He considers a system constructed from modular platforms, each consisting of a pair of pontoons held together by a pair of beams. The rectilinear platforms were constructed by assembling the modular units. The geometry of the system is very similar to the grillage structure used for the auditorium of the Seiwa Bunraku Puppet Theatre, the difference being that all the joints of the platforms are designed as hinges. Figure 2.32. shows an example of a grid of modular platforms studied by Gat.

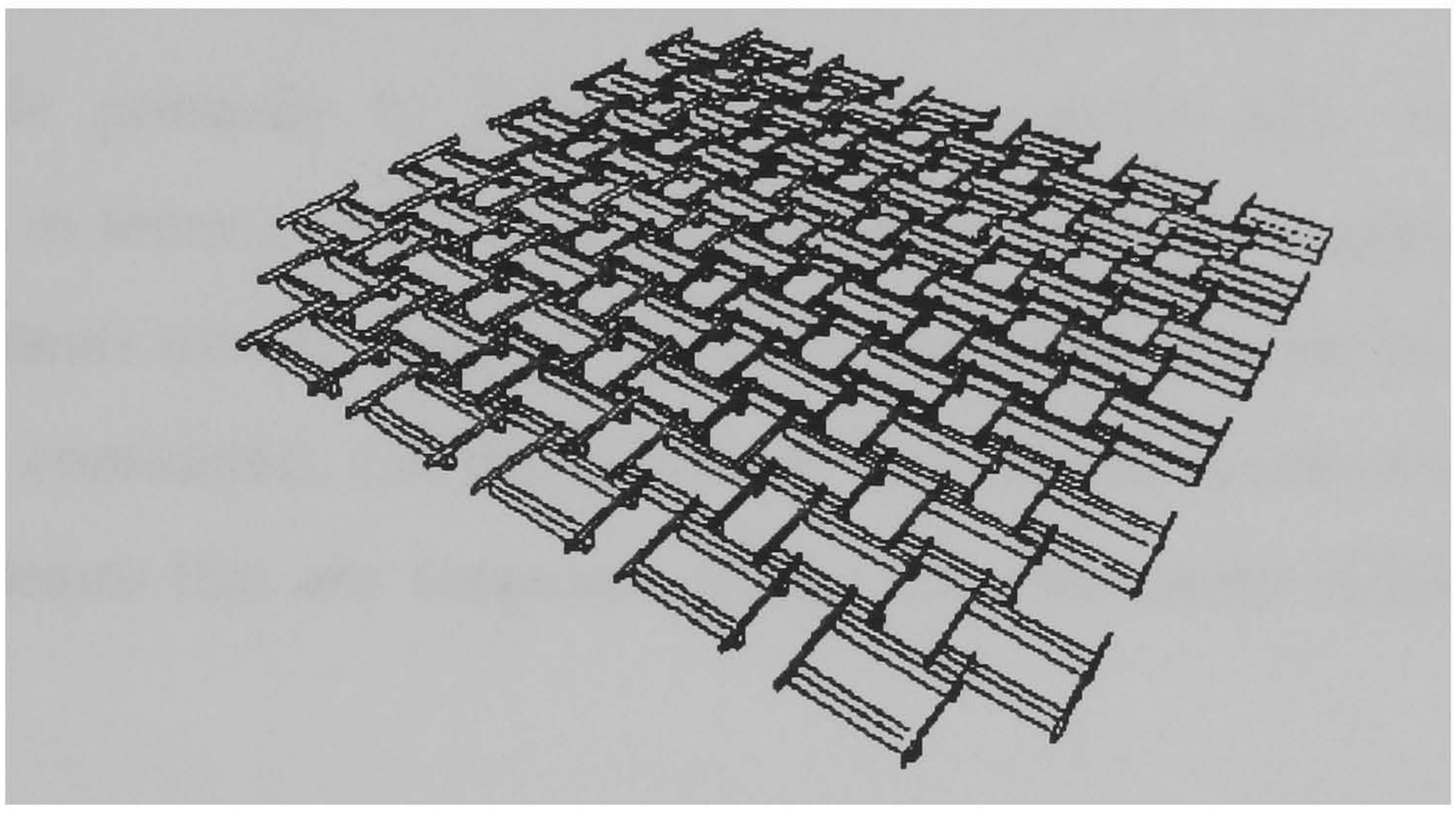


Figure 2.32. Example of a grid of modular platforms

The problem of framing a staircase in order to provide a central lift shaft is discussed by Evans, who looked at the planar four beam assembly (grillage) presented on Figure 2.33. The symmetrically arranged steel beams, as a result of the applied uniform load over half of their span, give always a reaction at one end which equals the load at midspan. It is interesting that altering the load does not change this (Evans, 1987). Although, the RF is usually a non-planar grillage structure, unlike the structure described by Evans, for a four beam symmetrical arrangement, the reaction at one end, as a result of uniform vertical load, will equal the load at midspan, as with the planar grillage.

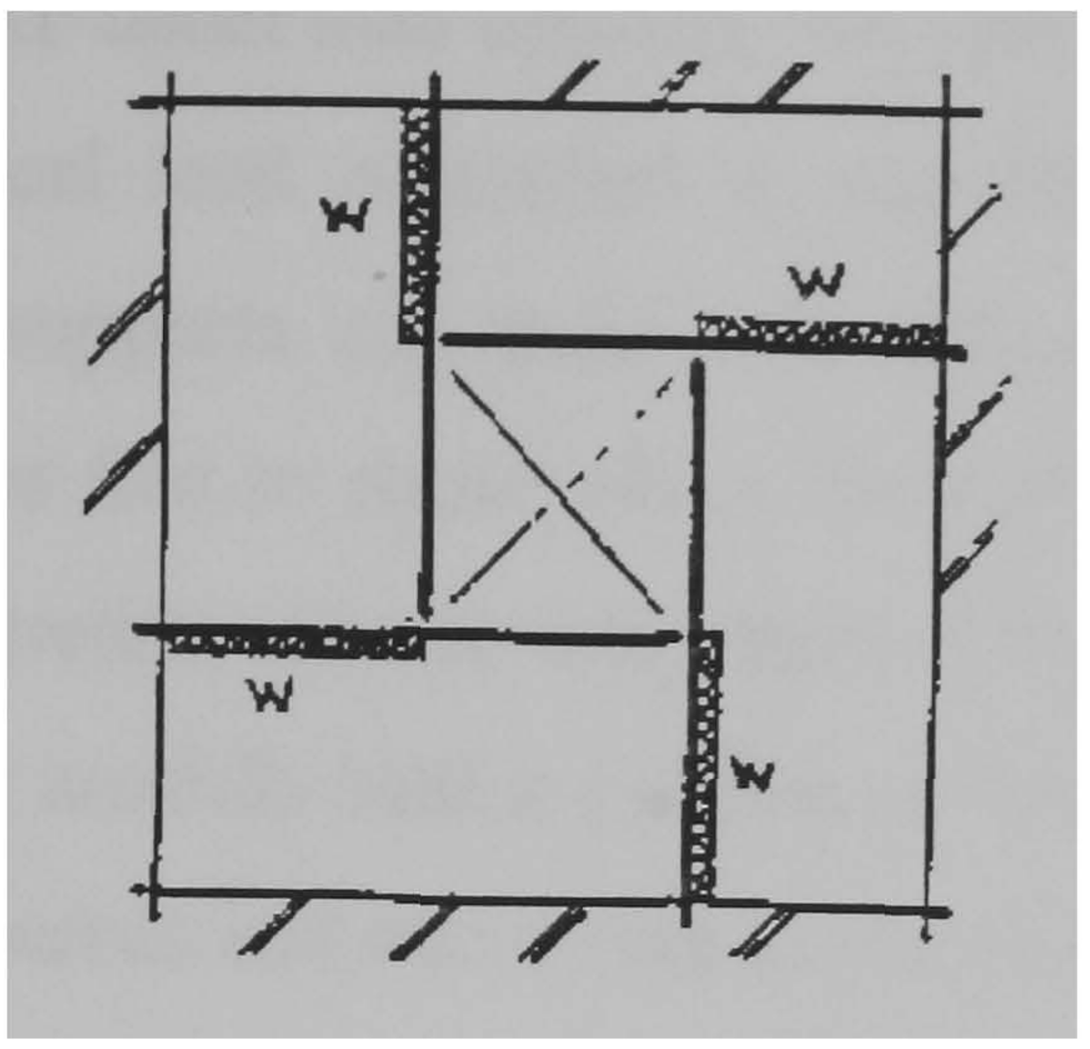


Figure 2.33. Four beam assembly used on a staircase to provide a central lift shaft

Research in to the structural behaviour of the RF has been recently carried out by Chilton and Choo. It has been noted that, since the structure provides resistance to vertical loads primarily by bending and shear rather than axial forces, no compression or tension ring is necessary. For a typical roof loading, the maximum bending moments usually occur at the points where the adjacent beams rest on the beams being considered, and the maximum shear forces usually are at/or near the end of the beams that are supported by the adjacent beams (Chilton and Choo, 1992).

The structure has been analysed considering the elements as simply supported, sloping beams carrying the load from one segment of the roof with an additional point load applied by the adjacent beams at the intersection point on the span. It was shown (on the five beam grillage which was examined) that load applied to any beam was distributed around the circuit to all the other beams, diminishing in magnitude as it was transferred from beam to beam.

The reduced load was applied back on to the first beam and again distributed - *ad infinitum*. It was noted that the final reactions were in direct proportion to the reactions obtained after the first circuit of distribution. Their magnitude depended very much on the geometrical configuration of the structure. In a RF, supported at the perimeter, with a regular polygonal plan form and a uniformly distributed vertical load, the beam reactions at the perimeter supports are equal to the total roof load divided by the number of beams (Chilton, Choo, and Yu, 1994).

The deformations of the RF under load depends very much on the support restraint conditions. When vertical load is applied to the RF, there will be vertical movement at the inner supports and horizontal sliding outwards at the outer supports, if the beams are free to rotate about the vertical axis and slide in the direction of the beam centreline. On the other hand, if the beams are free to rotate about the vertical axis but are fully held in position at the outer supports, the inner polygon will move downwards and also rotate in the direction of the spiral of the beams. Again, the magnitude of the movements very much depends on the geometrical configuration of the structure. Prestressing is a possibility that has been suggested to improve performance (Chilton and Choo, 1992).

Since every beam supports and, in turn, is supported by the others in the RF, if one beam is lost there is a great probability of progressive collapse of the whole structure, unless some secondary structural action comes into effect. In order to avoid the danger of progressive collapse, several methods were proposed: *"....provision of a separate ring beam round the inner polygon, projection of each beam past the intersection point with the beam on which it rests, duplication of all main beams and overdesign of the joints at intersections round the inner polygon, a double system of beams that spiral in opposite directions and are connected at the inner polygon and other points of contact."* (Chilton and Choo, 1992, p. 107).

All the proposed methods have a common main requirement - that a continuous load path is provided around the whole inner polygon, so that if one beam from the system fails for some reason, then the load is transferred adequately between the rest of the beams, thus avoiding collapse of the system. If any of these methods is applied, because of the possibility of dissipation of energy in the interlocking joints, the structure becomes ductile and a very good solution for earthquake resistant design. This is one of the reasons why the structure has been used with success in Japan.

The RF is a grillage structure in which the beams support each other by resting on each other (the rise of the beams is from the outer to the inner ends). There is no reason why a 'hanging' RF can not be constructed. If the beams hang from each other (the rise of the beams is towards their outer ends), a structure founded upon the same principles will be generated (Chilton, Choo, and Yu, 1994). This can be especially useful if long span RF structures are designed and the beams can be trusses. In the case of sports stadia and long span halls the main advantage of this would be that the unnecessary volume inherent in a pitched roof would be avoided. The geometry of the RF is quite complex. The simplest possible planar configuration of a planar grillage is the one consisting of two overlapping beams, both shorter then the distance they need to span. But, since the RF is a 3-dimensional grillage structure, the minimum number of elements required is three.

The possibilities for the creation of different plan forms using the RF are infinite, but the simplest and most natural forms are circular or regular polygonal forms. The main variables that define the geometry of the RF are the number of beams, their length, the sizes of the inner and the outer polygons, the rise of the roof and the direction of rotation of the beams. (Chilton, Choo, and Yu, 1994). If some of these variables are varied and some of the conditions of regularity are relaxed, very interesting forms can be obtained (organic, irregular polygons etc.).

It is difficult enough to draw even the most regular configurations of the RF in 3-d, but as the irregularity in the geometry increases, it becomes extremely complicated and almost impossible to visualise the structure in 3-d. Therefore, the use of a computer-aided drawing packages (such as AutoCAD) is an unavoidable necessity. Because of the complex geometry of the structure a 3-d drawing in AutoCAD requires quite a long time. To overcome this the author has developed a AutoLISP routine which automates the drawing of regular polygonal RFs, thus shortening drawing times considerably. This is presented in detail in Chapter 6, Section 6.1.1.

All the RF structures used in buildings constructed in the UK recently use cladding panels installed between the RF grillage beams to produce a roof form very similar in appearance to the blades of a turbine (Chilton, 1994). This is not the only possible way of cladding the roof structure. For example the final roof covering at the Seiwa Bunraku Puppet Theatre was obtained by use of smooth conical tiled surface which was laid on radial rafters, supported on secondary purlins spanning across the primary beam grillage. Alternative methods of cladding could be hyperbolic paraboloid surfaces or lightweight membranes, but there are no known RF buildings covered in this way. Some preliminary ideas are presented in Chapter 6, section 6.4.

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2.4 List of illustrations:

CHAPTER 3: RF buildings in Japan

3.1. Japanese RF buildings

Although the Reciprocal Frame structural system (RF) has been patented in the UK, Japan would appear to be the real homeland of RF structures. Structures very similar to the RF have been known and built for centuries in Japan, although not known under that name. The spiral layering of timber beams used for RF-like structures has been a feature in Japan since the 12 C. Since then, they have been used in Buddhist temples (Ishii, 1993/2) and the construction technique was passed from generation to generation. Unfortunately, there are no known existing buildings dating from this period. This could be because they had been destroyed over time (fire, deterioration, etc.) or simply because they are very hard to locate, since they are not specifically named.

On the other hand there are several known and indeed very beautiful RF buildings constructed in Japan in the last 20-30 years. The 'Spinning' house in Tokyo, the Puppet Theatre in Seiwa and the Sukiya - Yu house are all produced by Kazuhiro Ishii. The engineer Yoichi Kan designed his own house in Nagasaki and the Stonemason Museum was authored by Yasufumi Kijima.

All the buildings seem to make the best use of the RF structure which has contributed considerably to the qualities of the spaces it has created. All the buildings will be described and analysed in detail, but before attempting to do so, one has to look at the precedents which have influenced (if not determined) the use of this specific structure in Japan. Questions such as *"why did this type of construction emerge in Japan rather than elsewhere?"* and *"how did tradition influence the use of the RF structure in contemporary Japanese architecture?"* will be investigated and possible answers offered. The buildings will also be analysed in terms of the qualities which they gained as a result of the use of the RF. But before one even attempts that, it is necessary to explain some of the principal reasons for the existence of the RF construction in contemporary Japanese architecture, such as the use of timber in traditional construction and the concepts of 'movement' spaces and 'Sukiya' in Japanese architecture.

3.2. Precedents for RF architecture in Japan

3.2.1. The use of timber

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"* (PA,1981/25, p.22). The main use of timber construction was a 'post and beam' structure most probably as a protection against earthquake; indeed another expression for 'God' is through use of the word 'post'. Timber construction has been developed to perfection, especially in those details which appear complicated but are, in fact a very sophisticated method of dissipating earthquake energy. Wood has been always used with special care, one of the reasons probably being religious. There were beliefs that when a timber temple is destroyed by fire, the spirits of the trees used in the building ascend to heaven. Timber was a 'living' thing therefore when used in construction of posts it was always installed in the structure in the direction it grew, having the root end down. Japan is probably the only country in the world where timber is stacked standing as opposed the conventional horizontal method in most Western countries.

Most Japanese temples, houses, prefectures and other traditional buildings have been built from wood. It is not surprising, therefore, that the largest traditional timber building in the world is in Japan. The Todaiji Temple in Nara is 57 m wide, 50 m deep and 47 m high and houses the Diabutsu, or Great Statue of the Buddha. The present building dates from 1708 and is only two-thirds in size of the original which had been destroyed in fire (Chilton, 1995).

The use of timber construction in Japan, most probably, has influenced an early development of the principles of modular composition and a high degree of standardisation which is typical for Japanese traditional architecture. This has definitely helped the emergence of a structural system such as the RF.

It is possible to write a whole dissertation on how successfully timber has been used in traditional Japanese architecture, but the intention has been to postulate that since 'real' RF structures are of timber, an entire culture of timber construction has probably been instrumental in the development of the RF as a structural system in Japan.

3.2.2. The concept of 'movement' spaces in Japanese architecture

When one looks at 17-18 C Japanese spaces and planning and compares them with Chinese from the same period, one of the most significant differences is the plan layout. The Chinese have a geometrical organisation of the buildings (and spaces) based on an orthogonal co-ordinate system. Every building and space in Chinese layouts from this period was related to the reference axes, and the compositional elements of the space had to be observed simultaneously (see Figure 3.1). They had their real meaning if they formed a 'prospect' or a 'vista'.

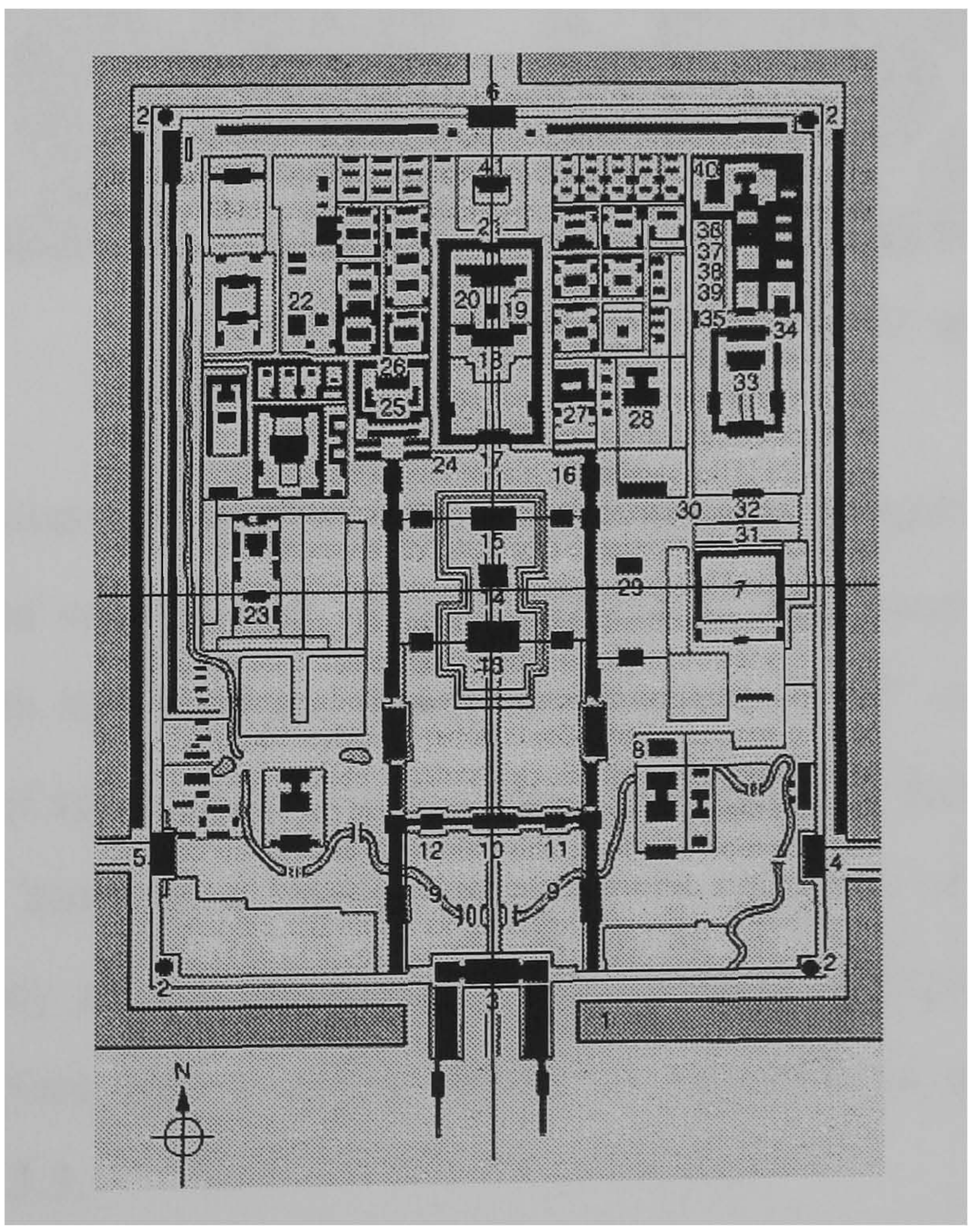


Figure. 3.1 Plan of the Forbidden City

On the other hand the Japanese buildings (and spaces) were mainly characterised with asymmetry, irregularity and indefinite organisation. There were no axes to which all spaces were related, only the preceding and the proceeding spaces mattered. A new scene is discovered at every turn and left behind at the next space. The emphasis is on the relative positions of spaces and rooms, rather than the spaces relative to their to axes. Inoe refers to these type of spaces as 'movement' spaces, as opposed to the 'geometrical', in the case of the Chinese temples (Inoue, 1985).

Figure 3.2 shows two diagrams of such 'movement' spaces. When one is in space "D" there is awareness of the existence only of spaces "C" and "E", and as one moves through the building one becomes aware of the next approached space. Although the two diagrams seem quite different, there is no significant difference, because the relationships between the internal spaces are the same in both of them.

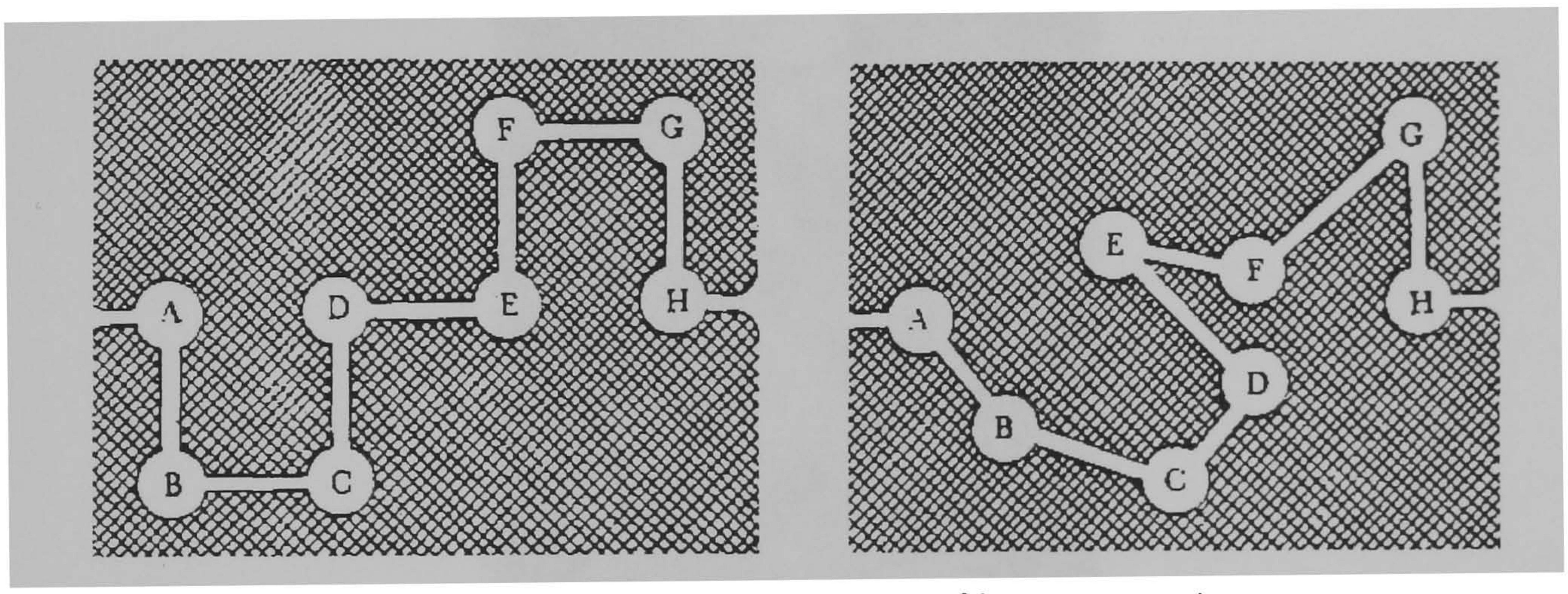


Figure 3.2 Diagrams of 'movement' spaces

The concept of 'movement' spaces is one of the major characteristics of Japanese feudal, or 'traditional' architecture. The expression of movement in plan results in zigzag patterns, with buildings and spaces organised in a "U" or diagonal layout. The fragmentation of spaces in plan was a major contributory factor in the creation of the concept of 'movement' spaces. Most of the elements of each building are designed so that they aid the formation of the 'dynamic' composition. Even the steppingstones at Nara had a zigzag layout as opposed to a straight line, as presented in Figure 3.3.

The layout of some Japanese towns also, suggests movement. While the Imperial Capitals 'miyako' were very much influenced by Chinese town layout (symmetrical) (Masuda, 1970), the castle towns followed in great detail the 'movement' concept and had an irregular town planning. Most modern Japanese towns have been influenced by them and kept their irregularity. If one questions the reasons for the development of this type of layout, one of the most probable reasons would be the creation of 'defensive spaces'. The Japanese people have been recognised throughout history as good warriors. In order to confuse their enemies they designed town layouts with spaces which were not easy to move through if one did not know what their disposition was.

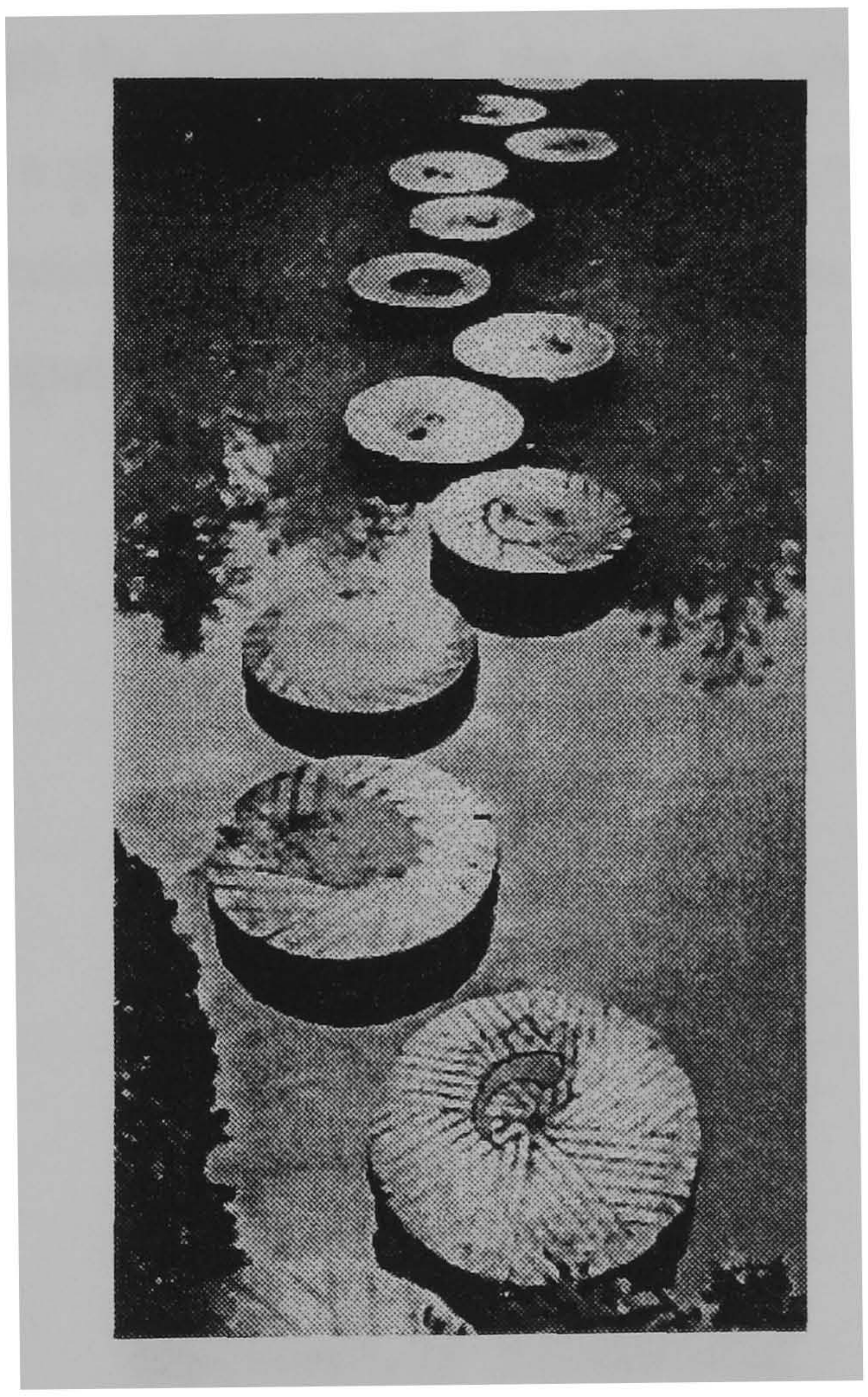


Figure 3.3. Stepping stones in Nara

It is very important to emphasise, that movement did not occur only in plan. Japanese traditional buildings gave a sense of three dimensional movement as well. When one looks at the 'rika' and 'shoka' styles of flower arrangement, the latter represents the Japanese idea of 'movement' in the third dimension (as presented in Figure 3.4).

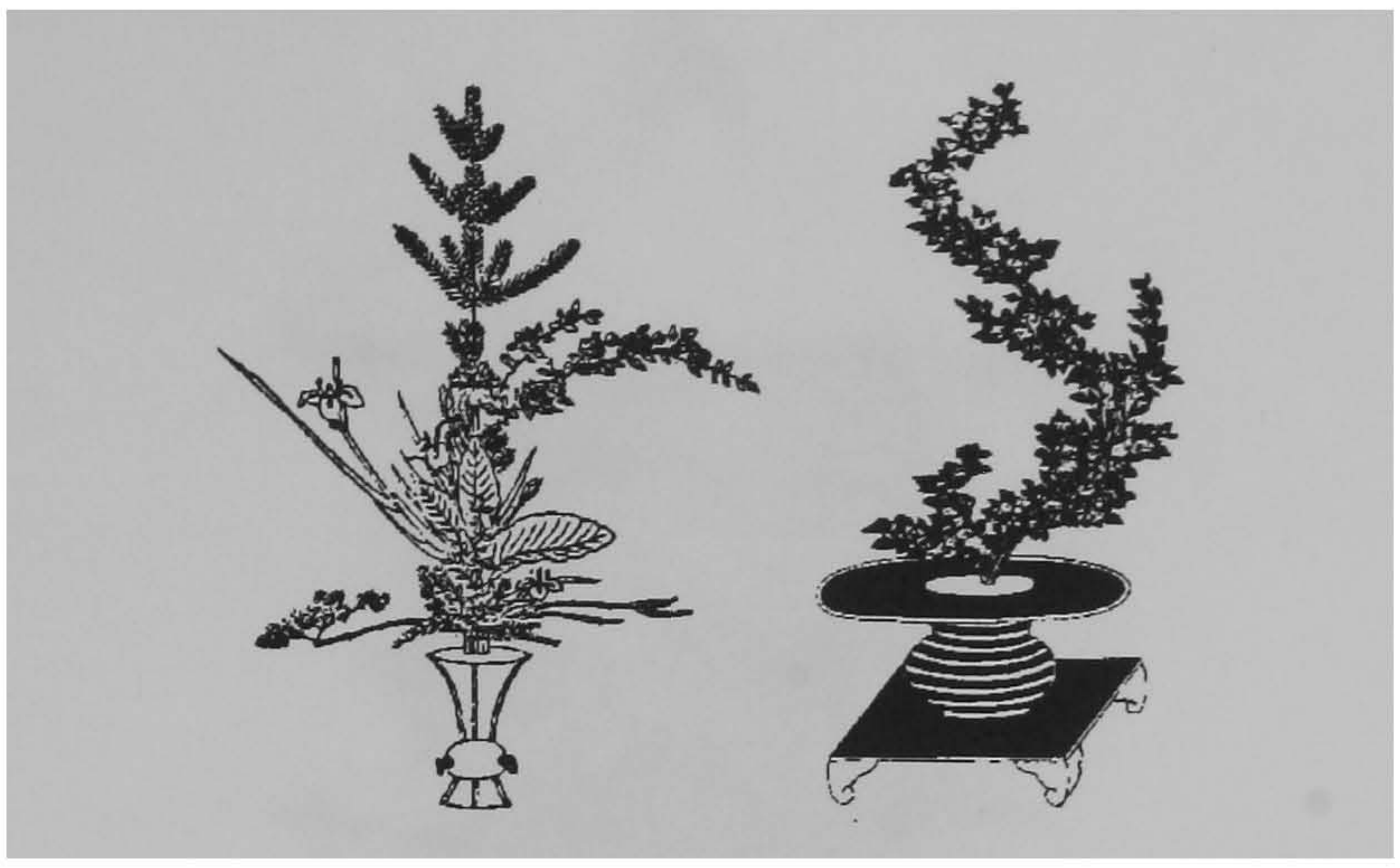


Figure 3.4 'rika' and 'shoka' style of flower arrangement

Similarly, as in the upward spiralling of the 'shoka', the 'movement' in the vertical direction is expressed very strongly by the specific arrangement of the castle donjon roofs. Although the alteration of the roofs as they progress vertically is irregular, it suggests a spiral composition and rotating movement. The Donjon roofs of Nijo Castle presented on Figure 3.5. change from level to level. They are a feature unique to Japan.

Figure 3.5. The Donjon roofs of Nijo Castle (18 C)

An even more evident example of 'movement' space in the vertical axis is the Sazaedo temple built in 1796 (Figure 3.6). It is a regular hexagon in plan with a double spiral ramp inside, which was used by the worshippers who ascended by the front one, and descended via a different ramp. Although this concept was an unique example in temple architecture, its upward spiral movement is very strongly emphasised.

Figure 3.6 Sazaedo temple

The Japanese spiritual idea of mutability has importance for the whole concept of 'movement' spaces. It comes mainly from the Buddhist religion which looks at all living things through their *"flowing movement through the three worlds of past, present and future"* (Inoue, 1985, p.170).

Bearing all this in mind, it is not at all difficult to visualise the RF concept in the context of Japanese traditional architecture. The structure itself suggests movement in the vertical axis. The beams which support each other give the notion of frozen upward spiral motion. It is an expression similar to the one achieved at the Donjon roofs of Nijo Castle and at the Sazaedo temple but using very different means.

3.2.3. The "Sukiya" concept

The Sukiya is a style used mainly for residential architecture and was developed in the 15 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"* (Itoh, 1974, p.115). It incorporates the use of timber and concept of 'movement' in a very sophisticated way. In Sukiya decoration is not put onto the structure, as in most other styles. Decoration is incorporated in the structure itself, and this could only be achieved by the versatility of timber as a material. As Ishii stated *"... Sukiya's decoration encompasses the ceiling, alcove, column, window, tea ceremony utensils, flowers and even the people in the room ..."* (Ishii, 1978, p.253).

Sukiya developed as a result of the investigation into the aesthetics of a house, in 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 stressed 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 (Itoh, 1969).

Kazuhiro Ishii described the essence of the tea house as: *"... a coded image of habitation which can be regarded as being connected to a return to the womb as a primordial mode of existence. In this sense the tea house is exemplary 'environmental'. In a twilit space you become sentient in the most complete manner. Here a world of relationships unfolds , not a world of denial. The sensation of movement, and the senses of hearing, smell, taste, touch, sight and time as well as sexual feeling are all wide awake in your body, seeking communication in an outward embrace. Your sense of hearing will be at its most sensitive to the boiling sound of the tea-water which has been said to strike the cord of an ear listening to the voice of a pine-cone, the sound of the winds whizzing by outside, the subdued rustling of the kimono of those present, the rubbing sound of tabi against the tatami, the sound of sliding paper doors being opened, the sound of hot water being poured from a tea-water dipper, the sound of the handle of the dipper hitting the rim of the iron teakettle, the sound of the handle of the bamboo tea-stirrer hitting the teacup, the sound of tea-sipping, the faint sound of breathing, the voices of people speaking, the sound of wiping the* *tea-ceremony paraphernalia, the sound of symbolic 'dotaku' bells, etc. The variety of taste of sweets and the deep, bitter taste of tea in harmonious interaction, the tastes of fishes, mountain plants, shells, meats, sake, etc. served before tea. Then we have the smells of tea, incense, and charcoal. The smell of charcoal, faint but distinct, appears to carry with it a subtle suggestion of warmth. A sense of temperature is assured by the warmth coming from the charcoal burning in the heart, the hot tea and the symbolical warmth of your heart."* (Ishii, 1978, p.253).

The 'movement' concept in Sukiya comes from the spatial composition of the tea house which is layered, and is a complex assemblage of small space units under a single roof. The Sukiya buildings provide us with 'discoveries' as we approach the next space. One never quite knows while walking through a building, what the next room would be, whether a small or a big space, a banquet hall or a tiny tea-room, or an inner garden instead. All the typical features of the 'movement' concept, such as asymmetry, irregularity and indefinite organisation described previously apply completely to Sukiya buildings.

Tradition and Sukiya have had a considerable influence on Japanese contemporary architecture. These concepts have been used in the designs of several Japanese contemporary architects, such as Yasufumi Kijima, Koichi Otake, Yoshio Taniguchi, Atsuo Hoshino and Toyokazu Watanabe (Suzuki, Banham and Kobayashi, 1985). The architect Ishii Kazuhiro was very much influenced by traditional Japanese architecture, and most of his designs incorporate some elements of the Sukiya concept.

The RF way of spiral layered timber beams was developed in the 12 C, long before the emergence of the Sukiya concept in the 15 C. Therefore, it is probable that the RF structural system influenced the Sukiya concept, rather than the other way round. On the other hand, when one analyses the contemporary Japanese RF buildings it is evident that Sukiya's main features are present in most of the buildings. Since Sukiya is something which 'grew out' of the Japanese culture, tradition and aesthetics, in the same way as the RF did, it is almost impossible to separate the two. Both the RF and Sukiya illustrate a sophisticated and balanced approach to design. Since Sukiya *"...does not imply an exact replica, but summarises solutions that incorporate and re-interpret traditional thinking..."* (Wright, 1995, p.25) the Japanese RF buildings gained a qualitative feature, which could have not been achieved by any other design concept.

3.3. The RF buildings designed by Kazuhiro Ishii

Kazuhiro Ishii is one of the outstanding contemporary Japanese architects. He graduated from the University of Tokyo in 1967, where he studied under Arata Isozaki. Between 1972-1975 he studied at Yale University under Charles Moore and James Stirling. After his return to Japan in 1976, he set up his own practice. He has lectured at Waseda University, Tokyo, the University of California, L.A. and at Yale.

He has designed a great number of buildings, the most notable being: A House of Fifty-four Windows, Naoshima Junior High School, Takahashi Residence, Takebe Kindergarten (54 Roofs), the "Sunrise" and "Moon-rabbit" villas, the "Spinning" house, the Puppet Theatre in Seiwa and the Sukiya - Yu house. He has also published several books and articles.

His designs are influenced as much by traditional Japanese forms as by modern architecture. He is very much attached to Sukiya which, for Ishii is something more than a *"residential style of wooden architecture which incorporates the features of tea ceremony arts"*. Ishii relates the word Sukiya to *"Suki"* which means - to be fond of , love and *"Sŭki"* which stands for - rare, select, something one is attached to for its uniqueness. He finds that the Sukiya concept and modern buildings from the late twentieth century have a lot in common, especially Post Modernist and Deconstrustivist buildings, one of the main reasons being *"the gathering together and arrangement of attractive elements, with emphasis on the final effect"* (Ishii, 1990, p.15). These and many other features mainly coming from Japanese traditional and Modern architecture are incorporated in Ishii's buildings.

3.3.1. The "Spinning" House

- **Designer:** Architect Kazuhiro Ishii
- **Period of construction:** 1985
- **Place:** Residential District in Tamagawa Gauken, Tokyo
- **Purpose (function):** house
- **Materials used:** mainly exposed concrete with steel RF Vierendeel trusses
- **RF span:** about 6 m at its longest, and decreasing on every level to 1.5 m
- **Influences:** 'movement' concept (Japanese tradition), modern architecture, Islamic art
- **Spatial composition:** radial disposition of bedrooms on ground floor around a central hall, living room on the second floor and a study on the third floor.
- **RF contribution:** sense of spinning motion, brightness and light coming from the roof, sense of floating and refined touch.

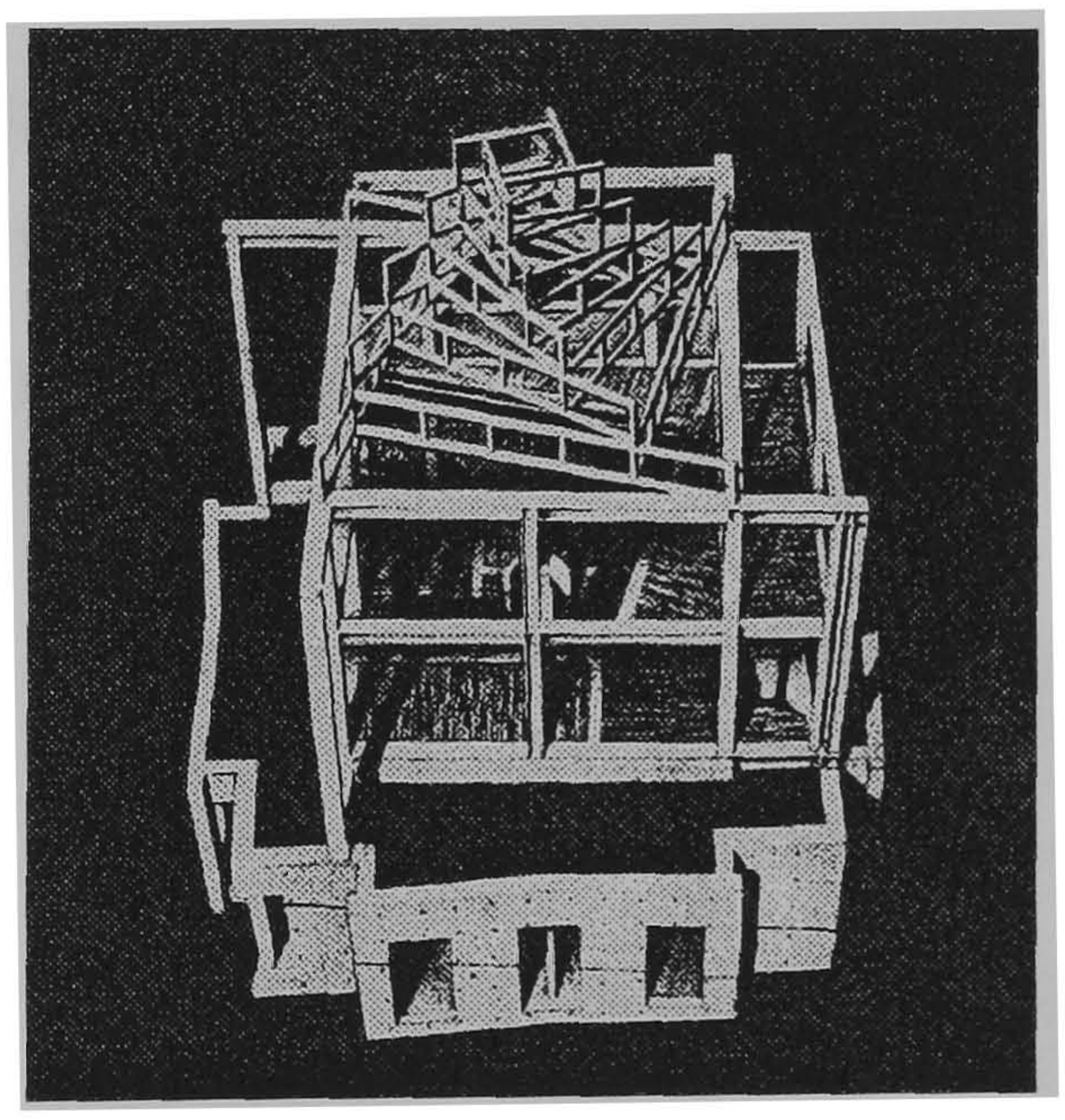


Figure 3.7. The "Spinning House" - model

When designing this building and looking for a structure, Ishii remembered a method of holding hands where there was no support for the load at the cross points of an arm and a hand, support being given at the outer end (Ishii, 1990).

The "spinning" effect, on the other hand, is achieved by rotating the steel Vierendeel RF trusses for fifteen degrees in comparison with the previous level.

The effect achieved is very similar to the pop-up tissue box. Ishii states that spinning (whirling) can be found in Islam as a very early expression of the image of the cosmos. Also, the "movement" concept is very much present in Japanese traditional architecture. The materials and technology used are very modern.

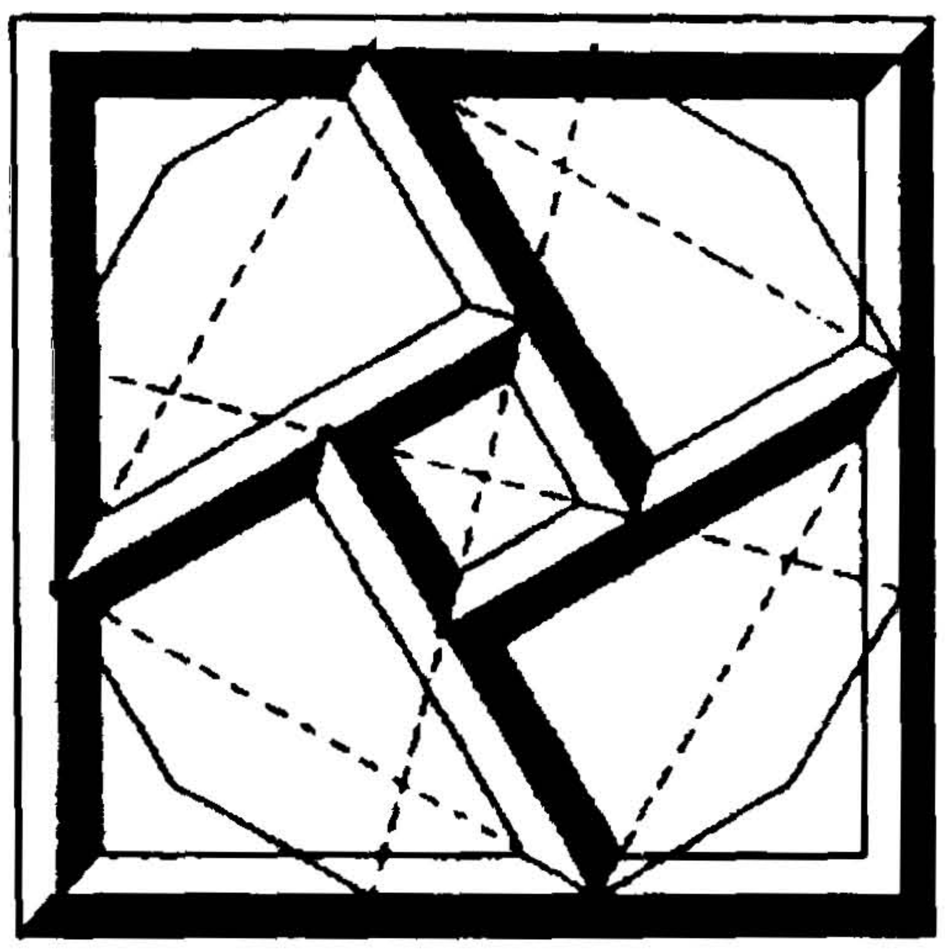


Figure 3.8. Islamic art "spinning" image

The structure has contributed considerably to the quality of the spaces not only by the lightness and the floating effects it creates, but also with the pronounced clarity and simplicity of the forms and spaces. *"The roof light formed with the RF makes one feel almost as if they had glimpsed the cosmos itself"* (Ishii, 1990 p.14).

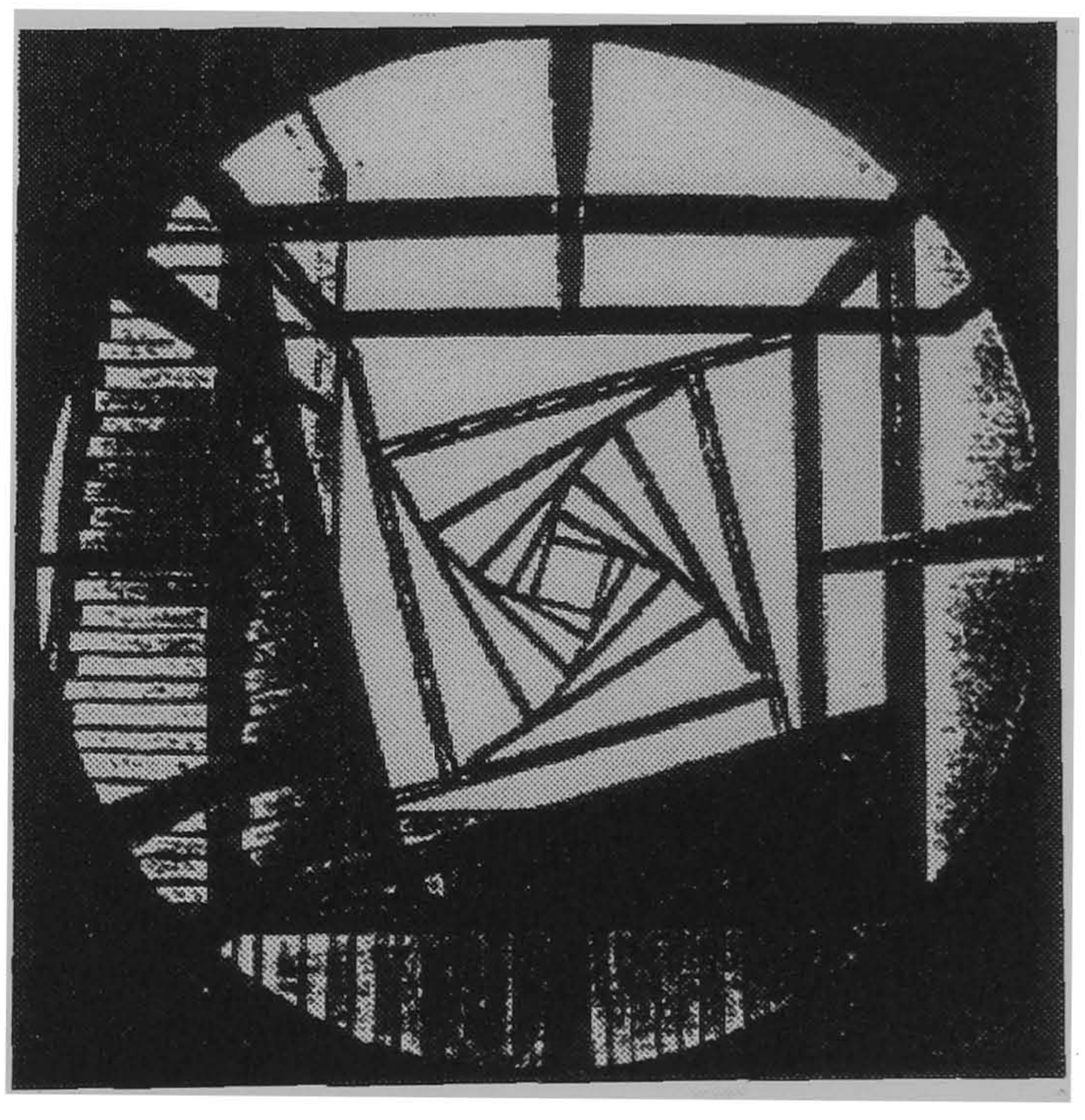


Figure 3.9. View towards the roof window

3.3.2. The Sukiya - Yu house

- **Designer:** Architect Kazuhiro Ishii
- **Period of construction:** 1989
- **Place:** Asakuchi-gun, Okayama Prefecture
- **Purpose (function):** guest - house
- **Materials used:** a variety of different structures and materials, the RF structure is made of timber and used over the parlour
- **RF span:** 7 m
- **Influences:** Sukiya tradition , Western architectural history
- **Spatial composition:** Hamlet (Japanese "Yu") of half-dozen different buildings forming a village-like assembly
- **RF contribution:** Sense of tradition. Load bearing structure for the Buckminster Fuller geodesic dome

The buildings that form the village-like organisation of the Sukiya - Yu house are scattered among bamboo and plum trees. When designing it, Ishii was inspired by the layout of the "Shizutani School" in Okayama where Confucian teachings were studied (Ishii, 1990). By use of these different elements, each with its own significance, the traditional Sukiya is given contemporary resonance.

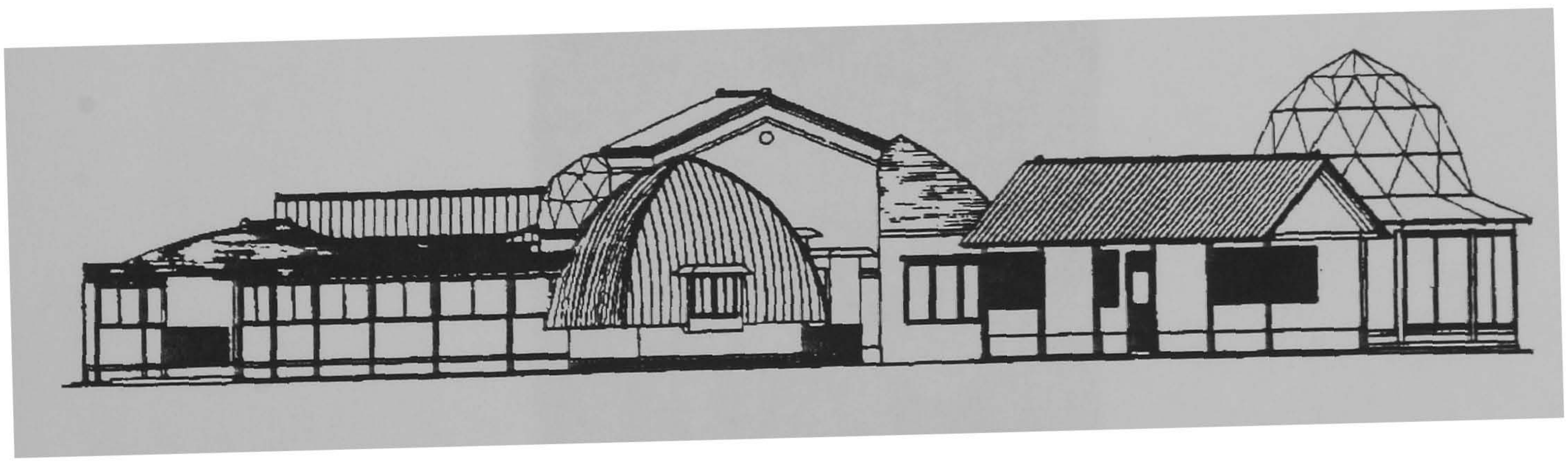


Figure 3.10. View to the Sukiya - Yu village-like assembly

The building where the RF structure is used as a parlour, is a single space 7m in span, named Yu-an. The horizontally overlapping timber RF beams support the wooden dome. By spiralling in two directions, they give earthquake resistance to the building. The circular plan, the door openings, the interior with the folding shrines and the construction details are all traditional. With addition of the wooden dome, the building becomes a interesting combination of old and new.

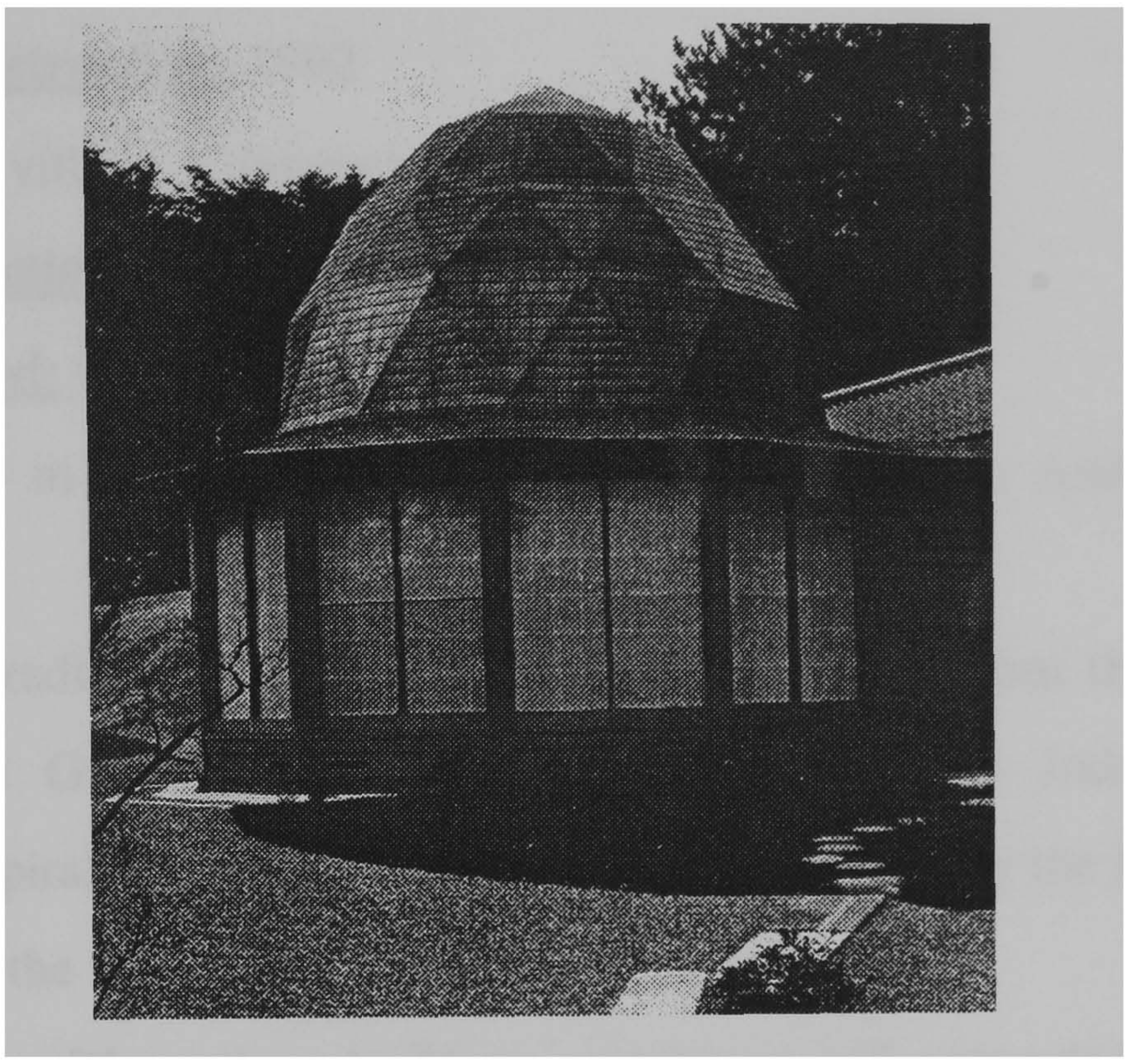


Figure 3.11. The Parlour of the Sukiya - Yu

The use of the RF in this building contributes to the spatial quality and emphasises the Sukiya concept by the use of natural materials (see Figure 3.12).

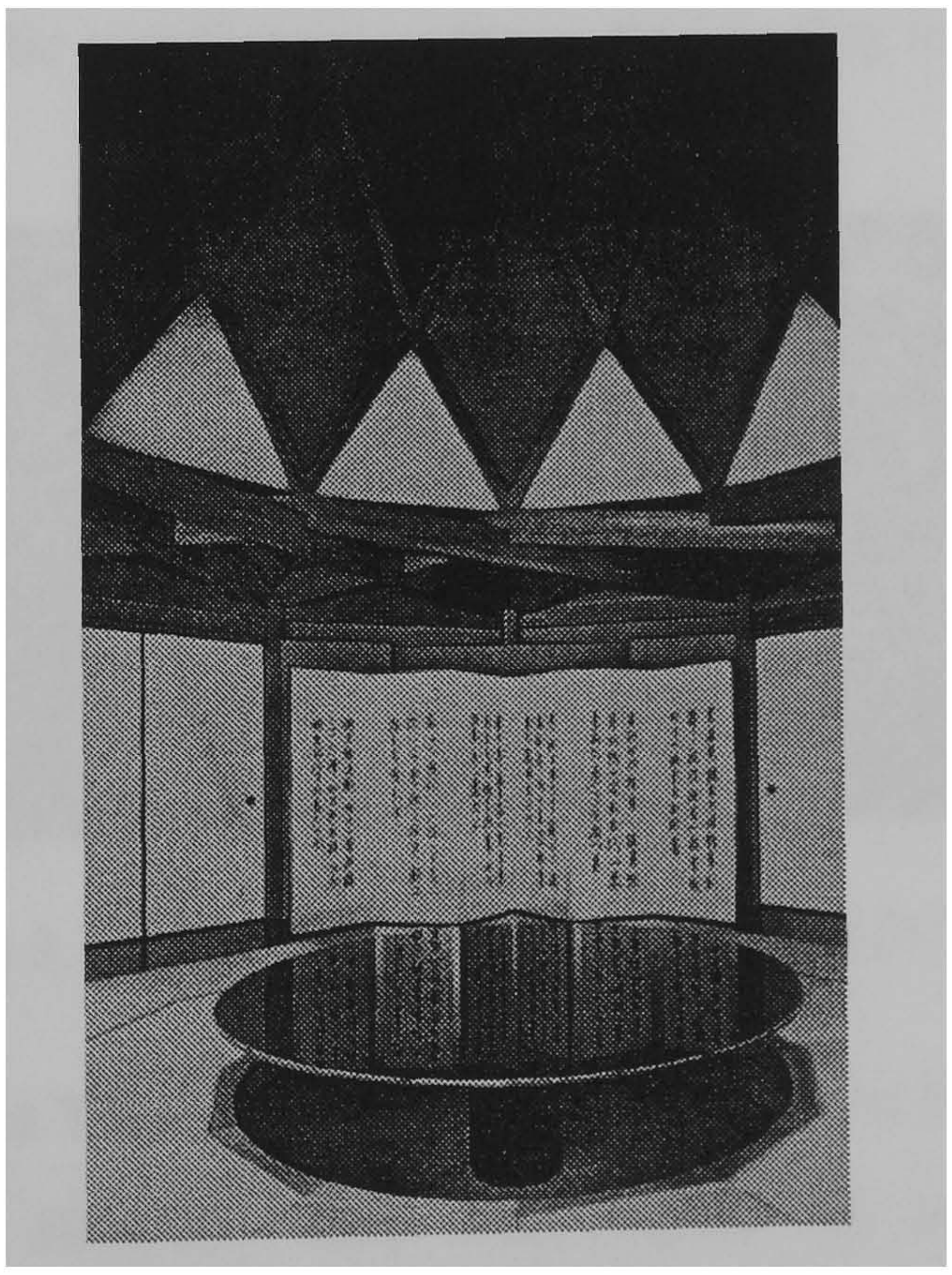


Figure 3.12 Interior of the Sukiya - Yu Parlour

3.3.3. The Puppet Theatre in Seiwa

- **Designer:** Architect Kazuhiro Ishii
- **Period of construction:** 1992
- **Place:**, Seiwa village, Kumamoto region, island of Kyushu,
- **Purpose (function):** Puppet Theatre and Exhibition Hall
- **Materials used:** timber
- **RF span:** 13 m in the Exhibition Hall and 17 m in the Auditorium of the Theatre
- **Influences:** traditional Temple and shrine architecture from the Nara region (Great South Gate of Todai-ji and Jodo Hall of the Jodo-ji in Hyogo Prefecture), spiral layering of wooden beams established by the Buddhist monk Chogen from the 12 Century
- **Spatial composition:** three buildings: exhibition hall connected by a covered exterior corridor to the auditorium and stage (theatre)
- **RF contribution:** The different beam configuration in each of the three buildings creates spaces which are dynamic and easy to distinct, as they all have different distinct functions. The RF structure in the exhibition hall emphasises the building's symbolic significance as the central facility in the village.

Figure 3.13. View of the Puppet Theatre in Seiwa

The brief for the Puppet Theatre in Seiwa requested use of timber to help the local wood industry (Ishii, 1994/3). Ishii was inspired by traditional construction methods and used timber for all three buildings. The grillage structures used are all different and define each space in a very sophisticated way.

The most impressive is the RF structure over the Exhibition hall. It is a 13 m. high space having on the ground floor two flat RFs spiralling in opposite directions and supporting each other. This occurs on the floor above as well, and the woven structure of mutually supporting beams supports the 8 m. span RF structure consisting of 12 beams which 'seats' over the woven structure (see Figure 3.14). The roof over the RF is made of clay tiles fixed to rafters laid concentrically. The exposure of the RF only in the interior of the Exhibition hall lends it further grandeur.

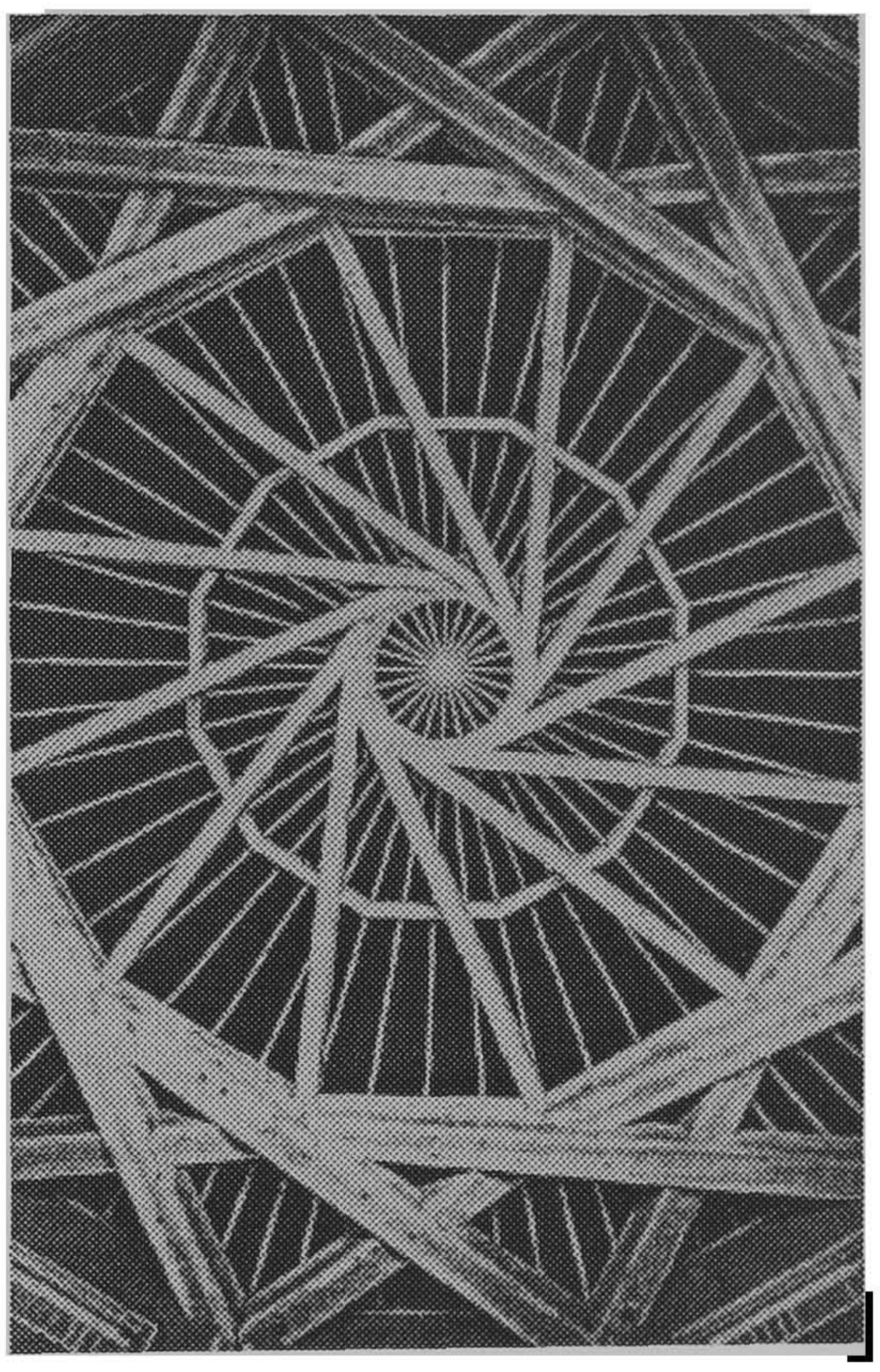


Figure 3.14. View of the Exhibition hall exposed RF structure

The other two main spaces (the auditorium and the stage) are covered with flat (close to planar) timber grillage structures. The structure over the auditorium consists of short timber elements which support each other and produce a woven effect (see Figure 3.15).

All three structures show how traditional construction methods can be incorporated in a contemporary building and can add to the quality of the spaces.

It is interesting to note that all the timber joints used are traditional and no metal connectors are used. Therefore it is not surprising that before construction, a 1:3 scale model was produced to demonstrate its viability to the building authorities.

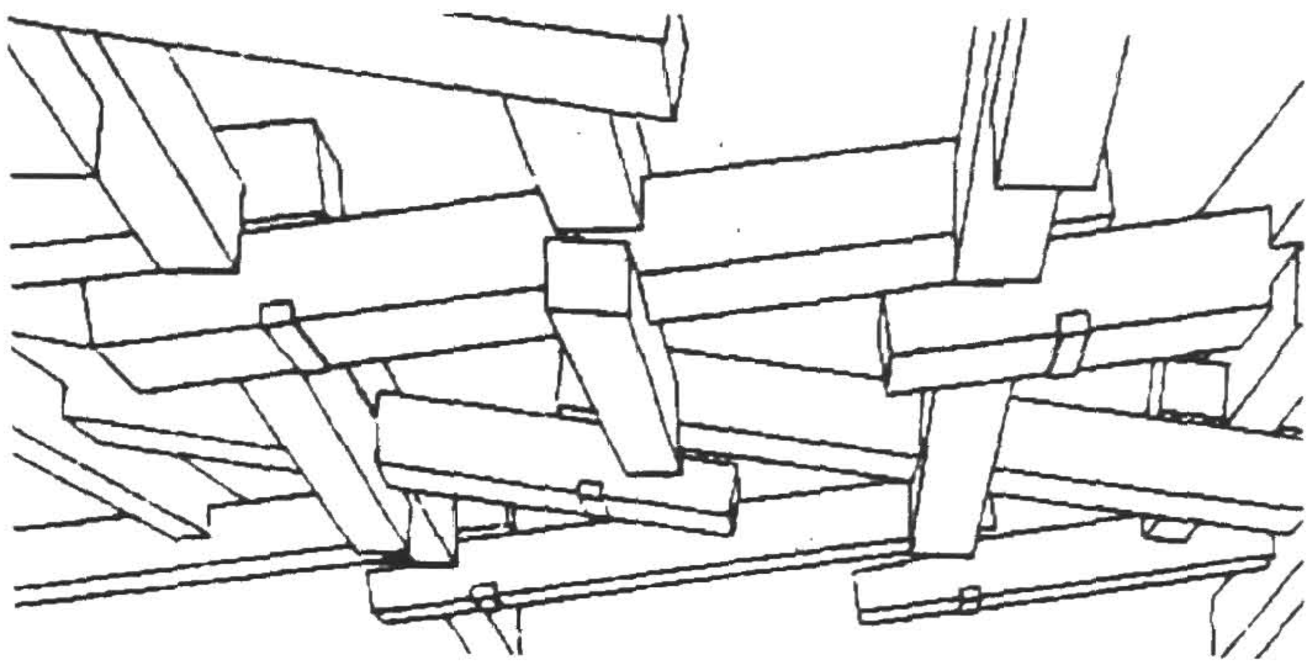


Figure 3.15. View of the auditorium grillage structure

The Puppet Theatre in Seiwa is a very successful building. The traditional puppet-art is housed in a building constructed to a traditional pattern with traditional materials.

3.4. Yasufumi Kijima's Stonemason Museum

- **Designer:** Architect Yasufumi Kijima
- **Period of construction:** 1990s (no precise date known)
- **Place:** Toyoson
- **Purpose (function):** museum
- **Materials used:** RF structure is made of timber beams supported by circular exposed concrete columns and masonry walls
- **RF span:** about 22 m. in the bigger hall and about 14 m. in the smaller hall.
- **Influences:** traditional Japanese architecture, contemporary architecture
- **Spatial composition:** the two main exhibition halls with an organic plan form, the main entrance being placed inbetween. The secondary spaces have circular plan forms.
- **RF contribution:** brings focus, light, and refinement of touch to the exhibition spaces.

The Toyoson Stonemason Museum has an organic form in plan with some circular and segmental spaces. The exhibition halls, as the two main spaces within the building, have spans of 22 m. and 14 m.

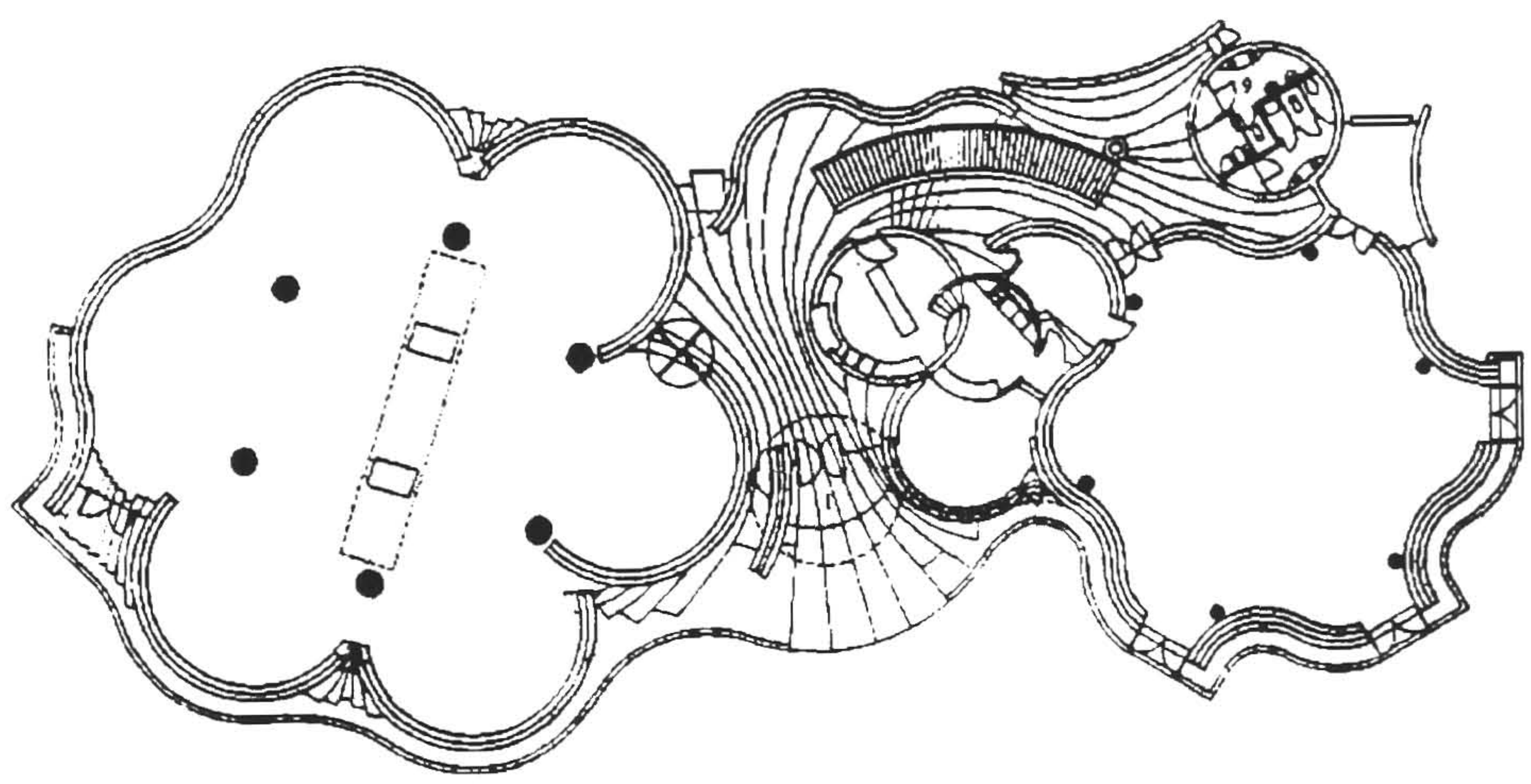


Figure 3.16. Toyoson Stonemason Museum - plan

Architect Yasufumi Kijima, known for revival of classical motifs, on the Toyoson Stonemason Museum has used a traditional form of Japanese complex roof timber structure. The mutually supporting and rounded timber beams of the RF structure lift a roof which admits light through windows at regular intervals. At the perimeter, the RF beams are supported by exposed concrete pillars and load-bearing masonry walls.

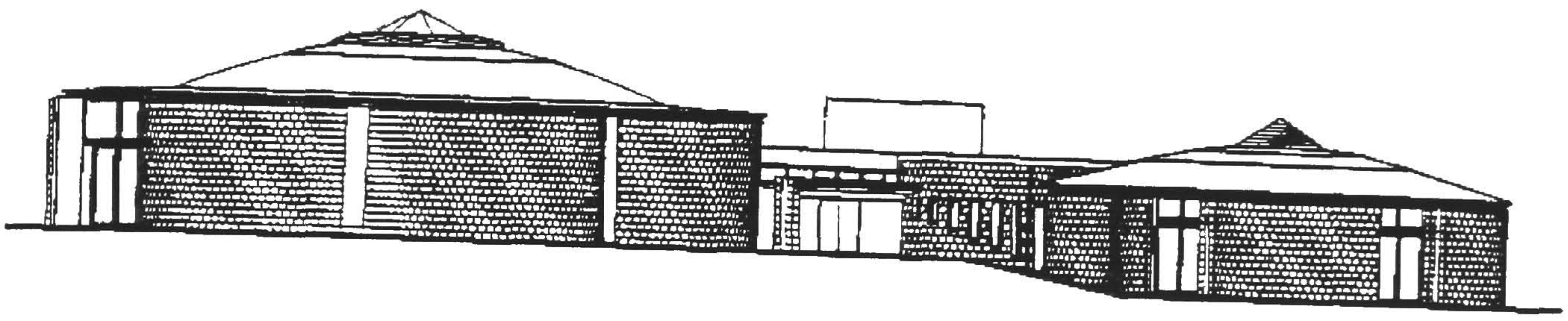


Figure 3.17. Toyoson Stonemason Museum - elevation

The whole 3-dimensional assembly, at first sight, looks very complex and even chaotic, but when one looks at the composition of the RF beams more carefully, they have very regular star-like form in plan which allows the creation of triangular roof windows as a completion of the pattern.

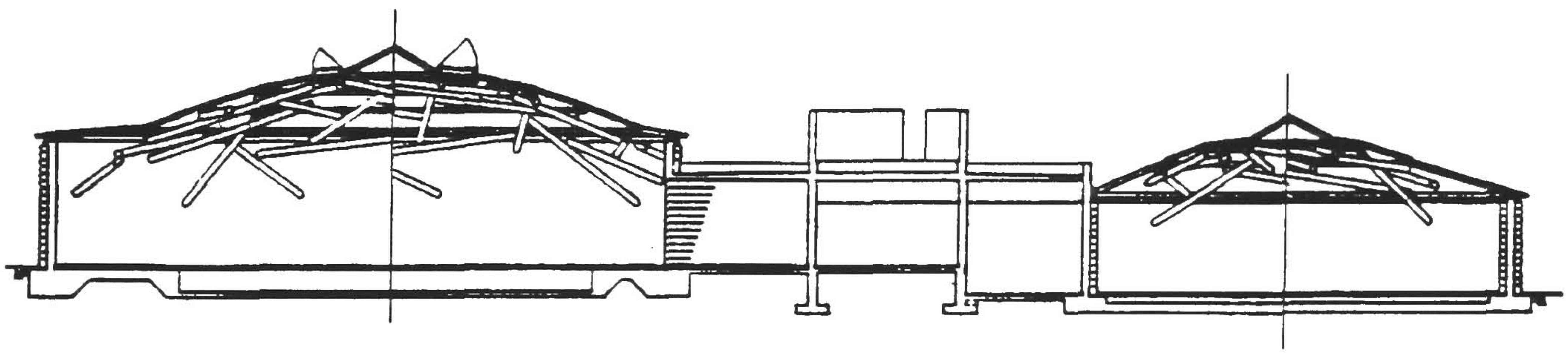


Figure 3.18 Toyoson Stonemason Museum - section

The use of the RF as an assembly of multiple units in the case of the Toyoson Stonemason Museum shows another successful application of the structural system, and demonstrates how a building of organic plan can be roofed.

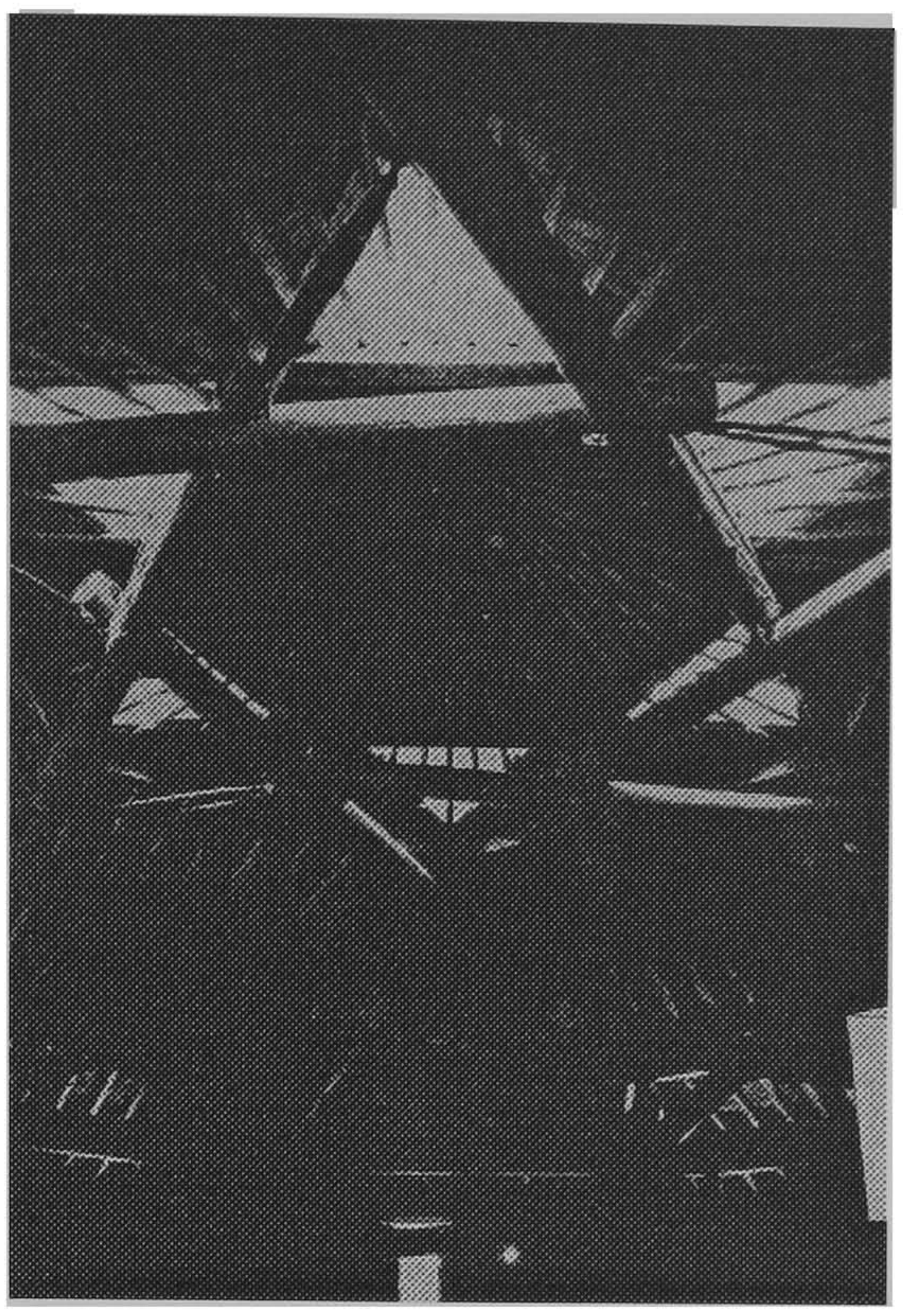


Figure 3.19 View of the "star-like" RF assembly

3.5. The private house of Yoichi Kan

- **Designer:** (of the structure) the owner Mr.Yoichi Kan himself
- **Period of construction:** 1992
- **Place:** Nagasaki
- **Purpose (function):** house
- **Materials used:** roof RF structure is made of timber beams supported by a semi-rigid timber frame system
- **RF span:** about 8 m.
- **Influences:** traditional Japanese architecture
- **Spatial composition:** traditional Japanese farmer's house, regular square in plan with lightweight movable partitions
- **RF contribution:** gives a very strong visual impact both to the interior and the exterior of the house, brings light into the space, provides the possibility of having a sleeping loft (gallery) and higher rooms

Positioned on the outskirts of Nagasaki the weekend house of Mr.Yoichi Kan fits its environment completely. The high surrounding mountains are echoed by the steep RF roof.

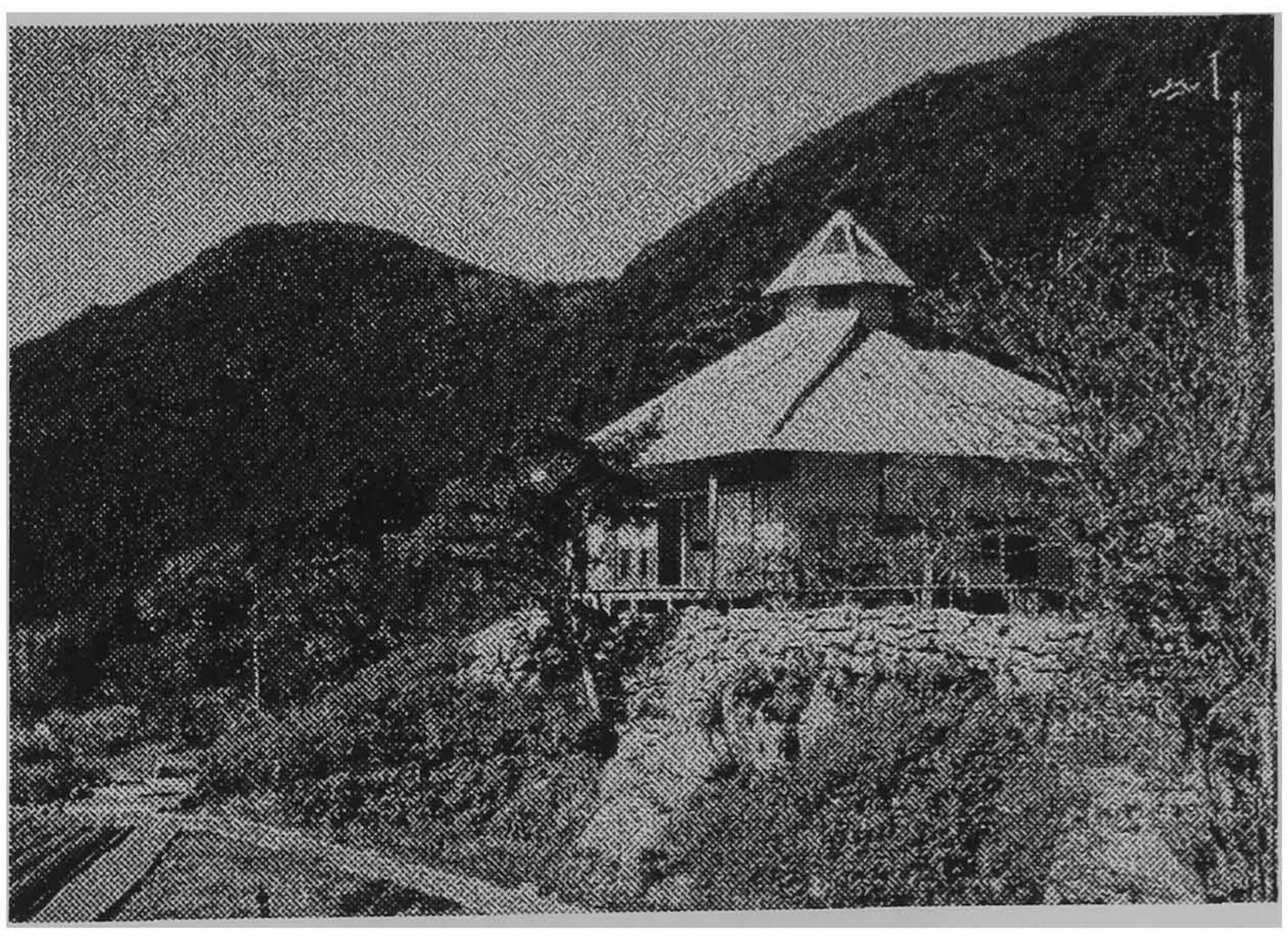


Figure 3.20. View of the house

The whole house is quite small, having only about 60 m^2. Having higher rooms gives an impression of a considerably more spacious house. The partitioning is done by movable lightweight panels, as in most traditional Japanese houses, providing the possibility of multipurpose rooms. The steep timber RF roof, gives enough height for a sleeping loft (gallery) to be organised over one of the spaces.

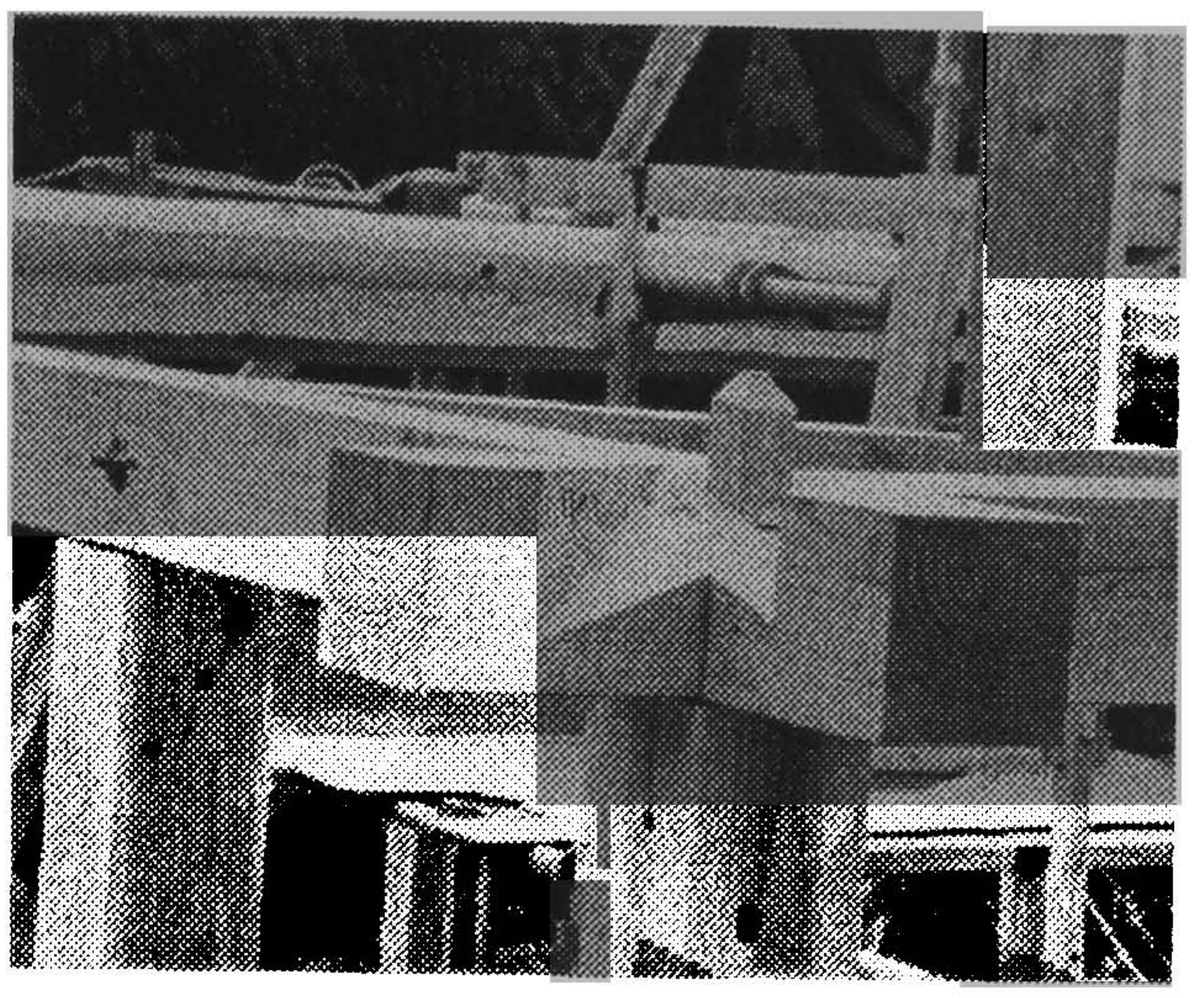


Figure 3.21. Timber joint detail

For the house mainly natural materials (timber, stone etc.) were used. All the independent foundations were made of natural stone, except under the exterior walls where reinforced concrete was used. For the beams and columns local timber (cruptmerica Japonica) was used. Also, traditional construction methods were employed, all the timber joints being formed without the use of any metal connectors (see Figure 3.21).

The 8 beam RF roof structure accommodates the regular square plan form. It was erected after the construction of the timber frame which supported a central 8 sided timber prop. The RF beams were supported by the prop until the circle was closed and they could support each other (see Figure 3.22 a., b. and c.).

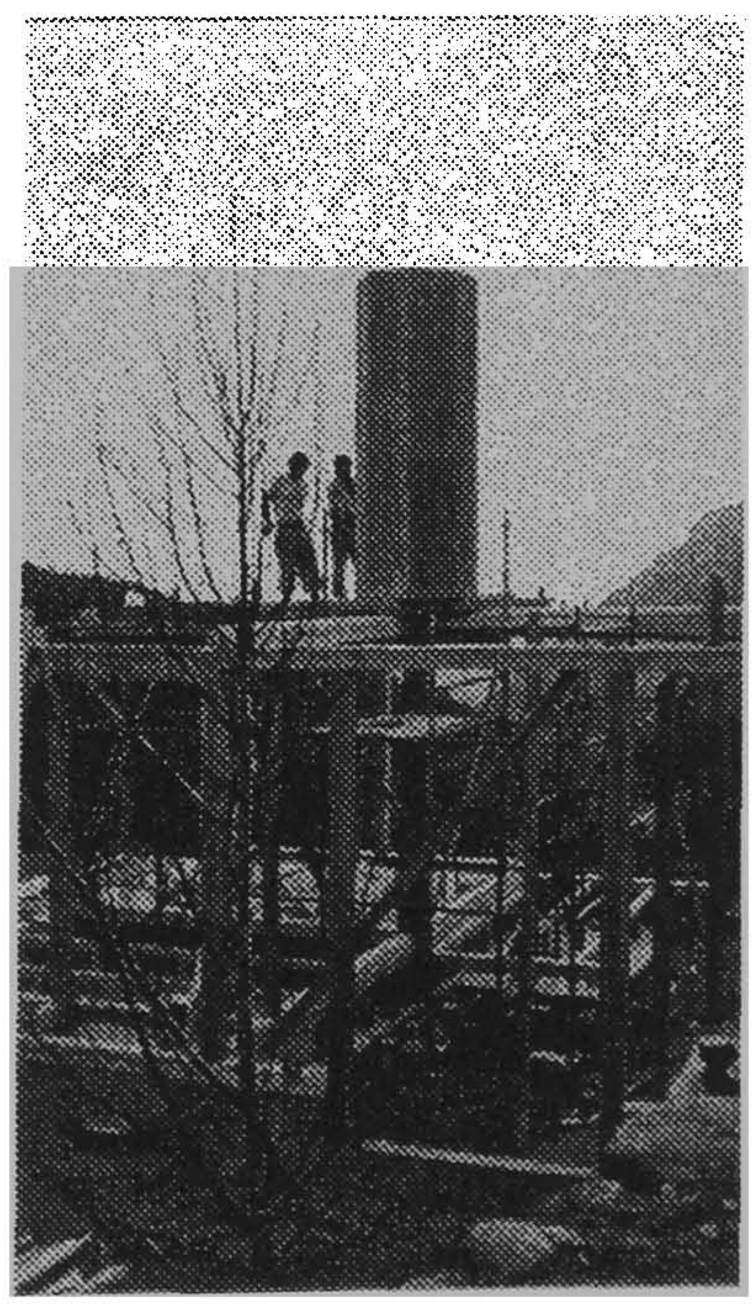
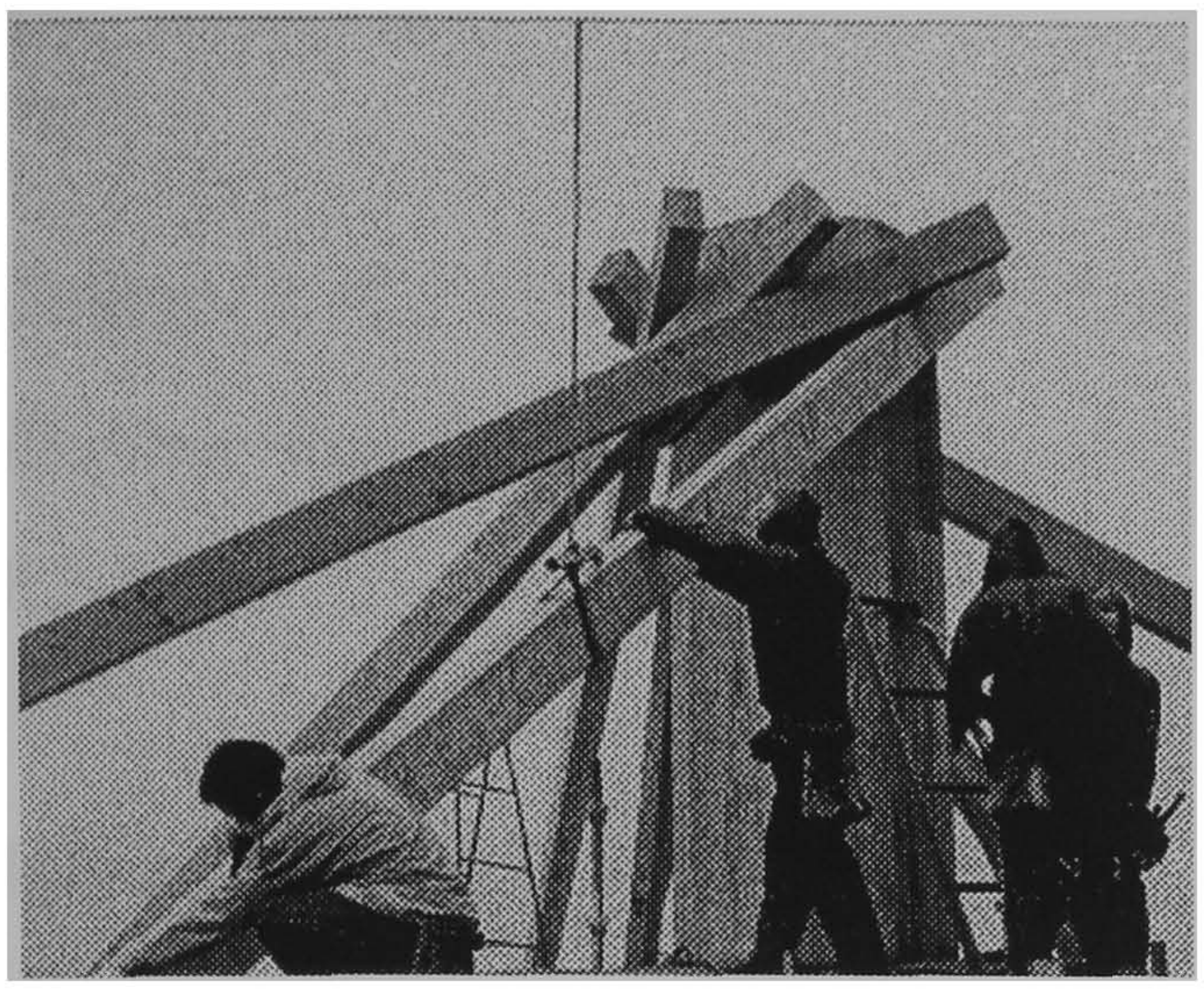


Figure 3.22. a. Construction of the RF house in Nagasaki



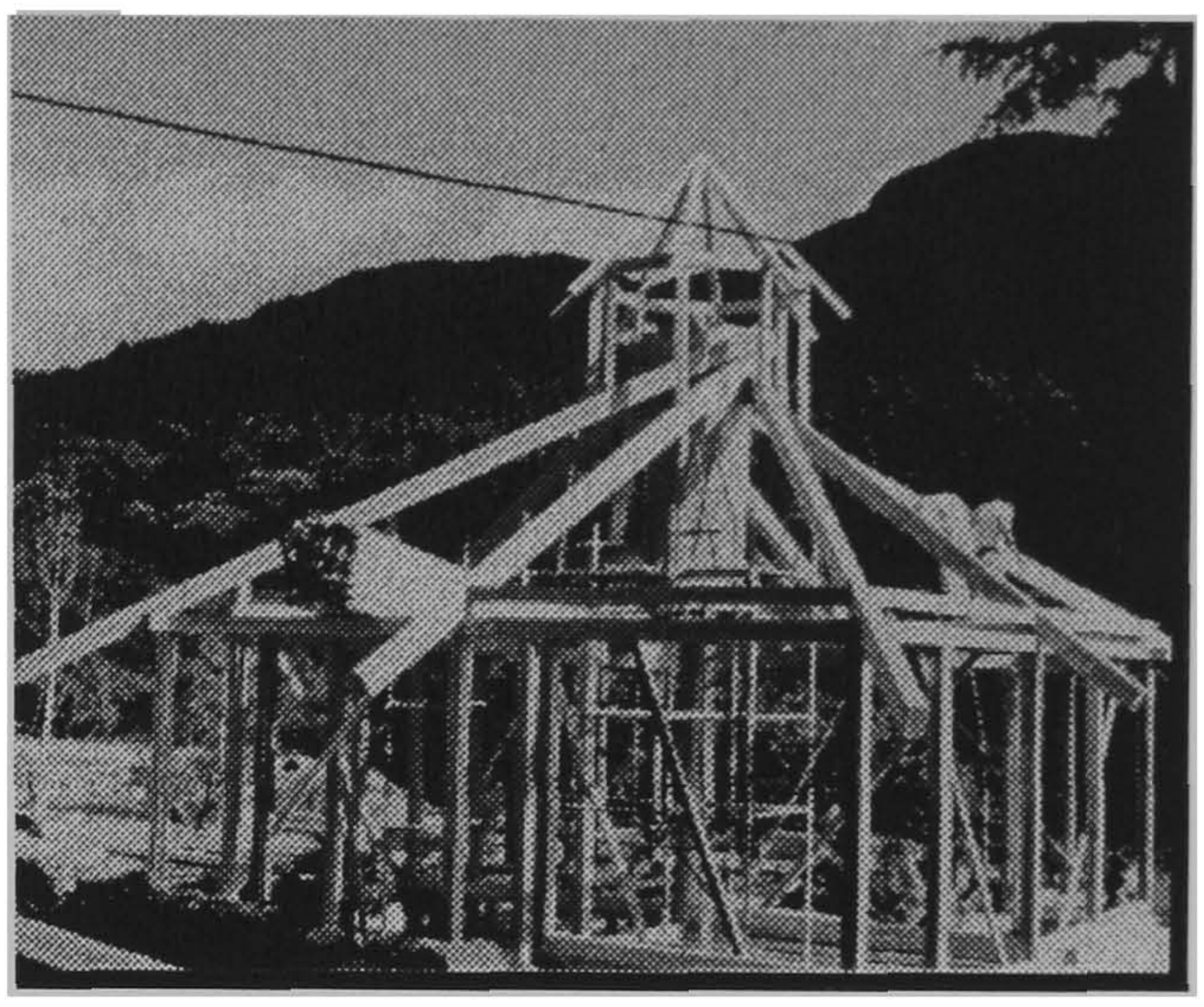


Figure 3.22. b. and c. Construction of the RF house in Nagasaki

The RF structure defines the building both externally and internally. It has a great visual impact and expands the size and quality of the space.

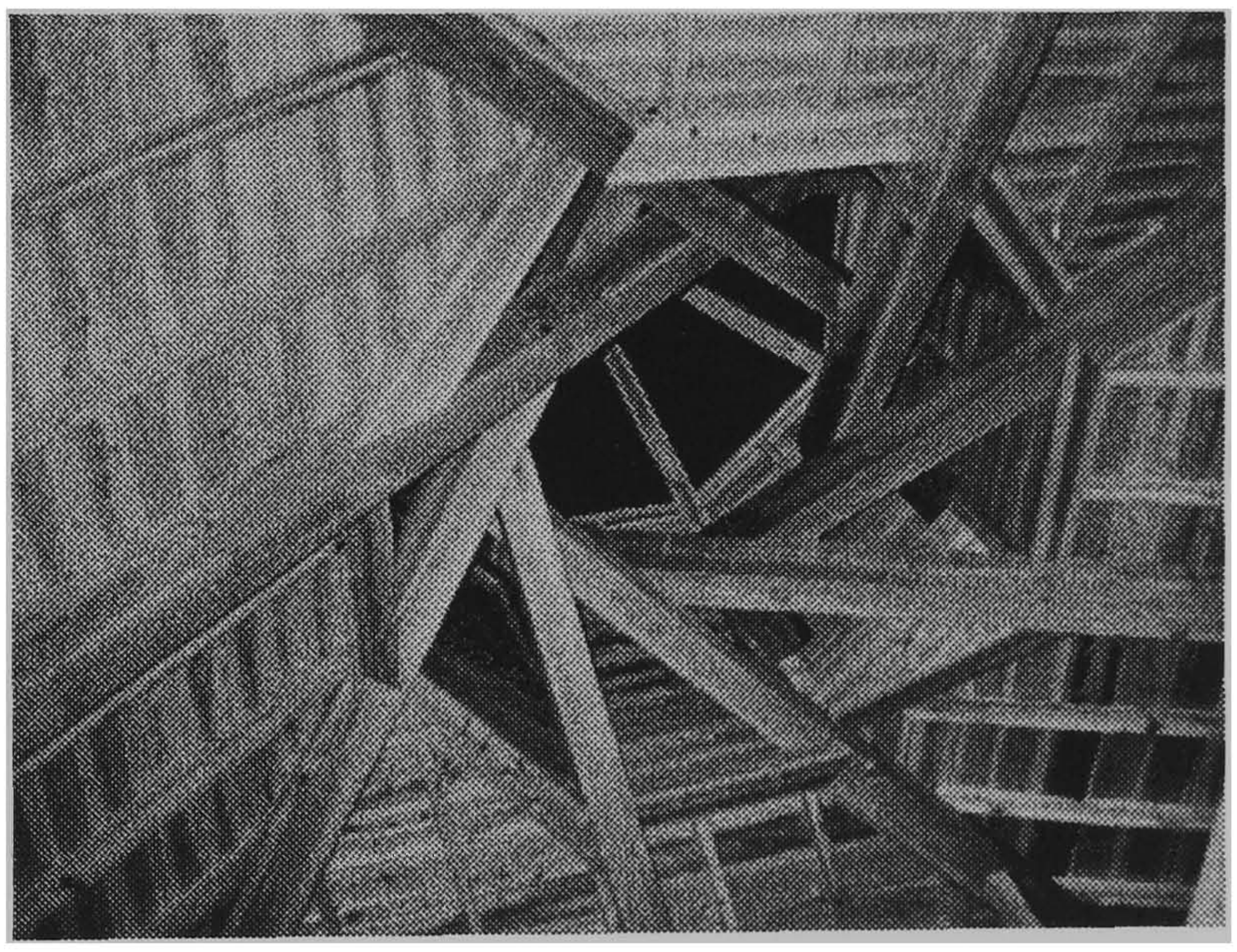


Figure 3.23. Interior view of the RF structure

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3.7. List of illustrations:

CHAPTER 4: Modular RF Construction

4.1. Modular Construction of RF buildings

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 (1972, p.7) stated*"...most of nature's forms are composed of identical elements, and yet the effects are far from monotonous..."*.

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 (1956, p.12) 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.

The modular industrialised systems employed in the construction of blocks of flats in Eastern Europe throughout the fifties and sixties, unfortunately 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 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 organisation of the function.

Modular construction of buildings using the RF can be achieved because for regular plan forms all of the structural elements (columns and beams) are 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 both temporary and permanent modular buildings can be achieved using the RF system. The differences between the two is in the building materials, the details and method of construction.

The term 'temporary' in this context is used for buildings (RF tents) used for a short period of time (several hours, days, weeks or months). Although no such buildings have been constructed to date, there is no reason why the idea could not become reality in the near future.

4.1.1. Temporary RF buildings

Zuk and Clark (1970, p.6) 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 (1968, p. 93) 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. They would need to be designed to be very rapidly erected and disassembled when they are no longer needed. These buildings could be a form of contemporary marquee, 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.

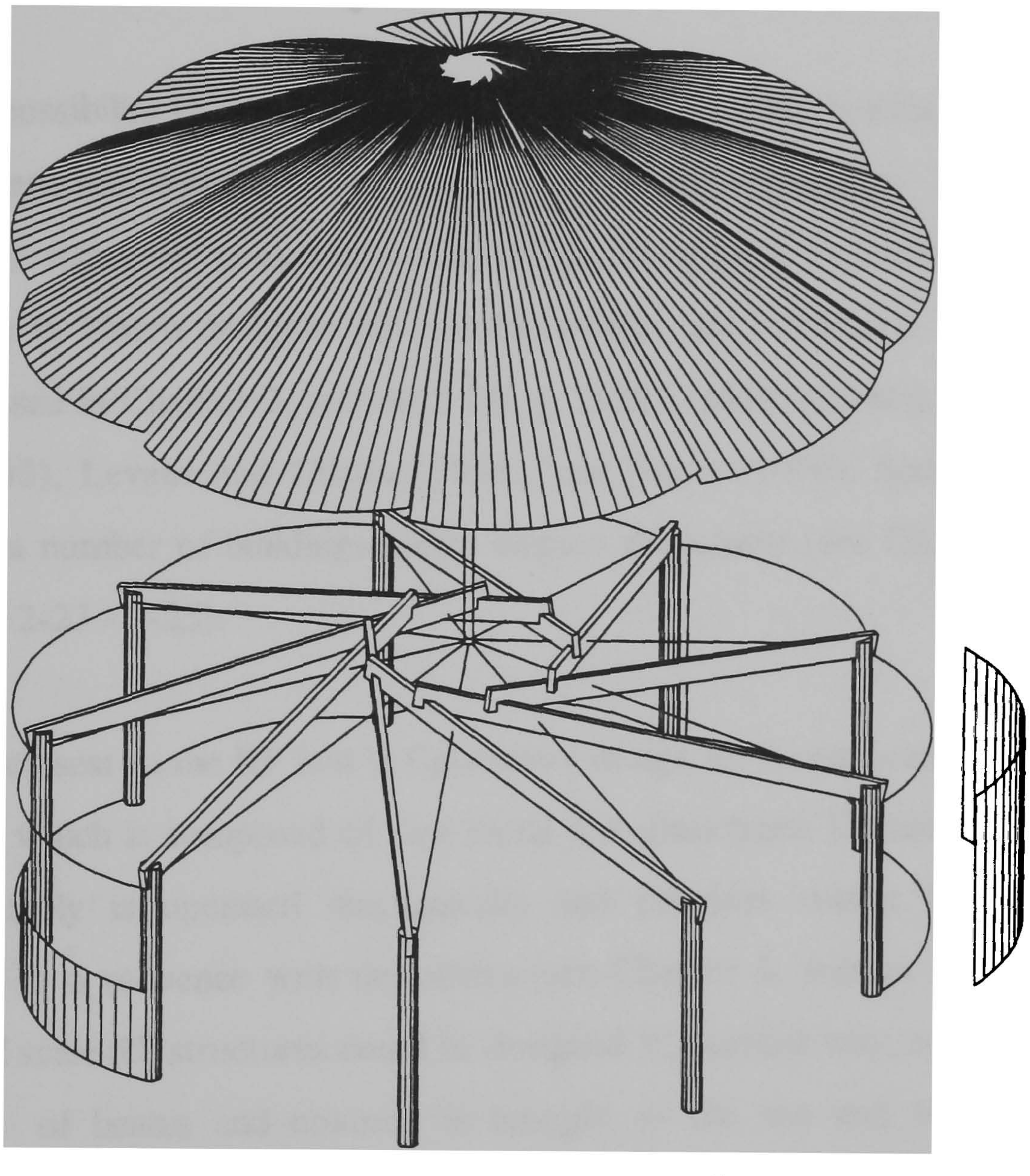


Figure 4.1. A temporary RF building - tent

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 (1994). 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. Research into further developing the method using small sections of roundwood or reclaimed telegraph poles has been carried out, and is presented in detail further in this chapter.

Another possibility of rapid construction of temporary RF buildings would be to create kinetic architecture by designing an expandable RF system. The research on expandable structures goes back to the sixties, as reported by Escrig (1993), when Emilio Peréz Piñero designed his foldable trusses and retractable dome structure (as discussed in Chapter 2, section 2.1.4, p. 2-20). More recently, as reported by Low (1993), Levane and Cecilia (1994), and Blaser (1990), Santiago Calatrava designed a number of buildings which employ movement (see Chapter 2, section 2.1.4, pp. 2-23 - 2-25).

The idea closest to the RF tent is Calatrava's design for a restaurant roof structure in Zurich which is composed of nine metal and glass trees 12 metres high. Each tree assembly is operated mechanically and provides shelter by folding and unfolding in a sequence with the others (see Chapter 2, section 2.1.4, p. 2-23). The small scale RF structures could be designed in a similar way, so that the whole assembly of beams and columns is brought to the site and simply unfolded. Research into similar RF assemblies has been carried out and is discussed further in this chapter.

The idea of expandable structures has been researched thoroughly by Hoberman in the last few years, as discussed by Hoberman (1992), (1993) and Wick (1992) (see Chapter 2, section 2.1.4, pp. 2-25 - 2-28). Future research could be directed to see if similar techniques can be found to make RF structures expandable along similar lines.

Construction techniques employed in other forms of deployable structures such as temporary military bridges, self-erecting camping devices and emergency shelters could also be applied to RF structures. These possibilities have not been developed as part of this project because of time constraints.

4.1.2. Permanent modular RF construction

One of the main characteristics of the RF system, as stated before, 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 for assembly buildings such as exhibition and community halls, restaurants, kindergartens and hospitals. Indeed, the research on the student project case study, to be presented in detail in Chapter 5, showed that RFs provide spaces with good spatial qualities for assembly open plan functions.

The RF structure 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 detracts from the visual impact of the structure. Also, it results in the formation of segmental spaces and the consequent difficulty of fitting furniture within them. These issues are addressed through analysis of the examples of RF buildings constructed in the UK, presented later in this chapter.

The most appropriate span for modular assembly RF buildings, using timber or glulam elements is in the 6-15 m range. 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 and a crane becomes necessary for lifting. However, use of steel RF members instead of timber, as well as appropriate design of the panels, would make this possible. Modular RF buildings can be constructed with shorter spans but would be too small and not appropriate for assembly buildings. However, if they are designed to have other functions, spans shorter than 6 m. are a realistic possibility.

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. The more complicated 3-d geometry of the buildings increases the cost, but it undoubtedly contributes to their architectural qualities, due to the infinite variety of regular plan forms which can be achieved. The comparison used by Ehrenkrantz (1956, p.17) *"...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.

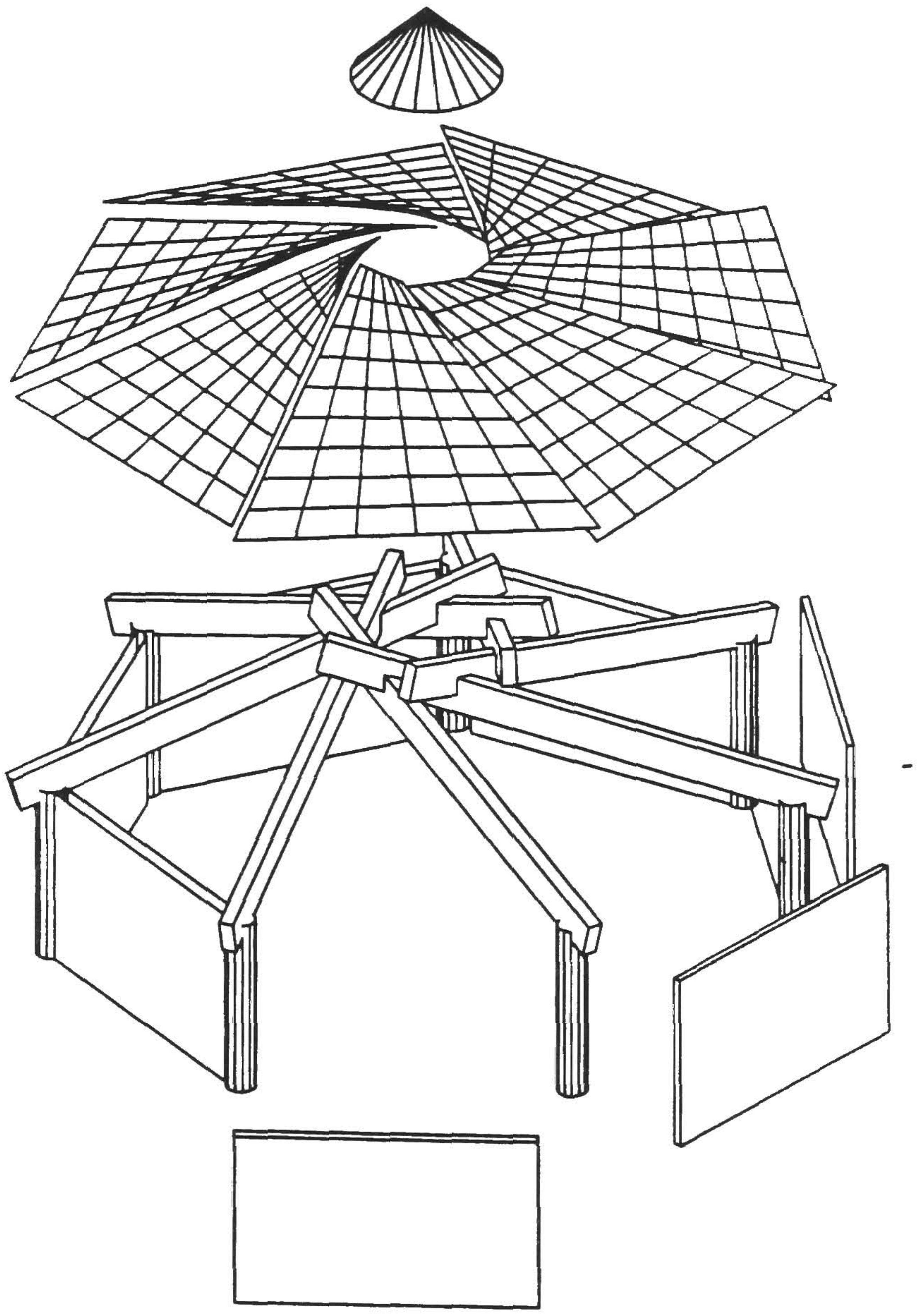


Figure 4.2. Modular RF building

The variety of forms results from the possibility of varying the number of beams (and vertical supports) and, in that way, creating 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 would make the transportation and construction easier because of the smaller sizes and weight of the elements. Some possibilities of clustered RF buildings are presented on Figure 4.3.

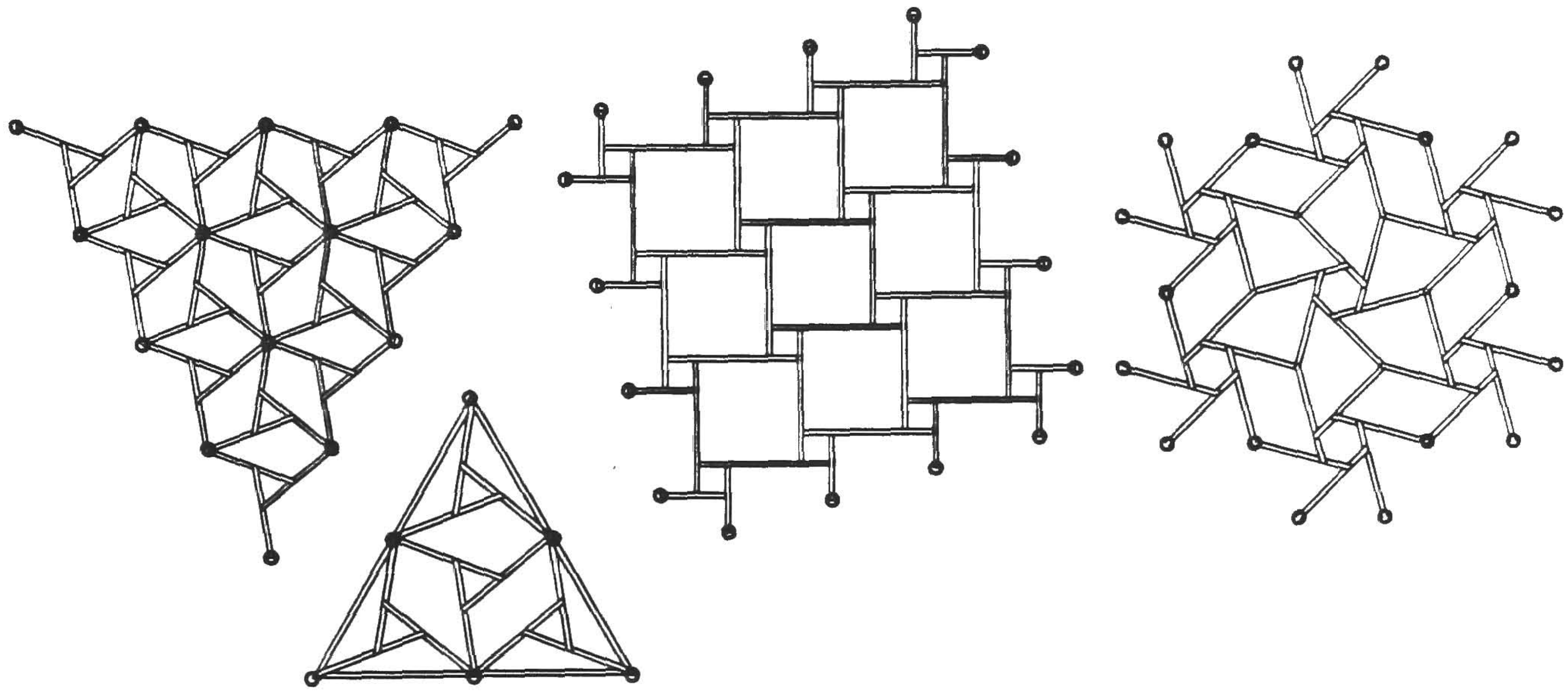


Figure 4.3. Some possibilities of RF clustered modular buildings

4.2. Roundwood RF structures

The potential for the fast and easy construction of RF structures using small sections of roundwood or reclaimed telegraph poles has also been explored. The construction process of these structures would be simple and fast, which would make it possible to use them both as temporary and more permanent structures. However, at present, they would be more suitable for temporary shelters since enclosure techniques and appropriate cladding details have yet to be developed.

Use of roundwood for construction is not an original idea. It is one of the oldest construction materials and, as such, has been used throughout history by primitive civilisations for building shelters. Most of the early dwellings, such as hogans, tepees, yurts and tupics were constructed out of small section roundwood. Also, the well known Norwegian stave churches are excellent examples of large section roundwood construction (Chilton, 1995).

Use of roundwood sections has some advantages over sawn timber because up to 40% of timber, by volume, is wasted by sawing. Although some of it can be used for cladding, there is still a considerable amount of waste. In some cases the cost of the structure can be reduced by up to 45% by use of roundwood (Dudley, Lowe and Riley, 1990). Also, from the structural point of view round timber has an advantage over sawn timber because in the process of sawing some of the longitudinal cellulose fibres which give strength to the timber are cut through and destroyed. By losing the helical fibres, which have pretensioning effect, sawn timber buckles more easily compared to roundwood (Winter,1995). Roundwood may be small section thinnings, with 50-200 mm diameter, or large section, with diameters over 200 mm.

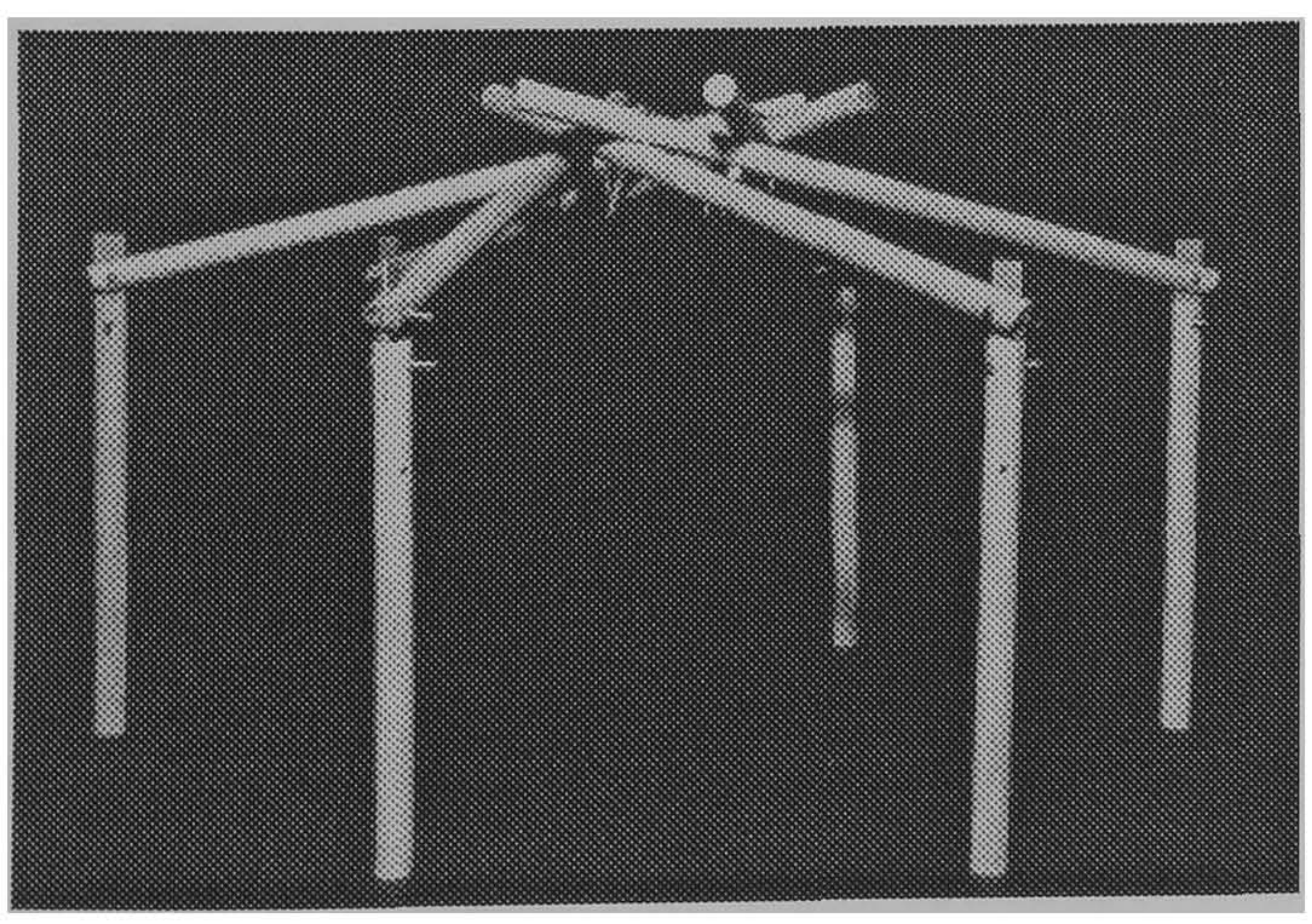
The only recent RF building known to the author to be constructed using roundwood, the Toyson Stonemason Museum in Japan, designed by Yusufi Kijima, represents a very successful use of roundwood (see Chapter 3, section 3.4, pp. 3-20 - 2-22). Constructed out of large roundwood sections that are left within the space, the RF structure considerably enhances the quality of the interior spaces of the museum. There is no reason why roundwood should not be more widely used for RF construction using both small and large sections.

The main roundwood structural elements are the beams of the RF and their supporting columns.

As the diameter of small roundwood sections is very limited, the RF structures would have limited spans. Even if the biggest in the range of small section round timber is used (up to 200 mm diameter) the building could only be a maximum 4.5-5 metres in span (assuming a span to depth ratio of 20 to 25).

For short span temporary RF structures composite members may also be used, made by joining together two or more small section timbers. This could be done by use of flexible metal strip connectors, or by tying the individual timbers together with straps made of jute, canvas or nylon. Similar tying methods are used on bamboo structures (Janssen, 1995).

It is necessary to note that using composite members would not increase the RF spans considerably, but would make use of the very small sections of roundwood which otherwise would not have been used for construction. Two models representing single and composite roundwood RF structures are presented on Figures 4.5 and 4.6.



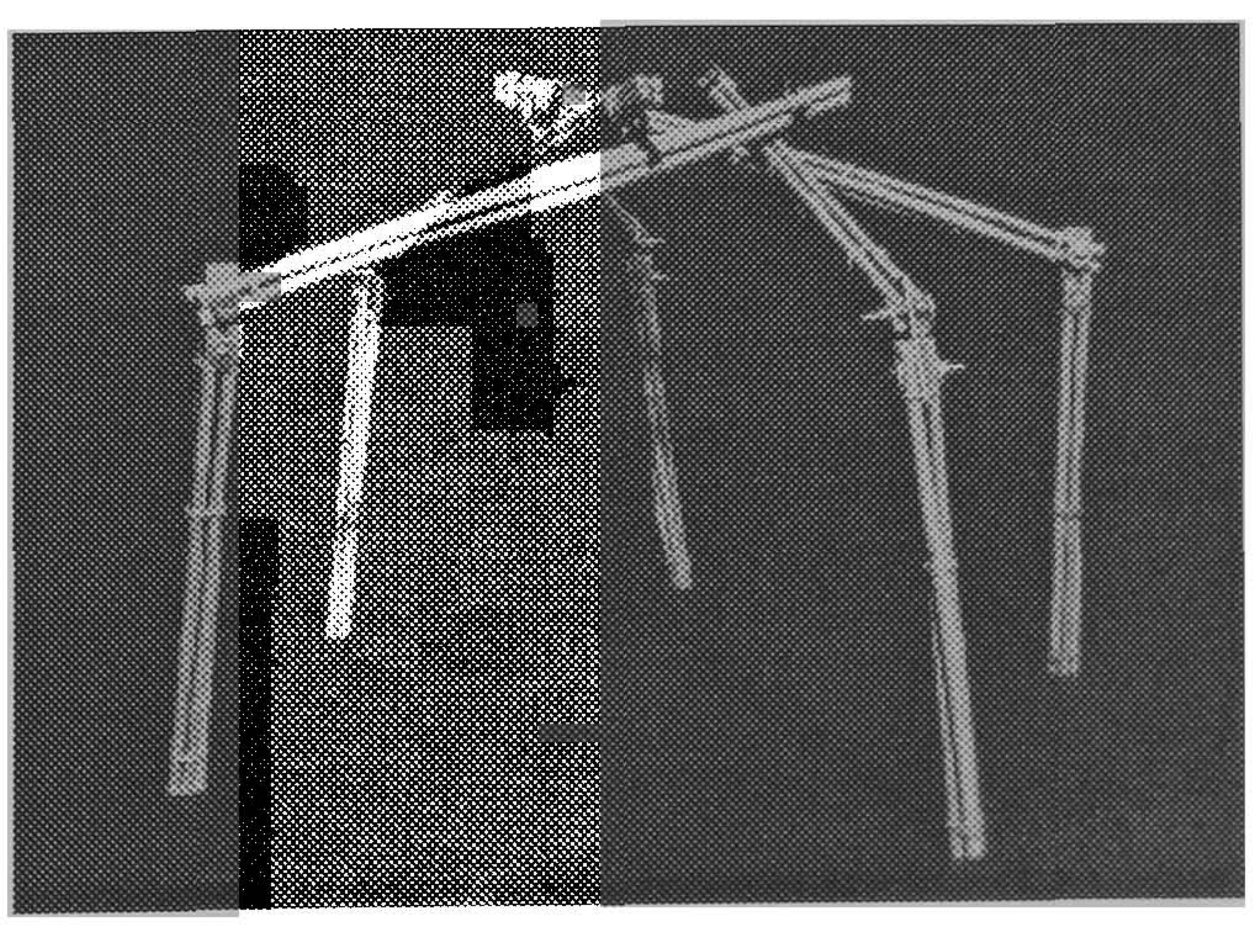


Figure 4.5. Single member RF model Figure 4.6. Composite member RF model

For the construction of the models the representation of the composite elements was made by using elastic bands to hold the bamboo sticks together.

4.2.1. Joints

To construct roundwood RF structures, employing single and composite members, the following joints need to be designed:
column - beam, and
beam - beam.

Their common feature must be that they need to be as simple as possible so as to allow fast and easy construction.

4.2.1.1. Column-beam joints

The single member roundwood column-beam RF joint presented in Figure 4.7 can be very easily constructed by inserting a steel plate in pre-cut notches in both column and beam. The steel plate is then tightened by use of bolts through the beam and column. For the model only one bolt was used through the beam and one through the column, but in reality the joint needs to be designed and calculated to be able to transmit the beam load to the column.

The distance between the column and the beam, depending on the size of the steel plate and the position of the bolt, can be adjusted to permit column-beam members to fold by allowing rotation at the joint. Folding is possible only before the bolts are tightened, and is important for ease of transport of the beam and column assemblies. These can then be unfolded on site at the appropriate point during the construction.

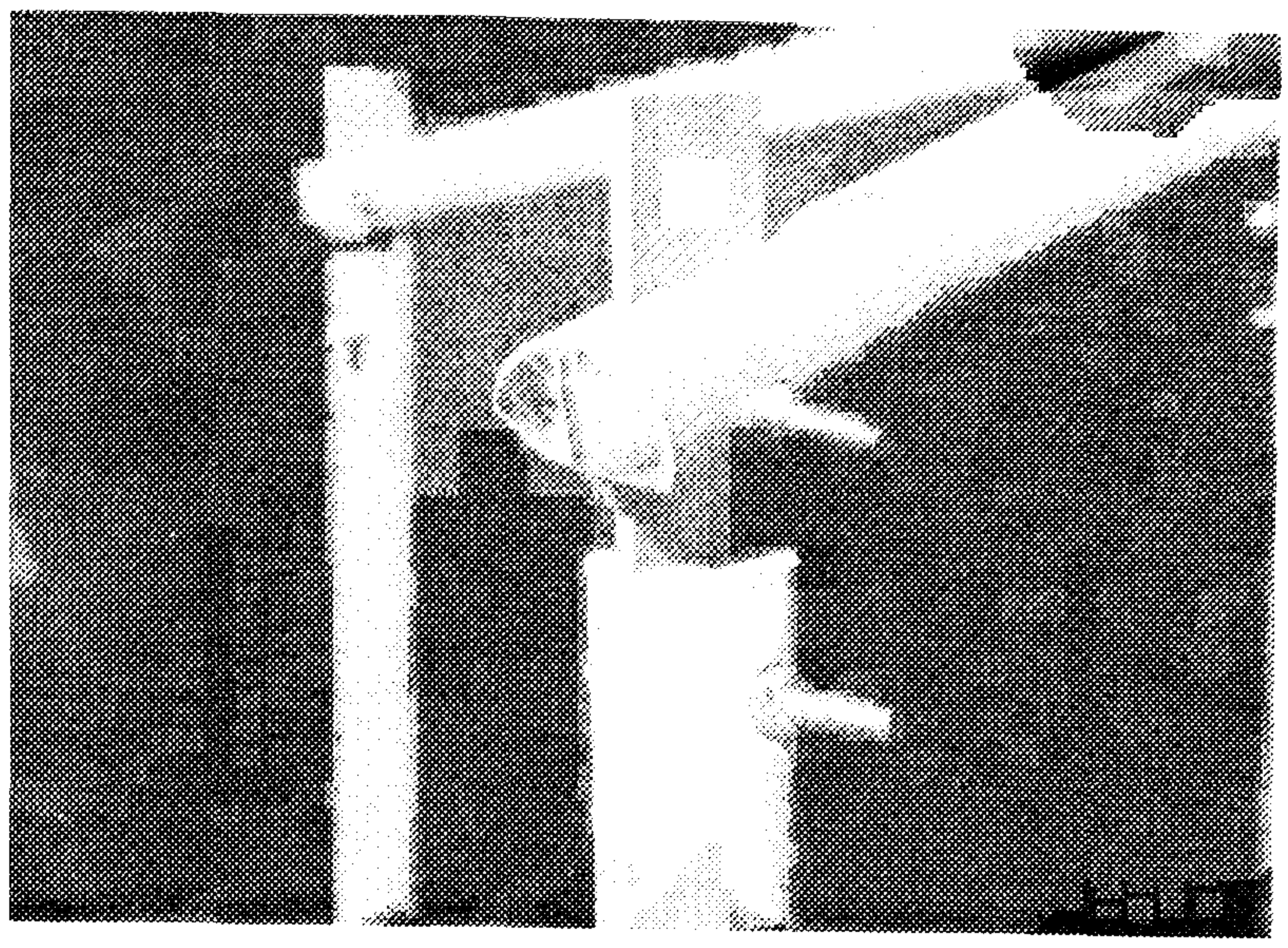
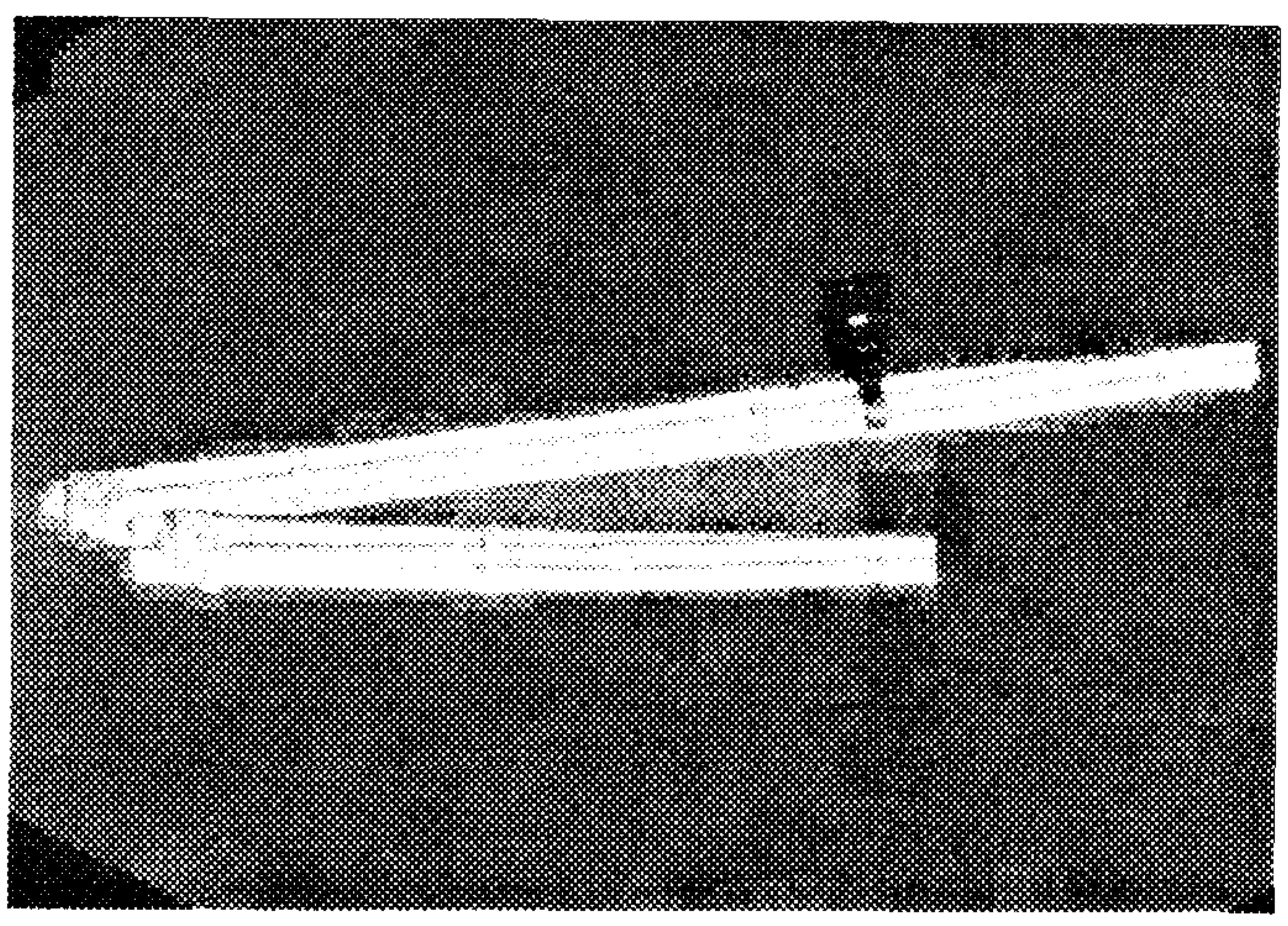


Figure 4.7 Single member column-beam joint

The column-beam joints for the RF composite members model (Figure 4.8 and Figure 4.9) were designed in a very similar manner, allowing folding of the assembly.



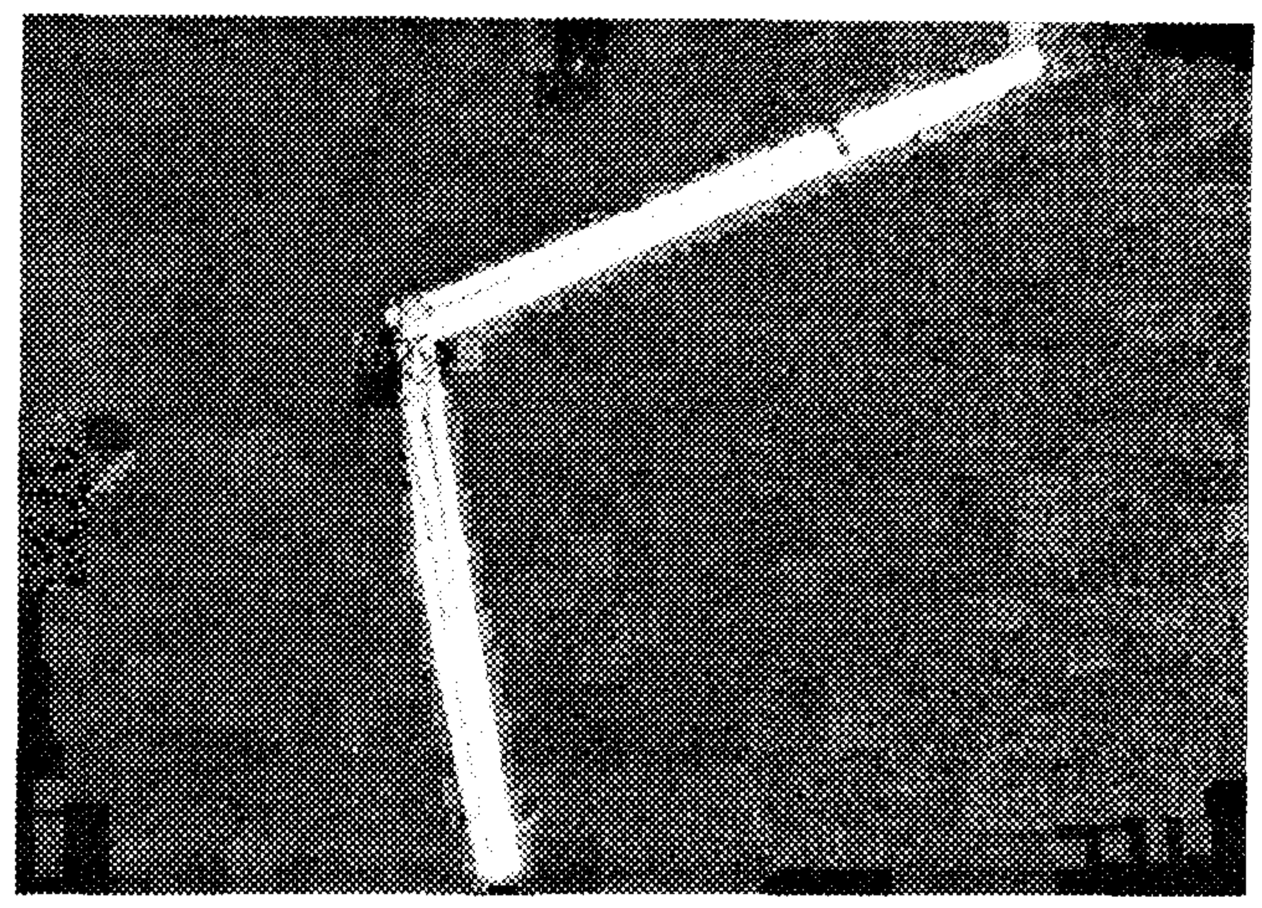


Figure 4.8. Folded and Figure 4.9. Unfolded composite beam-column RF assembly

4.2.1.2. Beam-beam joints

The beam-beam joint design was different for the two RF models. The composite beam model used a type of universal joint which consisted of two steel rings connected by a bolt (Figure 4.10). The composite members were put into the rings, which were then tied. The rotation allowed by the bolt connection of the metal rings helped the whole joint to accommodate the rotation necessary for the beams to support each other by resting on each other. On the small scale model the unwanted movement - sliding of the beams was prevented by tightly tying the RF beams. Friction held the composite beams together.

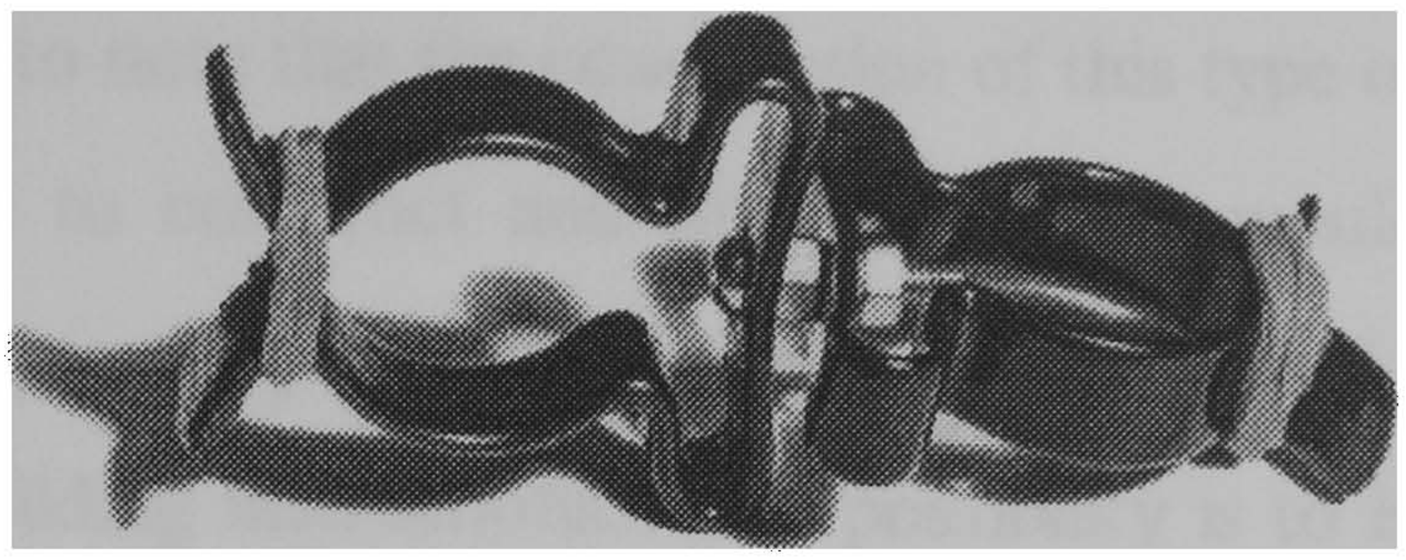


Figure 4.10. Composite member RF universal beam-beam joint

The beam-beam joint for the single member RF model was made by using a single bolt connection. The bolt was inserted in a large tolerance hole through the two beams, which allowed the beams to rotate and adjust until they rested on each other and formed the structure. The main criticism to this type of joint would be that the beam member is drilled through the middle, which reduces its load bearing capacity considerably. However, if the RF members are designed assuming the reduced strength and if light roof materials - membranes are used this should not be a problem.

Both ideas for joints worked on a small model scale, but in reality would need to be designed and tested on a full scale model, which has not been done because of time constraints.

The real joints would most probably be different in appearance from the model joints, but the main feature they need to have is that they allow the beams to rotate and adjust until they touch and are able to support each other. This would only be important if the RF members need to be re-used on roofs with different slopes such as temporary RF structures for different spans, or if the members and joints are designed as universal to be applicable to a range of spans and slopes of the roof. However, if the RF beams need to be applicable to only one slope at all times it is not necessary that the joints allow rotation for the beams to adjust. In this case the joint would need to be designed so that the roof has the desired slope.

4.2.1.3. Construction and buildability

It is very important to note that the construction of this type of RF structure would be easy and simple to construct and that the builder would not need to know anything about the geometry. Pre-fabricated elements would be sold as a kit, with simple to follow building instructions. One possibility is to have the columns and beams connected and folded so that whole assemblies are brought to the site. The column-beam assemblies would then be unfolded, the columns put into foundation sockets and the beams connected. A single prop would be used to support the beams until they are connected to form a closed circle.

A further possibility, but only for very light RF structures, would be to bring the column-beam assemblies on site, connect the beams together and then unfold the columns which would lift the whole structure (Figure 4.11).

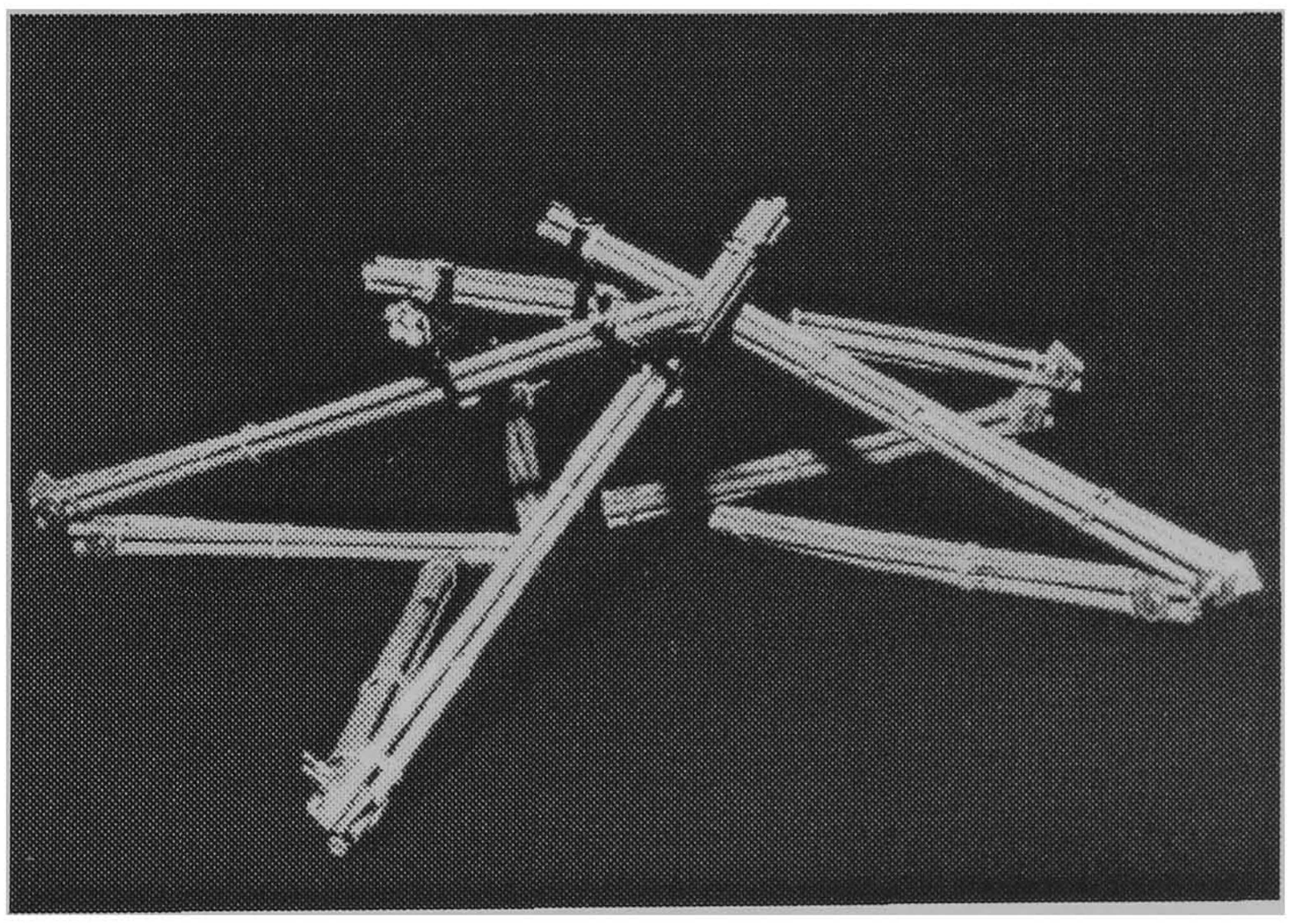


Figure 4.11. Assembled RF structure before being lifted

The proposed discussion about roundwood RF structures would be very easily applicable to temporary buildings if simple fabric membranes are used as enclosure. However, if the buildings need to be used for more permanent functions, appropriate materials, techniques and methods need to be explored which would fulfil the requirements of the brief of the building. These should be developed according to the requirements of the separate function to be accommodated by the RF. This has not been done as part of this project as it was beyond the scope of the research project.

4.3. RF Structures and sustainability

Although *"...there is an environmental dimension to all human activities..."* (Papanek, 1995, p.17), and *"...the way one person makes an alteration to the planet has an effect on the other 4,999,999,999 inhabitants..."* (Vale and Vale, 1991, p.7), architects as one of the main creators of the built environment have a special responsibility. They need to be aware of the shared responsibility they have for the Earth's resources.

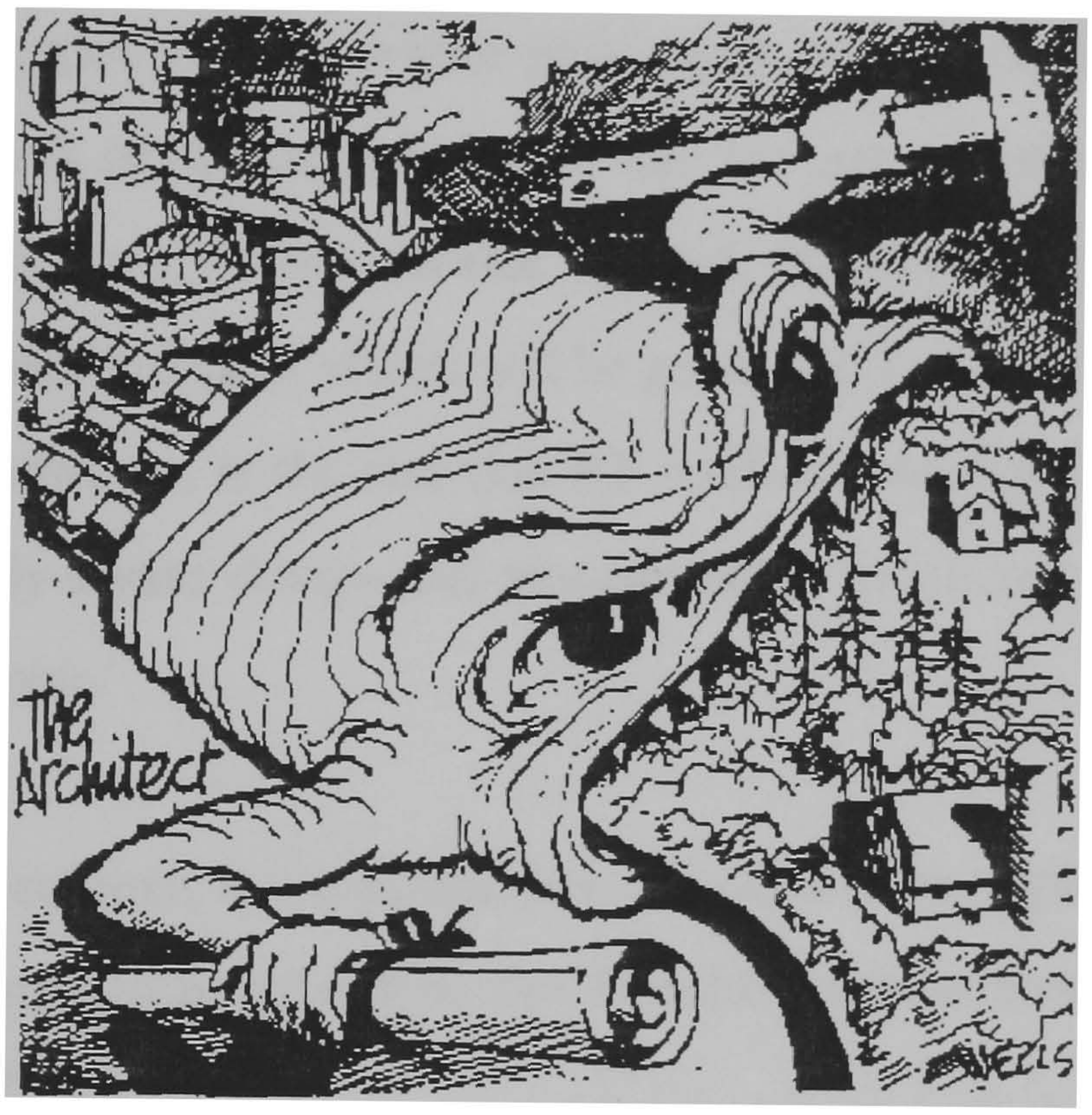


Figure 4.12. Architects and sustainability

In that sense, where architecture is concerned, the general environmental considerations regarding the choice of materials are:

- *embodied energy. Considering the raw material extraction, transport and manufacturing, fossil fuel energy usage,*
- *sources of the raw material and percentage of recycled content,*
- *pollution from manufacture. Discharges to aquifers, air and disposal to land-fill*
- *hazards during demolition, removal and final disposal* (Curwell, 1995, p.46).

Lipschutz gives a definition of what sustainable development is, from the aspect of resources:

"... Sustainable development is a broad notion that human consumption of resources and environmental services must be sustainable and should not exceed the capacity of the biosphere/environment ..." (Lipschutz, 1991, p.35).

However, to achieve sustainable development and environmentally aware design it is not enough just to be aware of the materials used for construction, but also, of the way in which they are used, the form of the building, the technology and method of construction and the whole philosophy behind the design. Therefore, many buildings have some 'green features' but few are completely benign to the environment (Vale, Vale, 1991). In that respect, the existing RF buildings in the UK have some 'green features', which will be presented further in the text. What is more important, however, is the fact that RF modular construction has a potential for environmentally aware design and sustainability, which will also be presented further in this chapter.

Therefore, in this context, the sustainability aspects will be applied in the broadest sense of its meaning and as defined by the World Commission on Environment and Development (WCED) as:

"... Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs". (Bruntland,1987, p.43).

4.3.1. The potential of sustainable construction of modular RF buildings

The potential that RF modular construction has in terms of sustainability, comes from the fact that this type of modular construction makes possible the application of most of the 'green principles', as given by Vale and Vale (1991, pp. 69-168):

1. *Conserving energy*, because:

- RF modular construction can be used to create clusters of buildings, which within a specific disposition of the buildings, can provide shading for hot climates or reduced external surface area to cold weather,
- uses panels which can be designed to have low "U" values,
- can be constructed mainly from renewable materials,
- the buildings give a possibility of having a sun space under the roof window.

2. *Working with climate*, because:

- RF buildings provide the possibility for having a roof window, which allows easier ventilation,
- sun spaces can be formed under the roof window which would help save energy for heating of the building.

3. *Minimising new resources*, because:

- demountable RF buildings enable re-use of the same material,
- re-use of telegraph poles is possible, as well as use of small roundwood sections not used otherwise for construction (this aspect is addressed more closely further in the text of this chapter),
- as there is no need for internal supports, RF buildings create open plan flexible spaces which allow change of function and re-use of the building.

4. *Respect for users*, because:

- they involve the users in the construction if they are designed as self-build,
- the open plan flexible spaces can be adapted to suit the needs of the users.

5. *Respect for site*, because:

- if designed as demountable structures, they can be removed from the site without damaging it, so that they *"...touch the earth lightly..."* (Vale, Vale, 1991, p. 141)
- they can be constructed out of local, natural and renewable materials such as timber with highly insulated panels for the enclosure,

- if necessary, buildings having turfed or planted RF roofs can be constructed (as discussed further in the text of this chapter).

6. *Holistic approach*:

Although none of the existing RF modular buildings respect fully all of the 'green principles', they have a potential to embody most of them, as will be expressed through the examples built in the UK.

4.3.2. Timber RF structures and sustainability

No structural system by itself makes the building sustainable. Still, it can be argued that RF structures made out of timber, especially if roundwood is used, can contribute to environmentally aware design because timber is a 'green' material.

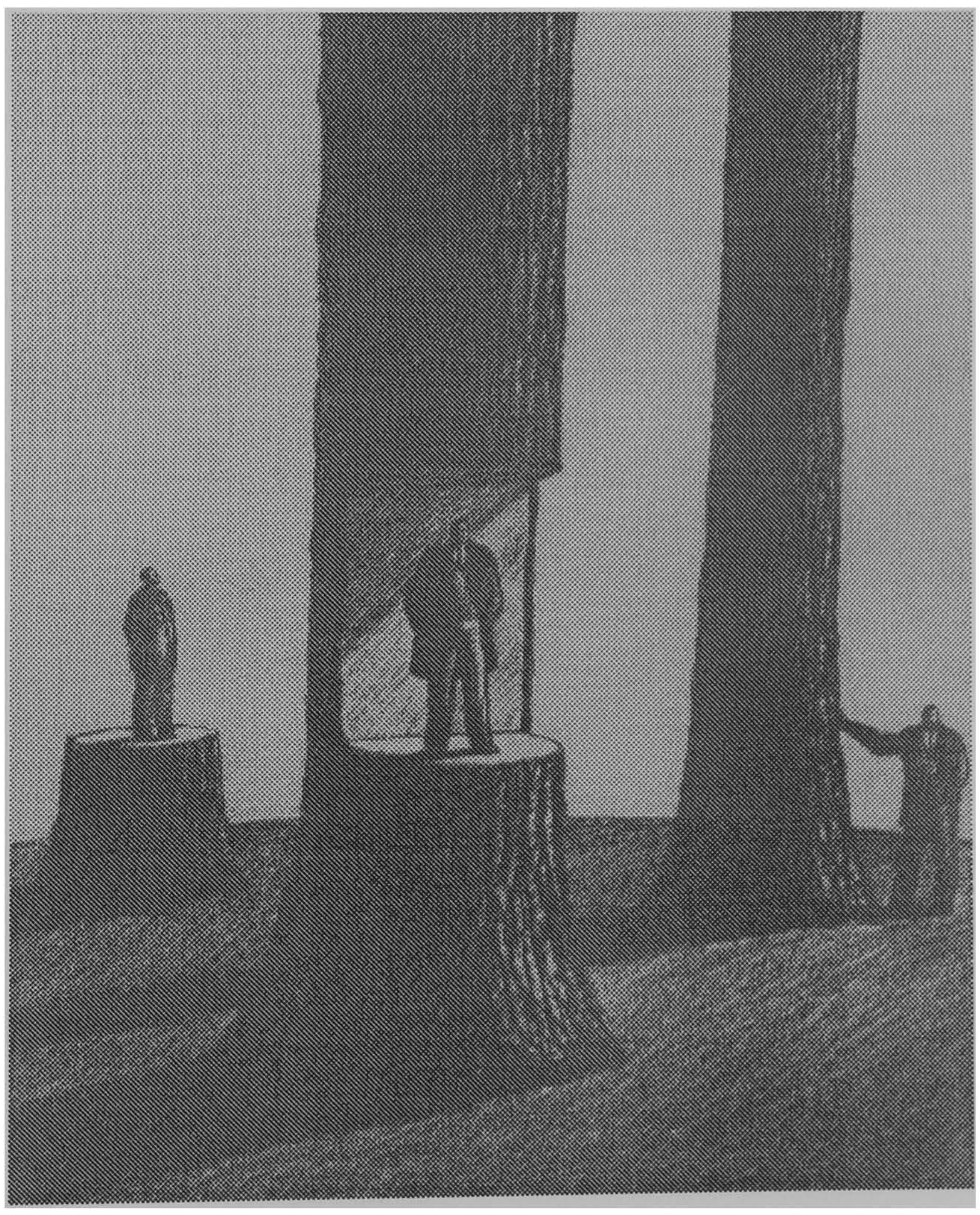


Figure 4.13. Unsustainable use of timber

Although it is very difficult to give exact figures for the embodied energy of materials because of the considerable differences in the production systems used, by this criterion timber is considered as one of the 'greenest' materials. Vihavainen (1995 p. A16/5) gives a range of 350 kWh/m^3 for sawn timber to 1200 kWh/m^3 for glulam. Turrent (1995, p.38) gives a value of 694 kWh/m^3 but does not state for which type of timber this figure is applicable. However, one needs to be very careful with these figures because they give no information on the transport distances, or whether the timber comes from sustainable sources.

In that respect RF roundwood low-cost construction can also contribute to sustainable development, as it uses small roundwood sections (otherwise used only for fencing posts, pulping up for chipboard, fuel and sometimes for agricultural buildings) for sheds, barns, shelters, temporary exhibition stands etc. Finding a broader use for the material locally would help reduce embodied energy and CO_2 emission.

4.4. Examples of RF buildings constructed in the UK

There are comparatively few RF buildings in the UK. They are all of modular construction, and have been constructed since 1988, after the structure was 'invented' by Graham Brown. They are:

- several Gazebos in Findhorn Bay, Oxfordshire and Nottingham,
- the RF roofs over two recycled whisky barrels to form small houses in the Findhorn spiritual community,
- a house in Ferryhill, Forres, Morayshire, Scotland,
- a house at Saorsa, Ardlach, Nairn, Scotland, and
- a Permaculture centre in Bradford.

Before going into analysis of the individual RF buildings it would be appropriate to say a few words about how the RF system emerged in the UK.

4.4.1. How the idea about the RF was born in the UK

It is interesting how often human history demonstrates that events happen only if there is a confluence of specific circumstances against a background of precedents. Regarding the RF, the system emerged in Japan as a result of the tradition of timber construction, the concepts of 'movement-orientated architectural spaces' and 'Sukiya' and Buddhist philosophy as discussed in Chapter 3.

However, it is even more interesting how history shows us that similar events can also occur as a result of completely different circumstances, with very different paths leading to similar and sometimes even the same solutions. Such is the story of the RF.

The idea about the RF with sloping beams in the UK does not go back for centuries as it does in Japan. Although examples exist of planar grillage structures with beams shorter than the span, such as the Medieval floors (as discussed in Chapter 2, section 2.1.2. pp. 2-6, 2-7 and 2-11), the RF structure 'revealed itself' to its inventor Graham Brown in November 1987.

Inspired by a game with sticks enjoyed by his daughters, Graham Brown made an assembly of sticks which, to his amusement, did not collapse. The next day he used larger sticks and assembled them using blue-tak to hold them in position. Not only did the heap of sticks not collapse but it could resist the pressure applied by Graham's hand. Graham realised he had created a structure.

Being a skilled wood craftsman, Graham decided to make a model. Although an equally skilful draftsman, it was still very difficult for him to draw the structure. However, he managed to make the model using his sketches. To his amazement - it worked. Not only did it not collapse but it seemed quite strong and could resist load.

Graham decided to investigate whether the structure would 'work' on real scale buildings and came to seek the expertise of the School of Architecture, at the University of Nottingham, which is how this research was initiated. Research into the structural behaviour of the RF has been done by Chilton, and by Chilton and Choo (as discussed in Chapter 2, section 2.2 pp. 2-30 - 2-33), which proved that the RF can be successfully applied to real buildings.

Graham Brown named the 'new' structure the Reciprocal Frame. It was called 'reciprocal' because, according to him, it represented the nature of the structure.

"*... In the Oxford dictionary the word 'reciprocal' has several meanings:*

- *Adjective: in return - I helped him, and in return he helped me,*

- *Mathematical*[1]*: so related to another that their product is unity."* (G. Brown, 1989, p.12).

The beams 'help each other': they form unity and, when load is applied, all of them share and resist the load together.

As the idea for the RF came 'out of nowhere', in 1988 Graham Brown decided to form a company, under that name, which would construct buildings using the RF. It is under the auspices of this company that a number of RF buildings have been designed and several have been constructed.

4.4.2. RF buildings in the UK

All RF buildings constructed by 'Out of Nowhere' are, without exception, of modular construction. 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 (1994, p.23), as discussed in Chapter 2, section 2.1.3, p. 2-18. The enclosure is of well insulated lightweight panels with built-in columns supporting the RF roof.

Five different types of panels have been used:

- floor panels,
- external wall panels,

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[1] It is interesting to note that the mathematician Clerk Maxwell used the term 'reciprocal' with the meaning of duality. *"Two plane rectilinear figures are reciprocal when they consist of an equal number of straight lines, so that corresponding lines in the two figures are at right angles, and corresponding lines which meet in a point in the one figure form a closed polygon in the other."* (Maxwell, 1890, p.165).

- internal wall panels,
- ceiling/floor panels, and
- roof panels.

The roof and floor loads are resisted mainly by columns built into the wall panels, which provides the possibility for different panel surface designs: solid, partially or fully glazed, with standard, French or patio doors. The construction of the RF buildings was fast and fairly simple. In order to achieve this, all the elements which form the structure, as well as the envelope, were prefabricated to close tolerances of several (2-5) mm in a workshop before being brought on site for assembly. The entire construction process could be completed in only a few days.

All the column-beam, and beam-beam joints and construction details were very carefully designed, to facilitate the assembly of the elements. This was especially important in the case of the sloping timber beams which were notched with variable depth notches in order to form the roof structure. For the roof to be erected, a prop was needed to support one or more of the RF beams at their inner end, until they could form a full circle (polygon) and support each other. A ring beam was 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 subject to axial forces (as discussed in Chapter 2, section 2.2, p. 2-30).

4.4.2.1. Gazebos

Designer: G. Brown

Structural Engineer: not engineered structures

Constructed by: Out of Nowhere

Date of construction: several constructed in the period 1987-1995

Place: Findhorn Bay, Morrayshire, Scotland, Oxfordshire, and Nottingham

Span: 4.2 metres

Function: meditation spaces, office, garden room or anything the owner decides

RF plan form: 7 sided regular polygon

Type of construction: modular

The smallest RF buildings are no more than gazebos with a diameter of 4.2 m. and possess only one space. The Findhorn Bay gazebo, presented on Figure 4.14 is used as a meditation space.

Figure 4.14 The Findhorn Bay gazebo

All RF gazebos were designed to be in human scale. The designer G. Brown designed them to have a radius long enough for him to lie on the floor and to have his head under the roof light *"...to see the stars at night..."* as Graham says[(2)]. Thus the gazebos are very well proportioned and give a pleasant feeling. The skilfully detailed interior timber finish and the exposed RF members, presented on Figures 4.15, 4.16 and 4.17 contribute to the warm and pleasing ambience.

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[2] G. Brown made this comment in a private conversation with the author during a visit to the RF buildings in Scotland

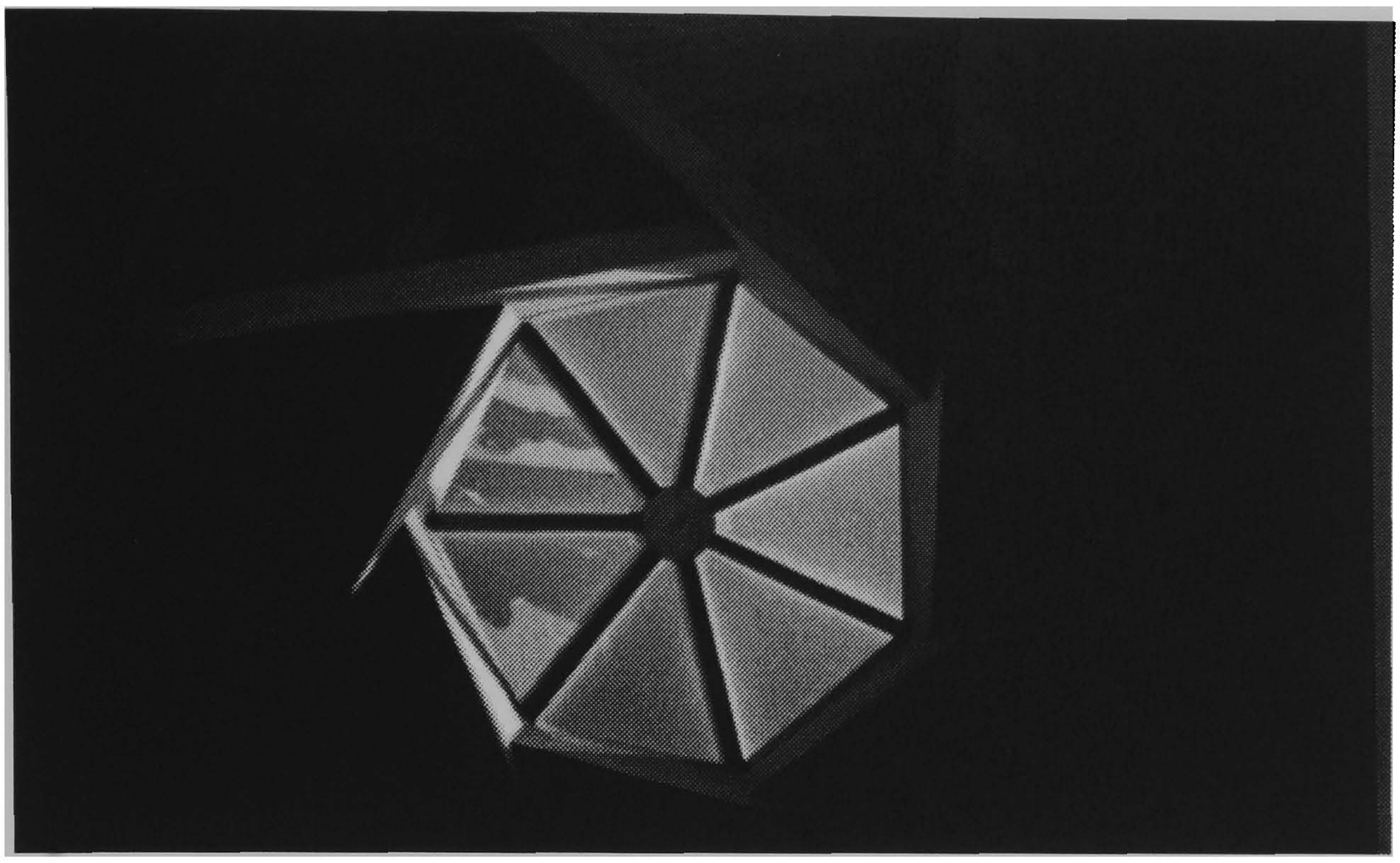

Figure 4.15 Roof light created by the RF structure

Figure 4.16. Interior of a Gazebo - RF beam and column (detail)

The erection of the gazebos took only a few days and was fairly straightforward. All the building parts were prefabricated in a workshop and only assembled on site. The wall panels are solid cedar 68 mm. thick with double tongue and groove jointing, whereas the triangular roof and floor panels are insulated with 100 mm insulation. The roof panels are supported by the RF beams, and thus they are offset, whereas the floor triangular panels have a radial disposition.

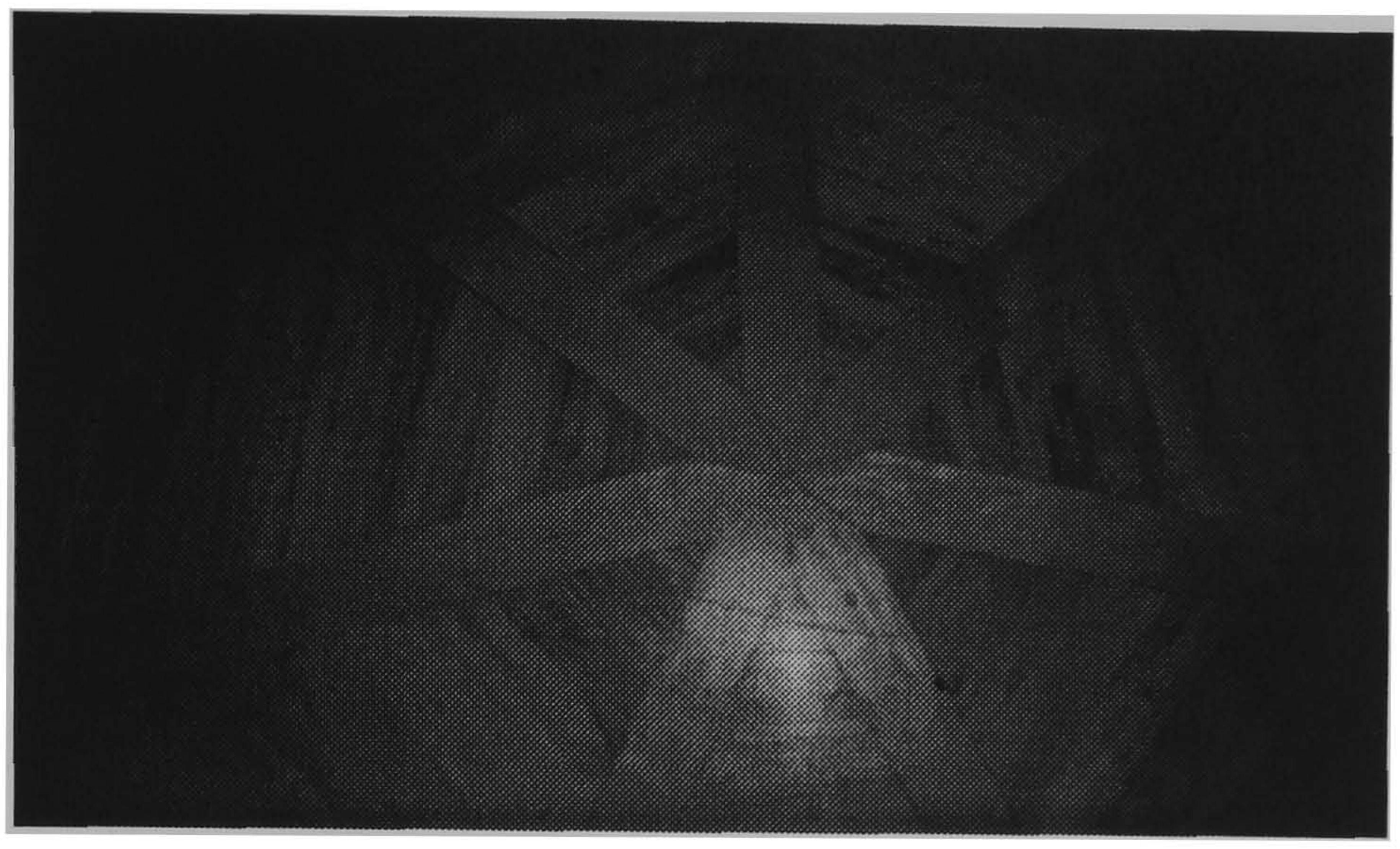

Figure 4.17 Interior of a Gazebo - view of the floor panels

The timber RF beams were supported by a central prop until a full circle was formed and the beams were able to support each other, after which the roof panels were installed. All windows are double glazed. The roof finish is with cedar shingles.

The gazebos respect some of the previously discussed (see pp. 4-15 and 4-16) 'green principles', because they:

- conserve energy by the use of renewable materials (timber),
- work with the climate by using a roof window to bring more light into the space,
- minimise new resources and respect their users because the gazebo space accommodated by the RF is unobstructed by internal supports, which allows change of function and reuse of the building for a new function.

However, the gazebos do not respect the 'green principles' fully. They could be improved by:

- insulating the wall panels in the same way as the floor and roof panels,
- using a roof window which can be opened for easier ventilation,
- being designed as self-build and sold in kit form.

Although not completely 'green' the gazebos represent a successful application of the RF structure for modular construction because they are well proportioned and create a beautiful architectural space.

4.4.2.2. Two recycled Whisky Barrel houses with RF roofs

Designer: G. Brown

Structural Engineer: J. Chilton

Constructed by: Out of Nowhere

Date of construction: 1990

Place: Findhorn Foundation

Span: 6.0 metres

Function: two dwellings

RF plan form: circular

Type of construction: modular

In 1990 the Findhorn spiritual community decided to reuse two second-hand whisky barrels and to use them as dwellings. The two Whisky Barrel houses were roofed with RF timber beams covered with triangular modular prefabricated panels clad externally with sheets of copper, as presented on Figure 4.18.

Figure 4.18 View of the Findhorn RF Whisky Barrel house

Both buildings have open plan organised spaces with a bathroom in the middle and a sleeping loft over it. The exposed solid timber RF beams and timber cladding create a pleasant and 'warm' semi-open interior space. Extra light is brought into the space through the roof light, which enhances its quality even more. This is presented in Figure 4.19.

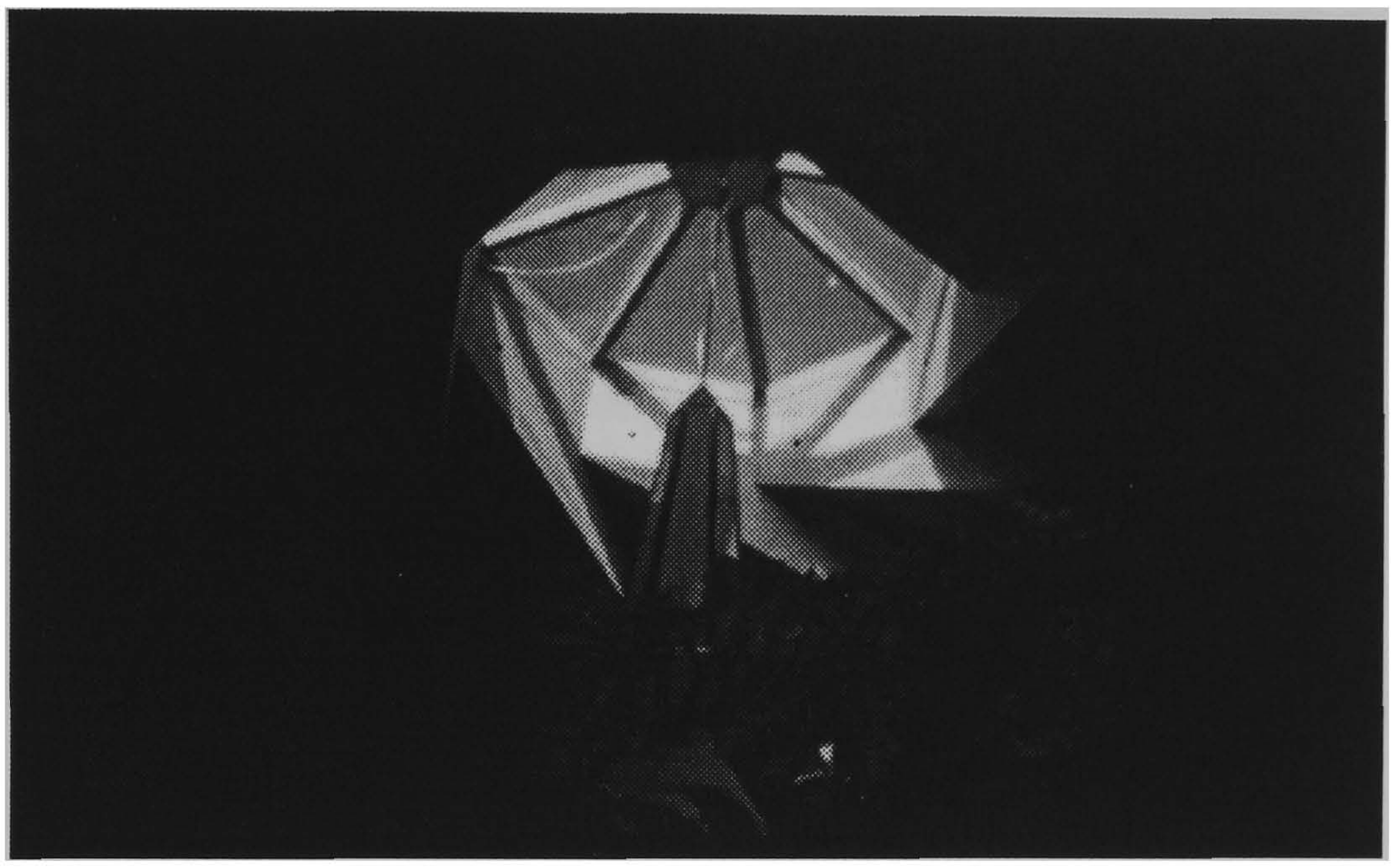

Figure 4.19. The roof light at the Findhorn RF Whisky Vat house

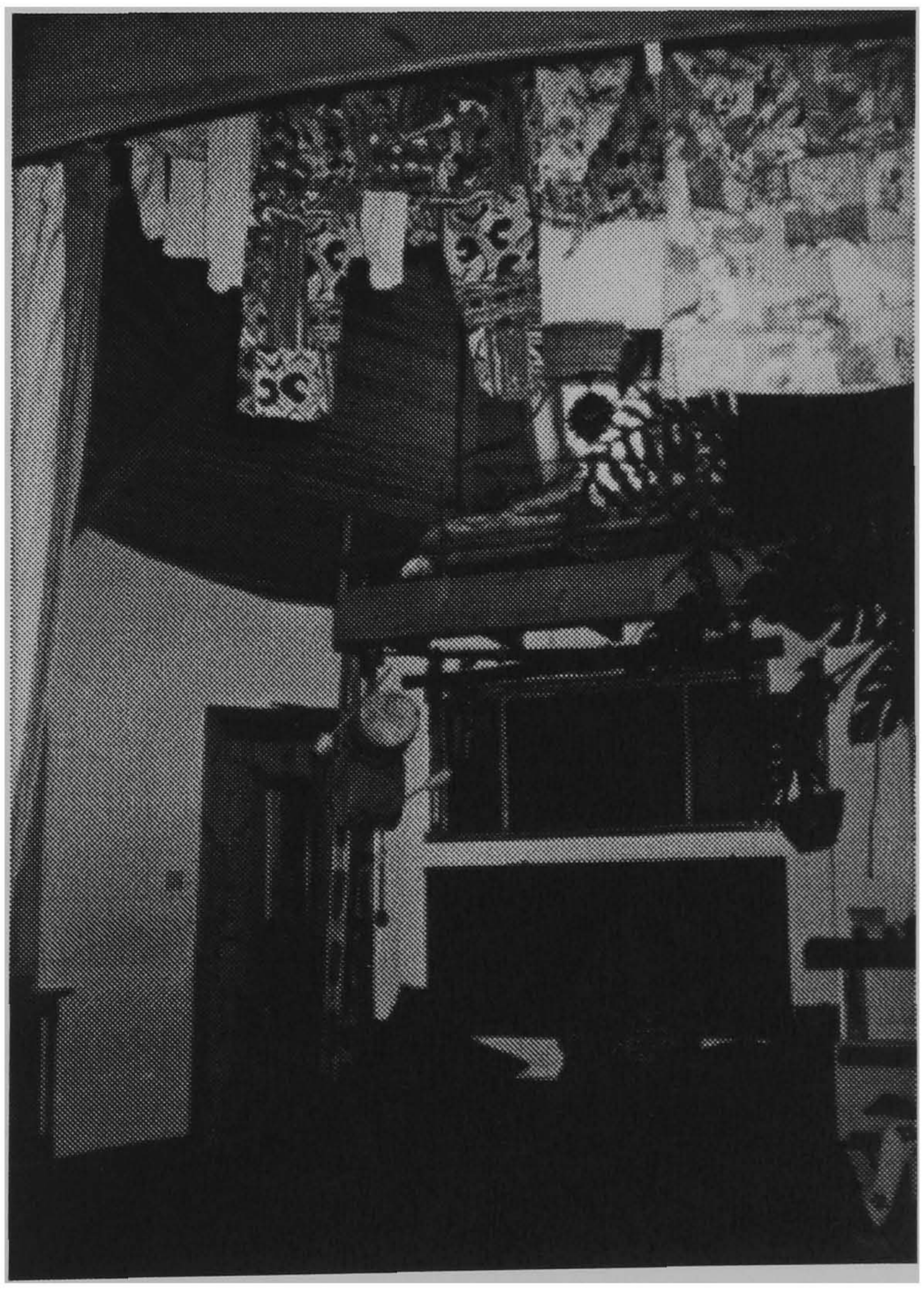

Figure 4.20. Interior view of the Findhorn RF Whisky Vat house

The RF beams supporting each other and without any internal supports give a sense of lightness to the interior space as well as a sense of movement: rotation. Both RF houses are well proportioned and to human scale. The open plan spaces are very pleasant to be in (see Figure 4.20).

Although quite interesting, it can not be said that the exterior of the Findhorn RF Whisky Barrel houses is as successful. The copper cladding seems to make the otherwise lightweight RF roof look rather heavy. On the other hand, this type of continuous cladding provides better protection against rain and snow with less danger of leaks than RF roofs which have lots of flashing. In that sense a conical surface would have provided an equally good protection from the rain and at the same time made the appearance of the building 'lighter' and more pleasing. From an architectural point of view, this approach would have the additional benefit of revealing the dramatic structure only after one had entered the building. The unassuming exterior would be unexpectedly contrasted by the seemingly unsupported sweep of the RF beams, as in the case of the Seiwa Bunraku Puppet Theatre (see Chapter 3, section 3.3.3, p. 3-17).

In terms of 'greenness' the Findhorn RF Whisky vat houses respect the same 'green principles' as the gazebos.

4.4.2.3. The house in Ferryhill, Forres, Morayshire, Scotland

Designer: G. Brown

Structural Engineer: J. Chilton

Constructed by: Out of Nowhere

Date of construction: 1993-4

Place: Ferryhill, Forres, Morayshire, Scotland,

Span: 11 metres

Function: dwelling

RF plan form: 10 sided polygon

Type of construction: modular

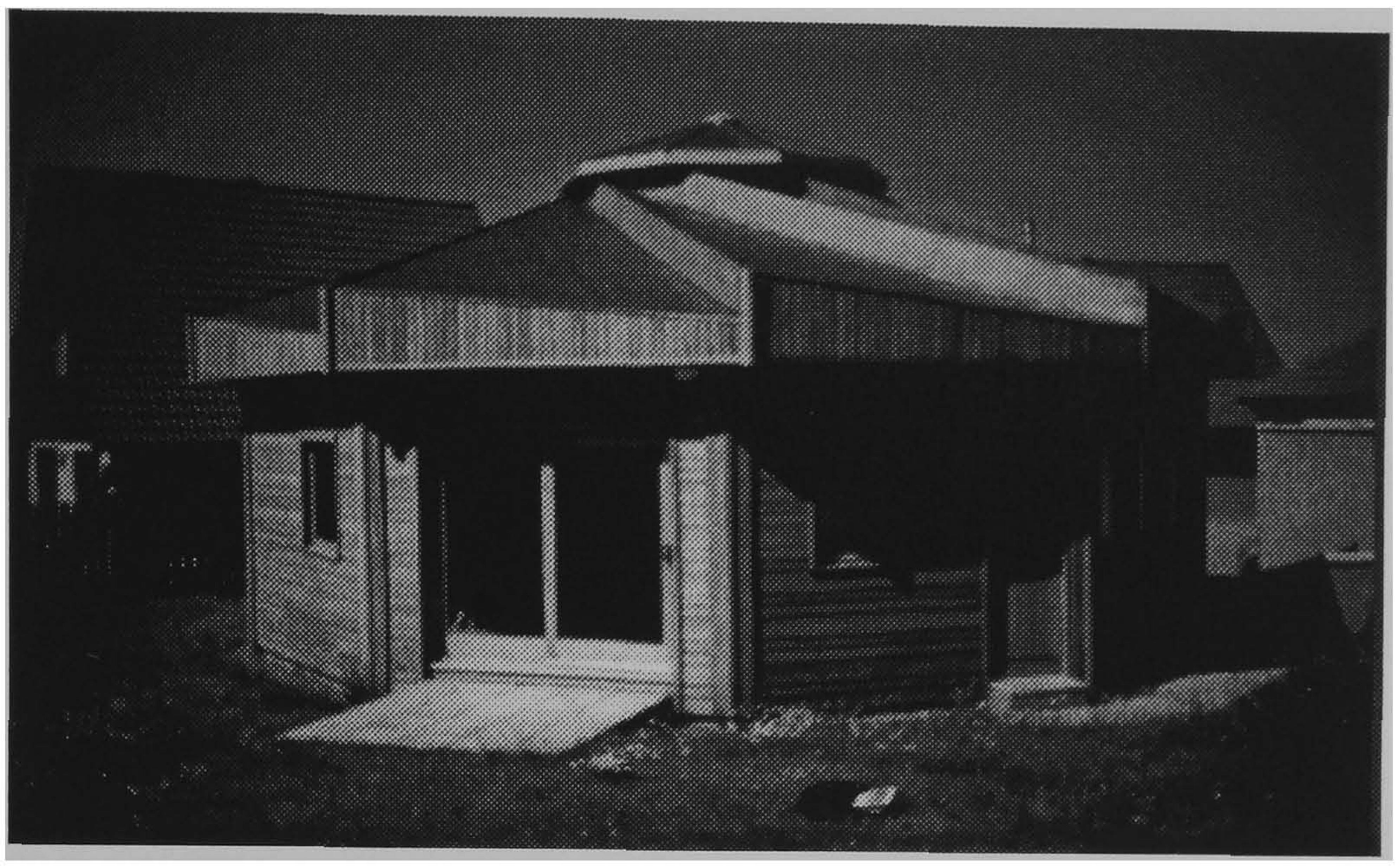

Figure 4.21. The modular RF house in Ferryhill, Forres, Morayshire, Scotland

The 11 metre diameter, two bedroom modular RF house, presented in Figure 4.21. was constructed in Ferryhill, Forres, Morayshire, in 1993-4 as part of a commercial development.

The house is designed to have a gallery over the ground floor rooms formed by inserting partitions which follow the beam lines. This is the first RF building constructed by G. Brown that has divided spaces. As a result of having the divisions which follow the beam lines in plan, the rooms have irregular forms (see Figure 4-22). This is one of the main disadvantages of partitioned RF modular buildings.

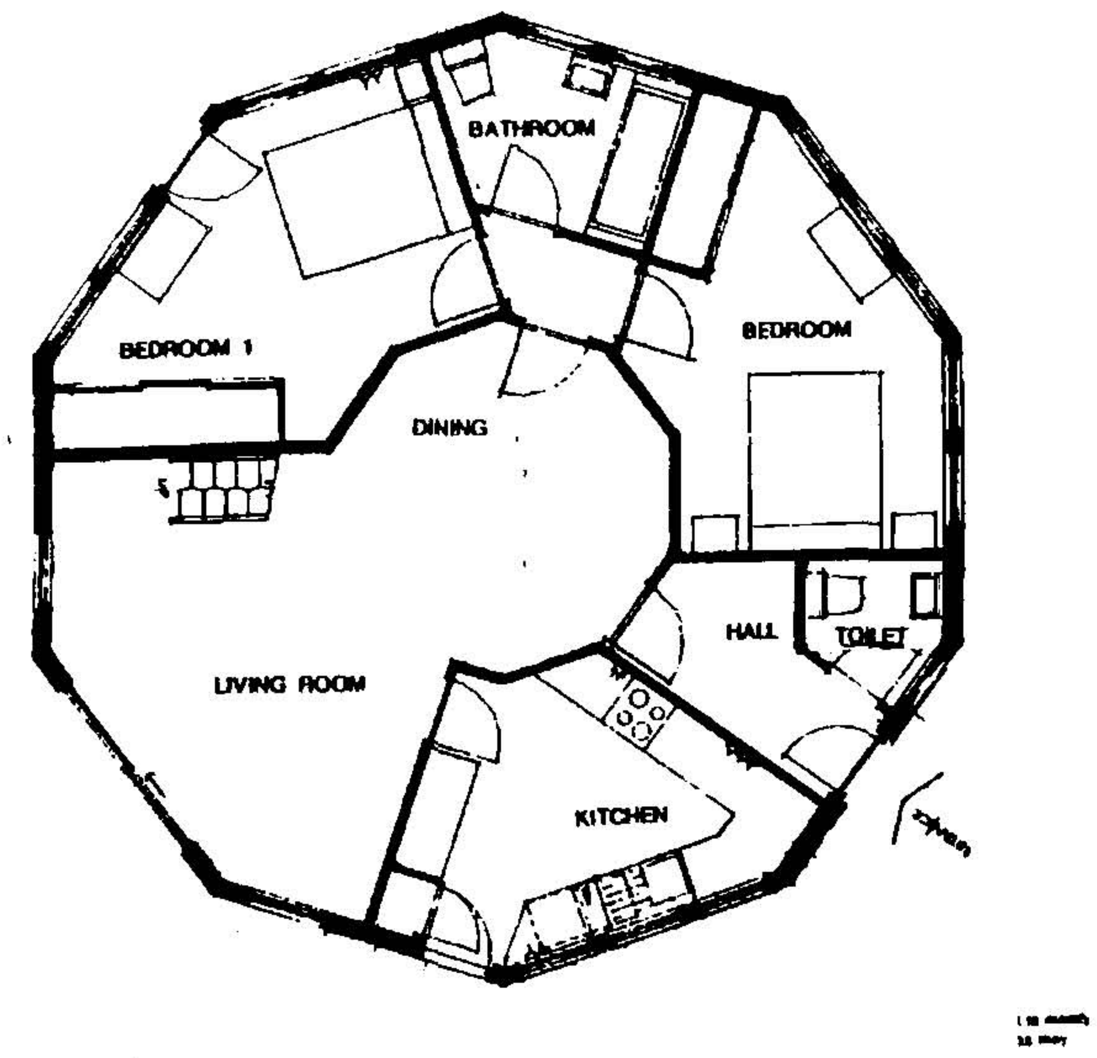

Figure 4.22. The Ferryhill house - plan view

The house has a sky light over the main hall which lets sunlight into the house. The external walls are constructed of timber panels which incorporate columns to support the 405 mm. deep by 115 mm. wide glulam roof beams. The timber frame 'breathing' walls are externally clad with lapped larch boarding and insulated with 145 mm Warmcel cellulose insulation. All the structural elements for this building were prefabricated in a workshop and the erection of the structure was completed in only two days.

There is a lot of wood in the interior which gives a warm feeling to the spaces, as can be seen on Figure 4.23.

Figure 4.23 The Ferryhill house - Interior view

The Feryhill house shows that it is possible to partition RF buildings but this needs to be done with a lot of care. Otherwise some of the spaces could have very strange plan forms. Also, because of the inserted partitions and ceiling, the dramatic structure of RF beams can not be seen and apritiated in the enclosed spaces of the rooms.

4.4.2.4. The house at Saorsa, Ardlach, Nairn, Scotland

Designer: G. Brown

Structural Engineer: J. Chilton

Constructed by: Out of Nowhere

Date of construction: 1995-unfinished

Place: Saorsa, Ardlach, Nairn, Scotland

Span: 13 metres

Function: dwelling

RF plan form: 10 sided polygon

Type of construction: modular

The longest span RF modular building is an unfinished 13 metre diameter house at Saorsa, Ardlach, Nairn, Scotland, shown in Figure 4.24.

Figure 4.24. The 13 m. diameter RF house in Saorsa, Ardlach, Nairn, Scotland

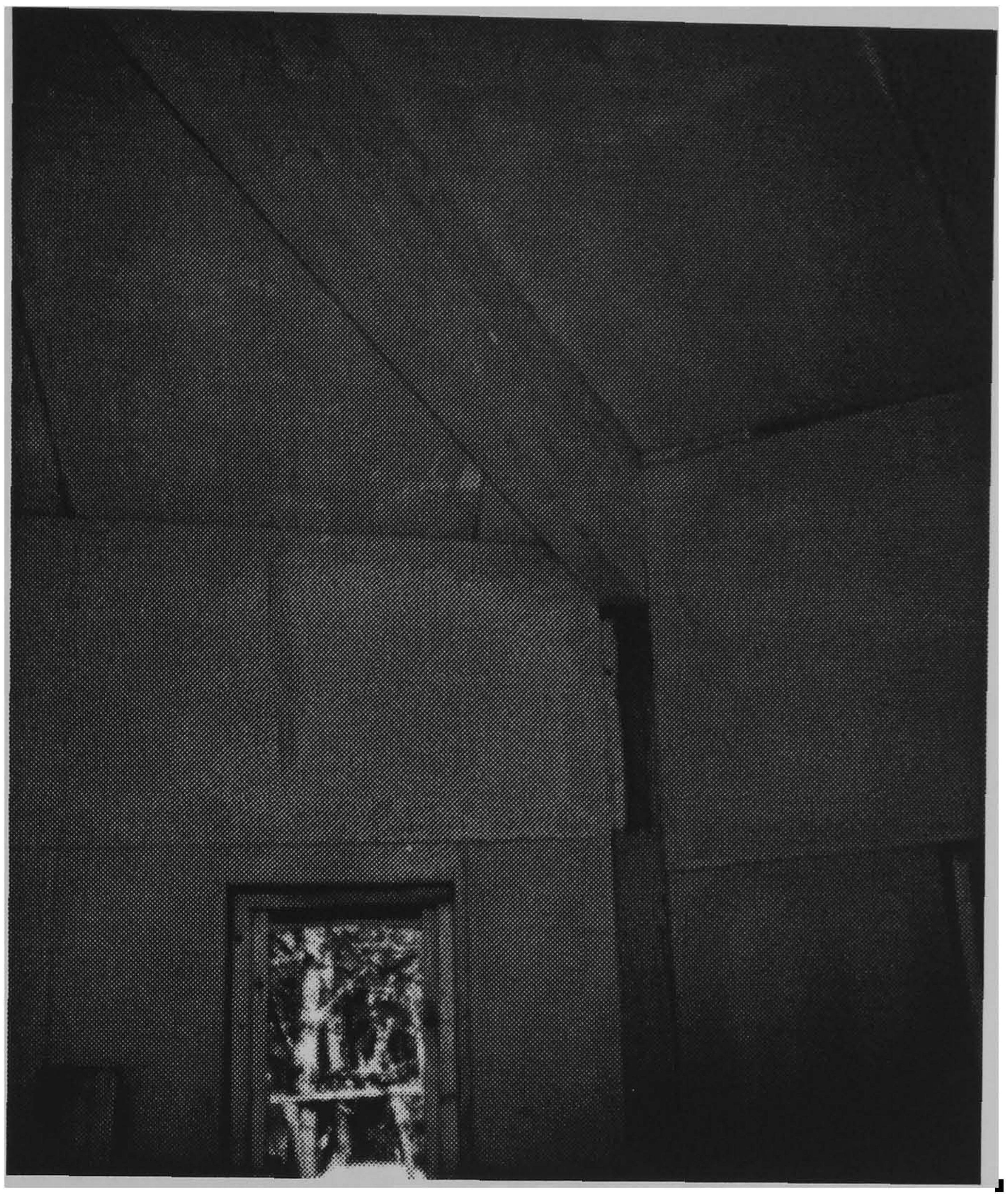

Figure 4.25. Timber built-in columns - detail (RF house in Saorsa, Ardlach, Nairn)

In plan the house is a regular decagon, and the main wall structure, as in the previous house, has built-in timber columns, supporting ten, 450 mm deep by 140 mm wide glulam beams (see Figure 4.25).

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 erection took only three days because all the beams, wall and roof panels were prefabricated in a workshop.

4.4.2.5. The Permaculture Centre in Bradford

Designer: G. Brown

Structural Engineer: J. Chilton

Constructed by: Out of Nowhere / Bradford Metropolitan District Council

Date of construction: 1995-unfinished

Place: Bradford

Span: 8 metres

Function: dwelling, workshop and meeting room

RF plan form: a cluster of 3 RF octagonal pavilions

Type of construction: modular

The three RF modular pavilions designed as a Permaculture Centre in Bradford represent the idea of forming clusters of RF modular buildings, as shown in Figure 4.26.

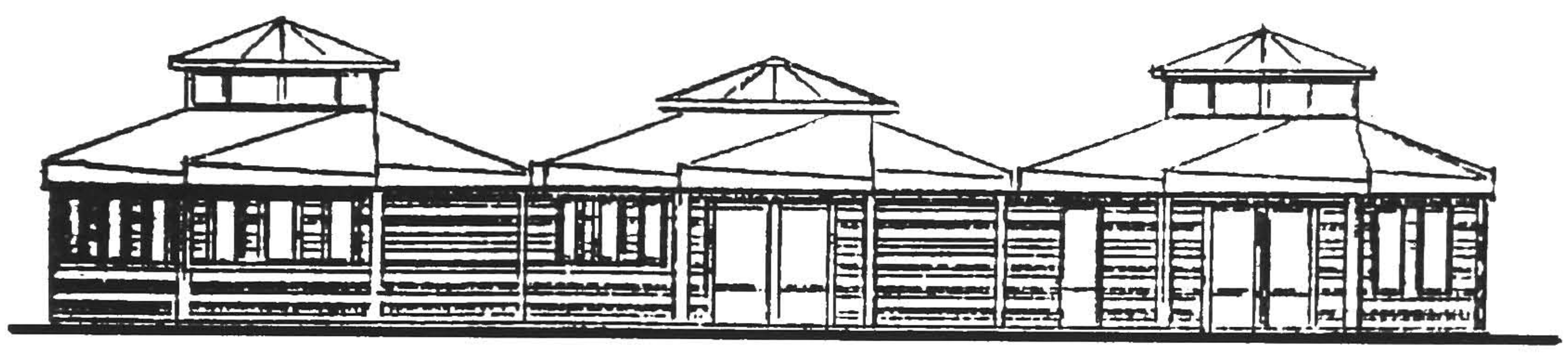

Figure 4.26. The RF Permaculture Centre in Bradford - elevation

In this case the RF octagons are connected by flat-roofed links. The three pavilions have different functions. One will be used as a workshop, another will consist of kitchen, meeting room and accommodation and the third will be eventually added and used for residential accommodation. This, once again, shows the adaptability and flexibility of the RF modular buildings and their ability to accommodate spaces with different functions, as shown in Figure 4.27.

There are no great differences in the configuration and method of construction of the Bradford Centre compared to the previously described RF modular buildings. The main difference is that the roof is designed to be turf covered and because of the relatively high dead load that this applies, the glulam RF beams are reqired to be 405 mm deep by 115 mm wide. This is the same size cross section as used for the 11 m diameter Ferryhill house in Forres, Morayshire, Scotland.

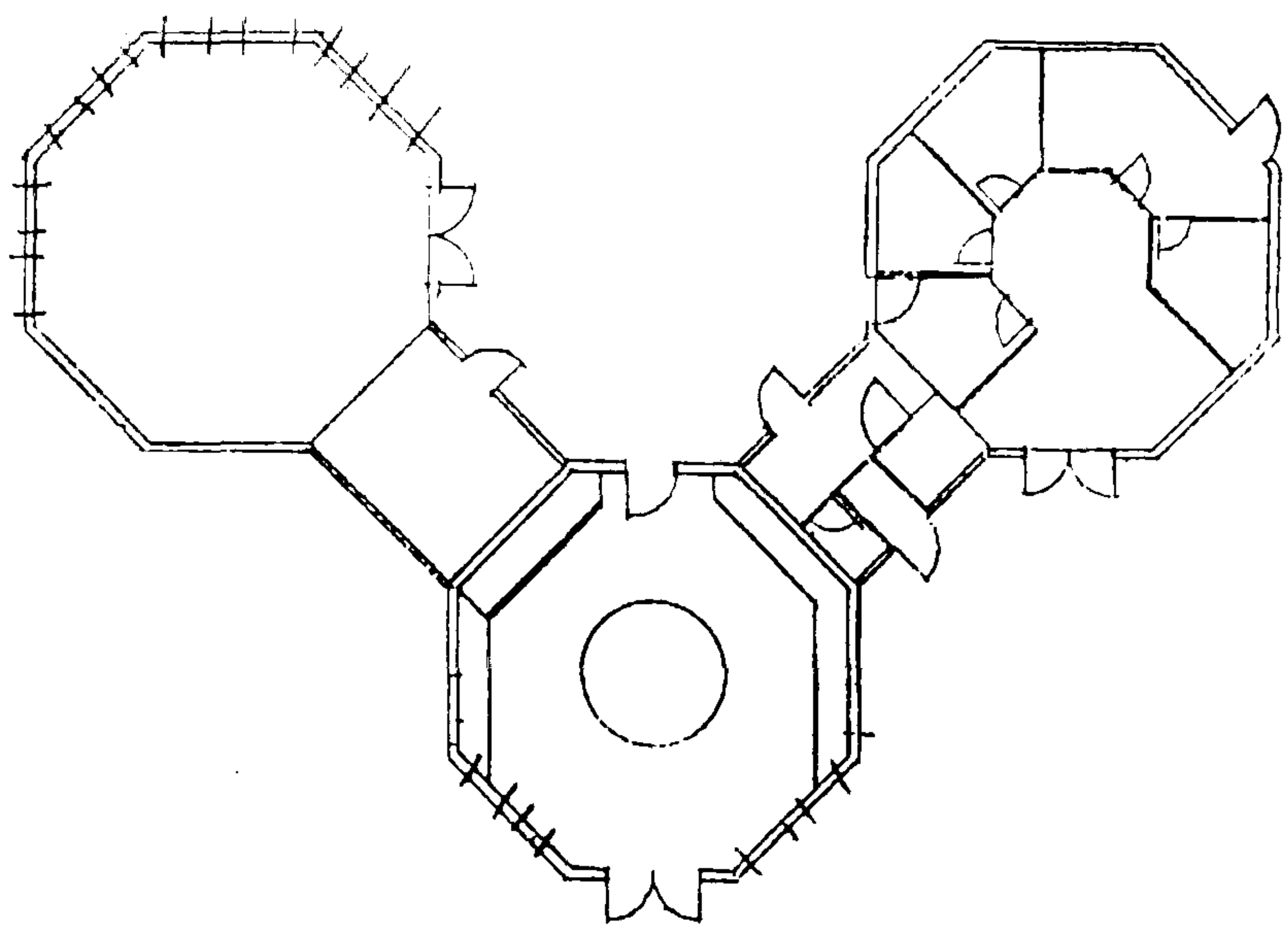

Figure 4.27. The RF Permaculture Centre in Bradford - plan

The RF Permaculture Centre in Bradford also respects some of the previously discussed 'green principles', the most significant being the respect for users, because the spaces accommodated by the RF are unobstructed by internal supports, which allows change and use for different functions.

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4.6. List of illustrations:

Figure 4.26. The RF Permaculture Centre in Bradford - elevation, drawing by G. Brown

Figure 4.26. The RF Permaculture Centre in Bradford - plan, drawing by G. Brown

CHAPTER 5: Case study: A RF Village hall

5.1. A New Fisherman's Institute in Staithes

As the RF structure is not very well known, there are very few buildings using it, compared to those using more conventional roof structures. Most of the constructed RF buildings (as can be seen from the previous chapter) are short span buildings.

The lack of built examples of medium and long span RF buildings made it difficult to analyse the RF structural morphology and to show how it affects the function and spatial qualities of the buildings. Also it is difficult to point out any advantages or potential problems of such buildings in actual use.

In order to explore the design possibilities of medium span RF construction, a case study was undertaken. Second year architecture students, at the School of Architecture, University of Nottingham, were given a project to design a multiple use village hall, and those who chose to do their technical study in structures were asked to use the RF structural system.

5.1.1. Students involved

All fifty one second year students were given an introductory lecture both in Acoustics and on RF construction. They were given two choices for their technical study:

1. A detailed study of the acoustic performance of their village hall design, or
2. To use a timber RF structure and study it, showing the load paths, approximate member sizes etc.

The students who decided to use the RF structure for the village hall design were *"....to prepare a sheet that gives a schematic structural axonometric which shoes the load paths through the structure to the foundations, together with an indication of the approximate sizes of the structural components."* Also, they were required to *"...provide a small scale plan of the building on the sheet to show the disposition of the space."* And, in addition to *"...provide a section at 1:20 (or other appropriate scale) that demonstrates the materials that clothe the structure both internally and externally. "* (Vale, 1996, p.2)

Although the students were given two choices, about half of them (25) were expected to do the acoustics technical study, with the other half using the RF for their design.

The students were asked to submit their technical studies after two weeks and the whole project was done within one month.

As part of the research on the RF structural system, questionnaires and interviews, both with students who used the RF for their design and those who did not use it, were carried out.

The questionnaires were completed by RF users in order to ascertain their design experiences with the system, the practical problems they had, and the advantages they could see from the application of the RF.

The questionnaires given to students who chose not to use the RF asked their opinions on the applicability of the RF system for the given brief and how they, as architecture students and future designers, see its potential. In order to gain more information concerning questions which were not answered in enough depth, a small number of students were interviewed. An analysis of the findings of the questionnaires and the interviews will be presented later in this chapter.

5.1.2. Main aim and objective of the project

In terms of a design exercise, the main aim of the project was to explore a large space for multiple use, combined with a number of ancillary spaces (the brief is presented later in the text). The fact that the site for the project was Staithes, which is a picturesque site and also a place where the Staithes group of artists worked at the turn of the century was of significance. The students were expected to investigate forms which would fit the environment.

In terms of the RF, the main aim of the project, especially the technical study of the structure, was to introduce the students more closely to a new structural system and help them learn about it by using it. They had been introduced to the RF through their "Timber and Masonry Structures" Module, but an additional lecture was given at the start of the project. The technical study, that they were asked to do as part of the Village Hall project, enabled the students to understand how the structure works and what the load paths are, as well as to learn about the approximate sizes of the structural elements, and typical construction details.

Although the RF users did a technical study in structures, the architectural design of their village hall as a whole was greatly affected by the use of the RF. The fact that the structure largely defined their space(s) (in particular the main hall) made them explore how to make use of the RF structure as part of the architectural expression. They explored the structural morphology in order to design a RF building which would fulfil not only the structural requirements, but at the same time would have architectural value in terms of spatial quality and good proportion, would be appropriate to the context of the site and would fulfil the required functions. The students did not have an easy task and they worked hard to make the most out of the RF. In the process they developed different spatial solutions which will be described in detail and analysed later.

The exploration of the morphology of medium span RF structures using designs produced during a student project was of great importance for the research. The fact that 25 students took part in the exercise meant that a significant number of different RF morphology examples would be developed to accommodate their alternative spatial solutions. The different examples developed have been grouped by their main characteristics and analysed. The analysis has indeed achieved the main aim of this aspect of the research in pointing out the advantages and practical design problems of the RF applied to a medium span assembly building.

Although young (only in their second year) and not very experienced in design, the students contributed considerably to the research on the RF. They provided data which could be analysed. It would have never been the same if one person (for example the author) had designed a building 25 times with the same brief, since the solutions would have been too similar to form a sample wide enough for research.

5.1.3. The brief and the site

The students were asked to design a village hall, which could be used for local concerts, film shows, dramatic productions, art exhibitions, playgroup meetings, small group meetings of clubs and societies etc. They were to accommodate the following spaces within their given brief:

Main space:

- A hall of 300 m^2 with either a fixed or removable stage area,

Secondary spaces:

- An equipment store for stacking chairs, screens, tables etc.,
- Separate storage cupboards for the playgroup,
- Small meeting room of 20 m^2,
- Office of 10 m^2 ,
- Kitchen of 20 m^2,
- Male and female cloakrooms with disabled WCs,
- Entry Lobby,
- External storage space for bins etc.,
- Parking and access to the building.

The site for the project was Staithes, a little picturesque village on the north Yorkshire coast of Great Britain. Dunbar described it as: *"...a jumble of houses built between two high cliffs, picturesque to a degree, with thatched and tiled roofs above brown ironstone walls, and a wooden quay, called the staithe, straddling the shingly beach..."* (Dunbar, 1975, p.51).

Staithes is also known for the group of painters who settled and worked there in the turn of the century. Their work is considered to be very important for British Art. Phillips described them as: *"This little group of painters working in Staithes set out the highest ideals, and showed at their exhibitions work which compared favourably with that on view in any of the galleries in London or the provinces. There is no doubt that this Group, which was at that time regarded as extremely Modernist, has had a great influence on British Art"* (Phillips, 1993, p. 11).

There had been a "Fishermen's Institute" in the village, built by the artists, with a multiple use: *"...At first we held our concerts in the life-boat house, and then the Fishermen's Institute was built with the help of the artists and used as a concert-hall. If you look at the Institute today (1939) you will see it has a lot of glass in the roof - it was built that way so that we could have part use of it as a studio..."* (Phillips, 1993, p.13), thus the project title: "The New Fisherman's Institute".

It is important to emphasise that the artists of the Staithes art group gave financial help to the Fisherman's Institute: *"...The second annual exhibition was successful and contained forty one framed paintings. An entrance fee of two pence was charged and all proceeds were given to the Fishermen's Institute..."* (Phillips, 1993, p.15).

5.2. Generated RF morphology and spatial solutions

When one attempts to analyse something it is always important to point out the objective of the analysis, in order to define the main criteria for the analysis. In the case of the student design project the main objective (in terms of the RF research project) was to explore the RF morphology on a middle span (15-20 m.) building with a given brief.

However, in some examples, it is very difficult to divide the structure and look at its morphology without examining the building as a whole. This results from the fact that in many of the examples the RF largely defines the spaces and the form of the building as a whole. Therefore, in the analysis, although the main emphasis is given to the RF morphology, the design examples are studied in terms of the quality of the design as a whole.

5.2.1. Grouped RF morphology examples

The RF morphology types generated by the case study have been grouped into three for easier analysis. The common element that defined each group is the specific RF form developed and applied. Within each group there are some differences which will also be described. The following RF morphology groups have been developed:

1. Single RF units, which are:

- regular / irregular
- constructed of simple timber beams / constructed of other timber main elements (trusses, string-tie beams etc.)
- used over the main space only / used over the whole building

2. Two or more RF units, over both the main and ancillary spaces, which are:

- regular / irregular

3. Multiple and complex RF units, which are constructed out of single RFs, being:
- regular / irregular
- constructed of simple timber beams / constructed of other timber main elements (trusses)

Before going in to the detailed description, comparison and analysis of each of the groups, one needs to point out that this was not the only possible way of grouping the solutions. The grouping was done in this way because it allowed the main emphasis to be put on the RF morphology, the main objective of the case study research.

5.2.1.1. Single RF units

The largest number of designs (14 out of 25) used single RF units, which accommodated the building as a whole or the main space (the hall) only.

Figures 5.1 a and b show an example of a regular RF structure over the main hall with a rectilinear plan form. The RF beams are made of solid glulam timber and are joined in the same plane. The use of the RF allowed light through the roof. When one looks at the elevation (Figure 5.1 b) it is not evident that the RF structure had been used in the building. This is an example in which the RF structure did not affect the form of the building. The student has used the RF but in a way so that it had a minimal impact on the design approach - the same space could have been formed by use of several alternative structures (e.g. beams spanning across the shorter dimension). This presents another possibility in the design of RF buildings.

The main advantages of the use of the RF, in this case, are the creation of a roof light and the fact that no internal supports are needed in the main hall.

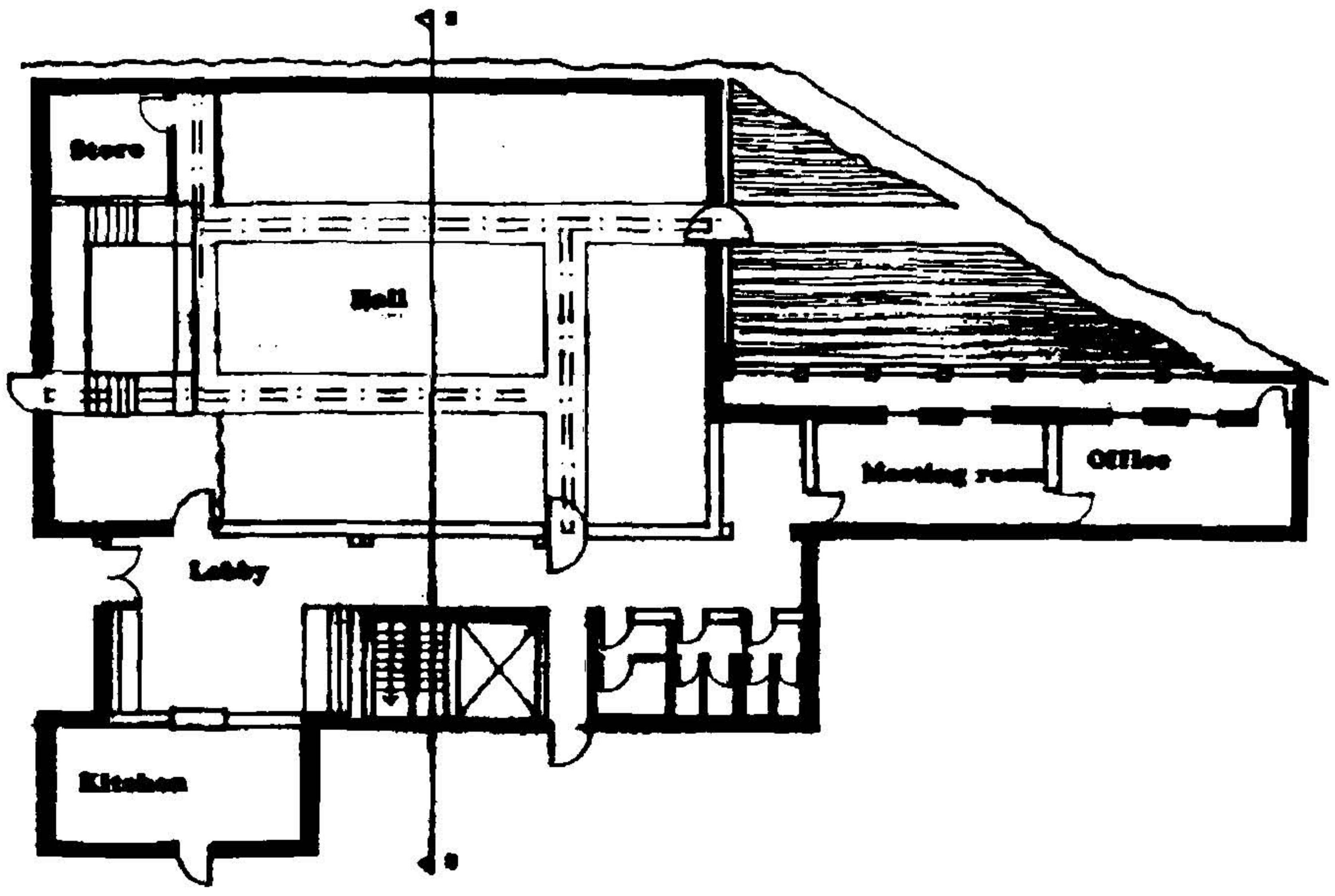


Figure 5.1 a

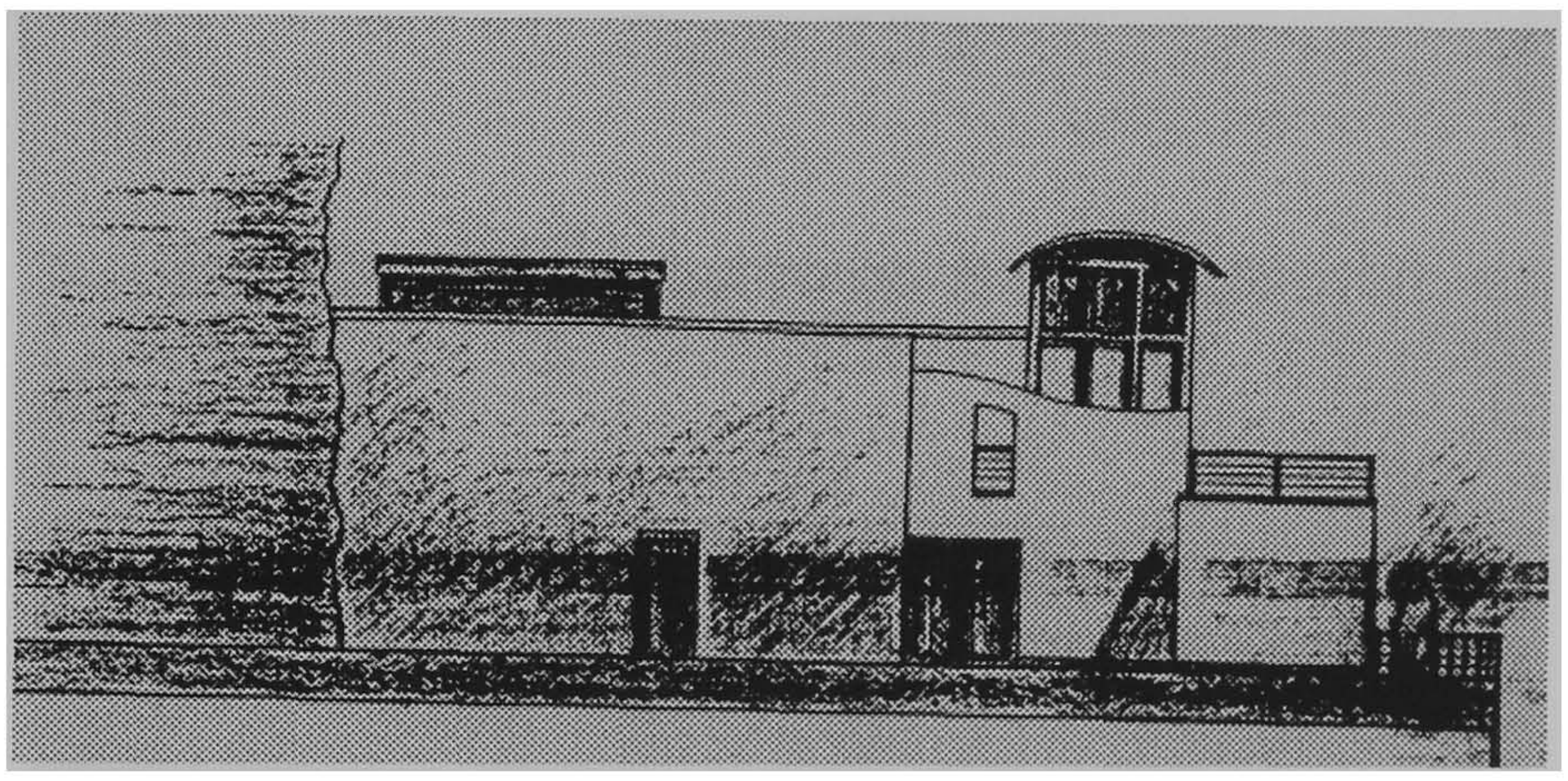


Figure 5.1 b

This example is very similar in plan to the medieval use of grillages (as presented in Chapter 2, section 2.1.2, p.2-6) when distances longer than the available beams needed to be spanned. Also it is identical to L. Kahn's use in the Mill Creek housing project (see Chapter 2, section 2.1.3, p.2-16). The main difference between these two designs and the student project is the material used for the RF structure. Usually in medieval times timber beams were used whereas L. Kahn used reinforced concrete beams and the student used glulam RF beams.

Another example of a regular RF accommodated in a circular plan form is given in Figures 5.2 a. and b. The RF roofs the whole building, both the main hall and the ancillary spaces. In this example the secondary spaces are tangentially positioned on one side of the main hall (as presented on Figure 5.2 a). The RF beams which form the roof structure over these spaces are longer. This makes the plan form look asymmetrical.

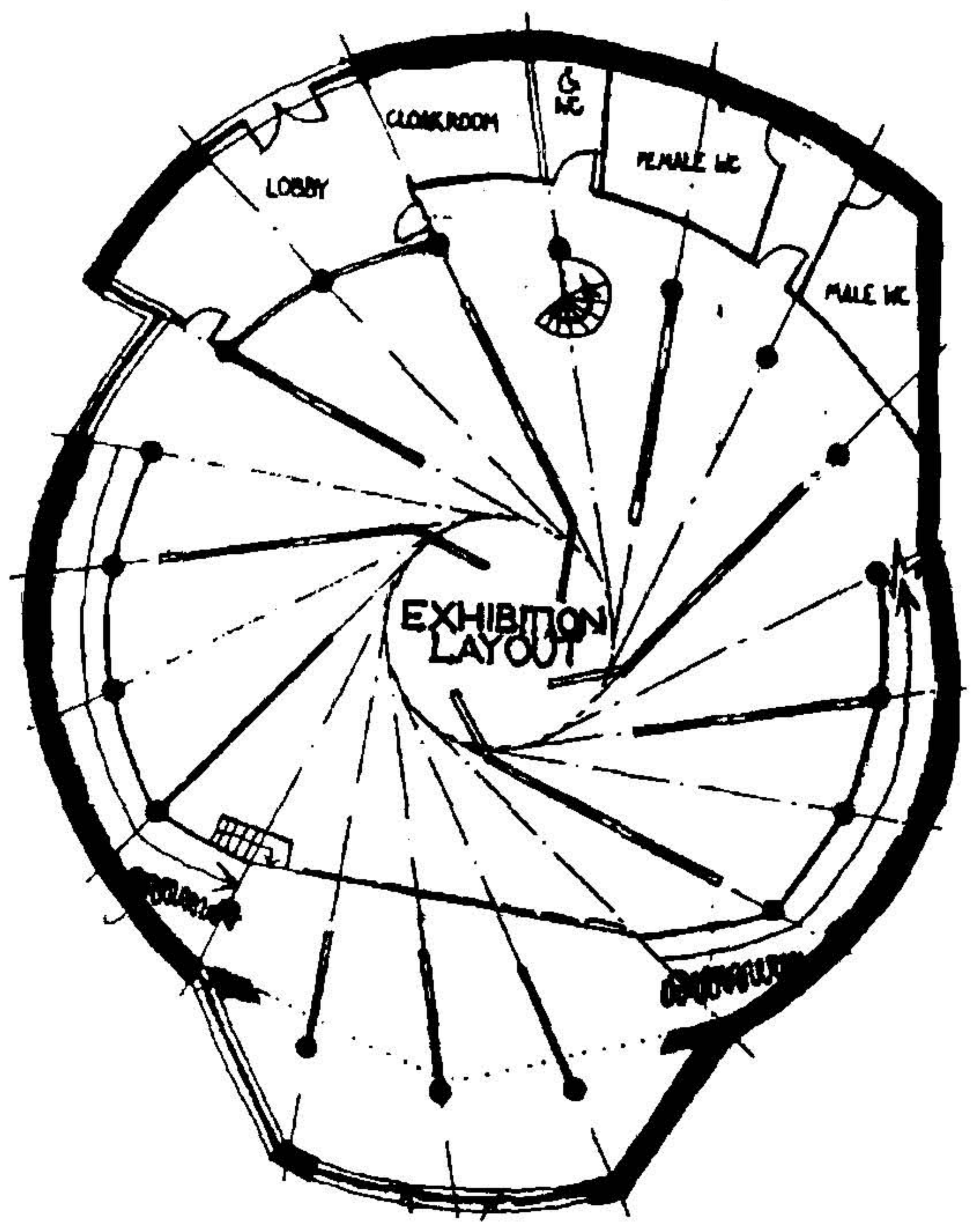


Figure 5.2 a

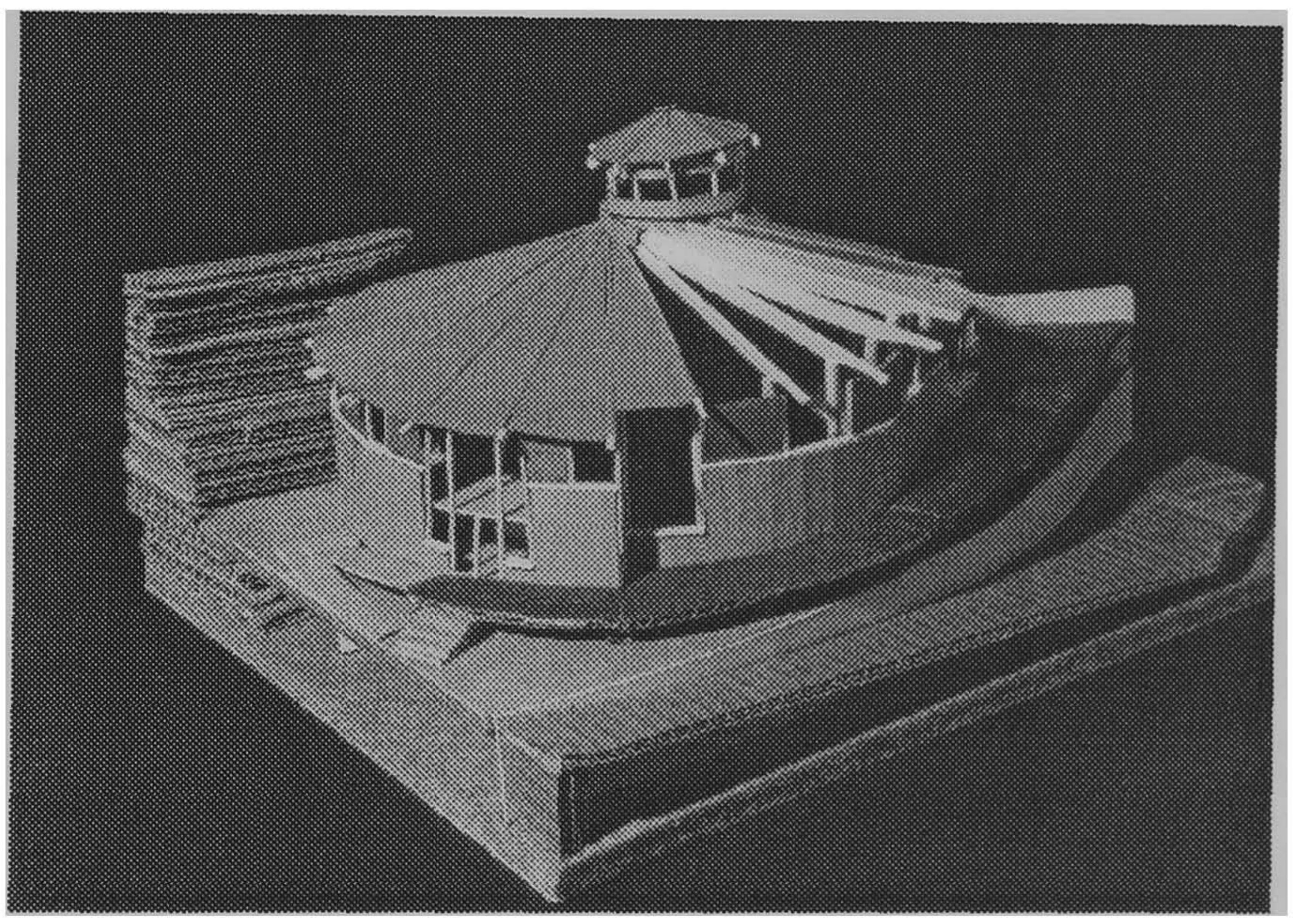


Figure 5.2 b

Conventional solid glulam members, mutually supporting and, joined with notches, are used. The only novelty in this case is that the RF beams have a significantly smaller cross sections towards their outer ends, where they are cantilevered to form the eaves. Although the span is probably on the verge of being too long for solid beams, the idea of having beams with varying depth depending on the bending moment and shear force that have to be resisted is definitely something worth exploring.

Figures 5.3 a,b,c, 5.4 a,b,c, and 5.5 a. and b. all use the RF to accommodate a polygonal plan form. While the examples presented on Figures 5.3 a,b,c and 5.4 a,b,c use a RF to roof only the main hall, in the example presented on Figures 5.5 a,b,c the structure covers the whole building.

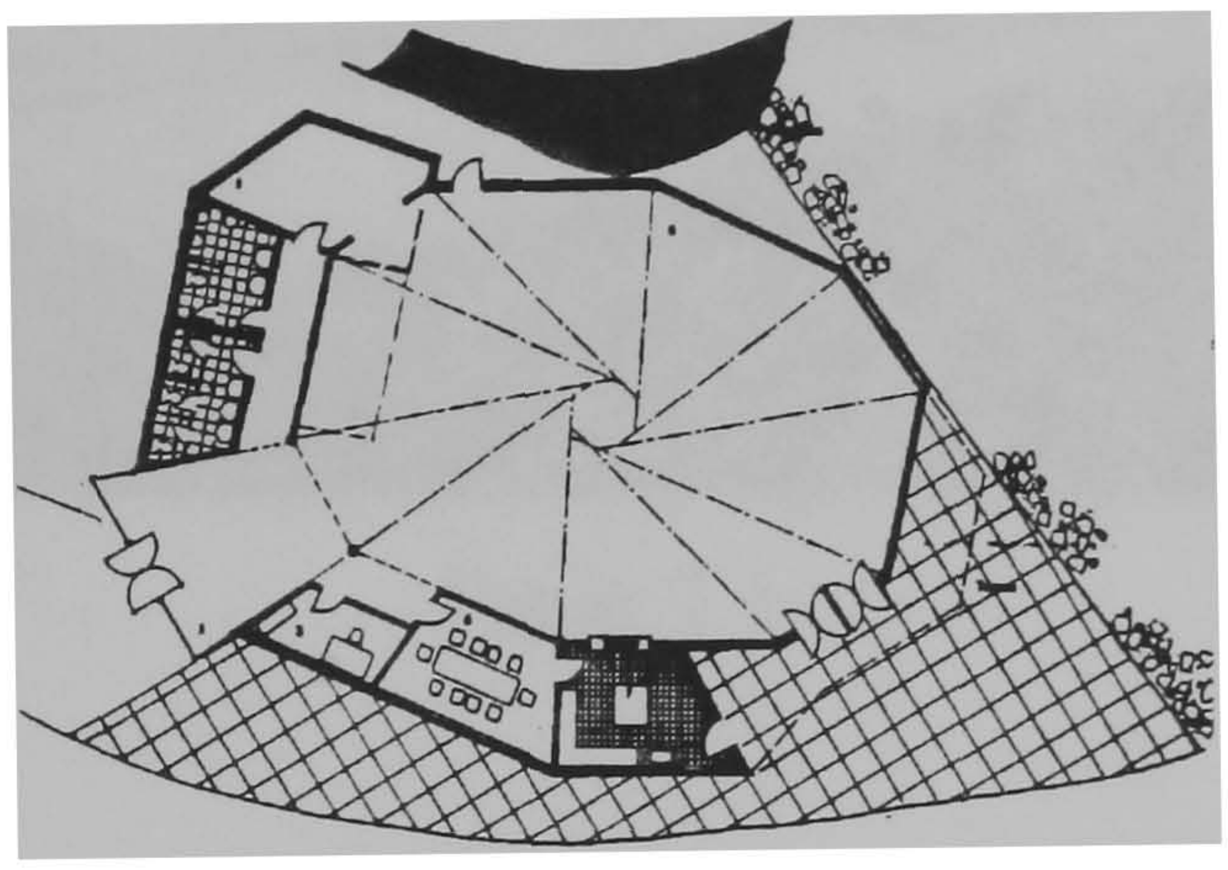
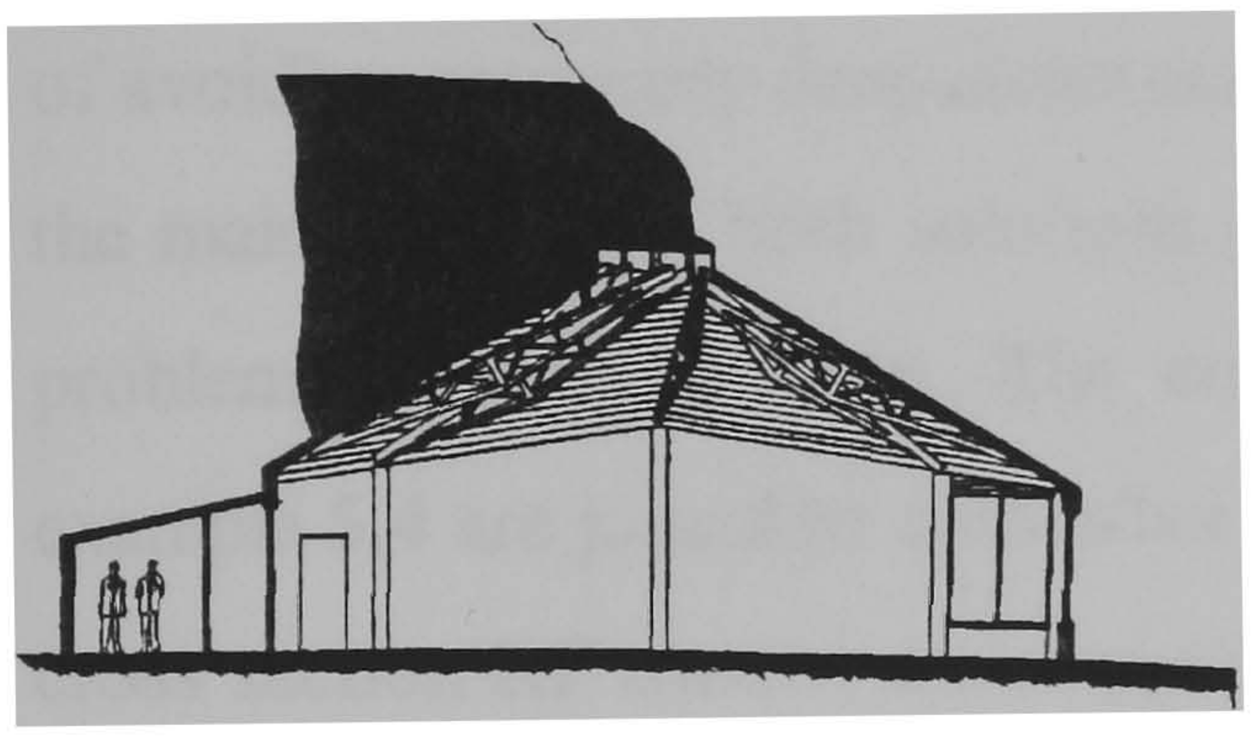
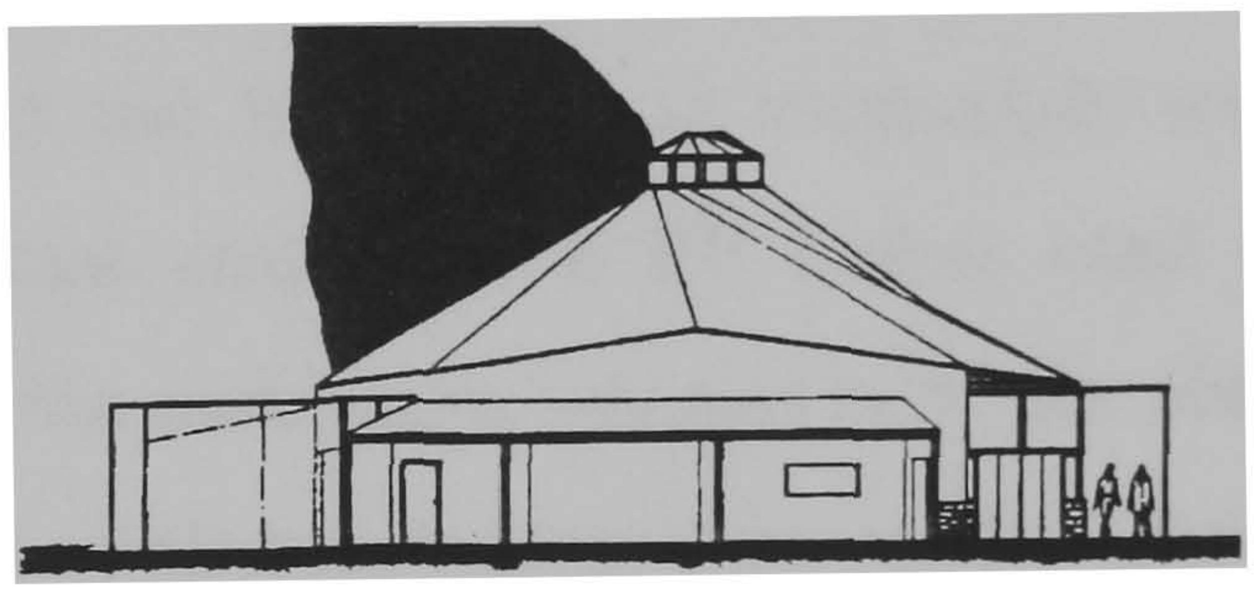


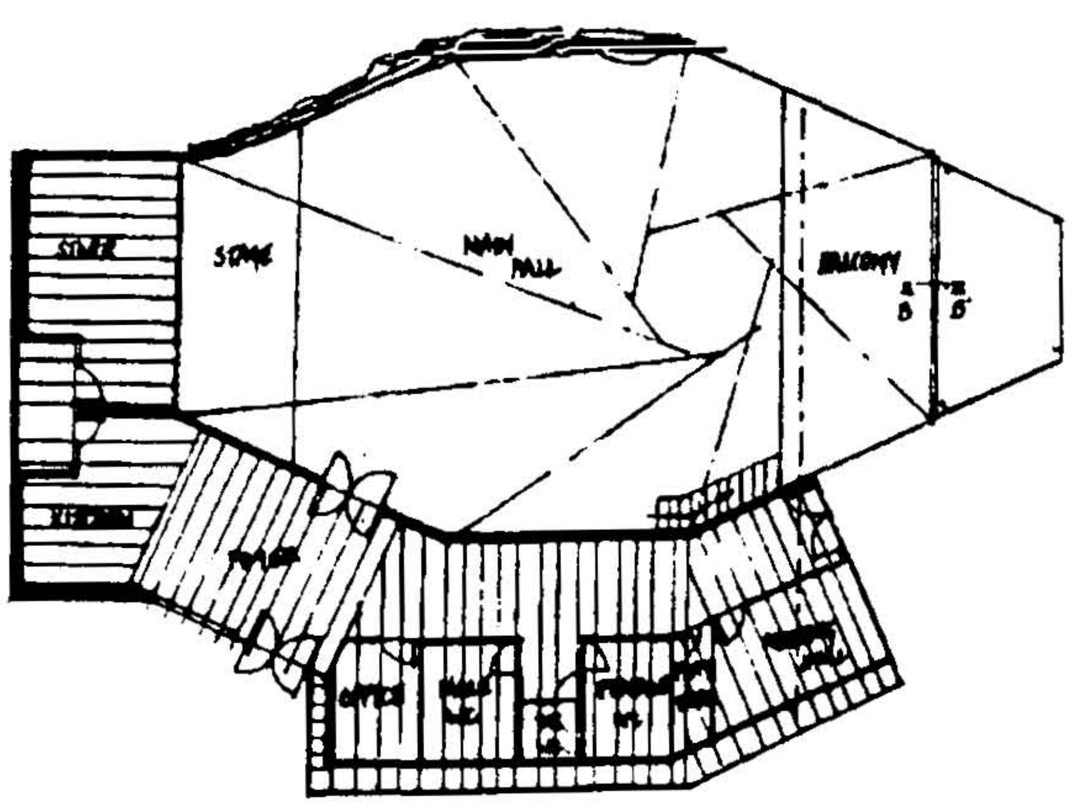
Figure 5.3 a

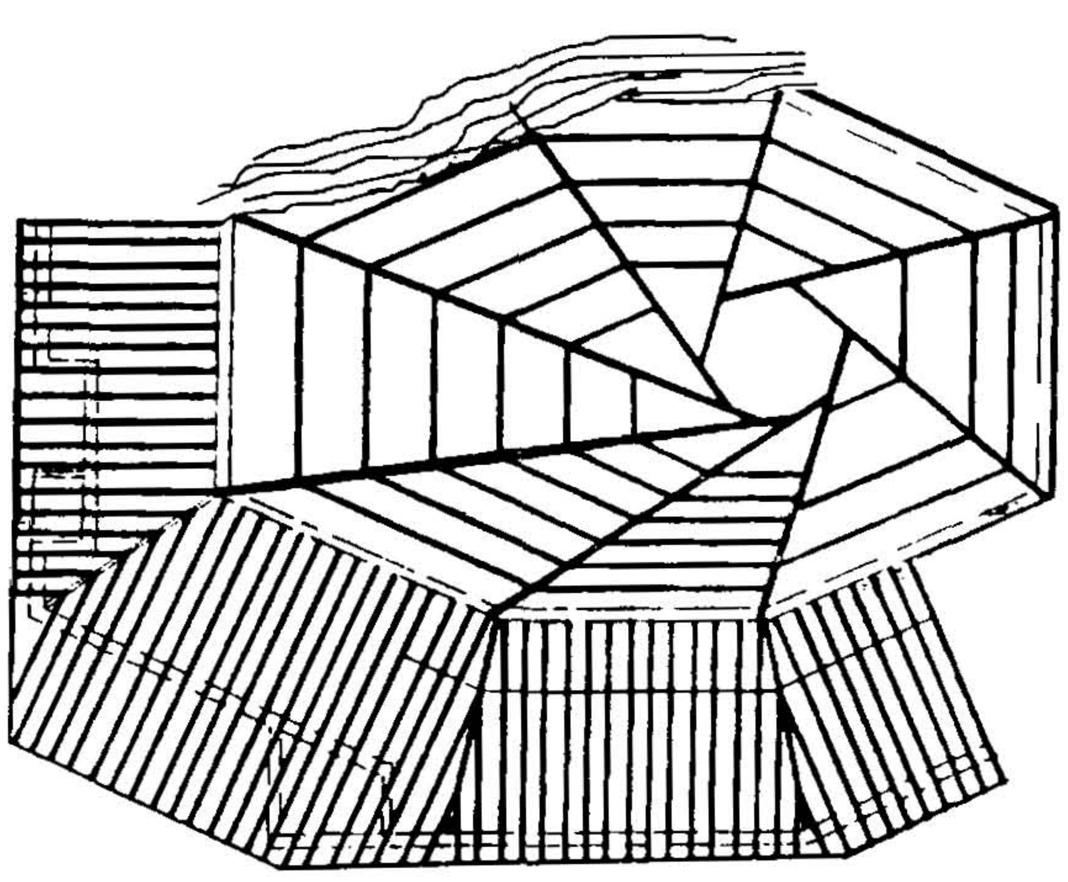




Figures 5.3 b and 5.3 c

Solutions 5.3 and 5.4 are very similar, both using a RF to accommodate an irregular, but symmetrical polygon, and having trusses as main structural elements. Also the main idea in organisation of the plan in both solutions is similar, having the ancillary spaces arranged round half of the perimeter of the main hall.





Figures 5.4 a and 5.4 b

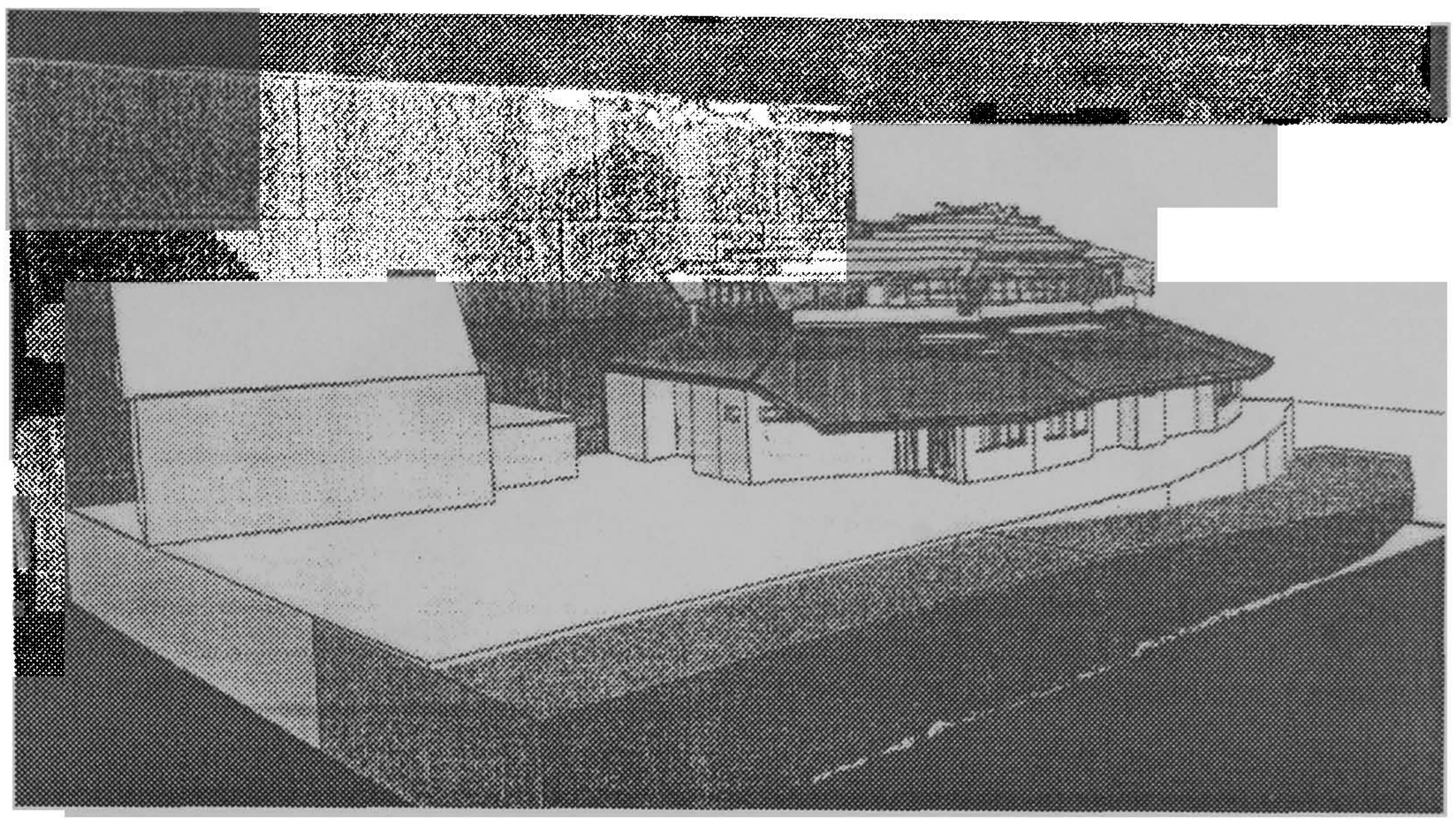


Figure 5.4 c

One of the main differences is that in the solution 5.4 the inner polygon is offset, thus the roof light is offset towards one side, whereas in 5.3 it is central. In terms of avoiding extremely deep structural elements (as a result of the use of trusses for the main members), both solutions (5.3 and 5.4) have dealt successfully with the problem in different ways. The constant cross section RF trusses used in the example 5.4 are joined to each other in the same plane, whereas in 5.3 the changing cross section RF trusses are connected so that each truss rests on the subsequent truss, done in the manner similar to notching of beams. Both solutions can be equally successful if the cross sections are designed to have sufficient load bearing capacity. Unfortunately, the students drawings do not include details of the joints. Probably this exploration is beyond their current level of knowledge and the time available for the project.

The RF structure in example 5.5 encloses the whole building. The RF beams over the main hall, accommodated in a more or less regular dodecagon, are extended to have different lengths in order to accommodate the secondary spaces. The effect is a very sophisticated spiralling form. The RF morphology of the structure, and the building as a whole, are in this case inseparable, which is one of the main qualities of the architectural concept of this solution.

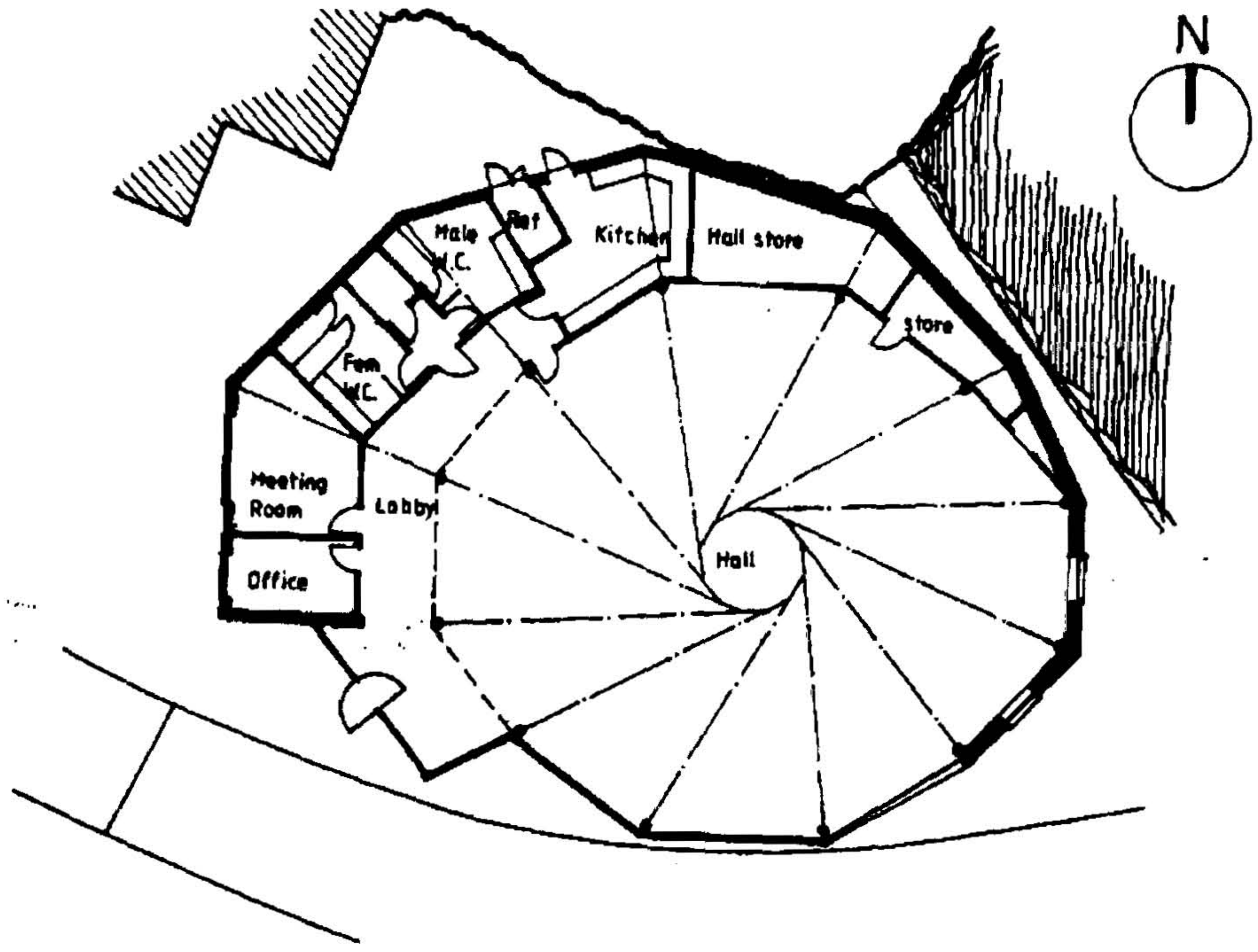


Figure 5.5 a

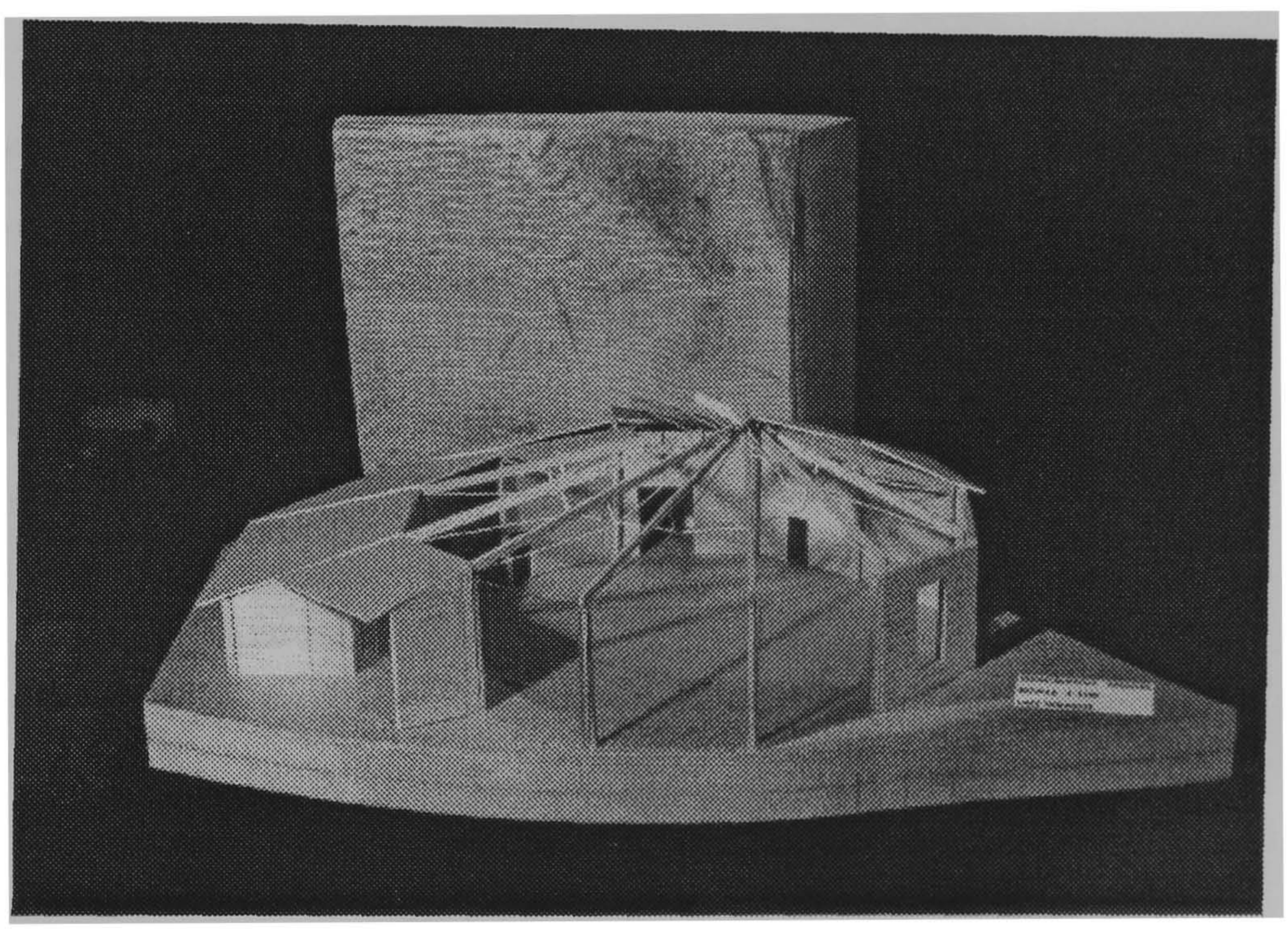
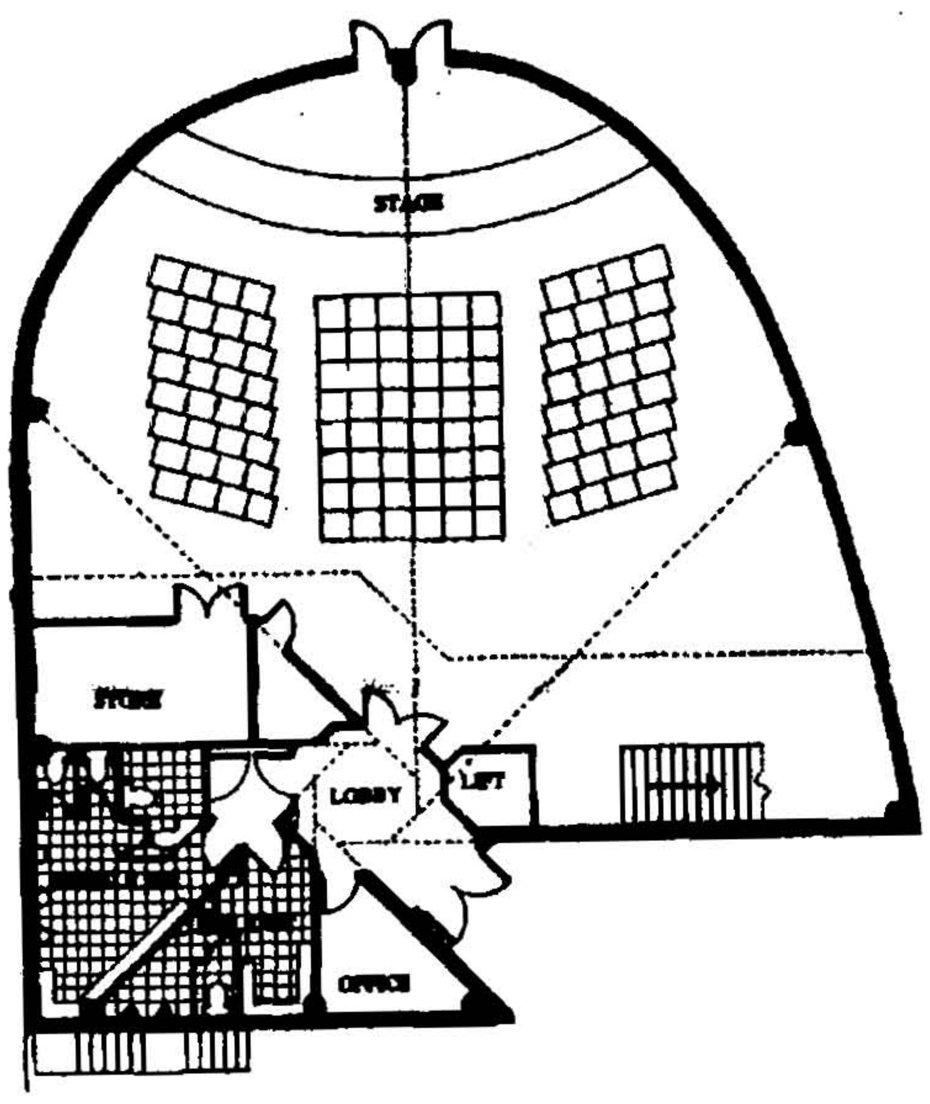


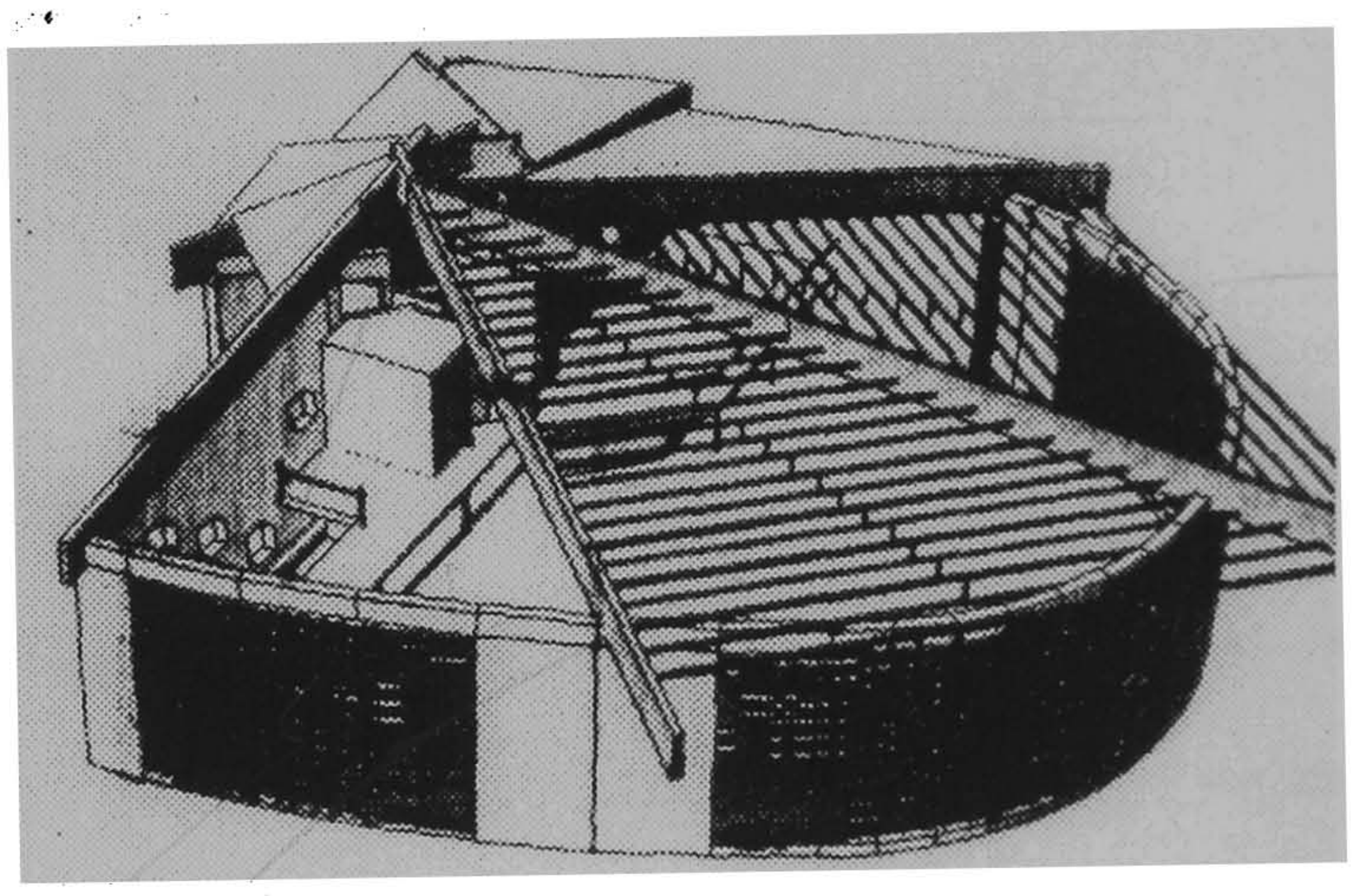
Figure 5.5 b

In terms of the structure, itself, bow-string glulam beams are used which make the structure much more efficient. As a result, the beam cross sections are much smaller, than if conventional glulam beams were used and this gives a sense of lightness to the building. Altogether, this is a very successful application of the structural system. It is interesting to note that this scheme was marked with an "A", reflecting the marking panel of architects' appreciation of the universal approach in the production of architecture. It is perhaps a reflection that good design is always recognised whatever the morphology or technology used to support it.

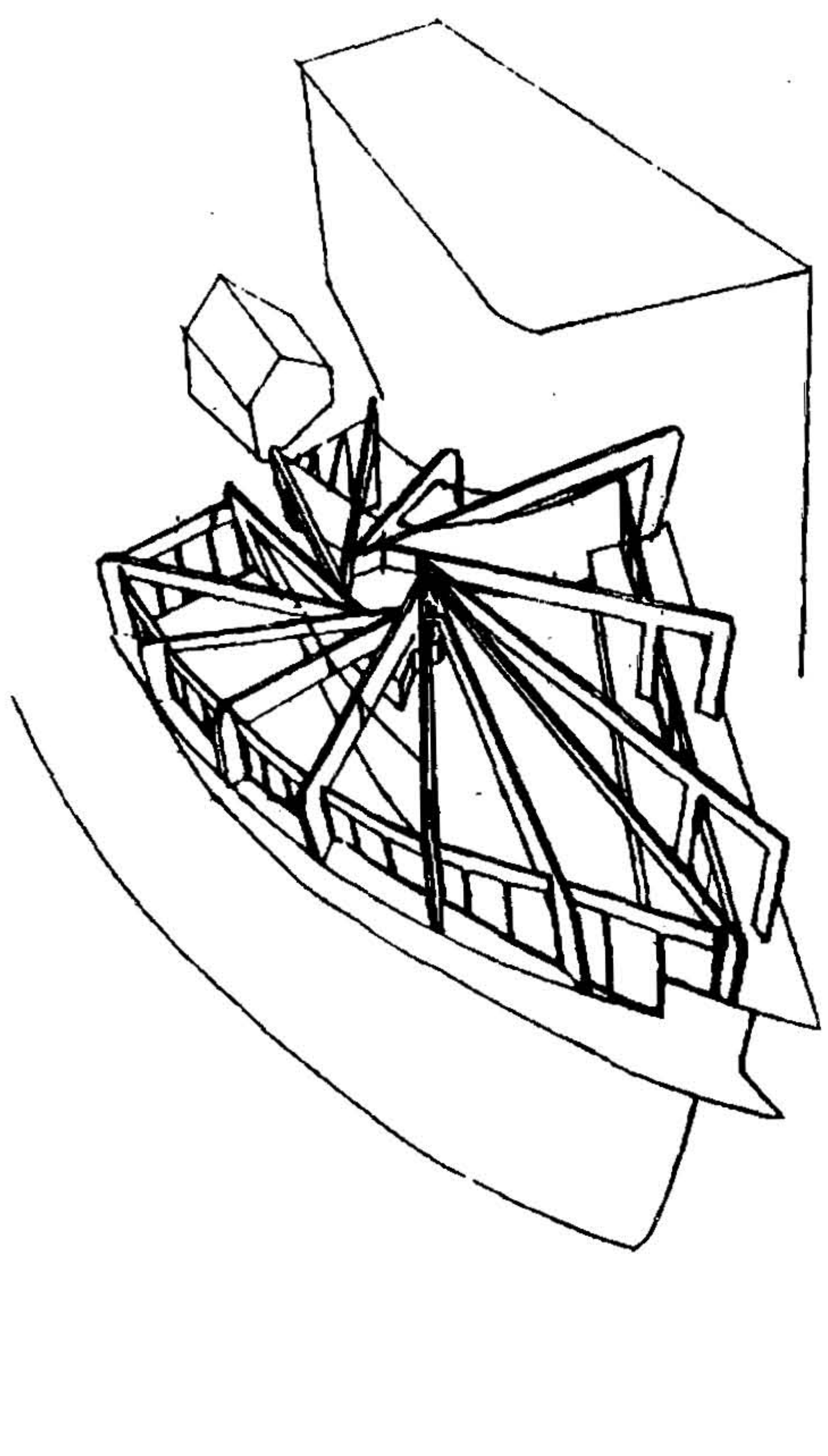
Examples 5.6 and 5.7 both use single RF units over an irregular plan form. In both cases the whole building is covered by a single RF unit. They are constructed of glulam beams, connected in the same plane which, in the example 5.7 seem far too long and slender, whereas, in example 5.6, the roof segments seem far too big. In both cases it is not very certain that the structure as proposed would work in terms of load transmissions.

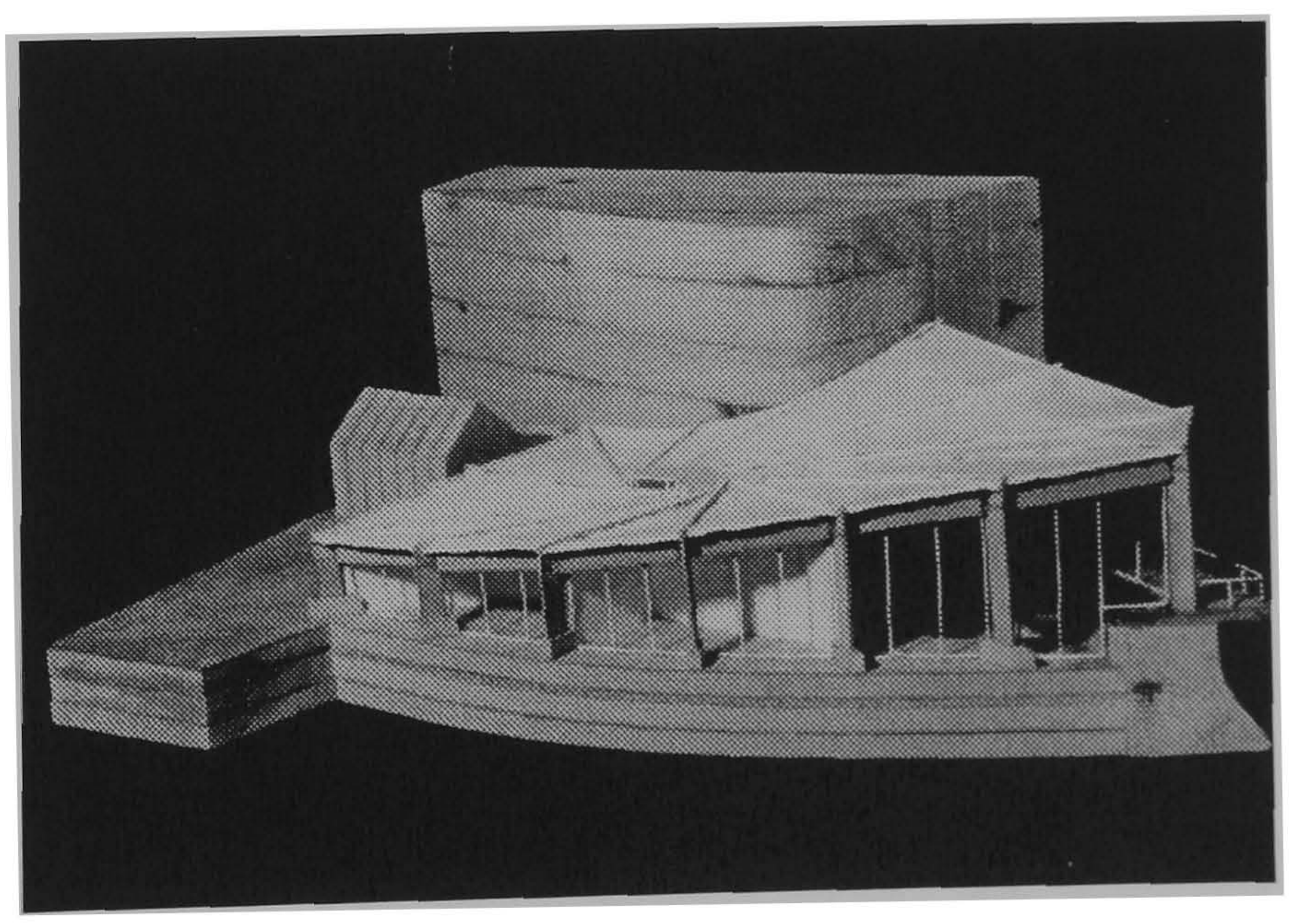
In case 5.7 it probably would have been a better idea if trusses had been used, or if the beams had had deeper cross sections. In case 5.6 it would be necessary to make the roof segments smaller by using more beams or inserting some other secondary structure. Also, for 5.6 with such a small central polygon the shear forces in the beams at the intersection would be very high.





Figures 5.6 a and 5.6 b





Figures 5.7 a and 5.7 b

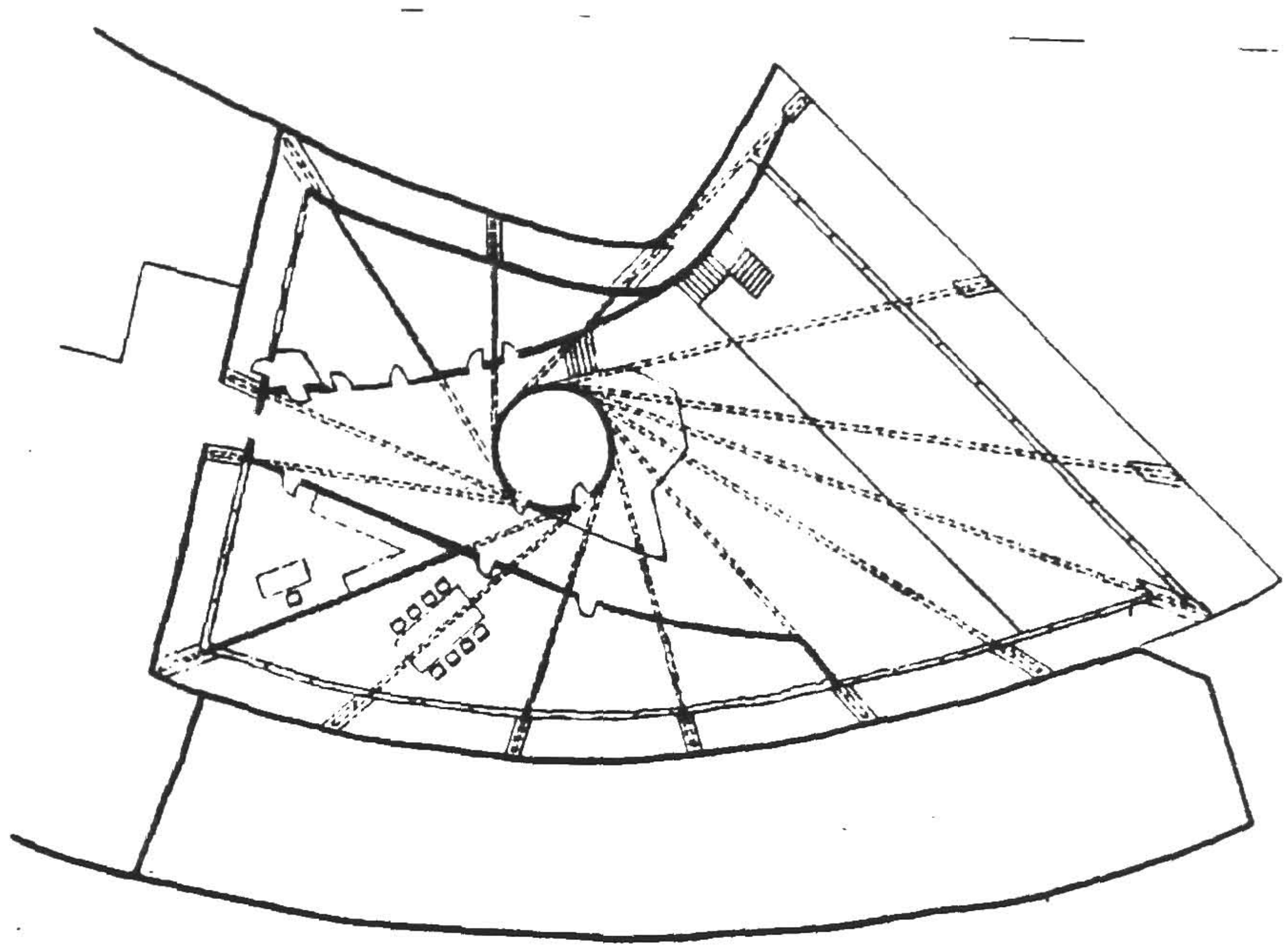


Figure 5.7 c

It is interesting to note that the structures sheet for example 5.7 was redone because the student had initially thought that it would be necessary to use a circular masonry core to support the inner beam ends. However, as the RF beams are mutually supporting, and the central core was not a structural necessity it was omitted from his final design.

The main quality of both examples is that they show that it is possible to use the RF to accommodate a completely irregular plan form. However, they have not dealt with the problem in the most appropriate way, because they try to use timber beams for the RF beyond their structural limitations.

5.2.1.2. Two or more RF units

A number of students found a solution to their design assignment in the use of two or more RF structures for their building. The main hall and the secondary spaces were housed in separate RF units, within the same building. In terms of the structural application of the RF this group could be included as part of the previous group of examples, or a subgroup, because there is no difference in terms of structural behaviour between the groups. However, architecturally the achieved expression of the two groups is significantly different, thus they are presented in a separate group.

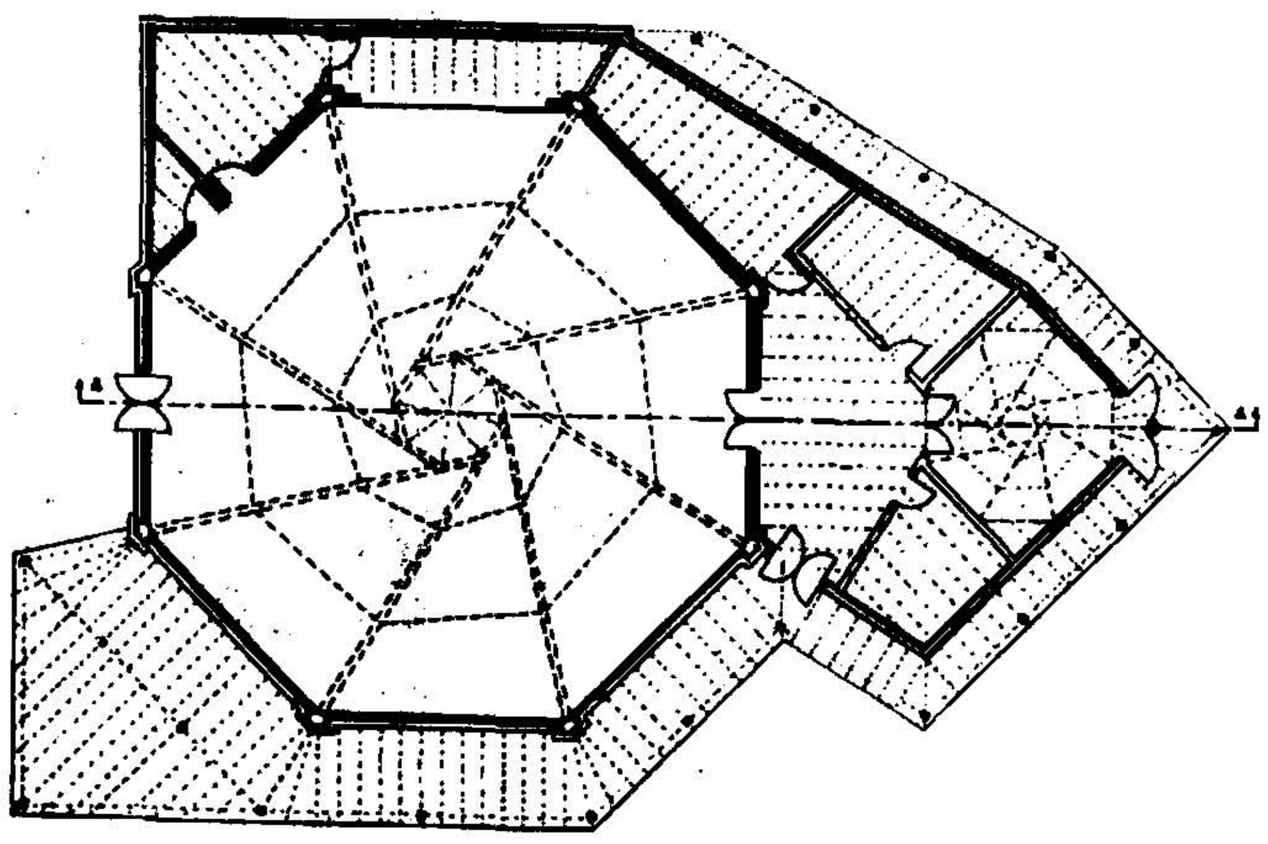


Figure 5.8 a

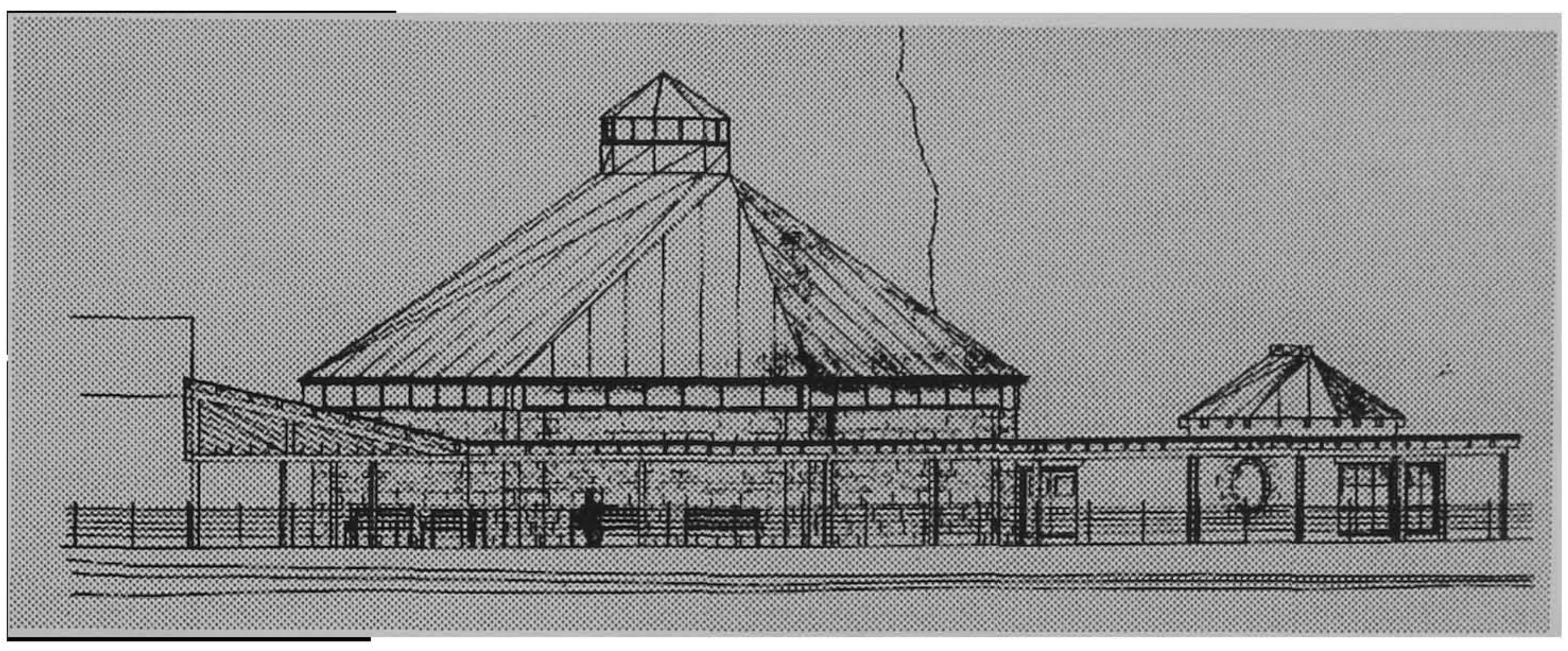
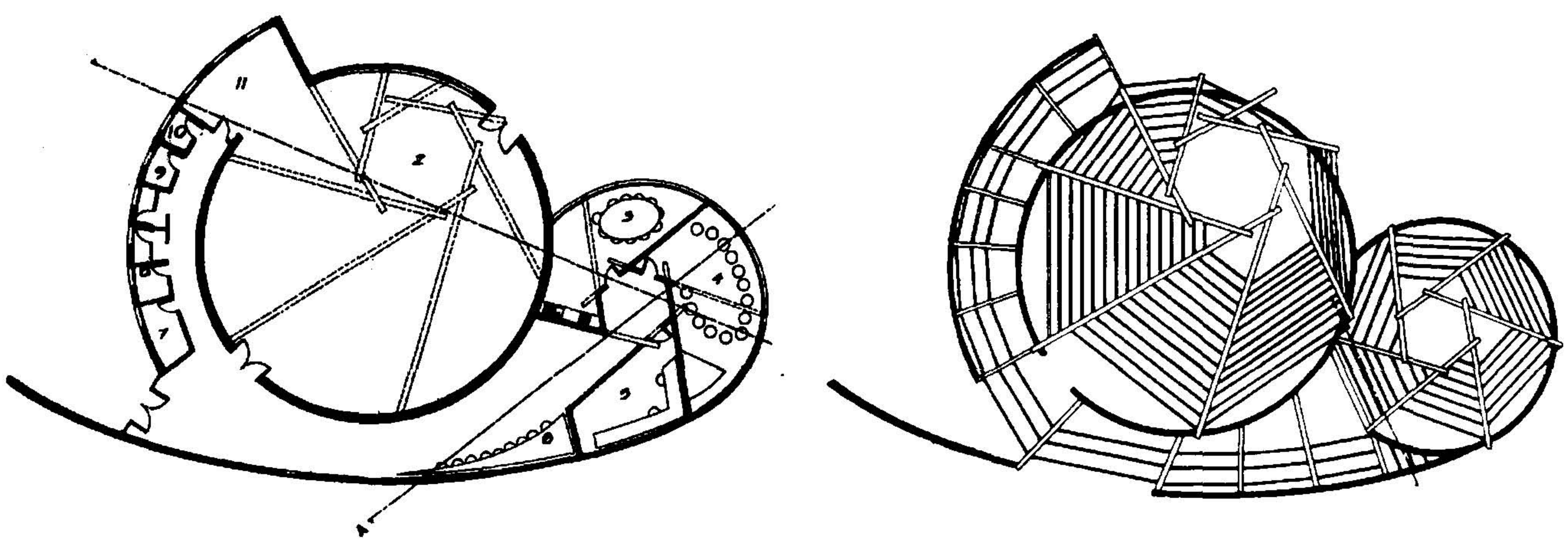


Figure 5.8 b

In example 5.8, two separate RF units are used, both roofing regular octagons in plan, the bigger one over the main hall and the smaller one over the meeting room. Similarly, in example 5.9, the two RFs are accommodating circular plan forms, the bigger one being placed over the main hall and a smaller one over the secondary spaces. The composition in this example is very successful, having a wall rolling round and creating the spiralling effect. Example 5.10 uses 3 RF structures, two small ones and a big one to form a very organic "fairy tale - like" type of building.



Figures 5.9 a and 5.9 b

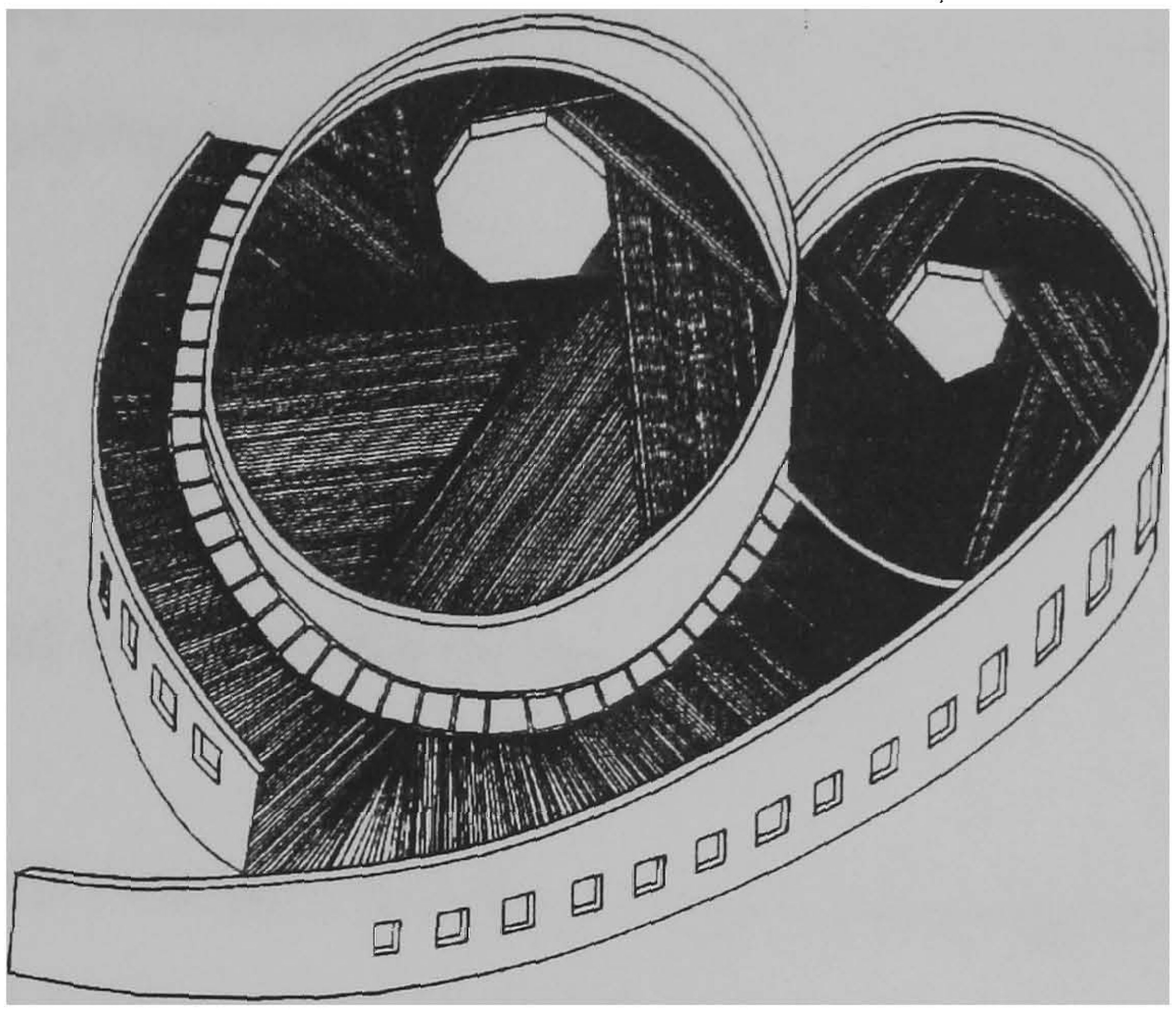
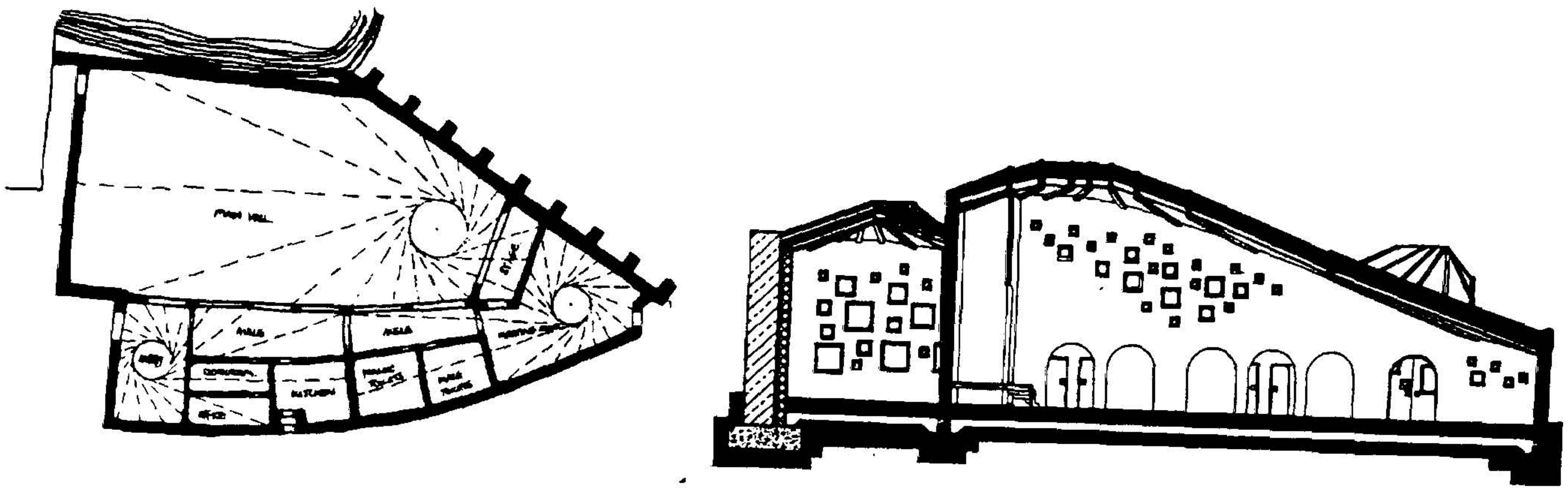


Figure 5.9 c



Figures 5.10 a and 5.10 b

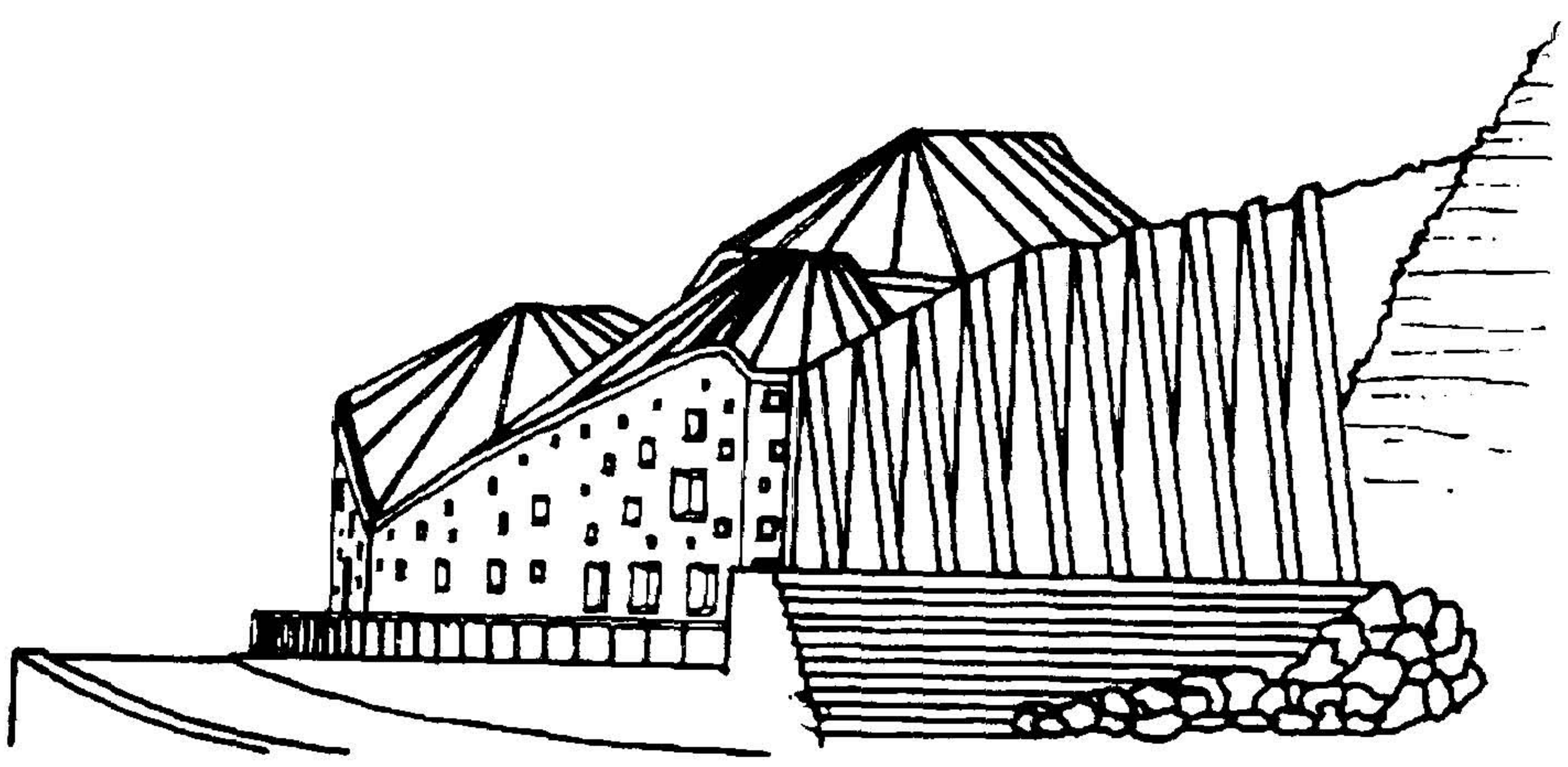


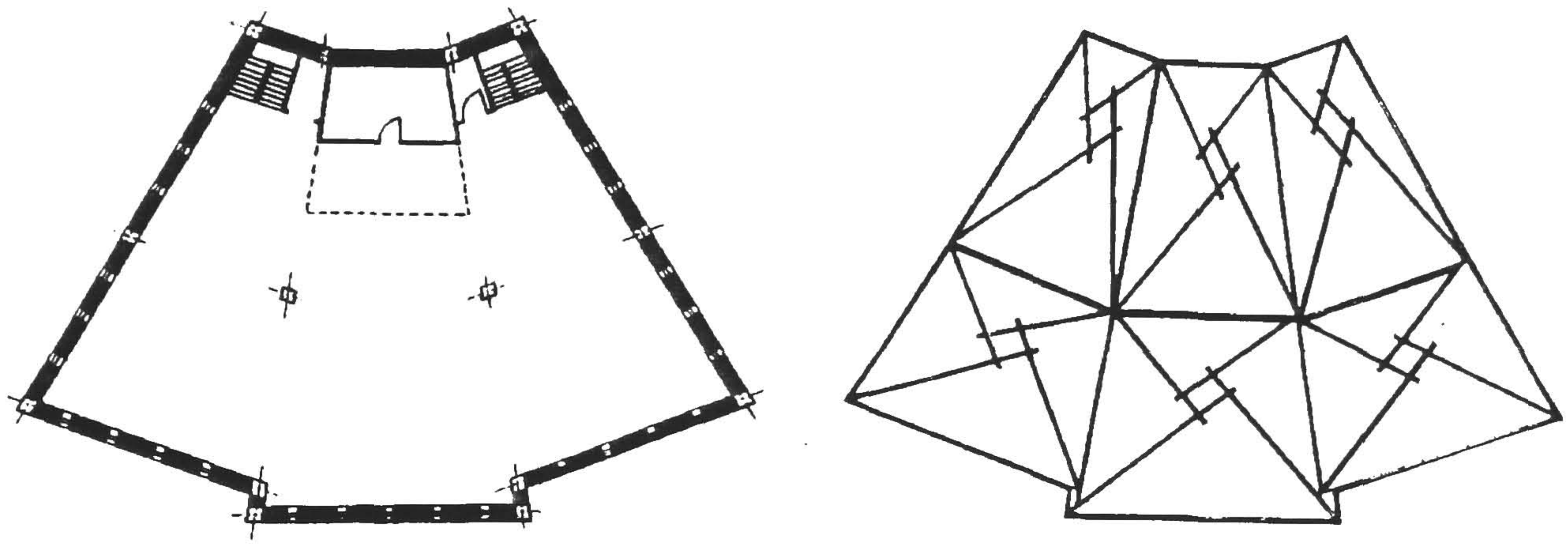
Figure 5.10 c

All three examples, although using the same RF structural system, create very different buildings, each with a very specific and unique expression. In some of them the lengths and cross sections of the RF members are unrealistic as proposed, but the configurations could be realised with structural elements of adequate size.

Nevertheless, all three examples have their main value in highlighting completely different ways of applying the RF.

5.2.1.3. Multiple and complex RF units

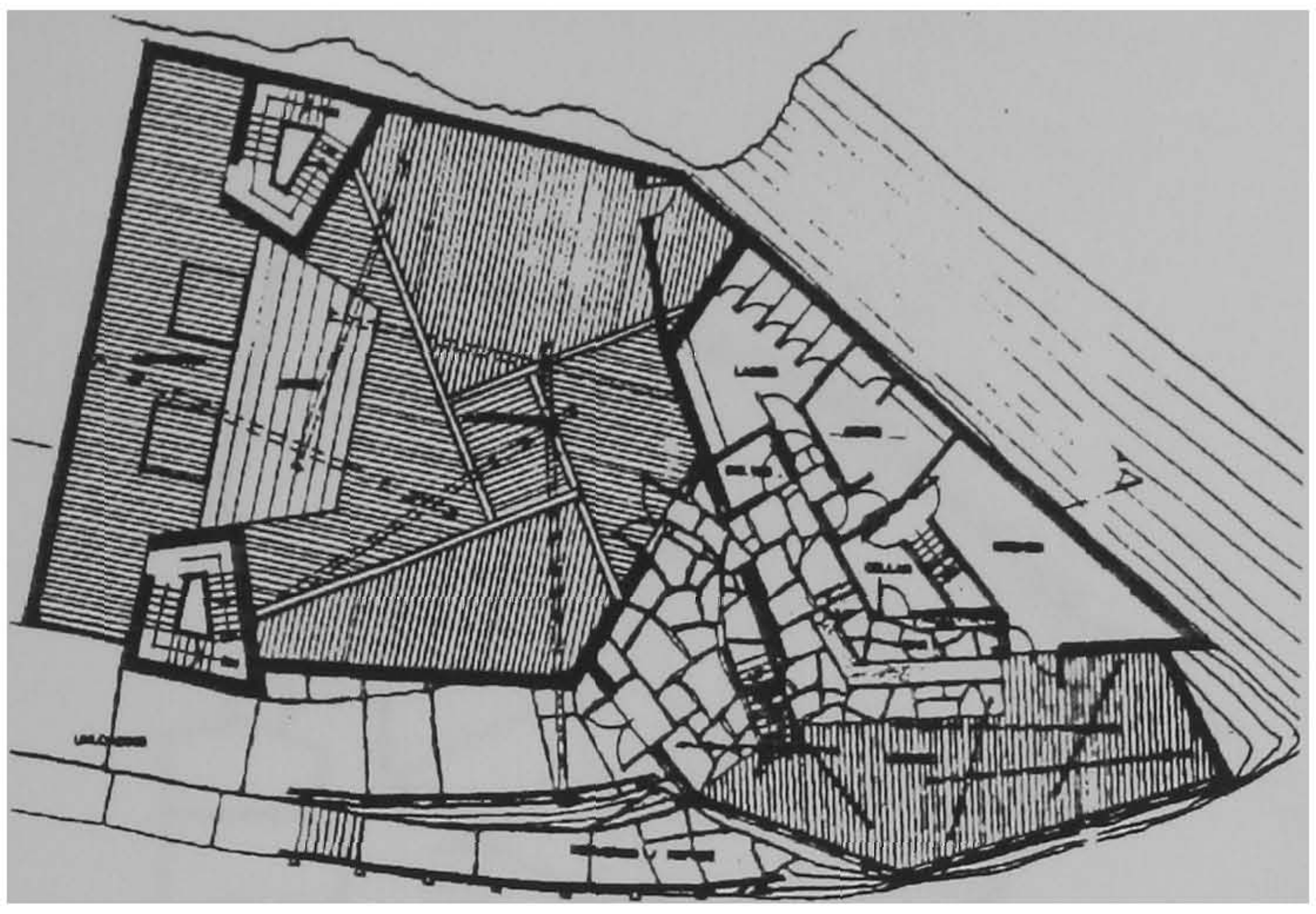
The third group of RF examples are the multiple and complex RF units. They are presented on Figures 5.11, 5.12, 5.13 and 5.14.

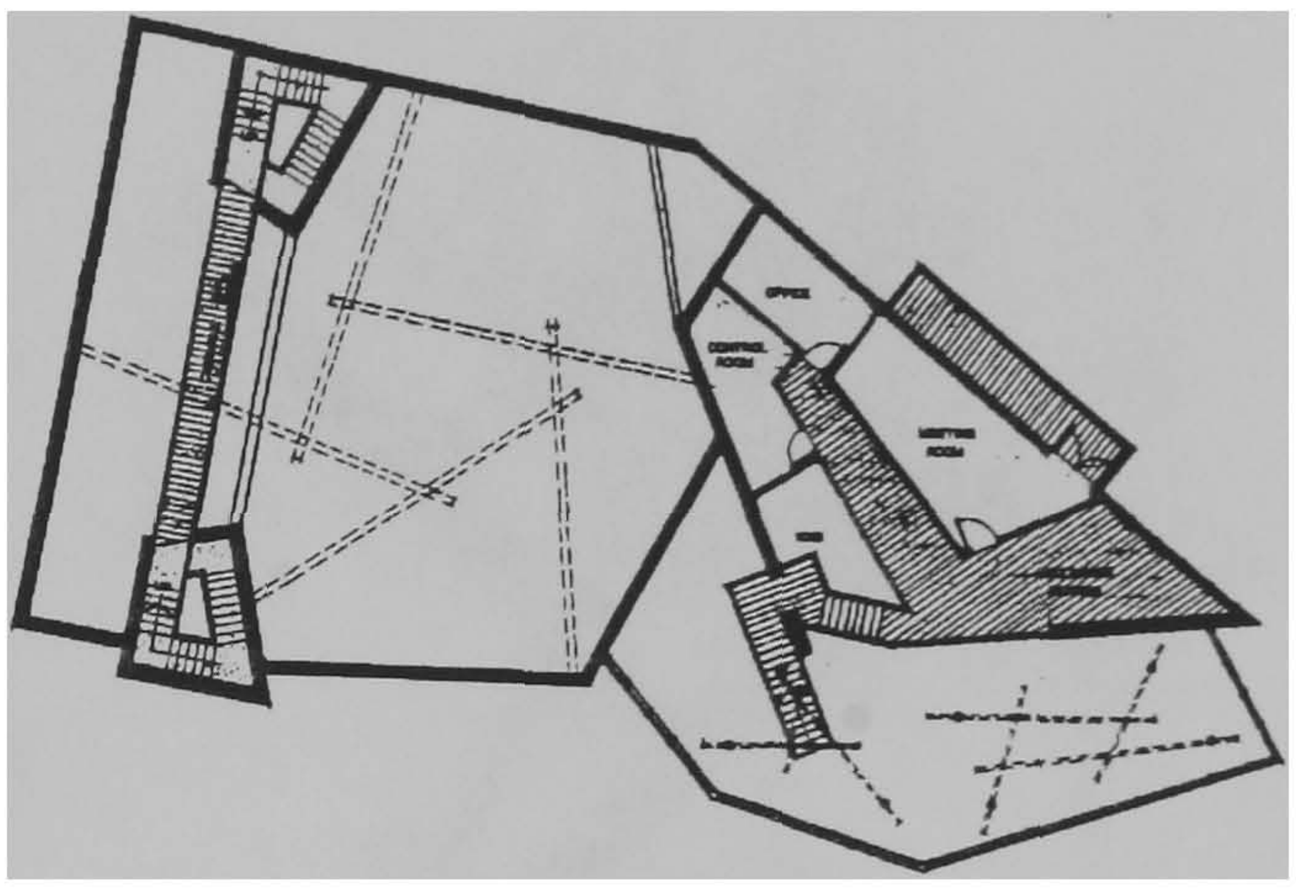


Figures 5.11 a and 5.11 b

In example 5.11, six single, four beam RF units are used to form the roof. Although the form of the building is more than pleasing, the main disadvantage of this solution is that there are internal supports (columns) which obstruct the function of the hall, in that the duality of the view for all the spectators fluctuates. However, this solution, or a similar one, could be very successfully applied in conditions where having columns in the space is not a problem, or having the RFs supported on major trusses or hung from masts and cables.

Compared to example 5.11, the example 5.12 seems, and actually is, much more complicated. When one looks at the plans, both ground and first floor, there seem to be RFs everywhere. They are all irregular and accommodate an even more irregular plan form. And when one looks at the cross section the confusion is even greater.





Figures 5.12 a and 5.12 b

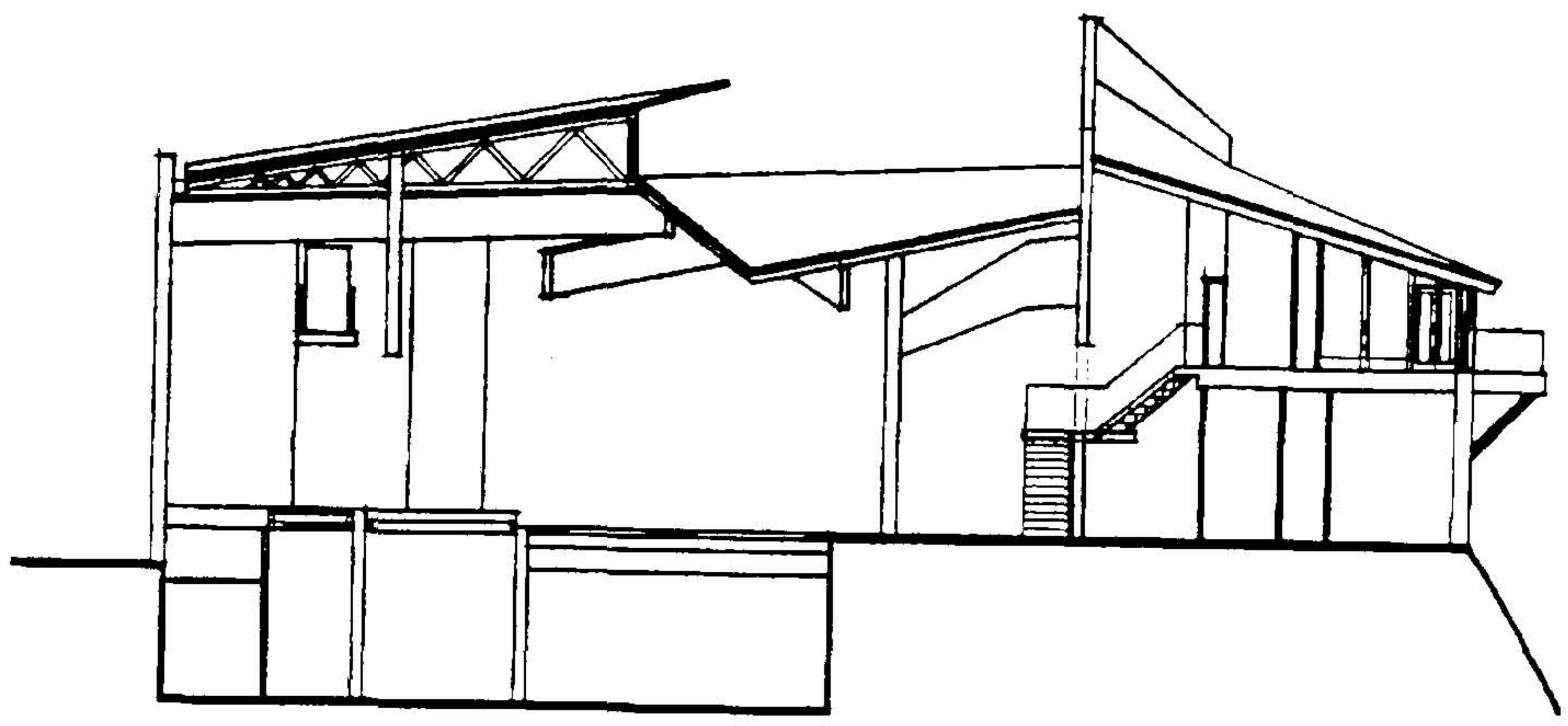
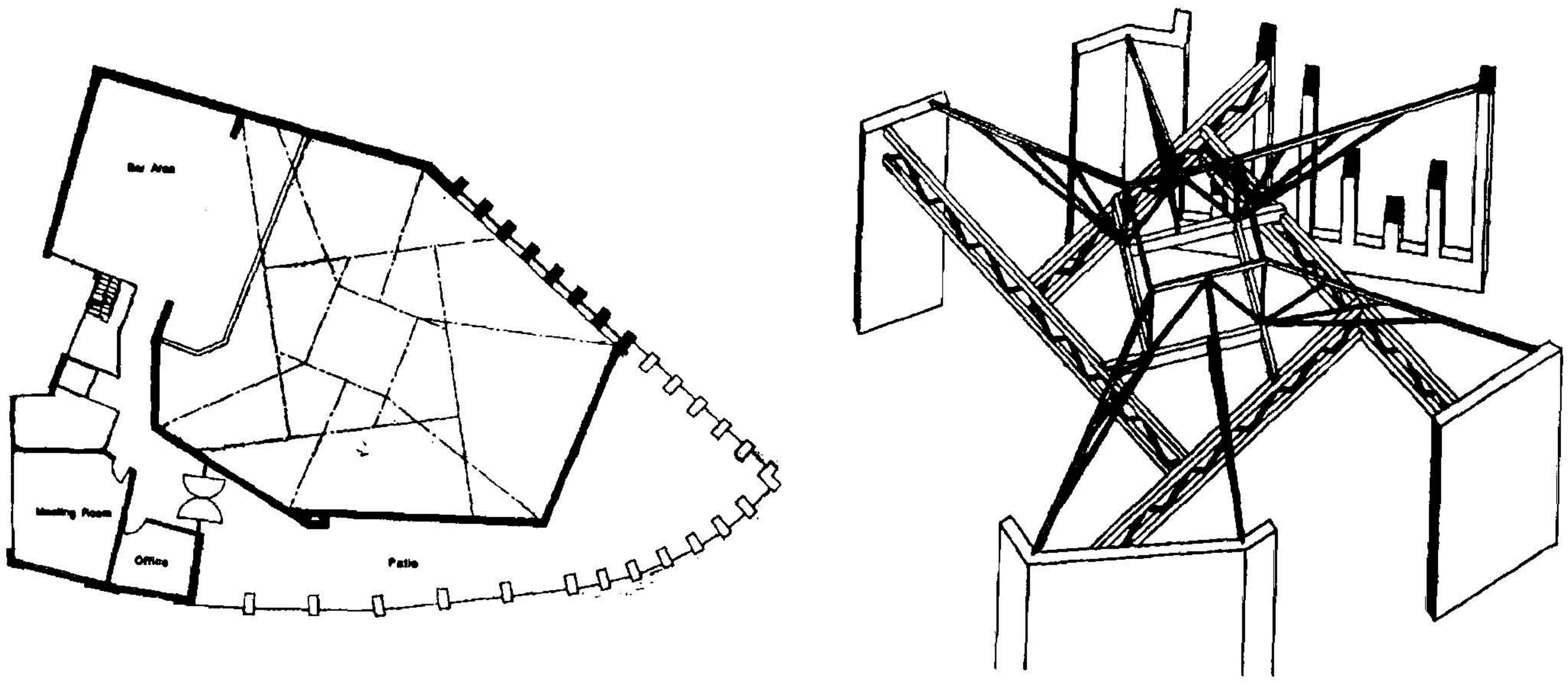


Figure 5.12 c

Some of the RF members are trusses and some of them are solid glulam beams which support trusses. The roof is very complex and slopes in all sorts of directions. It is very uncertain if some of the RFs would work if applied in this way, because some of the members do not have supports at their outer ends. For the other RFs it would be necessary to see how efficient they would be, as some of the beams/trusses may have to be quite deep. However, the building as whole is quite interesting because it creates a special architectural expression (discussed in section 5.2.2.2). The main quality of this example is that it shows that there is room for research in complex RF applications.



Figures 5.13 a and 5.13 b

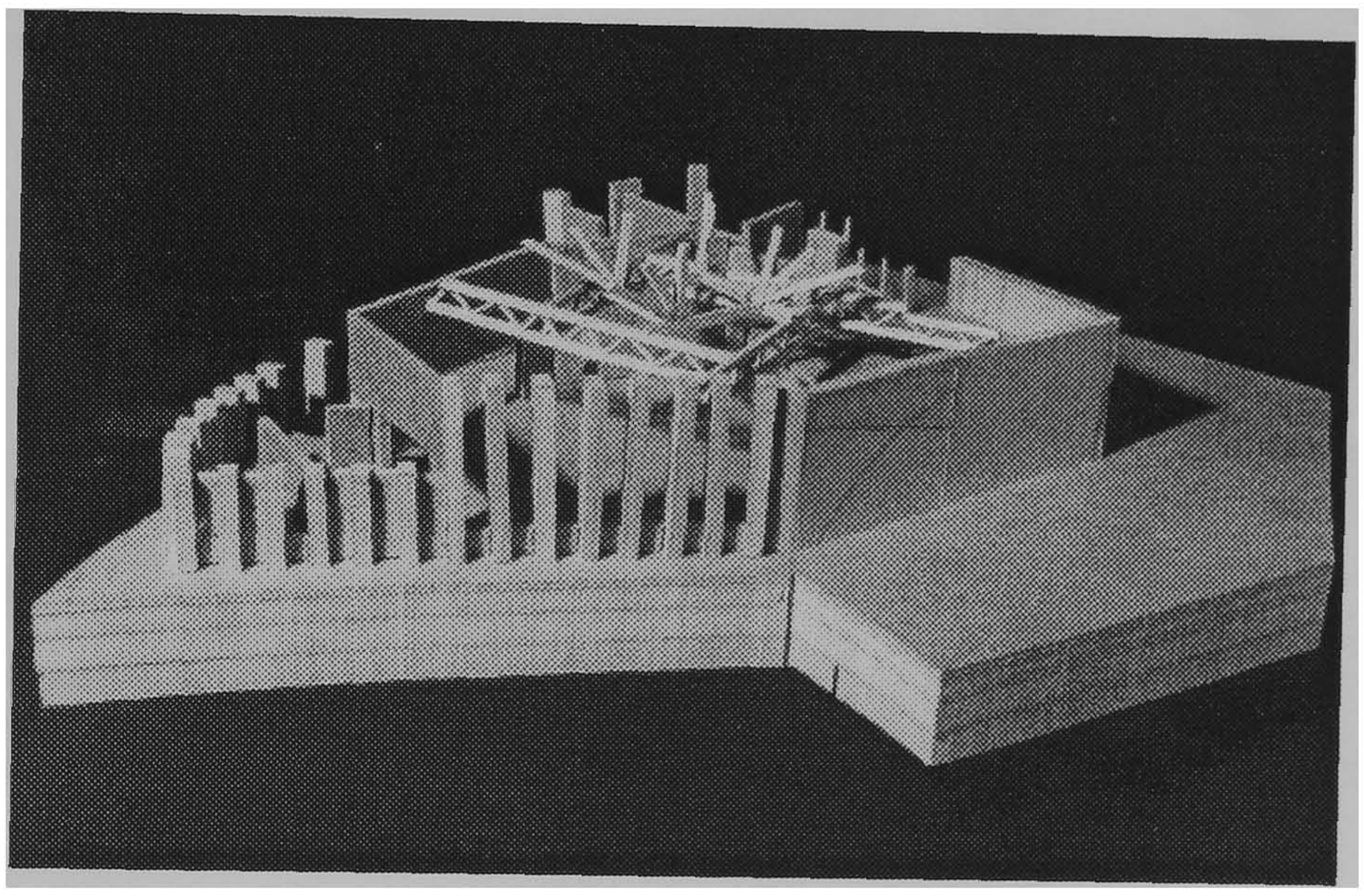
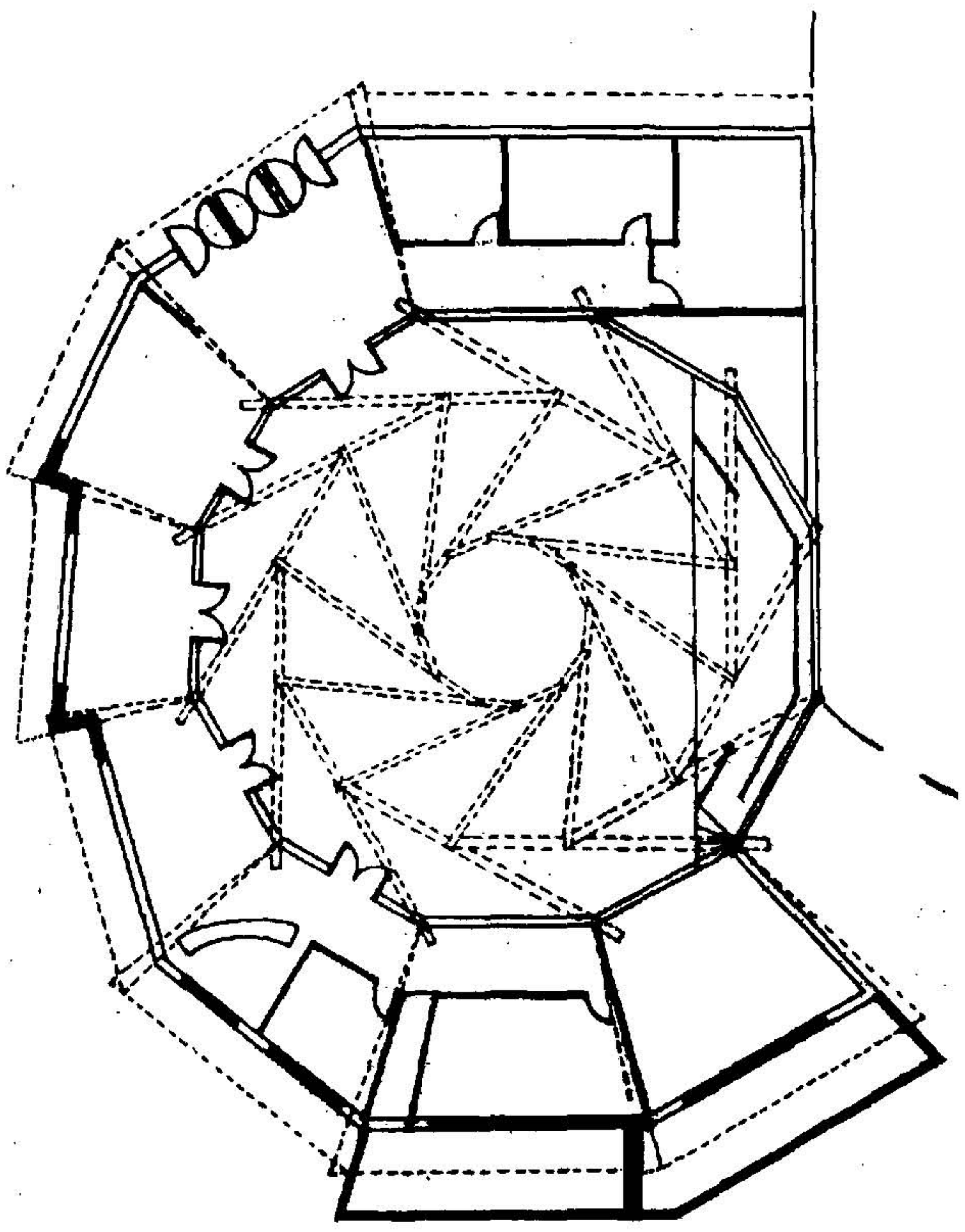
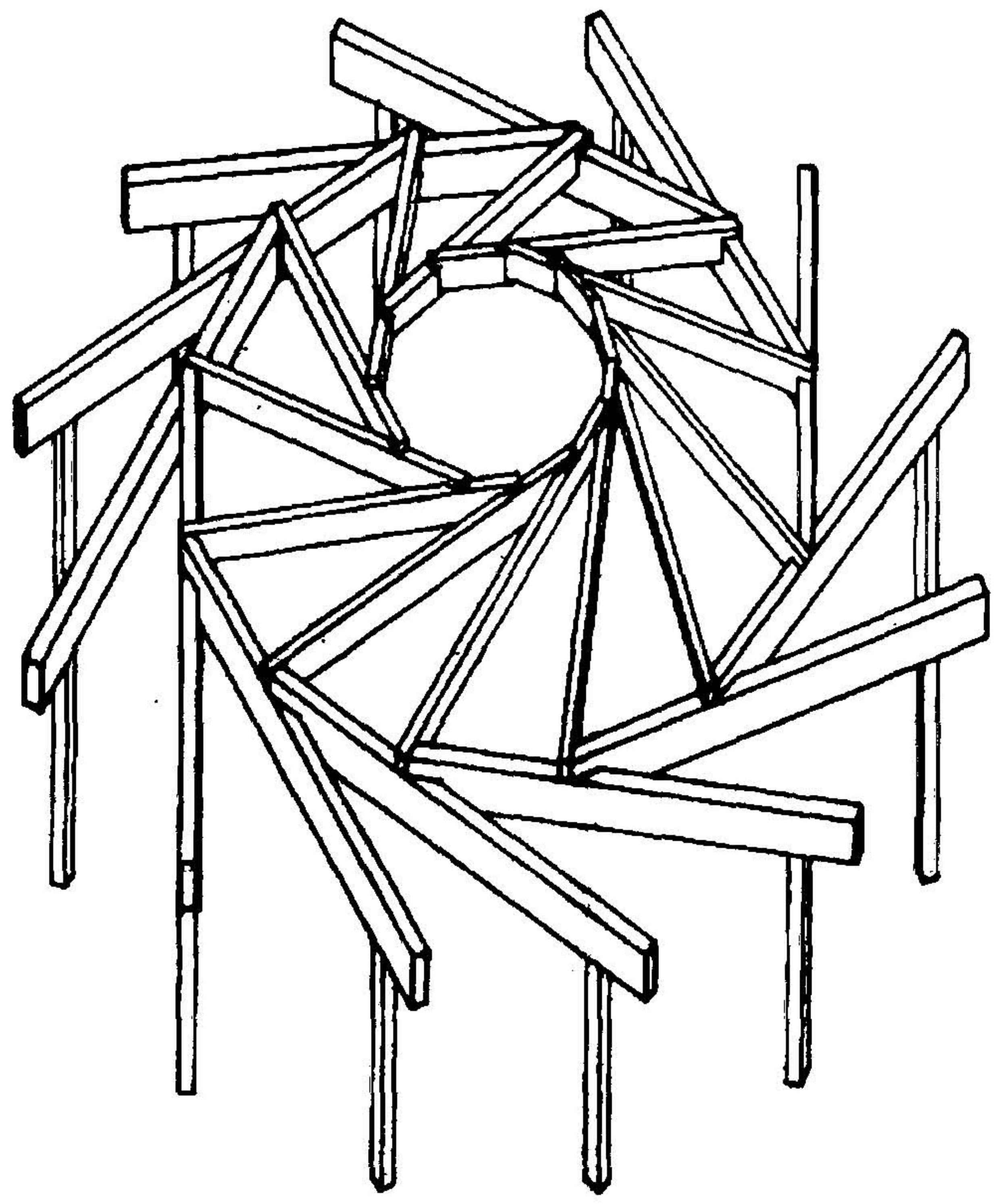


Figure 5.13 c

Example 5.13 is another complex application of the RF. A four sided regular RF truss structure supports another, again regular, but rotated RF structure, which supports six trusses placed over the second RF (see Figure 5.13 b). The idea is very confusing and overstructured. It would have been a better idea to have sloping trusses as main RF members, or not to have them at all and have a flat RF roof structure.

The last example in this group is shown in figure 5.14. This multiple RF structure is very similar in terms of the morphology, almost a copy, of the RF structure at the Puppet Theatre in Seiwa (see Chapter 3, page 3-18, Figure 3.14), and so has to be viewed as a successful way of applying of the system. The two RF structures, both spiralling in opposite directions give a very interesting expression to both the interior and exterior of the building as a whole. As a result of the specific use of the RF, the whole building gives an expression of upward spiral movement. Also, when looking at the plan and elevation, the way in which the secondary spaces are attached to the side of the main hall and have different heights, helps to strengthen the spiralling effect.





Figures 5.14 a and 5.14 b

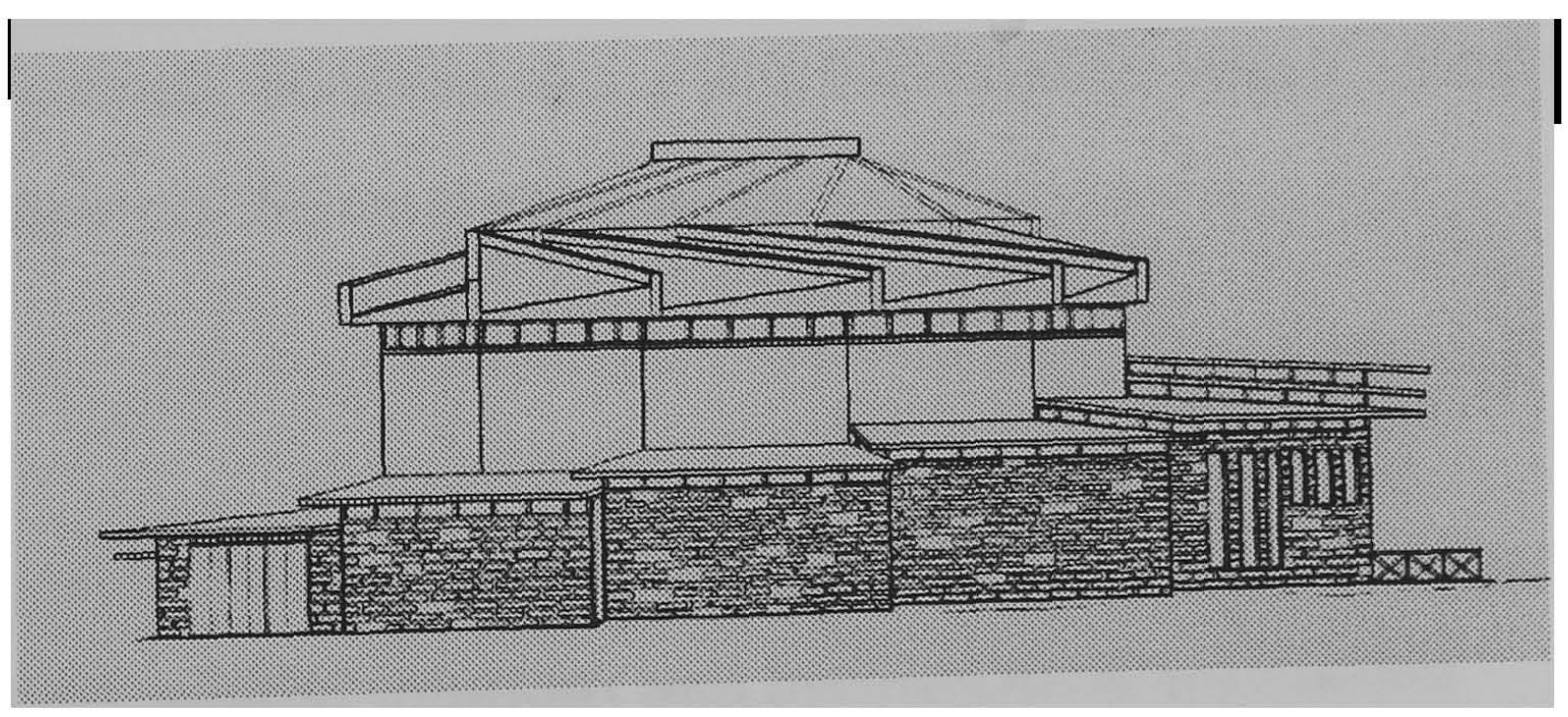


Figure 5.14 c

The main difference between this solution and the Puppet Theatre in Seiwa is in the exterior treatment of the RF roof structure. In the student example the RF is expressed both in the interior and the exterior of the building, whilst in the Japanese example one becomes aware of the RF only in the interior. In the Puppet

Theatre this is achieved by use of conical surfaces. The example 4.14 is an interesting and successful application of the RF.

In terms of further research of the RF morphology, the complex and multiple RF units offer the greatest scope for interesting solutions. Although, they would be more complex to design and construct (geometry, structural analysis, presentation etc.), compared to the single RFs, visually they would be worth exploring. There is no end to the possible combinations and forms that could be achieved by using them, but they would need to be explored from the aspect of buildability, efficiency and cost. This has not been done as part of this project as it was not part of the research programme because of time restrictions.

The single RF units also have a future. They hold out the prospect of very different forms and spatial solutions as well, all of which need to be explored further and on different briefs. At this stage the intention only was, as stated earlier, to explore medium span RFs and their applicability on a given brief. As this is the first and only known research into the RF morphology it was never expected that it will answer all questions. The case study has been designed to highlight the necessary directions for future research.

However, the whole exercise in terms of the RF morphology and different forms that could be created, demonstrates a structural system which offers an indefinite number of completely different expressions.

5.2.2. Plan forms, spatial solutions and architectural expression

As mentioned previously, it is very difficult, if not impossible, to assess individually the plan forms, spatial solutions and architectural expression of any building. However, although the division may seem at times unnatural, it has been done in order to simplify the analysis. It also needs to be highlighted, at this stage, that the developed plan forms, spatial solutions and architectural expression are looked at in relation to the use of the RF.

5.2.2.1. Plan forms

There is a large range of different plan forms developed in the Village Hall design, which are all accommodated by the RF. Although anything from organic to completely irregular plan forms can be found among the designs, the most common are the polygonal (regular and irregular) and circular solutions.

Before looking more closely at the plan forms and their classification and in order to avoid any possible misunderstandings, one needs to define the context in which the terms 'regular', 'irregular' and 'organic' plan forms are used. When referring to the RF the regularity and/or irregularity is represented by the arrangement of the outer supports in plan. Usually, this coincides with the plan form of the building or space roofed by the RF. Depending on the position of the supports and their distances, polygons with equal side lengths - regular, or polygons with sides which differ in length - irregular can be created. However, in some cases the supports are arranged in such a manner that it is possible to enclose them with curved walls in plan which then form irregular forms which remind of forms in nature (such as human cells, ponds or lakes). Those forms in this context will be refereed to as 'organic'.

The regular polygonal plan forms are:

- four sided, as in example 5.1
- eight sided as in example 5.8 (there are two RFs, short and a medium span)
- twelve sided as in examples 5.5 (with extended beams to accommodate the ancillary spaces) and 5.14 (two RFs supporting each other).

The irregular, bi-axially symmetrical polygonal plan forms are those with:

- a central roof light as the ten sided polygon of example 5.3,
- an offset roof light as the eight sided polygon from example 5.4.

All of the six, four-sided, RFs in example 5.11 have one axis of symmetry and have a central roof light each.

The circular RF plan forms are those with:

- a central roof light as example 5.2 (with extended beams), or
- with an offset central polygon (roof light).

In example 5.9, which consists of two RFs, the short span has a central, and the medium span RF an offset roof light.

Examples of irregular and asymmetrically based RF plan forms are 5.10 and 5.12. In example 5.10 the softly curved plan form created by three offset and irregular RFs. Two short and one medium span are used to form the organic image of the building. In example 5.12, on the other hand, the RFs are completely irregular, unrelated to the plan, and slope in various directions. Most, but not all, of the RFs in the building are constructed from glulam beams. On the first floor, trusses are used for the RF structure. The complete irregularity and asymmetry gives a "deconstructive" image to the building.

The fact that the polygonal and circular solutions are most common shows that they are easy to accommodate with the RF and at the same time are appropriate for the functional and spatial requirements of the main assembly space of the village hall, or in some cases the whole building. The regular polygons and the circular plan forms with a central roof light are easier to imagine, draw, design, and construct then the asymmetrical and irregular solutions. As all the beams are identical in regular RFs with a central roof light, once the 3-d geometry of the whole structure and one member has been resolved, although quite complex, all members are identical.

The irregular polygons, and circular RFs with an offset central polygon, require more time to design, as the 3-d geometry becomes more complex. In these structures the beams are of different lengths, intersection points of beams are at different heights and, as a result, construction details are more complicated to design. However, use of 3-d computer drawings for presentation and production of drawings could make this possible.

Use of RFs with an offset internal polygon creates more interesting forms, than regular and symmetrical RFs. However, one needs to be careful not to offset the light too much, as it could result in unrealistically long timber beams (see example on Figure 5.10a, section 5.2.1.2, p. 5-17).

Although almost difficult to imagine and draw in 3-d, the significance of the completely irregular and asymmetrical RFs (examples 5.10 and 5.12), is that it opens up a new possibility for RF application. As discussed earlier, both examples of the students project have a number of unresolved (but not resolvable) structural problems (see sections 5.2.1.2 and 5.2.1.3). Nevertheless, they show that the RF structure, in theory, could be used to accommodate literally any plan form. However, to make this realistic, it would be necessary to invest time and effort in resolving the 3-d geometry and details.

It is important to note that students found it difficult to build physical models of RF structures - the easiest way for them to develop complex spatial forms - as the modelling process had to reflect the real process of making and the RF provides support when all beams are in place.

5.2.2.2. Spatial Solutions and Architectural Expression

The principal partition of the Village hall spaces is between the main (the hall) and the secondary (all other spaces). Given this and from the aspect of the RF, the developed spatial solutions can be grouped into three:

1. those which have the all spaces of the village hall accommodated within only one RF structure,
2. those which have the main space and the secondary spaces accommodated within two or more RFs, and
3. those in which the main space is accommodated by a RF and the other spaces are roofed by another structural system.

Examples of one RF structure which accommodates the building as a whole are 5.2, 5.5, 5.6 and 5.7. All four solutions have in common that the grouped ancillary spaces are positioned at one side of the main hall.

In the examples 5.2 and 5.5 the RF beams are extended to roof the secondary spaces. The functional requirement for different heights of the main and secondary spaces, is fulfilled very naturally in this way. In these two examples the spatial solution and the structure complement each other and they represent a successful application of the RF.

Examples 5.6 and 5.7 are both irregular and asymmetrical, but also have the ancillary spaces grouped on one side of the plan. However, the spatial solutions and the RF structure do not correspond as successfully as in the examples 5.2 and 5.5.

In example 5.6 the irregular plan form is roofed with a RF which has the rooflight over the entrance lobby, which gives an additional quality to that space, but on the other hand, the ancillary spaces, because of the nature of the structure, are unnecessary high. False ceilings are a solution for avoiding the unnecessary volumes of these spaces, but then the glulam RF structure is covered. It is important to stress that the appeal of the RF is to have the whole structure exposed or at least the central polygon suspended in mid-air.

The ancillary spaces in example 5.7 are arranged in plan at the side where the RF beams are lower, which offers the possibility of leaving the beams exposed. The main criticism of the spatial solution in terms of the RF use in this example, is that the roof light is over the backstage (see Figure 5.7 c). As mentioned before (see section 5.2.1.1 p. 5-15), in the initial design the backstage was enclosed by a load bearing masonry core. In the revised scheme, this unnecessary structural wall was substituted by a partition wall.

The spatial solutions of the buildings in which the function is organised in two or more RFs (group 2) can actually be subdivided into two groups:

- one RF roofs the main hall, and the ancillary spaces are accommodated within one or several shorter span RFs as in the examples 5.9 and 5.10.
- more RFs are used, but they do not coincide with the division of spaces to ancillary and main, as in examples 5.11 and 5.12.

The use of two RFs in the example 5.9 and 5.10 coincides with the division of the spaces. The main hall in both cases is roofed within a large RF, and the secondary spaces in a small RF structure (in example 5.9 in one, and, in example 5.10, in two small RFs). The division and importance of the spaces in both solutions is expressed with the size of the RFs used, small for the secondary and medium size for the main hall. This also coincides with the functional requirements in terms of the volume, light and height of the spaces. In terms of spatial solution, both examples, although different, are equally successful. The structure and the space complement each other. They work as a whole, not as two separate entities. The main criticism, as discussed earlier, of example 5.10 is that the student has shown beams that are excessively slender.

Examples 5.11 and 5.12 use several RFs to accommodate the plan of the building, which does not coincide with the main and secondary spaces. In example 5.11 the six RFs only roof the main hall, which is on the first floor, and the ancillary spaces are organised on the ground floor. In this example the division of the spaces is in section and not in plan, as in most other discussed examples. This shows that RF structures can be used for two or more story buildings. In this example the RF has been used as a roof structure and only on the top floor. It is equally possible to use it on the other floors, as a planer configuration. An example is the Mill Creek Housing project by L. Kahn (see Chapter 2, section 2.1.3, p.2-16).

The use of the RFs in example 5.12 does not coincide, or correspond with anything, especially not with the division of spaces. The completely irregular spaces in plan are roofed by completely irregular RFs.

The third group of examples consisting of RFs which roof only the main hall and the secondary spaces, are roofed with another structural system are: 5.1, 5.3, 5.4, 5.13, and 5.14. In example 5.8, two RFs are used, one for the main hall and one of short span which accommodates the entrance hall. All other secondary spaces are roofed with another structural system.

Due to the short time available for the student project, as well as the students being only in their second year, these examples do not go into detailed design of the structural system which roofs the secondary spaces. Still, they open up a possibility of creating a different type of architectural expression by use of the RF. In all these examples the importance of the main space is glorified by the RF structure because it defines the spaces. It also gives them an extra quality implying rotation about some invisible vertical axis.

5.3. The RF design experiences

The idea of carrying out the student case study in terms of the RF research was to obtain a number of examples which could show different RF design possibilities in terms of morphology, plan forms, spatial solutions and architectural expression. It was also a chance to investigate the experiences of actually applying the structure from a designer's point of view.

In addition, having a group of students who worked on the same design project, but did not use the RF, gave an opportunity for testing their opinion of the applicability of the structural system on the given design brief of the Village Hall. This was done by use of questionnaires and by interviewing a number of students.

At this stage it should be pointed out that the sample was not big enough for any serious statistical analysis. If there had been at least ten times more participants one could apply statistical tests to analyse the opinions. With a sample of 51 students this was not possible. While doing this research project, it was not possible to increase the number of students who took part in the exercise because of very practical and understandable reasons. The curriculum is set well in advance and it is was a great success to be able to fit the RF design project into the set programme. One could perhaps, in future, consider collecting several years of data, or data from several schools of architecture, by giving students a brief to design a building using the RF and then examining their opinions. On the other hand, the analysis of the designer's opinion for itself was not the main aim of this research project.

Nevertheless, the results obtained from the analysis of questionnaires and interviews were valuable, as will be presented later in the text, because they indicate clearly what the difficulties were that the designers faced. Some of them could be overcome, which would make the system more easily applicable. They also indicate the potential of the system, as seen by the students.

5.3.1. Questionnaires

Each of the 51 students was given a questionnaire and asked to fill it in and return it, when they handed in their project. Two types of questionnaire were designed: one for RF users, and the second for those who decided not to use the RF. Out of all 51 students 33 (64.7 %) answered the questions and returned the completed questionnaires, of which 21 were RF users and 11 were students who did not use the RF.

The answers of the RF users were more important because they provided the main material for analysis. Therefore, the fact that 21 questionnaires were returned out of 25 (84 %) is significant. Although less questionnaires were returned by the students who did not use the RF, 11 out of 26 (42.3 %), they still demonstrate a body of opinion about the design opportunities and problems of the RF.

Both types of questionnaires are structured in the same way. They contain 16 questions, with three optional answers each, and space for written comments at the end about the advantages and disadvantages of the RF system (the questionnaires are enclosed in appendix 5A and 5B).

The order (positive, neutral and negative) for the optional choice answers, is the same for all questions. Although, there is always the danger that the person who answers could realise that there is a pattern in the choice answers and could answer them mechanically, the risk was taken consciously because it simplified the analysis of results. Also, as all questionnaires had a space for written comments at the end, even if the choice answers had been filled in without thinking, the final remarks would be personal opinions.

5.3.1.1. Questionnaires filled in by RF users

The structure of the questionnaires for RF users was:

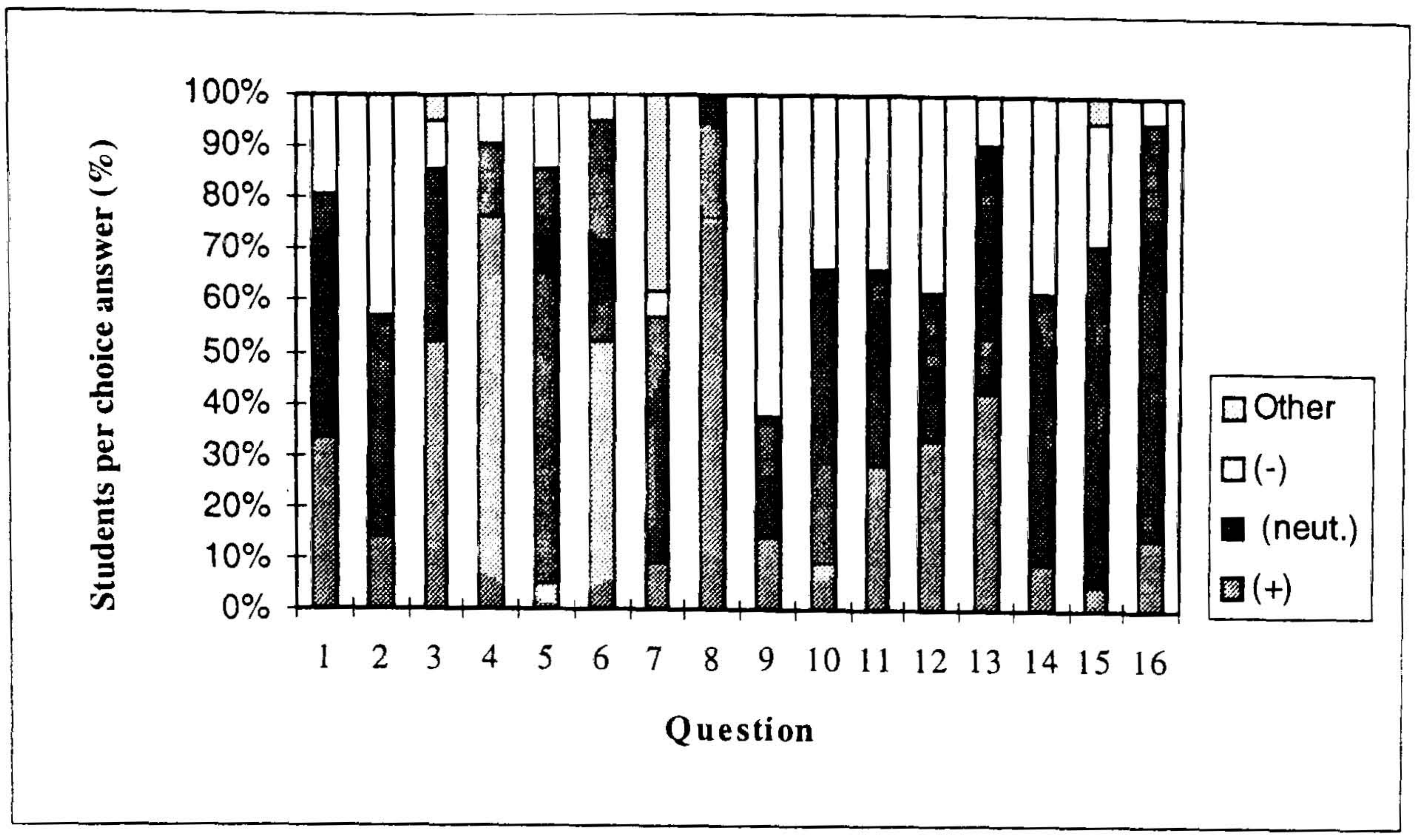
- Questions 1-7 were about how the RF structure influenced the design solution of the designer as regards: organisation of the function, division of spaces, plan form, spatial quality of main space, acoustics, views of spectators and spatial quality of secondary spaces.
- Questions 8-12 were designed to show the understanding of the structure and practical issues related to it: how it works, efficiency, geometry, design of appropriate enclosure and buildability.
- Questions, 13 and 14, were to do with the final image of the building and its appropriateness to the environment of Staithes.
- Question 15 was about the relation of the RF and the services design
- Question 16 was about the possibility for future use of the RF for other design projects.

As mentioned previously, in the end the students were expected to give their comments about the main advantages and disadvantages related to the RF and the design project.

The analysis of each question was done by coding the choice answers. They were then, counted for all 21 returned questionnaires. The coding system was numerical: 1 for the positive (first), 2 for the neutral (second) and 3 for the negative (third) option. In cases where the student did not chose any of the given optional answers and gave another written answer instead, the answer was coded as 4 (see appendix 5C). The students' answers, and their distribution are presented in table 5.1 and graph 5.1.

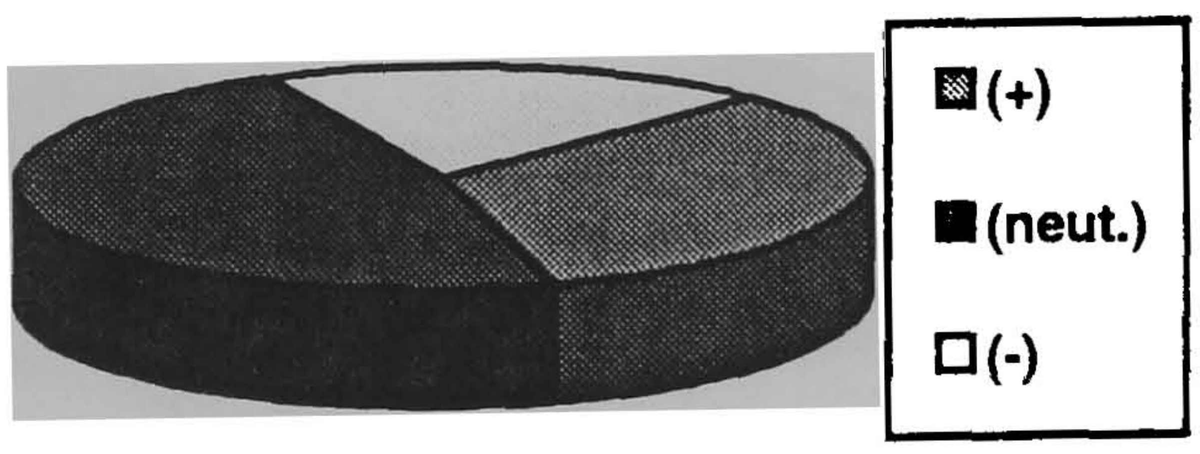
Question	Option 1 (+) (n)	Option 2 (neutral) (n)	Option 3 (-) (n)	Other (n)
1	7	10	4	
2	3	9	9	
3	11	7	2	1
4	16	3	2	
5	1	17	3	
6	11	9	1	
7	2	10	1	8
8	16	5		
9	3	5	13	
10	2	12	7	
11	6	8	7	
12	7	6	8	
13	9	10	2	
14	2	11	8	
15	1	14	5	1
16	3	17	1	

Table 5.1. Distribution of number of students (RF users) per choice answer



Graph 5.1. Distribution of number of students (RF users) per choice answer

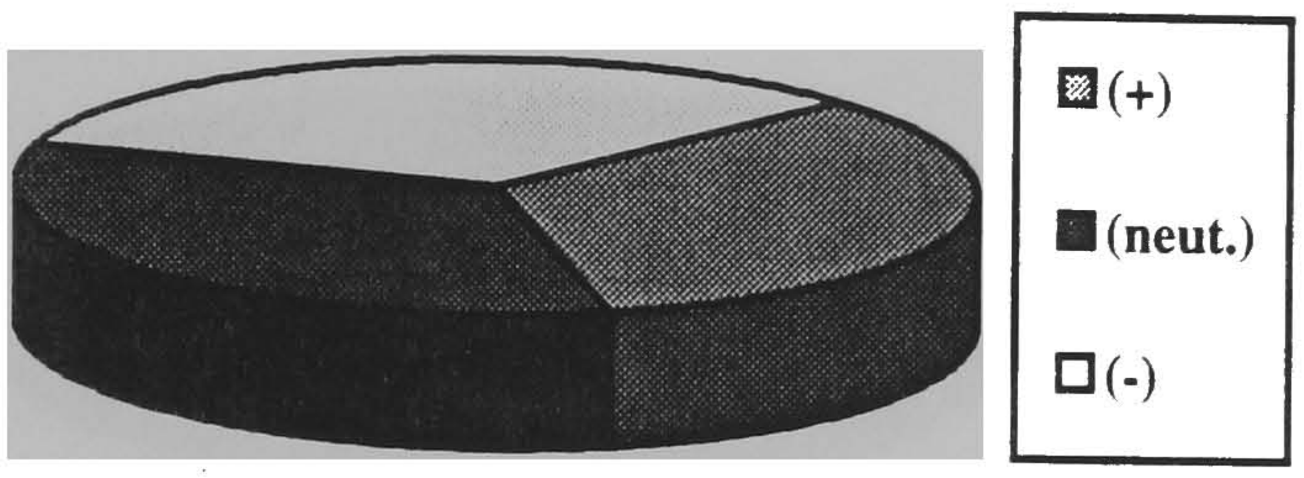
Looking at the answers to the first group of questions (1-7), the questionnaires revealed that for 34.7 % of the students the RF contributed positively to the quality of their design solution represented through the organisation of the function, division of spaces, plan form, spatial quality of main space, acoustics, views of spectators and spatial quality of secondary spaces. 44.2 % of the students were neutral and 14.9 % thought the RF use was a disadvantage for their design and 6.1 % had no opinion. Or, as presented on Graph 5.2, for 78.9 % design solutions the RF was not a disadvantage.[1]



Graph 5.2. RF influence on the design solution

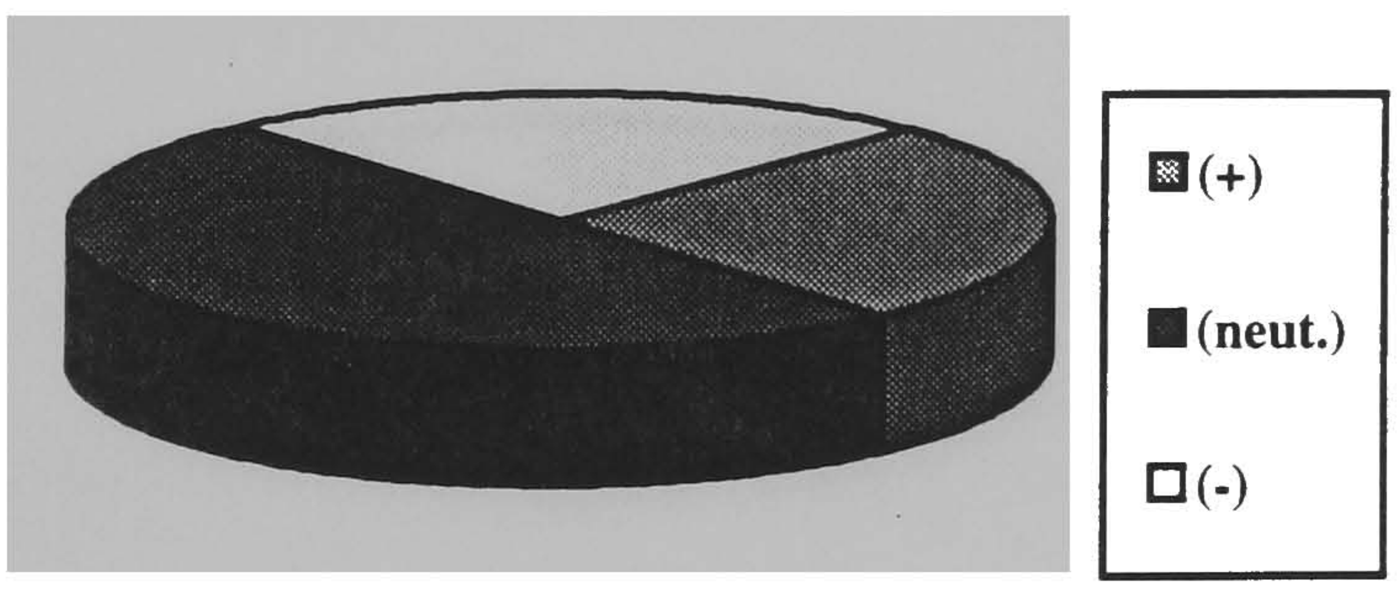
[1] It is important to note, that for a significant number of students (8) question 7 was not applicable because the secondary spaces were roofed with another structural system.

Questions 8-12 were related to practical issues: how the structure works, efficiency, geometry, design of appropriate enclosure and buildability. For 34.4 % the practical issues were not a problem, 34.3 % were neutral and 33.3 % thought the use of the RF made life difficult. Only the last group actually realised the practical implications of the RF. Still, 66.7% were not put off by the practical issues.[2] (See graph 5.3)



Graph 5.3. The RF in relation to practical issues

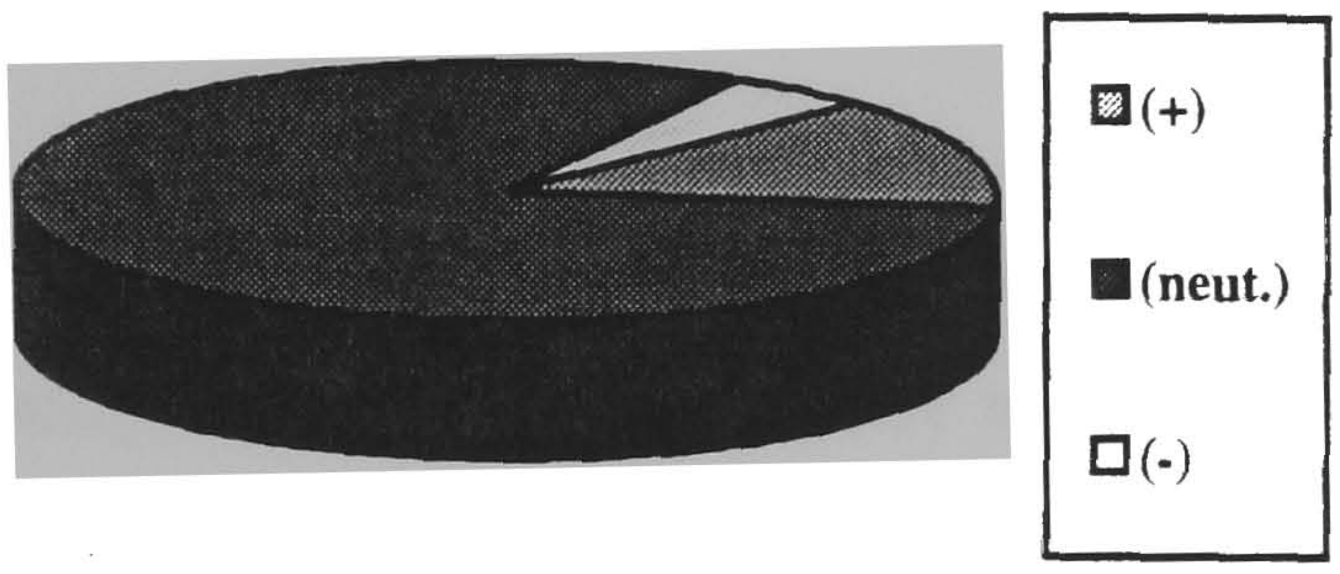
Questions, 13 and 14, were to do with the final image of the building and how it fitted into the environment of Staithes. For 26.2 % the use of the RF contributed to the final image of the building and made it easier to fit the building in the environment, 50 % were neutral and for 23.8 % it was a disadvantage in relation to these two questions. In other words, 73.8 % would not be put off the use of the RF because of the specific image it creates nor because of their concerns about fitting the building in the environment. (See graph 5.4)



Graph 5.4. The RF building final image and its appropriateness to the environment

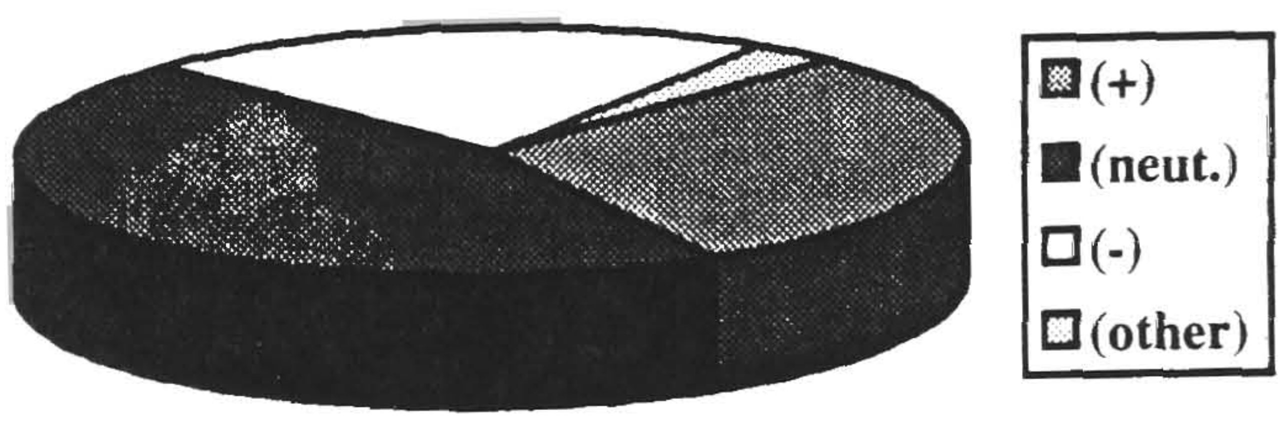
[2] Question 15 has not been included in the practical issues because it is very difficult at an early stage of the design project to say objectively how or would the RF at all influence the services design. The answers to question 15 should be looked at more as something worth considering, rather than a statement of the real situation.

Question 16 was about the possibility for future use of the RF for other design projects. 14.3 % would most probably use it and 80.9 % would consider the possibility of using the RF. In other words, 95.2 % would either use it or would consider the possibility of using it, and only 4.8 % think that they will not use the RF on any other design projects. (See graph 5.5).



Graph 5.5. Possibility of using the RF on a future design

The use of a structural system should be a choice that a designer could have freedom to make. In that respect and when grouped all the choice answers together, they reveal that because of various reasons, only 21.7 % of the students felt that the RF did not provide enough advantages, 45.5 % were neutral and 29.8 % thought it brought advantages. In other words, the majority of 75.3 % of the students did not think that the RF application was a disadvantage for their project.[4] (See graph 5.6).



Graph 5.6. Advantages and disadvantages related to the RF use

[4] As for 3 % of the survey questions were not applicable, these answers have not been included.

The answers to the all individual choice questions will not be analysed independently. However, looking at table 1 and graph 1, it can be noticed that:

- 76.2 % thought that the main space gained in terms of spatial quality from the use of the RF, (question 4)
- 76.2 % found it easy to understand how the structure works (question 8),
- 52.4 % thought that the RF contributed to the equally good views for all spectators (question 6),

The most important disadvantage of the RF for most students:

- 61.9 %, of them thought that the 3-d geometry was quite complicated (question 9).

The written comments about the most important advantages and disadvantages related to the RF use were read carefully and the common statements that appeared in several questionnaires were assembled into four main groups for the advantages and into three for the disadvantages. The following answers were obtained:

Advantages from the RF use:

1. 25 commented about the quality of the spatial solutions[5]:

- interesting schemes, solutions,
- regularity, versatility and simplicity of plan forms,
- defines the form of the main space,
- good structural solution for open plan functions,

2. 12 commented about the aesthetics of the building as a whole:

- interesting appearance,
- attractive (3-d) forms,
- special image,

[5] The number of answers is not how many times those answers appeared, but that in that group they were 25 in total. This applies for all other group of answers.

- nice feeling,
- picturesque uninterrupted quality,
- interesting dynamic spiralling forms.

3. 9 commented about the RF itself:

- has a special, individual "look"-appearance,
- it is an interesting and dramatic structure,
- gives a sense of movement,
- provides different possibilities - versatility in forms, having roof lights,
- could be made out of different materials,
- efficient and easy to construct.

4. There was one comment that:

The constraints of the project helped them in the design. The structure provided a big enough scope for design possibilities, but at the same time constrained their ideas and helped them not to get lost.[6]

The disadvantages from the RF use were the following:

1. 18 commented about the RF itself:

- difficult to imagine and draw the structure and sections without CAD,
- difficult to understand the geometry,
- roof shapes constrained,
- large cross-sections necessary, can look heavy and clumsy,
- construction problems - difficult to build,
- danger of leaking (if roof panels are used) due to lots of flashing.

2. 12 commented about the building as a whole:

- difficult to design a building with the RF,

---

[6] If one looks at the students marks they show that his is indeed true, because not only the good and average students did well but even the not very good students managed to get average marks, far better than on other design projects.

- the incorporation of the secondary spaces complicated whether they are roofed with the main RF, or if secondary RFs or separate roof structures are used. It is difficult to join them smoothly,
- restricted plan forms,
- complicated to organise the plan, especially if irregular RFs are used.

1. Other (few answers):

- restrictive in columns location,
- not very good in terms of acoustics,
- problematic in case of fire.

If one looks more closely at all obtained answers, most of them show a tendency for positive experiences by the RF users. The main disadvantage came from the difficulty to imagine the structure, understand it completely and draw it in 3-d, which is something worth considering and suggests that a system needs developing its easier presentation. In that respect, as part of the research an automated CAD routine (written in AutoLISP) has been developed. It simplifies the 3-d presentation of the RF to a great extent. It is presented in Chapter 6.

Also, especially when looking at the written answers, there is a need to provide more information on other practical issues such as buildability and efficiency, because some students had positive and other negative opinions on regarding these matters.

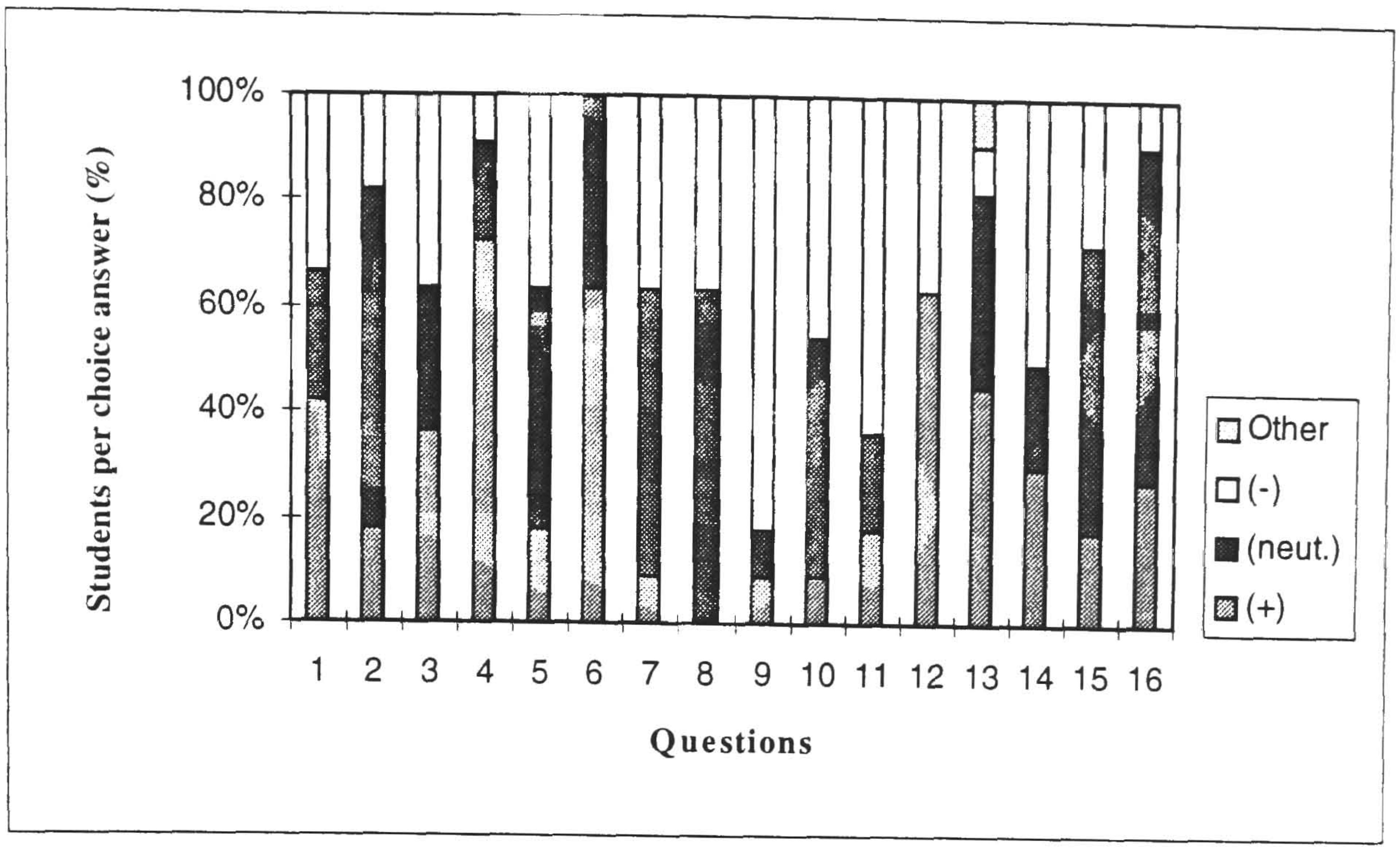
5.3.1.2. Questionnaires filled in by students who did not use the RF

The structure of the questionnaires for the students who did not use the RF for their design was identical to the one for the RF users (see p. 5-23 and appendix 5B). The only difference was that the RF users were expressing their experiences, whilst the group of students who did not use the RF were expressing their opinions about the applicability of the RF on the design project for the Village hall.

The analysis and the coding system were also, identical. The 11 returned questionnaires were coded and the answers to the optional choice answers were counted. The written answers in the end of the questionnaires were, also grouped.

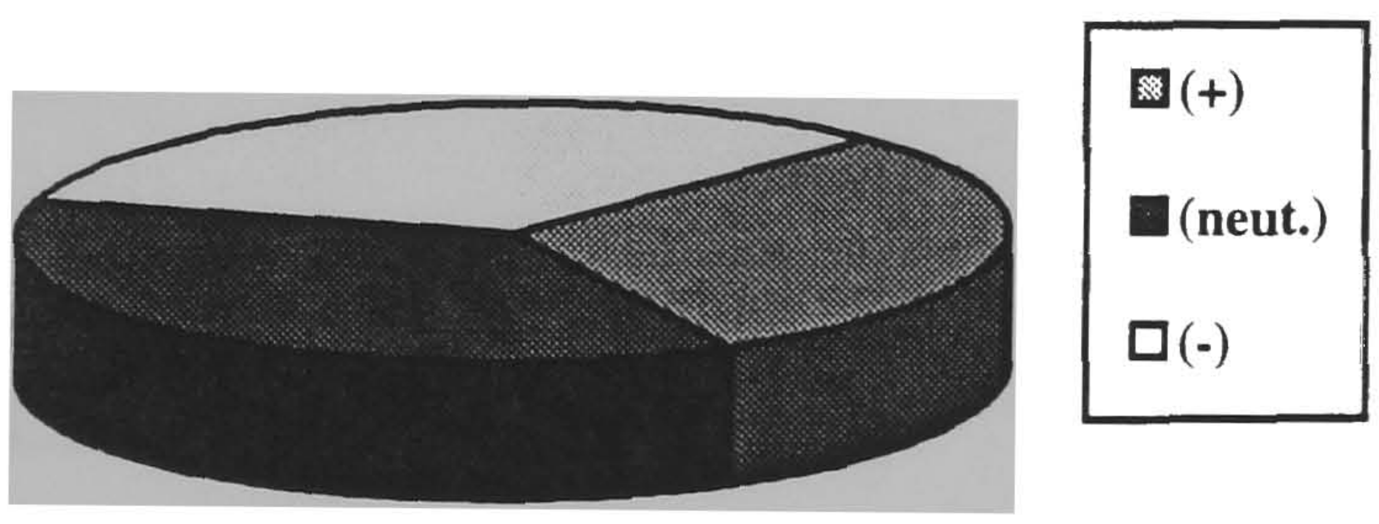
Question	Option 1 (+) (n)	Option 2 (neutral) (n)	Option 3 (-) (n)	Other (n)
1	5	3	4	
2	2	7	2	
3	4	3	4	
4	8	2	1	
5	2	5	4	
6	7	4		
7	1	6	4	
8		7	4	
9	1	1	9	
10	1	5	5	
11	2	2	7	
12	7		4	
13	5	4	1	1
14	3	2	5	
15	2	6	3	
16	3	7	1	

Table 5.2. Distribution of number of students (who did not use the RF) per choice answer



Graph 5.7. Distribution of number of students (who did not use the RF) per choice answer

The answers of the students who did not use the RF for their design project could be grouped, and analysed in a similar way to the ones obtained from the RF users, but this has not been done as the sample of 11 is too small. However, the tendency of the opinions of these students, looking at all their choice answers is that 30.1 % thought that the use of the RF was an advantage, 36.4 % were neutral and 32.9 % thought it was a disadvantage. Or in other words, the opinion of 66.5 % of these students was that the RF was not a disadvantage.



Graph 5.8. The tendency of the students opinions who did not use the RF

On the other hand, if one looks at table 5.2 and graph 5.7 at the answers to separate questions, it can be very easily noticed that the most positive response was for question 4 (i.e. for 72.7 %) the main advantage of applying the RF was that it contributed to the quality of the main space. The most negative response (question 9) showed that the main disadvantage (for 81.8 % of the students) was the complicated 3-d geometry of the system. It is interesting to note that they coincide with the RF users' answers to the same questions.

Looking at the students written comments their opinions about the advantages of the RF use can be grouped into four, and the disadvantages into two groups. The main advantages, according to them, were:

1. 14 students commented about the building as a whole[7]:

- unobstructed plans without internal supports can be achieved, thus good for flexible multipurpose spaces,
- the building is aesthetically pleasing, beautiful interiors and exteriors,
- special effects are achieved with use of multiple and complex RFs.

2. 3 students commented about the relation of the building and the structure:

- gives a clear form to the building through structure,
- impressive structure which leads to an impressive building.

3. 3 students commented about the RF structure itself:

- creates interesting roof shapes,
- it is efficient.

4. One student thought that it:

- reminds a bit of a Chinese gazebo.

The main disadvantages as a result of the application of the RF, according to the written answers of the students, were:

1. 9 students commented about the building:

- the structure constrains the plan forms,

[7] The same applies as note [5]

- it is difficult to organise the function in plan, especially in terms of division of spaces,
- difficult to integrate main and subsidiary spaces.

1. 8 students commented about the RF):

- difficult to draw, especially sections,
- difficult to construct models,
- complicated structures, especially if they are irregular,
- inefficient (large cross sections).

If one looks more closely at the written comments by students who did not use the RF, in common with the RF users' answers, they reveal that the RF contributed to the spatial qualities, but it was difficult to imagine and draw the structure in 3-d. The answers reveal that there is need for more information on the practical issues such as geometry, simple presentation methods, buildability and efficiency.

However, it is significant that the majority of both groups of students would either consider or would use the structure for their future designs (See p.5-33 and p.5-40, tables 5.1 and 5.2 respectively, question 16 in both cases). Also, for both groups the experience and/or opinion in total related to the RF use was not negative. (See p. 5-36 and p.5-41, graphs 5.6 and 5.8 respectively).

5.3.2. Interviews

As part of the research on the students' opinion of the RF applicability on the Village Hall seven students were interviewed. The interviews were used as data complementary to the one obtained from the questionnaires and were used to expand on some aspects which were important and were not explored in enough depth through the questionnaires.

The seven chosen students were a random stratified sample. The choice of whom to interview was done to have three RF users and three students who did not use the RF for their research, with marks A, B and C for their design project. The idea was to see what students, who gained excellent, very good and good on the project, thought about the RF and what were their experiences. A number of students had been sent a letter explaining the reason for undertaking an interview, that it would be confidential, have no consequences on their studies whatsoever and asking them to take part in it.

Not all students replied to the sent letters, but some others (in the same range of marks) volunteered to be interviewed and were accepted instead. As a result four RF users, with marks A, two Bs and a C, and three students who did not use the RF, with marks A, B and C were interviewed.

The interviews took place in the School of Architecture in the Staff coffee room from the 8 until the 12 February 1996. They were recorded and transcribed afterwards (see appendix 5 D).

Each student was interviewed at the time they preferred and again before the interview took place the aim of the research and the reasons for the interviews were explained. The place and way of conducting the interviews were chosen so that the students did not feel threatened. The students were seated beside and not opposite the interviewer (the author) so that they could choose where they wanted to look. It was important that they felt comfortable (Wragg, 1992).

The interviews were designed as semi-structured, with 12-16 questions in order to allow the students enough freedom to answer the questions in greater length, but also to prevent aimless rambling. Depending on the previous responses some questions were not asked if it was felt that the student had already given an opinion whilst answering another question.

The students interviewed were coded by giving them numbers 1-7. The RF users with marks A, B, B and C were given codes 1-4 respectively and the students who did not use the RF with marks A, B and C were given codes 5, 6 and 7 respectively.

The transcribed interviews (see appendix 5D) were then analysed. Although very difficult to separate because most aspects overlap, for easier analysis the answers were grouped by subjects and each group was analysed separately. The following groups were identified:

- questions 1,2,7 and 8 were to do with aesthetics,
- question 3 was about the RF efficiency,
- question 4 was about design and construction of the RF,
- questions 5,6,9,10 and 11 about the organisation of the space,
- question 15 was about the RF morphology, and
- questions 12, 13, 14 and 16 were about the future of the RF.

However, very often the students gave answers to several aspects within the response to one question. While analysing, and in order not to omit any of the relevant comments, if within any answer a student had given an opinion on a certain subject, the comment was put in the appropriate group although it was not obtained from the relevant question, but from another. This practically meant that all answers regarding the aesthetics, for example, were grouped even though they were not always obtained from the responses to questions 1,2,7 and 8 only. This was done with all answers.

The analysis of the interviews showed the following results:

1. About the aesthetics:

- all students, without any exception (regardless of if they had used the RF for the project or not and also, regardless of the marks obtained) thought that the structure had aesthetic good qualities.
- they described it as: definitely interesting (3 students), interesting (3). For most of them the main quality was that the beams overlapped which produced

a sense of movement, a spiralling 'feel' and it was the focus point of the building.

- also some students thought that it was a novelty, gave a different 'feel', was very attractive, had interesting massing, gave a sculptural 'feel', had a certain character, was organic, looked good if exposed and one student even thought that 'it would be a nice thing to cover the world with'.
- only one student thought it produced an uncomfortable-unstable 'feeling'.

2. About the RF efficiency:

- the opinions had a lot in common and were not related to the marks nor were different for students who did not use the RF and RF users,
- most students thought that the RF was not efficient (5 students) because of the large sections of beams used, some did not know if or how efficient it was (3 students), some thought that it would become more efficient if trusses were used, and some thought that it is efficient in what it does and that not always the cheapest is the best.

3. About design and construction of the RF:

- both students who had obtained an "A" for their projects, thought that it was very difficult to imagine and draw the RF, also the "B" marked student who did not use the RF and the "C" marked RF user shared the same opinion. The latter had chosen a planer RF for the project because it was easier to draw. The RF user marked with "B" for her project thought that the drawing was not a problem and having to work out the geometry was something enjoyable. One student thought that it all depended on the knowledge one has.
- regarding the construction most students did not know if it would or would not be complicated to construct the RF.

4. About the organisation of the space:

- most students felt that the RF was very good for open plan functions. It defines the space which has a special spatial quality because it focuses as an iris, most felt that it was not as easy to organise subdivided spaces.

- the answers were not influenced by the marks obtained for the project, nor by weather the students had used the RF or not.

5. About the RF morphology:

- most students liked the irregular RFs (4 students), some thought that the multiple configurations were the most interesting and one student did not specify the form, only thought that best results are obtained when the building as a whole is roofed by one RF.
- the answers were not influenced by the marks obtained for the project, nor by weather the students had used the RF or not.

6. About the future of the RF:

- all students thought that the RF would be used by architects in future, that there is need of more information about it and for user-friendly computer programs for easier drawing. Most of them felt that future research needs to be about exploring the RF morphology, especially the irregular RFs and practical problems related to them: geometry, joints, buildability and efficiency.

As the RF users had more knowledge about the structure, because they had studied it in more depth they sometimes had stronger opinions. However, it can be said that the responses from the two groups were not dissimilar.

5.4. References

Dunbar, J. (1975) *Laura Knight*, Collins, London

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Wragg E.C. (1992) ed. Youngman M.B., *Rediguide 11, Conducting and Analysing Interviews,* Nottingham University, School of Education

5.5. List of illustrations

CHAPTER 6: Practical issues

6.1. The geometry of regular RF structures and 3-dimensional CAD presentation

Previous chapters described the precedents of the RF structure and structures related to it throughout history, examples of RF buildings constructed in Japan and in the UK, as well as different examples of RF morphology studied on a student project case study. This chapter explores the practical issues regarding the planar and 3-dimensional geometry of the RF, used both as a static and retractable structure, the development of easier ways to present the structure using CAD, and possible ways of covering the RF roof.

In order to be able to design appropriate construction details one has to understand the RF geometry and the parameters which describe it.

The geometry of the regular polygonal and circular 'single unit' RF structures can be described by the main variables which define the structure, shown in Figure 6.1. These are:

- the number of beams (n)
- the radius through the outer supports (r_o)
- the radius through beam intersection points (r_i)

- the vertical rise from the outer supports to the beam intersection points (H)
- the vertical spacing of the centrelines of the beams at their intersection points (h_2)
- the length of the beams on the slope (L).

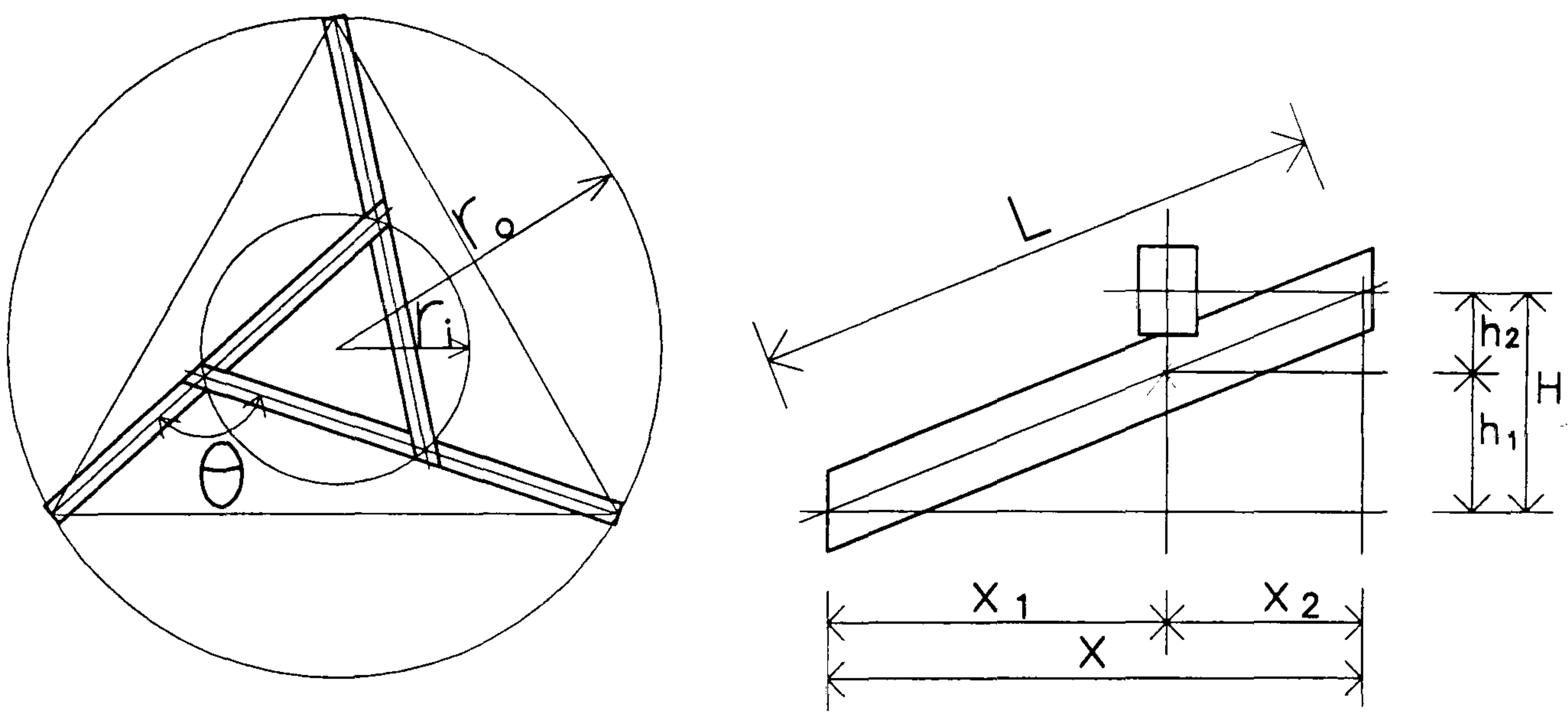


Figure 6.1. Geometrical parameters for RF structures

Usually, the radii through the outer supports (r_o) and through beam intersection points (r_i), and also the vertical rise from the outer supports to the beam intersection points (H), are determined by architectural and/or constructional requirements and, once they are set, the other variables can be resolved (Chilton and Choo, 1992).

The parameters which define the geometry of the RF, both planar and three-dimensional, can be determined from the equations (6.1) to (6.7). In these equations θ is the sector angle between the beams (i.e. the angle between the beams when viewed in plan); x is the overall length of a beam in plan, and, x_1 and x_2 are the plan length to first intersection and plan length between intersections.

$$\theta = \frac{360}{n} \qquad (6.1)$$

$$x_2 = 2r_i \sin\frac{\theta}{2} \tag{6.2}$$

$$x_1 = \left[r_o^2 - \left(r_i \cos\frac{\theta}{2}\right)^2\right]^{\frac{1}{2}} - \frac{x_2}{2} \tag{6.3}$$

$$x = x_1 + x_2 \tag{6.4}$$

$$h_1 = H\frac{x_1}{x} \tag{6.5}$$

$$h_2 = H - h_1 \tag{6.6}$$

$$L = \left(x^2 + H^2\right)^{\frac{1}{2}} \tag{6.7}$$

Basic trigonometry has been used to derive these equations and their validity has been checked using 3-dimensional AutoCAD drawings.

6.1.1. 3-dimensional CAD presentation of regular RF structures

Using the presented relationships between the RF parameters and AutoCAD R12 for Windows, an AutoLISP routine (given in Appendix 6a) was developed as part of this research project. The AutoLISP routine simplifies and automates the 3-dimensional CAD presentation of the RF structure. It is written in a manner to be user friendly and to help designers have a clear presentation of the structure on the screen within seconds.

The routine was written out of necessity, since the research showed that the presentation of the structure was one of the greatest difficulties for the students during the student project case study (see Chapter 5, sections 5.3.1.1 and 5.3.1.2, pp. 5-37 and 5-42 respectively). Before having developed the AutoLISP routine, the author also experienced difficulties in drawing the RF structure in 3-d.

The requirements for a user are to have a computer powerful enough to run AutoCAD (depends which release, but 16 Mb Ram is sufficient for AutoCAD R12), to have the routine installed on the computer and have a basic knowledge in the use of the software. Also, one needs to know the terminology used to describe the RF main variables (as given on pp. 6-1 and 6-2)

Once AutoCAD is running, and after having loaded the AutoLISP routine into the computer, Frame9.lsp (the developed AutoLISP routine) is designed to prompt for the user's RF morphology choice. The drawing would then automatically appear on the screen. The following prompts appear on the command line:

- "Please enter number of beams"
- "Please enter centre point of circles"
- "Please enter plane length of beam"
- "Please enter inner radius"
- "Please enter total rise of beam"
- "Please enter beam width"
- "Please enter beam height"

The dimensions are entered in the units and precision set by the user after starting AutoCAD. These can be scientific, decimal, engineering, architectural or fractional. Both AutoLISP and AutoCAD use the same units for measuring distances. On the other hand, angles in AutoCAD are always measured in degrees, whereas in AutoLISP they need to be entered in radians. If there had been a prompt for an angle, either the angle would have had to be entered in radians (not very straightforward) or the routine would have had to use converting functions. To avoid confusion and to make the routine user friendly, Frame9.lsp is written so that only distances need to be entered. Using the information entered the routine calculates the necessary angles.

After answering each prompt, a 3-dimensional representation of the centrelines of the RF structure, as well as a solid beam, appear within a second or two on the screen. Obtaining the complete 3-dimensional drawing of the solid RF roofs only requires moving the solid RF beam to the desired position (given by its centreline). Using the "3darray" command will then display the 3-dimensional solid beam

Extension) available on their computer, then the software will automatically generate all the intersections and chose the correct visibility (hide the lines which are not visible).

At this stage, however, and for the research project, the intention was to show that the problem of representing the structure is something that could be easily overcome with the aid of reasonably powerful CAD software and a computer, as was done with this AutoLISP routine.

The Frame9.lsp routine that has been developed, significantly simplifies the RF 3-dimensional CAD representation. Having a device which does all the geometrical calculations and provides a 3-dimensional RF drawing within seconds, will undoubtedly help future designers who decide to use the RF roof. At this stage it must be noted, however, that Frame9.lsp. can be further developed to fulfil the future designer's requirements, such as drawing RFs with a downward slope of the beams or even irregular RF assemblies.

6.1.2. Variation of the parameters

As part of this investigation, research has been carried out regarding how the variation of the main RF parameters, which describe the geometry of the structure, affects the others. In that sense, and considering the physical construction of the RF, the effect of varying the spacing of the beam centerlines at their intersections on the depth of the beam or truss cross-section has been examined.

For instance, where h_2 is equal or less than the depth of the solid beams used in an RF, the upper beam is usually notched on its underside so that the desired vertical beam spacing can be obtained. The size of the notch also depends on the width of the beams and their angle of inclination. The notch weakens the upper beam at a point of high shear and can necessitate reinforcement of the joint, as in the case of the beams and their angle of inclination. The notch weakens the upper beam at a point of high shear and can necessitate reinforcement of the joint, as in the case of the 13 metre diameter modular RF house at Saorsa, Ardlach, Nairn, Scotland (see Chapter 4, section 4.4.14, pp. 4-31 and 4-32).

On the other hand, where h_2 is small (or zero) it is easier to connect the supported beam onto the side of the supporting beam at the intersection points. In this way, a planar RF structure is formed, similar to the medieval examples discussed in detail in Chapter 2 (see section 2.1.2, p.2-6).

In cases where h_2 is large, the beam or truss depth may have to be increased solely so that the RF members come into contact at the point where they cross. Alternatively, packing pieces or stub columns would be required to transfer loads between the primary structural elements at the intersections.

In practice all this means that a set of well-chosen ratios of RF parameters needs to be decided upon to form the 3-dimensional RF structure. If, for example, five beams are used for a RF with a ratio between inner and outer radii of 0.3 (a structure with, for example, an 8m. outer radius and a 2.4m. central opening radius) and a rise of 2 m. from the outer supports to the inner polygon, the required vertical spacing between the beam centerlines is 0.615 m.

The parametric studies presented on Figure 6.2 indicate that to avoid excessively deep structural elements where a small number of beams is employed, the central opening should be relatively small. If, whilst keeping the rise H at a constant value, the number of beams is increased, a larger central opening can be accommodated by structural elements of a given depth, while still maintaining direct contact at the beam intersections. Conversely, where a large number of beams is employed, deep notches may be required in the underside of each beam, especially where H, and consequently h_2, is small, unless the central opening is large in relation to the overall span of the structure (i.e. it has a large r_i / r_o ratio).

The graph in Figure 6.2 is a convenient tool for preliminary design of RF structures. Given the plan dimensions (r_i and r_o) and the rise H of a regular polygonal RF roof, the curves can be used to select the most appropriate number and/or depth of beams for the structure.

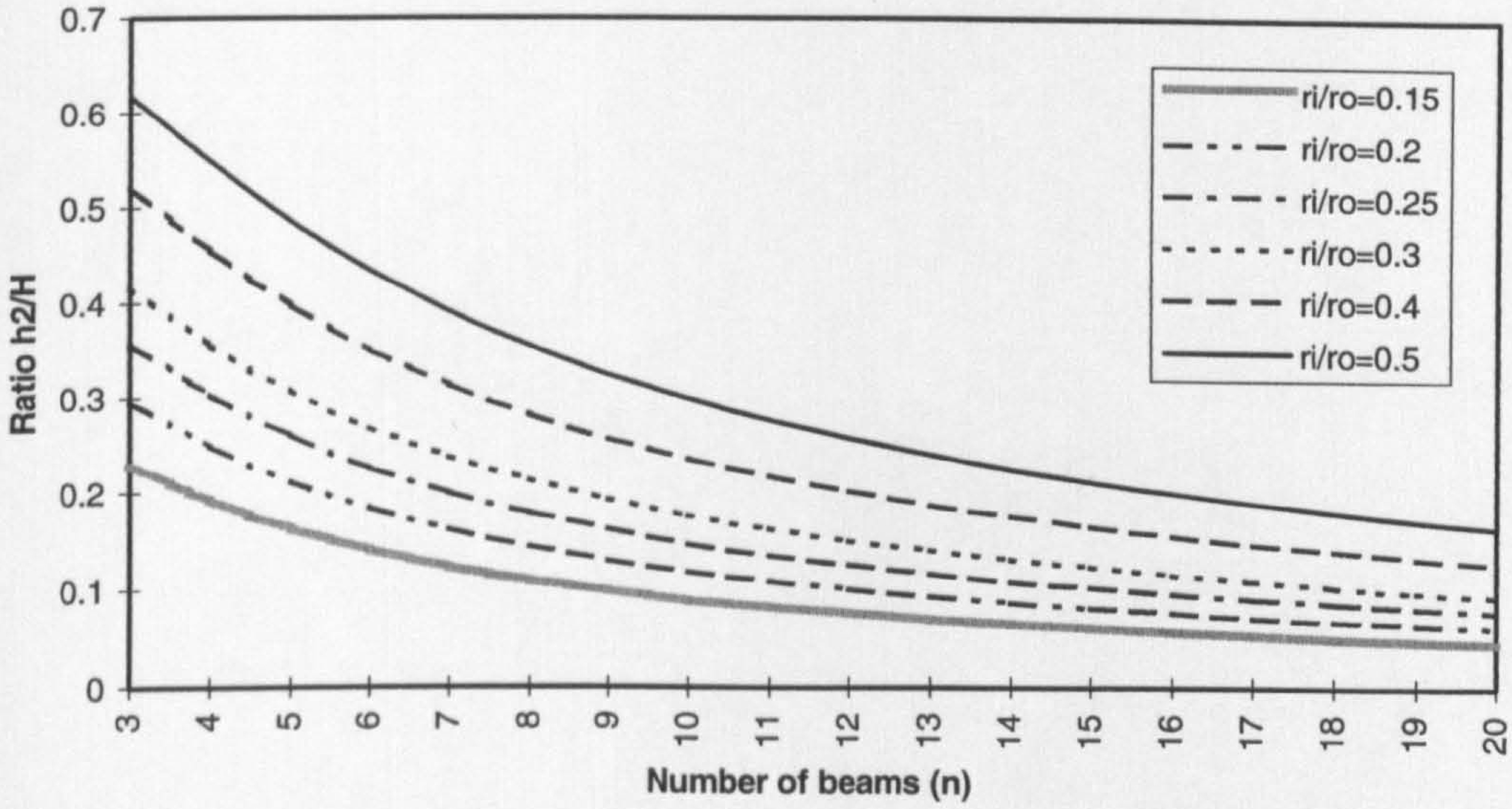


Figure 6.2. Relationship between the ratio h_2 / H and the number of beams for different ratios of r_i / r_o

In this discussion only geometric parameters have been considered. However, the ratio of r_i / r_o affects the perception of the building architecturally and also, from the structural point of view, the distribution of shear forces and bending moments in the beams of the RF, as will be presented in Section 6.5. With small openings relative to the overall span of the roof, both shear and bending are usually high in the portion of the RF beams between the two intersections (i.e. between the point where the beam being considered supports the previous beam and the end where it is supported by the following beam in the circuit). Therefore, when possible, small openings relative to the overall span of the roof need to be avoided.

A further investigation has been made of the relationship between the ratio of the length of the beams on the slope to the radius through the outer supports (L / r_o) and the number of beams in the RF. Figure 6.3. shows this relationship for a number of RF beams (n) in the 3 to 20 range, and for different ratios between the inner and outer radii. The rise H is set at 0.05 r_o for this graph, but any required rise can be chosen and used depending on the desired slope of the roof structure.

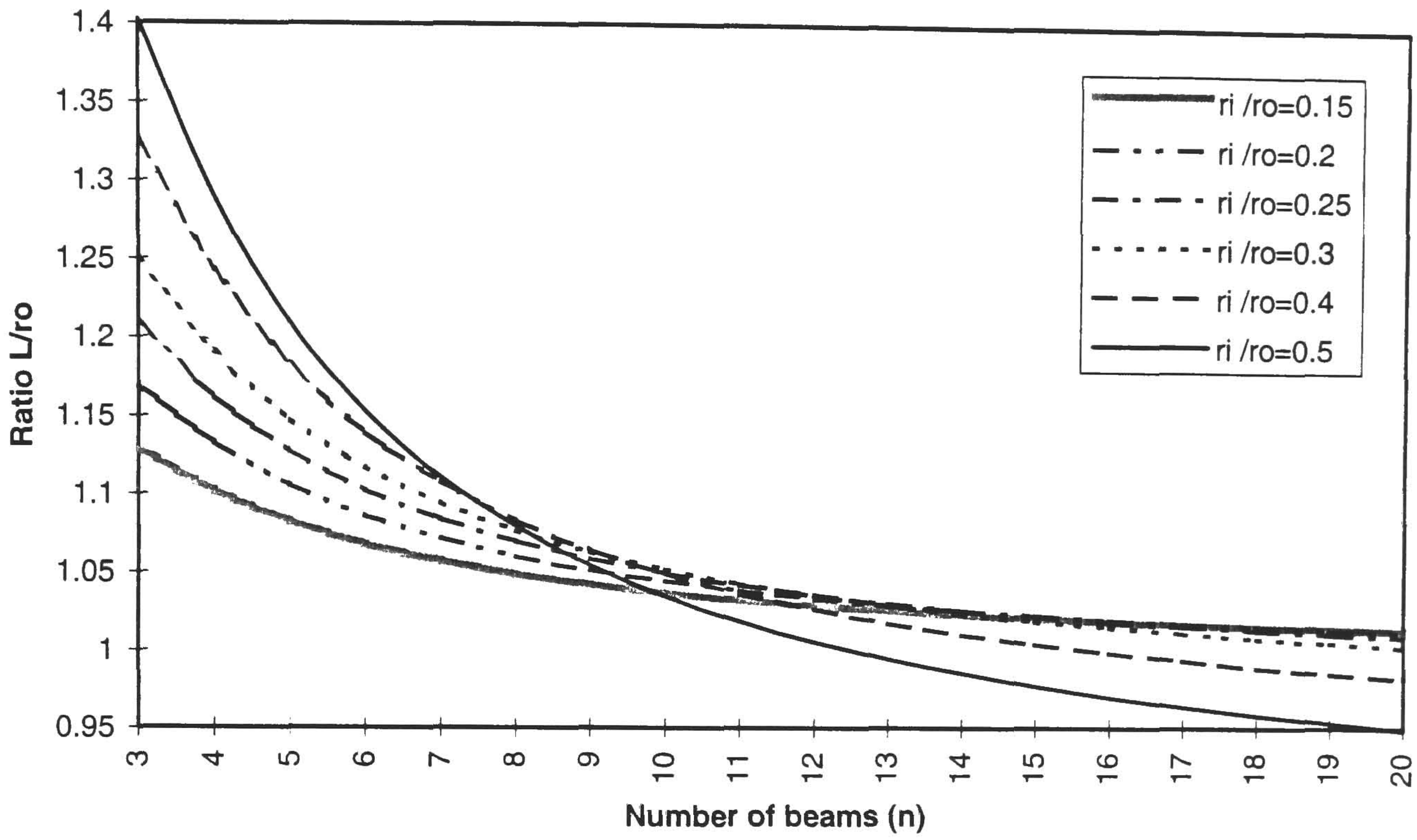


Figure 6.3. Relationship between the ratio L / r_o and number of beams for different ratios of r_i / r_o where H / r_o is 0.05

It can be seen from Figure 6.3 that as the number of beams in an RF is increased and all other parameters remaining constant, the length of the individual beams decreases. This effect is most noticeable for RFs with large r_i / r_o ratios that have a small number of beams. As the number of beams in the RF is increased, the curves tend towards a limiting value for L / r_o. These values are given in Table 6.1 for ratios r_i / r_o ranging from 0.15 to 0.5 and H / r_o in the range 0.05 to 0.3. The values have been calculated using the equation (6.8) below:

$$L = \left(r_o^2 - r_i^2 + H^2\right)^{\frac{1}{2}} \qquad (6.8)$$

	H / r_o					
r_i / r_o	0.05	0.01	0.15	0.20	0.25	0.30
0.15	0.990	0.994	1.000	1.009	1.020	1.033
0.20	0.981	0.985	0.991	1.000	1.011	1.025
0.25	0.970	0.973	0.980	0.989	1.000	1.014
0.30	0.955	0.959	0.966	0.975	0.986	1.000
0.40	0.918	0.922	0.929	0.938	0.950	0.964
0.50	0.867	0.872	0.879	0.889	0.901	0.917

Table 6.1 Limiting values of L / r_o for r_i / r_o ranging from 0.15 to 0.5 and H / r_o in the range 0.05 to 0.3.

Figure 6.3 is important because it shows the RF beam length for set ratios of the outer to the inner radius r_i / r_o and a chosen number of beams. Looking at Figure 6.3 and Table 6.1 it is obvious that if the total rise of the beams (H) is set to be equal to the inner radius (r_i), then the length of the beams (L) equals the outer radius (r_o). This practically means that although the beams in the RF structure are not radial, if the ratios between the parameters are chosen adequately, they could be set to have a length equal to the outer radius. Knowing the optimal length of the beams can be used in efficient design of modular RF buildings as well as for planing of the transportation from the workshop to the site.

The variation of the RF parameters was carried out to show how they can be adjusted to suit the architectural requirements (slope, number of beams, sizes of inner and outer polygons etc.) and at the same time not to conflict with the nature of the geometry of this 3-dimensional structure.

6.2. Irregular RF units and assemblies of multiple RFs

The preceding discussion on the geometry of the RF considered only regular polygonal plan forms (3 - 20 sided polygons). If some of the conditions of regularity are relaxed, some very interesting plan forms can be obtained. For example, if all the beams are not of the same length, the outer and the inner polygons need not be regular, and the angles between the beams can also be different. The case study undertaken in the student project, discussed in Chapter 5 (see pp. 5-1 - 5-28), showed that very interesting irregular RF morphologies can be developed. Also, the questionnaires and interviews revealed that the students tended to be in favour of irregular forms, which, according to them, were architecturally more interesting (see Chapter 5, section 5.3.2, pp. 5-45 and 5-46).

In the case of application of irregular RF forms the geometry becomes more complex than when regular RF structures are used. In order to define the geometry of these structures the irregularity needs to be described for each individual case. This has not been pursued as part of this research project because it was felt unnecessary. However, some possibilities of different RF plan forms are presented in Figure 6.4 (a-h).

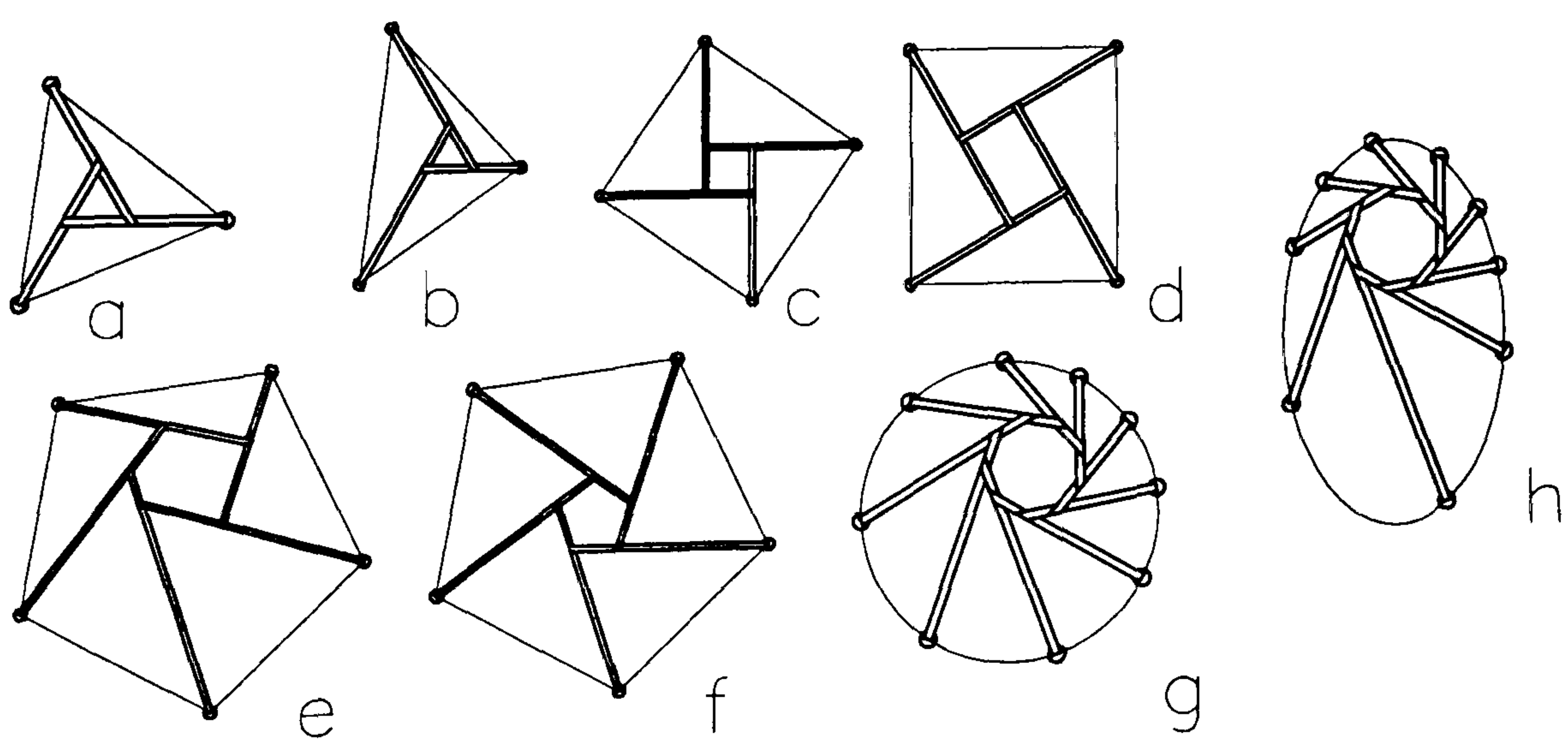


Figure 6.4 (a-h) Some examples of regular and irregular RFs

Figures 6.4 a., 6.4 c. and 6.4 f. show regular and symmetrical RF configurations, where the inner and the outer polygons have a number of sides equal to the number of beams in the RF. All of the beams have the same length and slope, and, as a result of this, the inner polygon is in the center of the structure. It can be seen that the inner polygon is slightly rotated relative to the outer polygon, which is because the beams are offset from the centre. For RF structures with big openings relative to the overall span of the roof, the inner polygon will be rotated more because the RF beams in this case are more offset, compared to RF structures with small openings relative to the overall span of the roof.

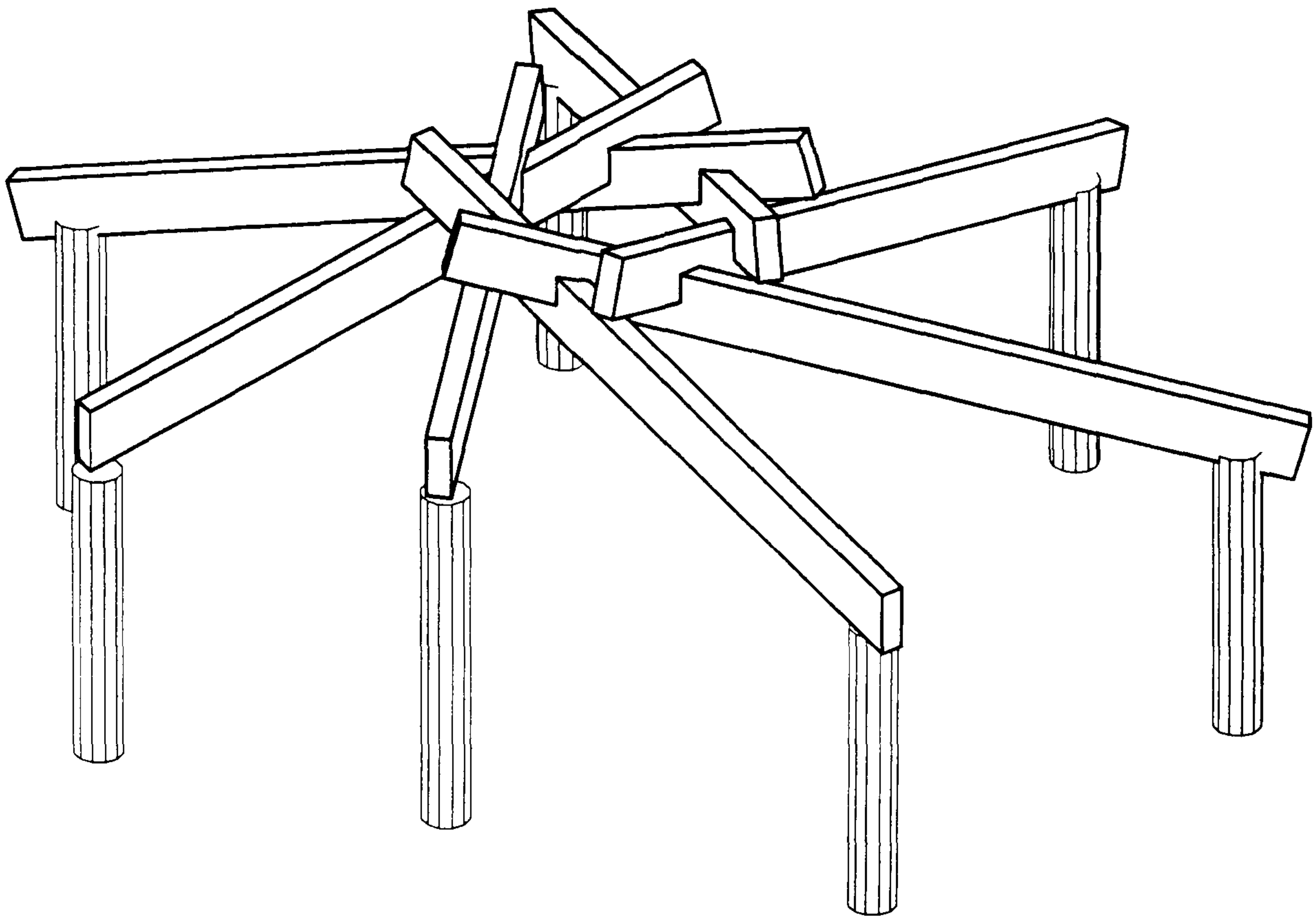
On the other hand Figures 6.4 b., 6.4 d., 6.4 e., 6.4 g. and 6.4 h. show RF configurations where some of the conditions of regularity have been relaxed.

The three beam RF configuration (Figure 6.4 b) is constructed to accommodate a three sided irregular polygonal plan form, and as a result of this, the beams have different lengths and also the inner polygon, which is regular, is not at the centre of the roof. In the four beam RF configuration presented on Figure 6.4 d. the length of the beams is different (there are two pairs of beams of the same length), but the inner polygon is centred in plan. In the nine beam RF configuration, presented in Figure 6.4 h., the inner polygon is not centred in plan and the beams have different lengths and slopes.

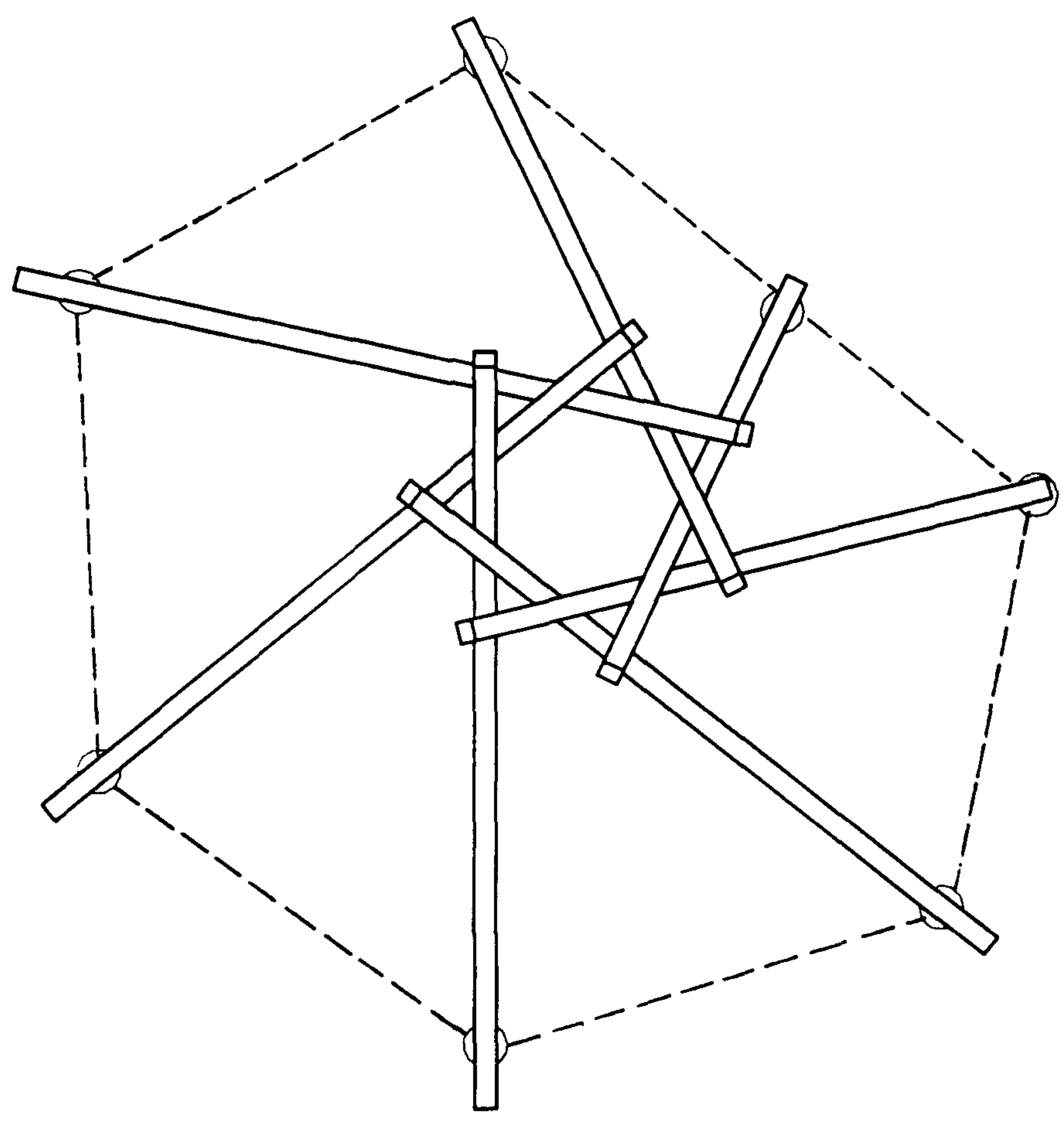
The configurations presented in Figures 6.4 e. and 6.4 g. are also constructed from beams with different lengths and Figure 6.4 e. has an inner polygon which is not symmetrically positioned with respect to any axis of symmetry, the inner pentagon being irregular, while the outer is regular. In Figure 6.4 g. the inner nine-sided polygon, which has been inscribed into a circle is offset from the centre of the circular plan.

As discussed previously in detail in Chapter 5 (pp. 5-7 - 5-28), all of these configurations both regular and irregular, symmetrical and asymmetrical, show the great variety of plan geometries which can be obtained with the RF. This undoubtedly adds considerably to the architectural potential of this structure.

An example of an irregular RF structure with beams having the same slope but of different lengths is presented on Figures 6.5 a. and 6.5 b. This shows us how a regular RF can be transformed into a an irregular one by shortening the beam lengths and using columns of different height.



Figures 6.5 a. An example of an irregular RF structure - 3-dimensional view



Figures 6.5 b. An example of an irregular RF structure - plan view

In the student case study single units of RF structures were connected together to form assemblies, refered to as multiple RFs, which are a successful solution for spanning long distances with relatively short beams without any internal supports, as presented in Chapter 5, section 5.2.1.3, pp. 5-18 - 5-22. Also, the Seiwa Bunraku Puppet Theatre is a good example of a multiple RF structure (see Chapter 3, section 3.3.3, pp. 3-15 - 3-17).

Two examples of assemblies of RF structures are presented in Figure 6.8 a. and Figure 6.6 b. Figure 6.6 a. shows an RF assembly which accommodates a triangular plan form, with four regular three-beam RF single units. The whole structure is supported by columns positioned under the outer ends of the beams. In this example, the beams of the three outer single RFs spiral in the same direction and the one in the middle spirals in the opposite direction. A further interesting variation can be created if the beams in each following single unit spiral in the opposite (clockwise and anti-clockwise) direction. Also, similar assemblies can be constructed from single units with a different number of beams, or with irregular single units.

Figure 6.6 b. also shows an assembly of several regular RF structures but in this case they are stacked one upon another. The largest (outer) RF has twelve beams and supports a smaller twelve-beamed RF on its inner polygon. In turn, an even smaller six-beamed RF fills the central opening of the smaller twelve-beamed RF. Of course it is possible to continue this process using ever smaller RFs but in reality a small, more conventional, capping structure fills the central occulus when it becomes small enough. Further interesting variations can be achieved by reversing the direction of the spiral for each RF in the assembly and/or by having alternate rings composed of upward and downward sloping beams. Again, visually exciting 3-dimensional structural configurations are generated which are particularly striking if exposed within the architectural space.

In the case of these two interesting multiple RF configurations the complexity of the geometry obviously increases. Describing the geometry of a multiple complex

RF configuration consisting of regular units, practically means defining the geometry of the single units as well as the interrelationships of the individual units within the complex system. For irregular multiple RFs, describing the geometry of the system would be even more complicated as it would require defining the irregularity of each individual unit and the interrelationships of the individual units.

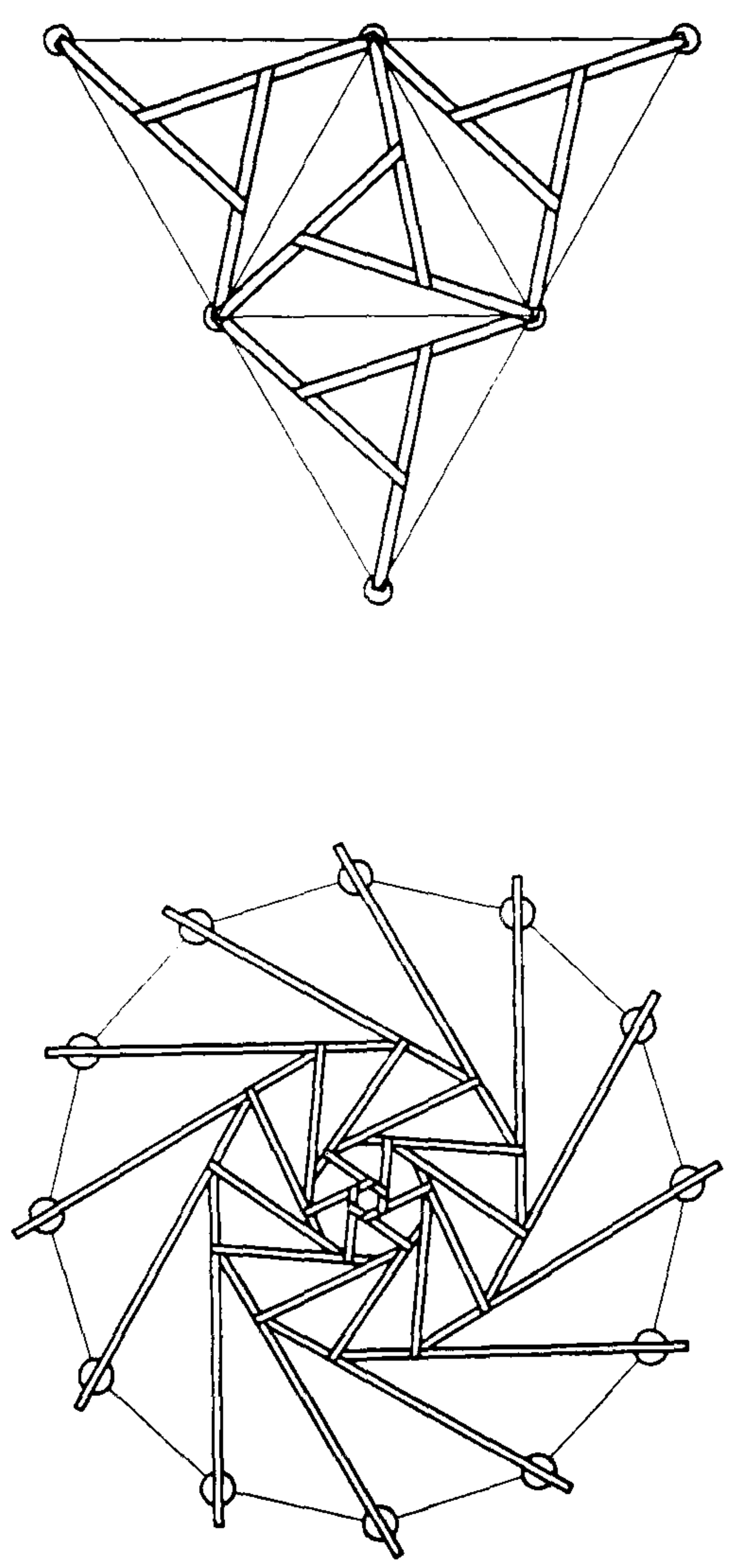


Figure 6.6 a. and 6.6 b. Multiple RF structures

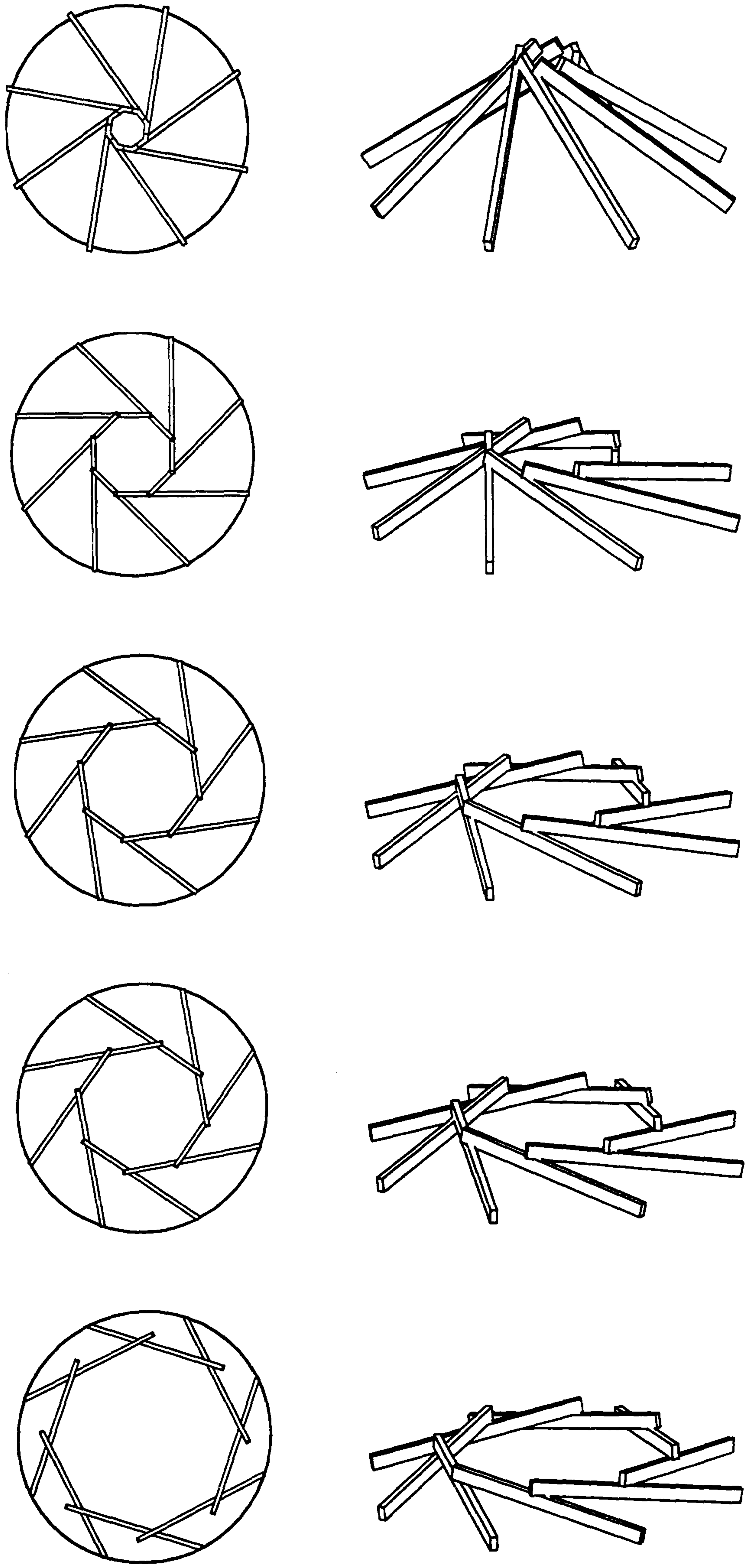
6.3. Retractable RF structures

Since the time when the first Olympic games were established people have been concerned with the design of sports stadia which provide an equally good view to all the spectators at the event. Therefore, sports arenas were usually designed with seats on a sloping plane forming a circle or a elliptical shape in plan. Also, people wish to be protected from adverse weather conditions. Thus, a number of mobile 'kinetic' structures (discussed in detail in Chapter 2, section 2.1.4., pp. 2-19 - 2-28) have been designed which can open and close as the weather conditions dictate.

Since the beams of the RF in plan remind one very much of the lines forming the iris of a camera shutter, it is very easy to envisage the possibility of a retractable RF (Chilton, Choo and Coulliette, 1994). Although no full scale retractable RF structures have been constructed to date, there is no reason why they could not be constructed in the future.

During the retraction process each beam would rotate both about a vertical axis and a horizontal axis perpendicular to the beam at its external support. If the beams are restrained in position at the outer supports, then at the inner support the upper beams would slide along and across the lower beams. Since all the beams would rotate simultaneously, the structure would look very much like the leaves of the iris diaphragm. For regular forms the angle (in plan) between the beams would remain constant during retraction.

Figures 6.7 (a.-e.) show plan and 3-d views of the RF designed as a retractable roof structure, at the different stages of retraction. All diagrams, especially the plan views, show the resemblance of the structure to a camera shutter. Although it appears that there is a similarity with Hoberman's solution for a retractable dome structure (Iris Dome), discussed in Chapter 2, section 2.1.4, p. 2-27, there are considerable differences. The only similarity is that they retract leaving a central void.



a.

b.

c.

d.

e.

Figure 6.7 a.-e. Retractable RF structure at different stages of retraction

6.3.1. Geometry of the retractable RF

The geometry of a retractable RF is determined in every retracted step by the same parameters as static RFs, as described earlier in this chapter. In the case of retractable RFs, the changes of the vertical and horizontal angles, due to the 3-dimensional rotation of each beam around its own support, also need to be defined. This can be achieved by determining the co-ordinates (x and y) of the projection in plan of the points where the beams intersect. For a regular polygonal plan, for example, as shown in Figure 6.8, the angle of beam 2 related to the x-axis is given in equation (1), where α_1 is the angle that beam 1 forms with the x-axis. The plan length of the beam from perimeter support to lower intersection (a) and from perimeter support to high intersection (b), can be found easily if the distance (s) between perimeter supports and the number of beams (n) are known (see equations 6.10 and 6.11).

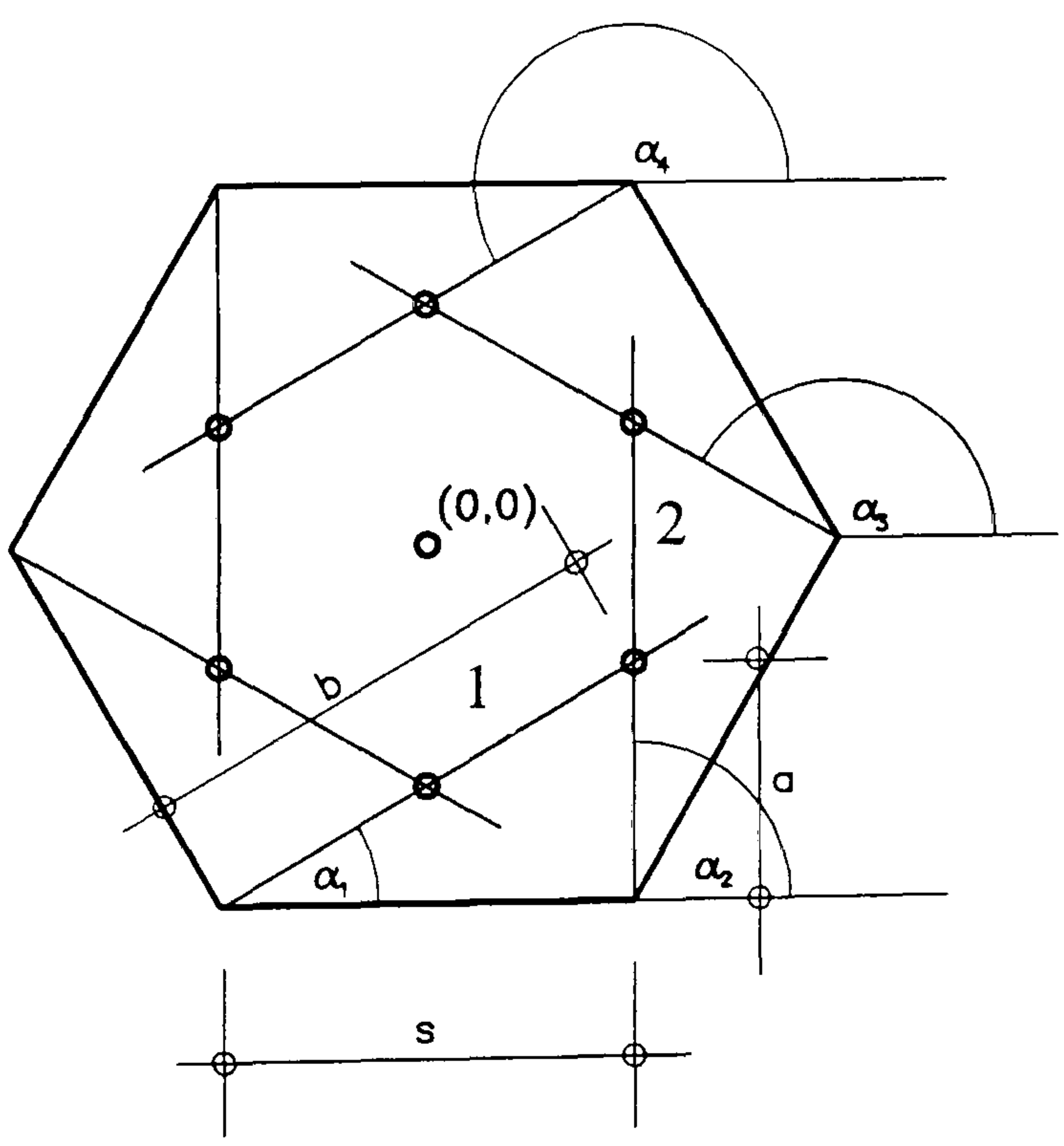


Figure 6.8. Plan geometry of a retractable RF

$$\alpha_2 = \alpha_1 + \frac{360}{n} \qquad (6.9)$$

$$a = \frac{s}{\left\{ \left(\frac{\cos\alpha_1 \sin\alpha_2}{\sin\alpha_1} \right) - \cos\alpha_2 \right\}} \tag{6.10}$$

$$b = a\frac{\sin\alpha_2}{\sin\alpha_1} \tag{6.11}$$

When the horizontal angles α are known it is very easy to determine the beam slope angle β, for a known depth of beam.

$$\beta = \sin^{-1}\left(\frac{d}{b-a}\right) \tag{6.12}$$

As an example, the relationship between angles α_1 and β is plotted in Figure 6.9 for a hexagonal roof with perimeter length of 5m and depths (d) of 500mm, 1000 mm and 1500 mm.

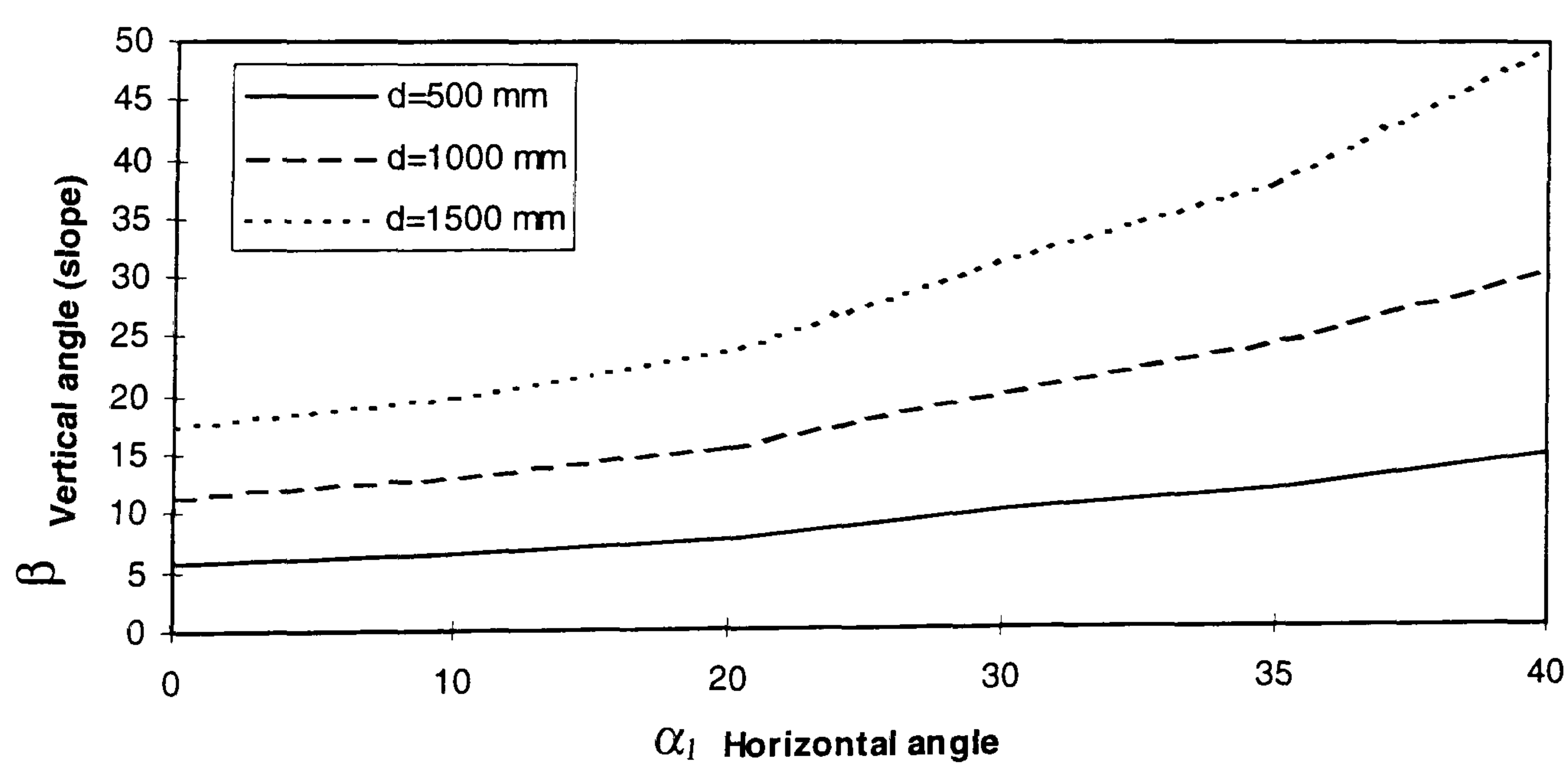


Figure 6.9. Relationship between beam horizontal angle α_1 and beam slope β

From Figure 6.9 it can be noted that:

- as the beams come closer to the fully closed position, the rate of change of the vertical angle β increases i.e., the slope of the beams changes considerably even for a very small change of the horizontal angle between the beams, and
- this effect is more pronounced for structures with a large dimension (d),
- if d=0, then the roof remains horizontal during retraction.

The first observation can be seen also in Figure 6.7 (a.-e.), which shows that as the beams approach the closed position the pitch of the beams increases very rapidly. Since the pitch depends very much on the vertical distance between beam centrelines at the intersections, this could be a problem when deep beams are used, as is the case when spanning large distances (as in sports stadia and arenas). A way to overcome this problem would be to use beams with a changing cross section that tapers towards the end of the beam, and increases towards the middle of the beam, e.g. a 'fish belly' shaped beam. This form is appropriate since the maximum bending moment in the beams usually occurs in the lower beam at or near the point of intersection, while in the upper beam there is no bending moment but a high vertical shear force where it rests on the lower beam.

6.3.2. Retraction of the RF

The RF becomes a retractable roof structure, as previously mentioned, when each beam rotates around its outer support and slides on the supporting beam. Therefore, the supports need to be designed as hinges, with certain boundary conditions. The investigation carried out on models, presented later in this chapter, shows that there are two basic mechanisms with different boundary conditions that permit rotation of the beams and make the structure retractable:

- a hinge that allows rotation in both the horizontal and vertical planes and constrains the sliding of the beam at the support (requires sliding in two directions at the intersection), and
- a hinge that allows rotation in both the horizontal and vertical plane, but also allows the beams to slide outwards during retraction (requires sliding in one direction only at the intersection).

The first solution for the mechanisms includes vertical and horizontal pins around which the outer ends of the beams rotate, while the inner ends slide on each other. As a result of this, each beam makes a 3-dimensional curved path and retraction is achieved. Since the horizontal movement (outwards) of each beam is constrained at the outer supports, the inner end of each beam slides across its supporting beam as well as along it.

In the second case, since the solution for the mechanism does not constrain the horizontal movement of the beams, they slide outwards at their outer ends while retracting. At the inner end the upper beam slides along a track on the top of the lower beam and rotates about a horizontal hinge.

In the first case, the support conditions at the perimeter are simpler in terms of practicality, since a vertical pin allows rotation of the beam in plan and a horizontal pin with its axis perpendicular to the beam centreline permits the required changes in beam slope. However, at the inner support, the connection must accommodate the movement of the point of beam intersection simultaneously along both beams and the change in slope of both beams during retraction.

On the other hand, the retraction achieved by sliding the upper end of the upper beam along the line of the top of the lower beam (the second solution), probably provides a more practical method for retraction of the beams. The outer support needs to be designed so that the horizontal movement of the beams (sliding outwards) can be controlled during retraction of the roof. On the model built this movement was controlled only by the friction which would obviously not be and cladding between the RF beams. Figures 6.10 and 6.11 show photos of the small scale models built.

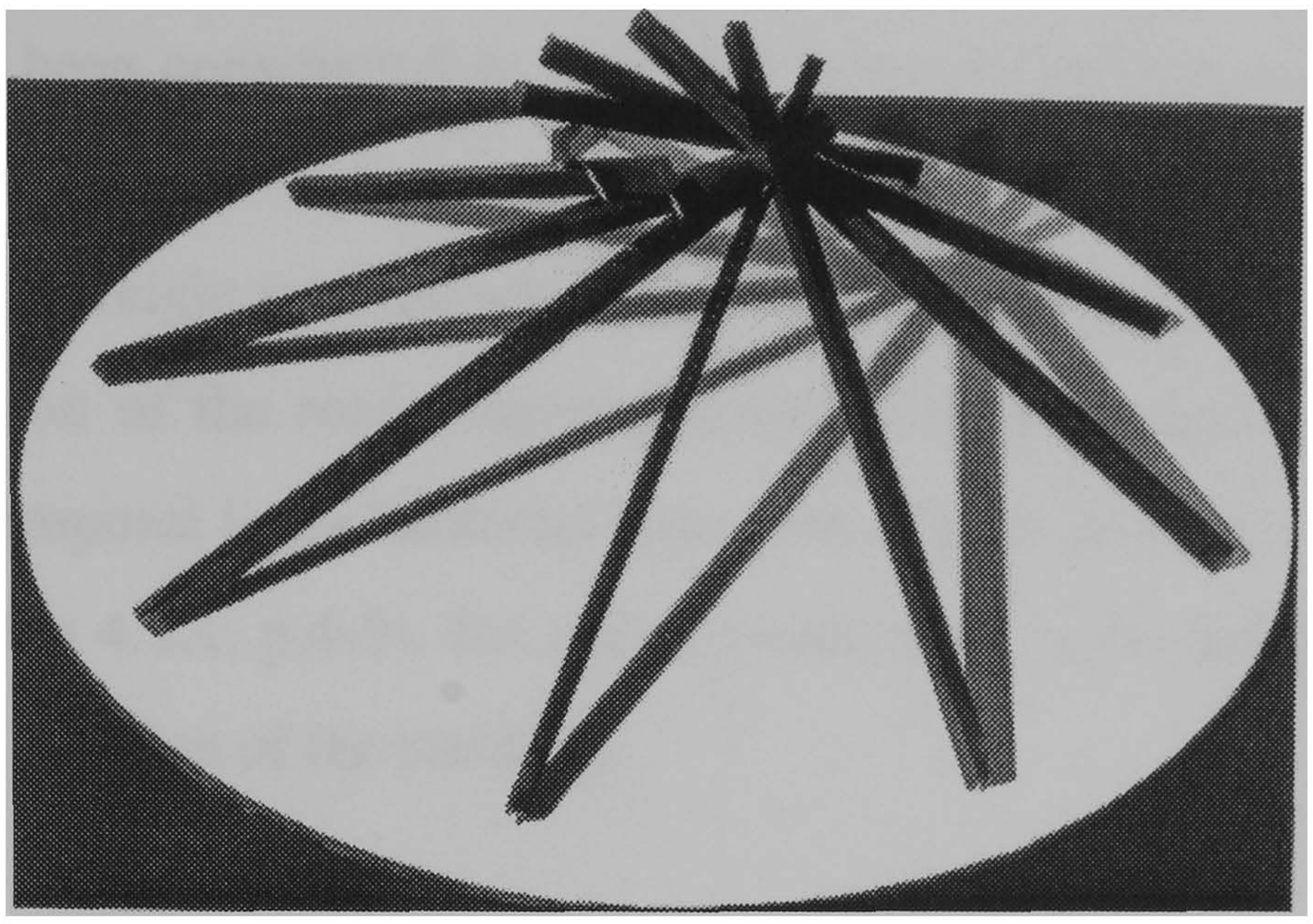


Figure 6.10 Model of the retractable RF structure where the beams are held in position at the perimeter supports

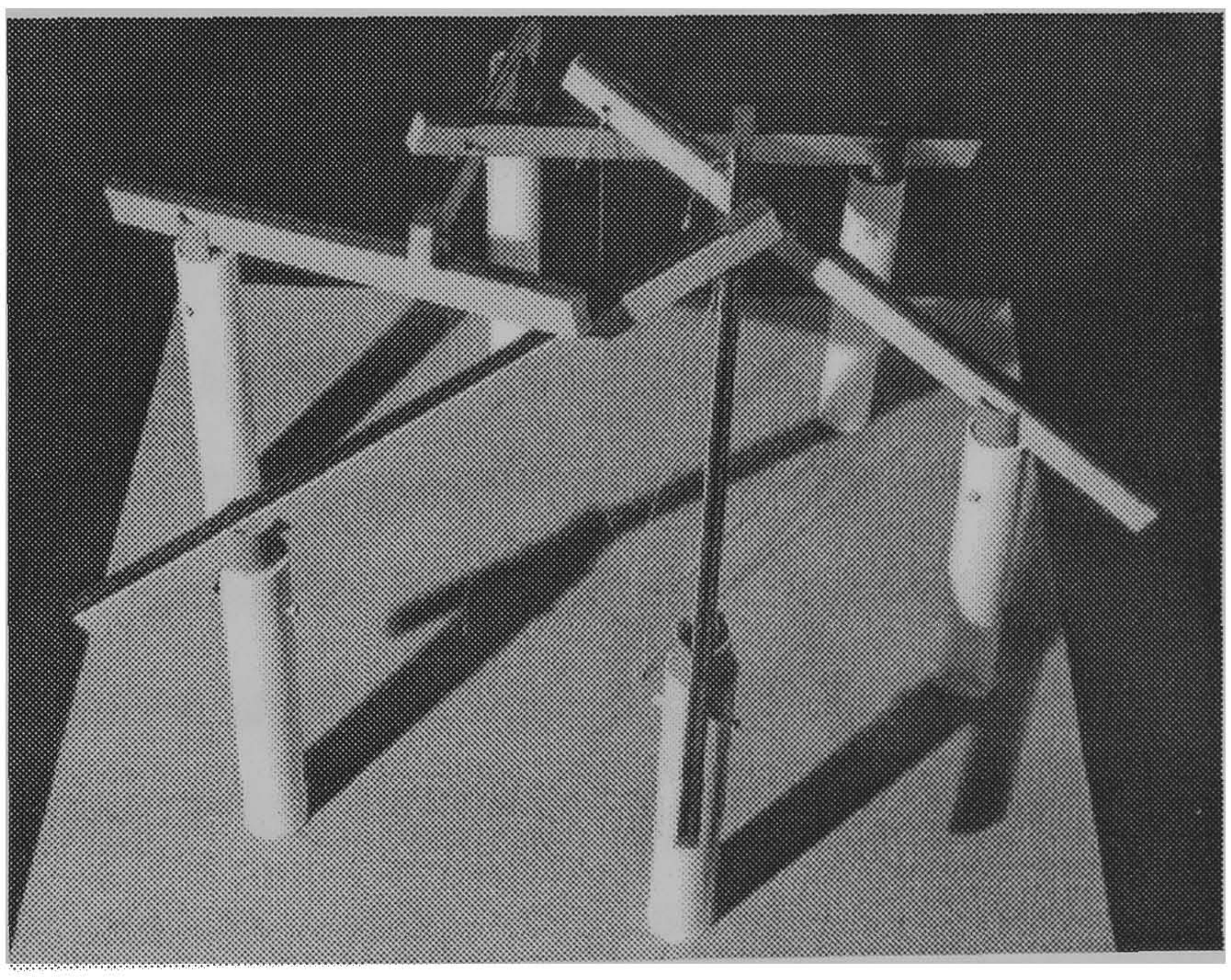


Figure 6.11 Model of the retractable RF structure where the beams are permitted to slide outwards at the perimeter supports

6.4. Covering the RF structure

There are several possible ways of covering RF structures. Since no retractable RF structures have been constructed to date, the ways of covering the RF structure described below are for static roofs. The retractable RF structures should be covered with lightweight systems which should be designed to retract in sequence with the retraction of the roof. Appropriately designed membranes would be a solution. One proposal is the 'umbrella' type covering (as presented on Figure 4.1, Chapter 4, section 4.1.1, p.4-3), but others would need to be designed depending on the span and function of the buildings.

All of the buildings constructed recently in the UK, described in detail in Chapter 5, use inclined panels between the beams. Flat roof panels are fixed to the top of each beam and to the side of the adjacent beam on which the first beam rests. Covering the roof in this manner produces a vertical step at each beam and this exposes the morphology of the RF structure both internally and externally.

Another possible way of covering RF roof structures is to use a more conventional conical surface, formed by radial rafters supported on purlins that are, in turn, supported by the beams of the RF. This is the method employed at the Seiwa Bunraku Puppet Theatre, in Kumamoto, Kyushu, Southern Japan, as described in Chapter 3 (see section 3.3.3, pp. 3-17 - 3-19). In this case the RF structure is concealed from the outside, whilst being exposed internally, thus maximising the visual impact of the non-conventional beam geometry when entering the building.

Another solution is to use double-curved, hyperbolic paraboloid surfaces which can be generated if a series of secondary beams are used to connect equivalent positions on adjacent RF beams.

The author knows of no examples of buildings having RF roofs that are covered with fabric membranes but there is no reason why this solution should not also be applicable.

They could be used in a great variety of forms, either to cover the triangular sectors that exist between the beams with individual membranes, or to cover the RF structure as a whole with one double curved surface. Additional curvature can be induced in the membranes by supporting them using struts suspended by cables or rods. Suitable anchorage points for the cables or rods exist at the outer beam ends and around the inner ring of beam intersections. Some proposals for alternative membrane covering systems are presented in Figures 6.12 and 6.13.

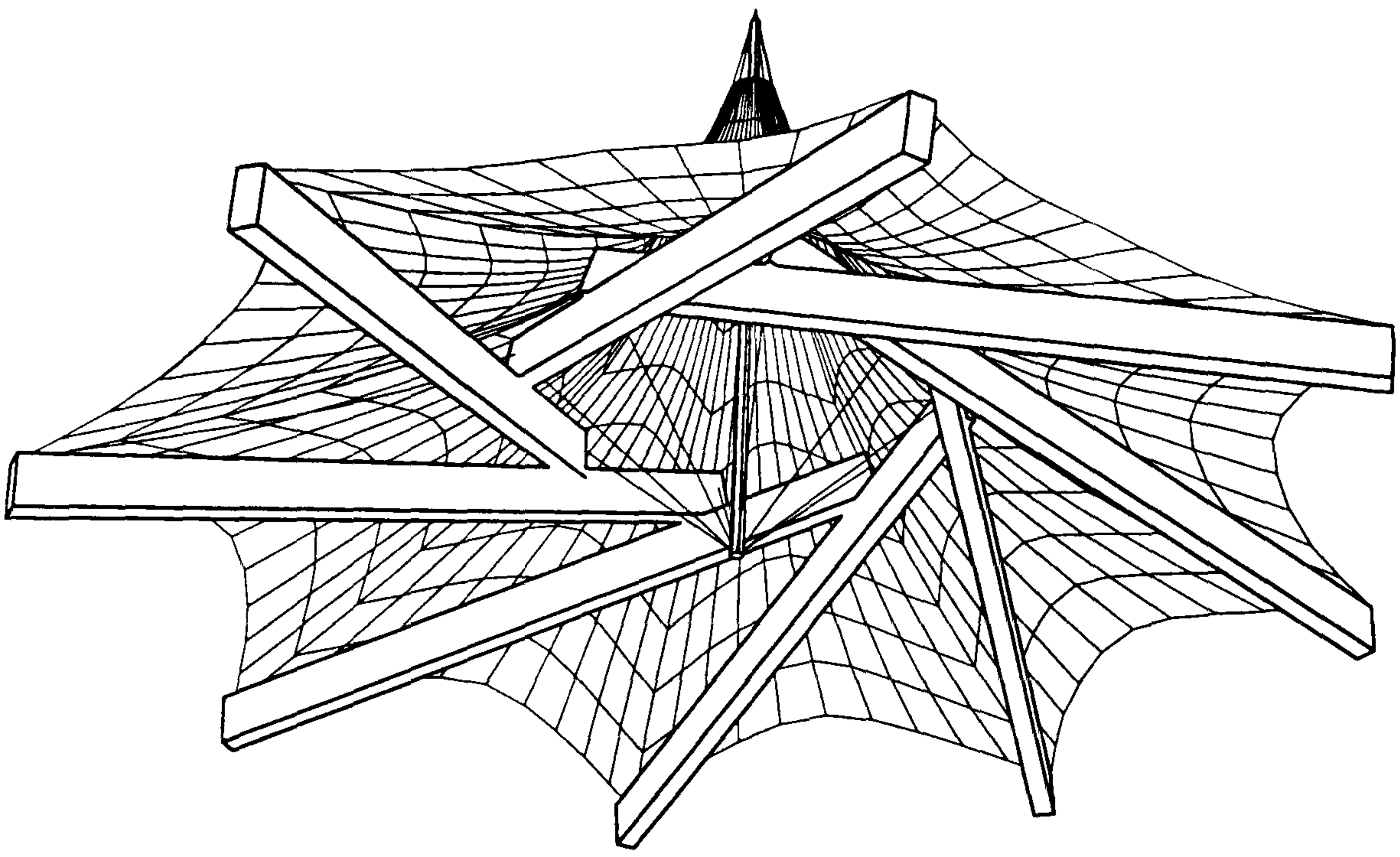


Figure 6.12. Single membrane used to enclose the RF

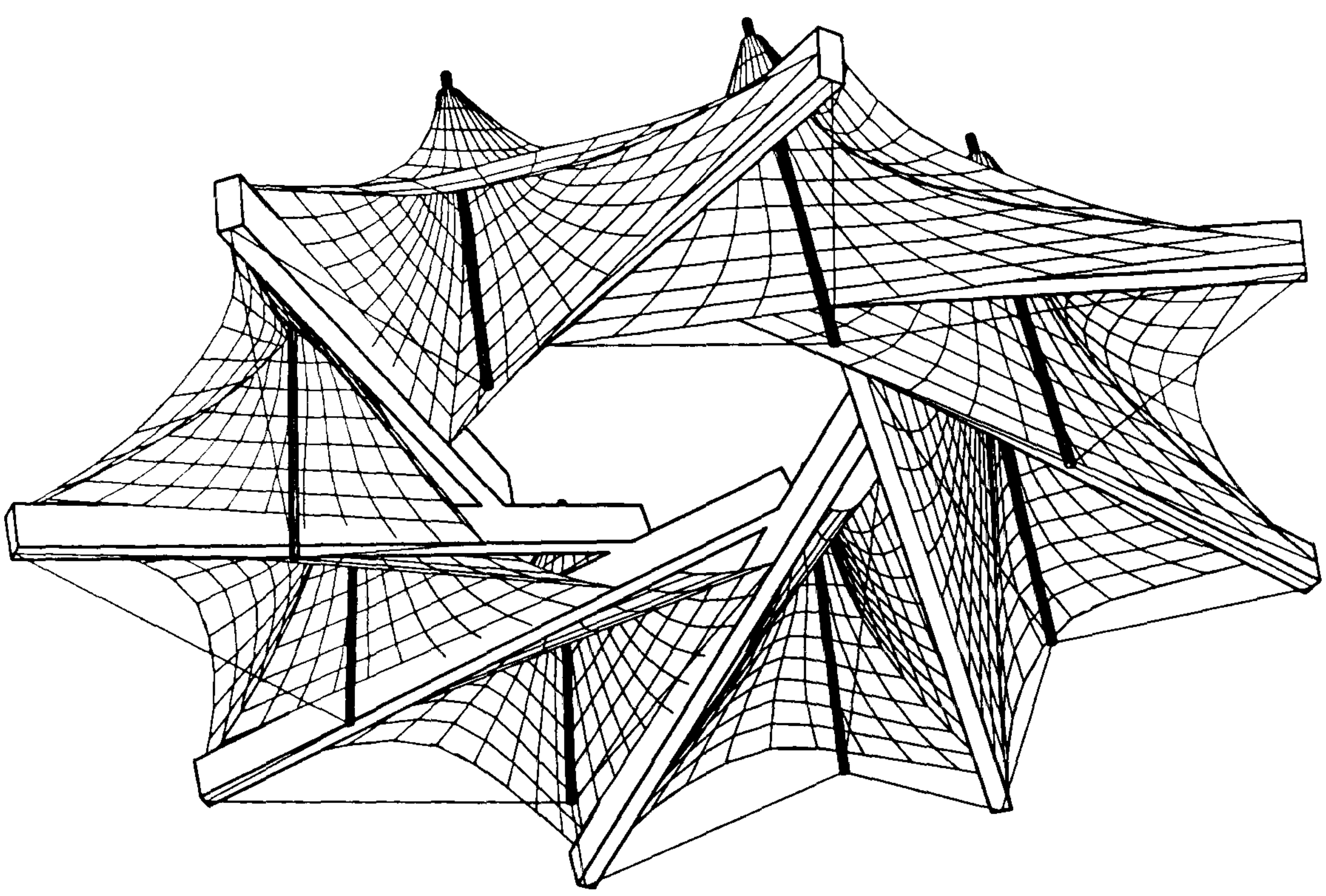


Figure 6.13. Several membranes used to enclose the RF

6.5. Statics of a four beam RF assembly

In order to show how the size of the inner opening affects the magnitude and distribution of the shear forces and moments, two examples of regular planar four beam RF assemblies with point loads are presented. The moment and shear force diagrams of a typical RF member are presented for different sizes of the inner polygon.

6.5.1. Regular planar four beam RF assembly loaded with four equal point loads where the beams rest on each other

If a four beam RF assembly (presented on Figure 6.14) is loaded with four equal point loads where the beams rest on each other, all reactions at the outer ends of the beams equal the point load (P). The inner reactions can be obtained considering a typical RF member (beam) and using the condition that the moment at the support equals zero (see Figure 6.15).

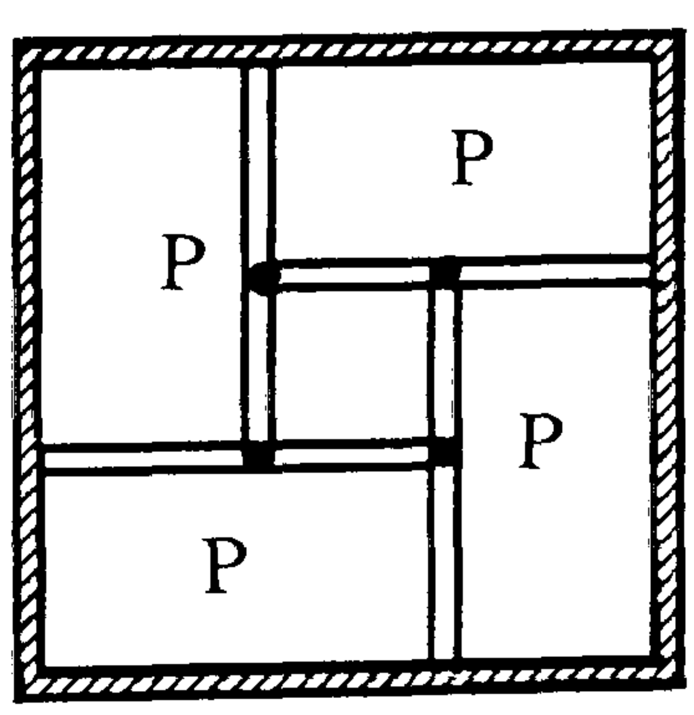


Figure 6.14 Four beam RF assembly with four point loads where the beams support each other

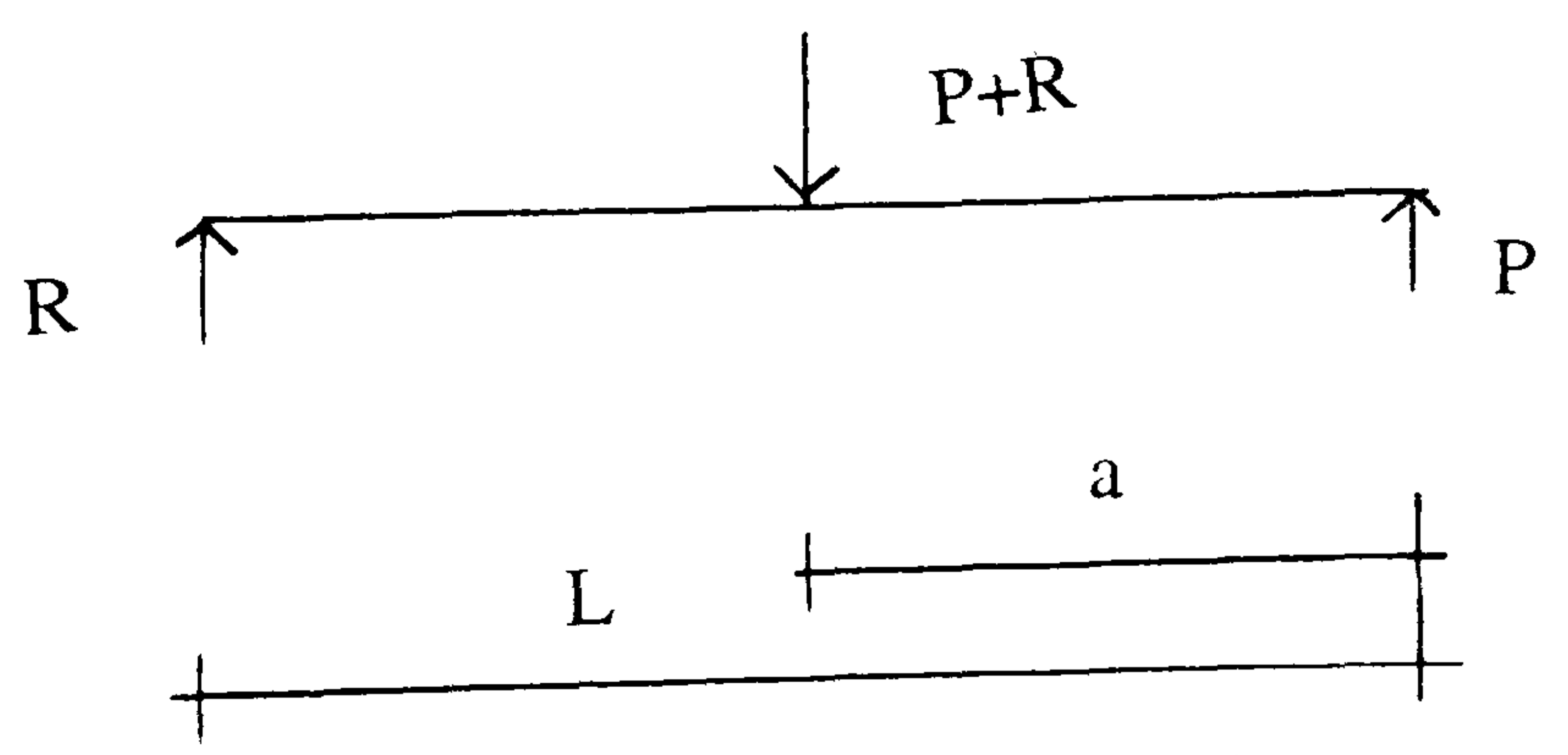


Figure 6.15. Typical RF beam

$$\sum M_A = 0 \qquad (6.9)$$

$$(R+P)\,a - R\,L=0 \qquad (6.10)$$

$$R = \frac{(R+P)a}{L} \qquad (6.11)$$

$$\frac{R}{L} = \frac{\frac{Pa}{L}}{1-\frac{a}{L}} \qquad (6.12)$$

Equation 6.12 can be derived by using the condition that the moment in A equals zero. Figure 6.16 shows that for small inner openings the shear force (R) is large and as the inner opening becomes bigger, R decreases. The shear force and moment diagrams of one typical RF beam for different sizes of inner polygons are presented on figures 6.17 a., b., and c.

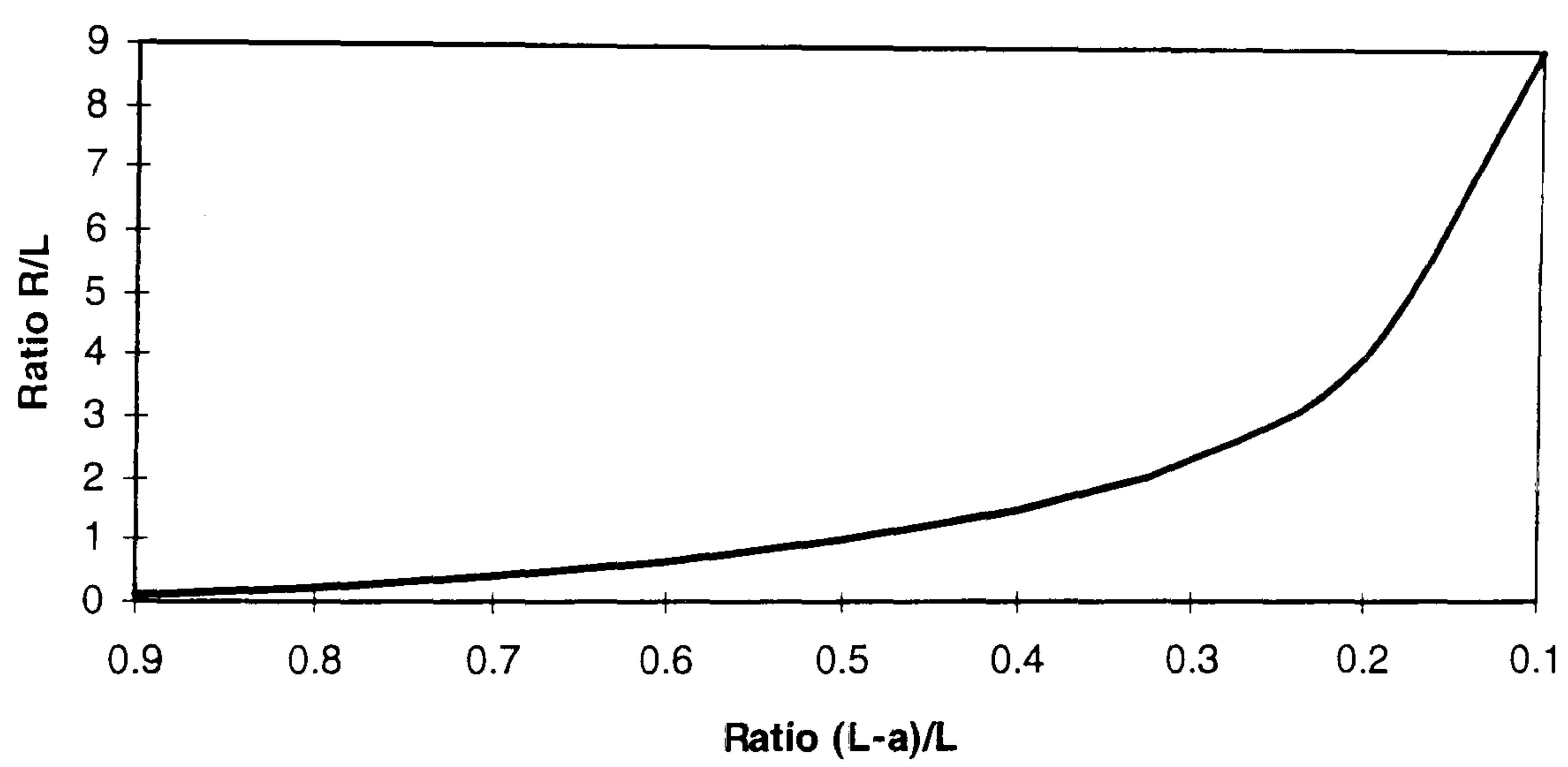


Figure 6.16. Relationship between R/L ratio and the size of inner opening

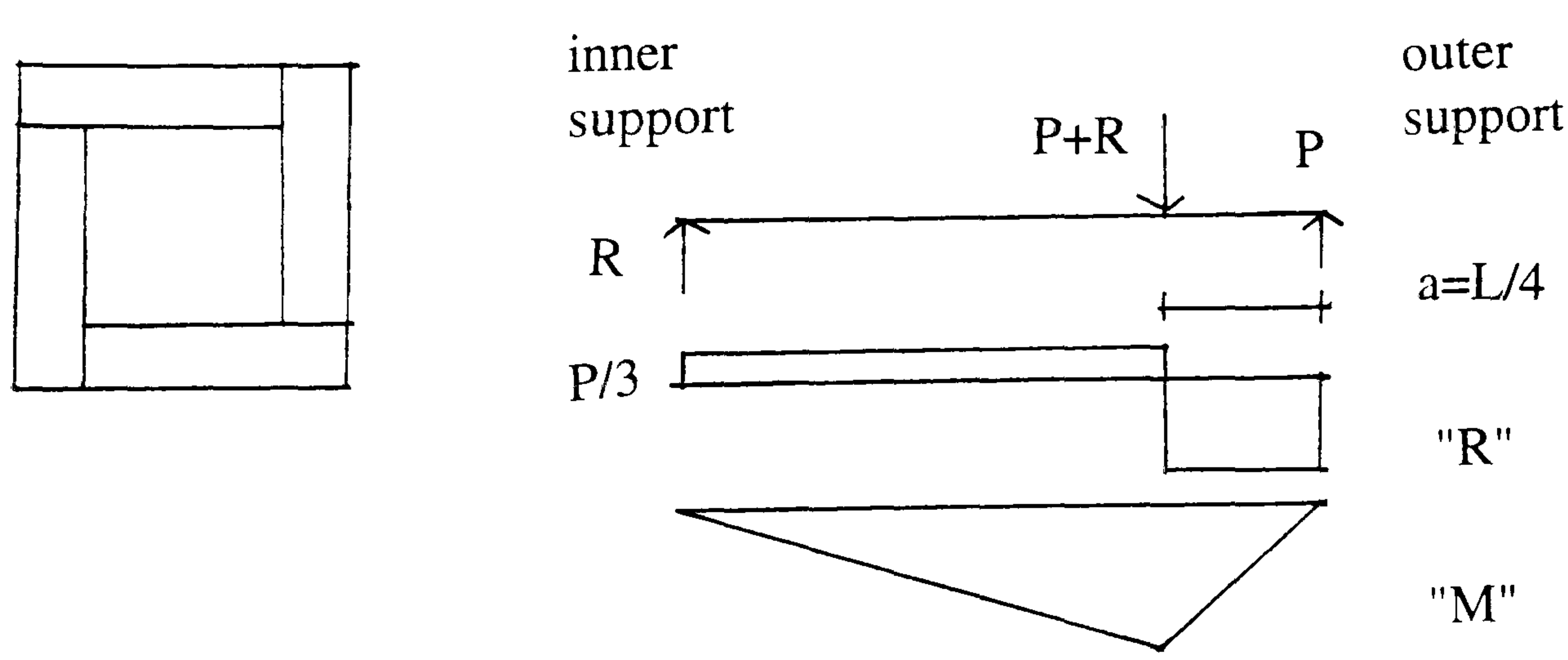


Figure 6.17 a. Shear force and moment diagrams for a=L/4

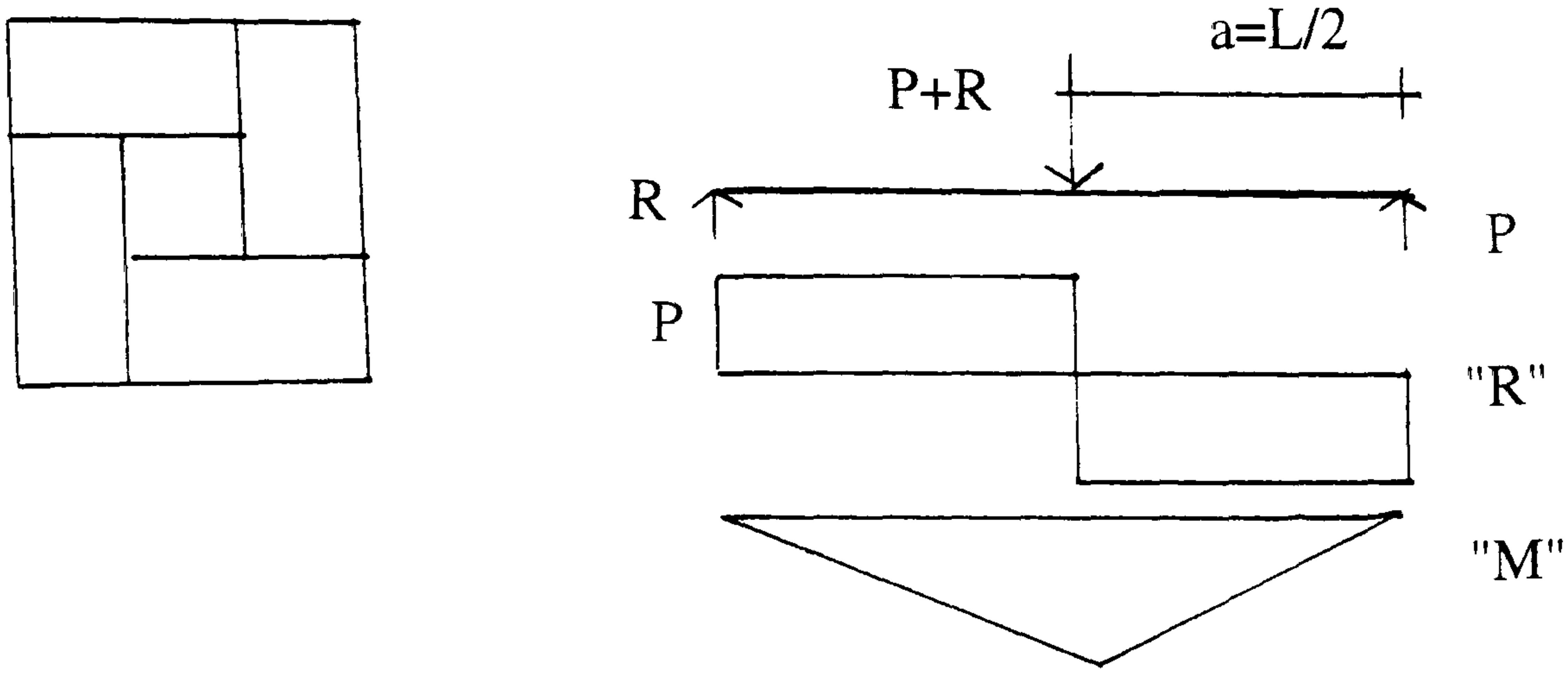


Figure 6.17 b. Shear force and moment diagrams for a=L/2

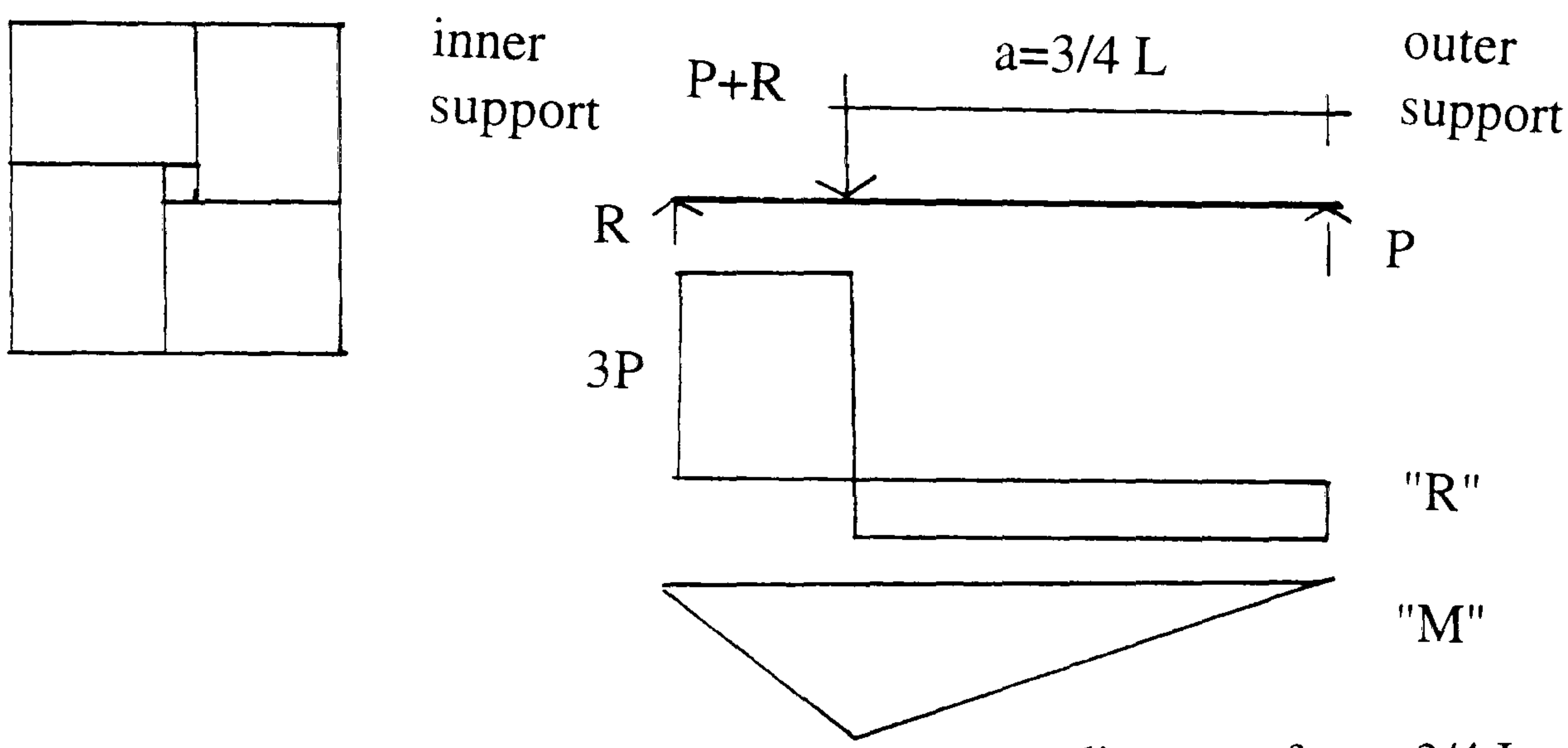


Figure 6.17 c. Shear force and moment diagrams for a=3/4 L

6.5.2. Regular planar four beam RF assembly loaded with one point load

If a four beam RF assembly (presented in Figure 6.18) is loaded with one point load it can be shown, similarly as in the previous case, that as the size of the inner polygon increases the shear force decreases. RFs with big openings will have considerably smaller shear forces compared to RFs with small openings.

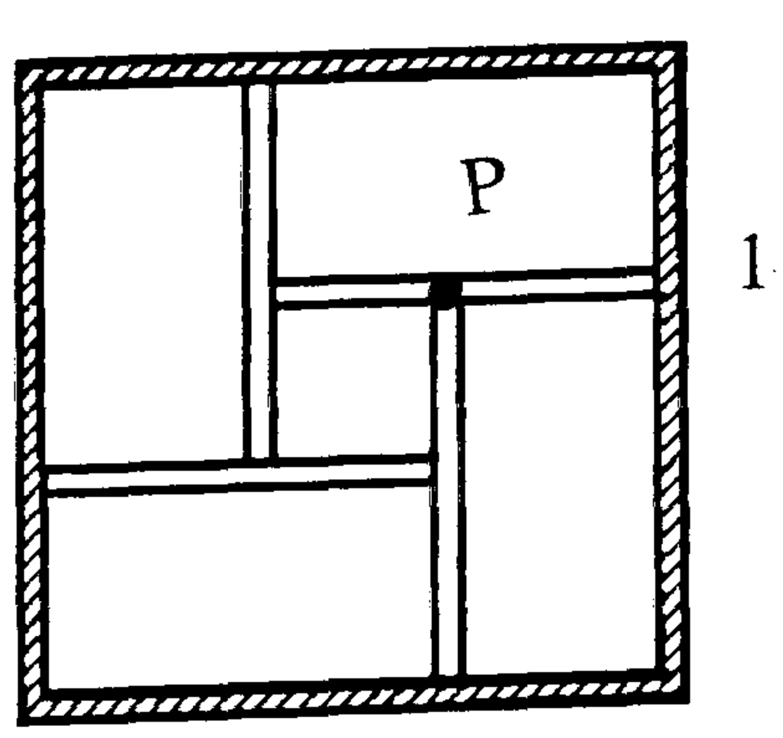


Figure 6.18. Four beam RF assembly loaded with one point load

The only difference between this loading case and the previous one is that when one point load is applied, the four RF beams will take different portions of the load. The shear force and moment diagrams of beam 1 of the RF assembly loaded with a point load for different sizes of inner polygons, are presented on figures 6.19 a., b., and c.

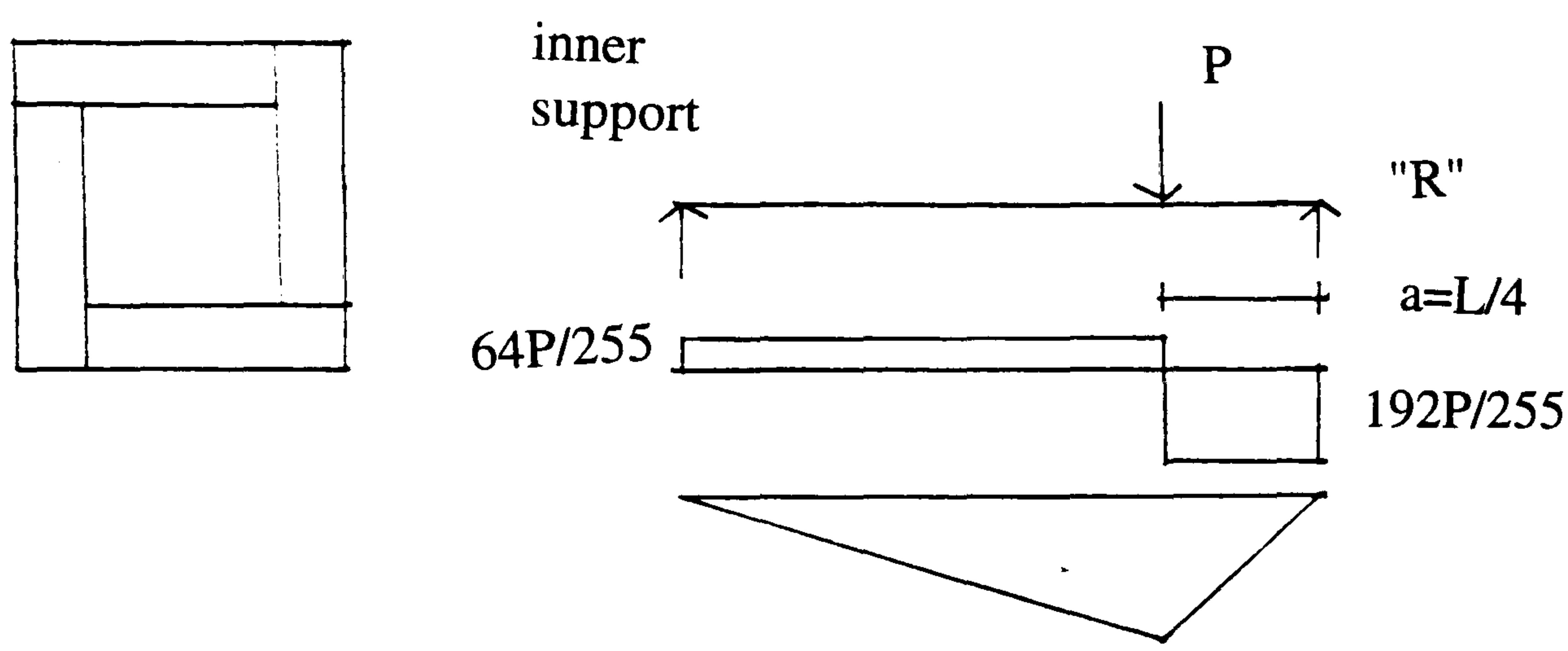


Figure 6.19 a. Shear force and moment diagrams for a=L/4

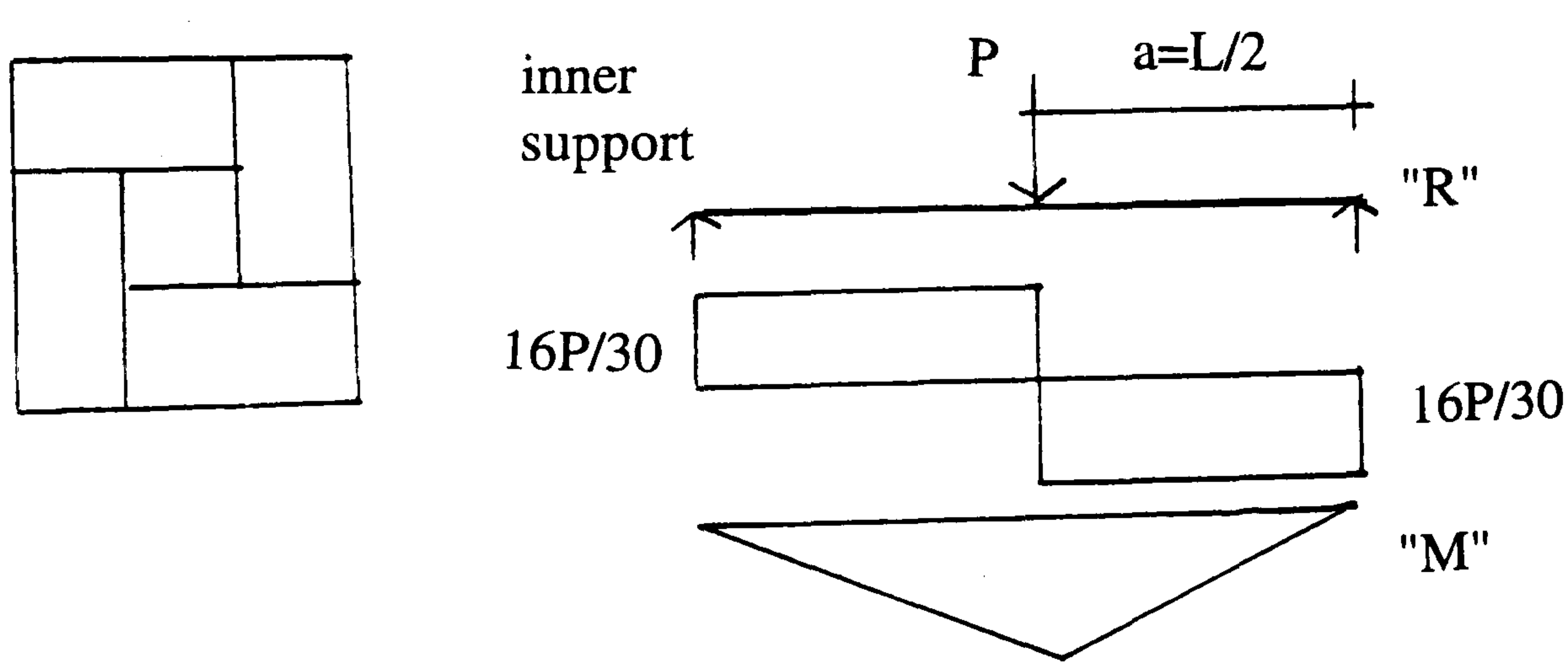


Figure 6.19 b. Shear force and moment diagrams for a=L/2

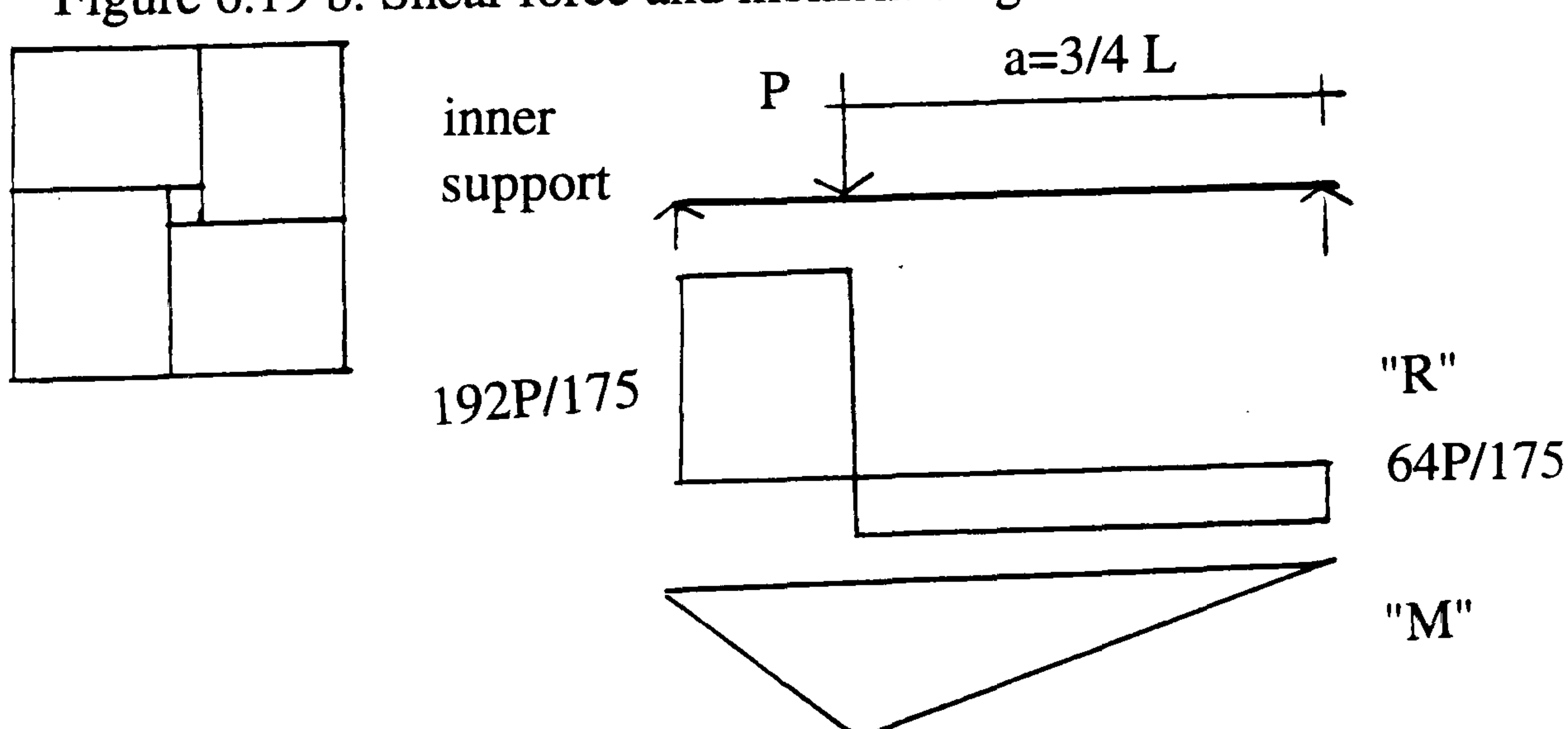
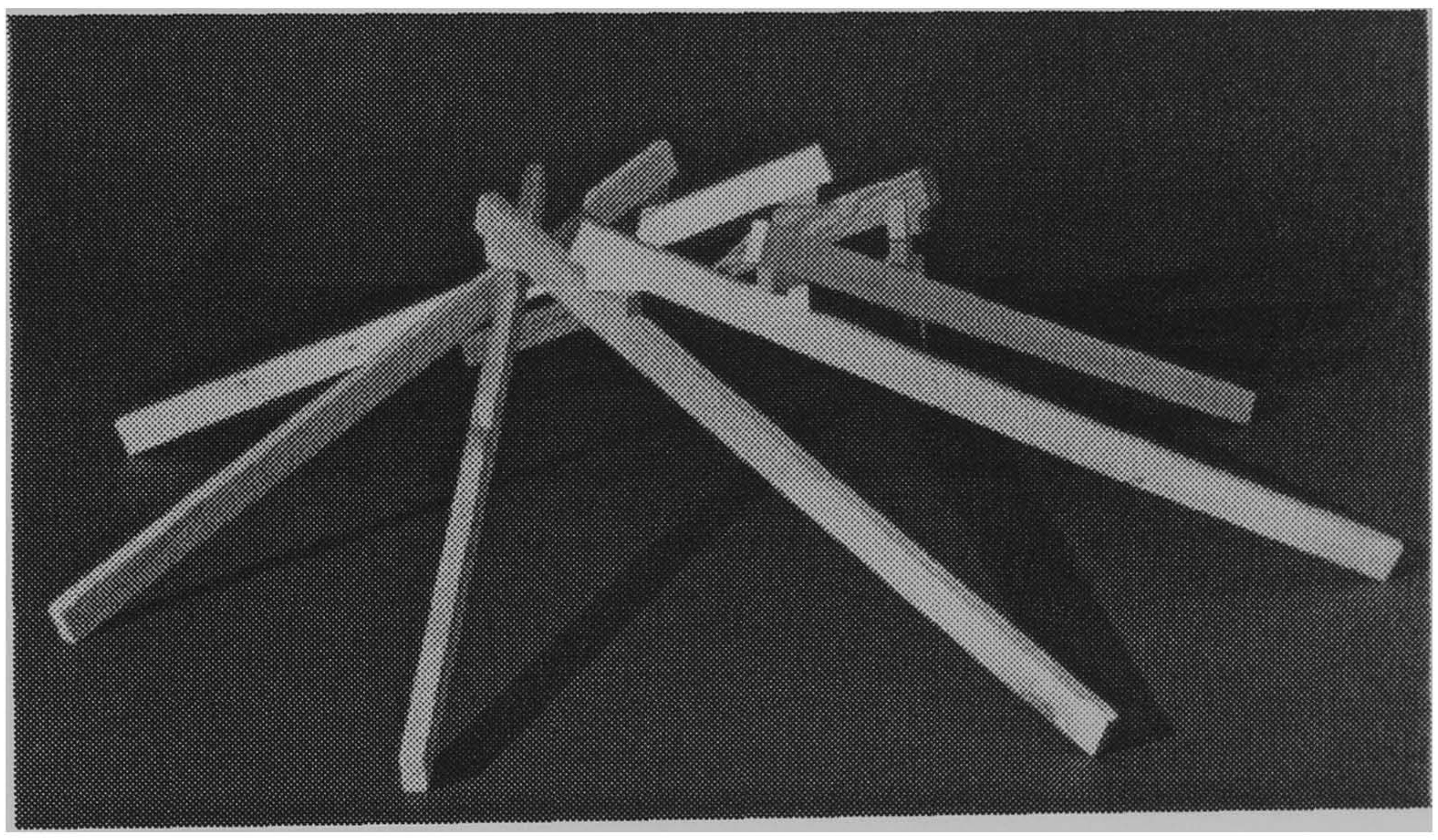


Figure 6.19 c. Shear force and moment diagrams for a=3/4 L

One will notice from the two different loading cases that the shear forces are very high for RFs with small openings, which is a reason to avoid these configurations. Also, in both cases the bending moments and shear forces are highest at the points where the RF members support each other. Therefore, the RF modular buildings in the UK (discussed in detail in Chapter 4), which use notched joints, are probably not the best solution. The notch weakens the member at the point of highest shear forces. Another possibility for joining the RF members which uses packing pieces and a pined joint, is presented on figures 6.20.a, b., and c. Figure 6.21 shows how irregular RF assemblies can be created by using the same type of pinned joint.



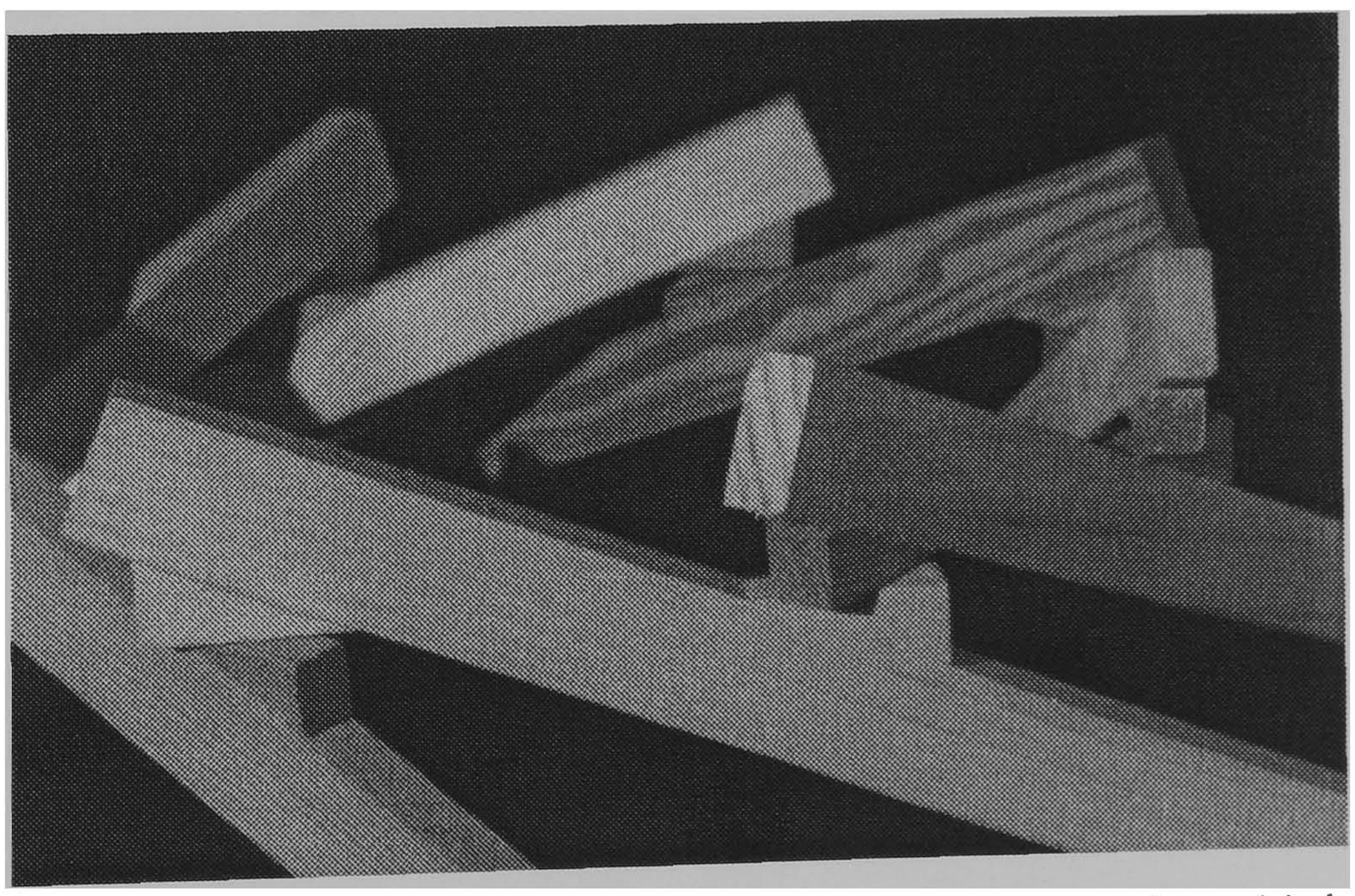


Figure 6.20 a. and b. Model of a RF assembly with pinned joints

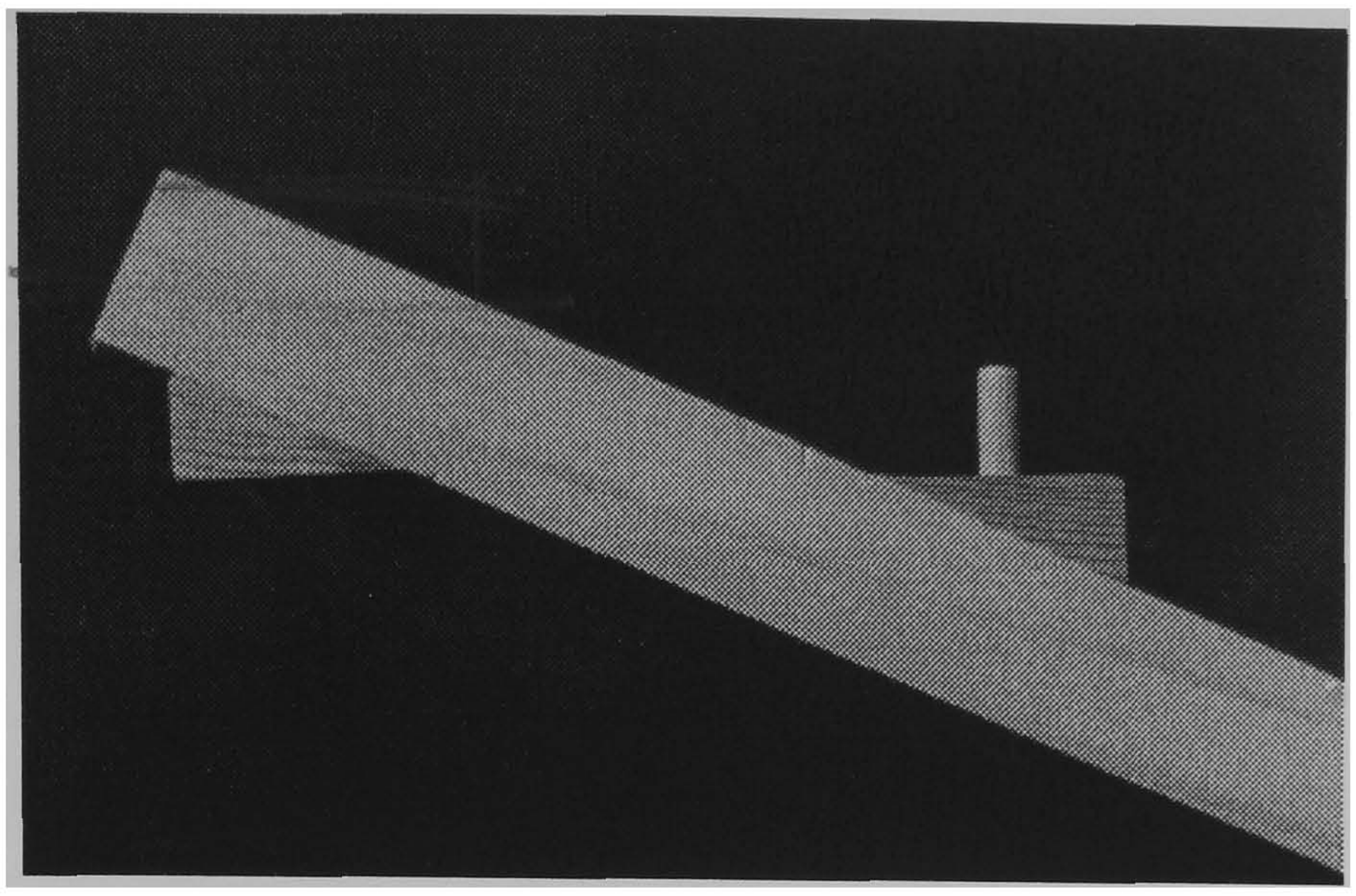


Figure 6.20 c. Typical RF member using a pinned joint

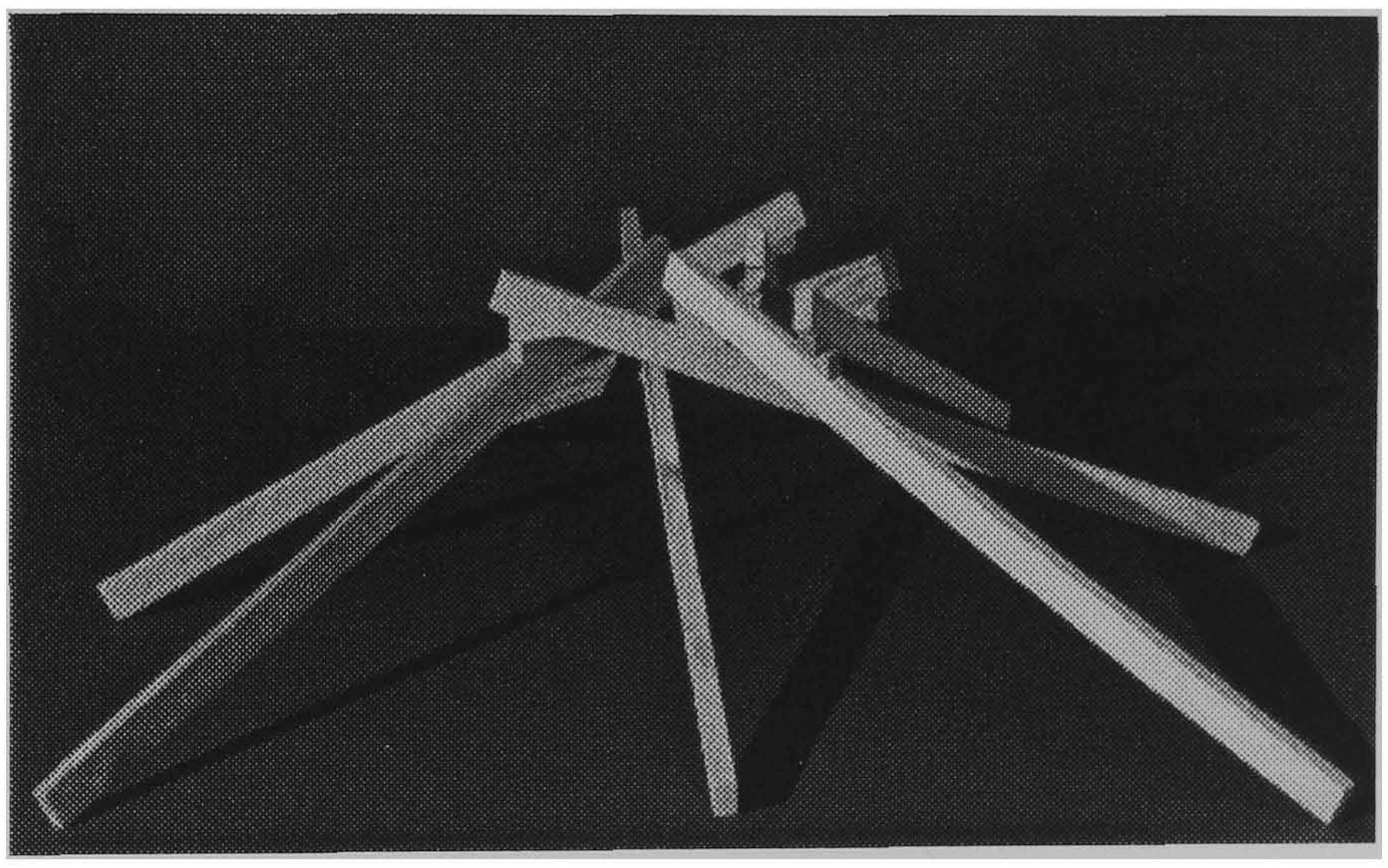


Figure 6.21. Forming an irregular RF assembly by rotation of the members

6.6. References

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6.7. List of illustrations

6.8. List of symbols

n	number of beams
r_o	radius through the outer supports
r_i	radius through beam intersection points
H	vertical rise from the outer supports to the beam intersection points
h_2	vertical spacing of the centrelines of the beams at their intersection points
L	length of the beams on the slope
θ	sector angle between the beams (angle between the beams when viewed in plan)
h_1	rise to first intersection
x	overall length of a beam in plan
a, x_1	plan length of the beam from a perimeter support to lower intersection
x_2	plan length from first to second intersection
b	plan length of the beam from perimeter support to high intersection
s	distance between perimeter supports
α	horizontal angles
α_n	angle that beam n makes with the x-axis
β	beam slope angle
d	depth of beam
R	shear force
M	moment
L	beam span

CHAPTER 7: Conclusions and future research

7.1. Conclusions

The main objectives of this research project have been fulfilled. These objectives were: the investigation of the architectural aspects of the RF and the study of practical issues regarding the system. The research shows that the structure has great architectural potential.

The literature survey showed that similar structures have been used for centuries and that the solutions were developed out of necessity when only beams shorter than the distance to be spanned were available. The RF was compared to primitive structures such as tepees, hogans and tupiqs. Structures related to the RF used throughout history were also presented. Since the RF provides a possibility to create 'kinetic' architecture, a detailed study of mobile structures was undertaken. In addition, a survey of the research on structural and geometrical aspects of grillage structures has been presented.

Since the RF structure has been known as early as the 12th century in Japan, the possible factors which influenced the emergence of the system over there were investigated. The theory of 'movement' spaces and the 'Sukiya' concept were described and possible reasons for the existence of contemporary RF buildings in

Japan were offered. The Japanese examples of RF buildings designed by Ishii, Kijima and Kan were analysed.

The possibility of modular RF construction was investigated for both temporary and permanent buildings. Although, there are no known temporary RF buildings, they would need to meet the following criteria:

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

In connection with the above, the constructed small scale models showed preliminary ideas for the use of roundwood for RF structures.

The idea of permanent RF modular construction was investigated and the buildings using the system constructed in the UK were presented. The Gazebos, the two recycled Whisky Barrel houses at Findhorn, the houses in Ferryhill and Saorsa in Scotland and the Permaculture Centre in Bradford, all using the RF structure were described. Aspects of sustainable development in RF systems were investigated. The investigation showed that the RF modular construction has considerable potential for 'green architecture'.

In order to investigate the RF morphology, a student project case study was undertaken. The developed morphology examples were grouped and analysed. They showed that RFs can be applied to buildings in the form of:

- one single unit,
- several units,
- multiple and complex units.

The RF system can:

- accommodate a great variety of both regular and irregular plan forms, and thus
- create very different spatial solutions and forms of architectural expression.

It must be pointed out at this stage that no other structural system provides the possibility of creating such a great variety of forms.

As part of the case study, the design experiences and opinions of both RF users and students who did not use the structure were examined. The analysis of the questionnaires and interviews revealed that:

- the structure was aesthetically pleasing,
- it contributed to the spatial qualities of the building,
- open plan functions were easy to design,
- subdivided spaces were not straightforward,
- it was quite complicated to imagine and draw the structure in 3-d.

As part of the research project the practical issues regarding the RF were also investigated. The parameters which define the geometry of the RF were presented and parametric studies were undertaken. Since the research showed that the presentation of the RF is complicated, an AutoLISP routine was developed to simplify the 3-d CAD presentation of the RF. Also, some ideas for creating retractable RFs were investigated and the geometry of the system presented. In the end some preliminary ideas for alternative covering of the RF were presented.

7.2. Suggestions for future research

The research project showed that there is room for further exploration and highlighted several possible directions for future research into the RF system:

1. Modular construction
2. Retractable and long span systems
3. Further development of the software for easy 3-d CAD RF representation.

The qualities and potential of most modular constructed RF buildings shows that they could find a broader application. To achieve that, however, an investigation would need to be carried out to:

- make them 'greener': to contribute to sustainable development,
- develop details for easy, simple and fast construction, possibly as self-built,
- develop appropriate layouts (and spans) for RF modular buildings for different functions,
- find the most appropriate ratios of RF parameters which would provide greatest efficiency.

Although retractable and long span RF systems do not exist there is no reason why they could not be developed. Use of the system for movable roofs would include investigation into:

- drive mechanisms which could provide simultaneous retraction of the beams and roof,
- appropriate covering methods and construction details,
- the efficiency of the system.

The developed AutoLISP routine Frame9.lsp significantly simplified the 3-d CAD representation of the RF structure. It could be further developed to include the representation of :

- irregular and/or multiple RF configurations,
- whole modular buildings using a library of pre-designed wall panels and a choice of roof covering systems.

In all, I believe the RF has a great future.

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APPENDIX 5A: Questionnaire for RF users

Questionnaire

(for those who have used the RF structure for their design)

Since you have used the RF structure for the design of the Village Hall (The New Fishermen's Institute), please answer the following questions which will show the experience you gained when using the RF structure.

1. How did the use of the RF affect the function of the building required by the brief?
   - it helped in organising its optimal function
   - it had no affect on the organisation of the function
   - it made organisation quite complicated

2. How did the use of the RF affect the plan form of the building?
   - the plan form was a result of all usual factors (function, space requirements, context, structure, systems etc.)
   - the plan form was to a certain extent influenced by the use of the RF
   - the plan form was largely constrained by the use of the RF

3. How did the use of the RF affect the division of the spaces (in plan)?
   - the division of the spaces (with partitions) was very straight forward
   - the division of the spaces was not as easy
   - dividing the spaces become quite complicated

4. How did the use of the RF influence the quality of the main space (the hall) of your building?
   - it gained in terms of spatial quality
   - it neither gained nor lost in quality
   - the spatial quality would have been improved if another type of roof structure had been used

5. Did you find that there was any advantage to the acoustics of the main hall from the use of the RF?
   - there was a considerable advantage
   - there was no noticeable advantage
   - it was a disadvantage

6. Did you find that there was any advantage in terms of equally good views for all the spectators from the use of the RF?
   - there was a considerable advantage
   - there no noticeable advantage
   - it was a disadvantage

7. How did the use of the RF influence the quality of the secondary spaces of your building? (This is if you have used a RF for the secondary spaces)

- they gained in terms of spatial quality
- they neither gained nor lost in quality
- the spatial quality would have been improved if another type of roof structure had been used

8. How complicated was it to work out the load paths for the RF?

- it was very straight forward
- it was not fairly easy
- it was quite complicated

9. How complicated was it to work out the 3-d geometry of the RF?

- it was very straight forward
- it was not fairly easy
- it was quite complicated

10. How complicated was it to design an appropriate enclosure for the roof for the RF you used?

- it was simpler than if a conventional roof structure had been used
- it was not significantly different (neither simpler nor more complicated)
- it was significantly more complicated

11. How complicated do you think that it would be to construct the RF roof structure you have designed?

- it would be quite easy to build it
- it would not be very complicated
- it would be quite complicated

12. How efficient do you think is the RF structure you designed?

- it is quite efficient, since no internal supports are needed
- it is as efficient as any other conventional structure
- it is less efficient, but it provides other qualities

13. How did the use of the RF influence the final image of the building?

- it contributed considerably to the overall good proportions, form and image of the building as a whole
- it influenced to some extent the final image of the building
- it influenced the final image of the building, but didn't contribute to it's quality

14. Did the use of the RF influence the possibility of fitting the building in the context (site)?

- it was easy to design a building which will fit in the context
- it was not more difficult than using any other roof structure
- it was quite complicated to design a building with the RF which will fit the context at the same time

15. Do you think that the use of RF construction has facilitated the integration of the services (ventilation, heating, electricity supply etc.) within the building?

- yes, to a considerable extent
- yes, to a certain extent
- no, it actually complicated the services design

16. Do you think that if you were asked to design an open plan space without any internal supports (columns), you would consider using the RF structure?

- most probably
- I would consider the possibility
- it is not very likely I would use it

In the end, please write very briefly what were the most important advantages and disadvantages for your design as a result of using the RF structure:

advantages:

disadvantages:

Name:____

Date:____

Thank you!

APPENDIX 5B: Questionnaire for students who did not use the RF

Questionnaire

(for those who have not used the RF structure for their design)

Although you did not decide to use the RF structure for the design of the Village Hall (The New Fishermen's Institute), by now you will have assimilated some information about the nature of the structure. Please answer the following questions:

1. How would the use of the RF affect the function of the building required by the brief, if used?
   - it would help in organising its optimal function
   - it would have no effect on the organisation of the function
   - it would have made the organisation quite complicated

2. How do you think the RF would affect the plan form of the building, if used?
   - the plan form would be result of all usual factors (function, space requirements, context, structure, systems etc.)
   - the plan form would be to a certain extent influenced by the use of the RF
   - the plan form would be largely constrained by the use of the RF

3. How do you think the use of the RF would affect the division of the spaces (in plan)?
   - the division of the spaces (with partitions) would be very straight forward
   - the division of the spaces would not be as easy
   - dividing the spaces would become quite complicated

4. Having seen some of the projects with the RF, do you think that the use of the RF would influence the quality of the main space (the hall)?
   - it would gain in terms of spatial quality
   - it would neither gain nor lose in quality
   - the spatial quality would have been improved if another type of roof structure had been used

5. Do you think that there would be any advantage to the acoustics of the main hall from the use of the RF?
   - there would be a considerable advantage
   - there would be no noticeable advantage
   - it would be a disadvantage

6. Do you think that there would be any advantage in terms of equally good views for all the spectators from the use of the RF?
   - there would be a considerable advantage
   - there would be no noticeable advantage
   - it would be a disadvantage

14. Looking at the projects, do you think that the use of the RF influenced the possibility of moulding the buildings to the site context ?

- it seems easy to design a RF building which will fit in the context
- it does not seem more difficult than using any other roof structure
- it seems quite complicated to design a building with the RF which will fit the context at the same time

15. Do you think that the use of RF construction facilitates the integration of the services (ventilation, heating, electricity supply etc.) within the building?

- yes, to a considerable extent
- yes, to a certain extent
- no, it actually complicates the services design

16. Do you think that if you were asked to design an open plan space without any internal supports (columns), you would consider using the RF structure?

- most probably
- I would consider the possibility
- it is not very likely I would use it

In the end, please write very briefly what the most important advantages and disadvantages would be, that you can instantly think of, when using the RF structure:

advantages:

disadvantages:

Name:____________________________________

Date:____________________________________

Thank you!

7. How would the RF influence the quality of the secondary spaces of the building, if used?

- they would gain in terms of spatial quality
- they would neither gain nor loose in quality
- the spatial quality would have been improved if another type of roof structure had been used

8. Do you think that it would be complicated to work out the load paths for the RF?

- it would be very straight forward
- it would not be fairly easy
- it would be quite complicated

9. How complicated do you think it would be to work out the 3-d geometry of the RF?

- it would be very straight forward
- it would not be fairly easy
- it would be quite complicated

10. How complicated do you think it would be to design an appropriate enclosure for the roof with a RF?

- it would have been simpler than if a conventional roof structure had been used
- it would not be significantly different (neither simpler nor more complicated)
- it would be significantly more complicated

11. How complicated do you think it would be to construct a RF roof structure?

- it would be quite easy to build
- it would not be very complicated
- it would be quite complicated

12. What do you think of the efficiency of the RF structure?

- it is quite efficient, since no internal supports are needed
- it is as efficient as any other conventional structure
- it is less efficient, but it provides other qualities

13. Looking at the projects with RFs, how do you think the use of the RF influenced the final image of the buildings?

- it contributed considerably to the overall good proportions, form and image of the buildings
- it influenced to some extent the final image of the buildings
- it influenced the final image of the buildings, but didn't contribute to their quality

SOME PARTS EXCLUDED UNDER INSTRUCTION FROM THE UNIVERSITY

APPENDIX 5D: Transcribed interviews

Seven students only were interviewed. This was done with 4 randomly chosen RF users and 3 students who did not use the RF for their design. They were chosen according to the marks they got for the project (A, B and C). The interviews were done in order to expand on some aspects which were important and were not explored in enough dept through the questionnaires.
Date: 8-12 February 1996
Venue: School of Architecture, Staff coffee room

Interviews:

1. Student (RF user A)

1Q: Do you find that the RF has a special individual look or not?
1A: Yes, because it overlaps. You could have a similar structure with a ring beam, but with it overlapping it gives a marvellous spiralling feel.
2Q: Do you find it interesting or not?
2A: I do find it interesting. It is something definitely new, I have not come before anything similar.
3Q: Do you think it is efficient or not?
3A: It wasn't when you first considered just strait forward beam, the beams were too big. But when we got into making trusses as members then it certainly become more efficient, but I was just wandering how something like that would get through disproportionate collapse. They all fail, don't they?
Olga: Yes, they do, but that can be overcome.
4Q: Do you think it would be complicated to design and construct it, I mean the structure itself?
4A: Designing it, picturing it, actually setting up a drawing trying to find out where the end of the beam would appear was very difficult. It is difficult to picture, as well. It was easier if you can use a computer or if you make a model. If you make the model you can make the real structure as well.
5Q: Do you think it contributes to the spatial qualities of the building?
5A: Yes.
6Q: Why do you think that way?
6A: You have to really design around it. If you going to use a RF you have to have a very clear idea how you are going to use it. The building I designed spiralled round it, it followed the RF. The building followed it so the centre of the frame was right in the middle of the hall.
7Q: Do you think the buildings (RF) would be aesthetically pleasing?
7A: Yes, they are different. Yes, you could make them very attractive.
8Q: Do you think that the RF gives a sense of movement?
8A: Yes, there definitely is a sense of movement.
9Q: Do you think the RF would bring advantages if used for open plan functions compared to, if other structural systems are used?
9A: I do not think it is an advantage, but it is just a different feel. You can do the job in a different way.
10Q: Do you think it provides great versatility of plan forms, or you find it too restrictive?
10A: I think I've not had much experience to answer this question. Once you decided to use the RF you should have the clear idea that the members shouldn't be cut by walls and that you should be able to see the whole frame, then it is quite easy to design round it, but lots of people did it in different ways. So it depends doesn't it?

11Q: Do you think that the structure would be equally successful if it is used on functions which require divided spaces as opposed to single space functions?
11A: That depends, doesn't it? You could use it for a house. The whole point of it is that you could see the ceiling, you should try to get cells in the building that interact with the RF rather then cutting through it.
12Q: Do you think the structure has a potential which needs to be explored and in which direction you see the future research on it?
12A: It is hard to say. I had actually never ever noticed it until you came on the interim lecture with the lovely Japanese ones. But as far as it is concerned I do not think there is actually anything unused about it.
13Q: We talked about this, but, do you think that the presentation and drawing of the RF are simplified, if user friendly computer programs were available, that more architects would consider using it?
13A: Possibly yes. It needs reading, educating about it. The software could help.
14Q: This is the same basically, do you think that if there is more available information, more architects would use it?
14A: Would certainly, consider it.
15Q: Which RF morphology did you find most interesting? You said that lots of people did it in a different way and we talked you could regular, irregular ones, which ones?
Morph. 15A: The one I used was irregular, but the hole inside was regular. It is up to the individuals to decide what they want.
16Q: Do you as a future Architect see any future for the RF or you think it constrains the designers imagination?
16A: It is a means to an end. I do not it constrains. I think the lack of knowledge constrains. It depends what kind of building you want in the end and the 'feel' of it. For small public building, for houses it is very nice to use. It depends, you can not really say.

2 2 Student (RF user B)
1A: Yes, but it has to be shown both inside ands out side, because if you have it hidden than it is as any other building. When you look at only a segment of it looks a bit uncomfortable, because it looks actually that it shouldn't work.
Olga: you mean that it might collapse?
Yes, it looks unstable. But when you go inside and see the whole structure, it feels a lot more safe. Basically you know that it will stand.
2A: Yes, it is definitely interesting.
3A: It is efficient in what it does, but as regards to material and traditional techniques it depends what sort of structure it is. For medium span I do not really know. I myself would go for traditional techniques but for long span it would definitely work a lot better and would be a lot more efficient.
Olga: So do you think it is better for long spans?
Yes.
4A: You would be able to do it, but it would require quite a bit of scaffolding and staff to put it in the final piece. All the other pieces would be all right, you will be able to fit them OK. You would need a way to support all of those while you put the final piece and then you would be able to take away all the scaffolding. So I can see you need quite a bit of structural support, but it wouldn't be too hard, I suppose.

5A: Yes. I would say so because it concentrates on an area, doesn't it? The iris. It actually focuses on an area. That area is hightailed or if there is light coming down on it that is special spatial quality.
6A: From the case studies I've seen the Japanese Puppet Theatre I find that very complicated to look at actually, on the inside. There is quite a lot of stretching? there. I do not know if that is good. But, yes I would say it produces some quite nice results.
7A: Definitely focuses on an area I have to say that again. It is like the iris of a camera, so it definitely focuses. But I would say it is used for big spaces. It is not like a corridor type structure. It does not actually lead anywhere but the centre, so it is for halls and other big spaces where you have to go in and you need to be attracted to. space
8A: Yes, I would say open plan definitely. Closed plan I would say not. It would be difficult to arrange the surrounding spaces. (space)
9A: You can manipulate it quite a bit, but if you want a simple RF the attitudes are quite closed, and if you want an irregular one but that would still work, you would still need to use a polygon of some kind. You couldn't use, actually you can use a cube but the effect would not be the same. It would have to be an octagon or something.
10A: I would say it definitely needs to be researched but I would be more interested having off centred irises, and how it is actually supported at the walls. If you have off centred irises and you just let the beam lead down than you have walls of different heights or you have beams all at the same height of the wall and an irregular iris. I think that needs to be researched, to see how it really works.
11A: Yes, I didn't know anything about it. I wouldn't have used anything like it unless it was shown to me. I would say that it needs to be used not as a simple beam but as a truss or something else otherwise it becomes very deep and fills quite a bit of the space, it becomes chunky. So, definitely more people need to know about it and how it actually works before it actually is used.
12A: Yes, definitely. The way Architecture is going with use of computers. If it is easier to draw it is easier to see how it works, then more people will use it.
ph.* 13A: The irregular ones with off centre iris.
14A: Definitely can be used. As I have seen all the of the projects of the year, all of them are different. It has a lot of variation in it. I might use it for future projects but only if only for halls or something like that and doing the surrounding in traditional techniques.

6 3. Student (didn't use it B)
1A: Oh, yes certainly. It seems, looking at other schemes they all had a certain character to them. They all look quite organic, quite nice in their own way.
2A: Yes, definitely (they look interesting), I wouldn't say only interesting I would say organic
3A: We discussed this. I am not sure weather you could similar sort of things with a ring beam rather than every member resting on the next or just a ring beam and than like portal frames. I don't know if that would be as efficient or more efficient. I do not know. Certainly, some of the members were quite large.
4A: To design it, I don't know, am It didn't seem. Some of them did have problems with the designing maybe they didn't know. I think it is more in the drawing, more than anything. Trying to get it on paper was very difficult. The actual construction must be, I wouldn't know. I mean I do not know what the problems are on site but obviously the fact that you have to rest each one on the next means that you have to give it temporary support during construction.

5A: Yes, definitely. I mean inside looking at the ones I had looked at it is really nice it gives a really nice hall space.
6A: Yes, I would say yes. I was going to say it is restrictive, little bit restrictive. Everyone who did a RF ended up with very similar looking buildings. Just the one odd here and there, but what people had done yes, they were very much the same, but nice in their own way.
7A: Yes, I suppose they have, because if you can span long distances with them you can have more open plan and as a frame structure it has the ability just has partition walls.
8A: That might be more difficult. Just in the fact, the actual structure, I can not remember but I think you can do it flat, the actual RF it would still be quite easy to divide those spaces. The pitched roof ones would be more difficult to divide the spaces easily.
9A: I would imagine more of research would need to go into it. It is quite a nice idea. than it all goes to is it more efficient or not, so you never find out until more research has not gone into it.
10A: Yes, I would say so. Just thinking about it one of the third years used it on a recent project and he did it because we were doing it. That is Mark K.... He did it for the design of his theatre. Just looking it that way he saw that we were doing it and got the information. I know Ian spoke to him a lot about it.
11A: Yes, definitely. I think a lot of people shied away from it because it is quite difficult to actually put it on paper.
M 12A: I would say the whole. The one large structure. I think it would have to be suited to certain type of building.
13A: Oh no, I would say there is definitely room for as I said for certain building types. I don't know if it has been used on houses, has it (Olga: Yes) and if it has been successful on those type of buildings. So, for some type of building types it would be a quite nice idea. I would imagine churches and that sort of thing. It gives a nice space internally.

5 4. Student (RF user B)
1A: Yes, definitely. It has got quite an interesting massing. I particularly like the overlapping forms, rather then those where it was not quite looking as if it was a RF.
2A: Probably no, because of the amount of timber frame reciprocal constructions. So, no it is not a efficient use of timber.
3A: Yes, I can see it would be a quite complicated construction. You would need to educate people on site how to supervise it on every step.
4A: Oh, certainly yes. (Contribute to spatial qualities)
5A: Definitely, it would be the focusing point of the building. (Aesthetically pleasing)
6A: Well in the sense that it seems that it is going upwards, whereas it actually doesn't it sort of trusses up. It is interesting and uplifting. It leads the eyes to the roof space.
7A: Well, yes I think it is an advantage. I think it defines the whole space very well as on our project.
8A: I think there would be less need for it, less call for it and it would give very odd shaped rooms.
9A: It gives a restriction, yes.
10A: I think more research needs to be done. Drainage and things like that. I think it certainly needs to be developed. It is a very interesting form.

11A: Only maybe because of cost considerations and things like that. I think that the general sort of Architect is trying to get a job as cheap as possible and might not choose the RF. Though, in cases when you can design what you want.. It is very good for students because we have no cost restrictions. I think one day maybe when there is enough materials I think it would be a very nice thing to cover the world with.
12A: I really enjoyed the drawing. That is something I enjoy doing, figuring things out. And I was really satisfied when I did work it out. I think that a lot of that sort of people who would find this sort of building aesthetically pleasing would be the sort of people who are artistic rather than computer models. Computers are used for working out space frame structures maybe if there was a package on RFs than some of the top designers might start using them. It is all education.
wrapk. 13A: I liked the ones that were sort of pulled out. I liked the feeling that sort of wrapping around. I didn't find that the Gazebo small ones worked so well spatially, and the irregular ones which were stretched out were still quite regular. Yes, I think I prefer the irregular shapes.
14A: No, I think I will go back to it. I've learned something from it, so...

5. Student (RF user C)
(9) 1A: Yes, no doubt. (special look)
2A: Yes, because it is sculpturaly formed. Yes it is good work. (interesting)
3A: It does call for quite large members on big spans and you would use it if you had a big open span
4A: No (not complicated to design and construct the structure)
5A: Yes, if you use a RF it should be seen (can contribute to spatial qualities)
6A: Yes. (aesthetically pleasing buildings)
7A: It does, I mean we used ours to give a sculptural feel and it is even better at Findhorn. It is just amazing. It creates a floor on the top of the building, and the edge pieces it creates.
8A: I wouldn't say it is an advantage using a RF, but it is not a disadvantage either. It is a choice. It doesn't limit you in any way. In my design it helped me. I had a RF and because we had to have a changing space art gallery and whatever it made a good point to put a partition up and something to fix at the top. I just had an old partition, small jacks on the top and the bottom, jacked on the top and the bottom, jacked to the RF and it made it a lot easier . It was not a disadvantage but I wouldn't say an advantage .
9A: No, you can change it into anything, in to any form. I mean you are not stuck to a specific shape at all. You could have shorter members, longer members.
10A: Yes, as I said in my project as it was a changing space I set up partitions.
11A: Yes, it is quite limited at the moment, and it creates such a good effect. (information)
12A: No, I didn't find the drawing difficult, but a lot of people did. Yes, if there was a user friendly computer system it would be an advantage. (Olga: how come you did not find it difficult to draw the RF?) One: because I had a flat RF which made it extremely simple. Yes, that is why I did not find it as hard as everybody else and that is the reason why I did a flat roof because it was easy to draw.
raph. 13: The multiple ones. I did not design a multiple because of the drawing. . It would just be too hard for me. But I would have loved to (designed) the spirals with in spirals within spirals.

14A: No it is not a dead end. For me it is a real good form. It creates a form I would look for, a sculptural form, sculptural in any way.
15A: Maybe a way of reducing, I mean on the massive spans when you use flat beams you would still have same size beams, so why not use a RF. It definitely has got a future, definitely. What research needs to be done, it needs exploring different forms, you know. I would say that is the main thing. All the RFs I have seen have been in a symmetrical shape. I'd like to see them used in a different way, asymmetrical. It can be done. Yes, I'd like to see some different forms like that. Maybe some more research in the way the joints are formed. Everybody seem to rest one member on another member, different ways of jointing, I mean they do come on in acward angels, so maybe another way of jointing them would need to be researched, I think. The membrane that goes on the top as well, can be awkward. What ever you try to do you get the steps, you can not avoid that. So another reason for me doing a flat one, as well as it made the covering easier and aesthetically more pleasing to me. It is a lot more man hours to construct a real RF than a flat beam structure.

5

6. Student (did not use it A)
1A: Yes, I mean I saw there were different types. There are flat with square beams across, then there is a particular shape as the shell or the spiral shape as for this project, but I didn't see what the building is going to look like for me. I had a mast so I didn't see how I was going to incorporate that with the RF. But, yes I think it has an individual look.
2A: It is definitely interesting. Some of the ones as far as I saw were definitely interesting. Especially, was it Ian's who did spatial sort of thing with it rather than others. It was slightly bigger than others, so the members had to be so big that it gave too much weight. The larger ones like that were interesting.
3A: I don't think so (efficient), really. Some of the member sizes I saw anyway. It is using a lot of timber anyway. But you can apply this to anything, can't you. It is not necessarily always the most efficient or cheapest form that you always want. Is it? It depends what you want to express with it. It is different.
4A: I am not sure. I haven't really studied it. I can't really tell. It seems to limit the layout in some ways, especially for, I mean it is certainly ideal for the hall because it is covering one large area, but when it came to the service areas it was juggling spaces around, under the beams and if they were carried past the beams it looked awkwarder the partitions met the beams and staff.
5A: As far as the roof spaces are concerned I think that it does. I am not sure really. (if it contributes to the quality of the spaces)
6A: Looking at these I don't think it restricts the plan, definitely. I mean you can use them more than one, can't you? You can use different configurations, you can also use square ones, which I can see you can start with, then the spiral. No, I would say not too much (it does not restrict plan forms). With the square ones, with the flat ones you can do pretty much anything, can't you?
7A: Mmm, I think it is something that needs to be made known. It is something I hadn't heard before. Yes, I think they probably would (architects use them more often).
8A: Yes, I think it put some people off that they are not easy to model on the computer, to get the right pitch and the right angle, setting the right perspective to draw it wasn't easy. I mean, that would not discourage me but I know that it did discourage several people.

9A: I think that the irregular ones are the more interesting ones. They sort of have more complexity and yes, I think they are more interesting.
10A: I can see it being used for things like lots of community projects, community halls and trying to think of others, (Olga: like open plan: Churches?), yes, definitely, things like that where you need large open spaces. In Japan, or in Scandinavia I can imagine people like that using them, for community projects and things like that, because you need timber. (Olga: you can do them out of anything) But I've seen them only out of timber, so that's why I see them that way. You would definitely see them on open plan functions and where there is not such a limited budget and obviously they cost slightly more.
11A: The efficiency, cost, maintenance. All this things need time, don't they. I think they need to be seen used more often so that people start being more comfortable using them. It is always with something new.

7

7. Student (didn't use the RF C)
1A: Yes I thought it looked quite good, especially better than normal ways of making roofs. It looked much better than normal ways yes.
2A: Yes (interesting)
3A: I wouldn't know (if it is efficient), because I did not design it.
4A: It depends how much you know about it (how complicated it is to design and construct the structure)
5A: Oh yes, because I think it looks better than a flat roof (contribute to spatial qualities)
6A: From the inside yes (aesthetically pleasing)(Olga: what about from outside?) The problem is that from the outside they would look the same as a conical roof. (Olga: but you could do them as a turbine) A?
7A: Yes, you can quite long distances.(open plan functions)
8A: That is more difficult to do I think, because as I can remember the beams are at an angle so it is more difficult to make partitions.
9A: Yes, it would help if there is more information.
10A: Yes, it can help a lot with the design (user friendly computer programs for drawing in 3-d)
11A: I think they are all interesting, but I think it would look nice with little ones making a big space, especially if it is a circular form.
12A: I really do not know. I am not sure about it. I mean there are some buildings which are useful to use a RF for, but it all depends on the building if it is open plan or not, and the materials you use to make it. It is very useful to use it with wood, with timber. (RF future).

APPENDIX 6A: Frame9.lsp routine

```
(defun frame9 (/ c t t1 b n l r h a a1 b1 w d)
        (graphscr)
        (setq n (getreal "Please enter number of beams:  ")) (terpri)
        (setq c (getpoint "Please enter centre point of circles:  ")) (terpri
        (setq l (getdist "Please enter plane length of beam:  ")) (terpri)
        (setq r (getdist "Please enter inner radius:  ")) (terpri)
        (setq h (getdist "Please enter total rise of beam:  ")) (terpri)
        (setq w (getdist "Please enter beam width:  ")) (terpri)
        (setq d (getdist "Please enter beam height:  ")) (terpri)
        (setq n (fix n))
        (setq a (/ pi n))
        (setq a1 (+ pi a))
 ;a1 equals 2pi devided by the number of beams, and it is the angle
 ;between the beems

        (setq t (list (car c) (+ r (cadr c)) 0.0))
 ;t has coordinates x=x centre, y=y centre+inner radius, z=0
 ;t is the point of intersection of the centrelines in plan

        (setq b1 (polar t a1 l))
 ;b1 is a point in plan at a distance l (beam length)
 ;from the point t and at an angle a1 =360/n

        (setq b (list (car b1) (cadr b1) 0.0))
;b is a point with coordinates x=xb1, y=yb1 and z=0.0
;b and b1 are actualy one same point and they have no hight

        (setq t1 (list (car t) (cadr t) h))

        (command "line" t b "")
;draws a straight line in the x-y plane with the plane beam length

        (command "array" "L" "" "P" c n "360" "y" )

        (command "line" t t1 "")

        (command "array" "L" "" "P" c n "360" "y")

        (command "3dpoly" t1 b "")

        (command "array" "L" ""  "P" c n "360" "y" )

        (ap_post_obj (ap_box l w d))
```