THESIS TITLE: "Structural Expression and Application in Contemporary
Architecture"

ABSTRACT OF THESIS

The development of structural technology has allowed the architect greater freedom in resolving problems related to the planning, aesthetics and construction of forms and spaces. As technology advances the range of structural solutions is increased to further enable the implementation of architectural ideas which develop independently from technology.

Two fundamentally opposite philosophies embrace the structural integration of architecture:

1 that although technology "frees" architecture, it does not determine architecture.
Thus ideas on which architectural forms are based may be sourced outside architecture and structure; for e.g. movements in art and analogies drawn from nature have influenced the ideology of several modern architectural movements.

2 that architectural form itself may be generated out of structural considerations and that the structural problem itself may serve as a rich source of architectural ideas from which forms and spaces may be generated.

Both approaches operate in the contemporary context and are a reflection of the need to merge the design philosophies of architecture and structural technology.

The thesis comprises three sections and is based on the assumption that structure is used to improve certain core aspects of architecture. This is related to allowing flexibility in architectural expression and planning, and the simplification of fabrication and construction processes.

<u>Section I</u> of the thesis proceeds by investigating the background to the different design philosophies of the architect and the engineer in order to provide an understanding of the differences in their design priorities. Significant Modern Movement examples are studied in relation to the abstract ideologies which influence architectural form and structural integration in order to hypothesise on the core aspects previously mentioned.

In <u>Section II</u>, these investigations are extended to case examples in the contemporary context and buildings are studied in relation to 4 main considerations:

a) architectural
b) structural
c) utilitarian
d) construction

Interviews with project architects and engineers were conducted to substantiate the information from publications in refereed Journals and reference texts and project design reports.

In addition to relying on papers written on the architectural and structural design development of the selected buildings, interviews with the relevant project consultants were arranged to obtain further background information relevant to the thesis.

Section III then further discusses the factors affecting the development and application of structure in the architectural context in order to arrive at conclusions based on the recurrent themes and approaches identified in Section II case studies. These conclusions are interpreted in relation to Section I ideologies on structural integration and architectural expression and establish the common design aims of both architect and engineer in order to attempt bridging the gaps in their professional understanding of building design.

The conclusions may be summarised as follows:

1) that there are three recurrent approaches to arranging structure in relation to architectural layout. Structure may occupy the
    a) periphery of the architectural plan
    b) the centre of the plan
    c) plan in intermittent fashion (as in the case of 2-way modules)

    There are also examples where a combination of the three approaches is possible.

2) that the recurrent approaches to using structure in articulating the external form may be summarised as follows:
    i) the form implied by an ideal structural model may be adapted as an architectural form (for eg. a portal frame shed)
    ii) that structural form is modified to suit functional and aesthetic requirements.

Nervi's Small Sports Palace in Rome is an example where a structural dome is modified at its peripheral edges and supports for utilitarian and aesthetic reasons).

iii) that non-load bearing elements may be articulated within a regular structural frame, (as exemplified by Corbusier's Dom-ino principle)

iv) that structure may be detailed as architectural ornament whilst maintaining essential structural action, (as in the case of Horta's Art Nouveau creation).

v) that an appropriate functional structural may be developed to maintain a 'sculptural form" initially conceived, without consideration of support, (as in the case of Utzon's Sydney Opera House).

vi) that structural form is developed intuitively and simultaneously as an expression of architectural form, (as in the case of the Pantheon).

These recurrent approaches (1) and (2) are perhaps related to the development and application of structural configurations which do not excessively constraint the design of architectural spaces and the expression of architectural forms.

Structural application in building is moving towards systems which use increasingly less material to achieve the required strength and rigidity required to transfer loads in ways influenced by the shape of architectural forms and spaces. This is directed towards reducing structural dead weight which in long-span and high-rise structure is critical to both performance and cost efficiency. This may be achieved by avoiding the development of excessive bending moments in the structure and this may be part of the reason for the increasing number of applications of structural systems which transmit primarily axial loads, particular tension in steel construction. However, pure tension or compression structures do not exist and the necessity to accommodate useable space and the shapes of architectural forms could imply the development of some bending in a system which first set out to avoid its presence. Bending necessitates the use of deeper structural sections which makes the structure visually bulky and more expensive in terms of material quantity. In this respect, the experimentation of flexible structures which acquire a satisfactory degree of rigidity with stressed cables and rods is aimed at providing more aesthetic and economical solutions than with conventionally rigid systems.

The engineering aims of developing increasingly slender structures could therefore be aimed at economy and elegance whilst the architectural implications could be:

i) A structural system which assists the aesthetic considerations of formal and spatial composition, or one which does not necessarily restrict modes of aesthetic treatment in order to provide support.

ii) A structural system which allows flexibility in the layout and use of floor space and in the interpretation of spatial character.

iii) A structural system with the means to optimise fully, the commercial potential of prime sites with complex building constraints.

iv) A structural system which effectively integrates mechanical service and electronic networks without compromising aesthetic themes.

v) A structural system which provides the option of satisfactory levels of natural lighting and ventilation as well as enabling an energy efficient building.

These ideals are related to the structural improvement to architectural form and space and could perhaps serve as the common design aims of both architect and engineer.

THESIS INTRODUCTION

1.0 Objectives

The objective of the thesis is to show that:

i) there are recurrent themes and approaches in the use of structure in architecture.

ii) and that these themes and approaches are related to the aim of improving essentially core aspects of form and space, and that these aspects might continue to be valid with future applications of structure in architecture

The core aspects are:

a) the enclosure of space and the resistance of forces with the elegant use of structural material which results in the creation of aesthetic forms in architecture

b) the improvement of the quality of enclosed space by arranging the structure in ways which define the space without causing excessive physical encumbrance to the use of space, and which enhances the degree of visual linkage between spaces, where this is appropriate.

c) the facilitating of the 'play of volumes in light' (1) in relation to architectural form by improving the extent of opening possible in the structure and the innovative framing of geometric forms brought together in artistic composition.

1.1 General

Architectural and engineering aims overlap to some degree in the design of the built environment, each embodying separate ideals and approaches to the design problem.

Up to about the 18th century, the architect was chiefly responsible for the structural and aesthetic detailing of masonry buildings (2). In the Industrial Revolution period, the adaptation of iron and steel as construction materials involved the application of engineering knowledge (for example, in the construction of railway station structures), and thus, an engineering approach to building was initiated, separate from that of the architect's.

The need to merge the two approaches becomes apparent when one considers examples where the main design task is essentially of a structural nature. In such cases, the structure is of primary influence to the architectural form and architects are faced with the problem of aesthetic integration either in visibly expressing the structure or concealing the structure and making visible forms which do not make their underlying means of support a matter of simple deduction. There are many other significant architectural and constructional considerations involved with the use of structure, the main ones in the contemporary context being:

i) the architect's individual design philosophy which is the rationale behind the architect's 'formal typology' or his vocabulary of forms: a system by which prototype forms are used to generate building forms for the purposes of architectural expression. This system is to <u>merge</u> with the structural considerations of developing form for the purposes of acquiring the strength required to resist forces and to transmit loads without excessive deformation of its structural members. One example is in Gothic architecture where the aesthetic system and the structural system are

(a)
closely related.

ii) the context of the design problem, for eg., is the intended form of structural expression appropriate to an urban conservation project which is considering the harmonious proposals to a traditional built environment?

iii) is there any constructional advantage with the adoption of a particular structural system? Is the construction process simplified by the structure given the site constraints and problems in fabrication/assembly? A structural system will have implications on the performance of other building components, for example, the use of cable stayed systems in some cases raises the problem of waterproofing when cables/rods penetrate the cladding element. The decision to reduce the number of penetrations affects the structural configuration of tension and compression elements, or it may influence the decision to adopt such a structure altogether.

(a): The various forms of Gothic vaults and buttresses are solutions to two main aspects of architecture:

i) the ornamental interpretations of the religious theme which were characteristic of different periods (Baroque, Roccoco, for eg.)

ii) the structural solution to resisting the outward thrusts of the roof vaults used to span the spaces of the cathedrals. Thus, flying buttress weighed down by pinnacles may be seen as a refinement of the buttress pier, with the result of using less masonry to resolve the aesthetic and structural problem; ie. the result of a more slender structure.

The pointed arch was developed also to reduce the horizontal thrust by increasing the rise of the arch in relation to its span and to accommodate the intersection of vaults with different spans whilst maintaining a constant height. This flexibility allowed for the provision of larger openings for natural light to the main interior spaces and the means by which the interior spaces and the external form could be articulated for aesthetic reasons (3).

iv) the shortage of skilled labour and the duration of the construction programme is a significant influence on the development and choice of a structure, structural systems which simplify the erection process making construction fast and convenient are advantageous. The faster a building is completed, the more the owner saves on interest on bank loans necessary to fund the project, and the faster he is able to begin recovering his capital outlay by operating the building.

v) extensive HVAC systems and electronic networks for business machines and computers are housed within the space of a sub-floor or false ceiling. It is in the owner's interest to obtain as many floors as possible from a given building height constraint on prime urban sites and therefore, the use of slender structural elements, such as the depth of the floor slab, alleviates the restrictions on useable headroom space, by false ceilings and sub-floors. The provision of column-free spaces is also advantageous in allowing maximum freedom in accommodating changes in layouts as a result of changes in useage.

vi) the structural system should also accommodate allowances for future growth and extension within the available site boundary.

vii) site constraints of existing structures and foundations, topography and geological conditions are also significant influences on the choice and development of a structural system.

viii) most importantly, the structure should be developed to <u>improve the quality of the architectural spaces and forms intended in the architectural concept.</u>

The thesis highlights significant ways in which structure has been successfully integrated with architectural aesthetics in respect of:

a) architectural and structural ideology

b) architecture in the historical and in the contemporary context.

1.2 <u>Thesis Framework</u>

The thesis comprises three Sections

Section 1	describes the differing ideologies of the architect and of the engineer in the light of differences in their historical origin and professional training. This provides the background in understanding the different design values, priorities and approaches to the generation of form. Related with this are viewpoints on aesthetics in architecture and the expression of structure in building. Structural development in the design process of a building is influenced by both intangible and tangible criteria, and this idea is explored with historical examples.

Section II explores with case studies in the contemporary context, the main criteria which influence the development of building form and structure in an attempt to identify relationships and differences in these criteria with those described in the historical examples in Section I. The forty-four case studies are bound in a separate volume, viz. volume II.(Vol. I comprises the thesis proper.) Section II also relates the key requirements described in para 1.1 (i) - (viii) with contemporary responses to the problem of architectural form, space and structure. The summarised observations form a basis for further discussions and conclusions in Section III.

Section III essentially considers the issues raised in Section I with the observations made in Section II to conclude on the following aspects of the relationship between structure and architecture in building:

i) viewpoints on the use of structure in architecture

ii) scope of engineering design with respect to building form

iii) typologies of form

iv) recurrent themes and concepts

v) approaches to using structure in architecture with respect to planning, layout and aesthetic expression.

1.3 Introduction to Section I

This Section provides a background to the differing ideologies of both architectural and engineering professions. A description of the separate origins of the two professions, and the differences in their professional training assists in the understanding of the differences in the approaches to the generation of form and in their design criteria and priorities. This leads to an appreciation of the fact that aesthetic and structural considerations represent two separate systems of generating form and that a 'merger' of the two systems is essential for successful architecture. This merger is manifested in the formal vocabulary of some architects, for example, Corbusier's Dom-ino principle is an integral part of his Villa Savoye scheme, and Foster's Willis Faber building at Ipswich shares with Mies Friedrichstrasse project, a similiar architectural expression which is integral with their structures.. (Fig. 1A, B)

A description of the differences in the content and context of the two professions is made with examples from Modern Architecture since 1900. It shows the different approaches to form taken by both disciplines. In particular, reference will be made to examples which use structure in architecture to further illustrate the idea of a merger between the two separate approaches.

The use of structure in architecture is aimed at the improvement of core aspects of architecture and the summary to this Section includes the definition of these core aspects which are mentioned in the thesis objectives, para 1.0. It will be shown in Sections

II & III that these core apsects continue to apply to the contemporary case examples some of which may be recognised as significant architectural works of our time.

1.4 Framework of Section I

- a) Historical origins of the two professions (para 1.6)
- b) Differences in Training (para 1.8)
- c) Differences in Aims (para 1.11)
- d) Summary of Differences in origin, training and aims in relation to Thesis Objectives (para 1.14)
- e) Structure improving the Intangible aspects of architecture (para 1.16)
- f) Structure improving the Tangible aspects of architecture (para 1.25)

1.5 The differences in the design priorities of the architect and the engineer leaves gaps in understanding between them. This situation is rooted in historical circumstance which have led to their professional roles today. These roles characterise a specialisation of skills that is required of industry and society, and is related to the differences in professional training and their respective design aims.

The differences in design approaches could be attributed to:

- i) historical divergences
- ii) differences in training and design values
- iii) differences in design aims, content and context and in the scope of work

1.6 Historical Origins

The Industrial Revolution, the advent of iron and steel developed for engineering purposes and its subsequent application to building resulted in an approach to design separate from those taken by architects of that time. These circumstances may be summarised as follows:

a) the need for engineering works and the development of modern infrastructures, in order to improve the quality of life, led to a need for the skills of engineers and emphasized the role of the engineer in society. In the late 19th century, the invention of the steam locomotive led to the demand for bridges and other construction works required to cross landform obstacles, and other works unrelated with the railway system, which were on a very large scale, such as those of exhibition buildings. This furnished the engineer with opportunities which the architectural profession had not enjoyed since the era of mediaeval cathedrals. The public wanted great engineering works and paid liberally for them and this need evolved engineers of distinction (4). Engineers were originally ironfounders who made engines and their involvement with buildings began when they designed structures to house the engines and the manufacturing processes they powered (5).

b) the emphasis on the engineer's role in society also affected their attitude in collaborating with architects in building. The early generation of civil engineers who were preceded by Telford and Brunel inherited a professional status equal to that of the architect and were unprepared to enter the field of ordinary building to work as architects' assistants (6). Smith (5) echoes this attitude when he commented on the Pantheon structure,

"the architectural effect ..... cannot be produced without structure, nor could the structural design be properly guided without an appreciation of them. Is such motivation and guidance the proper province of architecture alone? If architects still had the degree of control held by Hadrian's designers then the answer might be yes, but this is not the case. <u>If the engineer is to avoid being led by the motivation of others</u> then he must be able to actively engage with forms of knowledge and understanding from which such motivation springs."

Conversely, the architect in order to be effective had to improve his understanding of structural matters, and this discussion leads to later considerations of training to bridge gaps in understanding. The architect's difficulty in leading the design team was compounded by technological developments which advanced beyond his expertise.

c) From the time of the Industrial Revolution:

i) engineers established a design culture of their own, which was distinct from those of the architect. Engineering structures featured an aesthetic distinct from the Classical-based notions of architects from that period. (4), (5), (7)

ii) the visible expression of engineering components used in architectural building first created controversy between the professions but this gradually led to a revision in the attitude toward aesthetics in building. Engineers used iron structural components suited to the scale and weight of machinery, without modification, in the buildings they designed.

iii) the revision in attitude occured when architects quickly recognised the advantages that 'modern construction' offered (7). The slender iron and steel frames improved the degree of useable floor area, took the load off the walls and allowed greater extent of openings for natural lighting and ventilation. Soon, expressions of mass and weight synonymous with masonry construction gave way to expressions of 'weightlessness' with the use of iron and steel frames. This allowed the development of ideas on generating building form, notably the tectonic compositions of parts of the entire building form, or the 'cluster assemblies' referred to by Stirling (8) in his early work.

1.7 These circumstances led to a number of viewpoints on the role of technology in architecture, which formed the basis of several architectural movements:

a) that technology should not be the determinant of architecture and its systematic pursuit could be detrimental to architecture itself (9). Architecture exists as a body of ideas, a system of thought and a set of principles which

(b)
do not necessarily incorporate building technology.

b) that architecture is concerned also with the physical presence of buildings and technology is still a desirable aspect for incorporation in architectural thought (11).

c) that technology creates new architectural possibilities whereas traditional architectural thought based on visual precedent could entrap instead of allowing opportunity to innovate. Technology by contrast did not depend on visual precedent in order to create its solutions.

These viewpoints are related to the training of the architect and of the engineers, which are primarily influential in the cultivation of design attitudes and values.

1.8 Differences in Training

There are a number of characteristics of architectural design which differentiate the training of architects from engineers. The architect's expertise lies in his ability to find artistic solutions to a complex relationship of functions and requirements, and to give delightful forms to spaces with which these functions are contained. His preoccupation with the intangible aspects of visual delight, spatial ambience and symbolism are attempts at bringing art into building. The skills with which the architect practises his craft cannot be taught in conventional ways; these skills are likened to innate abilities

(b): Newby (10) in 1962 referred to Nervi's buildings as being mediocre architecture with jewels of structure within them; and commented that a brilliant structure did not necessarily lead to a good building.

which studio tutoring can only 'bring to surface' through encouragement and guidance. One viewpoint maintains that the architect cannot be taught in a prescribed manner <u>how</u> to design and this is due to the complexity of variables, and innumerable approaches with which to adopt; instead, the design process is likened to one of personal discovery with which the architect has to define his own aims and criteria. The adopted approaches do not necessarily have to follow an ordered, sequential manner characteristic of conventional problem-solving.

In this respect, the architect in the early process of design will engage not so much in convergent thinking (unless in a decision) but more in lateral thinking in order to generate optional solutions to a complex range of design constraints. Because the architect is engaged in a mode of thinking which Ornstein (12) describes as synthetic, intuitive, spatial and diffuse, his training in design cannot be adequately structured into some form of an ordered teaching curriculum, nor can a system of approaches be prescribed for the design act.

1.9 By contrast, the engineer is very much involved with convergent thinking and his training involves mathematically defined tasks where objectives are defined as performance specifications, and numerically interpreted. Engineering design involves the application of scientific-based knowledge and this is directed to the solution of tangible aspects of building design, often after the architect has defined these aspects to him in the form of sketch drawings. The engineer's mode of thinking is primarily analytic, sequential, linear and rational. These characteristics of engineering design provide more opportunity in the application of comprehensive academic curriculums with which to impart both general and specialised skills.

1.10 The training of the two professionals is related to the differences in design aims and priorities which influence their design approaches. The following paragraphs describe the differences in design aims of the architect and the engineer.

1.11 Differences in Aims

Perhaps the differences in aims are best understood when trying to differentiate engineering structures from architecture. Engineering structures are those mainly concerned with the forces of nature, overcoming difficult soil conditions, retaining earth and water, containing grain and liquids, spanning rivers, creating terra firma in deep water, moving mountains and taming rivers (13). "The age-old troubles of man-starvation disease, floods - could be largely overcome by a proper use of engineering by the construction of dams, reservoirs, drainage schemes, and communication networks"(42)

Architecture is involved in giving physical form to a social establishment, it provides the screens which the passer-by outside and the user-participant within recognise as the demarcation lines of a social situation whether it is a bungalow or a city hall (14).

In this respect, architects dealt with the needs of people which were very often not clearly defined, making the task a rather vague situation. Therefore, they had to attempt to interprete the implicit needs of their clients into a design brief and often there would be conflicting requirements which necessitated their prioritization.

By contrast, engineers had clearly defined tasks and the structural engineer was chiefly concerned with the safety, strength, stability and economy of the structures he designed. The engineer's (15) interpretation of delight was derived from an economy of means, in the recognition of inventive simplicity, of directness and in the clarity of structure, appropriate to the 'spiritual quality' expressed in the combination of forms and spaces.(c)

Where visual effect and artistic expression were important to the architect, who avoided their compromise through reasons of cost where possible, the engineer's priority was in 'fitness' and economy of material. The structure in the engineer's viewpoint had to be fit for its purpose in order to be good and the 'goodness' of the finished structure was fundamental to the 'goodness' of the total design. By using materials economically, the engineer sought to reduce the dead weight of the structure by minimising whatever material was unnecessary to its stability.(d)

(c) However, engineers such as Maillart and Freyssinet believed in a "harmonious balance between utility and beauty so as to achieve excellence" (44). Thus, a 'craftsman's sensitivity' was also necessary in engineering.

(d): This may be argued by the fact "Engineers appreciated the attitude of the Forth Railway Bridge designer in making the width of the base of central tower wider than necessary in order to convey to the public, a sense of great security" (42)

In this respect, engineering priorities in design aesthetics resemble Nietzsche's definition of ugliness:

"That which we feel instinctively opposed to us, according to longest experience, felt to be harmful and dangerous."

By contrast, the architect loved mass and the weight of the material for its own sake, for its effect in providing a monumental character to the architectural form, and for 'visual stability' (16).

1.12 If the architect's values were characteristically artistic, then the engineer's were mainly pragmatic in nature (17),(e) and the latter would strive for a design which would:

i) fulfill its function(s) in the best possible way
ii) not tax human resources more than necessary
iii) enhance the human environment rather than spoil it

These priorities are best reflected in Newby's and Schollar's (18) criticisms on the Hongkong and Shanghai Bank structure:

"The engineer follows natural laws in his designs, but in this case, the expressed structure follows anti-natural form to create excitement....."

and in Hunt's (19) criticisms of the Lloyd's Building structure:

"The economics of such a complicated system are more questionable since by structural separation of floor from beam you lose the 'T' beam effect and hence structural efficiency."

Higson and Hough (20) in commenting on the Shotts Factory development mentioned that the architects (Ahrends, Burton and Koralek) wanted the structure not just to fulfill its several functions but to be seen to fulfill them as well.

(e) Carmichael (42) points out that the brilliant engineer had the audacious quality of being able to extend theories beyond what were thought to be the theoretical limits of their time.

The eventual consequence was a highly articulated structure of low redundancy which (from a practical viewpoint) faced the danger of progressive collapse. Higson and Hough (20) wrote,

> "Whether such a structure is likely to be more or less edifying to its users than a more visually complex one is probably a less important question than whether such an attitude to structural design is consistent with other design attitudes throughout the building; whether it is becoming a contrived response to a simple problem; and whether it is becoming too expensive."

1.13 Hunt's (19) example of the architectural aim of expressing load and support <u>compromising structural efficiency</u> is also similar to the case of the Imperial War Museum (Southwark) extension where the joist and slab elements of the composite floor construction in the upper galleries are separated.

It may be useful to point out that the architect in being preoccupied with the 'legibility of the structure', should consider the structural action and behaviour of the system, so that the <u>architectural idea of support is appropriate to the supporting mechanism of the structure</u>.

1.14 Summary of Differences in Historical Origins, Training and Design Aims in relation to the Thesis Objectives

The evolution of the present roles of the engineer and architect have arisen from their historical origins and their influence on their professional and social status, as well as the influence of their training on separate design values and aims. Their separate attitudes are a consequence of the industrial need for specialised knowledge and skill to widen the scope of possibilities in production and building. Arup (6) observed that the specialisation in design of related entities was preventing effective integration between members of the design team. This was caused by gaps in understanding which were often neglected in academic training that was geared toward professional competence Gutman and Frampton (21) argued that the gaps in understanding would persist if no attempts were made to 'bridge' them at a level of principles and ideas. The introduction of structures in architectural curriculums has not been effective with input from predominantly engineering viewpoints. In this respect, the understanding of structural principles may also be approached by discussing their relation to architectural design aims. What is significant is that structural engineers design structures for reasons very different from the ones which prompt the architect to use them. Some of the more fundamental questions related to the architectural use of structure may be,

a) How can structure be used to improve architecture?

b) What aspects of architecture are we using structure to improve?

c) What are the strategies or approaches related to the above questions? The answers to the preceding questions are related to each other: the aspects of improvement establish the common (overlapping aims) of the architect and the structural engineer and could improve a better understanding of the divergent approaches taken by both of them. This could lead to a better integration of both design approaches and better architecture.

The thesis assumes that one architectural aim is to use structure in ways which could improve the architectural design. The 'core' aspects have been hypothesized in para 1.0 and in order to achieve the objectives of the thesis (also defined in para 1.0), this Section proceeds by studying Modern Movement and contemporary examples of architecture to:

i) relate the more significant architectural concepts and design philosophies with the core aspects described

ii) extracting the salient architectural strategies in using structure and relating them with the core aspects.

1.15 i) How can structure be used to improve architecture?

Let us first consider the architect's aims. The architect seeks to innovate by improving the quality of architectural spaces and forms. The architect seeks original solutions to each design problem because he tries to avoid repeating solutions to different problems. The 'quality' he seeks is equivalent to the Vitruvian ideal of 'delight' achieved through the intangible effects of spaces and forms.

When structure is used for the purposes of improving architectural spaces and forms, then structural criteria alone is inadequate consideration in the process of generating solutions. The development of structural configurations and the shaping of its elements must be subject to the influences of architectural criteria as well. (Problems arise therefore, when engineers are expected to consider subjective and intangible criteria in achieving their aims of strength, stability and economy. Also, architects with little appreciation of structural aims may not be able to successfully motivate and guide the development of structural concepts in tandem with those of their aesthetic and utilitarian aims)

ii) What aspects of architecture are we using structure to improve?

Structure may be used to improve both the intangible and tangible aspects of architectural form and space.

1.16 The Intangible aspects

Rykwert (14) who defined architecture as being involved with giving physical form to social establishments, believes that architectural forms are shaped by more intangible criteria,

"As the social milieu cannot be differentiated, (nor) read without isolating establishments within it, whether they be families, communes..... so the world around us cannot be read and therefore not understood without isolating forms and sequences of form within it."

a) The intangible expressions and functions required of architectural forms are those of:

i) artistic themes (for e.g. Cubism in the International

Style)

ii) abstract symbolism (for e.g. as in the works of Wright, Kahn)

iii) character or imagery (as in the context of icons or 'objet-types' borrowed from forms of construction other than those of building)

iv) hierarchy and order (in order to identify important spaces and ancillary spaces, and to ensure a coherent composition of the architectural whole)

v) visual cues required for the identification of entrances, circulatory routes, sequences of space and transitions from one space to another.

b) In order that these intangible aspects are communicated coherently to others, the architects would use a set of typical forms (or elements of forms) organised into whole which themselves take on characteristic, generic patterns. Such a set of forms or a typology of forms would embody a sort of 'system' whereby the building forms could combine and recombine according to grammatical and intuitive rules. The architect would view each building task as a new opportunity to further explore the ideal type (22). Chernikov (23) believed that these typologies served as 'rational and principled exits from what had become vague and indefinite situations caused by the indeterminancy of clients' needs which changed as technology developed. The following paragraphs will illustrate the various typologies which attempted to communicate the intangible aspects described in para 1.16 (i) to (v) through the use of structure.

1.17 Artistic themes in typology expressed through structure

i) The typologies of Mies and Corbusier were influenced by the artistic ideologies established by the De Stijl movement, characterised by the paintings of Piet Mondrian and Theo van Doesburg between 1922 and 1929.

"Mies' Barcelona Pavillion....like Corbusier's villas, was also an elegant solution to broader shared problems of expression of the period. Historians have rightly drawn attention to the similarity of the plan to Mondrian's paintings...." (24)

"Spatial ideas that were later drawn into the architecture were often first revealed at the smaller scale of painting or sculpture..." (25)

"By 1917, it so happened, the influences of FL Wright and P Mondrian had fostered a vocabulary in which simple geometrical forms, rectilinear grids and intersecting planes were indeed part of a shared style which seemed to have an almost universal application from painting to typography, from sculpture to furniture design and to architecture."

Similarly, the architectonic constructions of Chernikov were in the tradition of combination themes characteristic of

Russian church forms. (Fig 2) Wright's childhood experiences with the educational Froebel blocks were also hypothetical influences on his typology (fig 3A) and Corbusier's vocabulary of primary forms were abstracted from Classical precedent (fig 3B).

In essence, the idea expressed by the architectural typologies of Wright, Corbusier and Mies was of the <u>independence of wall planes from their traditional supporting roles</u> so that:

a) enclosing elements of space other than those of load-bearing walls could be used and thus there could be less constraint in the layout and configuration of the shapes of enclosing elements

b) the facade of the building could be articulated freely without excessive constraint of structural elements within the plane of the facade

c) building forms with less visual bulk could be detailed to give the sense of weightlessness to all parts of the building

1.17 ii) In these ways, Wright (26) was able to eliminate the room as a box..... by minimising separate rooms so that spaces flowed from one to another. In this respect, Wright in his early houses limited the use of load-bearing walls to short stretches on plan and relied on brick piers instead, to support the pitched roofs which expressed its 'Prairie' character. Large openings were therefore possible and the enclosing elements assumed a perforated nature suitable too ventilating and lighting requirements, and the aspects of relating the spaces of the house with those of its natural site and surroundings. The brick piers were appropriately proportioned to suit Wright's concept of expressing 'horizontality' in the forms of his houses. With the piers carrying the main load, the enclosing walls could be made of thin elements, screen-like and articulated with patterns to provide visual relief. The use of slender supports and thin walls also made possible the 'atrium' spaces of his Unity Temple and the Larkin Building. Figure 4,5

The Kaufmann House (1930) used 'cantilevered concrete trays rooted to a core embedded in the boulders' on it sloping site over a dramatic waterall. Walls were avoided almost entirely and together with a sense of shelter created by its deep overhangs, the horizontal elements appeared to soar free of apparent support and the surrounding landscape appeared to flow around the house and into its spaces making it merge dramatically with the natural landscape.

1.17 iii) Corbusier (1) used the pilotis to support the weight of the building so that its interior and exterior walls could pass in any configuration according to functional or aesthetic requirements. The 'free plan' allowed rooms of different sizes (and shapes) to be slotted into the skeleton and spaces could then be composed according to architectural sequence. This concept was inherent in his Dom-ino House, a structural prototype designed in 1914-15 as a concrete housing system, for the rapid reconstruction of Flanders, ravaged by war. It comprised three horizontal slabs, smooth below and above, each of the two supported on square sectional posts of concrete (whereas the pilotis was cylindrical in form), the lower level lifted from the ground with squat concrete blocks. Employing the structural principle of the cantilever, the slabs extended well beyond the line of supports and this effectively separated the structure from the screening functions of the wall by removing the fill from the frame. The 'fill' was attached to the end of the slabs which could be expressed as a void or composed without interruption from the structural frame, according to aesthetical intention or functional demand. In the Dom-ino houses, glass was placed at the corners and in other places where traditional masonry structure would have been most solid, structurally.

Similarly, Corbusier's scheme for a house in Carthage, Tunisia 1926, Villa Stein at Garches, 1926 and Villa Savoye, Poissy, 1929 featured overhanging slabs which created deeply shaded terraces where the pilotis were set back from the facade separating structure from cladding, and the 'strip window' which expressed planarity and transparency whilst admitting the most light to the interiors. (In Villa Stein, no pilotis were expressed but the extension of the windows to edges of the facade expressed the non-loadbearing function of the latter.)

The curvilinear walls in Villa Savoy are separated from the pilotis and they (the walls) express the use of cylinders in the abstract which harmonises with the rectilinear grids and upper volumes of the Villa, whilst defining movement through the building. (The curved wall at ground floor level guides the arrival of the automobile whereas the curved wall of the rooftop solarium appeared as a curved ship's funnel floating above the glazing below). Thus Corbusier uses primary forms in abstract within the context of his 'Five Points of Architecture' and the structural prototype of the Dom-ino. Le Corbusier was able to apply a wide range of ideas within his 'Five Points' of architecture, and to generate a wide range of building forms (with several projects) from the Dom-ino skeleton, which embodied the philosophy of the 'Five Points'. With La Tourette (1957-60), the Dom-ino was able to respond to the sloping site and the abstract requirements of a monastic college, whereas in the Unite, the site was of little consequence and subordinate to the Dom-ino archetype. In this and many other respects, there were similarities between Le Corbusier and FL Wright and common differences with Mies van der Rohe.

1.17 iv) Although Mies was not in search of different geometrical forms in response to varying design briefs, his prototype was the 'minimalist' box, immaculately detailed in varying arrangements of the rectangular grid frame with which he accommodated any function. Mies believed it possible to transform naked construction into the most basic underlying form:

"I believe that architecture has little or nothing to do with the invention of interesting forms or with personal inclination. True architecture is always objective and is the expression of the inner structure of our time from which it springs" (28).

Mies' entry to the Friedrichstrasse skyscraper competition of 1921 was an attempt at expressing the essential structure of a tall-framed building in what Curtis (29) believed was a minimalist solution. The glass curtain wall made visible the underlying structural system of floor slabs and columns. The curved floor plans radiating from a circulation core were a later modification which responded to three fractros: sufficient illumination of the interior, the massing of the building from the street and the play of reflections to reduce its visual impact, Foster's Willis Faber and Dumas Building follows in this tradition where the structure is as minimal as possible to create a 'weightless' visual whole.

Fig. 1B.

Mies' concrete office building (1922) expressed the horizontal layering of space with the use of upstand cantilevers (Fig.6) and here there is some similarity with Corbusier's Dom-ino prototype. His 1923 brick villa design consisted of walls which were expressed as planes in the formal composition, these overlapped without creating any dominant axes (such as those seen in Classical plans) and allowed the spaces to flow from one to another. The extension of some exterior walls to the surrounding site further emphasized the horizontal element of the composition used to merge the building form with the site. Here, the abstract paintings of Mondrian and van Doesburg are translated into the architecture of the brick villa. (Fig.7A, 7B.)

1.17 v) However, the <u>independence of wall planes from its load bearing role</u> which allowed significant innovations in space and form with architecture of the Modern Movement was better exemplified by Mies' Barcelona Pavillion 1929 (together with Corbusier's Villa Savoye, of the same year). The Pavillion was a temporary structure designed to represent the German national dedication towards technological and cultural excellence. The use of a thin roof slab "poised delicately" on cruciform steel-section supports coated in chrome is similar in expression to the Dom-ino idea, and was intended to demonstrate how structure could be used to create unprecedented effects of space. (Fig. 8.)

Mies' Crown hall at IIT (1952-6) was significant in two aspects:

i) it expressed the Miesian concept of the 'universal space' and

ii) the use of the vierendeel girder in providing a column-free space within which various functions could be flexibility accommodated

The steel frame with glass infill became the Miesian typology, from which evolved the Lakeshore Apartments 1950 and the Seagram Building of 1957. The Berlin Art Gallery (1963) also expressed the notion of Mies' 'universal space' subdivided by supports, with planar partitions for pictures. (Fig. 9) Curtis (30) described the Gallery as a cross 'between the thin planes of the Barcelona Pavillion and the symmetry and spatial ideas of Crown Hall, IIT. The steel supports were proportioned to recall Classical columns, while the vast overhanging steel roof evoked the idea of the entablature."

1.18 Structure used in abstract symbolism

i) Venturi's (31) anecdote 'The Duck versus the Decorated Shed" described the relationship between form and meaning and that the 'decorated shed' communicated its meaning indirectly throught symbolic form. (The duck represented an approach which used forms that were very obviously related to their intended meaning, or a modern building where the construction, structure and volume become the duration). There are different aspects of structural symbolism in relation to form and two extremes may be represented by Gustav Eiffel's Tower and the Statue of Liberty. Colquhoun (32) wrote, "In the (case of the Tower), structure is the (essential) and necessary condition of meaning; and in the case of the Statue, structure is purely enabling and plays no part in the object as a (symbol)"

ii) Both aspects may be exemplified with Wright's house designs;

a) the fire-place was the unifying element of the prairie household and its importance was symbolised by the load-bearing function of the chimney core centrally located on plan. In this case the structural role of the element was used to symbolise its importance

b) the use of structural cantilevers in the Kaufmann House allowed the building form to hover over the natural landscape thereby creating interesting transitions in space between the interior and the exterior. In this respect, the structure is 'enabling' the organic form which appears to be 'growing' out of the landform

iii) Corbusier's pilotis were symbols of the cylinder, one of a few primary forms associated with perfection and beauty, according to his Purist philosophy. In the eary Villas, this element of architectural form was both structure and symbol.

iv) Gaudi's forms (33) were "rooted in structural principles and an elaborate private world of social and emblematic meanings inspired by nature". To Gaudi, the 'laws' of structure were not mere laws of materialist physics, but were evidence of the Creator. In this respect, Gaudi used the parabola as a symbol for the sacral as well as in the geometry of his structural forms. The structure of the Sagrada Familia (1884-1926) and the crypt of the Santa Coloma de Cervello (1898) were also pragmatically based on the optimization of structural forces related to the use and variation of parabolic forms.

v) Graves' work has been interpreted by Colquhoun (34) as a form of abstract representation where its aim is opposite to that of 'Classical' architecture which sought to translate the 'ephemeral' into the 'durable'. Graves' philosophy is seen as a dialectic between architecture as a product of reason setting itself against nature, and architecture as a metaphor for nature. Consequently, Graves does not always use structural forms for load-bearing functions as in the case of the Benacerraf House addition (1969), where the structural frame is 'pulled away' from a wall to define a roof terrace. Here, structure is reduced to pure geometrical figure (form) to enable the release of primary and archetypal sensations, an idea explored by Ledoux in the classical idiom.

1.19 Character in Structure

This is perhaps a subjective but (nevertheless) real problem in the selection or the development of structure for the purposes of architectural expression. Not only do buildings have to be designed to function effectively, but they have to visually imply their functions as well. For example, a church design has to have a 'religious' or 'spiritual' character in its spaces and forms in order to be differentiated from a community hall, or a school assembly hall. This depends on:

i) visual precedent

It is not uncommon for certain concepts to be associated with certain building types, for eg. the expression of verticality in religious buildings or the use of massive walls with gloomy interiors that leave the altar areas illuminated which indirectly affect structural choice and development, according to the building forms used to enclose these spaces.

It is also not uncommon to observe that certain structural types are related to certain building types, for e.g., the use of arched steel trusses in Britain is associated with railway stations and market halls, and for some reason, the barrel vault roof (framed by arches) has been incorporated in most commercial buildings today. Indeed, the Lee House, Embankment Place, Lloyd's Building and the Baltic Quay developments all share the same typological form: a mid-rise block with a barrel-vaulted roof. (Fig 10A)

ii) iconic representation

Related to the notion of visual precedent is the association of certain shapes (or forms with) certain functions. For eg. the wedge shape and rectangular flytower is an icon for an auditorium ; its shape is determined by the volumes needed for their functions, and this icon is observed in Melnikov's Russakov Club, Moscow (1928) and in Stirling's Leicester University Engineering Building (1963). (Fig. 10B) In this context, structure is configured to follow the volume determined by the function, and if the 'volume' is expressed, then the structure may comprise load-bearing planes, or shells to form the surface of the volume, or it may be a frame supporting (and concealed by) cladding system to form the surface of the volume.

iii) interpretation of architectural issues

Rogers (34) in rebutting Prince Charles' 'vision' of a better Britain, pointed out that new expressions of forms were sought for pragmatic reasons of accommodating changes in use, accelerated by economic fluctuation. Classical precedents of planning, layout and proportions based on aesthetic theory no longer reflected the true character of modern building today, because they failed to accommodate change flexibly. The Lloyd's Building reflects this attutude and in the case of the Georges Pompidou Centre, the expression of an art gallery with the engineering aesthetic recalls the Eiffel Tower, where technology characterises and compliments the innovative spirit of artistic effort.

The Georges Pompidou Centre (1971) featured the use of vertical tension bars with gerberettes which according to Newby (10) is a quality that transcends mere style. After this building, structures which adopted the system of cable-stayed civil engineering bridges were designed to provide for a range of wide-span requirements. Whilst one body of architectural opinion believed in the expression of forms unrelated with the engineering aesthetic, another group may adapt the engineering aesthetic without necessarily containing significant technological or architectural innovation. Although engineering structures in the Industrial revolution contributed significantly towards infrastructure improvement, they were not initially considered examples of architecture due to their unprecedented aesthetic. By contrast, several contemporary buildings adopt the engineering aesthetic as a form of architectural expression, without the technological significance of its origin.

For example in Rogers' Inmos Building and Patscentre, Grimshaw's Oxford Ice Rink and Homebase Brentford, the cable-stayed structure is applied to wide-span single storey buildings with recreational, commercial or industrial functions. The exposed structural steelwork and metal components are intended to imply the association of sophisticated technology with business and political concerns whilst the structural configuration resolves the utilitarian need for flexibility, although it has been argued (45) at unjustified cost and complication.

iv) <u>the architectural differentiation of spaces and forms</u>

Where architects differentiated the character of spaces and forms they created with different geometries and shapes, it would be the artistic considerations of formal composition that would determine the choice of structure and its configuration. In Kahn's Dacca Parliament Building (1963) (Fig. 11A) and the Philips Exeter Library at new Hampshire, (1969) (Fig. 11B) the shapes and sizes of individual spaces and forms are varied to characterise their functions and hierarchial order. The forms were also varied to suit the scale of individual functions, and in the case of the Richards Medical Laboratories (1962), (Fig. 11C) service and stair cores were used to link up small parts of the design with larger parts, in order to create a more visually balanced composition.

Like Kahn, Stirling's notion of formal composition involved the use of 'cluster assemblies' (Fig. 11D) where functions and spaces were articulated with variations in geometrical shape and size. Consequently, different structural systems are selected to suit varying spans and geometrical configurations; as in the case of the Engineering Faculty in Leicester University:

> "...the structural support changes for different parts of the building - the type of construction chosen being most appropriate to the dimensions and activity of a particular space, ie. industrial spaceframe roof across the workshops; disconnected acoustic shell within an rc insitu box for the lecture theatres; rc diagrid spanning between peripheral columns over the research labs. There are many structural systems as there are major differences in function and the choice of the type of structure was a later decision in the design evolution."

1.20 One of the most basic and important aspects of architectural design is the expression of the building entrance, and the definition of clear circulatory routes through the building. Problems arise when primary spanning elements are expressed visibly in the external architecture and these may be arranged in one or two-way systems which may or may not allow much flexibility in varying the appearance of the entrance or its location.

Briefly, the arrangement of structural elements relates to the following visual aspects of architectural planning:

a) the expression of entrances and primary circulatory routes (such as circulation spines)

b) the variation of shapes and forms with different parts of the building for the purposes of visual identification.

c) the cross-sectional profile of the building

d) the simplification of visual patterns and outlines implied by the structure for eg. space frames may not be appropriate for interior ceilings which are to be uncluttered in appearance.

e) assymmetrical and symmetrical expressions of form; for eg. the structure may comprise repeated elements which give it a symmetrical appearance particularly with one and two-way systems. This may not be appropriate to the architectural idea of creating assymetry with atypical expressions of different parts of the building.

These aspects (a) to (e) will be elaborated in the case studies of Section II, to see how they influence the development of the structural solution.

1.21 The visual organisation of forms for the purposes of communicating with the users and participants of a building involves for example, the expression of abstract notions of balance, order and hierarchy. These abstract notions sometimes differ from the organisation of forms implied by structural ideals of simplicity, economy and stability. The following paragraphs discuss some of these differences.

1.22 The structural and architectural implications of expressing the abstract notion of balance in configurations of form

The structural interpretation of forces balanced in a state of equilibrium implies that the size, shape and position of the structural element depends primarily on the direction and the magnitude of the force it is to resist and its effects on the formation of the structural element, for eg. a tendency for buckling or sagging. Under uniform loading conditions, the resistance of forces by equal and opposite forces imply symmetrical arrangements of form, for example a three-pin arch structure has its second pin centrally located at the crown of the arch. By contrast, the architect's interpretation of balance takes on a more abstract nature. Balance may be implied even with assymetrical compositions of parts that differ in shape and size. Figure 12A shows Stirling's Olivetti Training School (1969) comprising a long wing balanced by a shorter wing with a special space. Ledoux's Hotel Guimard (1770) (Fig. 12B) has an assymetrical floor plan balanced by three major living spaces. Aalto's Saynatsalo Town Hall (1952) (Fig. 12C) has a special space with a detached form that balances the remainder of the town hall.

As mentioned in para 1.19 (iv), Stirling's interpretation of 'balance' involves the notion of 'stable' compositions of form which to the eye, appear to be in equilibrium. In his Leicester Engineering Faculty, the tower block and the auditorium are perceived as 'masses' located in positions that make the entire building composition look stable. (Fig. 13A) The structural frame is therefore configured to provide this composition.

He wrote of the Engineering Faculty (38).

"All built form has weight and properties of stability or instability dependant on shape and it is necessary to make a grouping of masses which is inherently stable. In the engineering building, the weight of the towers above counterbalances the overhang of the lecture theatres under, (in other words), the extent of the cantilever of the lecture theatres is dictated by the amount of weight over; if you removed the top floor, the building would overturn. No doubt there is a certain architectural quality inherent in the composition of stable masses particularly when they are assymetrical."

Thus, architectural 'balance' is an abstract notion applied to the composition of form and space, similar in context to artistic compositions, and may involve symmetrical or assymmetrical arrangements of component elements, whereas structural 'balance' related to the equilibrium of forces, depends on the scientific laws of statics.

The ideal shape of the room is retained and its distortion is avoided particularly when attempting to fit it into a structural module or preconceived shape. <u>Instead the structure is developed to support the stable compositions created</u> by Stirling, for eg. in the History Faculty, (Fig. 13B) the room shapes are stacked to become the total building form which show that smaller rooms are on the top floors with increasingly larger rooms at the lower levels, giving the 'L'-shaped block a buttress profile in section. The thrust from the 'steel-truss' roof which allows daylight to filter through the library, is stabilised by the buttressing effect of the 'L' shaped block, and the "total building mass is a resolvement of various structural forces". (38)

The Dorman Long Building (1965), is another example where Stirling's architectural judgement influences the use of structure: The engineers presented Stirling with six alternatives for the framing pattern of an external grid of columns, all using approximately the same weight of steel and incurring approximately the same costs. Eventually, Stirling proposed a pattern which related in scale to the building section and the arrangement of smaller accommodation at the top and larger accommodation below:

Horizontal wind stiffener beams were used adjacent to each of the upper floors and diagonal struts were used on the splayed front of the building, maintaining the strength of the structural mesh even though the stiffener beams were ommitted at every other level for the aesthetic reason aforementioned. (Fig. 13C)

The thrust created by the splayed front of the building is counterbalanced by shafts of vertical circulation which Stirling 'pulled out' to express their stablising function as 'buttresses'. (38)

1.23 The differences between architectural grid expressions and ideal structural grids

There are also differences in the ways architects and engineers use grid patterns in design. The architect conceives of grid patterns as repetitions of basic geometries, thus Mies' Crown

Hall, IIT (1956)(Fig. 14A) has a grid pattern generated by a square, the resultant form being rectangular whereas Wright's Unitarian Church (1949) (Fig. 14B) and Boomer Residence (1953) (Fig 14C) have equilateral triangular grids with triangulated floor plans. Kahn's Trenton Bath House (1956) (Fig. 14D) and van Eyck's Visser House (1975) (Fig. 14E) illustrate the use of tartan (plaid) grids where the sectional profile of the vertical supports assume a variety of shapes depending on requirements of enclosure, structure and aesthetics.

Gridlines may also shift at junctions to spaces and forms which undergo a change of size or shape. Stirling's Leicester Engineering Building (1959) (Fig. 14F) and Aalto's Turun Sanomat Offices (1929) (Fig 14G) are examples which show a shift in the gridlines in the floor plans where changes in spans occur. Grid patterns may also be rotated when building blocks are placed at angles to one another, this being exemplified by Wagner's Anker Building (1895) and Isozaki's Gunma Museum of Fine Arts (1974). (Figs. 14H, 14I) The overlapping of gridlines occurs when elements of form keep their 'autonomy' as they intelock to form a composition.

Meier (35) uses the geometry of overlaid grids to induce a sense of spatial compression at certain points of his Atheneum project (1979), tension at others to create spaces which begin to narrow and which begin to open up. (Fig. 14J). A similar grid expression is exporessed in the Desourdy Residence by Cayonette and Saia Architects. (fig. 14L)

From a practical viewpoint, structural grids were used for the identification and location of structural supports, and an indication of nominal spans for structural design. It is not uncommon for architects to simplify the 'setting out' of the building geometry by avoiding complex configurations which need more points of reference to describe the locations of supports on plan. There is thus a tendency for builders, engineers and surveyors to favour regular grid patterns, from a pragmatic point of view. Grid patterns are also used to locate other building components, such as services, electrical and lighting outlets, and non-load bearing elements such as wall partitions. Ideally, partition and service grids should by-pass structural grids so that walls, partitions, services, equipment and circulatory space do not interfere with structure.

Schodek (46) points out that structural grid patterns develop in response to the design developments of other criteria. "While exact criteria for system choice are often elusive during early design stages, it is possible to begin identifying some of the basic issues involved and to begin developing strategies for (grid) pattern development ..... which could potentially lead to viable and efficient structural systems.

The structural engineers's concern with grid patterns would be related to thier implications on the choice of and association between vertical and horizontal support systems.

"The type, pattern and scale of the vertical support system present in a building greatly influences the type of horizontal spanning system used and vice-versa. The support geometry is in turn, ultimately related to critical dimensions derived from considering the intended functional usage of the building.

The vertical continuity of the structural system is also an essential consideration between floors with different support spans which may arise with mixed-used buildings.

The structural engineer will also consider the inherent flexibility with which the grid pattern may accommodate one or two-way structural action. Arup (47) summarises the engineering considerations in relation to planning in reinforced concrete.

"It is difficult to say beforehand which system is the more economical. So much depends on the spans of slabs and beams. It is important to get the maximum regularity and it will therefore mainly depend on which scheme can best be combined with the architectural requirements."

In terms of planning in reinforced concrete; slab spans are kept as small as possible. As the floor slab is the biggest item n such construction, the amount of reinforcement required for spans beyond 16ft will cause a noticeable cost increase.

The span of beams is to be minimised as far as possible and as the columns do not cost so much (as the beams) it pays to have many columns and short beams.

Slabs and beams are to be made continuous over several supports and therefore, the direction of the span should therefore, preferably not be changed. The slabs are often made approximately square to that they can be cross-reinforced and a saving of cost is obtained urban only two-thirds of the total load need been considered when calculating the moments. The grid pattern implied is shown in Fig 14L. In engineering terms, if the advantage of cross reinforcing the slabs is not being used it is pointless in having beams spaanning both directions. Similarly, there is no point in using the grid system unless a column can be placed at each point of intersection between the beams. This rigid imposition on column location restricts the lay-out of interior spaces unless the architect is able to integrate these elements into the spaces, as Corbusier was able to do. (Consequently, structural systems could perhaps be developed in response to minimising the constraints on architectural layout. These aspects will be investigated in Section II case studies and elaborated in Section III para 3.9.1)

This is very much a question of the effects of bay proportions, for example, when square grid modules form one-way serial aggregation patterns, many of the structural advantages of two-way action are not easily achieved because continuity for the horizontal spanning system is directly possible only in one direction rather than two.

Construction considerations might also cause one-way elements to be preferred for linear patterns. One-way systems are also used with square bay dimensions which are very long because there are not many long-span two-way constructional systems available. One-way systems are therefore used in large square bays, so that individual elements in the system can be designed easily to meet the unique load and span requirements. As such - the structural factors associated with the proportioning of grid patterns are not necessarily related with those of architecture. This could lead to problems in expression: for example - the gable-end elevation of a long span one-way system may need to be articulated in order to reduce its visual impact. It is common to find two-way expressions in what are actually one-way structures. (Fig. 140). This is related to the awkwardness of turning corners with one-way systems. As illustrated in Fig. 14 M Isozaki Fujimi's Country Clubhouse and Kitakyushi's Central Library Fig. 14N illustrates one reponse to this problem.

The structural engineer would also consider the adequacy of lateral load - carrying mechanism within the architectural grid configurations in order that the resultant assembly is essentially stable bending. A general structural objective is always to minimise bending and this is not done by using spans of unnecessary length, however, spanning less than the minimum capacity of any typical system is uneconomic.

With the expression of buildings as "composite forms" (viz the buildding form comprises a union of different shapes and columns) more than one generalized structural pattern is used in a building and the intersections of <u>different</u> grid patterns is a structural design issue. Schodek (46) proposed three structural strategies in this respect:

The first would be to align one grid with another such that one grid becomes a subdivision of a larger one. This alignment is aimed at reducing one additional number of vertical supports which might be required in the case of two different intersection grids.

The second strategy involves the use of mediating spaces between the two grids so that the intersection of two structural systems is avoided.

The third strategy involves the use of a mediating structure which is adaptable to characteristics common to both systems. A structural grid that is much smaller than either of the primary systems but a logical subdivision of each may be used to join the two primary systems.

However these structural considerations of geometrical alignment and subdivisions of span will have to be integrated with those implied by the architectural composition of spaces and forms. Conversely, these structural grid considerations could also serve as generators of form and space.

1.24 The architectural expression of order and its structural implications

Related with the use of grids was the notion of order essential to the expression of hierarchial elements. This allowed the identification of relatively more important spaces from 'servant' or secondary spaces. Hierarchial order could be expressed in a number of ways:

a) the size of the interior spaces relative to the peripheral space as indicated in the section of Ledoux's Director's

House (1779). (Fig. 15A) This would influence a change in grid-spans thereby emphasizing the predominance of architectural aims over the economic preference for regular and repetitive spans.

b) concentric plan configurations imply an increasing importance of spaces approaching the centre of the plan, as in the plan for the Deal Castle (c1540), (Fig. 15B) architect unknown. The concentric plan configurations could also imply 'layers' of space separated by varying types of vertical supports depending on aesthetic effect; these may range from columns to perforated screens to solid walls.

c) Corbusier's Ronchamp chapel (1955) (Fig. 15C) expresses hierarchy as a function of the height of the interior space and the complexity of wall openings in the main wall.

d) In Kahn's Dacca Assembly (1974) (Fig. 11A) the plan form at the centre transforms through a series of changes to a different form at the perimeter. In Tange's St Mary's Cathedral (1963) (Fig 15D)and Corbusier's Church at Firminy (1963), (Fig. 15E) the transformation occurs in the building section in a vertical direction from the ground level to the top of the building. This 'transformation' of configurations in plan at different levels influences the alignment and continuity of vertical supports and the horizontal spans of the structural frame.

e) Very often architects would propose to accommodate different major activities which require large spaces, in separate buildings, where site area permits this option. This also reduces the visual impact of one large building mass and thus a whole or major part of a building is reduced and expressed as separate entities, or it may be included as a part in the whole or added on to the primary form. thus Utzon's Sydney Opera House (1968) (Fig. 15F) comprises two blocks, one smaller than the other with similar forms. Lutyen's Salutation (1911), (Fig. 15G) Corbusier's Villa Shodan (1951), (Fig. 15H) and Wright's Unity Temple (1906) (Fig 15I) express the servant space with a reduced form of the primary space. Gunnar Asplund's Woodland Crematorium (1940) (Fig. 15J) show scaled down spaces of comparable function, 'nested' in the floor plan configuration. Aalto's Wolfsburg Parish Hall (1962) (Fig. 15K) expresses a series of scaled reductions in the floor plan. These reductions influence the structural question of using one support system for different spans in a same geometrical configuration, or separate structures for the different spans in the same geometrical configuration. Again, the decision is more likely to be architectural, than a matter of economy in span.

1.25 Structure used to improve the Tangible Aspects of Architecture

The previous discussions on using structure to improve the intangible aspects of architecture are now related to the improvement of the tangible aspects. These may be summarised as follows:

1.26 The prevalent trend that may be observed in the development of building structures is that structural load-bearing capacities have improved with:

i) material strength

ii) the shaping and configuration of structural form (in relation to the development of structural types, such as the truss

1.27 The configurational possibilities have been widened by production methods or the application of methods from other fields of production. For eg. the cast-steel noduli of the Lee House transfer structure were fabricated with ship-building methods and were essential components of the structure without which the architectural advantages detailed in (case study 4) would not have been realised. The cable-stayed structure originally developed for bridge construction has been adapted as a building structure in several of the Section II case studies. These systems have also been developed in relation to the following practical advantages:

i) economic production and fabrication processes.

ii) ease of transportation

iii) ease of assembly and in site handling

iv) the ability of the components to assemble flexibly into various forms

1.28 Lafaille (36) wrote "to accomplish a task with the minimum use of materials is finally the only interesting problem". Translated in terms of architectural considerations, the Modern Movement examples sought the following advantages:

a) the structural means to improve the range of architectural expressions in the design of spaces and forms. This will be enlarged in the summary on architectural approaches to using structure. (Section III)

b) The improvement in the variety of possible expressions widens the architects' typology of forms and influences their aesthetic ideologies on form and space. For example the steel frame allowed the expression of 'visual lightness' and hovering forms characteristics of buildings such as Gropius' Fagus Shoe Last Factory. Previous to this, the introduction of steel construction in the nineteenth century brought on changes to architectural proportions of buildings which were traditionally based on Classical notions of aesthetic form, and brought much controversy in architecture. Structural technology continues to facilitate the development of several ideologies in relation to the expression of architectural forms and spaces.

c) the reduction of space occupied by structure increases useable floor area on plan and alleviates problems with headroom clearances in buildings with height constraints, by reducing the sectional depth of horizontally spanning elements. Therefore, buildings are able to accommodate more space with less structural bulk.

d) the extent of opening between structural supports is increased; this allows for more effective natural lighting and the articulation of infill panels for architectural effect (for eg. as in the case of the Corbusian villas)

e) buildings were required to fulfill increasingly complex functions and had to accommodate a range of mechanical and electrical services in order to operate efficiently and comfortably. These HVAC, computer and electronic systems (such as the ones in the HK & SB building) through a system of false floors and ceilings and effectively reduced the headroom clearances in each floor. The problems were resolved with structural systems configured to maintain thin floor slabs without intermediate support.

In single-storey buildings, the use of trusses in the primary span allows the distribution of services between the struts. The roof structure to the Shotts Factory serves as a gantry and it is configured to accommodate moving loads caused by machinery, without incurring excessive bulk and structural depth, nor the monotonous expression of an rsj frame shed.

f) an increasing demand for flexibility in buildings to cope with changes in use and future expansion (or contraction) has brought on a number of structural responses and influenced architectural form and space. These are described in the case studies of Section II.

The significance of this response is seen in Wachsmann's (38) structures, Kurokawa's expo pavillions (1960) and some of Tange's works in the 60's particularly the expo '70 theme pavillion and the Yamanashi Communications building (Fig. 16).

Rogers (34) summarised the problems involved with the requirements of flexibility,

".... the use and form of modern buildings change dramatically over short periods of time. A set of offices today might become an art gallery tomorrow; a perfume factory may switch to making electronics. And quite apart from the fact that buildings must be able to expand and contract, and change their function, a third of a typical modern office is occupied with technology which will need to be replaced long before the building itself needs to be demolished. All this makes flexibility an essential feature of effective modern design...."

<u>To cope with the need for flexibility</u> in accommodating changes in the use of buildings, architects would prefer structural configurations which provided the advantages of column-free spaces and the ability to modify, replace or add to the essential engineering services required for the operation and comfort of the buildings. The futuristic ideas of the Archigram group were emulated by Kurokawa's Metabolist philosophy which essentially emphasised change and replaceability, in architecture. Consequently, buildings were conceived as entities with replaceable parts supported by a 'permanent', more durable framework (likened to a city infrastructure). This led to the use of

structural cores which characterised the more permanent 'aspects' of the building and the expression of floor slabs or services as modules supported by these cores.

However, in the experimental buildings of Kurokawa viz the Takara Pavillion in Expo '60, (Fig. 17) the execution of the idea posed problems, as the electrical and sanitary plumbing interferred with the concept of replaceability. Taylor (39) pointed out that the floor slabs to the Yamanashi Communications Building (Fig. 16) designed by Tange were cast into the structural cores, and therefore could not really have been replaceable. It was the expression of the idea which led to the use of the structural elements and their arrangement, although they could not be replaced in reality.

In the Lloyd's building, the idea of replaceability of mechanical components, services and circulatory elements is expressed by the 'satellite towers' which vertical propped cantilevers supported by the rc frame of the main building. The satellite towers located on the periphery of the building allow access to the parts to be replaced.

The need to cope with future expansion and growth has also led to the use of structural modules arranged in two-way and three-way spans. This is typified by Rogers' Fleetguard Factory and Patscentre projects, and Foster's Renault Centre

(g)
at Swindon.

g) Sometimes, functional and practical requirements of the design brief play a strong influence on the building form and layout. These indirectly affect the development and choice of structural systems. For example, the design of roof structures to stadium grandstands must allow for the provision of adequate ventilation, unobstructed view and spectator circulation. This implies that visually and structurally, the forms and structures chosen are often slender and light in appearance, such as those of tent (membrane) structures where cantilevered supports confine the location of columns to the rear periphery of the sports arena. Examples in the contemporary context include the Sydney Football Stadium, Piano's Bari Stadium, the designs for the 1990 World Cup Stadiums in Italy and the Lloyd's Cricket Stand in St John's Wood, London.

In Stirling's (40) Stuttgart Art Gallery practical considerations of cost, of the suitability of the structure to the plan configuration, and storey height constraints influence the aesthetic arrangements of the gallery spaces and changing exhibition rooms:

Reinforced concrete wall construction was cheaper than

(g) Gardner and Johns (39) identified two different kinds of flexibility; built-in flexibility and the ability to adapt at a future date. Built-in flexibility involves investing additional capital at construction stage so that future changes in use can readily be accommodate. The latter form of flexibility sets out to provide only what is initially needed, but to do so in a manner that permits future additions or extensions within agreed guidelines.
Gardner and Johns believed that there was no such thing as total flexibility

column infill block construction in Germany, so the use of walls as beams was a cost effective decisions, given the compatibility of wall structures to the gallery floor plans. Flat slabs supported by these storey-height wall beams kept the horizontal structural depths to a minimum.

Columns were introduced to support the flat slab construction which carried the terrace and upper galleries. The alternative solution was a significantly more expensive composite steel/concrete grillage with slots cut out for services distribution, without intermediate columns. The former solution was adopted for reasons of cost and also because the columns were used to introduce a more intimate sense of scale to the larger spaces.

In this example, it can be seen that aesthetic notions of character in spaces and forms are influenced by practical considerations such as those just described.

1.29 In summary, structural forms may be developed in ways closely related to the purposes of their application ie. towards improving the degree of their adaptability to the requirements of architectural planning and expression, and the least problematic form of construction to achieve that aim, within justifiable costs.

Conversely, architectural concepts may involve:

i) the selection of appropriate systems and the generation of ideas on space form and expression within the constraints inherent in each of these systems. Carmichael (41)

described two modes of design creativity: "the creativity has to be realised within their constraints but can also be the springs of creativity."

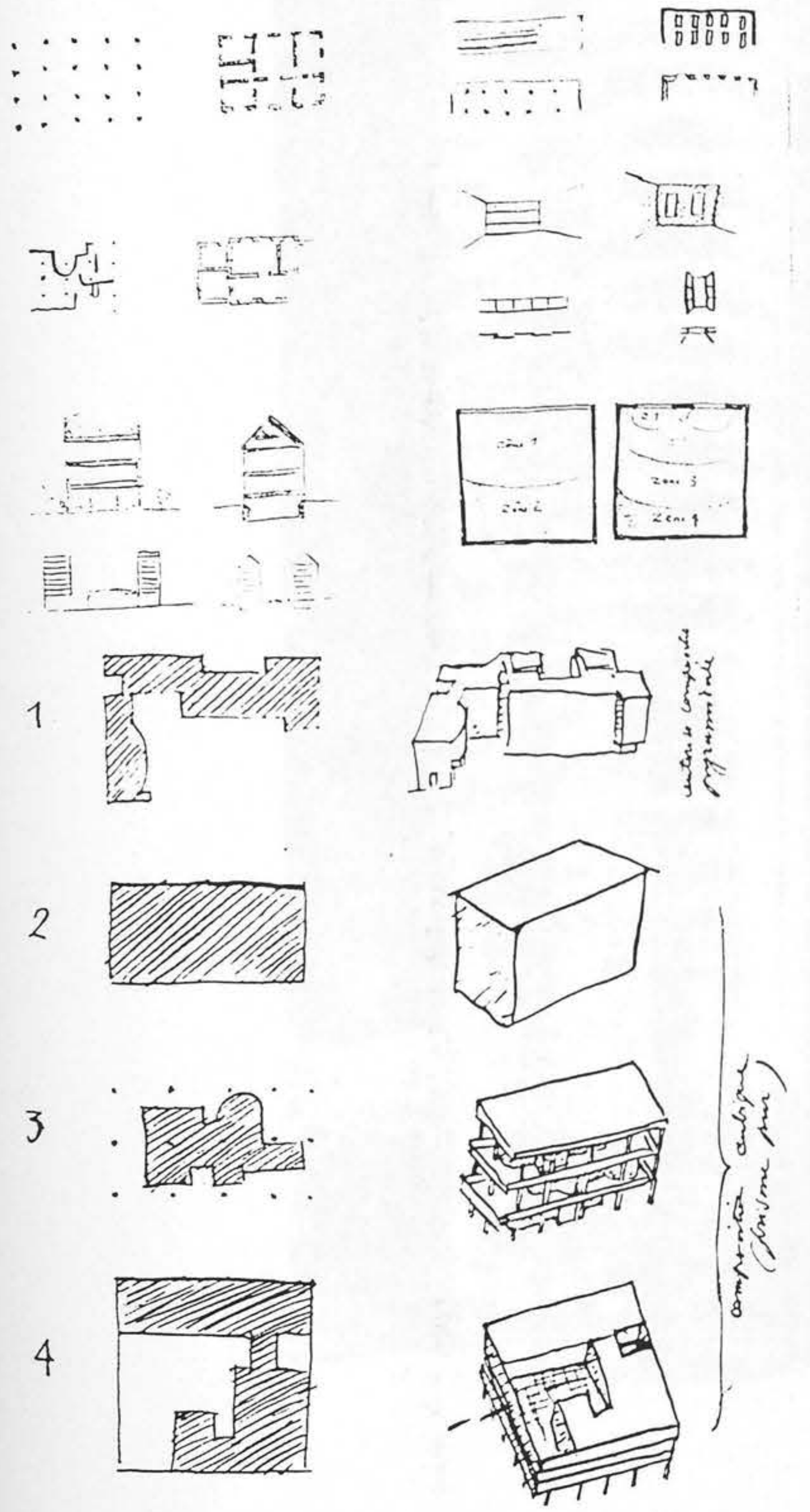
ii) 'hybrid' or one-off systems may be specially developed to better accommodate a complex range of criteria.

In the case of point (i), both Mies and Corbusier were able to make significant improvements to the architectural planning of spaces and forms with the use of ordinary steel and rc frame construction; in other words, the aim in architectural design is not to create structures which are significant from an engineering point of view (unless the design problem requires it to be so) but that innovation lies in the application of structure to achieve architectural aims.

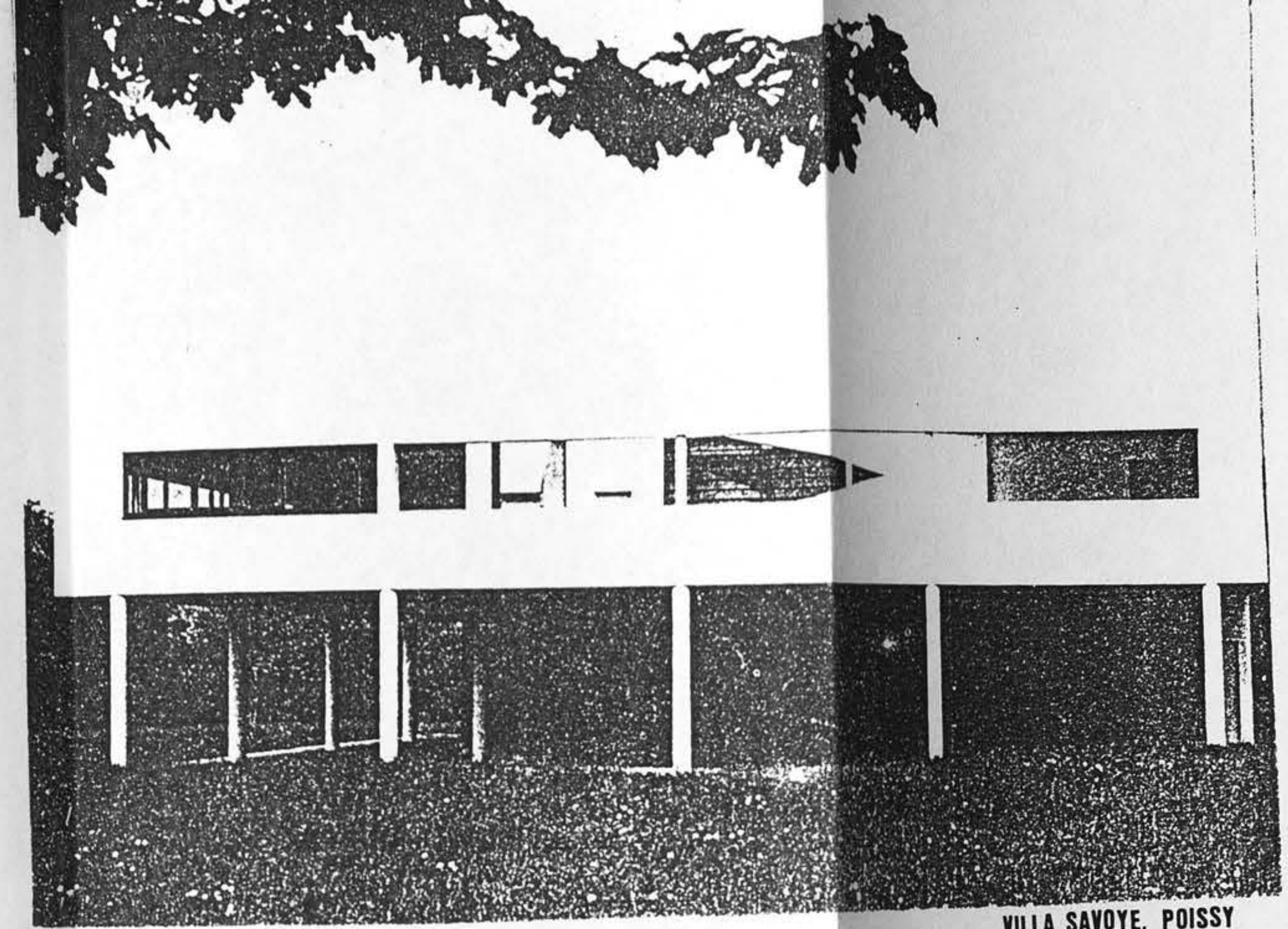
Although the engineer may generate a range of alternative solutions to the structural problem, the final choice on the most appropriate solution may seldom be made on purely structural grounds. Carmichael (41) points out that "the link between the social, the emotional, the space planning and the technological elements have been so intimate that it would be folly for either one to take a secondary role."

Section II then investigates with contemporary case examples, the ways in which aspects of architectural design and construction influences the development of structure in relation to the ideas raised in Section I.

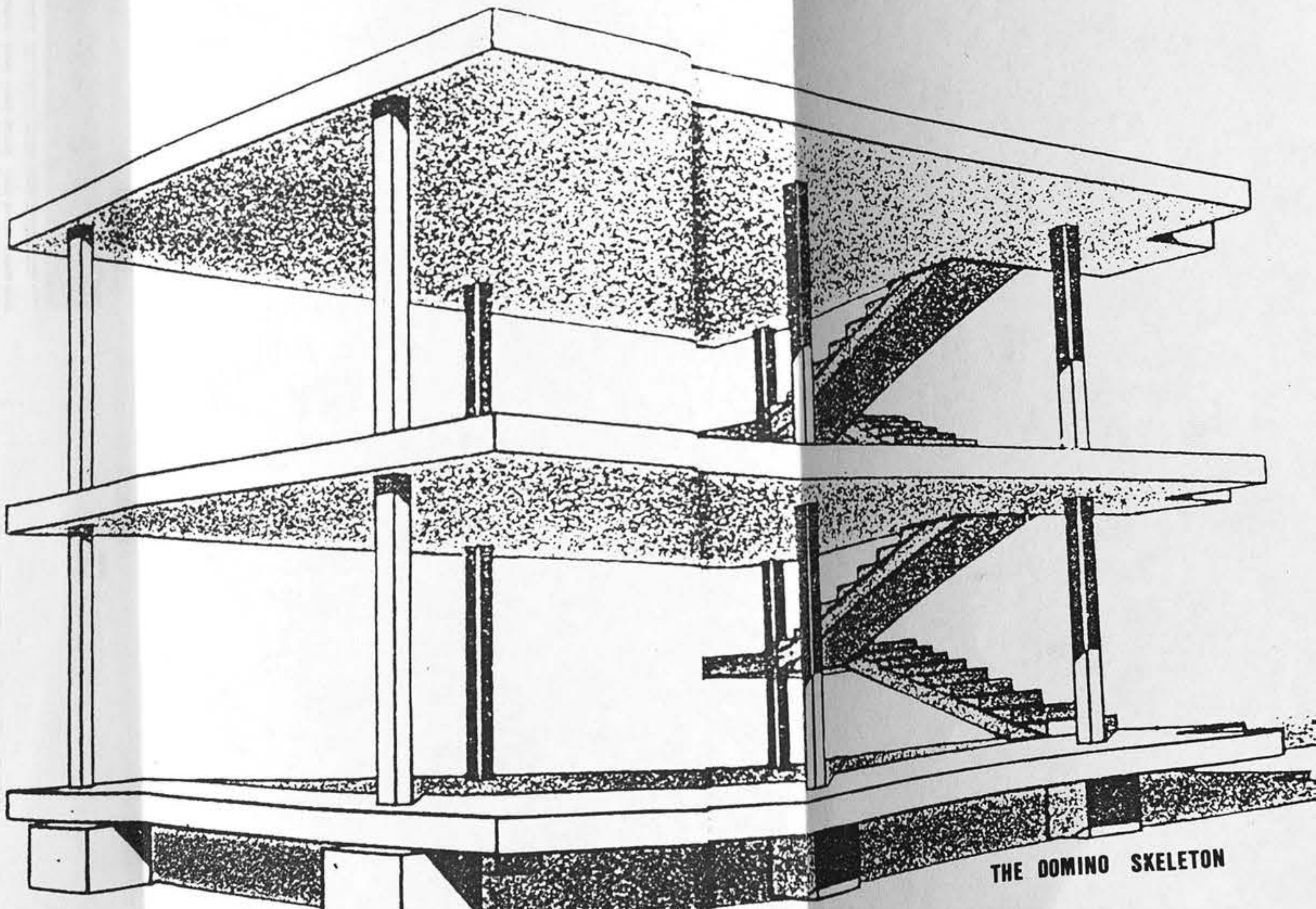
Fig 1A A MERGER OF AESTHETIC AND STRUCTURAL SYSTEMS



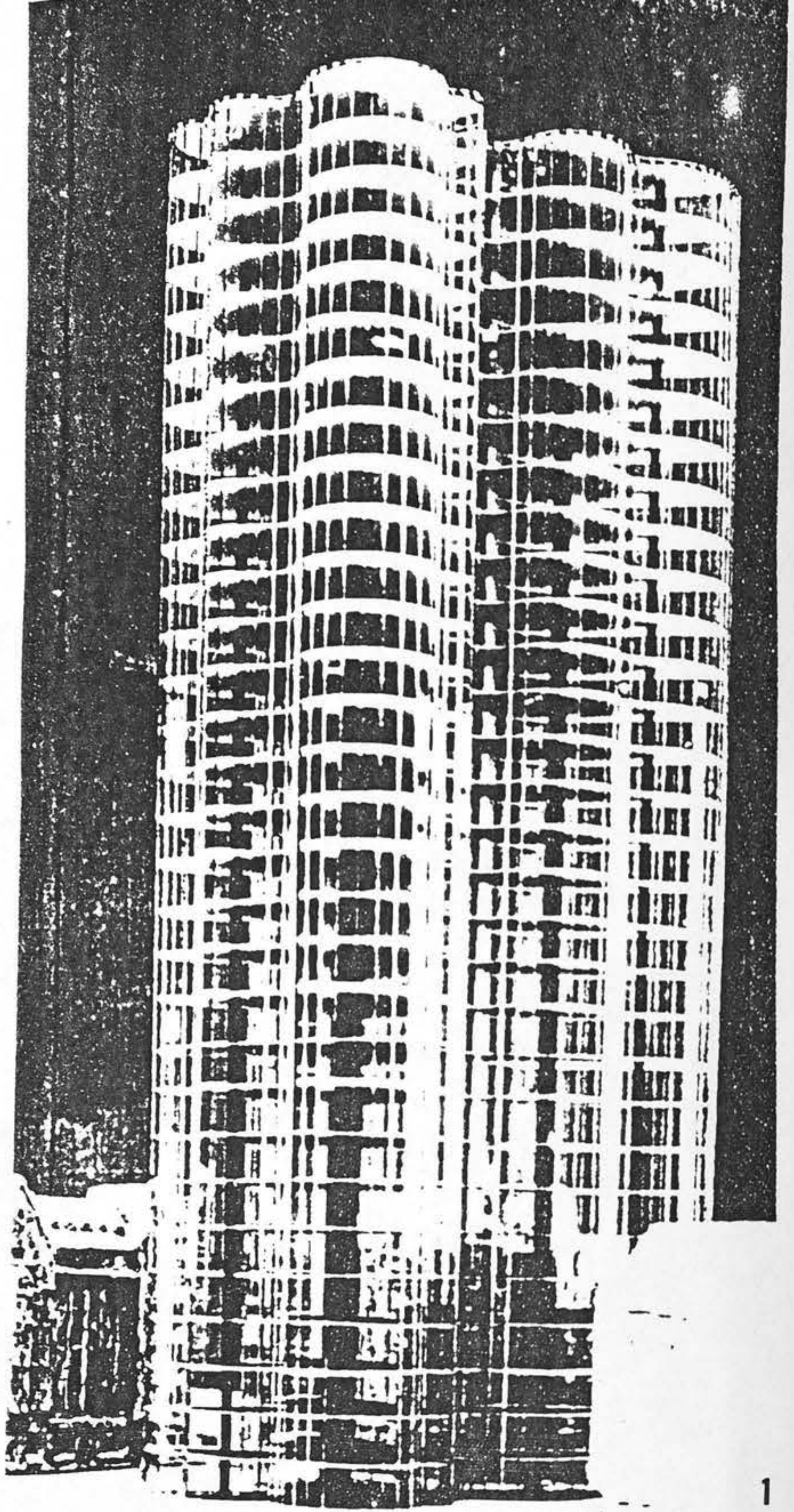
1 SKETCHES ILLUSTRATE CORBUSIER'S APPROACH TO ARTICULATION WITH DOM-INO PROTOTYPES



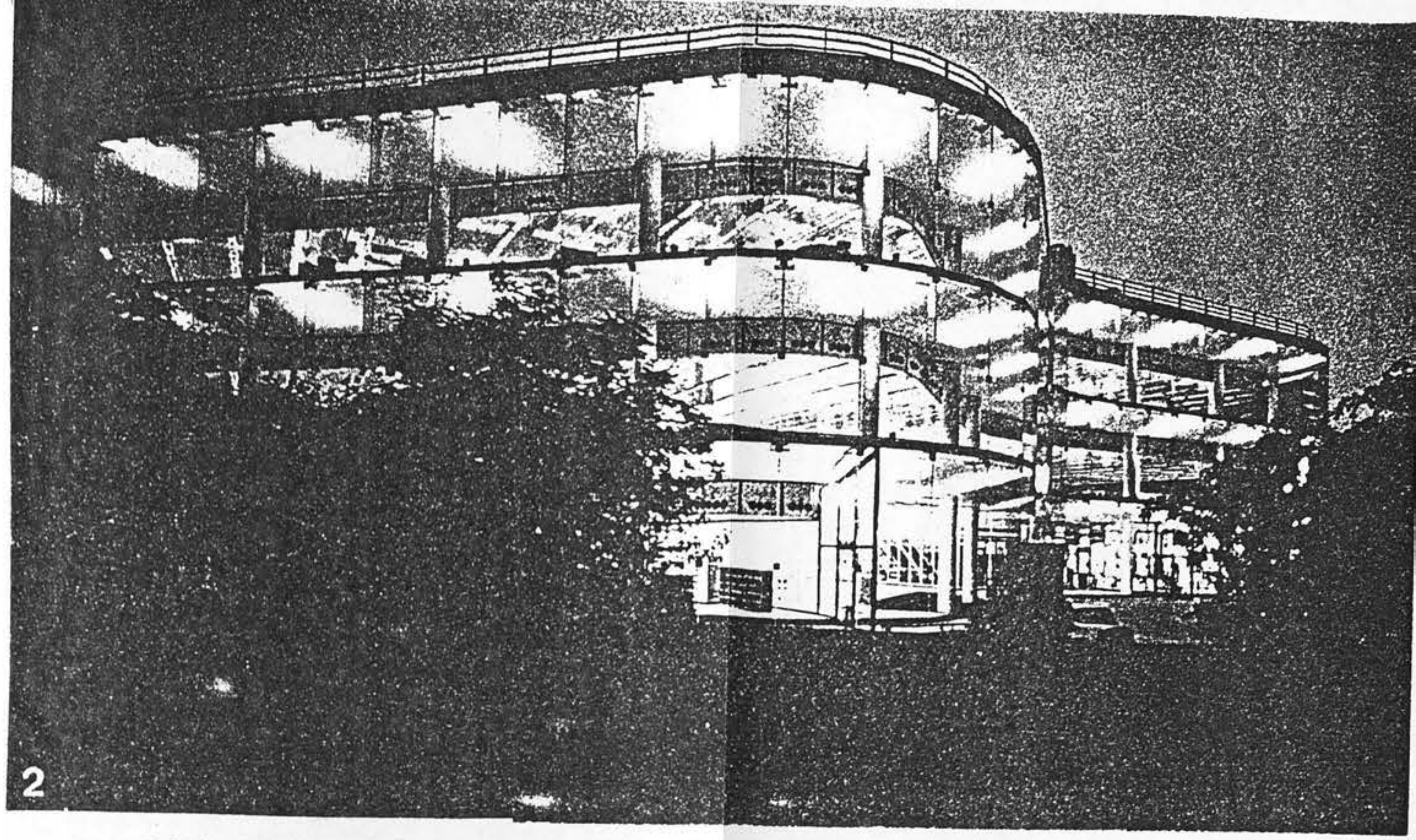
VILLA SAVOYE, POISSY



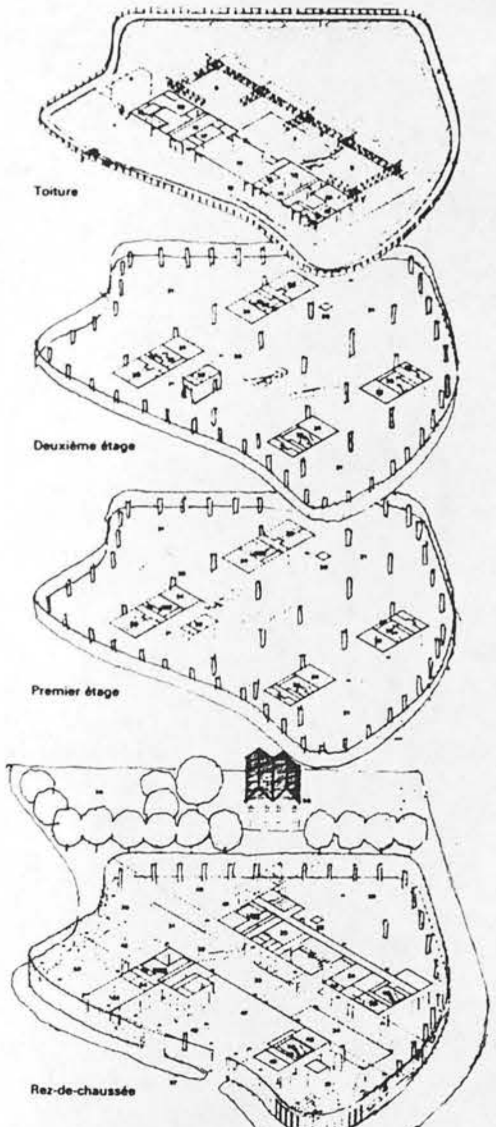
THE DOMINO SKELETON



1



2



3

FIG 1B

1 MIE'S FRIEDRICHSTRASSE TOWER PROJECT

2,3 WILLIS FABER DUMAS BUILDING, FOSTER

FIG 2 THE COMPOSITIONAL THEMES OF THE RUSSIAN CONSTRUCTIVISTS WERE BASED ON CLASSICAL PRECEDENT

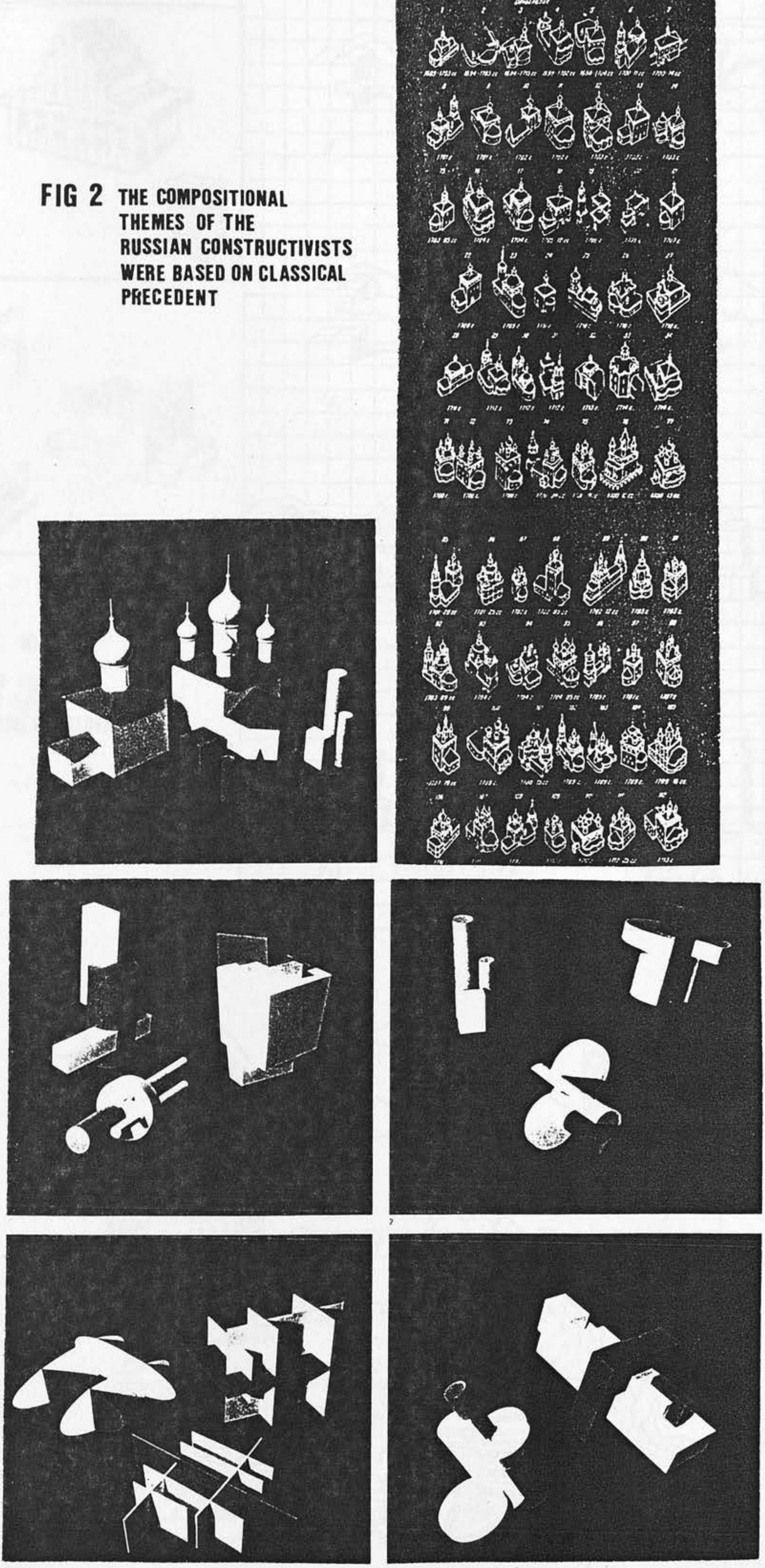
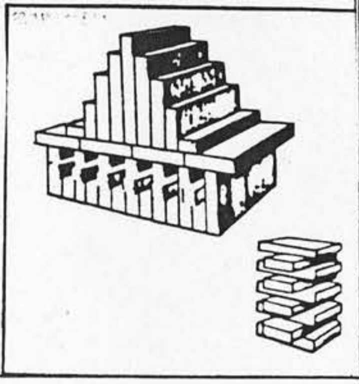
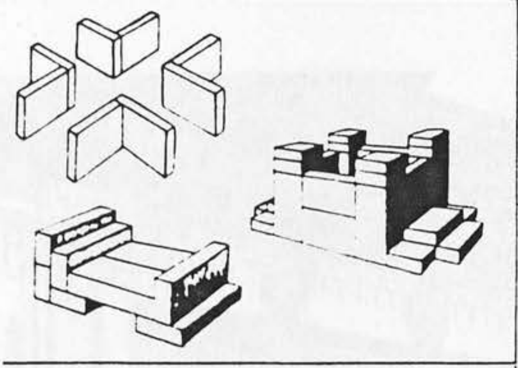


FIG 2





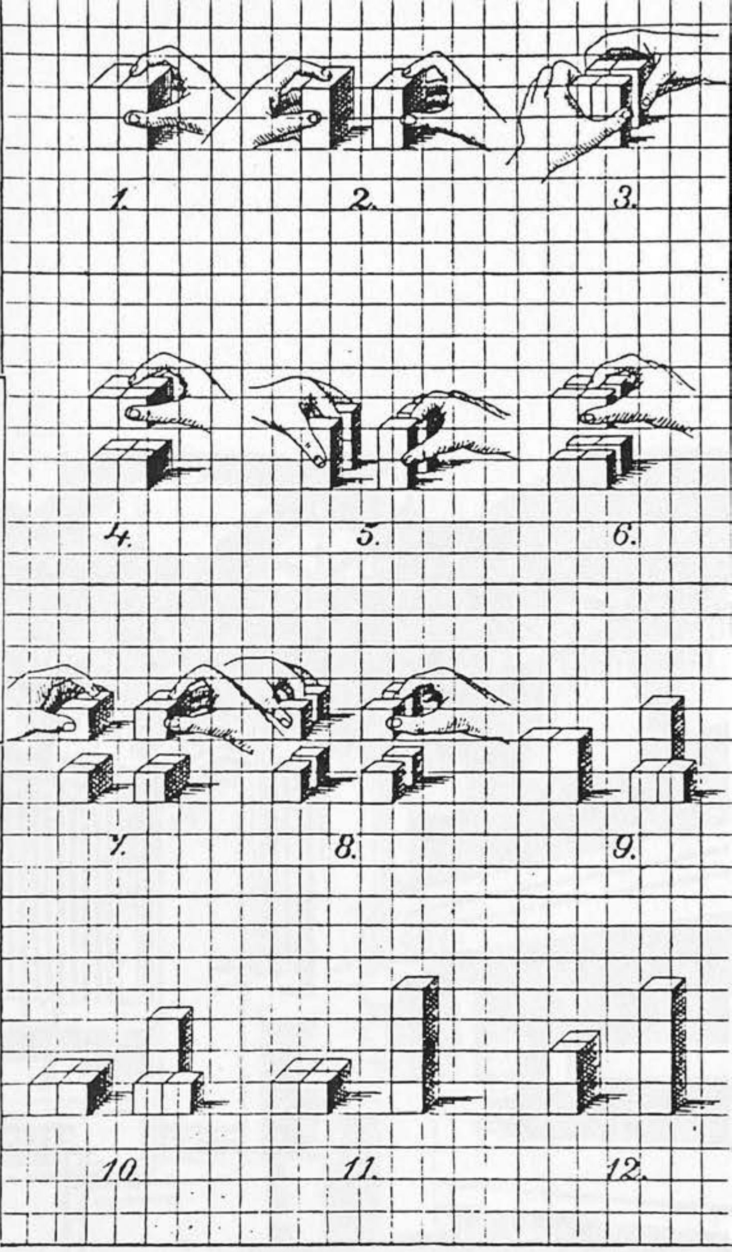
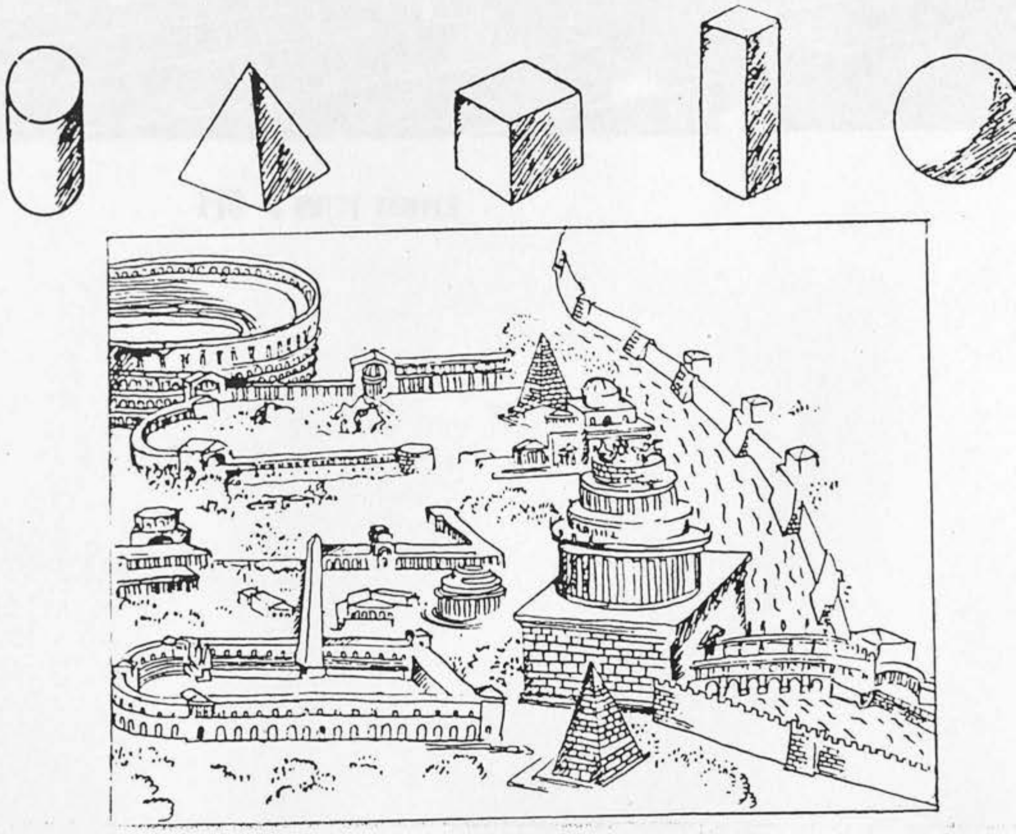


FIG 2 FROEBEL BLOCKS

3 PRIMARY FORMS
DERIVED FROM
CLASSICAL PRECEDENT

FIG 3



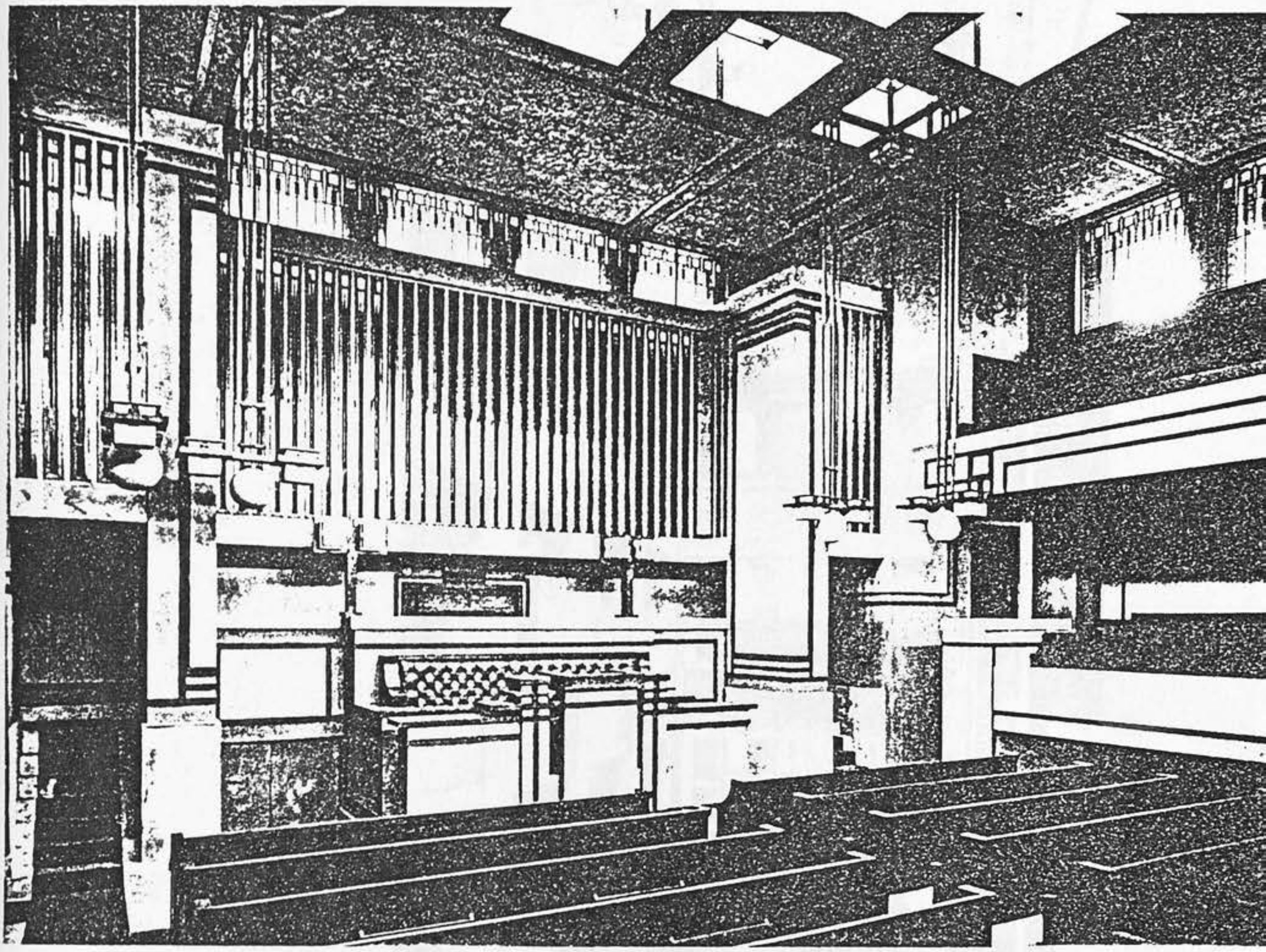


FIG 4 UNITY TEMPLE

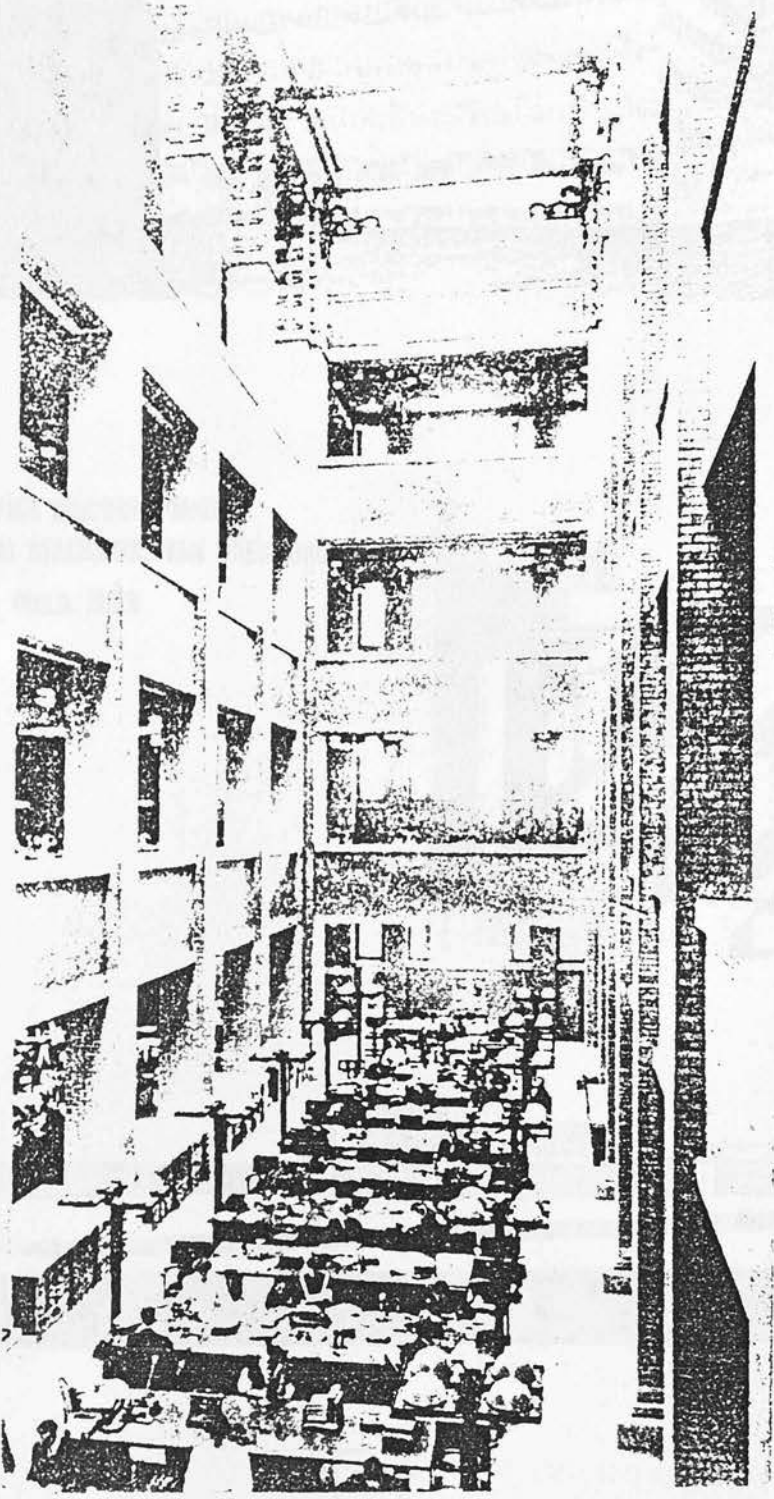
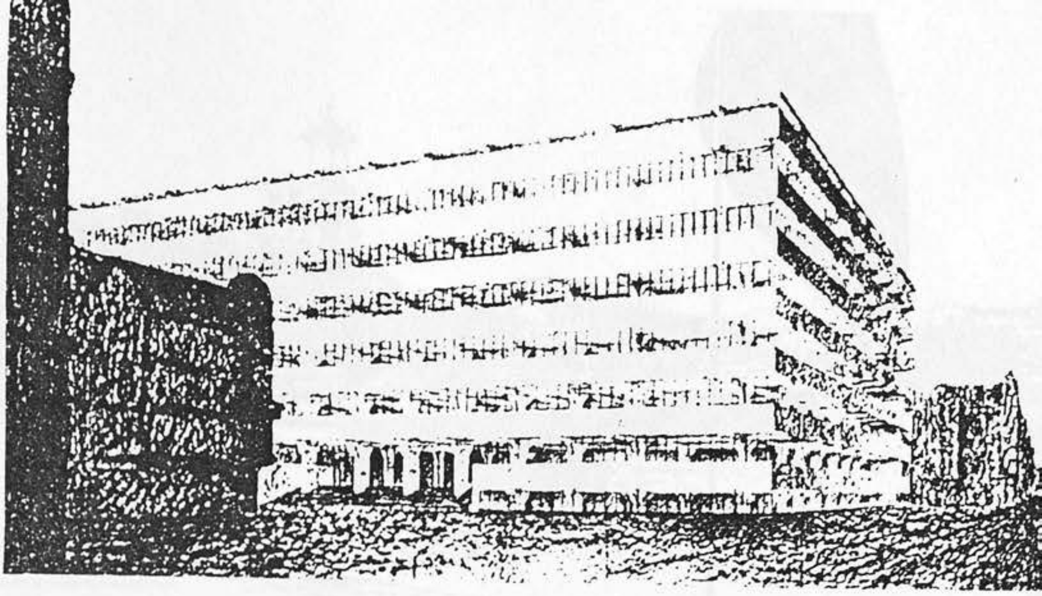


FIG 5 LARKIN BUILDING

FIG 6



6 RC OFFICE BUILDING, MIES
7A SPATIAL DIAGRAMS, VAN DOESBURG
7B BRICK VILLA, MIES

FIG 7A

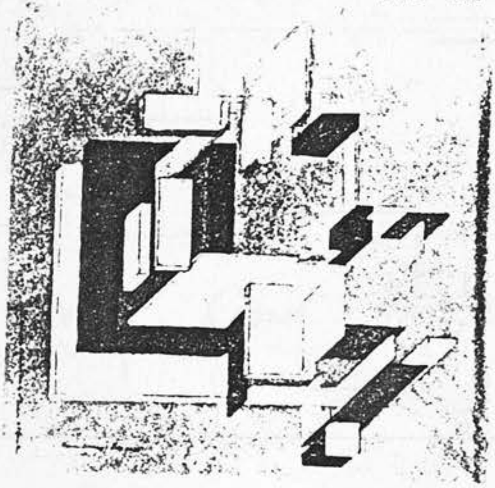
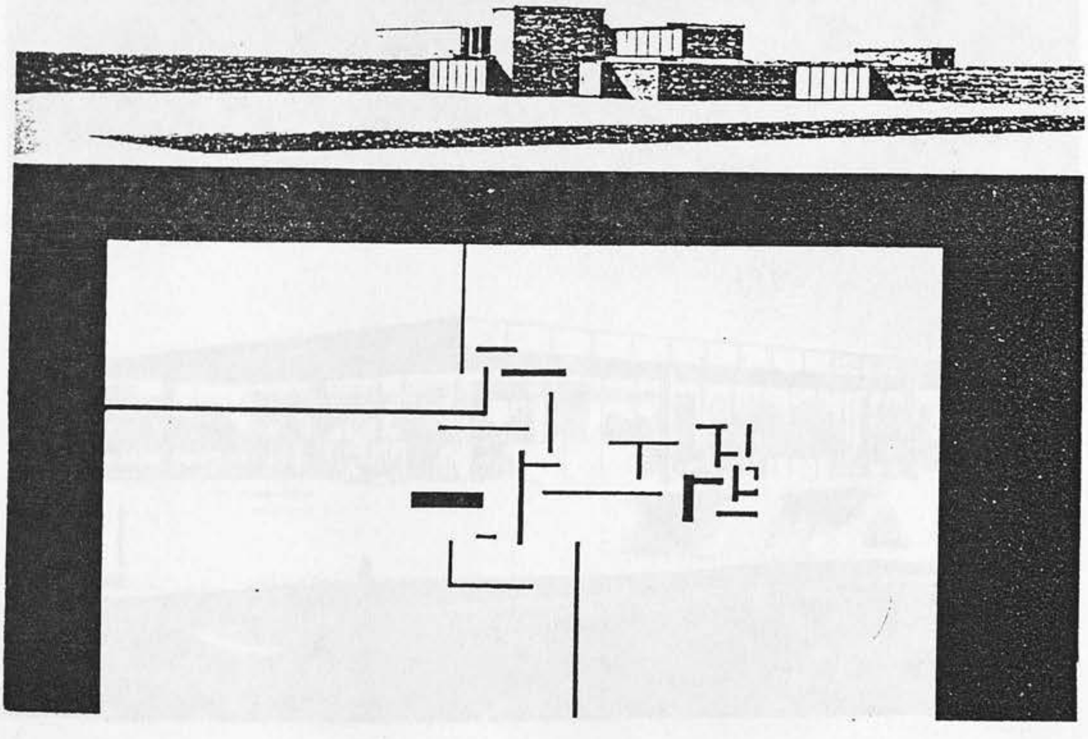


FIG 7B



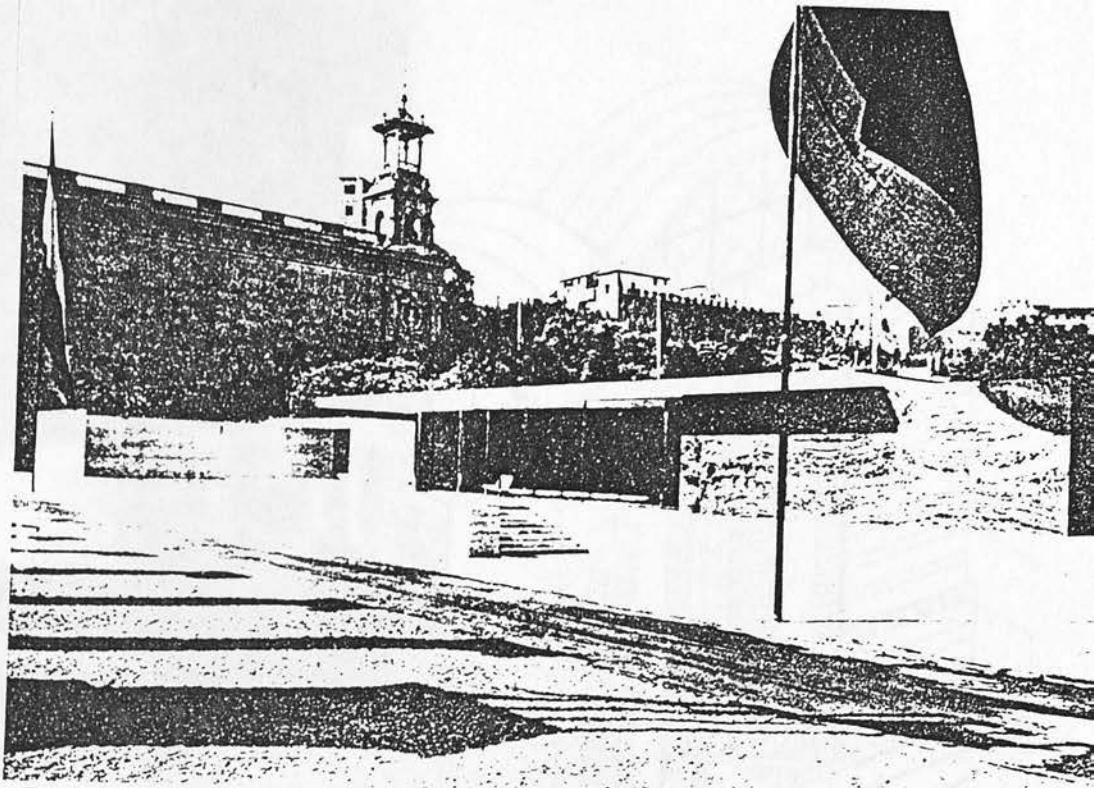
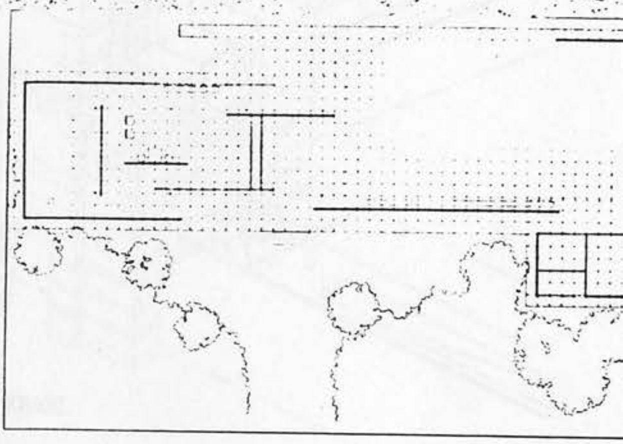


FIG 8 MIE'S BARCELONA PAVILLION



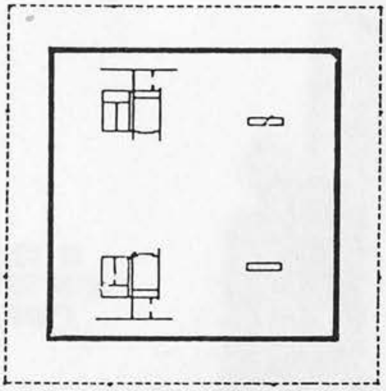
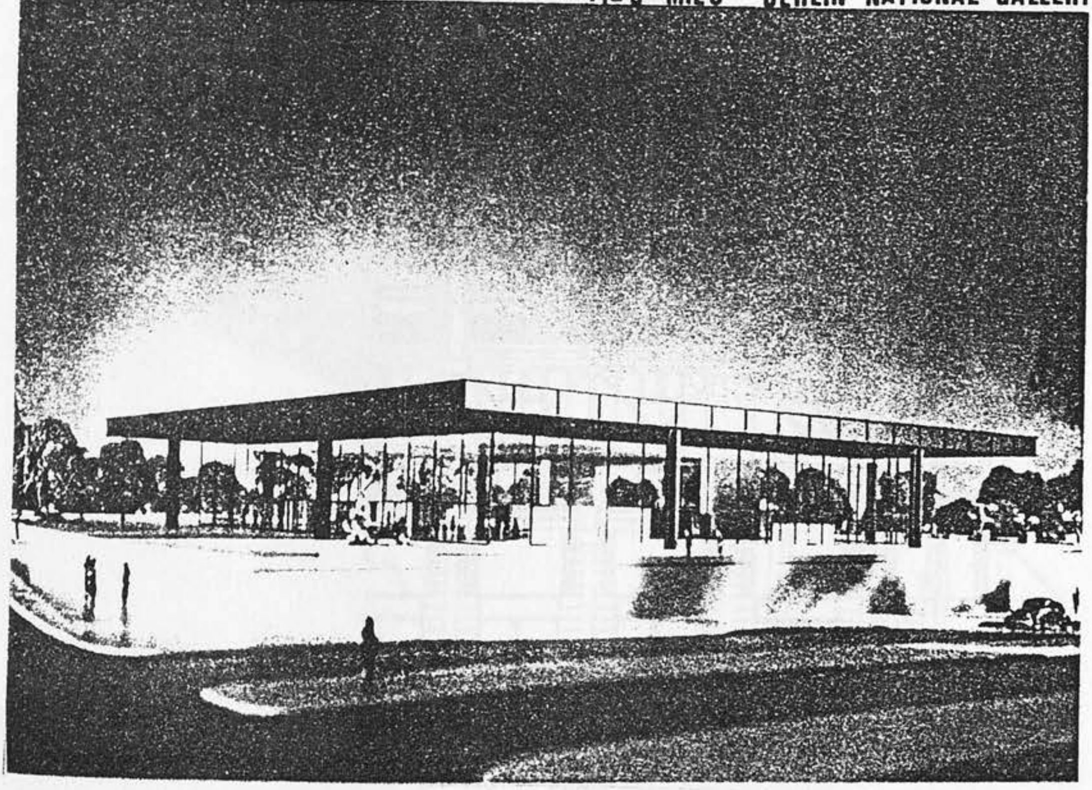
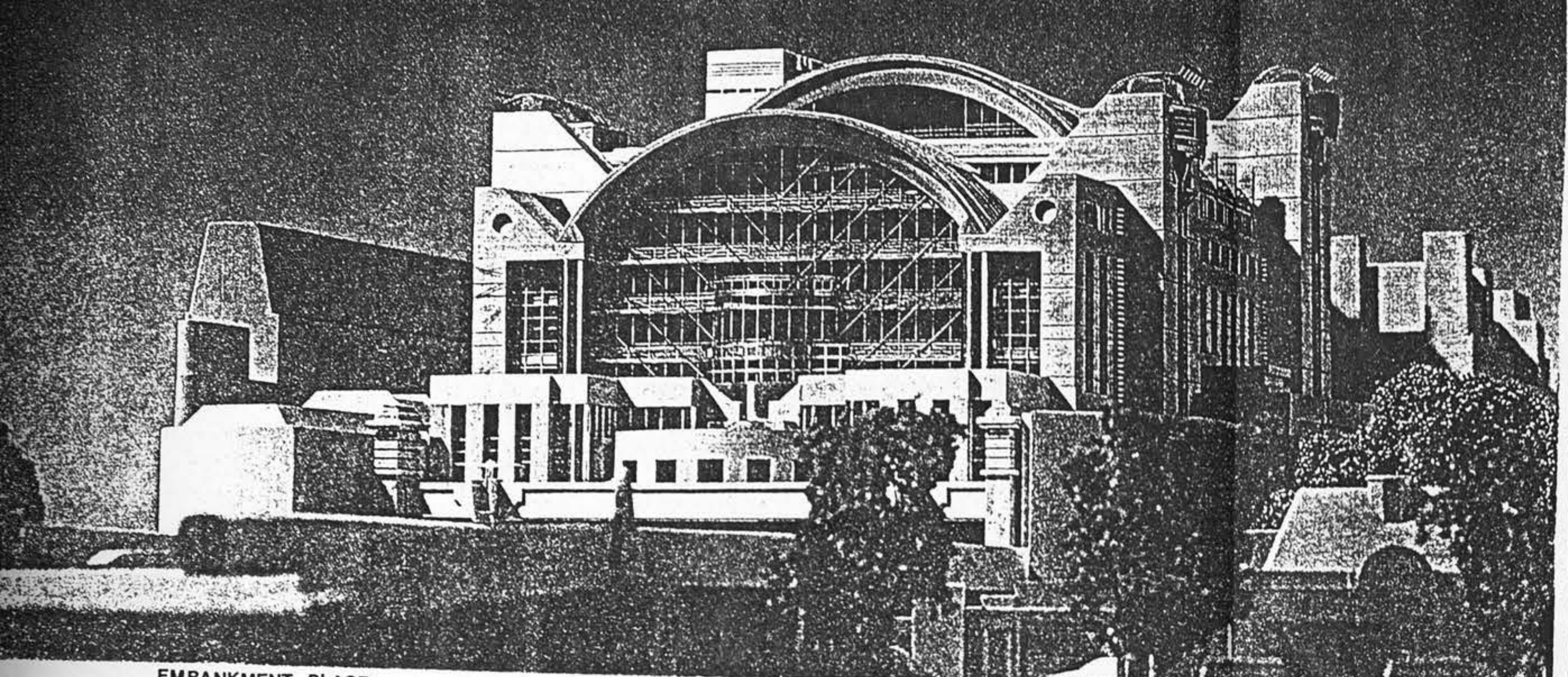
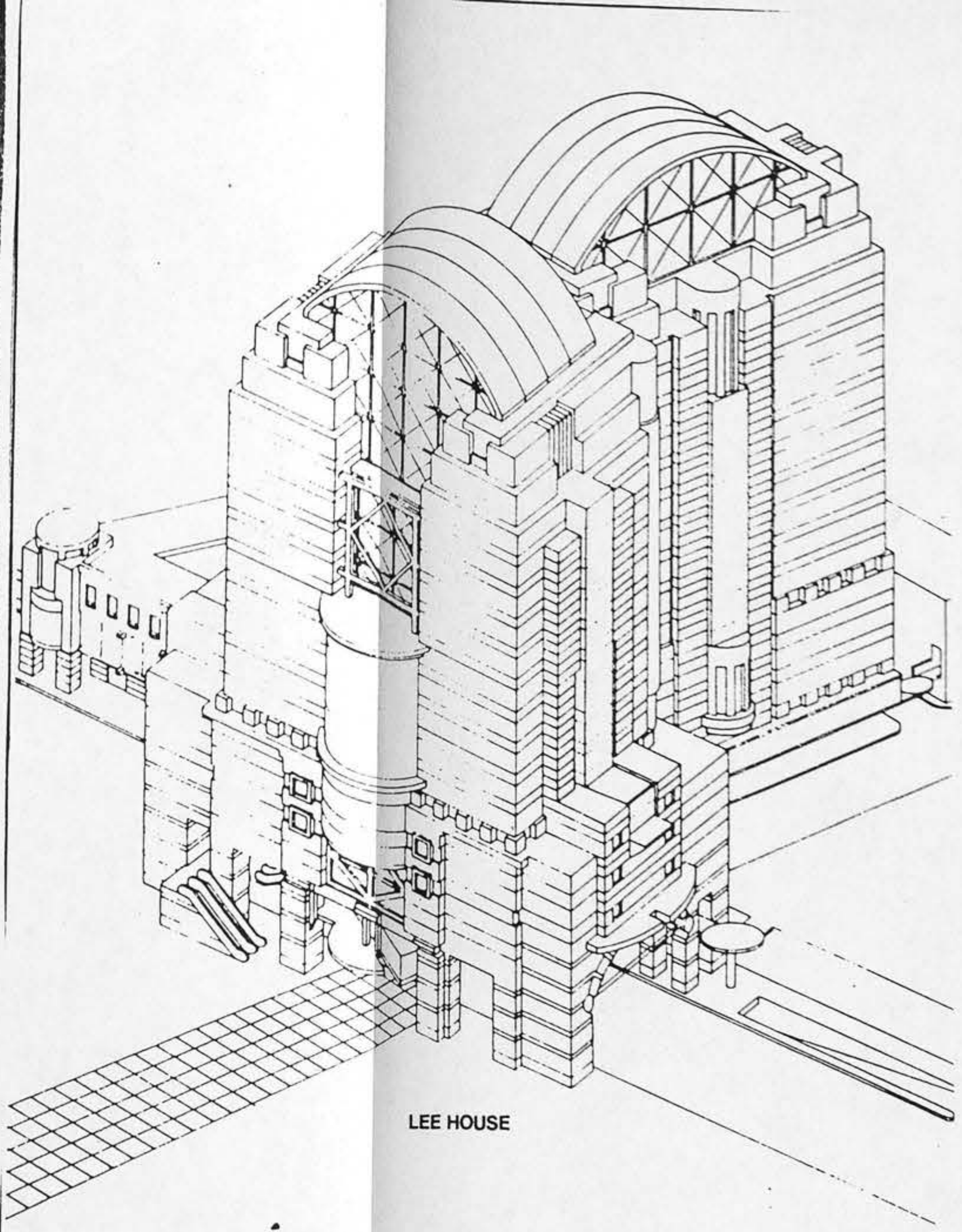


FIG 9 MIE'S BERLIN NATIONAL GALLERY



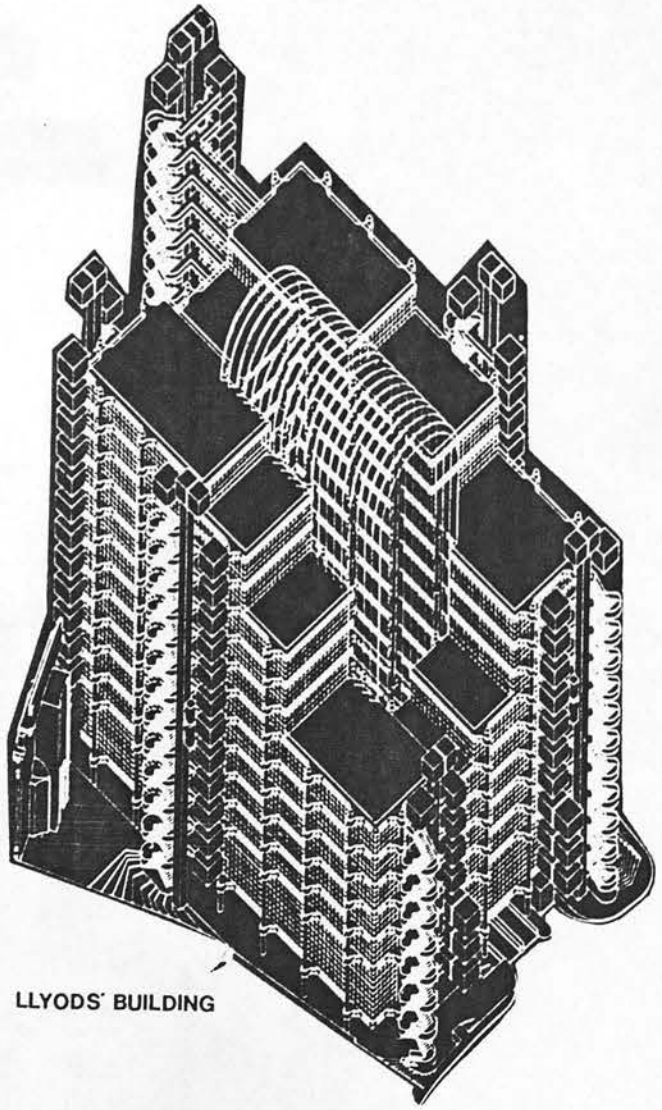


EMBANKMENT PLACE

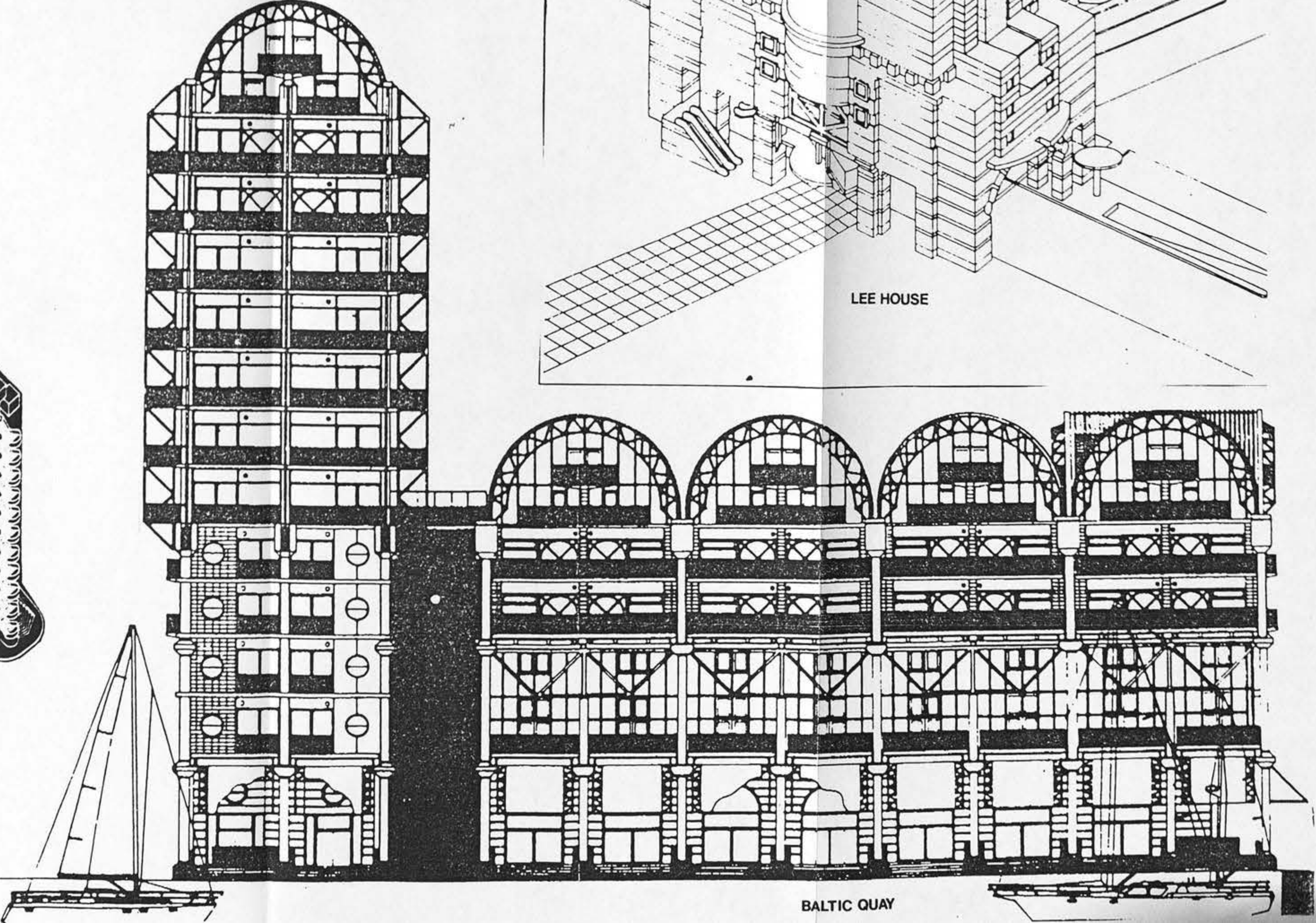


LEE HOUSE

FIG 10A EXAMPLES OF BUILDINGS WITH BARREL VAULT ROOFS



LLYODS' BUILDING



BALTIC QUAY

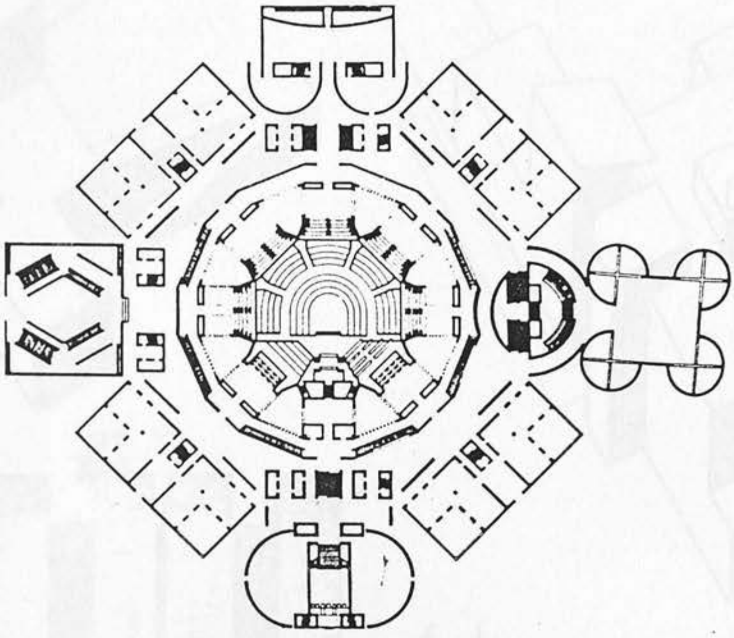


FIG 11A DACCA PARLIAMENT

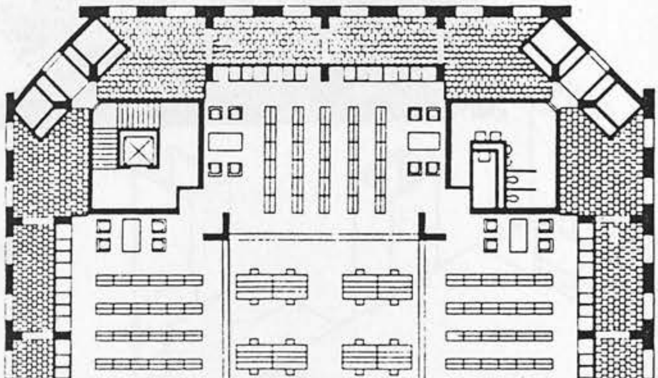
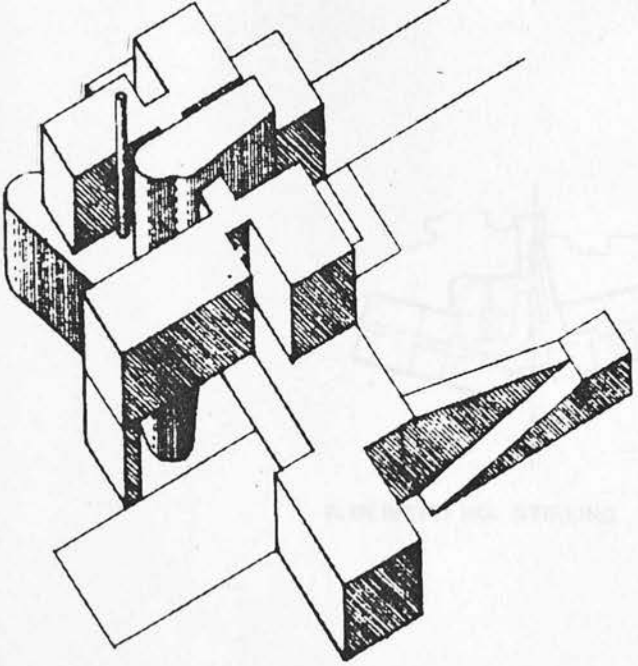
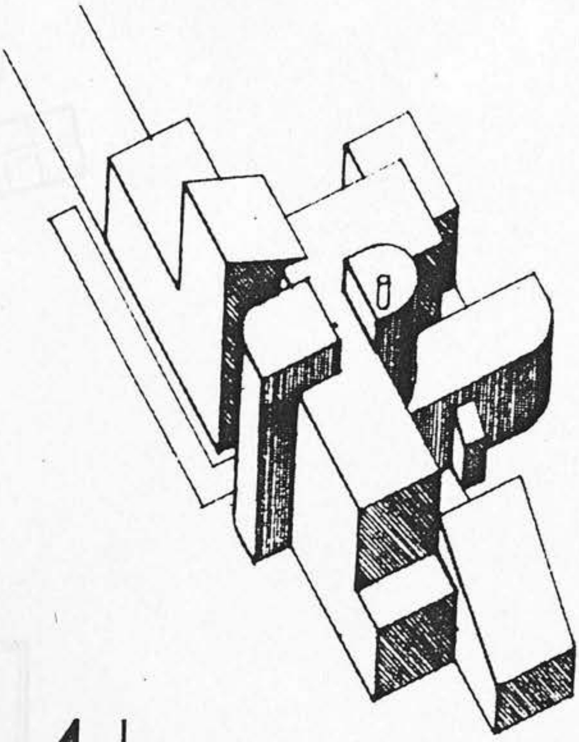


FIG 11B PHILLIPS EXETER LIBRARY

FIG 11C STIRLING'S CLUSTER ASSEMBLIES





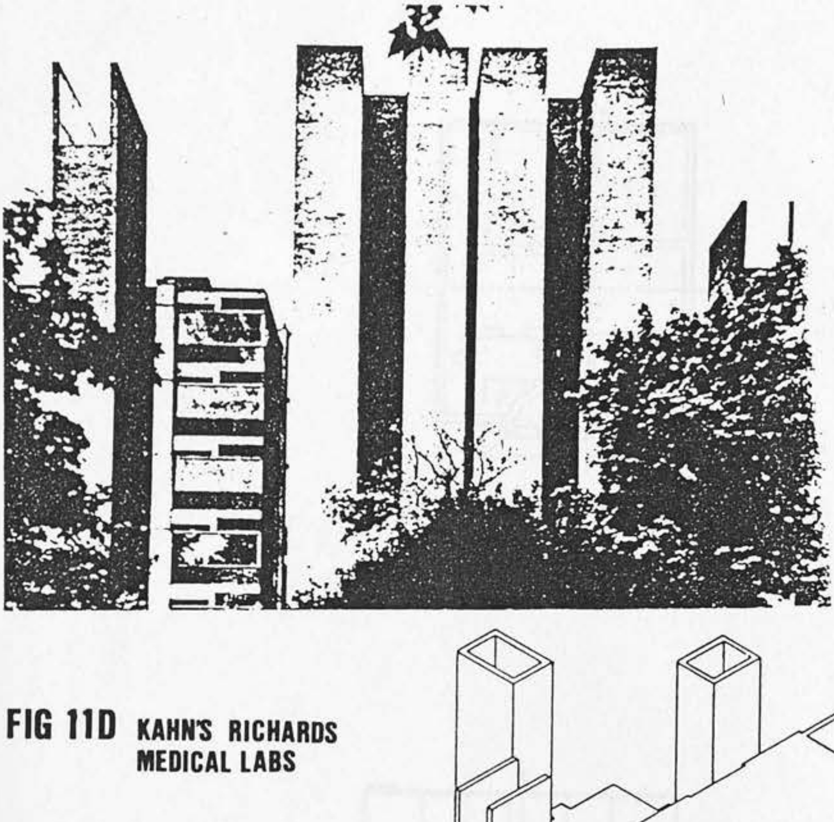
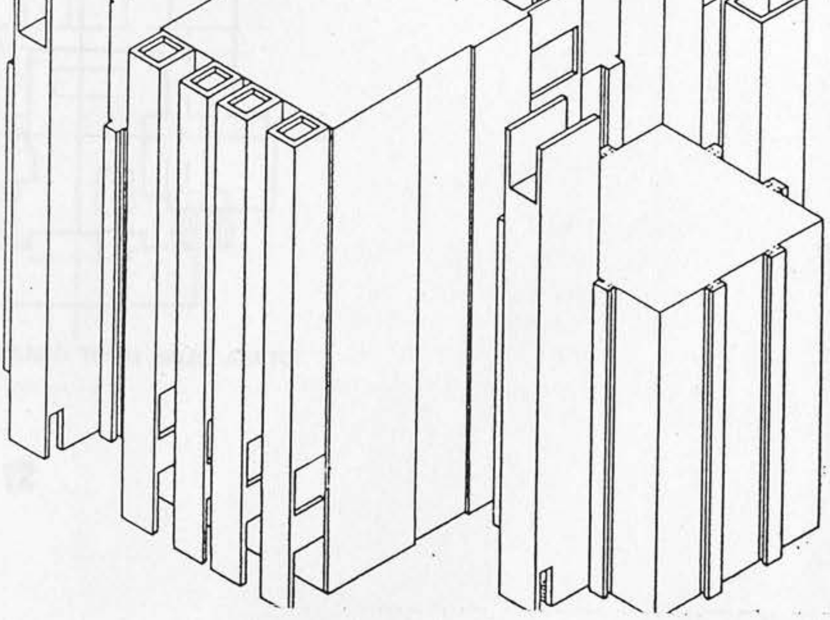
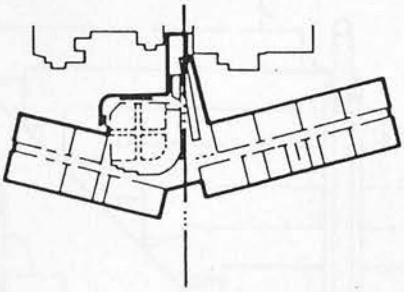
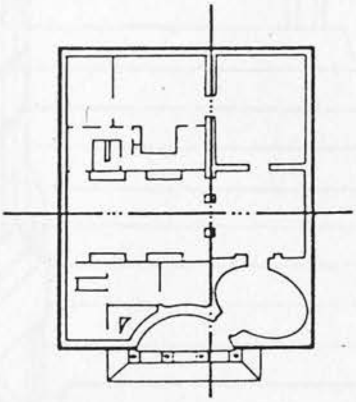


FIG 11D KAHN'S RICHARDS MEDICAL LABS

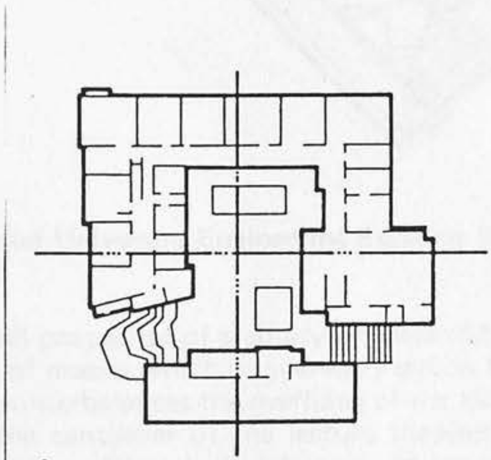




A. OLIVETTI HQ, STIRLING



B. HOTEL GUIMARD, LEDOUX



C. SAYNATSALO TOWN HALL, AALTO

FIG 12

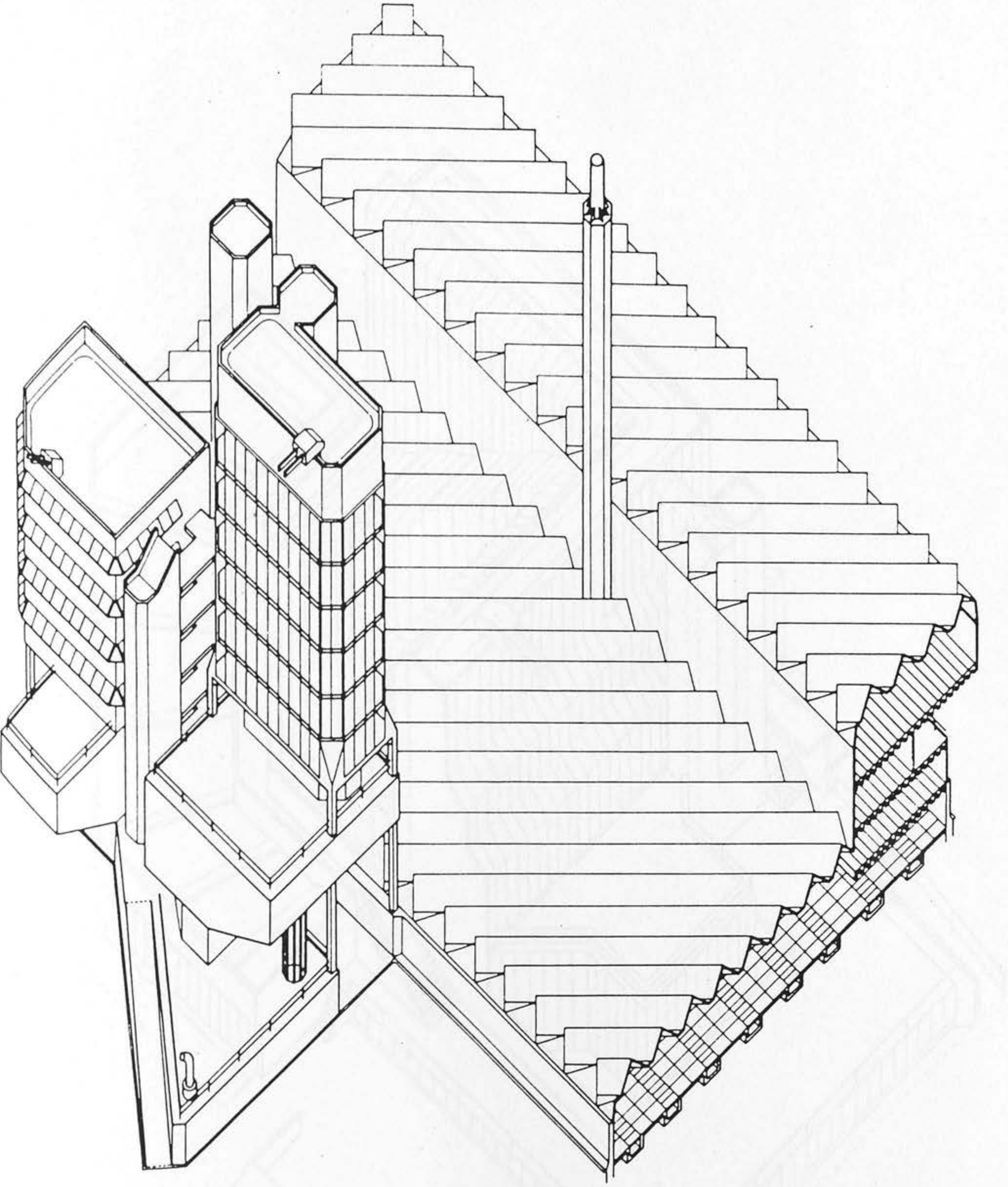


FIG 13A Leicester University Engineering Building 1959/63

'All built form has weight and properties of stability or instability dependant on shape and it is necessary to make a grouping of masses which is inherently stable. In the Engineering Building, the weight of the towers above counterbalances the overhang of the lecture theatres under, or to say it another way, the extent of the cantilever of the lecture theatres is dictated by the amount of weight over; if you removed the top floor the building would overturn. No doubt there is a certain architectural quality inherent in the composition of stable masses particularly when they are asymmetrical.'

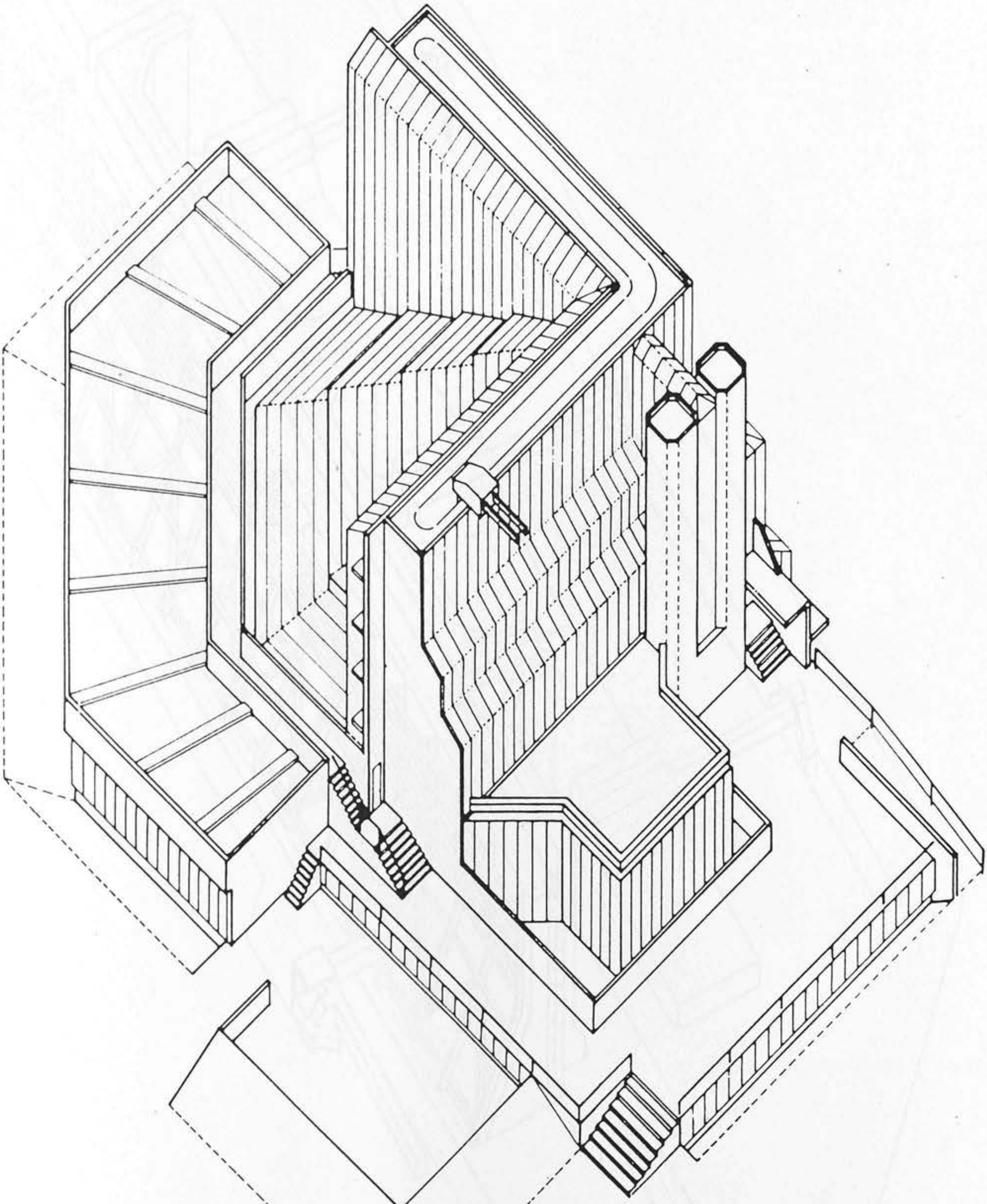


FIG 13B LEICESTER UNIV ENGINEERING BLDG

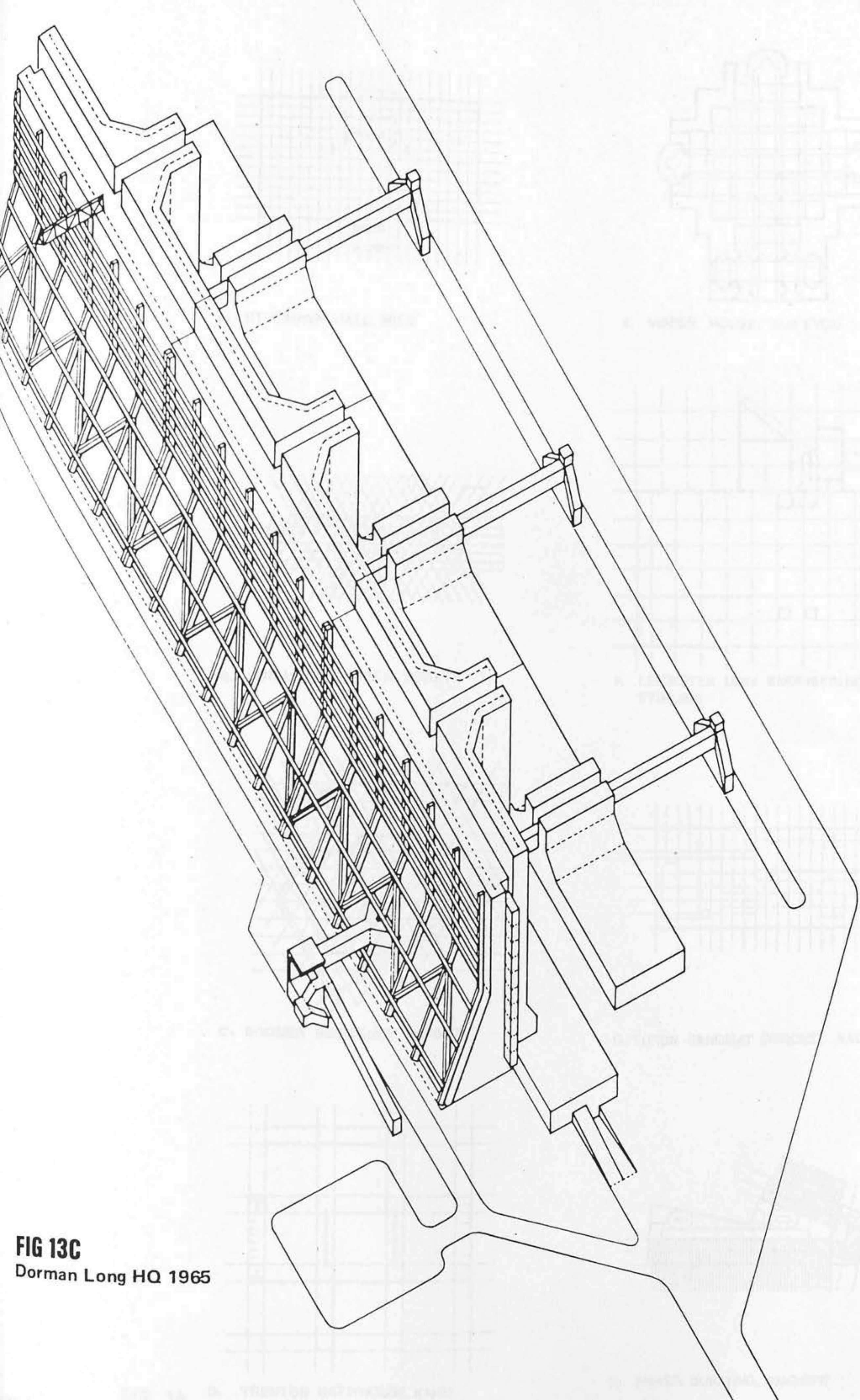
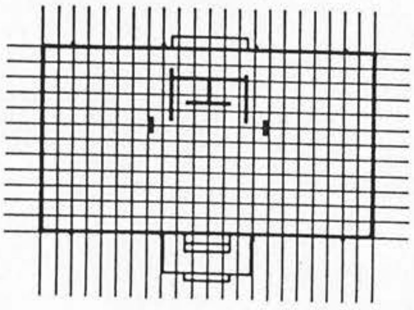
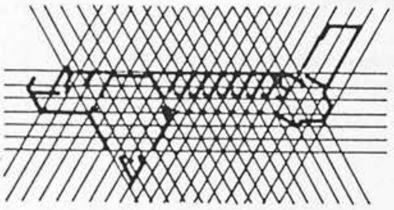


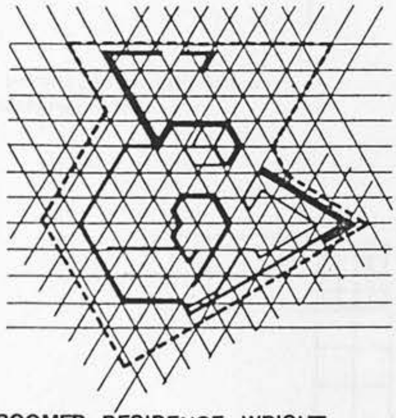
FIG 13C
Dorman Long HQ 1965



A. IIT CROWN HALL, MIES



B. UNITARIAN CHURCH. WRIGHT



C. BOOMER RESIDENCE, WRIGHT

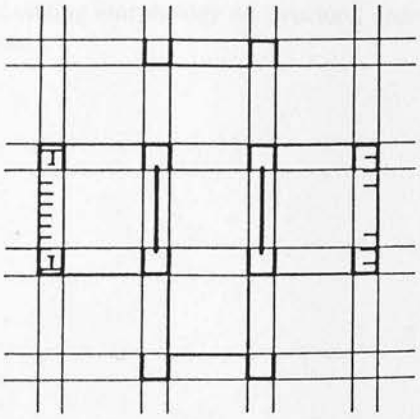
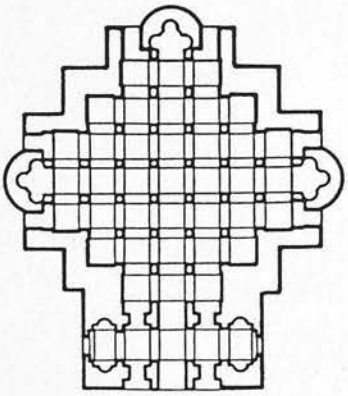
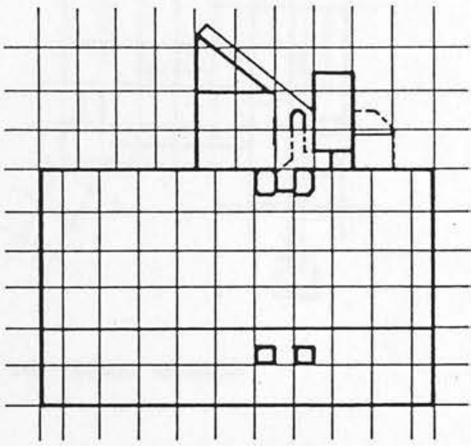


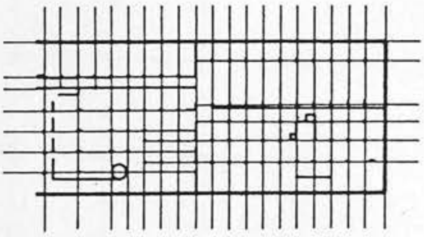
FIG 14 D. TRENTON BATHHOUSE. KAHN



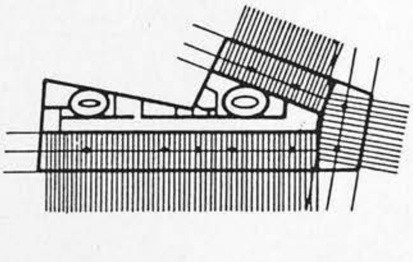
E. VISSER HOUSE, VAN EYCK



F. LEICESTER UNIV ENGINEERING BLDG, STIRLING



G. TURUN SANOMAT OFFICES, AALTO



H. ANKER BUILDING, WAGNER

FIG 14 EXAMPLES OF INTERSECTING GRIDS

J. THE ATHENIUM, MEIER

L. DESOURDY RESIDENCE, CAYOUTTE

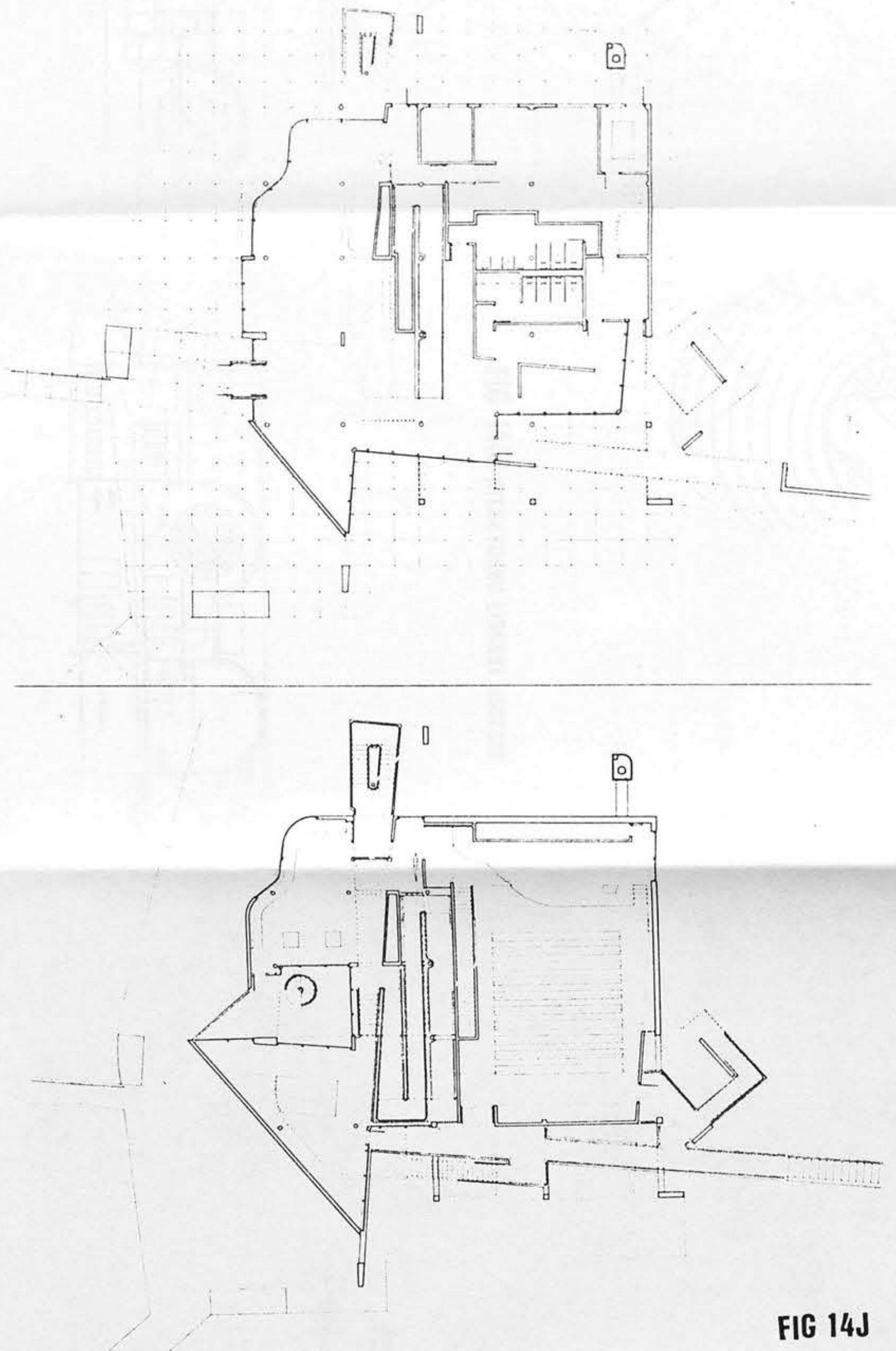


FIG 14J

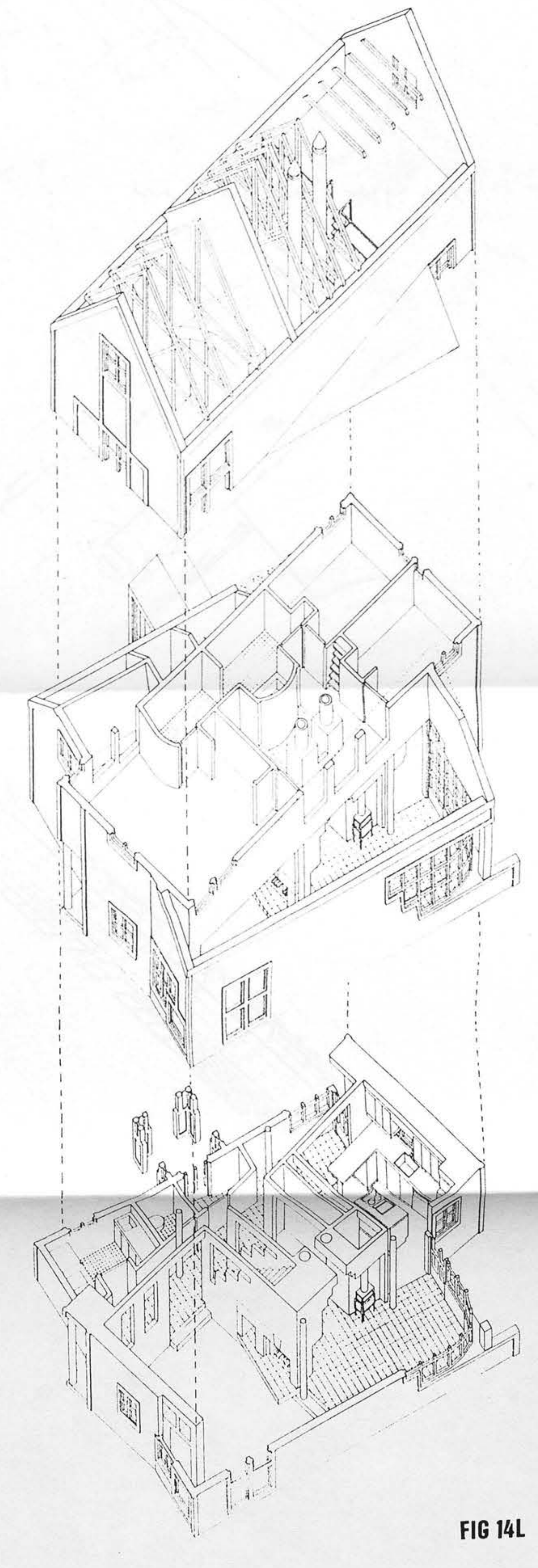
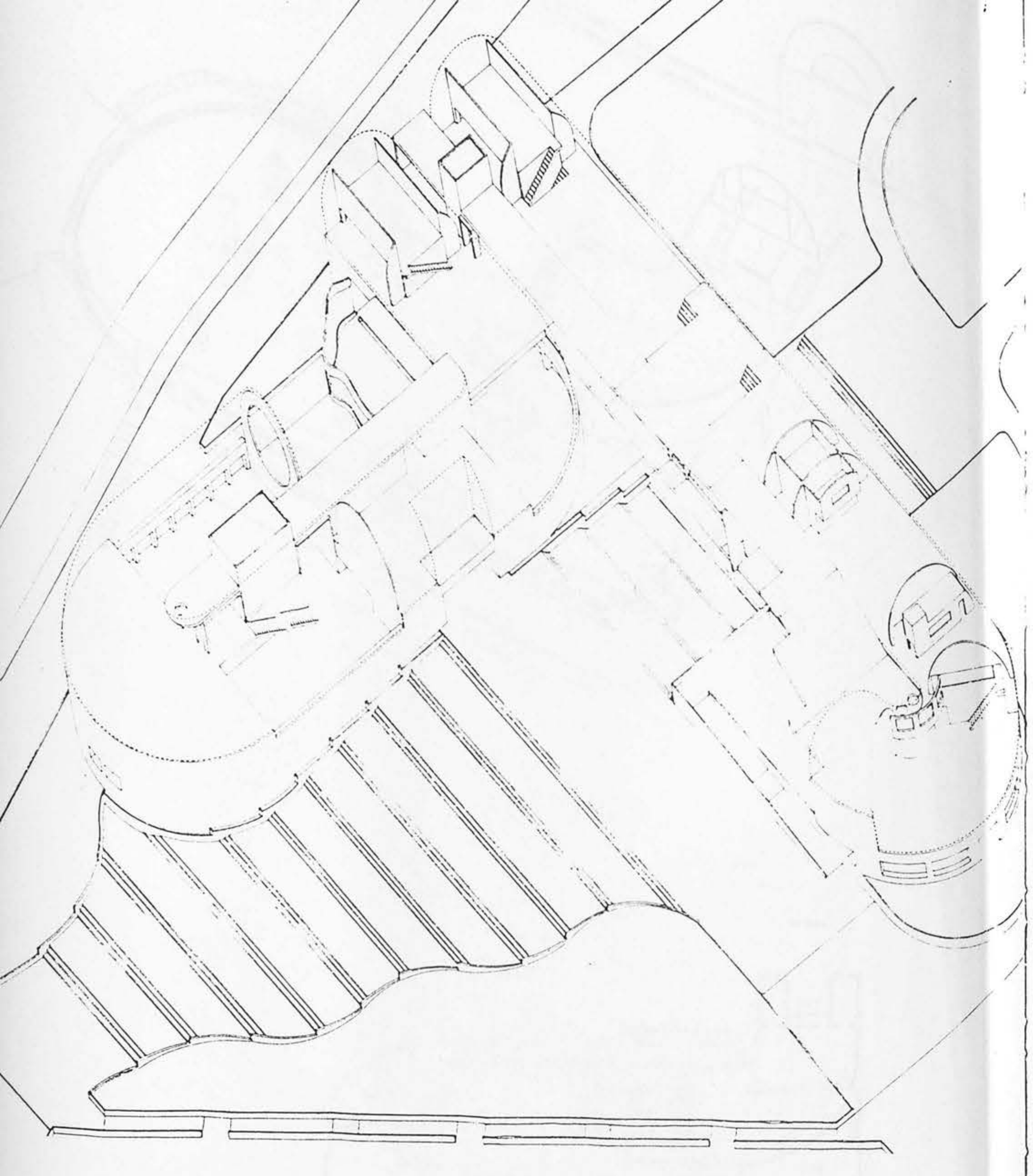
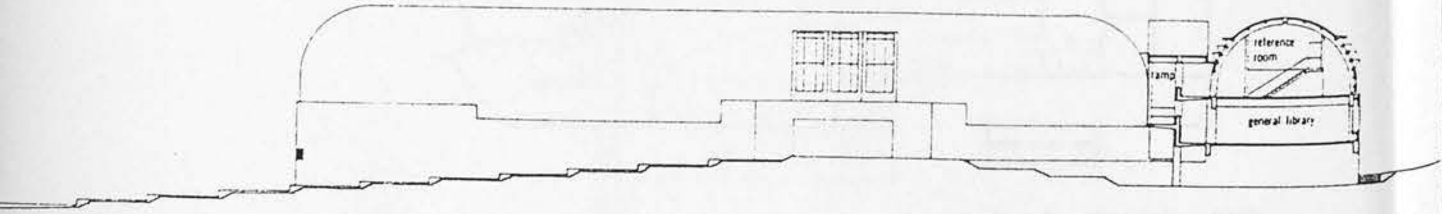


FIG 14L





h section; scale: 1:600.

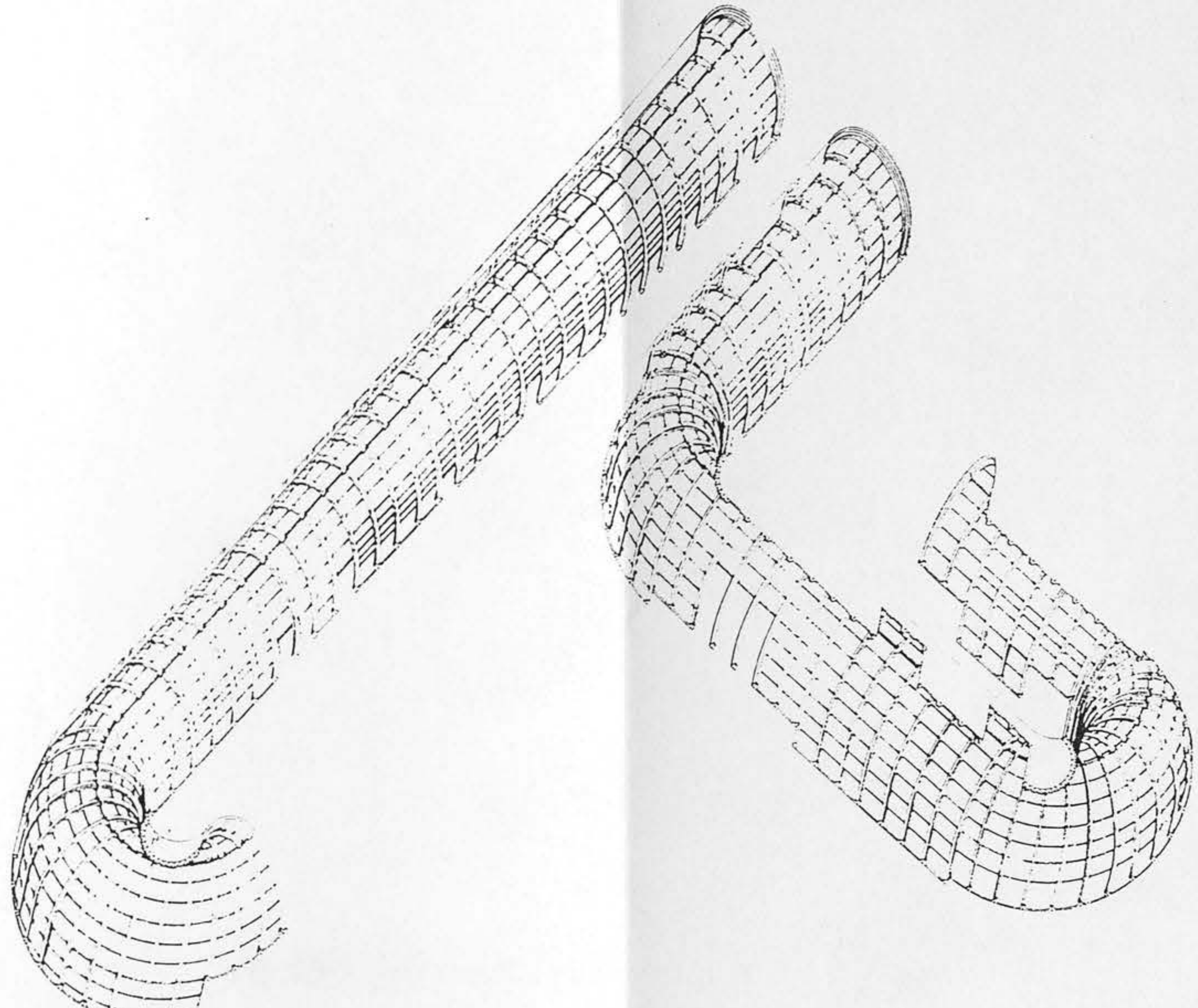
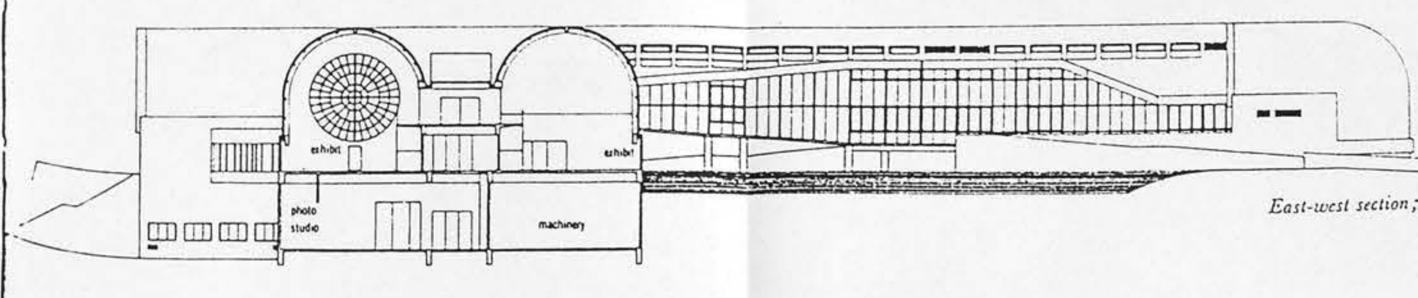
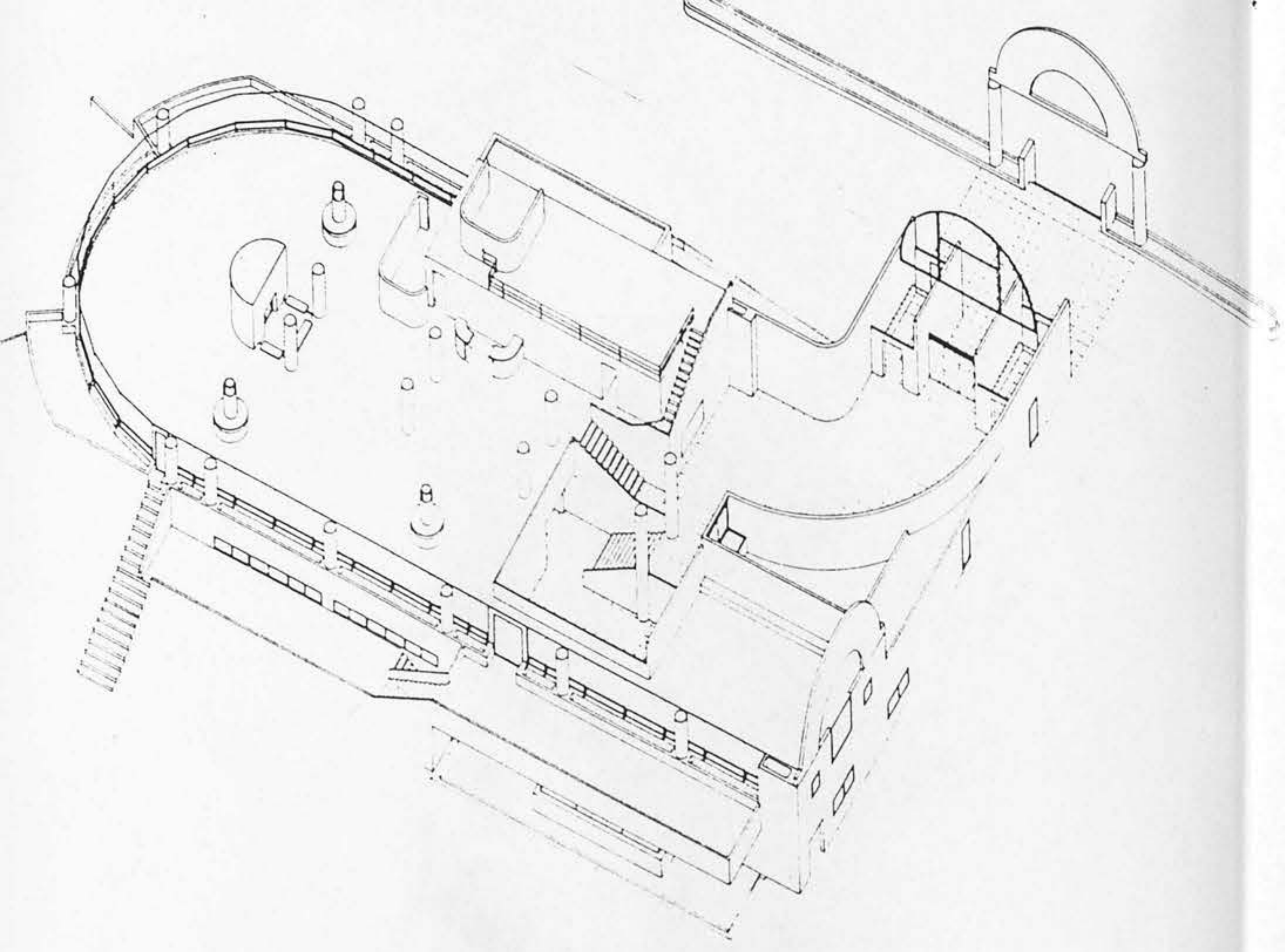


FIG 14Ni KITAKYUSHU LIBRARY, ISOZAKI



East-west section;



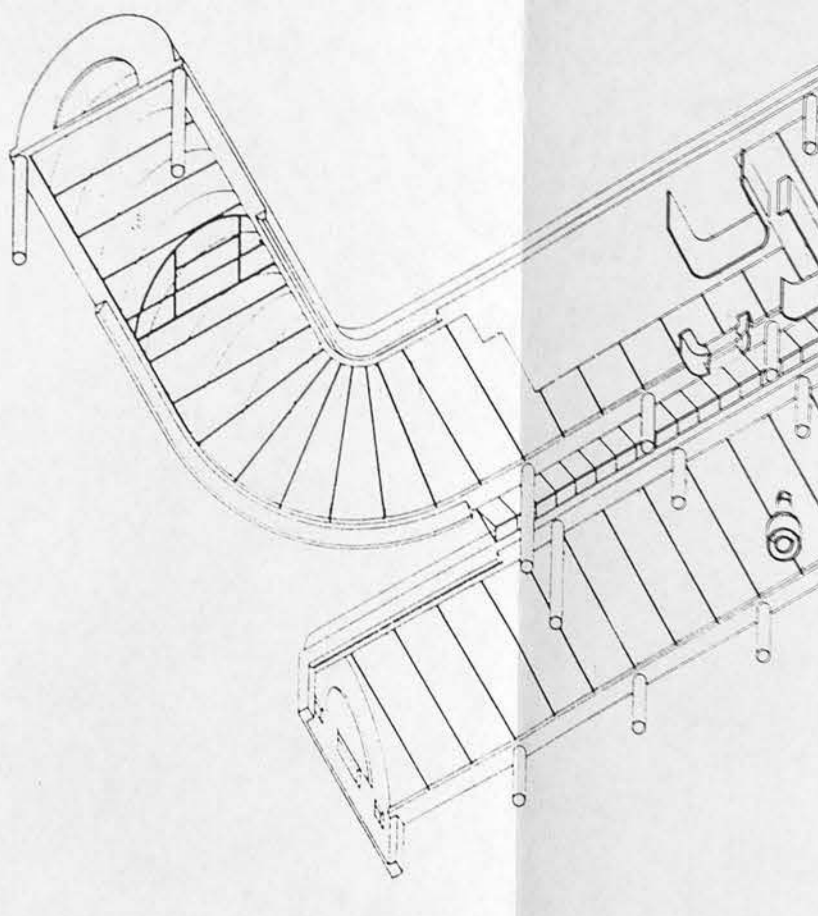
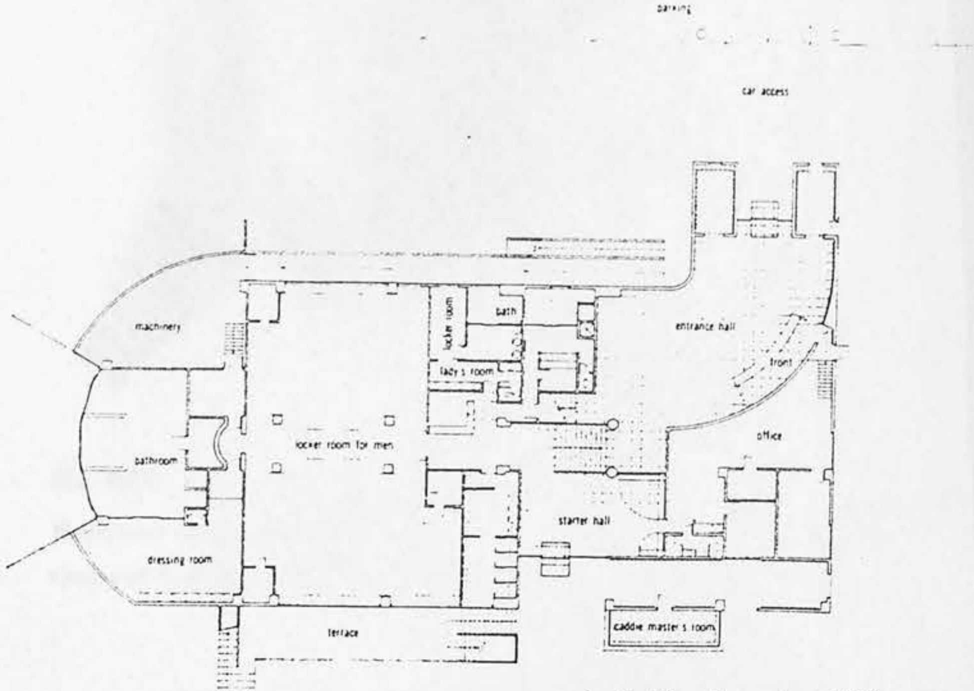
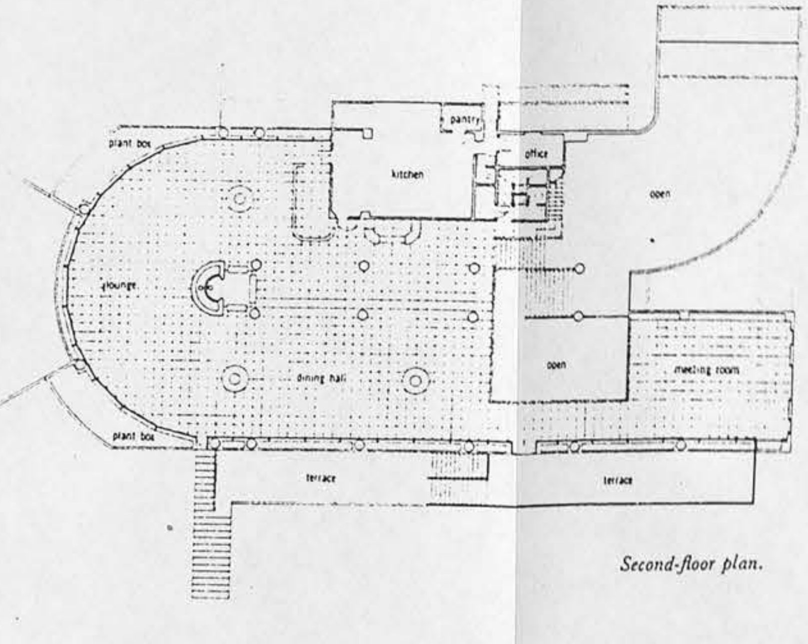


FIG 14N ii FUJIMI CLUBHOUSE, ISOZAKI



First-floor plan; scale: 1/500.



Second-floor plan.

location: Oita, Oita Prefecture
design: Arata, Isozaki Atelier
general contractor: Sato-Gumi Construction Co., Ltd.
site area: 714,524m²
building area: 1,267m²
floor areas: third floor—89m²
second floor—691m²
first floor—1,061m²
total—1,841m²
structure: reinforced concrete, 2 stories, partly 3 stories
construction term: December, 1973—September, 1974

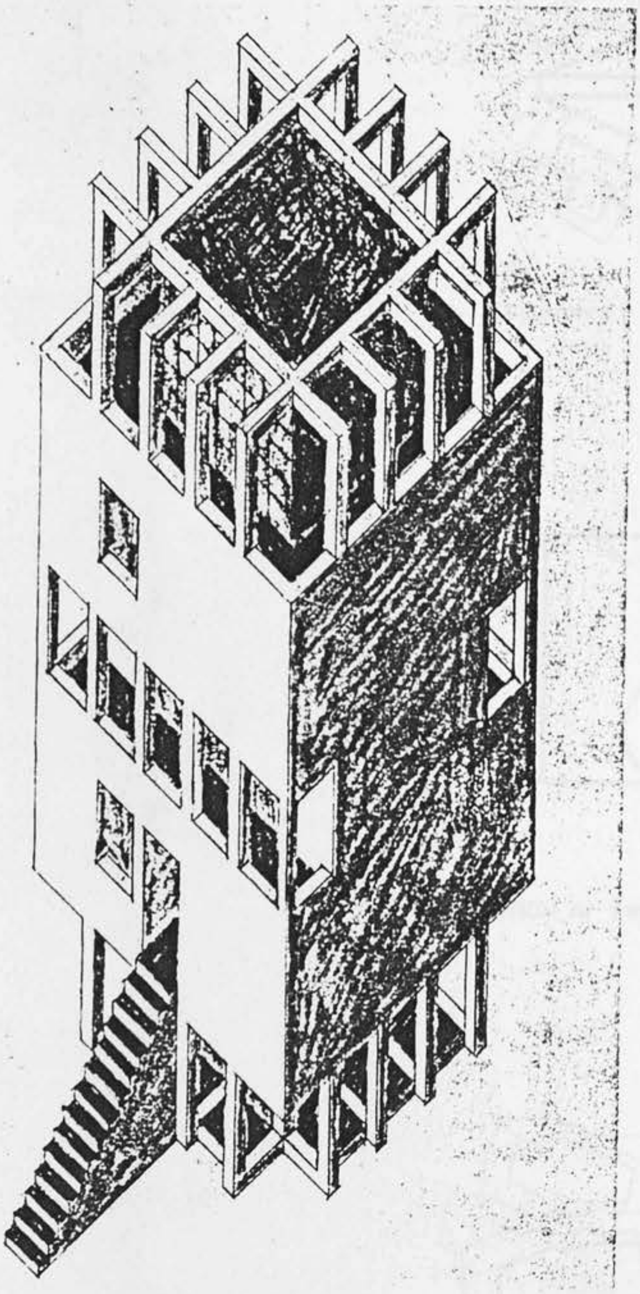
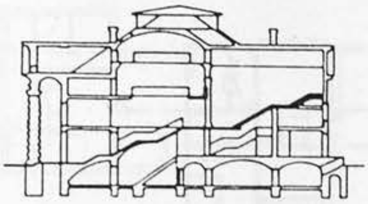


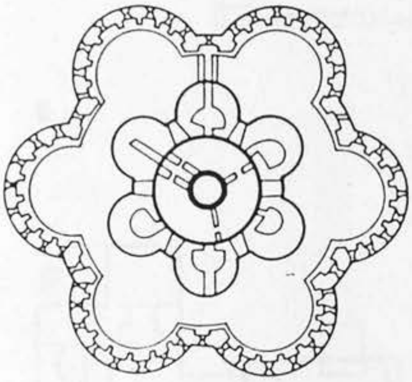
FIG 14(0)

Marburg town houses; typological studies.

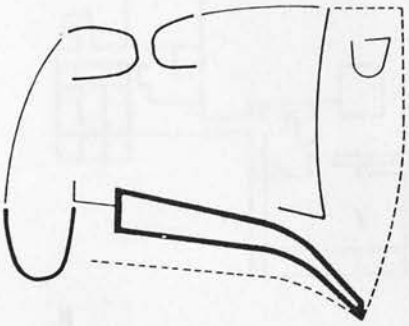
Credits: H. Kollhoff, Th. Will, K. L. Dietzsch



A. DIRECTOR'S HOUSE, LEDOUX

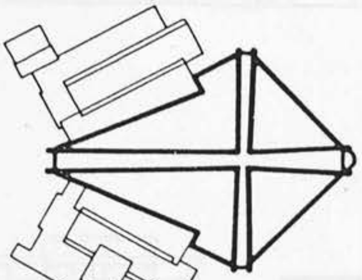


B. DEAL CASTLE

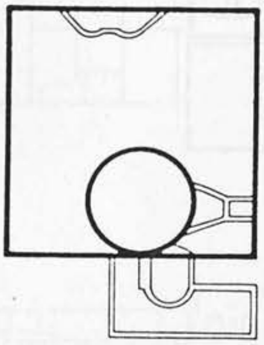


C. RONCHAMP, CORBUSIER

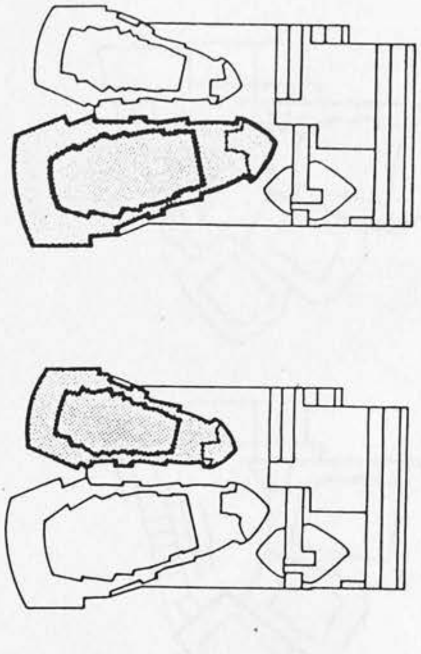
Fig 15



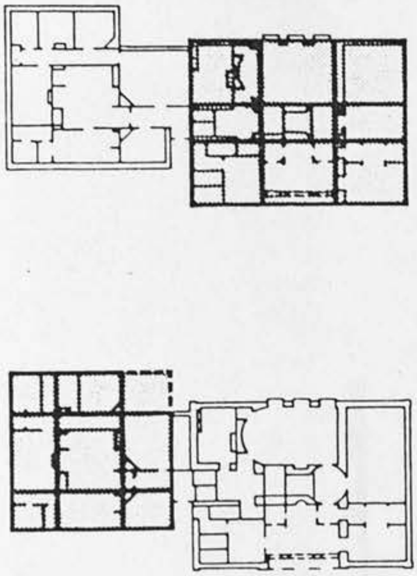
D. ST. MARY'S, TANGE



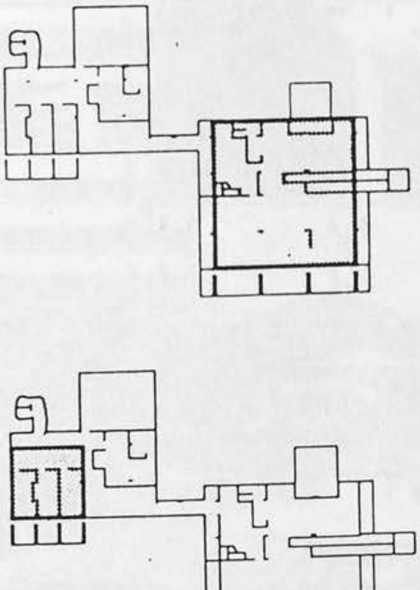
E. CHURCH AT FIRMINY, CORBUSIER



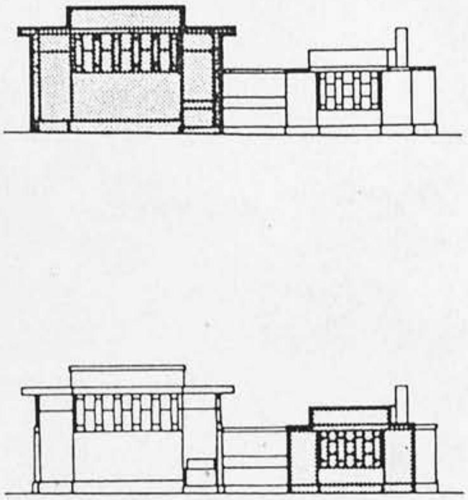
F. SYDNEY OPERA HOUSE ; UTZON



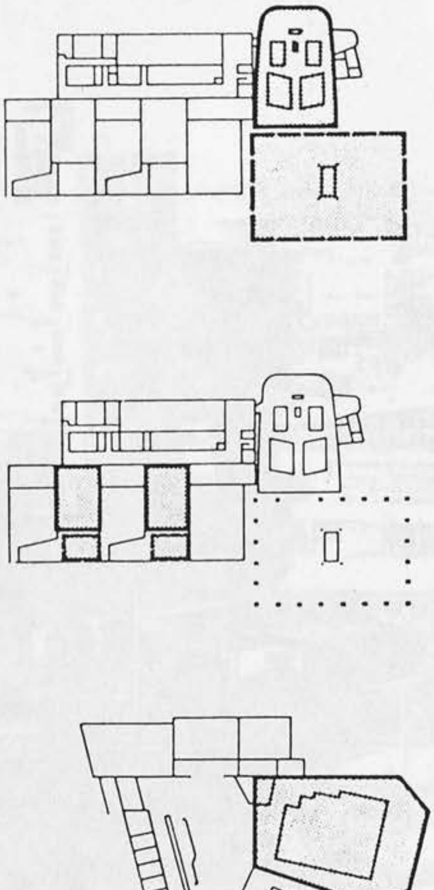
G



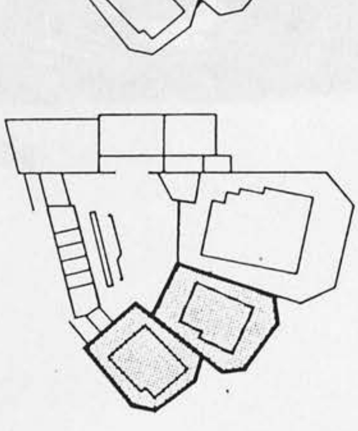
H



I



J



K

FIG 15(G-K)

G. THE SALUTATION, LUTYENS
H. VILLA SHODAN, CORBUSIER
I. UNITY TEMPLE, WRIGHT
J. WOODLAND CREMATORIUM, ASPLUND
K. WOLFSBURG PARISH HALL, AALTO

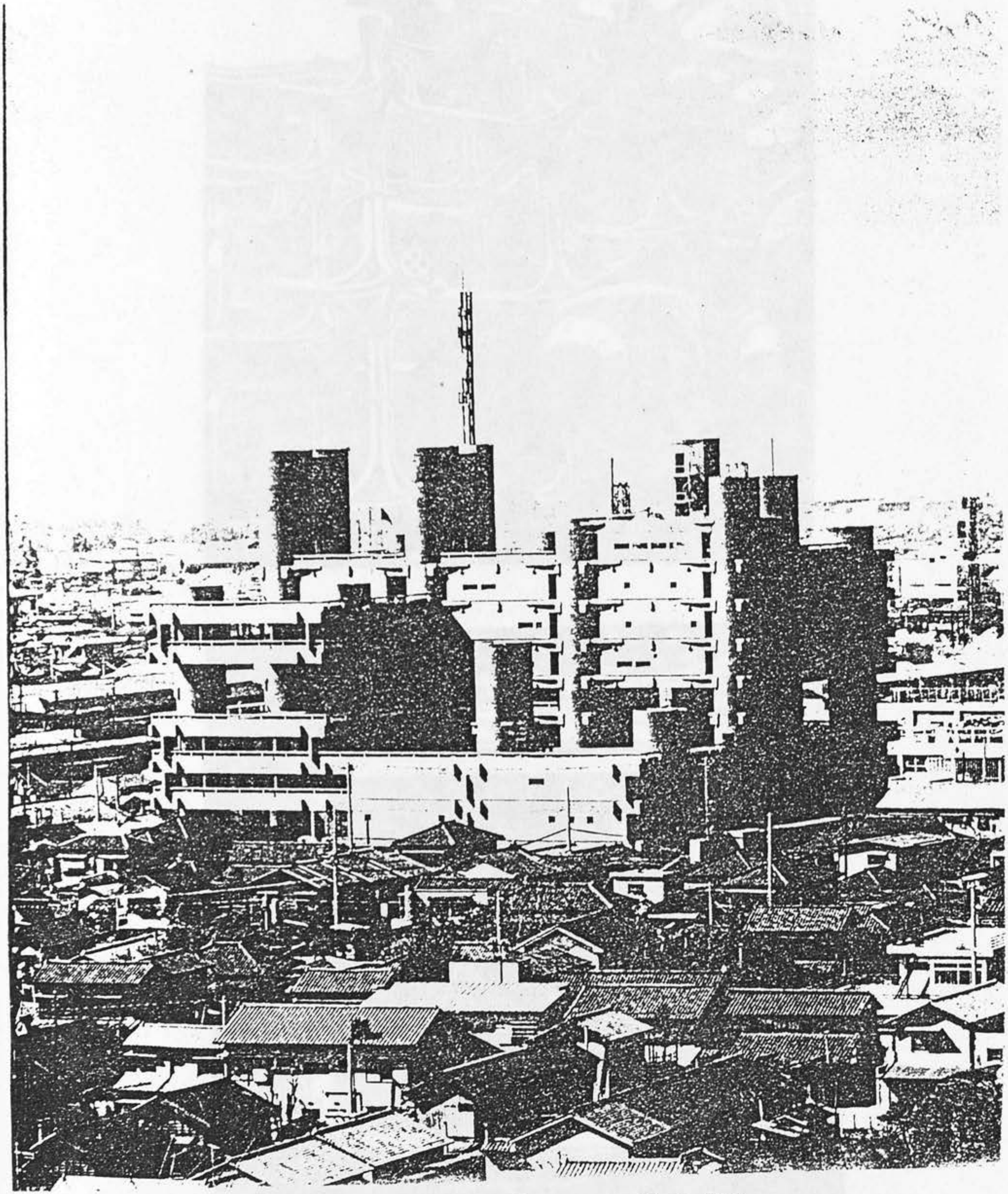


FIG 16 Yamanashi Communications Bldg

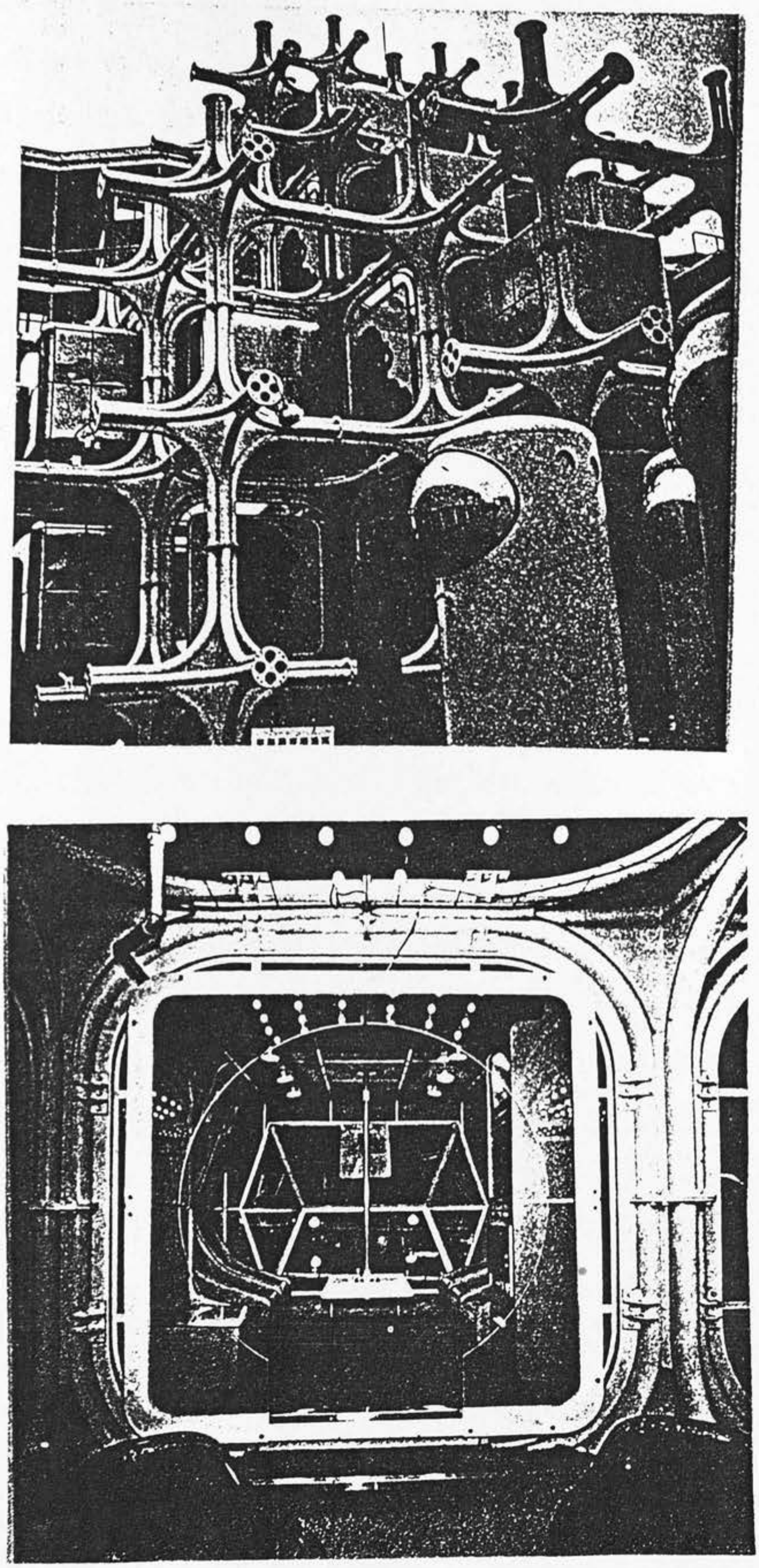


FIG 17 TAKARA PAVILLION, KUROKAWA

SECTION II

2.0 Summary of Case Studies

This section summarises the case studies described in Volume II of the thesis (please refer to Vol. II introduction).

2.1 The summary is made in respect of four main aspects:

i) architectural considerations
ii) structural considerations
iii) utilitarian considerations
iv) construction considerations

2.2 Architectural considerations

2.2 a) Influence of architectural concept

The case studies reveal that the architect's concept is the primary generator of ideas in the development of structural configuration and the choice of structural system. This is evident in the cross-sectional profiles of Piano's Kansai Airport scheme and Maki's Tokyo Metropolitan Sports Centre (case studies 31, 35) where the structural arch is configured to express abstract ideas conceived by the architect. In the IBM Travelling Exhibition Pavillion (case study 13), Piano's concept was to use the transparent cladding elements as part of the support system. The structural design was then evolved from this decision, and the need to counteract the effects of differential thermal expansion between the polycarbonate cladding and the laminated timber arches. Marks and Barfield's Bridge of the Future (case study 25) entry was inspired by D'Arcy Thomson's interpretation of the 'quadrupedal bridge' found in the skeletons of animals. The influence of visual precedent is also obvious with the Lee House proposal resembling the original Cripplegate architecture which features a building arranged in the form of a gateway (case study 4). The Embankment Place development by Farell and the King's Cross proposal by Foster use architectural forms to relate to the existing buildings ie. the barrel vault which typifies the railway station, and in these instances, form and structure are selected primarily for the purposes of visual relation. The use of barrel vaults in the Liverpool Festival Hall and the Frankfurt Stadium proposal is related with their contextual precedents viz, the Kew gardens and German steel lamella construction respectively. (see Case Studies 1, 2)

This is also the case of the Crystal Palace extension (case study 22) where the retention of the visual leitmotiv provides a link between the existing and the new stands and reflects the consistency and the continuity of the architectural design. (The sources of architectural concepts and their influence on structural development will be discussed in detail in the following paragraphs.) Architectural form is influenced by the use of visual metaphors and the adaptation of structural mechanisms inherent in those of for example, natural organisms. Design considerations transcend the functional and the constructive, to incorporate aesthetic ideas derived from these sources and structural configuration stops responding to a strict modulation of form suggested by economic and direct ways of supporting load, as implied by the ideals of basic structural design concepts.

2.2 b) Influence of geometry of form

The structural configuration for the Lee House took into consideration, the visual compatibility of the building form with the road widths beneath the podium block (case study no 4), and so internal spans were adjusted to allow symmetrical loading of columns. (There were three centre lines implied by the building form, the roadway and that for symmetrical loading, all of which were misaligned). Similiar situations arose at Embankment Place and at Broadgate (case studies 3, 5) where column positions were constrained by the layout of railway platforms, and the need to minimise the structural depth of horizontal spans within a height constraint led to the development of transfer structures. The external expression of the arch transfer structure at Broadgate Phase II (case study 5) was also intended to visually relate to the vault structure of the existing Liverpool Street Station. The structural patterns for the barrel vault proposals to cover the atrium of the Imperial War Museum and the Frankfurt Indoor Stadium were adopted for visual reasons more than for those of structural efficiency. (Case Studies 7, 1) Similarly, the assymetrical profile of the Debden arches (case study 10) was arrived at out of the consideration of providing appropriate North light for the interior, and the provision of adequate headroom clearances for machine operators in the Production Hall. The parabolic funicular for uniformly loaded arches was not observed in this case and the use of prestressed steel tendons to keep the resultant thrust lines within the sectional profile was a relatively costly and complicated procedure. The barrel vault form and the use of structural arches is also related to the use of geometries which are thought to be sympathetic and congrous with site characteristics, for example, both the Liverpool Festival Hall and the Frankfurt Indoor Stadium (case studies 2, 1) have curvilinear geometries which were thought to be appropriate to land forms in their natural surroundings. For this reason, the arch was selected from a range of one-way systems studied by the designers of the Frankfurt Stadium. In the Liverpool Festival Hall, the structural detail of the buttress-trussed arch junction was dictated by the visual requirement of expressing a smooth unbroken exterior curve from the support level of the arches to their crowns.

In Piano's Bari Football Stadium (Case Study 36), the arched profile of the roof structure are in essence, structural cantilevers. The profile was dictated by the "bowl-like" form of the Stadium, where the roof and grandstand were expressed in curved lines.

2.2 c) Influence of architectural massing

As described in Stirling's use of cluster assemblies para 1.19(iv) Section I, large buildings are often articulated by 'breaking the whole' into identifiable parts which express their varying functions and which may relate in scale to existing buildings on site. Stirling uses abstracted primary forms as compositional elements in his buildings, the shapes of which are also used to characterise the external spaces enclosed by them. Both his Dusseldorf and Stuttgart art gallery/museums (case study 37) are shaped to enclose central circular-plan plazas. This particularly a feature of urban design schemes where the architectural proposal has to respond to existing features on site in order to act as a harmonious intervention. In an extract from Stirling's Cologne Museum competition report, he wrote:

"The building is in three parts: a long gallery wing; an intermediary entrance building and a gateway/auditorium building. The physical appearance of the plaza is determined by a series of architectural elements..."

Stirling then adopts structural systems that are appropriate to the intended architectural expression and there are as many types of systems as there are different spans, volumes and spatial effects required; for example, flat slabs and structural walls were used in the Stuttgart Gallery to eliminate the visual presence of beams in the gallery spaces, and columns were introduced as colonnade expressions and in large spaces to reduce their scale. (Case Study 37)

In floor plans where their shape is determined by relatively 'free-form' spaces, such as those of the Corbusian villas and some of Stirling's works, where cylindrical towers form part of the building expression, the architects would prefer ceilings without beams, as their presence may not visually relate to the irregular plan form. Schodek (46) describes the directional effect of column spacings and grid patterns; these are appropriate for regular (rectilinear) plan forms but may not be easily adapted to 'free-form' spaces. For this reason, the flat slab construction is used for floor structures, or alternatively, false ceilings have often been used to conceal beams which do not relate to the definition of spaces beneath them, as well as to conceal HVAC ducting where these may be required. Closed column spacings may be used to limit the structural depth of the slabs and this must also be considered in the spatial composition.

In Piano's Kansai scheme (case study 31), the transverse section comprises one main central vault and two peripheral vaults of different curvature, identifying the different zones in the scheme. The tripartite arrangement also breaks down the scale of the large building form. Similarly, Maki's Fujisiwa Gymnasium and Tokyo Metropolitan Stadium use the varying curvature of the roof structure to demarcate seating and activity zones; the external form is also articulated to resemble their metaphors and to keep in scale with their respective sites (Case Study 35). Large single-storey complexes may also be scaled down with structural modules such as those of Fleetguard, Nantes, Stansted and Swindon. All four case studies exemplify the ubiquitious cable-stayed 'umbrella roofs' where the entire whole comprises articulated typical modules of defined space and structure. Most significant is Foster's Stansted which integrates structure, space and services with the utmost visual clarity. (Fig. 1)

2.2 d) Providing visual cues with Structure

i) As mentioned in para 1.20 the external expression of one or two-way spanning system may constraint the appearance and the location of building entrances. Further to this is the problem with symmetrical structural arrangements which lack visual hierarchy with which to provide some suggestion of a sequence or of a direction of movement of people; in short, the provision of visual cues.

In buildings like the Fleetguard Factory, the Renault Centre, and Stansted Airport, (case studies 16, 15, 27) the use of typical modular units arranged in two-way systems make it difficult to identify the entrance due to the homogenity of the building form. From the exterior of the building, there is no hierarchy of forms to provide some idea of a direction or a change of function and this is due to their symmetry.

For example, the exterior forms of Rogers'INMOS and Foster's Renault Centre at Swindon (case studies 23, 15) do not reveal the presence of accommodation (such as restaurants and offices), other than those of fabrication and assembly. Separate functions are fitted into homogenous free-plan spaces designed for flexibility and future expansion, with the addition of extra bays or modules of structure, making the architectural form typical and symmetrical. It might be argued however, that secondary and backup functions may not be of such significance as to require an architectural expression separate from those of the primary function, but visual cues for entrances and routes through the building are considered necessary, and it is the repetitive and symmetrical structural units that are assembled in ways which do not make their articulation very obvious. (Figure 2 illustrates Maillart's Dortmund music pavillion which typifies a clever structural form but with an ambigious entrance expression.) The entrance to Grimshaw's Rank Xerox HQ are invisible from the photos in Fig. 3, and both entrances of the Oxford Ice Rink and Foster's Sainsbury Visual Arts Centre are implied at the glazed gable-ends whereas they are actually at the side of the building. It may not always be possible to locate entrances at 'gable-ends' of one-way structures and other devices for articulation are possible.

ii) Rogers' Fleetguard factory recognises this problem with two-way symmetrical modules and here, entrances are marked by missing modules in the structural pattern. In Foster's Stansted, and Renault Centre, potre-cocheres are created by setting the cladding element back from a row of structural modules. Foster's Frankfurt Indoor Stadium proposal incorporates an entrance at the gable-end of the barrel-vault form, Fig. 4 Hough (48) mentioned in his design report that some thought was originally given to extending the roof from the gable-end to cover part of a straight-run sprint track as shown in Fig.5; this was part of

Foster's idea to articulate the gable-end in a pattern related to the diamond-grid of the main-vault, but this was later rationalised to the existing solution in Fig. 4 when the engineers pointed out that any extension beyond the last bay supported by the buttresses were in fact cantilevers from the roof-edge of the gable-end, and therefore effectively constrained by limitations of span.

iii) Cable-stayed structures may be configured to define both entrances and routes through a building. This can be seen in examples of one-way spans such as those of Grimshaw's Homebase Brentford, Rogers' Patscentre and INMOS buildings (case studies 24, 20, 23) where the compression masts are centrally located to define entrance and the circulatory spine through the building. The vertically accentuated masts reduce the amount of tension in the suspension cables or rods by increasing the angle between cable/rod and horizontal span. This is achieved by connections to higher points on the mast, therefore the mast cannot be too short and this also provides passing motorists with better visual cues, at high speed from a distance. The Homebase Brentford Store and the Oxford Ice Rink were structurally configured with this consideration as one of its design criteria. Similarly, the high points of membrane structues which assist in the creation of double-curvatures for stability, may be arranged on plan to accentuate the major architectural spaces.

Areas of low headroom in membrane structures may be appropriate for implying entrances, which then lead to spaces of progressively higher headrooms.

iv) Spaces may be differentiated from one another by varying their scale and geometry. In structural terms, it implies variations of spans, beam depths, column locations and changes in structural systems brought on by changes in modes of load transfer.

This approach is typified by Stirling's Berlin Science Centre Competition entry (1979) which expresses its components as a group of relatively independent buildings whose architectural forms relate to familiar building types. (The relation to 'familiar building types' is associated with the use of icons).

"There is a church, a stoa, a campanile, an amphitheatre and a fort or castle"

Very often building forms are arranged to accentuate external circulatory routes through them such as Corbusier's Carpenter Centre of Visual Arts in Harvard University, Stirling's Northrine-Westphalia Museum scheme (1975) and the Stuttgart Art Gallery. (Fig. 6) Building forms are also configured to enclose open spaces such as Queen's College at Oxford (1971) or to define circulation decks within levels of the building, as in Corbusier's Unite and in the St Andrew's residential expansion scheme (1968) by Stirling.

Consequently, structural patterns have to incorporate changes in span and configuration in order to articulate changes in architectural rhythm and in the shapes of forms. The axes of one-way spans may not always be linear as in the Olivetti HQ at Milton Keynes (1971) and the vertical continuity of supporting columns may not take the most direct and efficient route because of the sectional profile of the building, such as those of the Dorman Long HQ (1965) and Queen's College (1971).

v) configuration of structural form in relation to the architectural idea

a) visual simplicity

Structural systems are selected or developed often to compliment the architectural aim of providing relatively discreet settings to the activities in the space. For eg. Nagashima's Ishihara Memorial Gymnasium featured a barrel-vault roof supported by structural steelwork exposed in the interior. The engineer was conscious of the possible visual complication that could arise from the structural configuration and so the latticed frames used for bracing were de-emphasised in relation to the main arched beams, by using slender sections. (Fig.7)

Leonhardt's (49) considerations of aesthetics in bridge design reveal a similar attitude towards visual effects of structural configuration:

> "Very delicate looking bridges can be built by joining slender steel sections together to form a truss. Again welding has improved the potential to good form because hollow sections can be fabricated and jointed without the use of big gusset plates. In this way, smooth looking trusses arise without the 'unrest' which occurs by joining two or four profiles of rolled section with lattice or plates." (Fig.8)

b) homogenity and irregularity

Structural systems are also selected on the basis of their ability to 'match' the patterns of architectural form or their ability to imply through structural forms, the architectural idea of irregularity or homogenity. For example, Rice and Thornton (51) describe the consideration of the visual compatibility of the structure to the 'stepped elevation' of the atrium glazing:

> "The structure had to be visually light from the inside. A space-frame was considered for a while but its homogenous appearance was not appropriate (to the atrium roof form) and a more hierarchial solution was devised."

By contrast, the use of space frames (such as those developed by Wachsmann(38) and the use of 'structural cells' allowed the generation of homogenous and symmetrical forms for eg. Tange's Theme Pavillion Expo 1970, and Fuller's geodesic dome. In today's context, the application of modular structures in generating architectural form is seen in the work of Foster, Rogers, Piano, Hopkins, Tange, Isozaki and Grimshaw. (case studies 15 to 17, 1, 2, 20, 23, 27, 28, 31, 13, 43, 44)

2.2 e) The expression of structural hierarchy

The case studies reveal that the architectural aim of expressing visual hierarchy has the following structural implications:

i) influence on the configuration of structural elements

The primary load-bearing elements may often be exaggerated as part of the formal composition; and this is because the ideal geometrical configuration in terms of structural effectiveness may not suit the compositional geometry conceived by the architect. Happold's (52) criticism of the Oxford Ice Rink reflects an alternative viewpoint to the manipulation of structure on visual grounds: "(In) the Oxford Skating Rink the mast had become a cable-braced flagpole rather than a structural necessity.... one has to pay for the masts and tie-downs, and although spectacular and with it structural behaviour easily understood visually, it is not often an economic building system. There have also been suspended multi-stayed buildings although probably most have been designed that way for visual impact rather than entirely for function".

Similar considerations went to the design of the HK & SB building, Renault Swindon, Homebase Brentford, Ladkarns Buildings. IBM Sports Hall, INMOS and Patscentre, (case studies 15, 24,12,23,20).

ii) influence on choice of structural system

Thornton in his design report on the Lloyd's Building (Case Study 8) wrote that two main considerations were given to the choice of structure for the atrium roof (Fig. 9):

a) that the structure should be visually appropriate to the serrated profile of the glazing elevation.

b) and that the supporting system should allow a consistent relationship between the rc superstructure and the surface of the glazing.

For these reasons, a space frame was thought to have a visual appearance that was too homogenious in relation to the 'serrated profile' of the glazing, and a system of planar trusses was adopted as the final solution.

Newby's (18) suggestion for an alternative 'compression system' for the HK & SB building instead of the existing tensile system, reflects his argument for a logical and more direct way of transmitting forces in the structure. It also suggests that the structure was conceived more for visual excitement than for effectiveness.

iii) influence on structural detail

As first mentioned in para 1.12, Section I problems arise when:

a) the architectural aim of visually differentiating the supporting elements from the supported elements is not appropriate to the structural behaviour of the system.

b) the architectural detail detracts from the effectiveness of the structure.

Hunt (19) makes two comments on the Lloyd's building: the separation of the floor structure elements from the beams, for services distribution, results in the loss of the 'T' beam effect and hence, structural efficiency; whilst the column/bracket/yoke detail induces bending into the columns because of one-sided loading, except at internal corners; this is a situation where engineers are at pains to avoid.

Higson/Hough (20) wrote in their design report for the Shotts factory:

> "the inclined facade props located proud of the inclined wall cladding to express better their structural function to outside observers, generated large biaxial moments on the castellated beams under lateral wind load. The moments arose from the large eccentricity between external prop and internal wall post an eccentricity created when the prop and post were forced apart at their top joint to allow the cladding envelope to pass between: from its normal position outside the structure, on the roof to a position inside the structure, down the wall."

In other words, the structure was complicated by the architectural aim of exposing it to exterior view. Other significant criticisms to this project included the vulnerability of pin-ended columns to accidental damage (for eg. forklift collisions) when these became a visual focus by setting back truss and beam elements from the column. In the case of the Shotts factory, its highly articulated structure and consequent low redundancy faced the danger of progressive collapse and the frame was checked for safety with the possible removal of tierods and external wall props. Similarly the Sainsbury superstore at Camden required an 'emergency truss' (see case study no. 9) in the event that one set of tie-downs were severed by vandals or saboteurs.

Two points may be raised:

i) the idea of expressing 'supporting and supported elements' in structure may have been appropriate with post and lintel precedents, but may not be so with the increasing complexity of contemporary systems today. For eg. it may be illogical to separate the components of a composite floor, say, the rolled-steel joists from the concrete slab, for the purposes of visual articulation if its structural effectiveness lies in their continuity (or unity).

ii) roof decks, wall panels and 'traditionally non-load bearing elements' of a building may serve as secondary means of support, in which case, the architectural idea of a non-load bearing element may not be structurally true.

Wachsmann (37) wrote in 1960:

"...the systems of supports may sometimes be so secondary that in the finished building, they will scarcely be in evidence. Moreover, their structural purpose will not always be apparent; as ties, panels and open space systems will act as load-bearing elements".

For example, Piano's Bercy - Clarenton Commercial Centre (Fig. 14) and the Berlin Bismark Strasse Development have similiar forms with different structural systems.

2.3 Structural considerations

2.3 a) General

What is apparent from the case studies is that the engineering aim of economy in providing the most appropriate solution that is cheapest to construct and to maintain appears to be related with minimising the weight and bulk of structures, and the avoidance of bending instead of direct forces. Members loaded by direct or axial forces make full use of the strength of the material, and therefore, there has been increasing interest in systems that use primarily tension and compression members.

In practice, there are almost no pure tension or compression structures because a thin arch or a hanging cable would not be stable under natural loads and would buckle or flutter. Such structures need to be supported or suspended at their periphery. It is therefore not unusual to see in the case studies, combinations of compression and tension members in one structural system and - seeming opposite to the initial design aim-with members acting in bending.

Schlaich (52) argues that it is this antithesis that challenges the designer's creativity with the reward of a natural, light and aesthetic structure, if he succeeds in striking the right balance between these potentially conflicting factors. For example, the Debden (case study 10) proves that arch profiles that vary extremely from their funicular ideal have necessarily bulky sections to counteract the induced bending, and its structural behaviour is tending towards that of a portal; the result is an expensive and complicated prestressing measure taken to counteract the horizontal thrusts. There are also several examples including Piano's Genoa Tube station, Fig. 10, which uses an elliptical profile where considerations of headroom below the arch curvature necessitate its detraction from the parabolic funicular under uniform loading conditions. The studies on optional one-way systems conducted by Hough (48) for the Frankfurt Stadium proposal, (case study 1) reflect these considerations of interior space and exterior form against considerations of minimised bending, and therefore lighter structures.

Hough (48) pointed out in an interview that cable-stayed solutions were initially considered but eventually ruled out when the site offered little space for the location of compression masts at the periphery. The Frankfurt Stadium (case study 1) was also an example where the low rise to span ratio was necessary to restrict the height (and hence the visual impact) of the building, thereby accepting the structural penalty of greater horizontal thrusts which would have been avoided with higher rise to span ratios. The Liverpool Festival Hall (case study 2) has a pin location on the axis of the top boom of the trussed arches, for architectural reasons of expressing a continuously curved vault surface from buttress to crown, and this detraction from the structural ideal of the mid-point position, in line with the centre axis of the trussed arch, resulted in an increase in the bending moment induced in the structure.

However, the increase was considered to be marginal and the architectural detail was pursued.

From an engineering point of view, it would be ideal if the aesthetic compositions of form and space could be based on funicular profiles, but in the case of the arch, there may be other reasons for adopting non-funicular profiles, particularly when assymetrical arches provide the desired visual and spatial effects, for eg. Piano's peripheral vaults in his Kansai scheme, and Maki's Tokyo Metropolitan Stadium which combines arch and cantilever systems (case studies 31 and 35). In fact, Maki's Tokyo Stadium, Rogers' and Calatrava's Austerlitz Bridge proposals over the Seine (case studies 35, 26) are unprecedented forms achieved by combining the structural arch with other systems. This perhaps is initiated by an approach that does not start first by considering the implications of basic structural design concepts on form, ie. that a vertical upright arch under uniform load should be parabolic in order to transmit mainly compressive forces, and to require the minimum sectional bulk of material. In the case of cable-stayed structures, Leonhardt (49) shows interesting examples of cable and mast arrangements with guidelines to the degree of inclination of cables to beams in order to avoid unacceptably high compression components in the beams. Indeed this is one significant consideration in the configuration of cable-stayed structures together with designing for wind effects (due to their extreme lightness), and the provision of longitudinal stability and resistance of out-of-plane forces without 'cluttering' the elevational composition of the building and structure.

With the Frankfurt Stadium and Imperial War Museum atrium roof structures (case studies 1 and 7), the architectural preoccupation with effect of the framing patterns of the vault was balanced by the structural precaution of preventing buckling with slender compression elements. Therefore, options were evolved from short, slender sections to longer, thicker sections, depending on the proportions that were thought to be appropriate to the dimensions of the cladding element, and for visual effect. In the case of cable-stayed structures, such as Fleetguard,(case study 16) the beam forces were largely controlled by deflections of the columns and cables. Therefore, the bulkier the beam sections, the more forces they attracted and eventually, both economy and visual elegance would be lost by increasing the beam sections. Thornton, Rice and Lenczner (53) then devised three load-carrying systems within one bay which kept the deflections of the structure in that bay without transmitting them to adjacent bays. The three constituent systems resisted downward loads, the second, upward loads and the third, out-of-balance loads (Fig.11) Therefore, the arrangement allowed for wind uplift forces to be taken by the tension structure rather than by adding dead weight or increasing beam stiffness. A similar approach is observed with the Nantes and Swindon schemes (case studies 17, 15). The cable-stayed configurations in these cases are as aesthetically interesting as they are structurally innovative.

2.3 b) Effect of structural development on Architectural expression

The development of increasingly slender structures as mentioned earlier, is related to the reduction of dead weight which is long span systems is economically advantageous, but more significantly, the visual impact of structural elements has been refined to a stage where they have become accepted as elements of architectural form and space. For example, the traditional beam requires a deeper section as its span increases. Where deep-sectioned beams may be visually unacceptable (see discussion on Debden case study 10), the introduction of a truss could be a preferred solution to supporting a single-storey roof particularly when the visual impact of the overall depth of the truss is reduced by the perforated arrangement of struts and ties. The visual distinction between strut and tie is further accentuated by the cable-braced members in steel construction. From the case studies, the configurational forms of trussed beams, trusses and portal frames are re-interpreted as illustrated in Fig. 12

Rigidity and moment joints are achieved with a system of cable-braced, pin-jointed steel members, as in the case of Renault Swindon (case study 15), the ties also reduce the span of the beams. A column may be interpreted as a cable/rod braced compression mast, as expressed in Grimshaw's Oxford Ice Rink (case study 18), a truss, as in Happold's Blackhealth House (case study 39) and Grimshaw's Ladkarns Building (case study 19), a trussed beam, as in the Lee House transfer structure, and a braced arch as in

Piano's Bari Stadium (case study 36). These 're-interpreted' structural forms have had significant influence on the architectural typology of forms observed in the case studies, and is testimony to Wachsmann's (38) predictions:

"... the idea of a building as a solid structural mass will gradually give way to the idea of combinations of functions and individual elements. The design will be dominated by the horizontal and vertical stratification of surfaces, conceived as planes of movement, at the same time, these surfaces will establish the porous character of the building mass enclosed by functional elements rather than solid walls. All planning is primarily influenced by free space; larger spans mean that space will be conceived in unprecedented ways."

The demand for column-free spaces has resulted in a number of structural developments related to long-span structures, and in systems where vertical supports may be confined to the external periphery of the building form. The long-span modular systems observed in the case studies invariably adopt the cable-stayed propped cantilever; for example, Grimshaw's Homebase Brentford, Roger's NAPP laboratories at Cambridge, Marks/Barfield's Bridge of the Future (case studies 24, 25). Although these structures had their precedents in bridge design (Poyet's stayed girder bridge proposal in 1821) and were later applied to aircraft hangar structures (10), they are increasingly popular as single-storey long-span systems capable of providing visual relief to the anonymous box-like sheds generated by commercial and industrial functions. The back-stayed cantilever is also the primary support to the roof of Grimshaw's Camden Sainsbury superstore, the main spine structure of the Homebase Brentford store and one-half of the transverse span of Roger's NAPP laboratories at Cambridge. Fig. 13. Marks/Barfield's Bridge of the future comprises individual cable-braced compression elements shaped in the form of vertebrate sections (see case study 25), which assemble to form an arched bridge. Structurally, it is a propped cantilever, and is a creative approach to spanning a landform obstacle; (note also proposed erection sequence related to structural concept).

2.3 c) Natural light and elevational expression

The slenderly proportioned structure with its increased extent of opening for screening or natural lighting has changed the traditional concepts of mass, and the two-dimensional treatment of building facades as visual composition. The exterior surfaces will no longer reflect the structural system as in Piano's Bercy-Charenton Commercial Centre (Fig.14), and these exterior surfaces are not facades in the traditional sense, but are re-interpretations of the Corbusian brise-soleil, instead of spanning full height between cantilevered floor slabs, these elements which control the admission of light into the interior spaces are being hung from the structure and exist quite independently as separate building elements. This is seen in Piano's Menil Collection, Grimshaw's UK Seville Expo

Pavillion and Foster's Centre d'Art Contemporain et Mediatheque (Fig. 15). These architectural expressions would not have been possible without the development of systems which use minimum material and which provide support with minimum bulk.

The structural forms of Foster's Mexican Television HQ & the King's Cross proposal are partially articulated by considerations of the admission of natural light in relation to spatial organisation on plan. The roof forms are not punctured to admit light, as this could disrupt structural continuity, but instead, the structural form is shaped around openings. For example, in Piano's Ravenna Sports Stadium (case study 33), the structural form 'cleaves' in the centre to allow a central band of light through the roof structure. Piano's Kansai scheme (case study 31) has a transparent rooflight element supported on the top plane of the triangulated arched truss. Therefore, the proposal for this form of natural lighting depends on the slenderness of the truss elements in providing minimum obstruction to lighting whilst achieving adequate rigidity against buckling and bending.

Maki's Fujisawa Stadium and Tokyo Metropolitan Stadium are configured to allow 'clerestorey lighting' whilst resembling its metaphorical image. (see Case Studies 34,35)

2.3 d) Design for Wind

The design of structures with minimum weight and visual lightness is significantly influenced by the effects of wind loading. Bartak, Kaye and George (54) in designing the Crystal Palace extension provide a comprehensive background to wind effects and their consideration in structural development . Two types of dynamic excitation may be experienced by structures even in wind of constant velocity: vortex shedding and galloping instability.

Vortex shedding occurs when a not ideally stream-lined body is subjected to a steady wind stream forming a turbulent wake. Eddies cling momentarily on the leeward side of the structure before detaching themselves in a random or regular pattern. Structural configurations with sharp-edged cross sections develop patterns in the critical range.

Galloping instability occurs when non-symmetrical forms are subject to a steady air flow. Geometrically symmetrical sections can become aerodynamically non-symmetrical when tilted relative to the wind stream and a lift force occurs which results in large amplitude cross wind oscillations, causing instability. Symmetry can also be disturbed by icing which distorts the cross-sections of cable-stays.

In practice, most cross-sectional configurations are far from the theoretical ideal of circular (round) geometry and both types of wind effects may be countered by high stiffness in the structure.

2.4 Utilitarian Considerations

2.4 a) General

The influence of utilitarian requirements has been a significant factor in the development and application of structural systems. Very often, the need for new and better buildings stems from the obsolescence of existing ones which are unable to accommodate user needs and functions which have evolved or expanded with time. Some of these requirements may be conflicting and it is interesting to see their influence on structural concept. The significant ones have been summarised as follows:

i) flexibility and growth

One of the most obvious and recurrent demands in industrial and commercial developments is the need to accommodate changes in use and future expansion. In order to survive, several commercial and industrial concerns either evolve or change their processing/manufacturing operations according to economic demand. The details of changes are often unknown to the client and the only guideline given is that the structure should not limit the range of alternative layouts possible within a permissible floor area for a given site. It is therefore not uncommon for architects to respond by locating supports outside the building envelope in order to maximise useable floor area. This strategy is seen for example in

Grimshaw's Sainbury Superstore at Camden, the HK & SB building by Foster and Rogers' INMOS and Patscentre buildings (case studies 9, 23, 24). These are invariably one-way systems which may be extended in one direction, by the addition of more structural bays. (The same applies to both the Liverpool Festival Hall and the Frankfurt Stadium which adopt a 'loose-fit' relationship between the space and the structural form) (case studies 2, 1). In schemes where the floor area is so large (for example, in Fleetguard and Renault Swindon) (case studies 16, 15) two-way structural modules are used and again, expansion is possible with the addition of extra modules. The span between columns is then decided by both client and architect based on equipment size, and the circulatory requirements of people and machinery functioning in the space to be provided. In the Patscentre and INMOS schemes (case studies 20, 23), the expression of the central spine was appropriate to the concept of services distribution and definition of arterial circulation, as well as dictating the direction of future structural addition.

ii) maximising floor area

The Lee House, Embankment Place and Broadgate Phase II (case studies 4, 3, 5 respectively) are perhaps the most interesting examples of utilitarian influence. It is in the interest of the developer to maximise saleable floor area in any building. This is not always a straightforward task when (as in the case of the mentioned examples):

i) existing site constraints limit the positioning and disrupt the continuity of vertical supports

ii) the limited number of positioning of vertical supports imply the need for deeper beams which are required to span uneconomical distances.

iii) the need for false ceilings and raised floors to accommodate HVAC electronic and computer networks, together with item (ii) would increase the floor to floor height in order to provide adequate headroom and structural clearances for service ductwork. This would mean that the overall depth per floor required for structure and services would limit the number of floors possible within a given height constraint.

Given these implications, the application of transfer structures to the case studies mentioned resolved the problems related to the commercial viability of the buildings. The Lee House steel transfer structure is configured in a way that it provides minimum obstruction to the retail function of the space it encloses. This is an improvement to prestressed/post-tensioned rc beams used as transfer structures where their structural depth normally necessitate the 'loss' of an entire floor.

2.4 b) Layout

In other cases the functional relationship of the interior (and exterior) spaces suggest a layout or arrangement which strongly influences the architectural form and structural development. This may be illustrated with the followwing case studies. The resultant building plan for the Patscentre (case study 20) was essentially linear with a dominant symmetry about the spine. Rogers (55) intended to reflect this in the building form from the inception stages of the design and he felt that the building was to be perceived as a series of slices, each representing a one bay module. Further slices could then be added whilst preserving the concept and visual integrity of the building.

The slices were interpreted by the cable-stayed spans arranged in a one-way system which could be extended in a linear direction whilst maintaining the original form of the building.

In the Sydney Football Stadium (case study 21), the most effective sightlines were achieved by arranging the tiers of seating such that they were slightly curved on plan and in section. This resulted in an undulating perimeter from which a continuous 'saddle form' roof was generated. The geometry then was used to arrange the structural system of rafter beams supported by cable-stays.

2.4 c) Loads suspended from roof structures

The design aim of achieving a visually light roof with slender structural elements is often possible when it is not subject to additional imposed loads other than dead and wind loads, and where applicable, live loads for maintenance purposes. This design aim is made difficult when the roof is subject to loads such as those of moving machinery in the Shotts factory (case study 14), and so the structure was designed to receive the heavy variable load by providing a few lines of specially strengthened beams. The other alternative was to dissipate the effect of the load over as large a spread of roof beams as possible. This option was not considered because the positions of the roof-mounted machines was subject to change.

In the case of the Imperial War Museum (case study 7), the load from the aircraft exhibits was received by the peripheral gallery structure instead of suspending them from the roof structure, which would have made the roof elements visually bulkier. The structural constraints (such as symmetrical loading at fixed points) on the layout of the exhibits would have caused much inflexibility. As pointed out in Higson/Hough's report on the Shotts factory:

"The obvious lesson was to try to avoid heavy local loads in a continuous lightweight roof."

2.4 d) Flexible Structures

Exhibition and experimental buildings provide the scope for the development of structural ideas. For example, Hopkins'

Patera nursery units (case study 11) demonstrate the versatility of pin connections whereby the central pin is so configured that under wind uplift, the structure behaves as a two-pin portal whereas under normal (downward) load, it behaves as a three-pin portal, the objective being that compression is kept only at the knee and in the legs, thereby eliminating the danger of buckling to the top booms, allowing for very slender sections of steel to be used. This system of planar trussed portals may be compared to the triangulated trussed portals of Grimshaw's IBM Sports Hall (case study 12) which appear to visually bulky and overdesigned.

McCarthy's 'responsive arch' (see case study 29) explores the possibility of maintaining equal tension on top and bottom chains so that the structure will find its own funicular shape under different loads. The idea of a flexible, less rigid structure is explored to provide cheaper structural solutions to exhibition buildings, such as the Glasgow Eurodrome 1990, for which this idea was proposed by McCarthy. It is noted that the arch is a cable-braced compression element with axle-joints between tension and compression members.

Similar ideas of 'flexibility' are explored in Marks/Barfield's Glasgow Eurodrome Entry, case study 29 and their Bridge of the Future entry designed with engineer Jane Wernick of OAP. All the proposals use cable-braced compression elements in steel construction, where moment joints are avoided in order to achieve visual lightness with less structural bulk. The degree of flexibility may be controlled in order that structural deflection is acceptable to design standards.

2.5 Construction considerations

2.5a) General

The influence of fabrication and construction considerations on structural design may be summarised from the following case studies:

In the Lee House development (case study 4), the decision to locate the transfer structure at the first floor level of the building was due to its erection sequence. The superstructure (18 storeys), was to be erected from bottom up in order to allow the installation of services, finishes and cladding with the completion of each floor. The location of the transfer structure obviated the need for temporary transfer decks above road level to allow continued use of the roadway, as well as to provide a working platform for the superstructure.

In the Embankment Place development (case study 3), a primary consideration in the construction sequence was the advantage to be gained by casting the first storey slab with temporary supports. These supports controlled the deflection of the slab until the prestressing operations including those of the transfer arch at roof top level, were completed. This enables the slab to be permanently connected to the braced cores to form a platform that was both vertically and laterally restrained. The stability of this slab was adequate to support the temporary bracing which was prevented from interfering with the station platforms at ground level. Temporary bracing was required for the floors above the first storey slab as these floors could not be braced by the cores until the arch prestressing was completed at roof level.

In the design for the cable-stayed structures at Nantes and Epone (case study 17), adjustment facilities in the ties were essential for the allowance of dead weight deflections and fabrication tolerances on the element lengths. The ties could only be tightened after roof construction could be completed. These design incorporations were in anticipation of boom deflections under their self-weight, as the ties were to be installed after the boom members were positioned.

In the Liverpool Festival Hall (case study 2), joist sections were selected for the main upper and lower booms of the three-way trussed arch, giving the arches clarity of line whilst minimising bulk and facilitating easy connections. The joist sections also served as runawys for access cradles.

In the Waldstadion proposal, joints to the three-way trussed arches were designed flush so as to allow sub-assemblies of units in the partially erected roof to slide vertically alongside adjacent assemblies of units.

In some of the case studies, sub-assemblies were preferred as this minimised the number of joints that would otherwise have increased with every component to be assembled on site. These components were also those which were sensitive to tolerance misalighments, as in the case of the IBM travelling exhibition pavillions. As with the Liverpool Festival Hall, the Patera nursery units, and the Ladkarns building, transportation of components meant that sub-assemblies were limited to carriage length constraints of 22m.

One of the most interesting case studies in respect of construction (related) considerations was the Oxford Ice Rink (case study 18). The subsoil conditions of the site necessitated the use of pile foundations. The structural configuration apparently limited the number (and hence the cost) to a total of sixteen pile foundations, thereby justifying one aspect for the selection of the structural system. In the structural configuration, considerations were also given to limit the number of penetrations made by the components of the cable-stayed system, through the roof cladding in order to prevent cold bridges at these points. The penetration of cable-stays through cladding elements is also a problem with waterproofing; these issues were also addressed in the design of the Renault Centre at Swindon (case study 15), and for that matter, most structures of this kind. (Fleetguard, Nantes (case studies 16, 17))

In the Fleetguard (case study 16), the structure was designed so that the bulk of the elements required minimum fabrication and simple joints. In this building, conical shrouds were welded to tubular elements which penetrated the roof, but there were more service penetrations than those of structure. Nevertheless, consideration was given to configurations which minimised structural penetrations of cladding elements.

In the Renault Centre at Swindon (case study 15), tender submissions revealed that external stiffening of columns were significantly cheaper than internal stiffening. The design of the column/tie connection was revised from castings connected to the columns by single pins through vertical plates welded to the wall of the columns, to restraining the vertical plates by annular rings placed around the column. The structure was then tested for lamellar tearing as a precautionary measure and found to be safe in this respect.

2.5 b) Iron and steel castings in tension structures

The detailed design of structural joints determines the success of the assembly, both architecturally and structurally. In practical terms, joints are designed with the basic criteria of:

i) durability and strength

(this is because in buildings which express their structure, the joints are likely to be external and have to be durable in exteme weathering conditions)

ii) economy in practical and reliable fabrication

iii) simplifying the erection procedure

Two types of materials are common to the case studies which use cast joints:

a) spheroidal graphitic iron (SG) with a high carbon content and a low melting point that makes casting less difficult, and which coagulates into spheres which enhance tensile strength.

b) cast steel with a lower carbon content and a higher melting point

Generally, both materials have grain structures and homogenous properties which are manageable in casting processes. This is important because the architectural forms of tension structures may result in highly stressed primary joints with unusual shapes and configurations (56). In the Renault Centre at Swindon (case study 15), the cast nodes made possible the structural connections between the stabilizing Macalloy tie rods and the span-reducing ties to the main compression masts. SG iron was used with the added advantage of incorporating weather sealing details in the joint.

In Stansted Airport (case study 27), steel castings welded into the steel structure were considered a cheaper and quicker alternative to the original design which proposed fabricated elements. It also allowed the same architectural expression of pin joints to be extended to the compression members of the structure. In the Lee House transfer structure (case study 4), the octagonal cast steel nodes carried very large tensile forces in the truss configuration. The forces were so large that plate thicknesses in a fabricated joint would have been excessively large and the implications of heat treatment, ultrasonic testing and weldment repair would have been uneconomical.

2.5 c) Corrosion of cable-stayed structures

Stadford and Watson (57) who have been involved in a world condition survey of cable-stayed bridges summarised the causes of cable-corrosion:

the presence of long-term unrelieved tension, wind and live-load vibration, mechanical wearing, environmental chemistry and the use of high-strength steel cables accelerates the rate of corrosion and the potential for stress-corrosion cracking.

The effects of corrosion depend on the cable-types:

The corrosion of <u>helical strand</u> cables used on Canadian stayed-girder structures have been suspected to be caused by stress reversals caused by inclined hangers similar to stay cables. Injections of a wax-type material infor the internal wires of the socket area was prescribed as a remedial measure, a process adapted from the mining industry.

Locked Coil cables are used in most European stayed-girders and these comprise interlocking steel wires which increase strand density and provide corrosion protection. The internal wires must not be allowed to vibrate, twist or oscillate to an extent where outer layers of wire are opened up to allow the entry of oxygen or water. For the same reason, the cables have to be regularly painted.

In parallel-cable types, a steel or polythene pipe with a cement grout, protective wax or grease injected into it serves as external corrosion protective jacket. With the vibration and dynamic motion experienced by stay cables, the reliance on crack-prone and brittle cement grout is being questioned. The use of inorganic materials such as copper appear to be better suited to long-term weathering performance.

These considerations affect the development and choice of cable-stayed structures, in relation to the design brief and requirements. The protective detailing described in the preceding paragraphs would affect the aesthetic considerations in the development of the architectural design and its application to the design task. It is interesting to note that inspite of these inherent problems, several of the case examples consist of buildings with cable-stayed structures. (The reasons will be described in Section III conclusions).

2.6 Conclusions to be made in the following section

From the observations made with Section II case studies and the main issues raised on structure in relation to architectural form and space in Section I, the conclusions to the thesis are made in Section III.

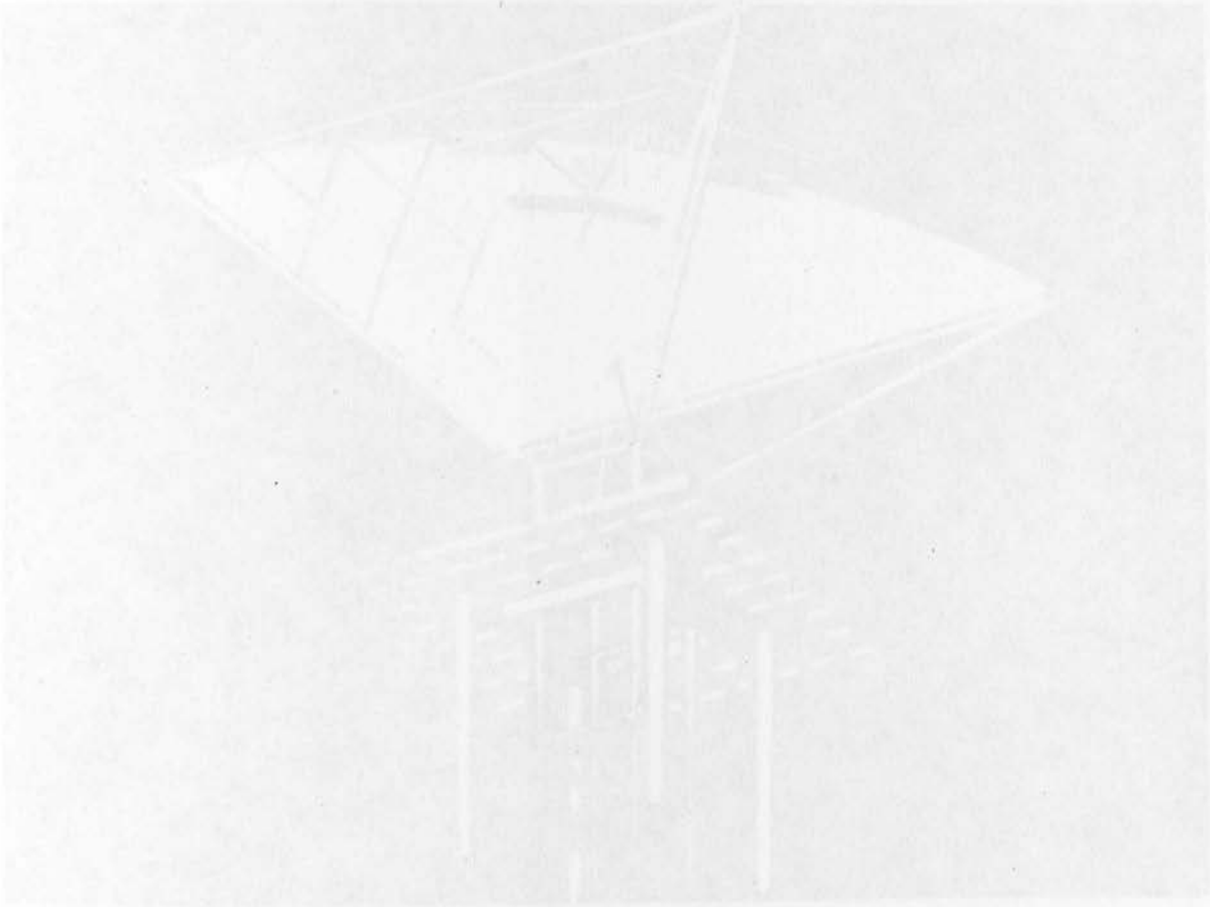


FIG. 1 STANSTED AIRPORT STRUCTURAL MODULE

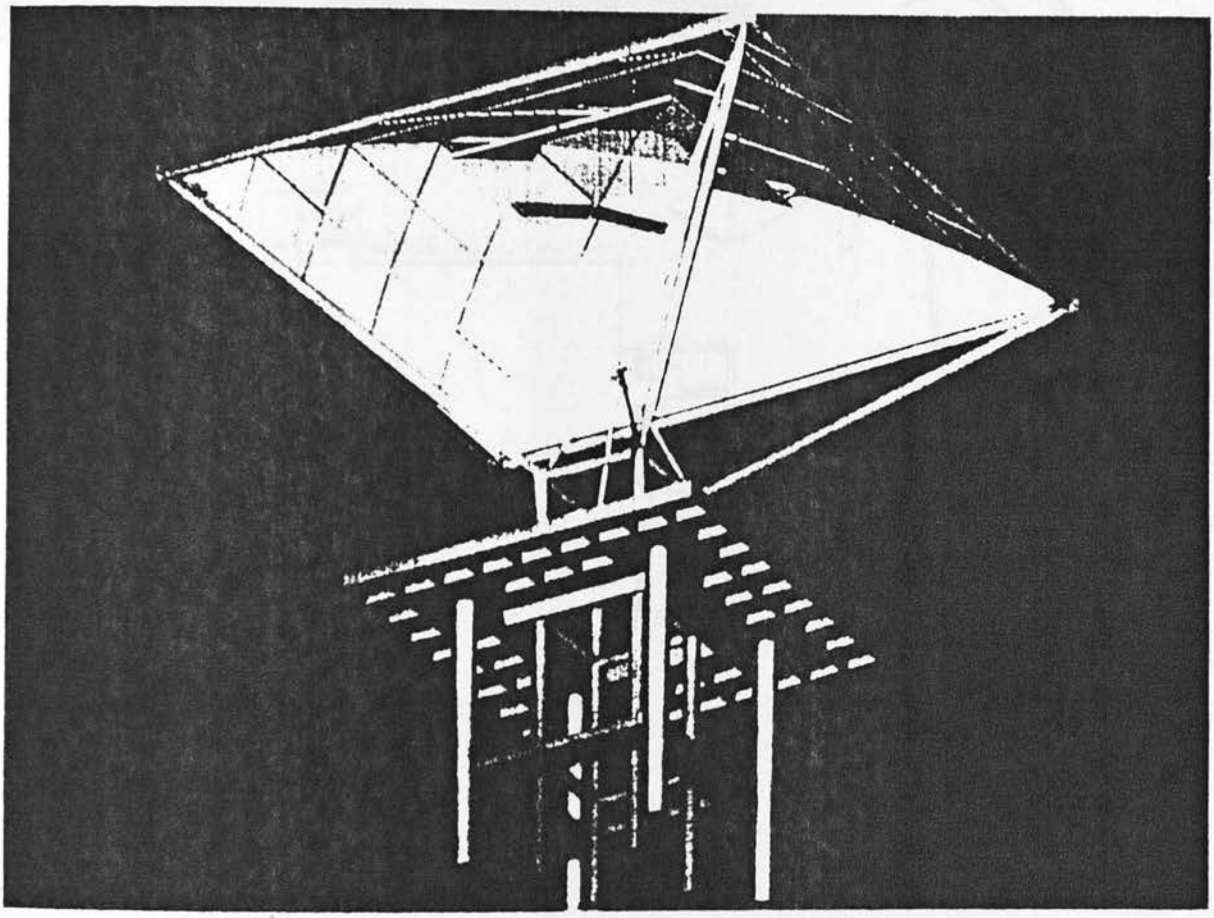
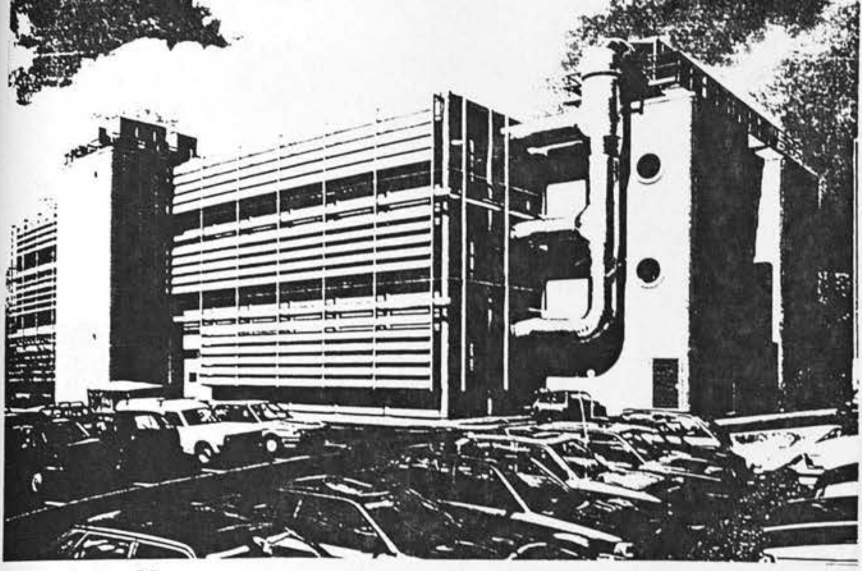


FIG 1 STANSTED AIRPORT STRUCTURAL MODULE



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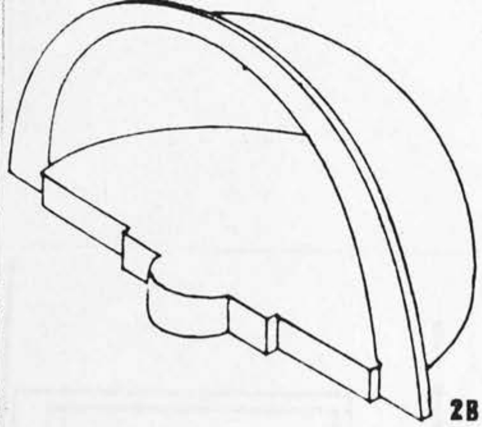
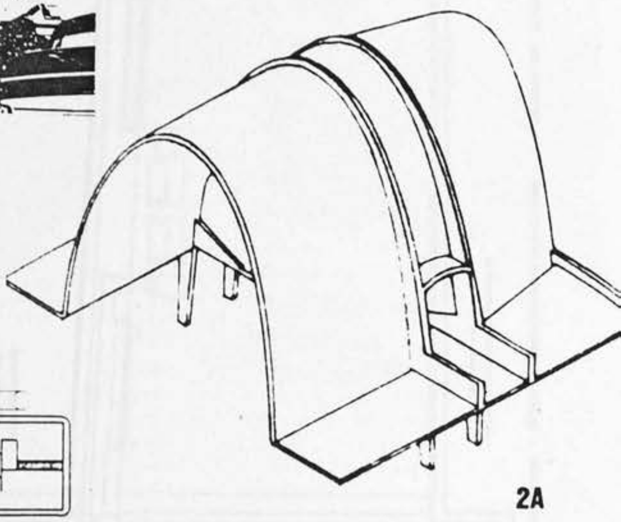


2B



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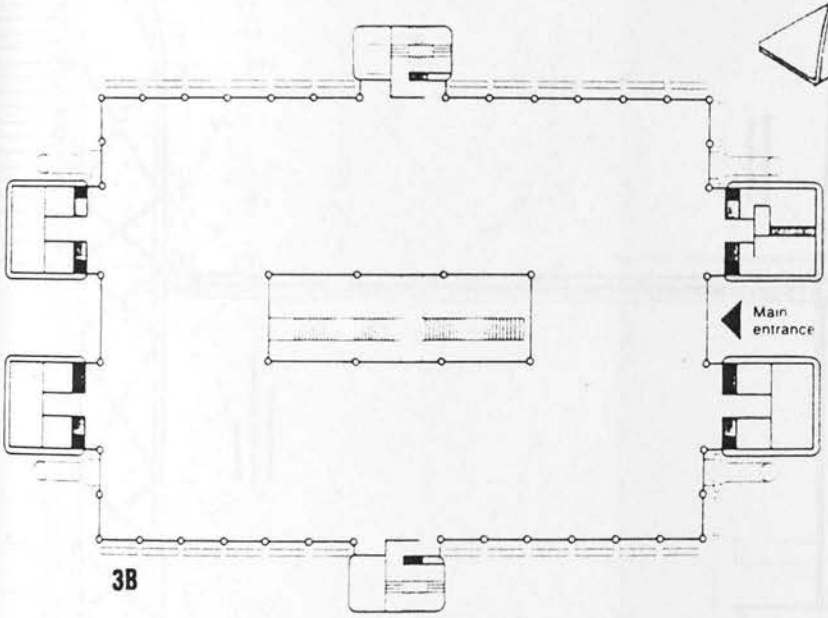

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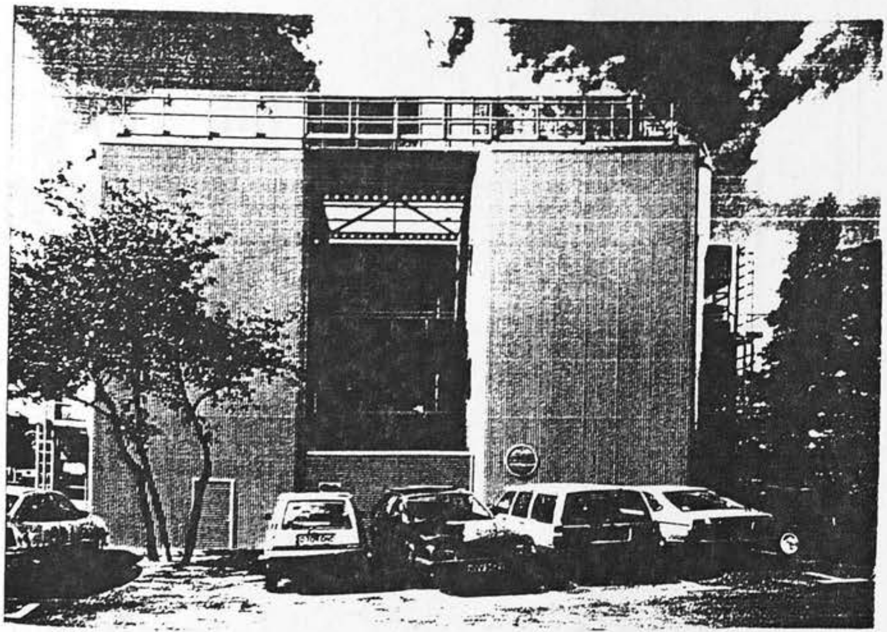


3C

FIG 2,3 **AMBIGIOUS ENTRANCES**

2A,B MAILLART'S DORTMUND MUSIC PAVILLION

3 A-C GRIMSHAW'S RANK XEROX, WELWYN

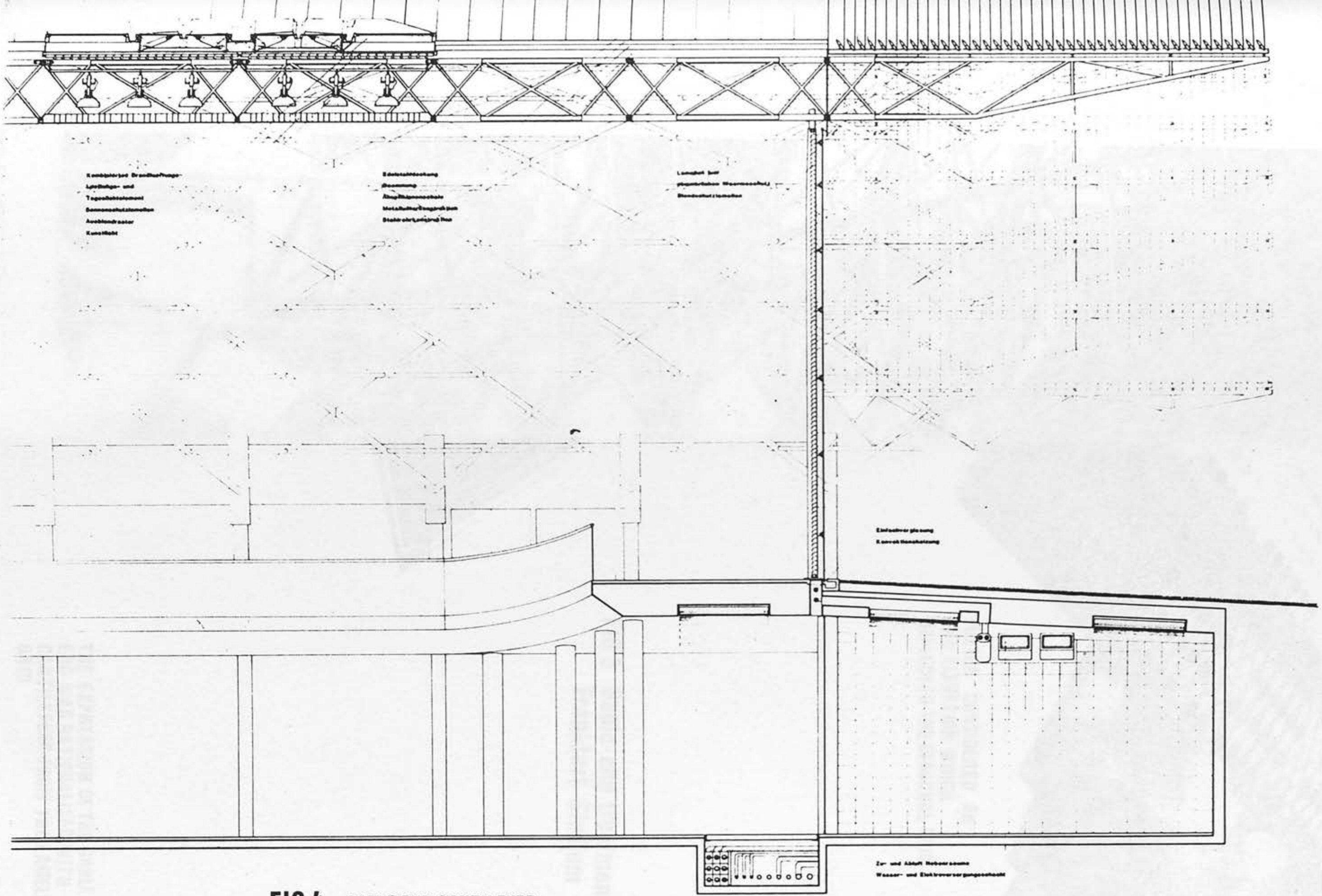
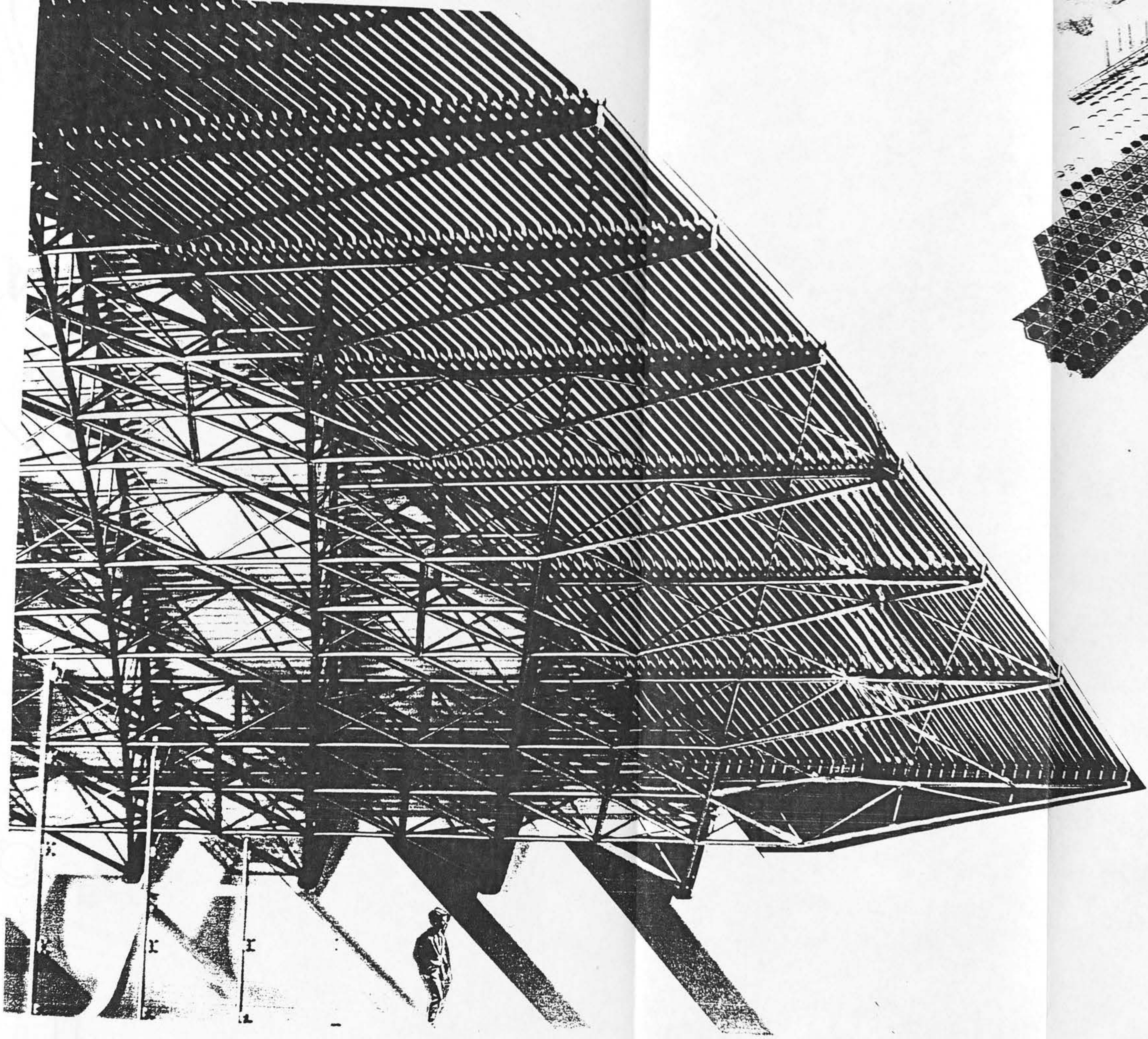
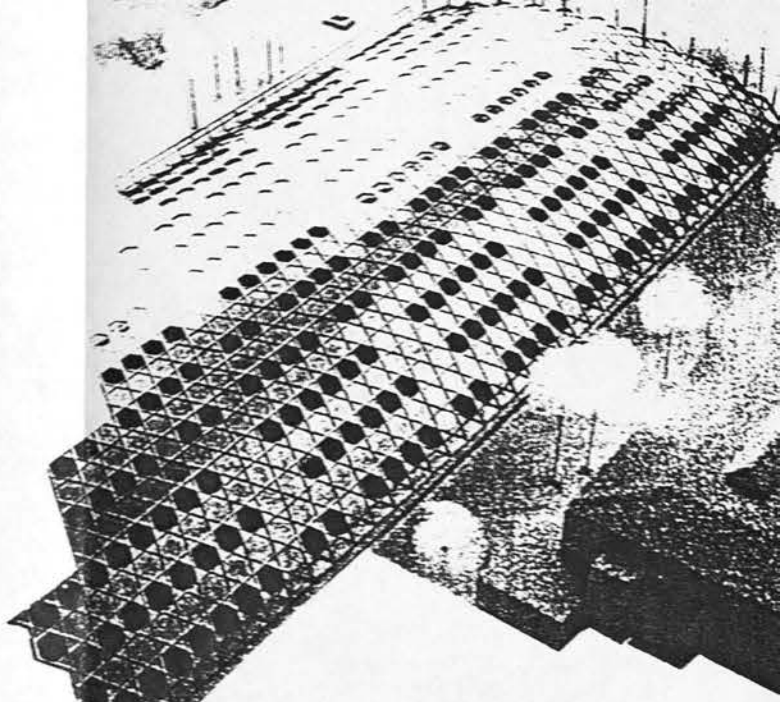


FIG 4 GABLE-END CANTILEVER

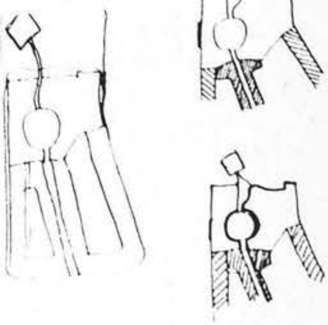




FOSTER CONSIDERED AN
END ELEVATION WHICH
REFLECTED THE DIAGONAL GRID

FIG 5 Gable-end treatment, Frankfurt Stadium

THE EXPRESSION OF THE GABLE
END WAS RATIONALISED WITH
CANTILEVERS FROM THE LAMELLA



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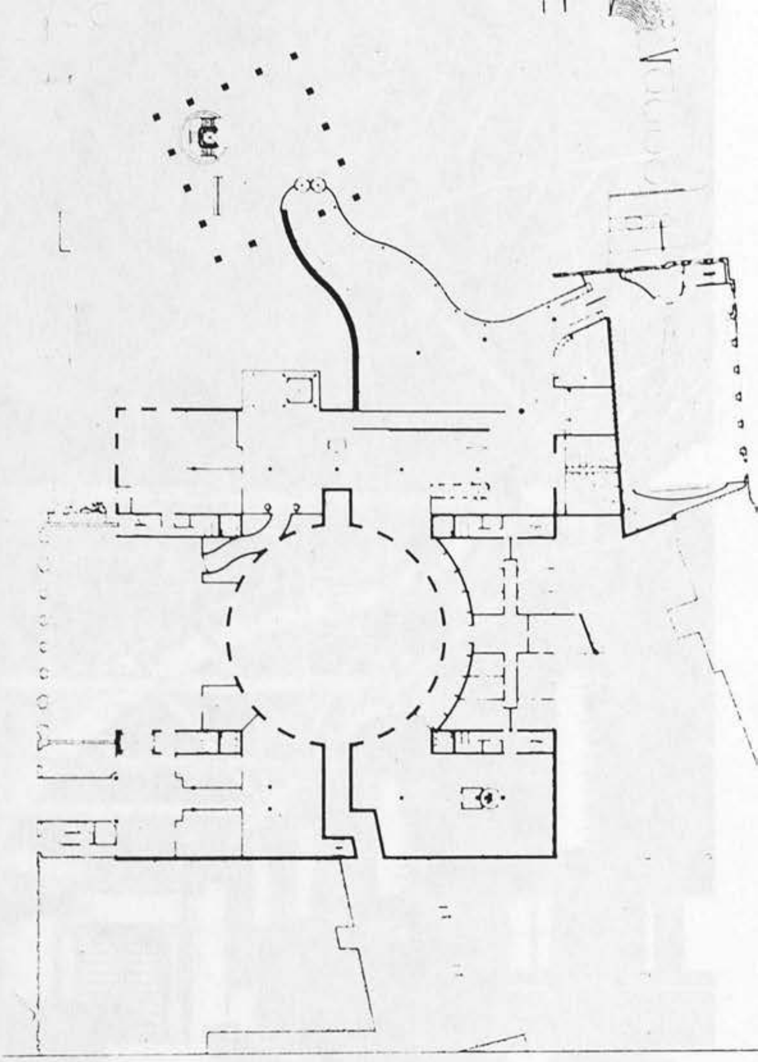
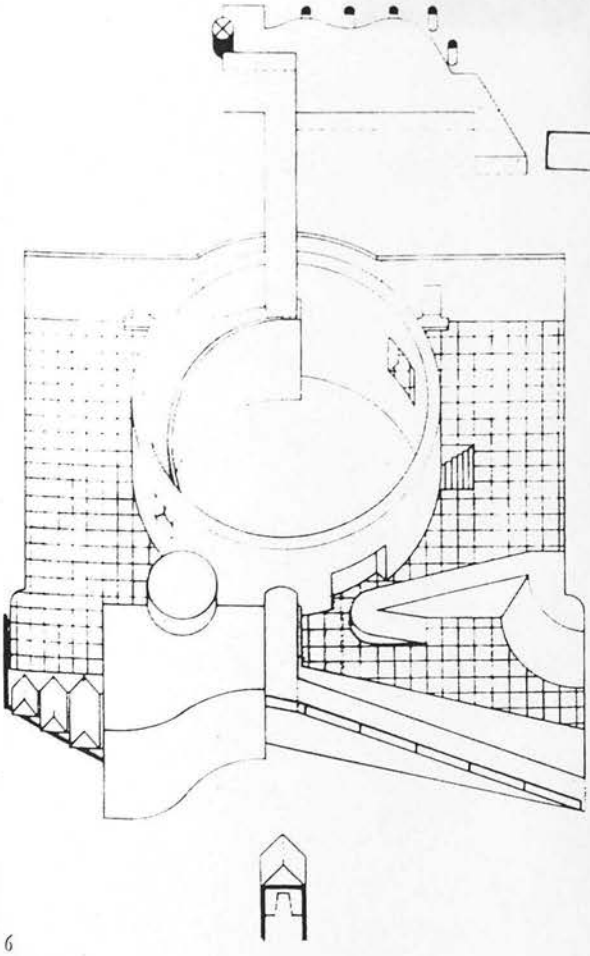


FIG 6 CLEAR CIRCULATION ROUTES



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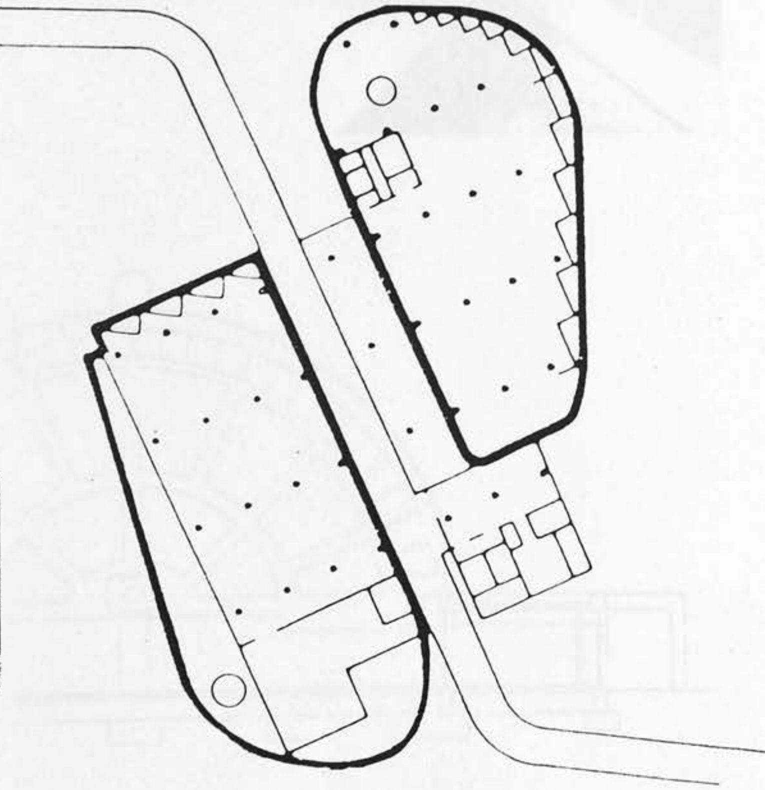


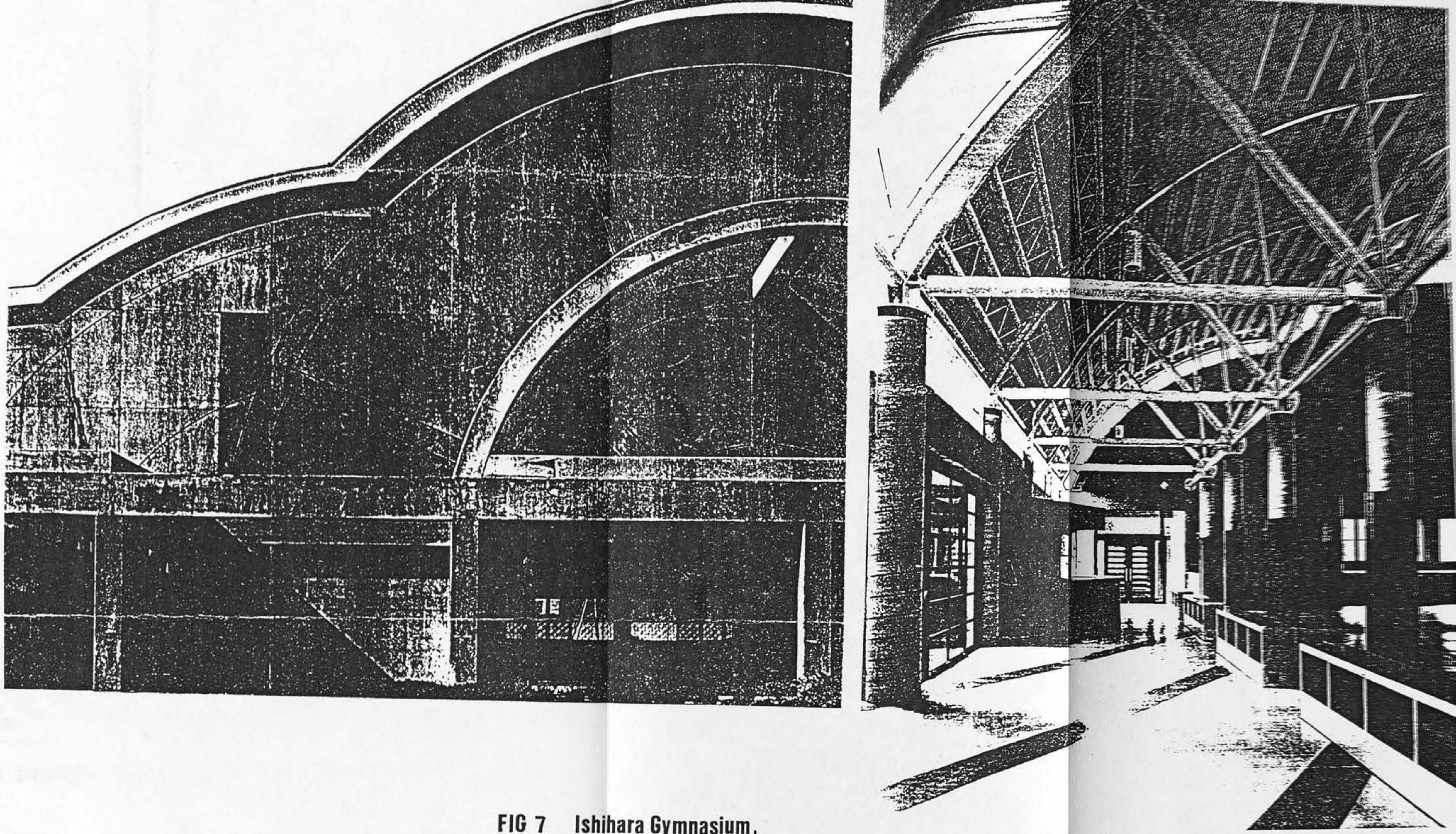
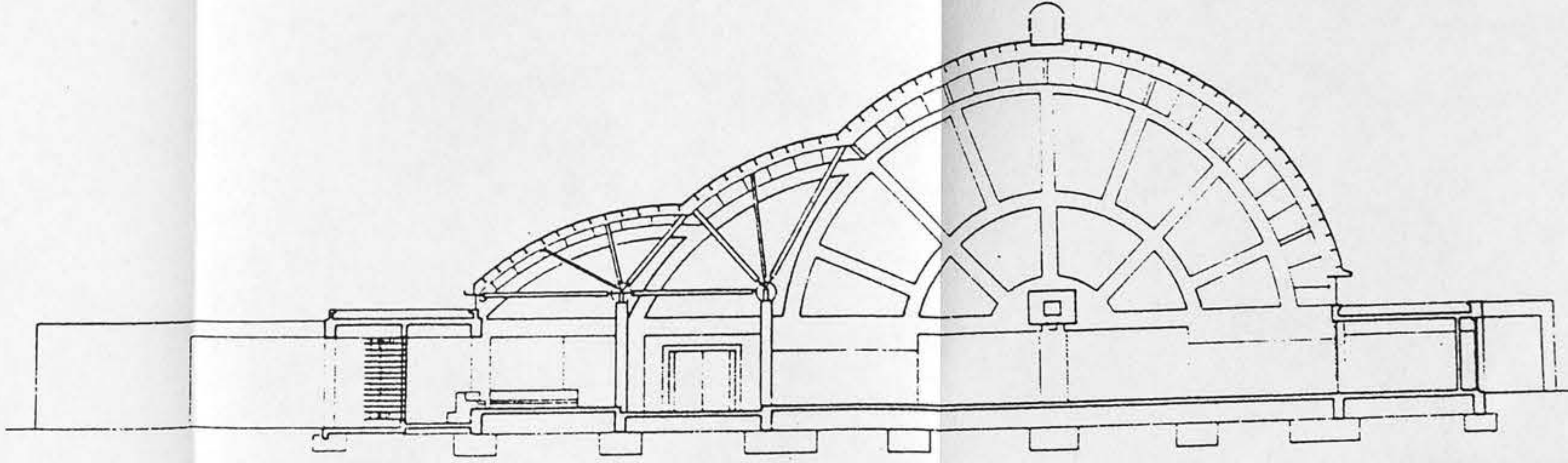


FIG 7 Ishihara Gymnasium, Nagashima



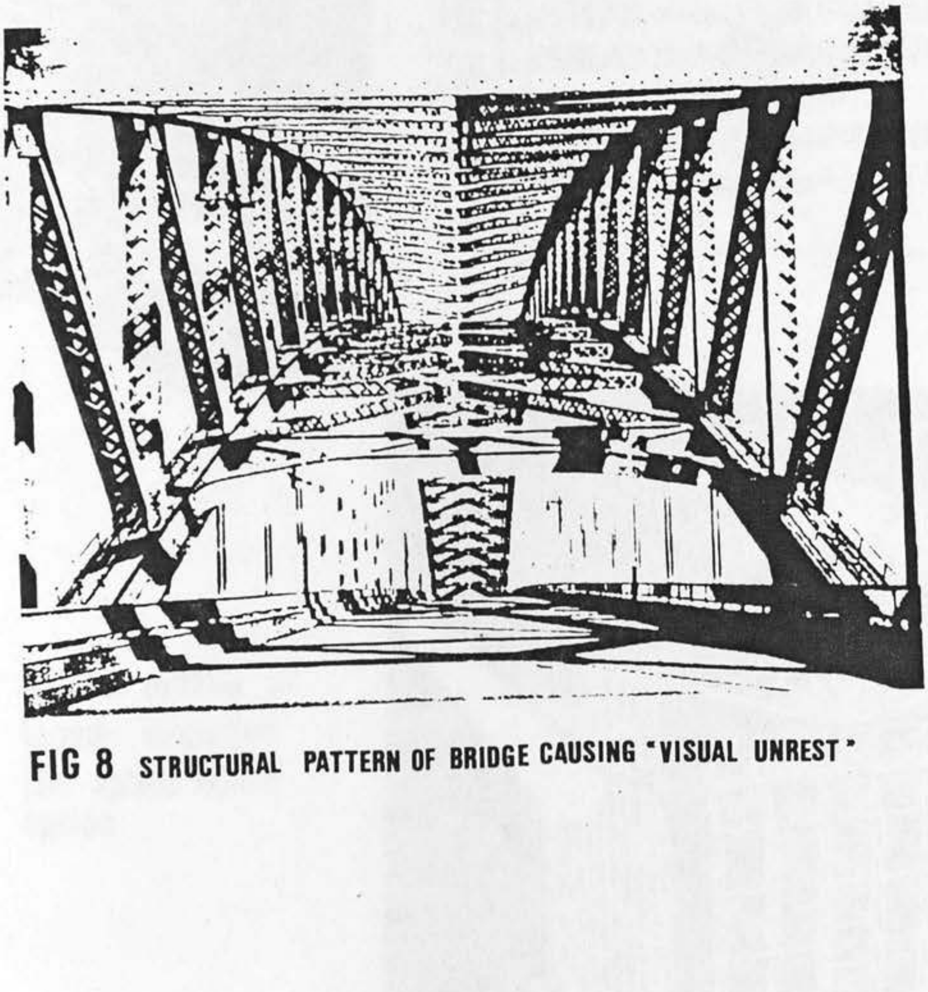


FIG 8 STRUCTURAL PATTERN OF BRIDGE CAUSING "VISUAL UNREST"

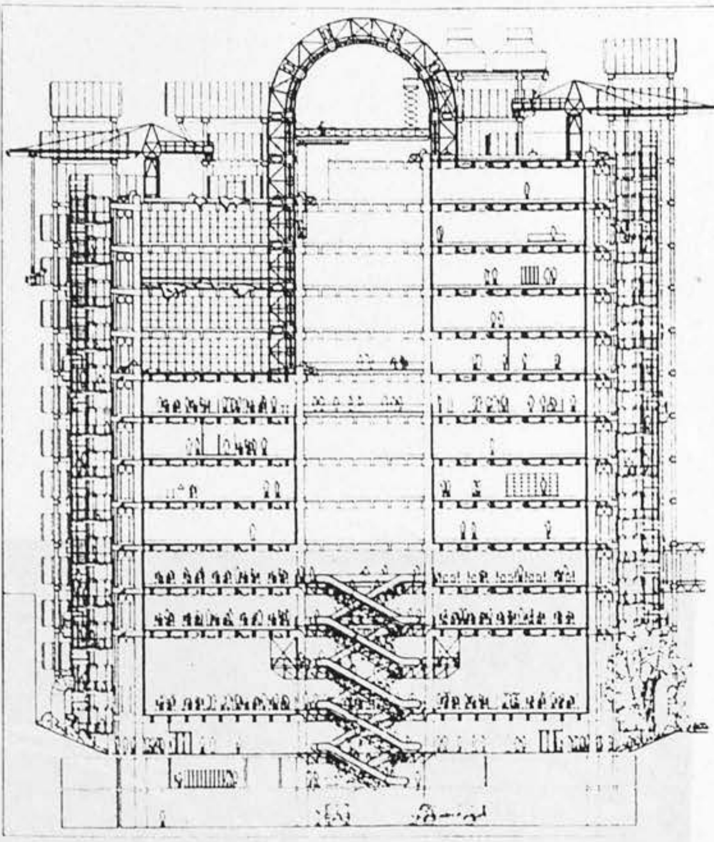


FIG 9 Atrium profile of Lloyds´ excluded the space frame option

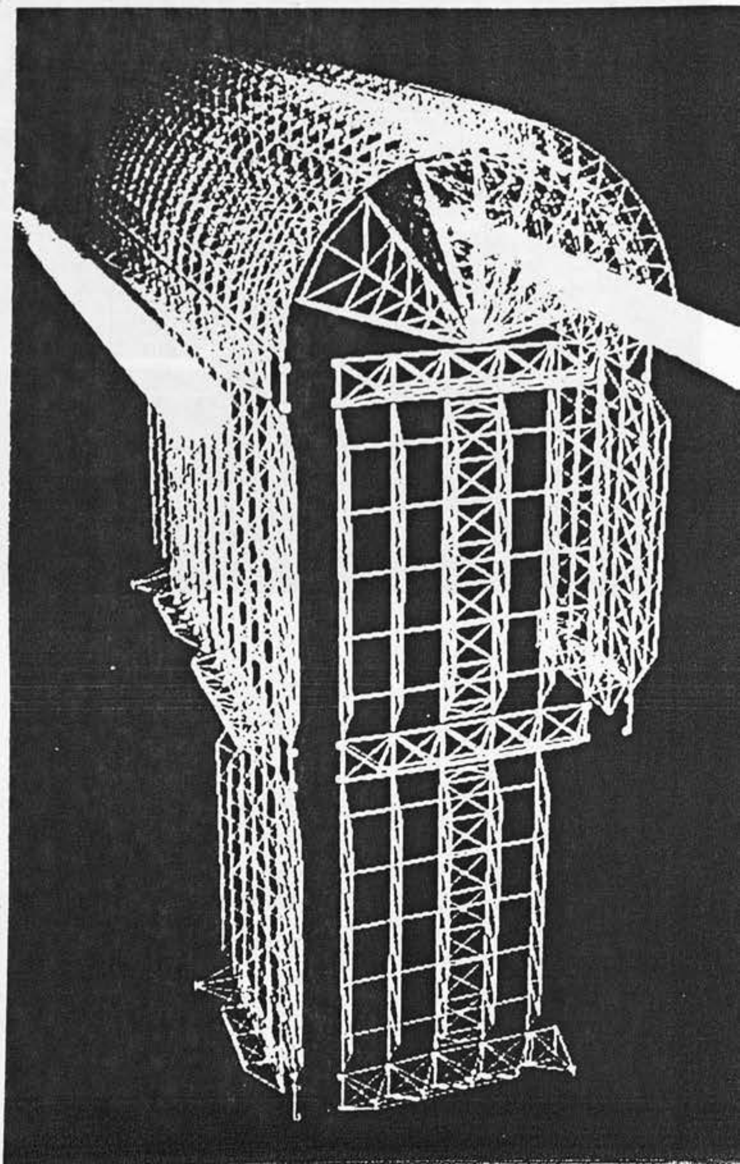
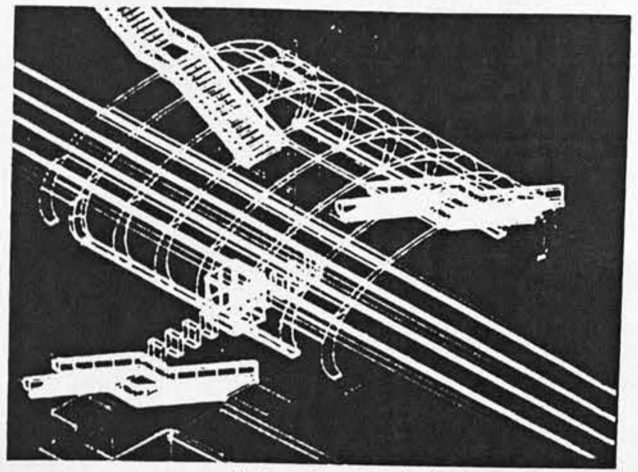
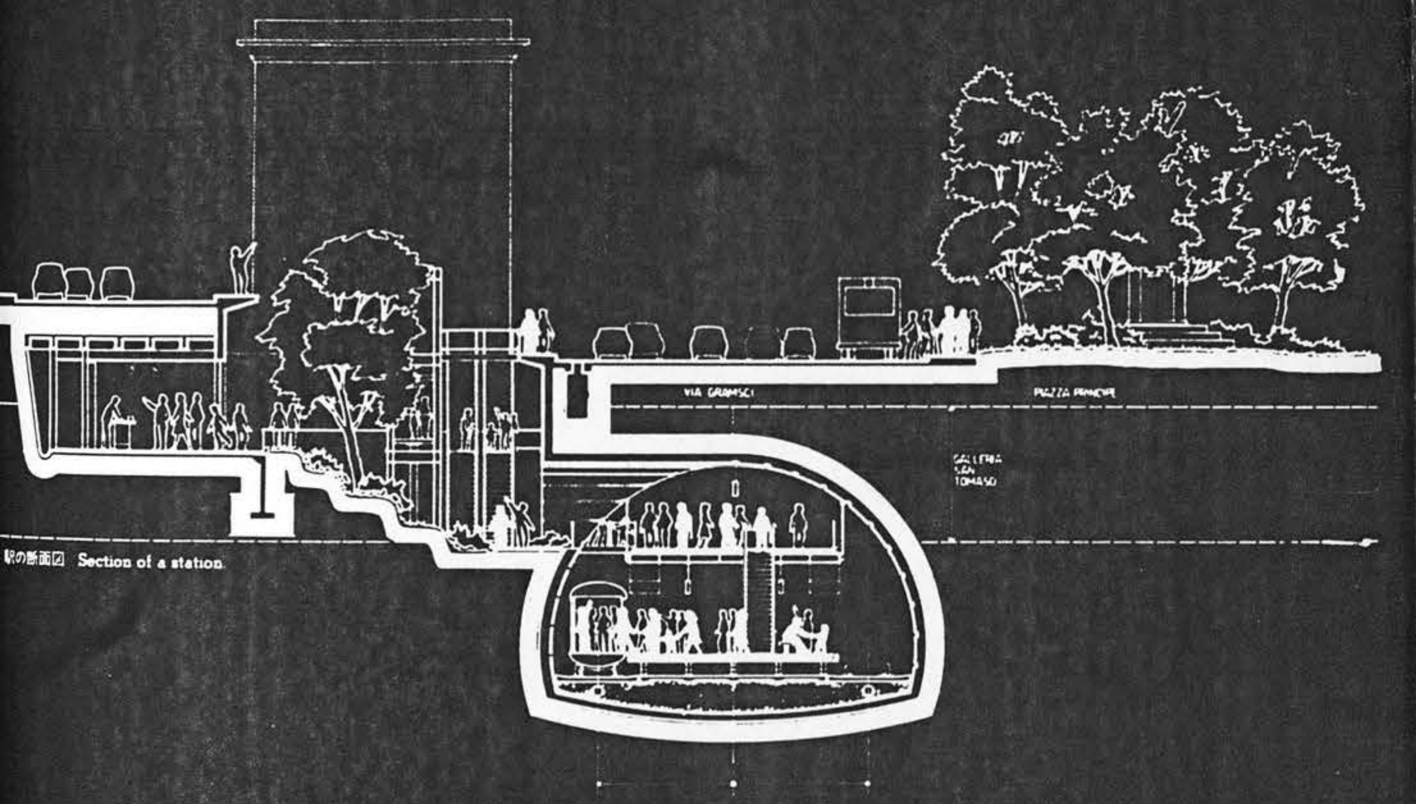


FIG 10 Genoa Tube Station, Piano

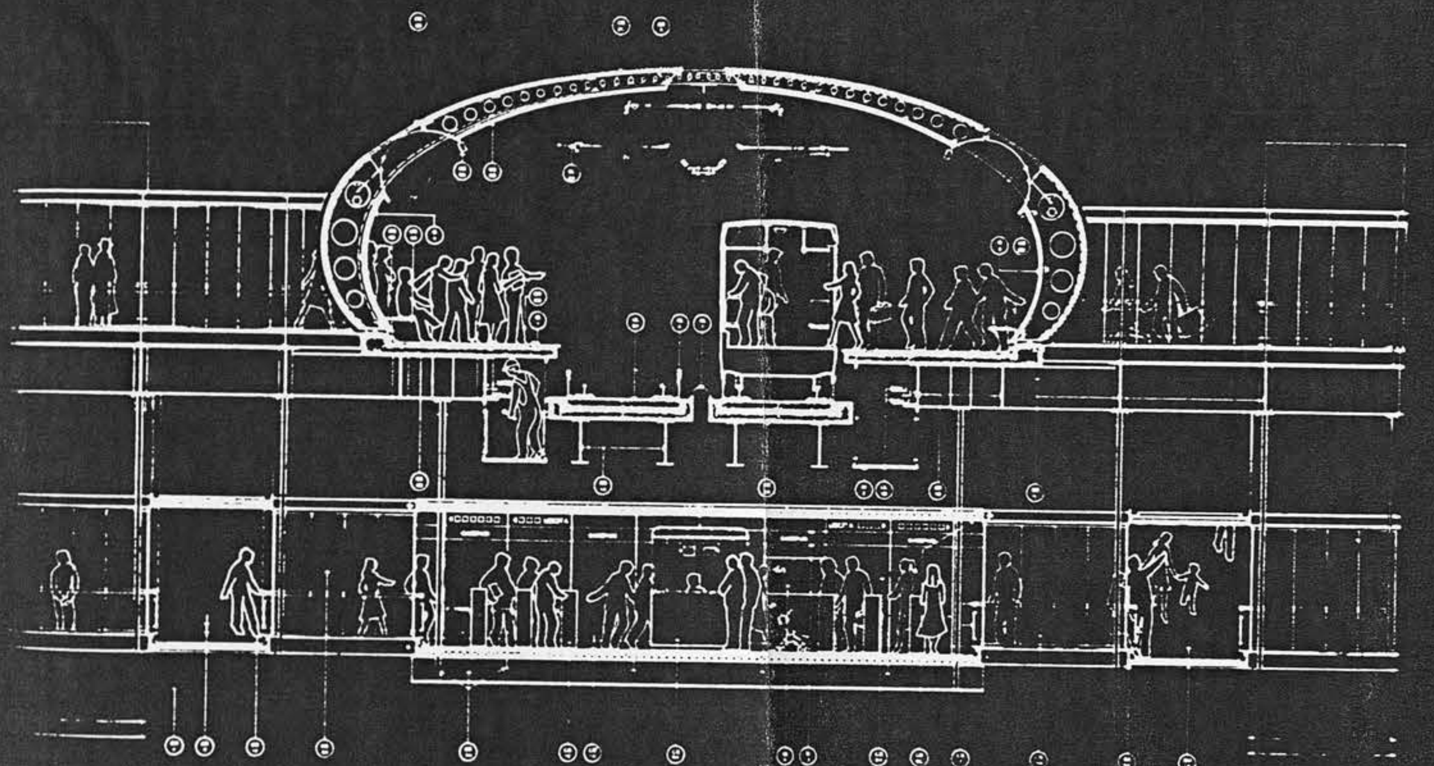


コンピュータ・ドローイング Computer drawing

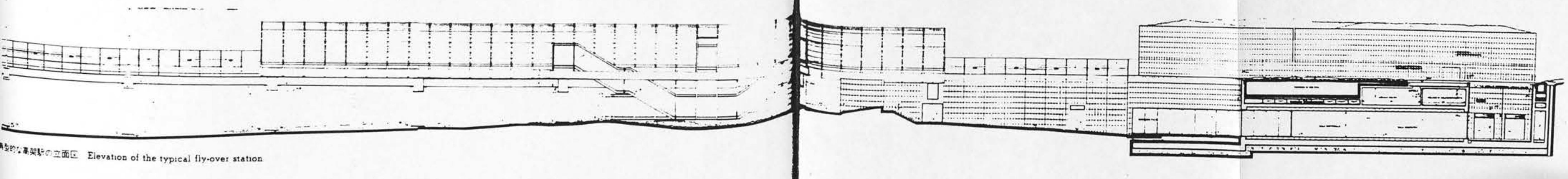
Photos except as noted by Archives Ansaldo Trasporti S.p.A



駅の断面図 Section of a station



典型的な高架駅の断面図 Section of the typical fly-over station.



典型的な高架駅の立面図 Elevation of the typical fly-over station

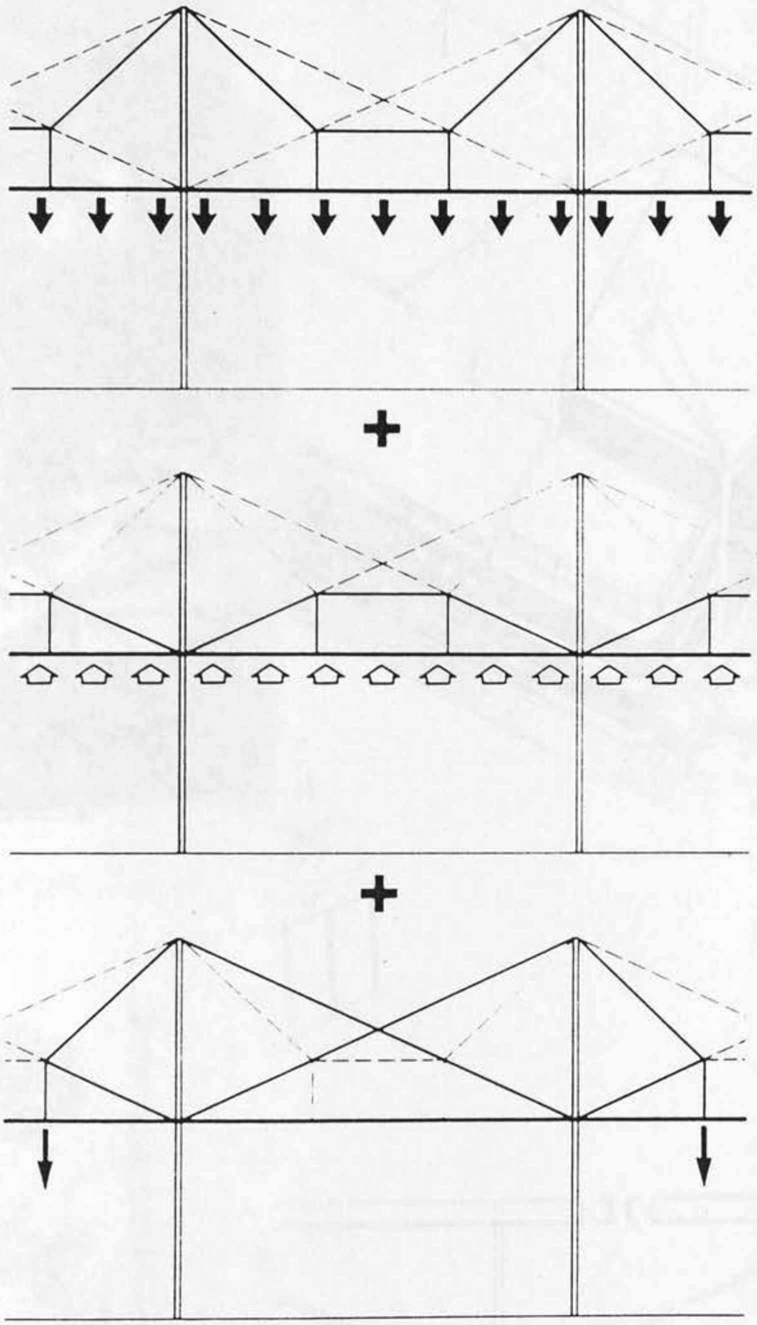
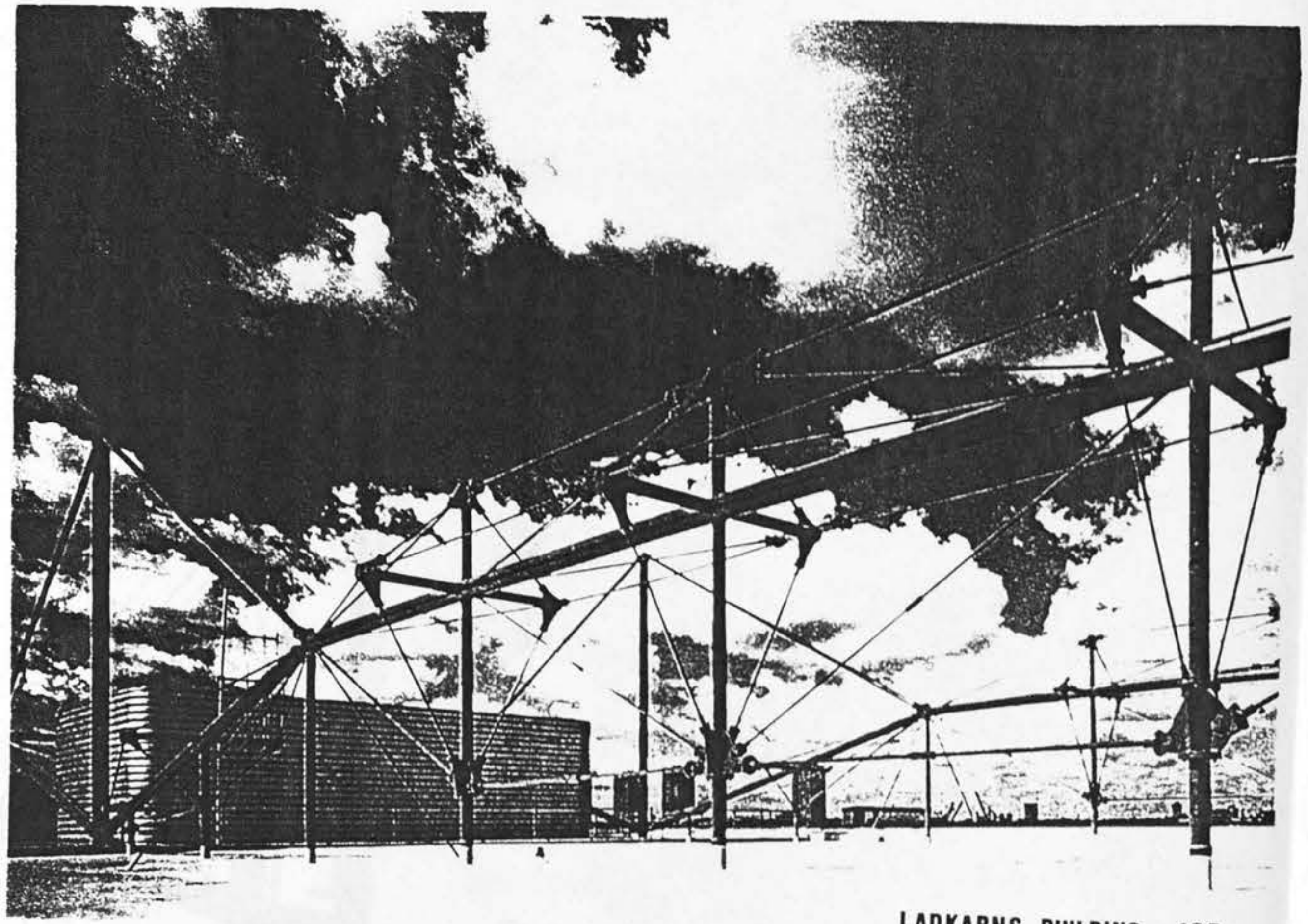


Fig. 11
The three primary load carrying systems within the overall roof structure

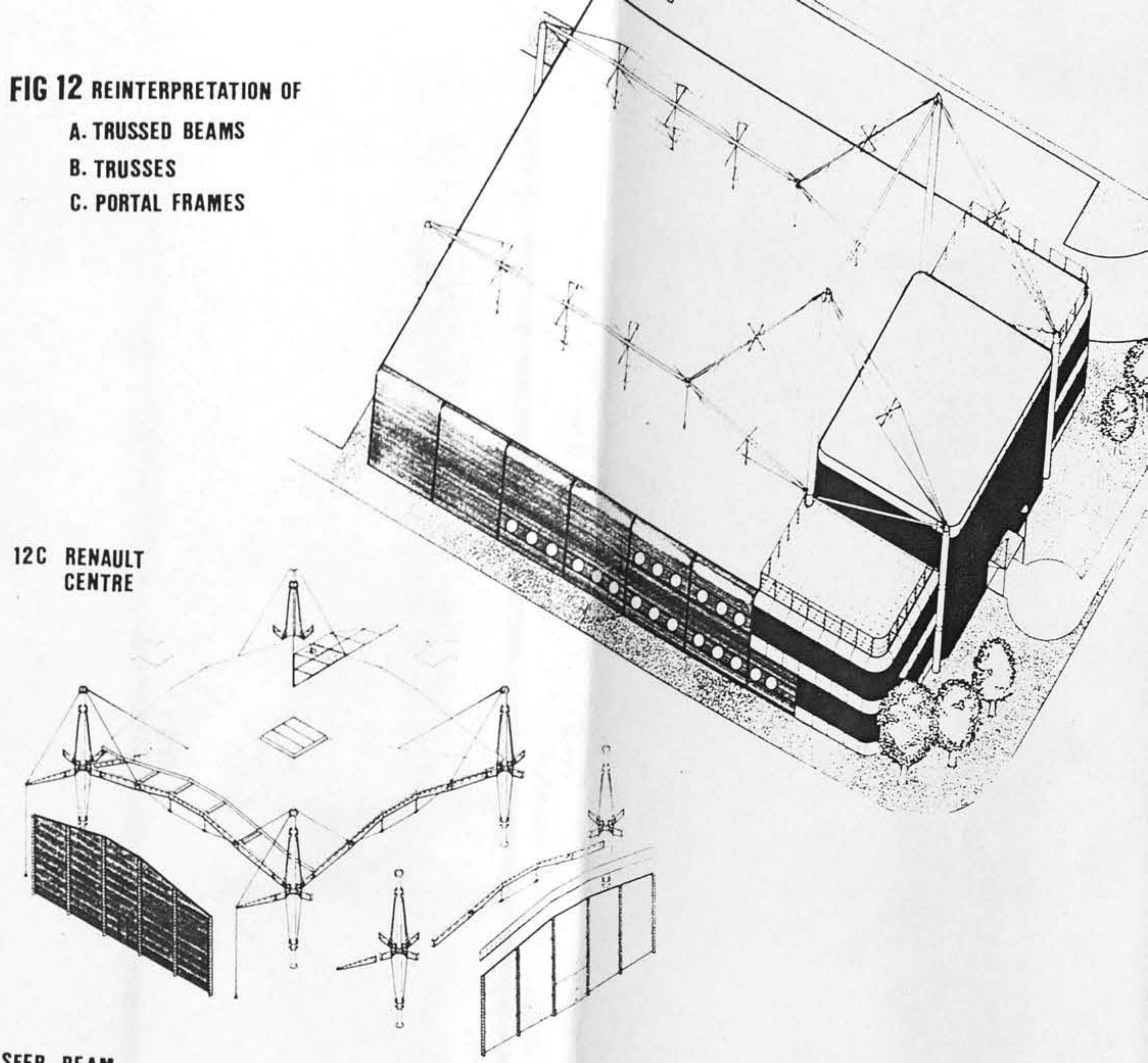
FIG 12 REINTERPRETATION OF

A. TRUSSED BEAMS
B. TRUSSES
C. PORTAL FRAMES

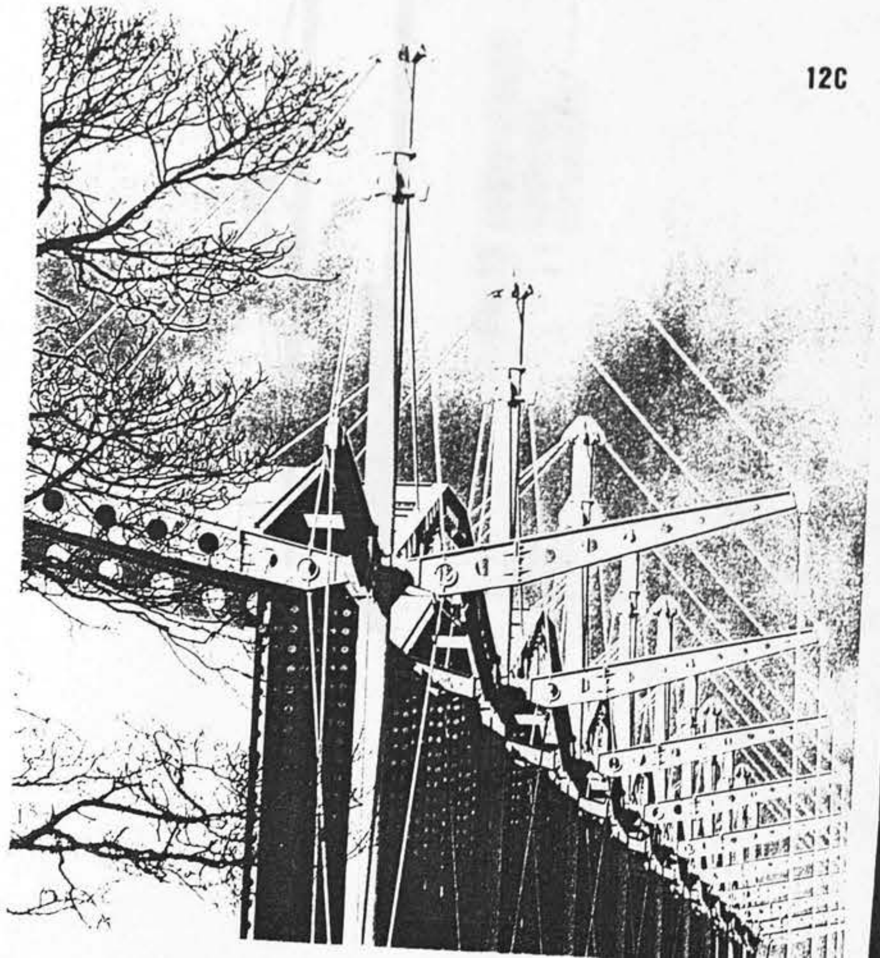


LADKARNS BUILDING 12B

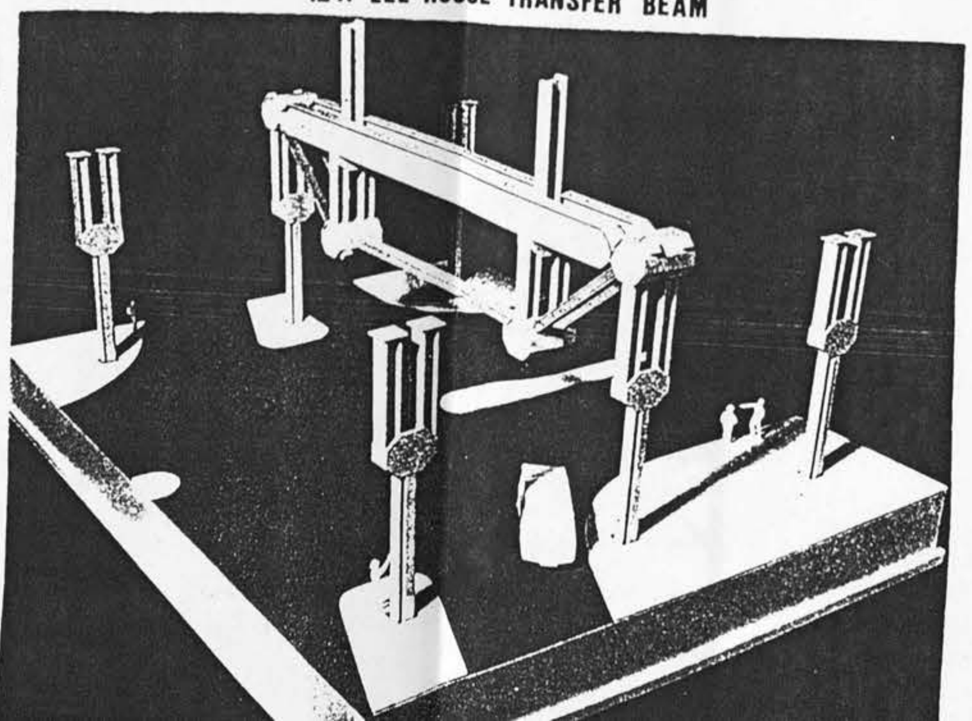
12C RENAULT CENTRE



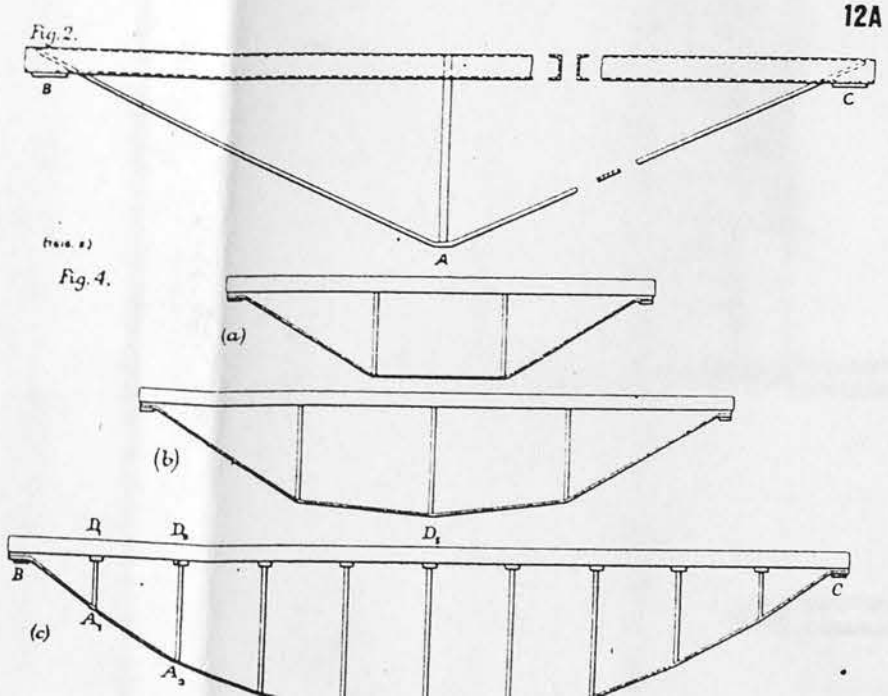
12C

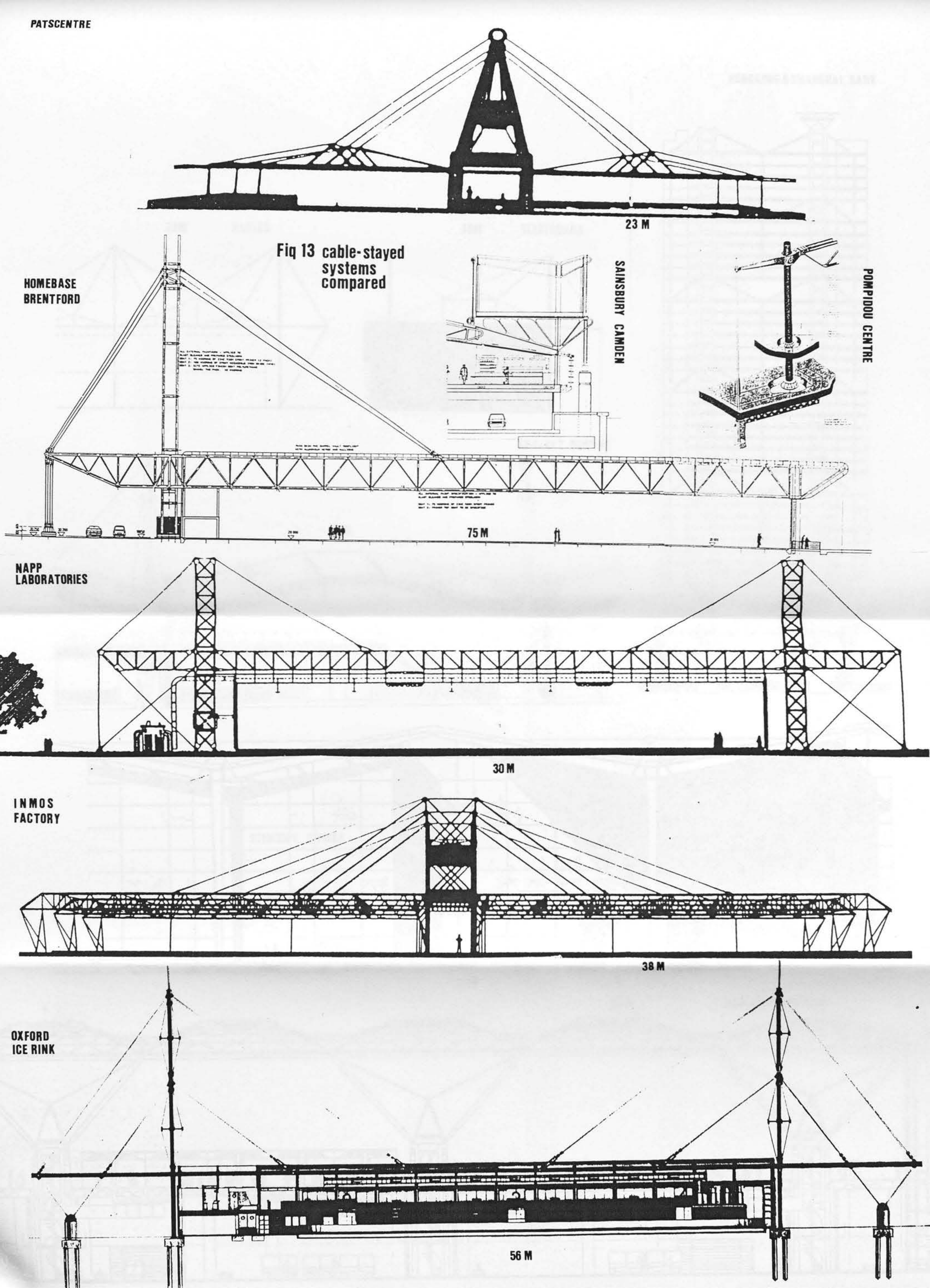


12 A LEE HOUSE TRANSFER BEAM



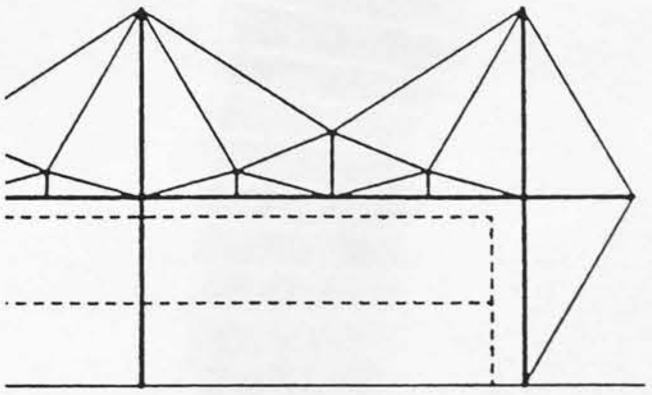
12A



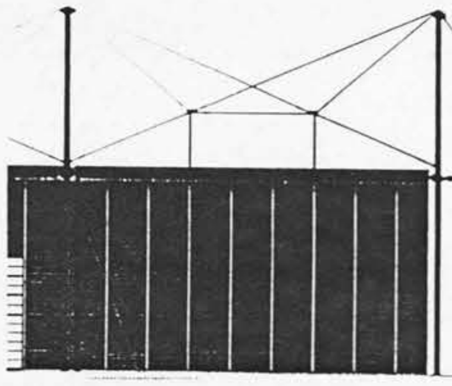


Fiq 13 cable-stayed systems compared

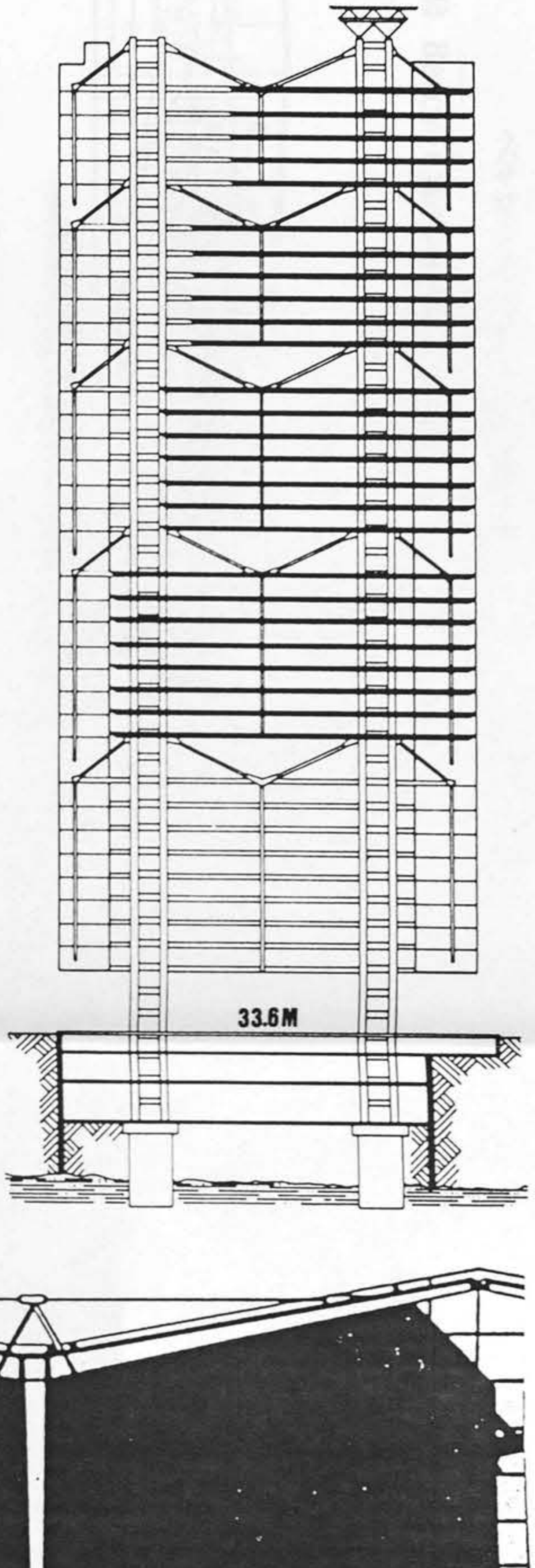
29M NANTES



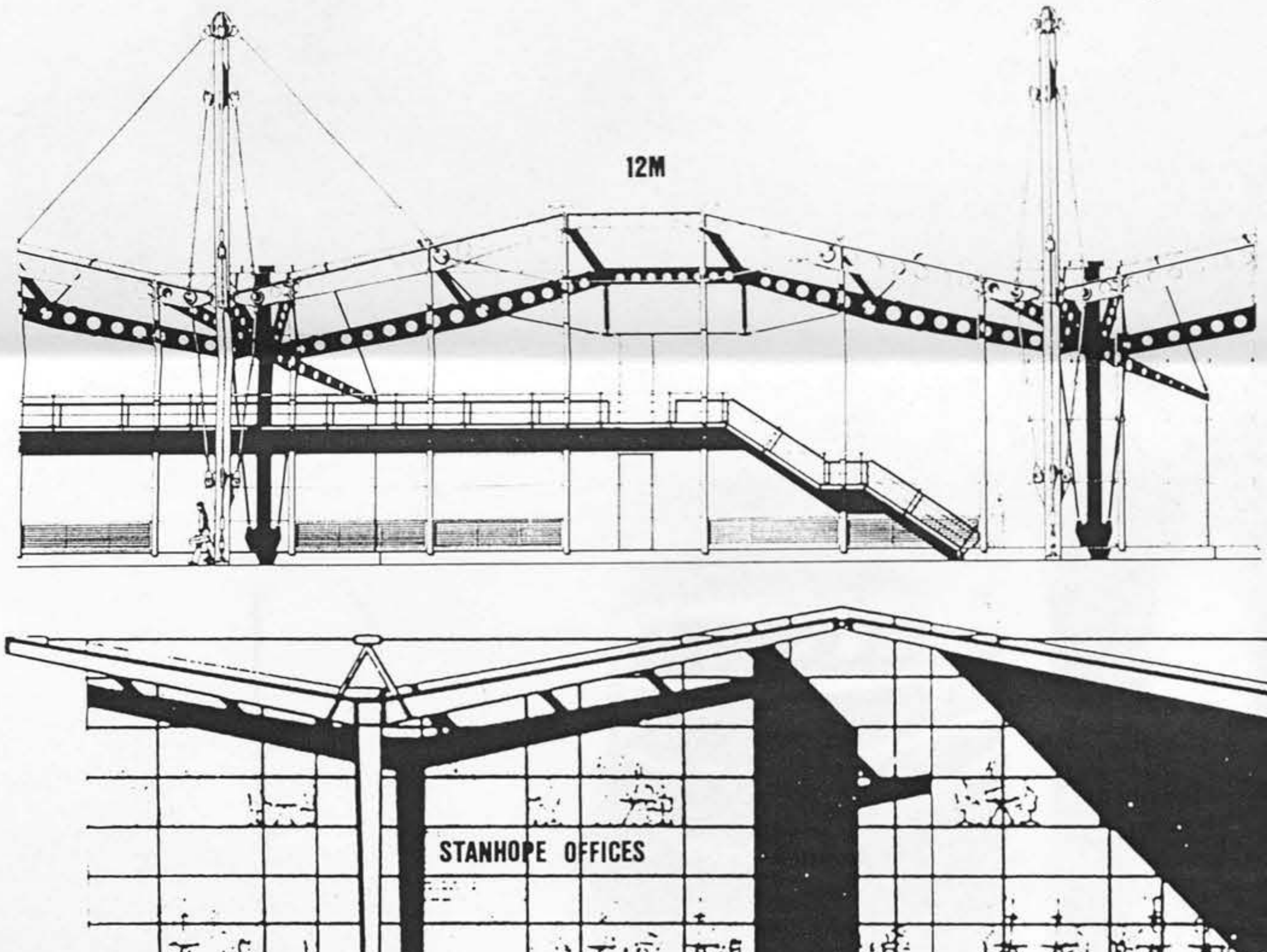
18M FLEETGUARD

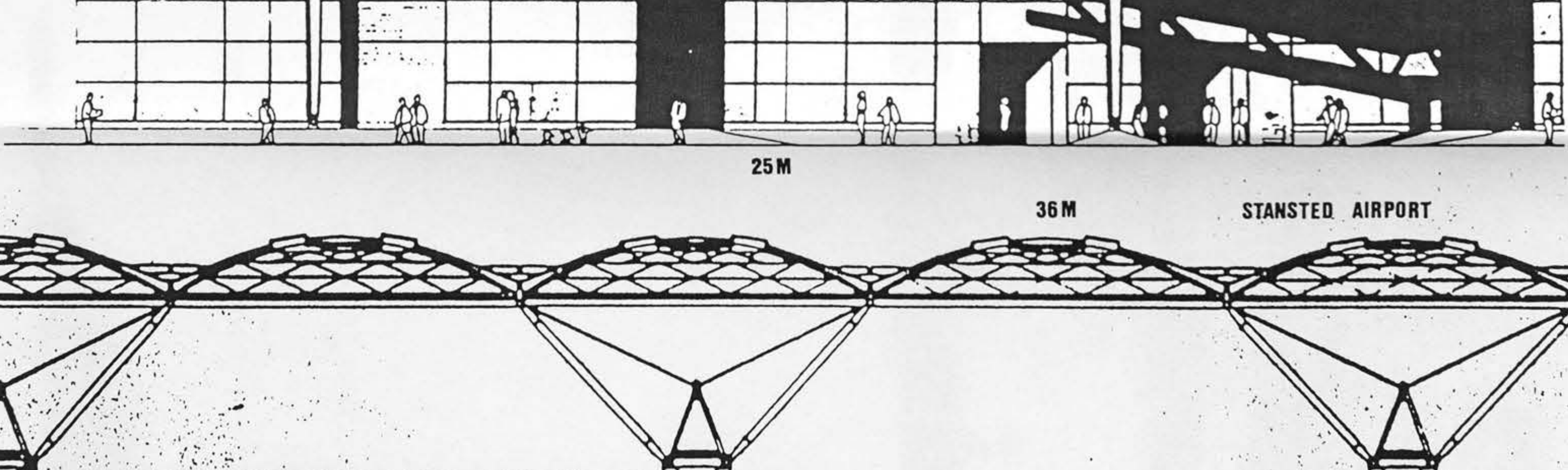


HONGKONG & SHANGHAI BANK



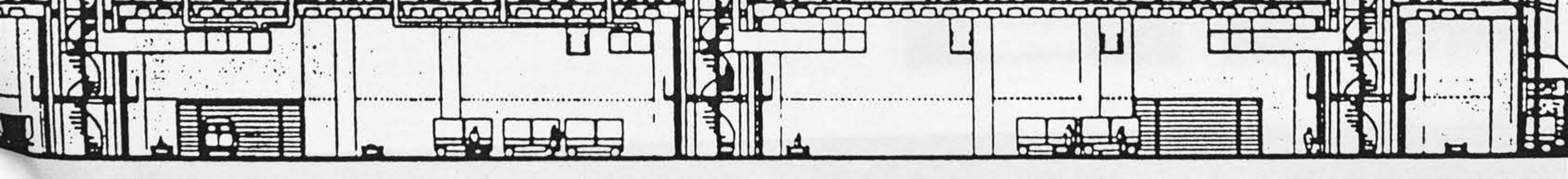
RENAULT CENTRE





25M

36M STANSTED AIRPORT



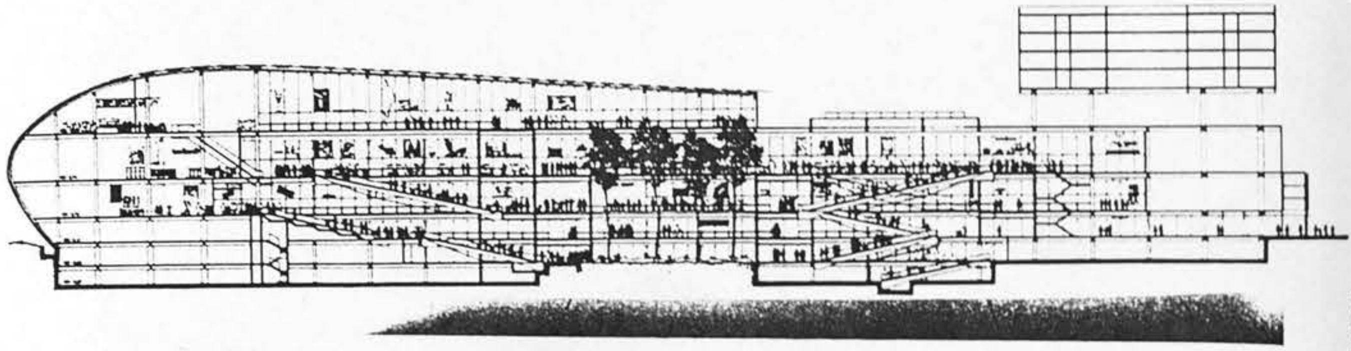
ベルシー・シャラントン商業センター

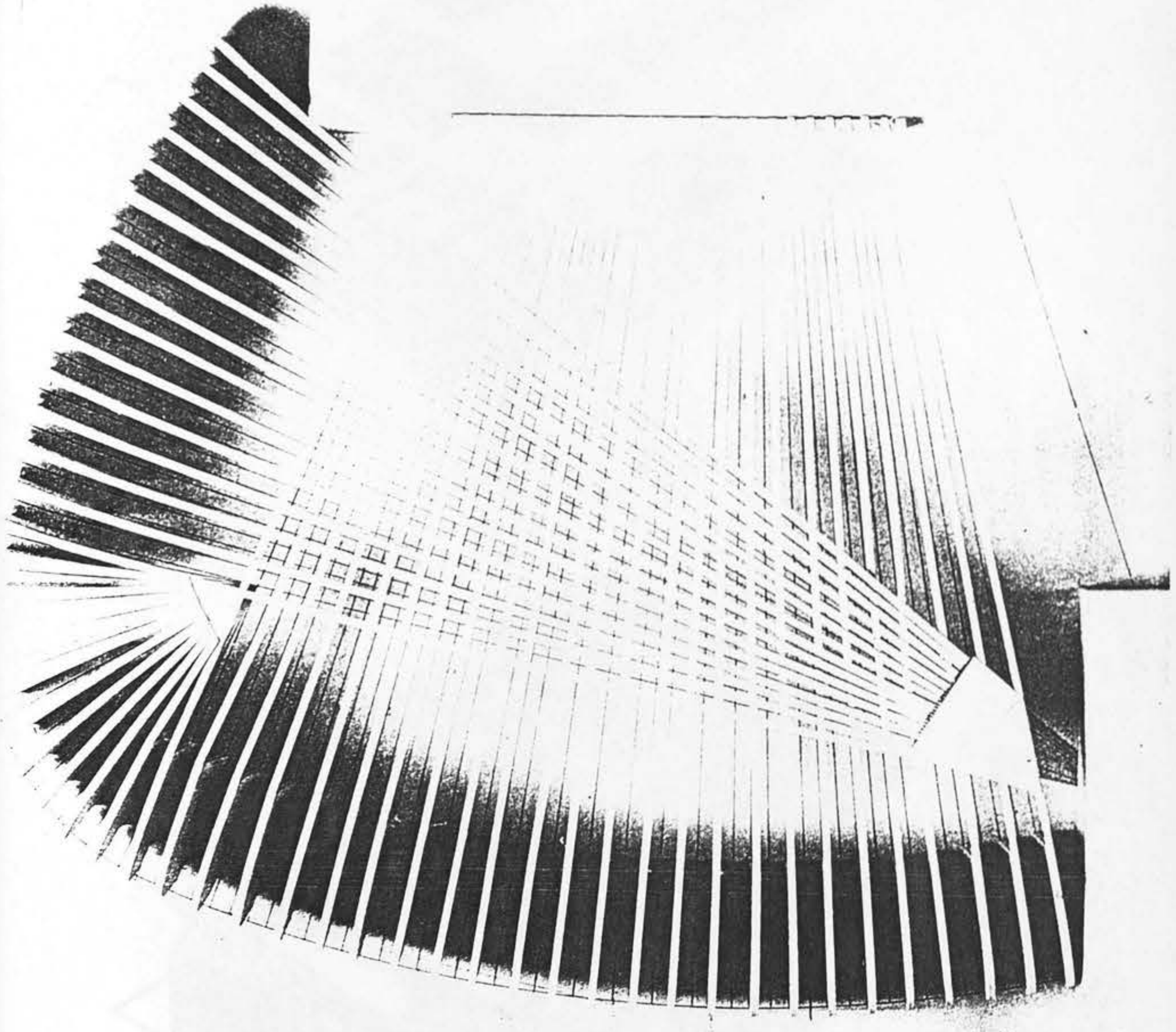
フランス，パリ

FIG 14 Bercy–Charenton Commercial Center

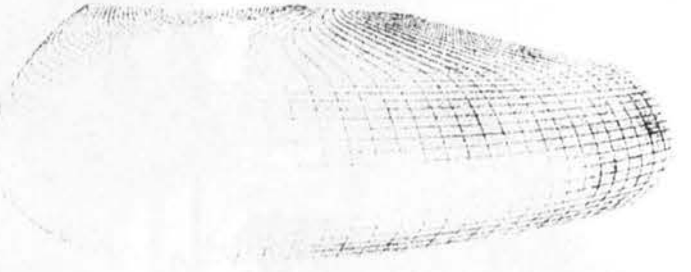
Paris, France

1987

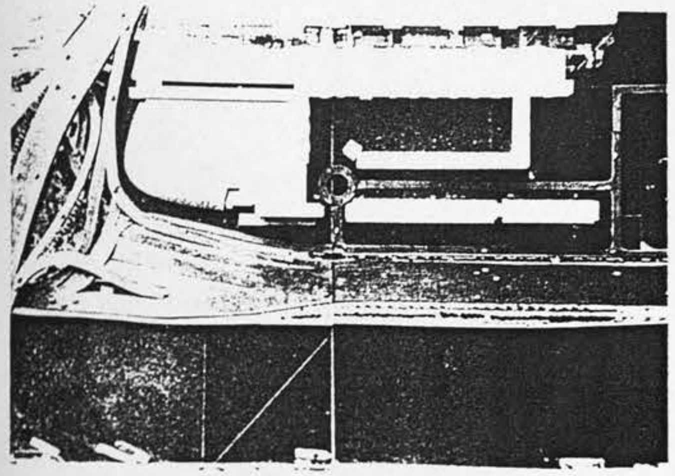




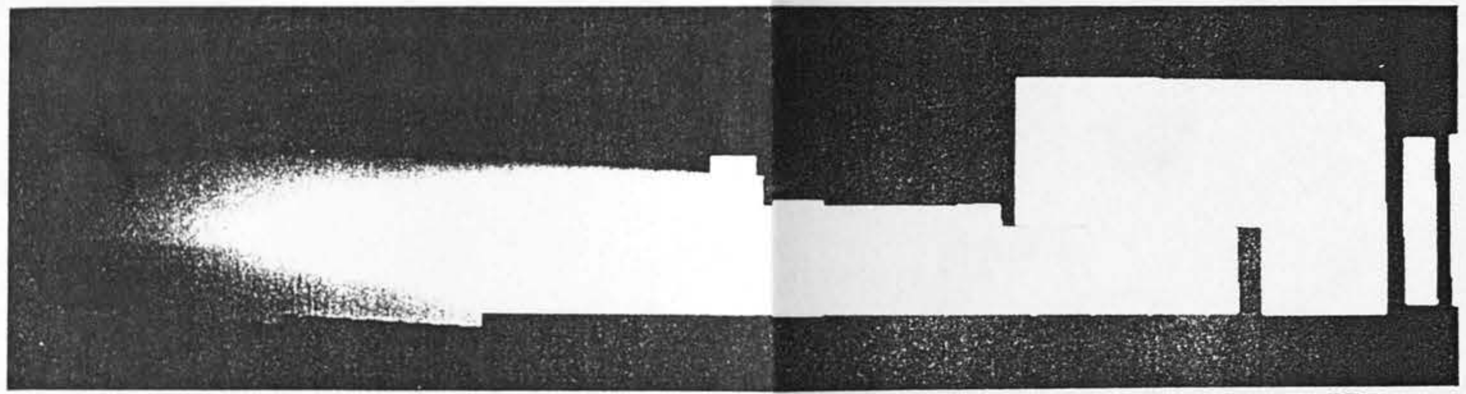
タディ模型／Study model for geometry.



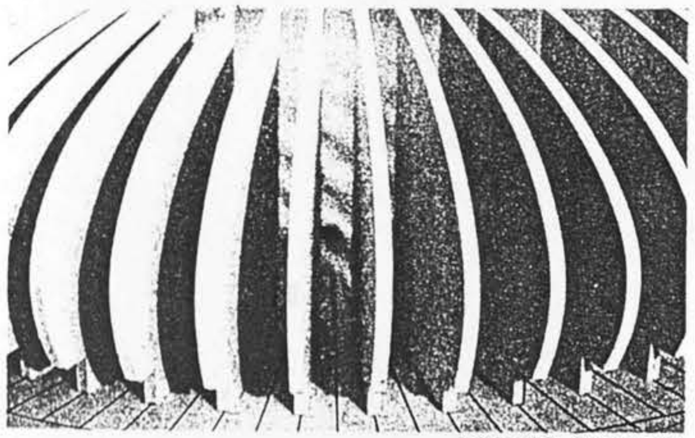
コンピュータ・ドローイング　Computer drawing



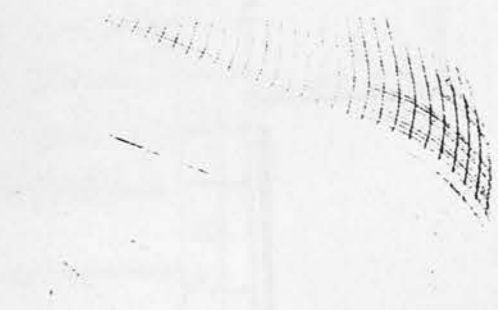
模型見下ろし　Overhead view



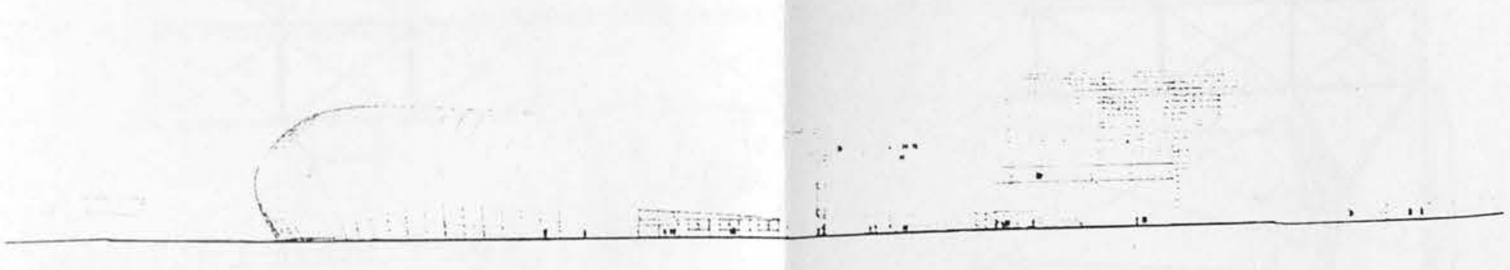
立面図　Elevation



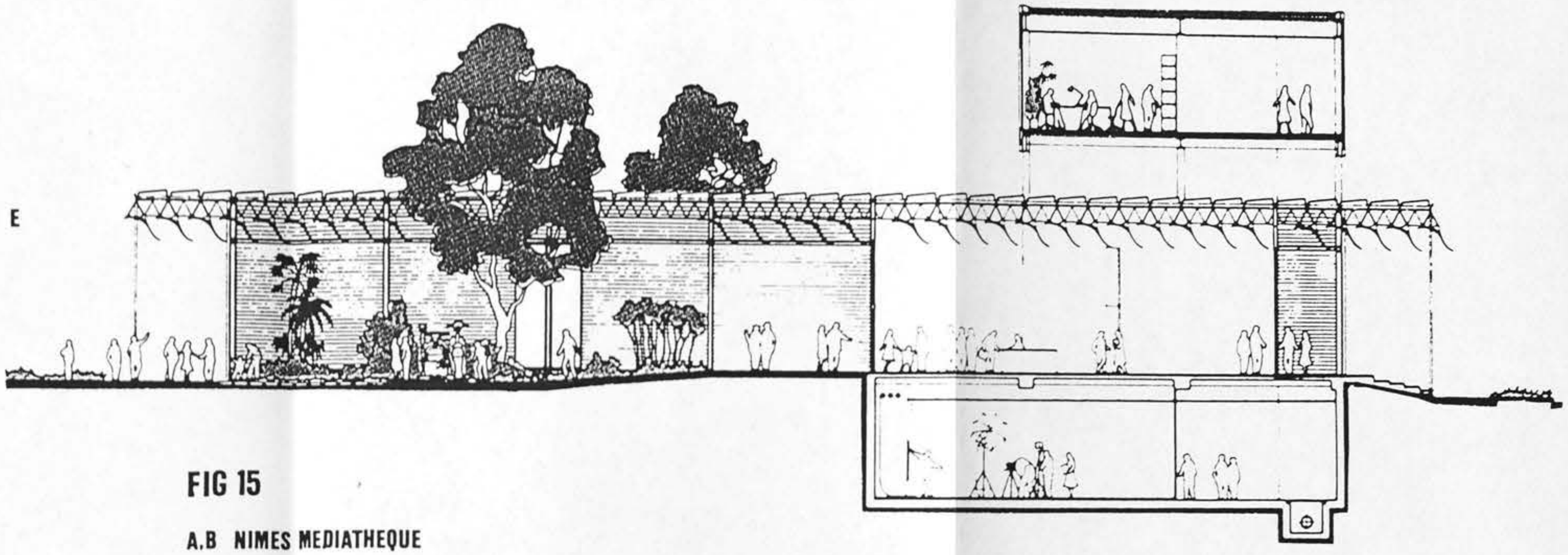
スタディ模型　Study model.



スタディ模型　Study model.



スタディ模型　Study model.



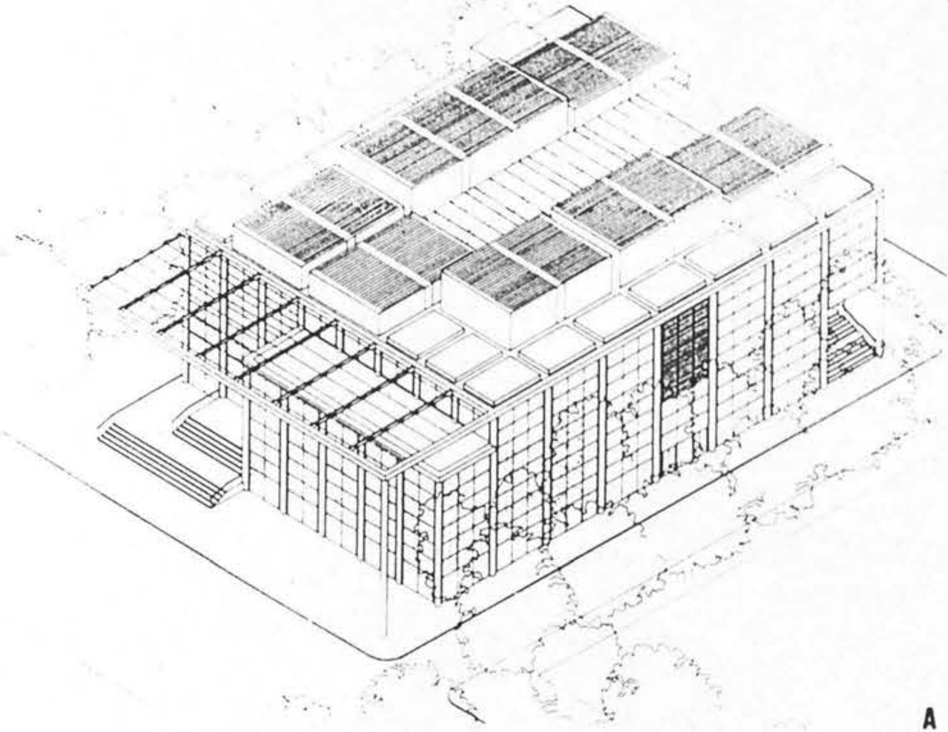
E

FIG 15

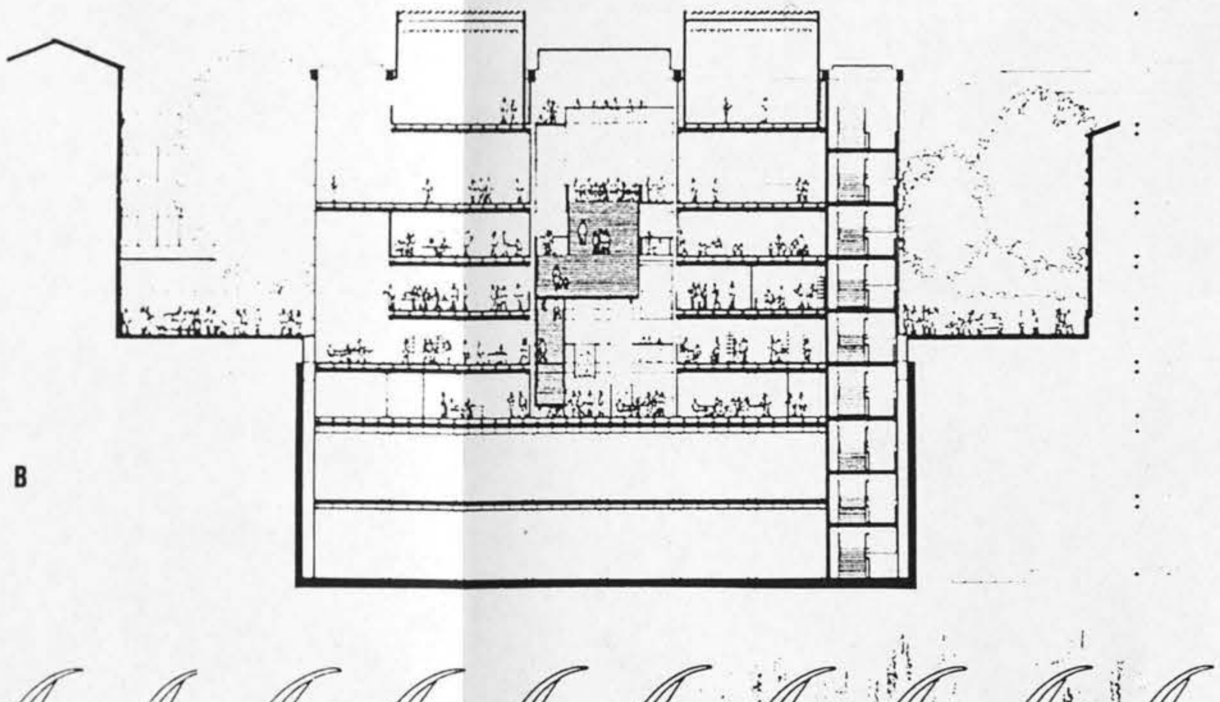
A,B NIMES MEDIATHEQUE

C,D UK SEVILLE EXPO PAVILLION

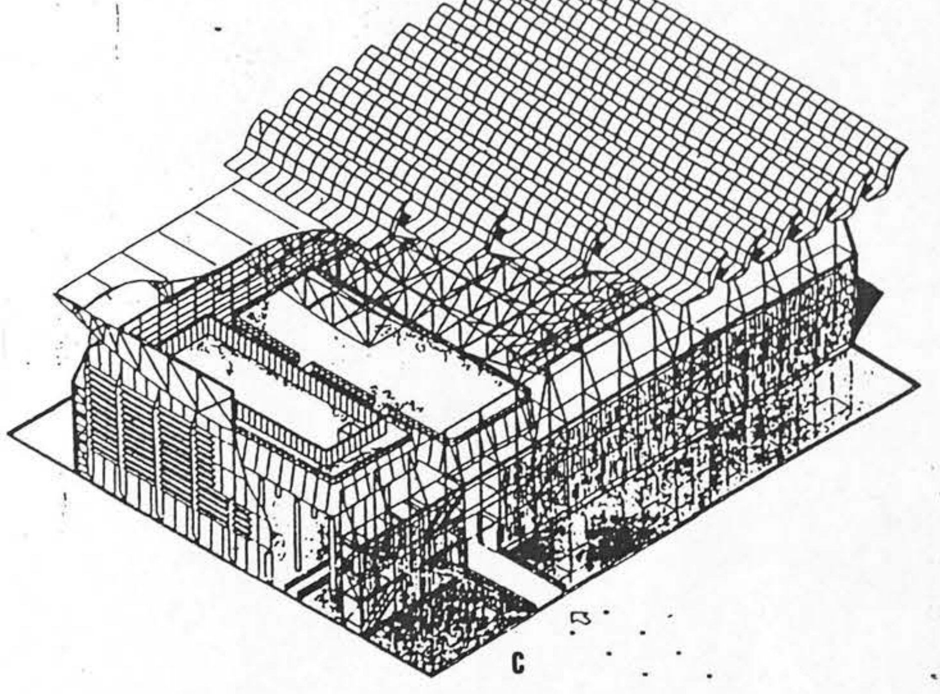
E MENIL COLLECTION



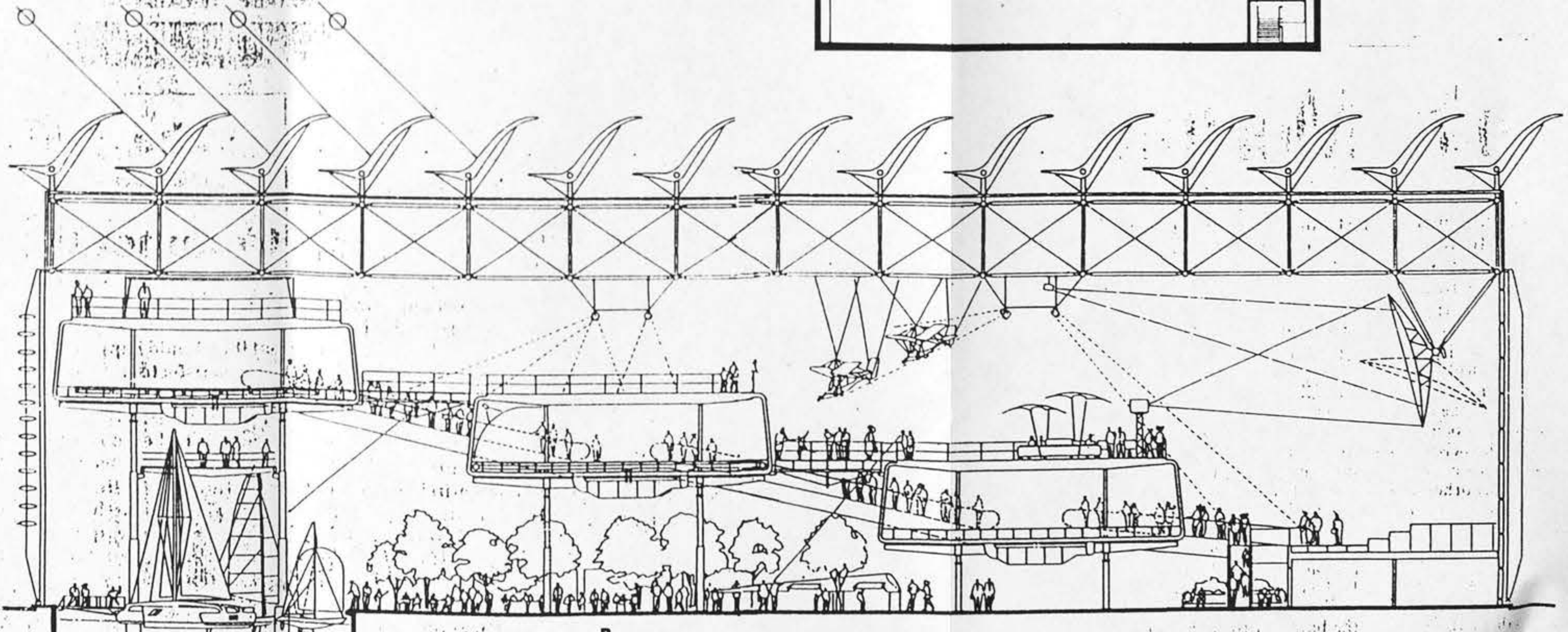
A



B



C



D

SECTION III: CONCLUSIONS

3.1 Introduction

Section III attempts to link the philosophic issues of architectural and engineering design described in Section I, with the observations made from case studies in Section II in order to conclude on the following points:

a) Views and arguments on the use of structure in architecture.

b) The structural engineer's scope of work in conception stages.

c) Unifying structure with architectural form and typologies.

d) Strategic approaches to using structure in architecture.

3.2 Views on the use of structure in architecture

3.2.1 Rykwert's (14) ideas in 'The Necessity of Artifice' represents one extreme view on the role of technology in architecture. It maintains that architectural thought is inspired by human ideals and aspirations which are intangible, unwavering and guiding. These ideas transcend pragmatic considerations of utility, function and technology, and the architectural product embodies a visual translation of the ideals. This viewpoint may be typified by the visionary architecture of Boullee where architectural forms are used as symbols of ideals interpreted by the architect. Such attitudes are reflected in architectural concepts which are conceived remotely from structural consideration;

in the case of Boullee's drawings, there is indeed very little indication of structural support. One assumes that technological issues would be addressed at a later stage of design, with an aim towards preserving the forms and spaces initially conceived without structural consideration. Utzon's Sydney Opera House reflects such an attitude towards the integration of structure to preconceived forms (58).

3.2.2 It has been argued that a brilliant structure does not necessarily lead to successful architecture; Newby (10) describes Nervi's buildings as being mediocre architecture with jewels of structure within them.

It has also been accepted that the ideal structure in engineering terms may exist in works of civil engineering but seldom in architectural buildings (59). The ideal structure is often modified to fit the forms and spaces that have been conceived to respond to a wider context of design problems. As observed in the Section II case studies, these problems comprise issues outside the scope of structure, for example building imagery in relation to function, to the character of the site and to the public image sought by the building owner.

For this reason, the inspiration for architectural thinking in relation to forms and spaces is often sought outside the fields of architecture and technology, for eg, the influence of art, culture and nature, which have been used recurrently as architectural themes in historical and contemporary contexts.

Therefore, Rykwert (14) argues that technology can never be a determinant of architecture:

> "Architecture cannot simply be the night-time release of tired workers and executives, it must be the constant ground of all our action and suffering. That is why ..... the human values cannot ever be abandoned for the joys promised by the dreams of a superabundant technological froth ..... the answer to our present and future concerns cannot come from the automatic, unfettered developments of technology ....."

3.2.3 Against this viewpoint, Rogers' (34) argues that the history of architecture is marked by changes and departures from tradition brought on by responses to social needs and developments in technology.

"Like the (works) of Brunelleschi or Wren, the designs of Sullivan, Le Corbusier and Mies van der Rohe offer a new aesthetic, responsive to the scientific and ethical movement of the times."

"..... the great Gothic churches, the palazzi of Renaissance Italy or St Paul's ..... embodied new building techniques and distinctive architectural forms quite unlike anything ever seen before."

Happold (60) believes that technology 'frees' architecture from ideas based on precedent, which could entrap. Art and technology should not be divided, but be allowed to influence each other in order to gain improvements in the quality of architectural design, towards a progressive architecture. This viewpoint maintains that ideas of technology should be part of ideas which determine the architectural concept: that 'how to build thinking' is part of 'what to building thinking'.

Williams (61) noted that the fundamental difference between engineering and architectural philosophy was the interpretation of the meaning of art; the engineer regarded art as the capacity to do a job effectively and that practicality was a method of achieving the effect without making the effect a method of achieving itself. On the other hand, the architect believed that by conscious effect, beauty could be deliberately achieved.

3.2.4 The case studies reveal that in the contemporary context, both extreme viewpoints are responsible for generating opposite approaches to structural development in architectural design.

In Figure 1A, B, C Stirling's Stuttgart Art Gallery and Northrine-Westphalia Museum, Maki's Tokyo Metropolitan Stadium, the Sho-Hondo Temple and Utzon's Sydney Opera House illustrate examples where the ideas on the building forms were not derived from sources specifically related to those of their structures nor were they initially conceived in relation to their structural support. In these cases, it may be argued that structural technology does not determine the architectural form, but instead, the architectural concept of form and space leads the development of the structure.

By contrast, the preliminary studies on the building form of the Singapore Indoor Stadium prepared by Tange's team, the conceptual sketches on the HK and SB Building, the Renault Centre in Swindon by Foster and Calatrava's drawings for the Lucern Post Office canopy structure and the Zurich Rail Station entrance exemplify building forms which may result in direct consideration of their structural support (Figure 3A, B, C, D). In these cases, it may be argued that structural technology is fundamental to the conception of architectural form and space.

In other cases, for example, Marks and Barfield's Bridge of the Future and Glasgow Eurodrome Schemes, Piano's Kansai Airport and Ravenna Sports Complex, Foster's Stansted Airport and Kansai Airport competition entry (case studies 25, 29, 31, 33, 27), it is unclear which of the two mainstream approaches prevail. In fact, these examples appear to be a result of a combination of both approaches, where architectural imagination has successfully merged with structural ingenuity in the articulation of forms and spaces.

3.3 Scope of design work in relation to 'architectural parts and wholes'

3.3.1 The preceding discussion on attitudes towards the role of technology in architectural thinking leads to discussions on the engineer's scope of design work, and the consideration of support by the architect when conceptualising spaces and forms.

In the first viewpoint, where the architect does not involve questions of structural support when translating abstract derivations from his sources of inspiration into a visual image (of forms and spaces), the structural engineer's scope of work is confined to the design of the parts to the whole predetermined by the architect. This may also be the case for design tasks which do not pose significant structural problems, such as those of small scale residential buildings, or in the case of temporary structures such as the IBM Travelling Exhibition Pavilion.

In the case of the HK and SB Building, the complexity of the banking functions was the starting point of the design thinking before the architectural and structural concepts could be attempted (62); in these examples, the architect leads the engineer in the design of the architectural whole.

3.3.2 The thesis points out that the engineer's scope of design work does not always have to be confined to that of the 'parts'.

Samuely (64) wrote in 1957,

> "Often the engineer may be instrumental in developing the architecture, where the architect is willing to base appearance on structure, it is up to the engineer to develop structures that are capable of expression. There will often be possibilities of which the architect is unaware and it is up to the engineer to inspire the architect ..... the engineer might also, if the architecture is not based on the structure, at least see to it that the structure is based on the architecture".

This is true for cases where the design task is primarily a structural problem and the structural solution has to be conceived together with considerations of space and form. Hough (48) was responsible for studying the structural options to the one-way systems for the Frankfurt Indoor Stadium, (case study 1); these options influenced the architectural form of the building and McCarthy (64) was responsible for generating alternative configurations for the transfer structure in the Lee House scheme with which the podium spaces could take shape, (case study 4). The design of Rogers' Fleetguard factory at Quimper, (case study 16) also reveal the extent of the engineer's role in determining the structural form (and hence, the architectural form of the building). In these cases, there is more scope for interaction between the engineer and architect in arriving at the initial architectural concept.

The complexity of such integrated approaches is apparent when architects incorporate elements of structure in their formal typologies in order to generate solutions to architectural space, and form. The relationship between structure in the architects typology of form is discussed next.

3.4 Structure in architectural typologies of form

3.4.1 The characteristics of individual typologies depend on a number of factors, for example:

a) Influences of art, as with the De Stijl movement on the Schroeder House or of nature in Art Noveau architecture. The interpretation of machine aesthetics by individual architects is also a strong influence on their typological forms.

b) The influence of building scale - for example, Tange's use of structural cores in the expression of his urban buildings were conceived in relation to the scale of city infrastructures in Tokyo (65).

c) The architect's personal design philosophy and the translation of his ideals into a set of "object-types" figure. This is related to the design preoccupation of the architect; for example, in Reid's case, his typology reflects an inclination towards historical precedent similar to Krier's (Figure 2A - 2D) their typologies reveal a preoccupation with the facade and its articulation where forms are used to harmonise with existing ones. These typologies are derived from visual precedent.

The typologies of the Constructivists, like those of Corbusier's 'Purist' forms, were derived from classical precedent (66), but re-interpreted with new combinations and expressions. These conveyed a strong architectonic emphasis of form as sculpture.

Otto's (67) system sketches (Figure 2E), by comparison, show a preoccupation with structural support and though there appears to be a strong expression of the idea that structural forms can be architectural, some of the generated "options" show little relation to ideas of architectural organisation and articulation: for example, there is a lack of the presence of openings or of hierarchies of form. In short, they show why structural forms often need to be modified when applied to forms and spaces in architecture.

3.4.2 The application of typologies continues in the context of contemporary architecture today. Of particular interest are those of Foster, Grimshaw and Rogers, which involve the use of structural elements. These architects exhibit an intuitive sense of support by which they are able to integrate aspects of structure in their expressions of building form and space. Figure (3A, B, C, D).

Two questions are raised in relation to this:

i) Have the structural forms been used out of necessity to fulfill significant architectural functions or have they been used as stylised motifs without any other significant intent?

ii) When the architect uses structural forms as "visual building blocks" to an architectural whole, will the resulting structure be an appropriate one from an engineering viewpoint?

The following conclusions are made with respect to these key questions:

a) There may be a conflict of design priorities, between architect and engineer, for example, the architect's composition with the structural elements (forms) may not be in the engineer's opinion, the most logical way of directing forces to the ground. Newby and Schollar (18) raise this point in their criticism of Foster's HK and SB Building (case study 40). The appropriacy of the two-storey deep suspension trusses is questioned in Newby's counter-proposal of a system that works in compression instead, without detracting from the ideas on the architectural massing and the expression of building form proposed by Foster.

b) The structural form of a particular system may often be dramatised for purely visual reasons. This is usually an aim to provide relief to a regular box-form and apart from the visual aspect, there is little advantage to be gained in terms of architectural planning or in the quality of the enclosed spaces. Both the Ladkarn's Office and the Oxford Ice Rink may be included as such cases (case studies 19, 18).

Against this viewpoint, it may be argued that the expression of the structure on the external periphery of a box-like enclosure does three things.

i) The presence of vertical supports within the useable space may be minimised thereby improving its flexibility in use.

ii) The structure may be freely interpreted to suit an intended architectural theme. The expression of the main trusses in the Ladkarns Building (case study 19) and the cable assisted span of the Oxford Ice Rink (case study 18) recalls the structure of sail masts appropriate to the intended nautical themes.

iii) The building envelope assumes a regular geometry simplifying water-proofing and cladding design although the penetration of the cladding elements by the structure needs special attention. This is an alternative solution to modelling the building envelope itself to express an irregular form for the purposes of architectural expression.

In this case, the visible form is the articulated structure set in front of the box-enclosure. This perhaps, distinguishes the designs from conventional portal-framed metal sheds which lack architectural identity.

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3.4.3 Summarising, there are fundamentally two different rationale in generating form and structure together.

1) The structural form may be conceived as an assembly of elements derived from the architect's formal typology with mainly visual considerations. This may be seen in the works of Grimshaw, Rogers and Foster. Figure 3A - D as in 3.4.2.

2) The structure is conceived with an aim to providing the necessary means of support and the directing of forces in a "logical" path without any particular influence of architectural language (or typology) on its form and shape.

Associated with Approach (1) is the use of structural forms either as functioning elements or as mere "applique". This is a recurrent trend with architectural development and is seen in the use of V-shaped structural supports and forked columns in the reinforced concrete buildings of the 50s and 60s. In the contemporary context, this trend is continued with the proliferation of cable-assisted systems and back-stayed cantilevers in several low-rise steel-framed buildings included as case study; viz case studies 15 to 20, 23, 24 (Figure 13, Section II).

Approach (2) is typified by the works of Calatrava and Piano for eg (case studies 30, 31) where the structure is used to improve the core aspects of architectural quality as described in para 1.0.

Approach (1) is related to the use of precedent in generating forms and structures. Figure 4 is a visual comparison between certain reinforced concrete systems used in the 50s and 60s, and the steel systems in selected case studies. The visual resemblance between both groups of structural forms indicates the reliance on visual precedent (Figure 4).

a) Competition project for Naples Railway Station and Stansted Airport.

b) Station roof, longitudinal shell and Mexican Television HQ.

c) Combined hyperbolic paraboloid shells and Renault Centre.

d) Back-stayed reinforced concrete T-Frame and Sainsbury Camden superstore cantilevered girder, Homebase Brentford spine.

e) Steel-lamella vault framework for reinforced concrete shell structure in Frankfurt (1927) and Frankfurt Indoor Stadium.

f) Cable-stayed reinforced concrete shell structure and Norman Foster's Kansai competition entry.

g) Surface Structure (reinforced concrete) and the IBM Travelling Exhibition.

h) Torroja's Fronton Recoletos and Nagashima's gymnasiums.

3.4.4 The following conclusions may be based on the above comparisons, (a) to (g)

i) That form could be conceived remote from ideas of structural support and material.[1]

ii) That form is often generated from ideas derived from sources outside the nature of building[1] materials and the technology of structure, for example:

"Sullivan discovered that function and structure could not on their own 'generate' an adequate form without the intervention of highly abstracted historical and natural examples." (68).

Curtis (68) wrote "Concrete ..... was one of the most flexible, one of the least determinant of forms (which) relied on the shape of the mould and the shaping intelligence of the designer ..... but the material in and of itself did not generate a vocabulary."

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(1) Provided that these forms may eventually be made to work with appropriate structural solutions.

(Curtis had implied that Hennibique's early reinforced concrete frames (1870) had proportions which resembled those of timber frames because of their timber formwork assembly).

However, Holgate ( ) points out that the roof profile of the Sydney Opera House required a complex structural solution because it could not be made into a structural shell. In this respect, not all curved geometries could be made into RC shell structures and therefore, by their structural nature, shell structures generated their own typologies.

iii) That more than one structural system or configuration may be matched with one architectural form.

iv) That the mode of structural action does not have to imply one structural form for example, the Renault Centre in Swindon achieves portal frame action with hinge-jointed members made rigid by cable-bracing. Thus moment joints are possible without monolithic continuity between the horizontally-spanning and vertically-spanning elements of a portal.

3.4.5 The initiation of the aesthetic aspect of structure and architectural form may therefore involve ideas which have their sources outside the mechanical aspect of the structure itself. The following paragraphs describe some of these ideas and their influences on structure:

Architectural aims generally involve:

a) The accommodation of new functions and needs due to changes and developments in technology, culture, the economy and politics.

b) The expression of these changes and developments in the design of buildings, as interpreted by the architect and this may involve the use of forms as symbols for such abstract interpretation.

c) The expression of building forms and spaces in an artistic manner, in respect of (a) and (b) which fulfill the Vitruvian values of function, commodity and delight.

To illustrate these points, Behrens (69) in the early 1900s felt that industrial tasks were the essential cultural ones of the time and the Deustcher Werkbund between 1913 - 14 cultivated an interest in engineering aesthetics in order to study the means by which abstract aims of the movement could be symbolised. The architecture of the 1920s was also characterised by the influence of Cubist-derived aesthetic doctrines, such as the Dutch De Stijl movement, Russian Constructivism and French Purism which shaped the use and expression of architectural forms and structure.

The historical developments (such as the Industrial Revolution) have inspired varied responses (often contrasting and opposing in view) from groups of thinkers responsible for the development of separate and related architectural movements. Each architectural movement has a broad base of shared motifs, modes of expression and themes from which a great variety of styles emerged. Design doctrines are translated to forms by means of architectural vocabularies which suggest their shape and mode of combination; and in this way influence the use of structure in architecture. These design doctrines may be radical departures or extensions of existing ideology, for example the ideals of the Arts and Crafts movement were in direct opposition to the technological ideals of the Industrial Revolution; craftsmanship in building was revived in contrast to the industrial methods of building which were revolutionised at that time. The Deutscher Werkbund and the Bauhaus School on the other hand, sought inspiration from the industrial world of mechanisation, and from the artistic themes of Cubism and Cubist-derived movements. This led to the development of the International Style and the extension of its aesthetic ideology is seen in the works of Meier, Graves and Eisenmann. However, the architectonic principles of the Russian Constructivists are currently being used by Deconstructivists such as Tschumi (70) for precisely the opposite intentions of questioning conventional notions of hierarchy, order and connectivity in composition. (Instead, the

Deconstruction proponents believe that the city is a fractured space of accidents).

Calatrava's works in essence, may be seen as extensions of the Art Nouveau tradition which is characterised by forms inspired by natural and organic evolution. Buchanan (71) likens Calatrava's works with those of Gaudi and Jujol who expressed structure adventurously with forms unprecedented in their time. Calatrava's engineering background is similar to those of Spanish engineer-architects such as Eduardo Torrojo, Felix Candela and Emilio Pinero.

In studying the architectural approaches to the generation of form in relation to structure, the presence of recurrent themes were noted. These themes are essentially related to those of art, technology and nature, and architectural history may be seen in the light of these recurrent themes as pluralistic responses to changes in needs influenced by technological development, economical growth, cultural and political development. The recurrent themes may be summarised as follows:

i) The need to balance transition with permanence.

   For example, the building case studies are generally required to accommodate a change of use in the planning and layout of the building. This invariably influences the location of structural supports and the development of configurations which could be extended in future to increase floor space, as well as to minimise restrictions to interior layout for the purposes of daily functioning. For this reason, several design strategies conceived in response to these requirements have to determine the extent to which building (and structural elements) may adapt to transitionary change, and this is one significant aspect which characterises the architecture of these buildings.

ii) The balance of modernity and tradition.

The introduction of new solutions to changing needs may often involve technological innovation, or new ideas on architectural expression, in response to new issues. The departure from tradition has always been controversial with architectural and engineering norms (for eg the initial reactions to the Eiffel tower and the Georges Pompidou Centre were unreceptive in respect of their aesthetic expression but the adoption of the engineering aesthetic became a norm contemporary sometimes when neither the construction nor the utilitarian needs required such an expression). In this respect, the introduction of new functions and expressions must take into consideration their relation to existing contexts. The Lee House and Embankment Place Developments (case studies 3, 4) are examples of innovative structural solutions within an architectural form based on precedent. Maki's Tokyo Metropolitan Stadium has a traditional icon expressed with modern technological means (The samurai helmet).

iii) The need to balance influences of engineering and technology with those of artistic and cultural ideology.

If engineering is involved in the production of objects useful and convenient to mankind (42), then the appearance of these objects are as important as their measure of effectiveness. Carmichael (42) points out that "while good appearance is very important, the appearance must be considered in relation to the optimal structural solution, since the value of considering appearance in the abstract is doubtful".

In respect of the case studies (for eg 18, 24, 12, 19) the structural solutions are largely a result of visual emphasis and not necessarily the most optimal in engineering terms. The effectiveness of such solutions is questionable, with regard to design excellence. Conversely, design approaches which are essentially on a structural bias, do not always guarantee architectural success. Newby (10) regards Nervi's works as mediocre, even though they were ingenious structures. Carmichael (42) adds: "Beauty is not something that comes after the engineer's solution". Instead, aesthetics and engineering must be conceived in relation to one another and architecture should perhaps aim at applying engineering technology to the creation of useful as well as visually delightful solutions. Engineering considerations of effectiveness must therefore be balanced by artistic influence.

3.4.6 For each of these main themes, corresponding architectural interpretations influence structural responses. The relationships between theme and interpretation will be discussed in 3.4.10 whilst the significance of their structural responses in relation to the hypothesised ideas will be summarised in 3.5.

The themes are interpreted by means of architectural analogy. Some of the more significant applications of structural principles through analogy will be discussed in the following paragraphs.

a) The adaptation of structural principles inherent in forms of nature.

b) The adaptation of bridge building principles.

c) The interpretation of "machine" aesthetics.

3.4.7 The adaptation of structural principles inherent in forms of nature

The use of mechanical analogies with vertebrate skeletons is observed in some of the Section II case studies.

i) The Quadruped Limb

Calatrava (72) describes his experiences with the use of skeletal forms as formal analogies,

> "Working with isostatic structures inevitably leads to skeletons (of natural forms). When a dog stands on his four legs, it constitutes an isostatic body ..... and the load is divided by the number of legs ...."

There is a visual resemblance of the structure of the quadruped limb shown in Figure 5 and Calatrava's Barcelona Communications Tower (1989). The line of the centre of gravity passes through the base of the tower structure, ensuring stability in a way similar to the quadruped limb. Figure 6A. The raised heel of the quadruped (naturally designed for effective mobility) is a profile used in articulating the base of the Tower to mark its entrance to the top. The 'ankle' portions of the limb are noticeably broader where bending moments have to be resisted. A comparison between biomechanical analyses of the limb structure with the form is made in Figure 7.

The pergola at Stadelhofen Station, Zurich and the entrance canopy for the Lucerne Station use skeletal cantilevers held aloft by supports, the forms of which are abstracted from those of skeletal limbs (Figure 6B).

ii) The Skeletal Ribcage

The entrance hall to the Wohlen High School in Switzerland (1988) is a form likened to the skeletal ribcage - it comprises laminated wood arched girders with cables and steel spindles, that together form the components of the ribcage and its supporting elements (Figure 8). The entrance canopy of the same project is a similar structure with its form generated by two conical surfaces, whose intersections form an arch. The inclined steel spine is a triangular girder from which the ribs supporting the glass panels are cantilevered. Maki's Tokyo Metropolitan Sports Centre (Figure 9A) may be likened to a structure comprising of a pair of large-span versions of the canopy arch designed by Calatrava. Piano's Kansai scheme is different in that its primary span is an arched beam. These forms represent innovative applications of the arch principle in combination with the cantilever.

iii) The Vertebrate Spine

Marks and Barfield's (case study 29) and Neil Thomas' (Figure 9B) Eurodrome Glasgow competition entries incorporate a structural concept analogous to the vertebrate spine and "the form of the building is inspired by the elegance, hierarchy and inherent strength found in natural structures". The arch spine is made visually slender by expressing the compression and tension elements with a system of tubes, struts and ties to provide a strong and flexible structure where the requirements of stiffness and rigidity are not critical factors in an exhibition shed needed for one year of festivities (Figure 9C).

Similarly, in Marks and Barfield's 'Bridge of the Future' competition entry, D' Arcy Thompson's (73) quadrupedal bridge is interpreted as one with main compressive skeletal spine elements stiffened by tendon-like cables in tension (Figure 9B).

The skeletal struts keep the cables (tendons) apart in the transverse plane and the tension members may be individually stressed between struts in a longitudinal direction in order to improve spine stiffness.

McCarthy's (case study 29) entry to the Glasgow Eurodrome features a less stiff, thus cheaper structure which is conceptually based on structural principles of flexibility. It relates the hanging chain which changes its shape to respond to changes in load with what he calls a 'responsive' arch which resumes its funicular shape on subsequent loading. The system comprises a star-shaped compression element balanced by prestressed chains forming 'top' and 'bottom' chords with their tension forces linked by means of a vertical axle incorporated in the compression element (Figure 10). In this system, the stiffness is not determined by the Young's Modulus of the chains but on the amount of prestress. Related to the experimental structures of Marks and Barfield and McCarthy mentioned in this section is Otto's flexible column (1963) which could be bent in any direction by shortening or lengthening its tension members (Figure 11). The vertebrate-type column comprises a flexible core under compression with cable sets under tension threaded through 3-armed discs incorporating a device which controls the tension in the cables to effect desired movements (74). Otto developed this column when he found that conventional compression masts to his tensile structures "consumed disproportionate amounts of material" and were visually not compatible with the forms of the tensile structures. Otto drew on analogies from nature and his choice of materials reflected his priority for engineering effectiveness indicated by a high specific modulus, his forms accomplished their tasks with the minimum use of materials (74).

iv) Limb Rigidity and Movement

In the same way that Otto's flexible column could be bent in any direction by controlling the tension in different sets of cables, the vertebrate limb may be made rigid, or made to move the vertebrate animal by the contraction and relaxation of appropriate sets of muscles (tension members/cables) connected to the pin-jointed bones (compression members/struts). Otto (74) writes:

> "The bodies of animals are of composite construction comprising individual parts which are flexurally rigid and withstand compression (bones, ribs,). These are surrounded by a multitude of tension-loaded components such as muscles, tendons and sheaths and thus form stayed and braced compression members. As a result of muscular movements the lengths of the 'stays', and therefore the mobility of the system, are variable."

Rigid joints therefore do not have to be the result of monolithic members which remain continuous even with a change of geometry or of material, instead, rigidity may be obtained with non-rigidly connected elements secured by bracing (Figure 12) whereby very light columns, poles, arches, domes plane girder-type structures and walls can be constructed. Braced tetrahedral shapes with rigid joints can be utilised for systems in which the compression members are discontinuous, such as Fuller's (75) 'tensigrity masts' (Figure 13).

Foster's Renault Centre in Swindon (case study 15) is a structure which achieves rigidity by using a system of pin-jointed steel sections braced by Macalloy rods (Figure 14). It functions structurally as a series of portal frames, each bay being braced by the neighbouring bays.

> "In essence the structural system is an unbraced continuous portal frame. Loading on one bay affects the behaviour of adjacent bays and the beam elements play a role in spanning not only between the prestressed ties but also between the masts themselves." (76).

As previously mentioned in para 3.4.4 (iv), this example is significant in that the concept of a rigid joint is associated with pin-jointed structures, and a portal frame in this context, does not have the usual deep-sectioned 'elbows' at the beam-column (Figure 15) junctions necessary to develop the stiffness it requires to resist bending forces on loading. Here, the structural mechanism of the portal frame is obtained by innovative means which result in a new interpretation of its structural (and architectural form).

The planar trussed portal frame structure used in Hopkins' Patera Building system (Figure 16A), (case study 11), features a unique central pin-joint which keeps the top boom of the truss in tension irrespective of the dead and snow loads which cause downward deflection of the frame or wind uplift which causes upward deflection of the frame.

Once compression is avoided in the top boom, chances of buckling are minimised and the portal frame can be made up of small tubular sections arranged in one planar truss. In effect, the structure behaves as a three-pin portal under downward deflection and as a two-pin portal under upward deflection (Figure 16B).

Although the project engineer Mark Whitby may not have drawn the structural analogy from an example in nature in the Patera example, the central pin-joint which becomes rigid under wind uplift may be likened to an elbow or knee joint of vertebrate animals. The advantage is an unusually slender structure for a 12 m span when compared to Grimshaw's IBM Sports Hall at Winchester, (which is a triangulated-section two-pin portal spanning 18 m designed for buckling), and the Crosby Kemper arena structure (Figure 17A, B).

The idea that natural forms are evolved from (amongst other significant influences like the need to survive in hostile environments) the economic use of its constituent materials, is one which is parallel with the engineering aim of developing minimal structures within a context of limited resources.

The development of structures which use a minimum of material influences their form and consequently the visible elements of the architecture that use these structures. Samuely (77) in 1949, believed that much lighter structures will be used in future concrete and steel construction. He wrote on welded trussed purlins in 1941 (78):

> "For long spans, purlins would become very heavy and the distance between the (primary spanning elements) is usually kept to within restricted limits ..... Trussed purlins of long span can be adopted (with a minimum of labour in their construction) so that a system with a reduced number of (primary spanning elements) may be employed."

Figure 12A Section 2 shows Samuely's trussed <u>purlins</u> which share a structural principle similar to the trussed <u>beam</u> used in the Lee House transfer structure. Here, beam rigidity and resistance to bending is improved by trussing it with struts and cables. In Whitby's Glasgow Eurodrome winning entry, (case study 29), a similar approach is adopted in the structural configuration of the intermediate struts to the primary spans. The struts are subject to compression and therefore prevented from buckling by bracing with cables. The appearance of these struts reflects the visual hierarchy of the structural system, where the primary spans are distinguishable from the secondary elements. (Of even greater interest is the roofing structure analogous with the nature of dirigibles described in case study 29 Mark Whitby's Glasgow Eurodrome scheme).

Similarly, Grimshaw's Ladkarns project (case study 19) in the London Docklands designed by Peter Higson, then with OAP, interprets the structural truss in a form different from its timber origins. The pair of plane trusses is composed of tubular compression members and solid bar tension members (Figure 18A, 18B). They resist dead and wind loads and vertical forces from the workshop box roof it carrries and since these vertical forces (from the box roof) can act in both directions, two sets of tension members are therefore provided. Thus, the application of cable-braced compression elements (analogous with vertebrate limbs) allows the use of slender long-span secondary elements which reduces the required number of primary spans and the creation of new structural forms which influences architecture.

v) Marine Shells

In the same way that Mainstone (2) implies the similarity of the structural pattern of the radiolaria coral with that of Nervi's small Sports Palace in Rome, sea-shells such as those of scallops and clams are corrugated to develop structural rigidity, and this natural analogy is adapted in the folded structure of Nervi's Turin Exhibition Hall (Figure 19).

The precast ferrocement sections in a V-shaped configuration are a protective measure against buckling when transmitting mainly compression forces. The thin walls also develop their bending strength through folding.

Renzo Piano's Ravenna Sports Hall, (case study 33), in Italy bears similar resemblance to the form of the sea-shell (and to Nervi's Turin Exhibition Hall in the profile of its component section) and Piano believes that the resemblance is due to the adaptation of structural principles similar to those of nature, in response to similar structural and geometrical problems (79). Its geometrical derivation is from a toroid (Figure 20) but unlike Barfield's Eurodrome vault, (which is a vertical 'slice' off the torus), it incorporates a radial segment illustrated in Figure 21, and divided in the middle to accentuate a central axis over a running track in its interior. Presumably, there is a linear strip of skylighting incorporated in this axial division of the shell structure. Like Nervi's Turin Hall, Piano's Ravenna Sports Hall is constructed from several hundred V-shaped ferrocement sections folded and ribbed for strength, precast in 12 - 13 moulds and held together as a coherent shell by steel cables, some of which are pretensioned and others post-tensioned. The width of ferrocement sections vary with the radial arrangement of the roof plan, and as the bending moments decrease towards the outer edges of the shell, the depth of each section decreases correspondingly (Figure 22A). Calatrava's roof structure for the Wohlen High School Great Hall uses laminated girders arranged in a radial plan and folded to give V-sections for strength and rigidity in a manner similar to the above examples (Figure 22B). The exterior roof is separated from the load-bearing structure to allow natural light to filter through.

The aforementioned works of Piano, Calatrava, Marks and Barfield incorporate the ways in which natural forms acquire strength through shape and through mechanical interaction (as in the case of muscles, tendons and bones) for the purposes of visual expression and structural function. Their significance in respect of the thesis will be discussed in para 3.4.10.

3.4.8 The adaptation of bridge-building principles

i) Needs and constraints

In commercial terms, buildings located at transport interchanges command premium rent making the investment of mixed-use developments on such sites fairly attractive. In London, a number of such developments occur at existing railway stations and road junctions where the supports to these buildings have to be necessarily minimised without interfering with existing traffic networks and structures, including foundations sensitive to earth movements caused by new construction.

These are the Lee House and Embankment Place Development and Broadgate Phase 11 at Liverpool Street Station, (case studies 3 to 5).

The structural task is to effectively span an entire building block between the limited number of vertical supports and some of the basic problems associated with this task are common to those of bridge construction. In a bridge, its structure must carry loads across a river, gorge or valley. In the case of these buildings, the loads have to be carried across a major traffic junction, or over existing railway platforms, avoiding existing structure and foundations of existing buildings adjacent to the site boundary. the structural task is complicated by a mix of practical, commercial and architectural requirements which act as further constraints to the design of the building.

a) There are limited positions for the placement of ground level vertical supports and where these occur.

b) They have to be as slender as possible in order to accommodate engineering service risers, fire-fighting control bays so that the enclosed areas at the ground floor are not too bulky to obstruct existing vehicular and pedestrian circulation patterns.

c) The design of the structure should assist the architectural layout of providing the maximum number of floors possible within a given height restriction, and in the enhancing of retail spaces.

d) The use of an entire floor for services and transfer structures in a mid-rise office block may be avoided, thereby making all floors of the building potentially saleable, and an ideal option from a developer's viewpoint.

ii) Why conventional spans are adequate in meeting the constraints.

The sectional depth of a floor beam may be minimised by controlling its span and the spacing of its supporting columns. In the examples where site constraints do not permit the use of intermediate columns (to break the span, and therefore control the sectional depth of the beam), at ground level, the idea of designing each floor under these circumstances to span the entire distance (30 m for the Lee House and 60 m in the case of the Embankment Place) would imply the use of floor beams of substantial depth. This would not meet with constraints (c) and (d) and the design would not yield the maximum number of floors possible for a given height restraint and site area.

In the architecture of bridges (49), the control of the depth of the deck beams is aesthetically and economically important from both architectural and engineering viewpoints, and some of its structural principles have been applied in the context of building to provide solutions to the aforementioned constraints. These may be broadly categorised as follows:

a) Building floors are supported on a 'platform' or transfer beam spanning the distance between the minimum columns allowed at ground level. Intermediate columns are allowed to rest on the transfer beam, and therefore reduce the span and sectional depth of all floor beams above the transfer beam. This may be similar to a bridge deck supported by an arch below it (Figure 23).

b) Building floors are suspended from a transfer structure located at the roof level of the building by means of intermediate hangers which break the span of all floor beams below the transfer structure, thereby reducing their sectional depth. This may be likened to a bridge deck suspended from a catenary or an arch (Figure 24).

c) Building floors span between bays of arches or catenaries supported by end cores of the building, which are the only supports at ground level (Figure 27, 28).

iii) Effect on architectural expression and form

In both the Lee House and Embankment Place developments, the structural arch is used in the architectural expression of the building forms, as well as being used as transfer structures in resolving the constraints of the design. The rooftop arched girder at the Embankment Place development recalls the barrel vault roof of Charing Cross Station whilst the arches in the Lee House development create the gateway effect of its Cripplegate precedent, intended by Terry Farrell architects. These two examples fall in the first two categories of analogies with bridge construction principles viz (a) and (b), and change the need for podium expressions in tower blocks, with reinforced concrete transfer beams which are of substantial depth, necessitating their concealment behind fascias that are one floor deep (Figure 26). In these cases, the deep transfer beam shares a floor with engineering HVAC service ducts and conduits which are branching off from main risers into outlet risers due to changes from large spaces to smallerr ones (for example, hotel suites located above large banquet rooms in an urban site), and there is a consequent loss of one otherwise potentially commercial floor.

The third category, (c) resolves the problem of structural depth in a more elegant way. The catenaries or arches are free to occupy the full height of the building in order to acquire their required structural rise (or depth) because they are located in the plane of the building facade (Figure 25A, B).

This results in their external expression appropriate to their individual site contexts, for example, Marks and Barfield's proposal of a new building in the form of a suspended bridge structure over the entrance to Battlebridge Basin in the Grand Union Canal; Skidmore, Owings and Merrill's Broadgate Phase 11 which reflects the arches of the Liverpool Street Station roof, (case studies 6, 5). In these systems, the interior spaces are completely free of columns, and in the case of the Minneapolis Federal Reserve Bank, 1973, future extension could be accommodated on top of the existing building by using an arch which would balance the inward thrust of the catenary by its outward thrust.

It must be pointed out that the use of catenaries and arches, which are comparatively slender structural elements, provides economical solutions to the problem of long span building whilst creating opportunities for architectural expression.

iv) Cable-stayed structures

After the first cable-stayed bridges were developed in 1950, it was discovered that a reduction in the distance between the anchors at the deck (to between 6 to 12 m) substantially reduced the bending moments of the deck beam, and this bending moment could be further decreased by making the beam even slenderer.

This development made it possible to build very long span bridges with extremely slender decks making them very attractive, visually. The towers could be designed with great slenderness because the cables exert only small wind forces and contribute to the safety against buckling in the completed stage.

Towers without cross-bracing were possible when cables were placed in a vertical plane. A-shaped towers were particularly suitable for large spans and high-level decks. The legs of the towers could also be inclined towards the inside, under high level decks in order to concentrate the forces onto a small foundation (Figure 29).

Apart from decks suspended by cables in two planes anchored along the edges of the deck structure, bridges with cables in one plane along the axis are possible with a single slender column. However, the deck beam in this instance had to resist torsional forces and therefore could not be as slender as systems with cables on either side of the deck. For this reason, the suspended main spine structure of Grimshaw's Oxford Ice Rink comprises a double-beam in section and the Homebase Brentford spine structure appears to be a box-section trussed beam (Figures 30).

Asymmetrical arrangements of cable-stayed structures are particularly popular with single-storey industrial and warehouse/wholesale buildings, (case studies 14 to 20, 23, 24). Here, cables are suspended from one tower only and at one end of the main span. The stays for the side span may be omitted by leading all backstay cables to one end of the side span. Alternatively, the backstay cables may be distributed over several small side spans which are supported by piers. This increases the stiffness of the entire structure. The pylons may also be inclined in a number of ways, thereby facilitating the expression of its architectural form.

Asymmetrical bridge forms are typified by the following examples:

Calatrava's Stadelhofen, Salzburg and Segre bridges, Rogers' Austerlitz proposal, and Marks/Barfield's Bridge of the Future scheme may be deliberately designed to 'belong' to one side and only tentatively touch the other.

In Marks/Barfield's bridge, the asymmetry is a result of its structural form which is a propped cantilever, and its erection sequence starting from one side of the site, (case study 25). The bridges are designed in extremely slender proportions and to appear as though they are hovering above the site. Leonhardt (50) associates the notions of slenderness and weightlessness with the aesthetics of bridge design. Schlaich (52) associates the same notions with all engineering structures, including structures in architecture.

The aforementioned works of Rogers, Calatrava, Grimshaw, Marks and Barfield incorporate the use of structural models developed for civil engineering purposes. They exemplify perhaps the oscillation between aesthetic and engineering considerations, mentioned by Carmichael (41) necessary for architectural and engineering design. Their significance in relation to the thesis will be discussed in para 3.4.10.

3.4.9 The interpretation of machine aesthetics

Behrens (27) interpreted the industrial tasks to be the essential cultural interests in 1907, at about the time when Muthesius founded the Deustcher Werkbund which sought to improve the quality of the national product designed, by forging links between German art and industry. Hence buildings expressed the imagery of being products of mechanisation (and an advancing technology). Reinforced concrete and steel frames were used with wide expanses of glass on external walls making transparent, what was not before, with masonry buildings. For example, the glass staircores which made visible the spiral staircase at the Werkbund Pavilion (1914). The structural frame was used to create crisp, precise forms with clear geometries which appeared as 'weightless' and transparent hovering volumes brought together in dynamic compositions. The Fagus Shoe Last Factory by Gropius and Meyer (1911) the 'Futurist' proposals of Sant' Elia (Figure 31) were perhaps early examples of such thinking. In 1910, Corbusier, Mies and Gropius worked in Behren's office and his influence on their later works showed through their individual interpretations of the machine analogy, which was a characteristic of the International Style. (The influences of artistic ideology related to this idea of machine aesthetics was first discussed in para 3.4.5).

The Russian Constructivists in 1920 also interpretated the machine aesthetic in an abstract nature.

Le Corbusier introduced his idea of the machine in his architectural works by using forms borrowed from nautical craft, for example in the exterior of the Maison Cook, the nose of the Farman Goliath 'Air Express' from 'Vers une Architecture' was used as a metaphorical fragment of a modern airplane (32). In this way, he suggested a direct analogy between the form and the structure of this modern machine and the new architectural aesthetic, which featured the juxtaposition of sculptural forms with gridded space. The composition of the Villa Savoye facade has been compared with the rear deck of the Aquitania whilst the 'little pavilion on the Villa Garches roof' appears remarkably like the front bridge structure of the Aquitania from Vers une Architecture (80). These forms then were said to become the architectural icons of modern culture.

In today's context, the use of nautical metaphors occur in some of the works of Foster, and Grimshaw. The Liberte Les Tours monument (case study 42) and the Hambourg Ferry Terminal (case study 32) are structures developed for their nautical image. In Foster's and Grimshaw's works, the bending members with cylindrical holes in the webbing (similar to the hexagonal holes in castellated beams) reduced the self-weight of the structural element and is a principle used in structures of aircraft fuselages and wings. These similar elements are seen in Foster's Renault Centre and HK and SB Building and Rogers' Llyod's Building. Grimshaw's Oxford Ice Rink (case study 18) is symbolic of the river sporting activities that characterise the town, as its structural elements comprise a single spine suspended from two cable-stayed masts, an arrangement likened to the image of a sailboat. Only 16 piles were used with this structural configuration, and this proved to be advantageous, given the soil conditions. The structure was configured, like the Ladkarns' Project (case study 19), to provide its deliberate nautical image aimed at avoiding a warehouse appearance with most long-span single storey sheds. The problem of articulating the 'box' shed was also addressed in Grimshaw's Homebase Brentford design (case study 24) which the architects claimed to be inspired by the structure of the Caproni biplane wing. Figure 23. The way that the roof breaks down into a series of 'wings' is clear. Rogers and Piano's Georges Pompidou Centre (1971) expresses exhaust ducts in a manner resembling ship's funnels and Piano (81) revealed that the building imagery was conceived in the metaphor of a spaceship, an approach to identify the building easily to its users and to 'bring' its function as an art gallery closer to the public. The arrangement of gerberettes, steel latticed floor trusses and slender cross-bracing members gives the building form its highly transparent nature which allows inner layers of space and ancillary functions to be legible. The 7 m wide zone provided by the gerberettes in the main structural framework is occupied by lifts, horizontal walkways, escape stairs and entrance zones on the Piazza facade, and by HVAC ductwork on the opposite facade.

After the Pompidou Centre came structures which had their precedents in cable-stayed bridges. These examples were described in para 3.4.8.

The use of exposed steelwork and industrialised components in architecture and building became associated with what was commonly described as the 'High-Tech" style. Newby (10) questions whether high-tech architecture fulfils the functionalist promise of its title or whether it is mere style. Some of the structures have been criticised as being over-elaborate with excessive diagonal bracing and are not the most economical systems, from an engineering point of view. However, part of the architectural effort in designing with structural engineers is to explore new possibilities with the consequent use of unconventional types of structure. If through the use and development of such unconventional structures, improvements to space and form may be made to the architecture of the building, then the additional costs incurred could be justified, better than if a more economical and conventional structure were used without any particular significant architectural advantage.

3.4.10 The preceding descriptions relate the aesthetic interpretations of architectural form and structure in the case studies with the recurrent themes noted in the history of architectural movements. The following conclusions are made with respect to this relationship between theme and interpretation:

a) Structural application in building is moving towards systems which use increasingly less material to achieve the required strength and rigidity required to transfer loads in ways influenced by the shape of architectural forms and spaces. This is directed towards reducing structural dead weight which in long-span and high-rise structures is critical to both performance and cost efficiency. One way is to avoid the development of excessive bending moments in the structure and this may be part of the reason for the increasing number of applications of structural systems which transmit primarily axial loads, particular tension in steel construction. Schlaich (52) has pointed out that pure tension or compression structures do not exist and the necessity to accommodate useable space and the shapes of architectural forms could imply the development of some bending in a system which first set out to avoid its presence. Bending necessitates the use of deeper structural sections which makes the structure visually bulky and more expensive in terms of material quantity.

In this respect, the experimentation of flexible structures which acquire a satisfactory degree of rigidity with stressed cables and rods is aimed at providing more aesthetic and economical solutions than with conventionally rigid systems. (Group Three of Section II case studies).

b) Where the engineering aim of developing increasingly slender structures is aimed at economy and elegance, the architectural implications could be:

   i) A structural system which assists the aesthetic considerations of formal and spatial composition, or one which does not necessarily restrict modes of aesthetic treatment in order to provide support.

   These aesthetic considerations will be elagborated from para 3.5 onwards, in relation to the thesis objectives.

   ii) A structural system which allows flexibility in the layout and use of floor space and in the interpretation of spatial character.

   iii) A structural system with the means to optimise fully, the commercial potential of prime sites with complex building constraints.

iv) A structural system which effectively integrates mechanical service and electronic networks without compromising aesthetic themes.

v) A structural system which provides the option of satisfactory levels of natural lighting and ventilation as well as enabling an energy efficient building.

These ideals are related to the core aspects of structural improvement to architectural form and space, first described in a Section I summary on Modern Movement examples, para 1.28, and perhaps would continue to apply to future applications of structure in building.

3.5 Recurrent approaches to the use of structure in architecture

The core aspects are related to the approaches adopted by designers in both the contemporary and historical contexts. The thesis proposes that the recurrent approaches are aimed at using structure to improve the core aspects of architectural form and space. These recurrent approaches may be described as one set which addresses the problems of arranging structure in relation to architectural planning whilst the other set of approaches is taken with regard to generating external form.

3.5.1 Structural arrangements in relation to architectural planning

Samuely (82), Yeomans and Cottam (83) discussed the merits of three forms of reinforced concrete structures developed for high-rise flats in the 1930s.

a) The wall frame which confined beam and column elements within the external facade.

b) The central spine beam for deep floor plans.

c) The box frame which was an improvement on the conventional cross-wall arrangement.

Of particular significance were:

i) The reasons for which these structural systems were developed, and they will be found to be related to the improvement of the hypothesised core aspects.

ii) The strategies adopted with regard to the arrangement of structural elements, and these were found to be similar in principle to those observed in the case studies, even with building types other than those of high-rise flats.

3.5.2 Reasons for which systems were developed

The steel and concrete structural frames used in the 1930s flats cited in Yeoman's and Cottam's (83) paper had the following common disadvantages:

a) A regular grid of beams and columns around which the planning of spaces and partitions had to be organised.

b) The awkward projections into the interior space by column and beam edges at wall corners and wall to ceiling junctions.

c) The reduction in the size of facade openings by edge beams and the structural constraints on the location and size of openings with the supporting function of the facade.

d) The rigid sub-divisions of space implied by the regularity of the structural grid.

In general, points (a) to (d) imply the need for a structural system which:

i) Allowed flexibility in the arrangement and layout of interior spaces ie the structure should allow a range of alternative plans and layouts and not dictate the ways in which spaces were to be divided or arranged.

ii) Allowed flexibility in the architectural composition of the external facade with regard to the shape, size and location of openings, balconies, overhangs and cladding panels.

iii) Did not visually and physically interfere with the circulation or maximum use of space.

3.5.3 Strategies in structural arrangement

To achieve the aims described in para 3.5.2, the following systems were developed for high-rise flats in reinforced concrete construction: whereby loads were transmitted by supports (Figure 34).

i) Arranged in the periphery of the plan.

ii) Arranged in the centre (and periphery) of the plan.

iii) Arranged intermittently throughout the entire plan in the case of extensively large floor areas.

3.5.4 Peripheral arrangement

As typified by the wall-frame system described in Yeomans and Cottam's (83) paper, column and beam elements are placed in the external facade of the building, flush and without projections from the wall plane. In this way the interior space is free from columns and without the visual intrusion of beams running in the transverse direction. Spaces and partitions are visually independent of the supporting elements and are free to take a wide range of forms required for aesthetic effect. Both the Broadgate Phase 11 and Battlebridge Basin bridge structures are essentially peripherally arranged structures, (case studies 5, 6). The structural elements are outside the interior space which are suspended by peripheral hangers in the facade plane. In the case of Broadgate, the arch bays are repeated in the longitudinal direction in relation to central atrium.

The preoccupation of beam projections from the ceiling plane is a less critical issue in today's context where false ceilings are required to conceal HVAC and electronic ducting and sanitary plumbing. Where large spans cannot be accommodated by flat slabs of economic thickness, the depth of stiffening beams is minimised to allow a reduction in the depth of the space occupied by the floor structure. This is considered a more critical issue when attempts are made to maximise the potential of sites with building height constraints. In the case of the transfer structure examples in Section II, (case studies 3, 4), the aim of minimising structural floor depths was a key consideration in locating the primary structure at the periphery of the floor plans.

The main disadvantages of peripheral load transfer is basically the constraint on the composition of the external facade. Yeomans and Cottam (83) explain that this is because the walls must act as columns between openings, whilst above and below the windows they must act as either upstand or downstand beams to carry the floor, so that the logical arrangement of the elevation would have been to provide clear zones for both these column and beam strip openings. Therefore, the beam and column function of the wall must be differentiated in its surface treatment (Figure 35).

In extending the structural idea of using walls as supporting elements, shear walls which provide lateral stability to high-rise buildings may be placed together, enclosing lifts, stairs or service shafts. These form vertical core structures which may be located at the periphery of the building, or centrally, and may be used to articulate the architectural elevation. However, these cores behave structurally as vertical cantilevers, and openings in the core structure may require reinforcement around the corners.

The development of 'tube' systems, shear truss and frame interaction systems in order to increase the plan area of the building which actively resist wind loads, has led to some examples where the structural elements have become accepted as part of the facade elements in architectural composition.

The HK and SB Building is an example where its structural frame is the main compositional element of the external form. The location of horizontal and vertical elements as required for optimum structural stability, such as the location of the 'coat-hangers' in the case of HK and SB Building, relative to its building height, may be the sort of aesthetic validation that appeals to pragmatists, in preference, for example to those of iconic or metaphorical expressions.

The principle of peripheral support to the structure of the building may also be observed in the following low-rise examples:

a) Sainsbury Camden Superstore, Case Study 9.

b) Patera Nursery Units, Case Study 11.

c) NAPP Laboratories, Cambridge, (Figure 13, Section II).

d) Ravenna Sports Stadium, Case Study 33.

e) Bari Sports Stadium, Case Study 36.

f) Crystal Palace Extension (Stadium), Case Study 22.

g) Hambourg Ferry Terminal, Case Study 32.

h) Frankfurt Athletic Stadium, Case Study 1.

i) Liverpool Festival Hall, Case Study 2.

j) Sydney Football Stadium, Case Study 21.

k) Berlin, Bismark Strasse Industrial Development, Case Study 38.

3.5.5 Central arrangement

Where it is preferred to free the facade from structural constraints, the structure may be arranged in directions transverse to the plane of the facade as in one-way systems. For the 1930s flats discussed in both Samuely's (82) and Cottam's (83) papers, this takes the form of cross-wall or central spine arrangements. Samuely (82) pointed out that prestressed concrete[1] had made the spine beam arrangement obsolete for the modest transverse spans of up to 20 feet (in this arrangement, the spine beam is located along the centre line of the linear floor plan, and the slab spans 10 feet on either side to the external walls, Figure 36A Arup and Tecton's scheme for the Roseberry Avenue flats (Figure 36B) feature a box-frame arrangement which is an improvement on the ordinary cross-wall system. Here, the front and back cross-walls do not have to be aligned and the alternate arrangement of divisory walls provides some flexibility in architectural planning.

In the case of squarish floor plans in high-rise structures, elevator shafts service risers and escape staircases may be grouped together by centrally located shear walls in combination with cantilevered slabs. This allows for slender struts/hangers at the facade plane to support the cladding and to stiffen the slab edges. Figure 37 shows Grimshaw's London Apartment (1968) where shear walls and frames are used in combination. The structure is not arranged in a rigid or regular manner and allows interesting plan forms on which the interior layouts could be based.

Footnote

[1] Prestressed concrete is also unpopular now due to high costs and difficulties in demolition.

In low-rise schemes with linear plan forms, the use of centrally-located supports to correspond with linear spine concepts may be interpreted in two ways:

a) A primary horizontal spine beam spanning the <u>length</u> of the building used to support secondary transverse beams spanning the width of the building. These transverse beams may be supported by props or walls at the external wall. This arrangement is seen in two of Grimshaw's schemes:

   Homebase Brentford where the transverse spans take the form of seven 'wings' on each side (case study 24) and the spine beam is simply supported and cable assisted simultaneously. In the Oxford Ice Rink, twin-beams supported by cables attached to two compression masts at opposite ends of the building break the span of the transverse secondary steel sections. In both cases, the spine beams are configured to resist torsional forces along its length and this adds to the articulation of the architectural element.
   Calatrava's (Figure 9A) design for the Wohlen High School entrance features an arched spine girder from which secondary sections are cantilevered (case study 30).

   Maki's (Figure 9A) Tokyo Metropolitan Sports Centre may be described as a structure comprising two trussed arch girders (acting as two separate spines) from which secondary trusses are cantilevered, creating the doubly-curved geometry (case study 35).

b) The spine concept may also be interpreted with one-way spans as in the case of Rogers' Patscentre andd INMOS factory schemes, (case studies 20, 23). In these schemes, the spacing of columns in the cross-sectional elevation of the building is symmetrical and defines the central corridor spine which forms the basis of the architectural concept. Main service trunks and circulatory routes are supported and defined by the structural spine. The main production spaces are located on either side of the spine and the primary spans are cable assisted to provide column-free areas. In both schemes, the central columns are extended vertically as masts to the cables, and collect primary compression forces under structural action. The bulk of structural material is therefore concentrated in these columns and consequently, the peripheral struts or props may be more slender allowing for flexible cladding arrangements and use of peripheral space. Other case studies which use structural spine systems include the Glasgow Eurodrome entry by Marks and Barfield (case study 29).

3.5.6 Intermittent arrangements (with modules or two-way spanning bays)

In buildings with large floor areas such as those for commercial, industrial and transport terminal functions, one-way structures may not be appropriate for the following reasons:

a) The structural form implies a building with a large unbroken mass that may be out-of-scale to its surrounding. Thus, the visual impact of the building involves its scale in relation to the surrounding site as well as to the interior spaces designed.

b) The floor plans may be so deep that the lighting and mechanical servicing of the innermost parts of the plan is a significant consideration.

c) The structure may be required to allow extensions of space in the case of buildings occupying sites with irregular boundaries.

In all three cases, the structure may be conceived in bays or modules, to allow the architectural form of the building to be 'broken' into smaller parts, to resolve the problems of natural lighting and ventilation to deep interiors, scale and capacity for expansion. Extensions of space are then possible by the addition of typical modules of structure which may be fabricated off-site and transported conventiently in sections to be assembled on-site.

Examples of such structural arrangements are:

a) Stansted Airport, Case Study 27.

b) Fleetguard Factory, Case Study 16.

c) Nantes Factory, Case Study 17.

d) Renault Centre Swindon, Case Study 15.

e) Ladkarns Building, Case Study 19.

f) Shotts Factory, Lanarkshire, Case Study 14

3.5.7 These forms of arrangements are inherent in all structural systems and are related to the aims of allowing flexibility in architectural planning and expression. Together with these structural arrangements which influence the conception of architectural spaces, there are related approaches to using structure in articulating external form.

These recurrent apprroaches may be summarised from case studies and other examples.

3.5.8 <u>Approaches to using structure to articulate external form</u>

i) The form implied by an ideal structural model (for example a portal frame used for a pitched-roof enclosure) may be adapted as an architectural form.

In these cases, the articulation of the structural elements expressed either internally or externally, provides architectural relief to the basic forms of the rectangular prism, the barrel vault and the dome.

In the case of the single-storey shed, the tradition of Mies' Crown Hall, IIT is continued by Hopkins' Patera Units or buildings like Rogers' Patscentre (case studies 11, 20 respectively). Some cable-stayed structures supporting single storey box sheds may also be included as examples in this respect (case studies 13, 15 to 19 and 23). (Figure 44) compares the simply supported span of the Sainsbury Arts Centre, the cable-assisted span of the Patscentre with the steel girders in Crown Hall. All three are structurally-articulated boxes.

ii) A structural form is modified to suit functional and aesthetic requirements, such as Nervi's Small Sports Palace (Figure 38) and Torroja's Torrejon and Barajas hangars (1945). Nervi's building was a variation of the dome in an rc shell structure, it features significant innovations at the shell edge and support junctions which characterises its architectural form. Torroja's hangar structures are a combination of trussed girders and cantilevered trusses, to resolve the particular clear spans required (84). In the contemporary context, Nagashima's buildings, (Figure 39), Piano's Ravenna Sports complex (case study 33), the Liverpool Festival Hall, and the Frankfurt Indoor Stadium (case studies 2 and 1) are essentially either domes or vaults, each with a different structure configured to suit individual functions and aesthetic requirements.

iii) A regular structural frame is used to support non-load bearing partitions. As typified by the Corbusian villas and Mies' early single storey buildings, the non-load bearing partitions could be used as expressions of free-standing wall planes or of curvilinear forms to improve the quality of the spaces that were defined (but not necessarily enclosed) by these 'free-forms'.

This tradition is continued with Foster's Willis Faber Dumas Building at Ipswich and the works of Meier, Graves and Gwathmey/Siegel. In these approaches, the structure maintains its effective form (as a frame) and architectural effect is achieved by manipulating the non-load bearing elements, supported by the structure (Figure 40).

iv) The structure is detailed as architectural ornament whilst maintaining essential structural action. The Art Nouveau works of Horta and Guimard typify this approach where the iron skeleton was expressed in tendril-like ornamentation which visually accentuated the actual structure. This tradition is continued with the works of Santiago Calatrava, (case study 30) where structural forms determined by bending moment diagrams and thrust lines are translated to aesthetic forms inspired by the skeletal forms of quadrupeds. Otto's tree structures study Bridge of the Future scheme by Marks and Barfield, (case studies 25, 29) also reveal similar sources of structural and aesthetic inspiration (Figure 41).

v) An appropriate functional structure is developed to maintain a 'sculptural form'. In this approach, the form is composed primarily for architectural effect and then its means of structural support is configured according to the preconceived form.

Kahn's approach may be likened to this, where his 'preforms' were inspired by the provision of light for architectural effect as in the case of the First Unitarian Church. Consequently, the church embodies a strong relation between space, structure and light (85). In the Dacca Assembly and the Philips Exeter Library, the expression of primary forms predominates structural expression. Stirling's Leicester and Cambridge University Faculty Buildings and the Florey Building at Oxford also typify this approach to structural integration.

In extreme cases, there is little relation between the shapes of the structural supports and the expressed architectural form, for example John Outram's design for two offices at Swanley, Kent (1986) Figure 45. In the case of Utzon's Sydney Opera House and the Bahai Building, New Delhi, by R J L Smith, the supports were engineered to make the form structural. After the forms were conceived remotely from considerations of structure (Figure 42).

vi) Smith (5) describes the Pantheon as an example of architecture where the structure literally occupies the space between the inner and outer surfaces of the resultant building form (Figure 43).

It is probable that buildings of that era were conceived of and built in that way, on studying their structural components, and the way they have been assembled. Smith (5) summarises this approach as one where structural support is a consequence of shape and construction process. This implies that the designers (of the Pantheon) had implicit knowledge or a qualitative sense of structure as support (Figure 43, A, B).

Mainstone (2) identifies three complementary types of intuition:

> "First, there is what might be called a geometrical or spatial intuition. This recognises the tendency of every object to fall but sees the possibility of preventing the fall by placing an obstacle in its way .....
>
> Secondly, there is a closely-related but quite distinct physical or muscular intuition derived from our own direct experiences of the pushes and pulls associated with extension and contraction and with different ways of supporting a weight.
>
> This suggests the existence of analogous pushes and pulls in inanimate structures and makes it possible to visualise these qualitatively to an extent that is limited only by our ability to visualise correctly the likely modes of deformation.
>
> Thirdly, and based on observations made in the light of the second, there is an intuition of the different deformational responses of different materials and structural elements to pushes, pulls, bending actions and the like."

Similarly, Tange's preliminary studies for the Singapore Indoor Stadium and Maki's Tokyo Metropolitan Stadium, (case studies 43 and 35) respectively reveal such a 'qualitative sense' of support without which their architectural forms would not have been conceived (Figure 43, C, D). Also, Stirling's sense of "stable compositions" in the Leicester University Building is one aspect of this intuitive approach, (para 1.19 (iv)).

3.5.9 These approaches are an expansion of Samuely's (77) observations on the use of structure in the history of architecture:

> "that the architect may show the structure, exaggerate the structure, or detract from the structure".

The approaches are also an indication of attempts to improve the architectural spaces and forms, the core aspects of which are detailed in para 1.0, and are a reflection of the common aims of the architect and the engineer. The core aspects will probably continue to apply irrespective of:

a) Future developments in structural materials and technology.

b) Future developments in construction technology.

c) Future developments in architectural philosophy.

d) The interpretation of aesthetics in architecture and engineering.

e) Future utilitarian needs of building users.

3.5.10 Samuely's (63) notion of a 'unity of purpose' (footnote) also suggest the overlapping aims of both professionals, irrespective of architectural style or structural system: that the structure should enable the expression of forms and spaces without excessive constraint to architectural planning, enable the integration of other engineering services and building construction without excessive complication and cost. These also formed the underlying aims of the case studies in Section II and it will be observed that in more successful solutions, there was a balanced compromise of both the aesthetic and engineering ideals without necessarily 'crippling' any particular design consideration of the architect and the engineer.

The different design attitudes of both architect and engineer are a characteristic of their specialised skills which have evolved from differences in training

---

Footnote

Samuely (63) believed that the cheapest structural solution did not necessarily lead to an economical building. This is evident in his summary of Frederick Gibberd's National Dock Labour Board Building in London.

a) The structure is slightly more expensive.

b) The lighting facilities are much better because the edge beam has a short span and can be lost in the floor thickness.

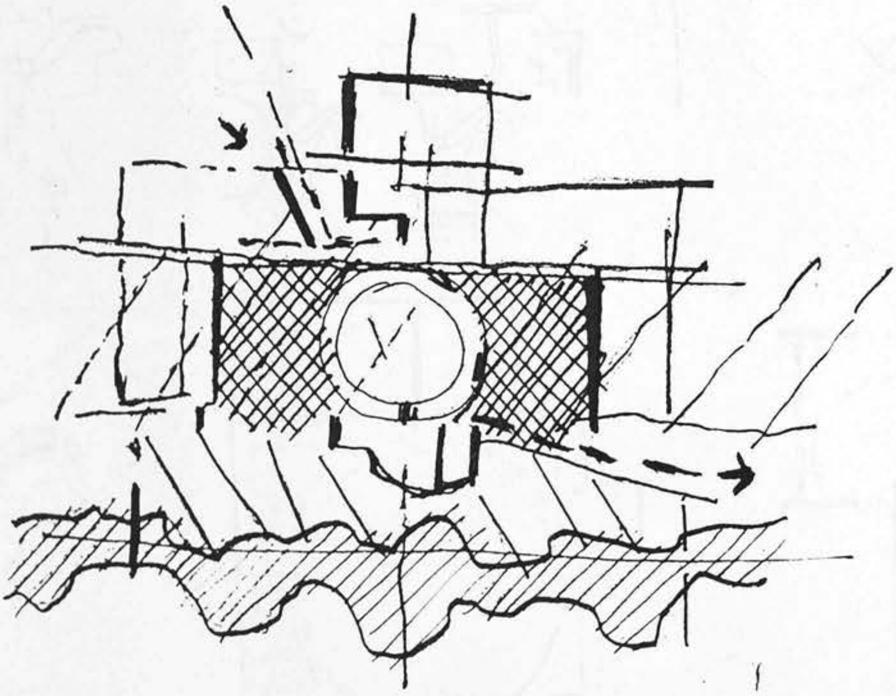
c) The planning is easier because there are no free-standing columns.

d) There is a greater variety of elevational treatment than with a curtain wall.

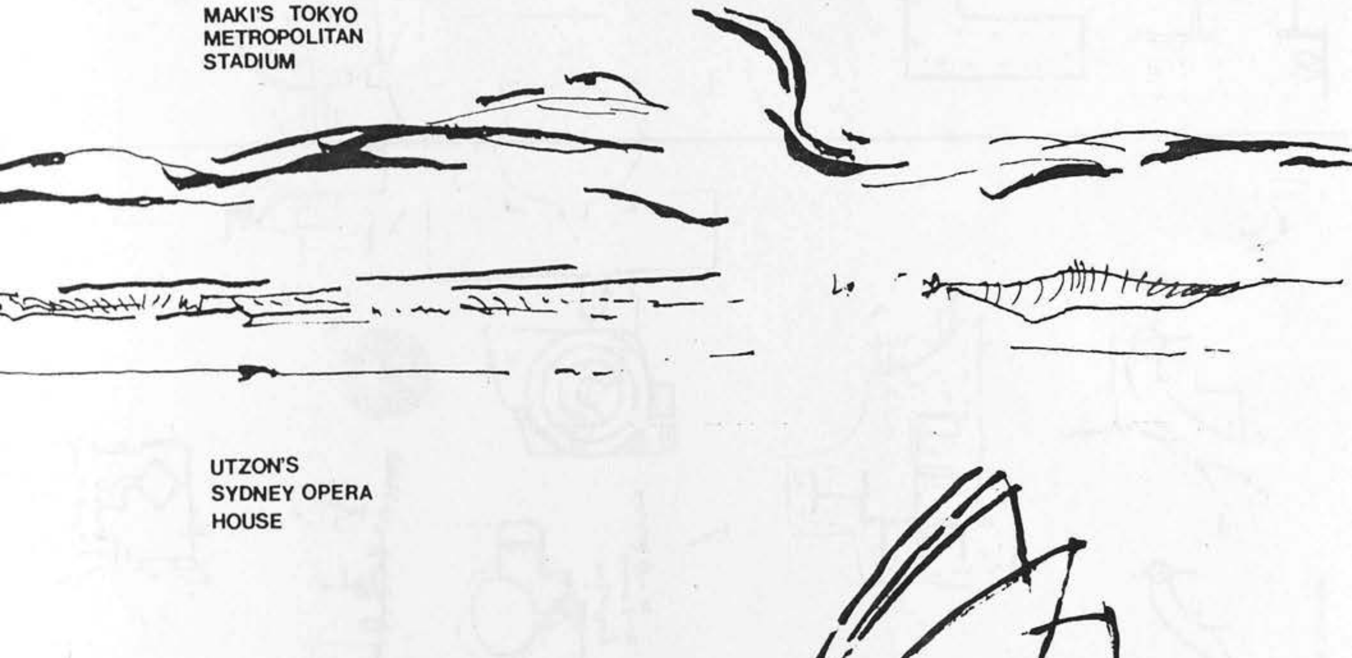
and in their professional origins described in Section I. These attitudes do not necessarily have to operate in conflict but the continued development of specialised skills, separate and unrelated to one another will hinder effective collaboration, the most extreme results of which are expensive contortions of structure with no significant gain in utility, function or aesthetics, from an architectural point of view.

The architect cannot effectively motivate nor establish the engineer's design aims if he is inadequately appreciative of the ways in which structure may be used to substantiate the quality and content of architectural design. In this respect, it is hoped that the thesis has contributed towards the "re-unification" of the design aims.

STIRLING'S
STUTTGART
GALLERY



MAKI'S TOKYO
METROPOLITAN
STADIUM



UTZON'S
SYDNEY OPERA
HOUSE

Fig 1A IDEAS ON BUILDING FORMS NOT CONSIDERED IN RELATION TO STRUCTURAL SUPPORT

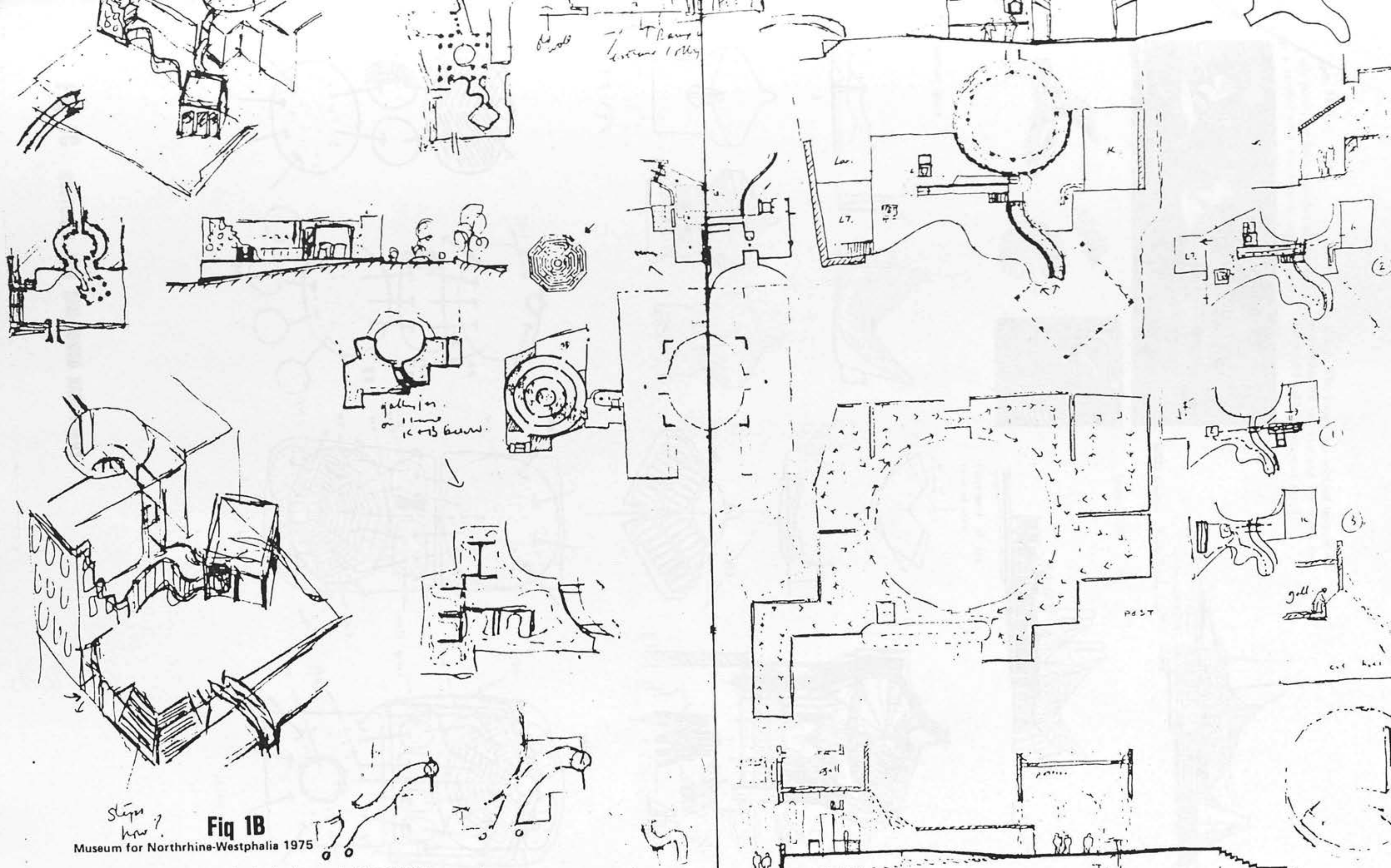


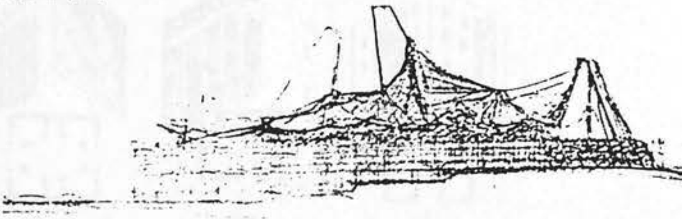
Fig 1B

Museum for Northrhine-Westphalia 1975

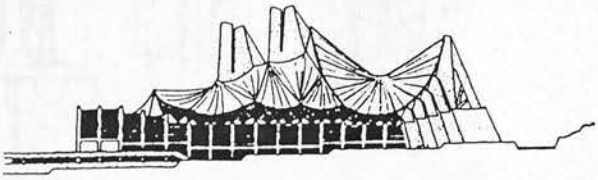
JS sketches from various stages in the development of the scheme.

umn, 1965

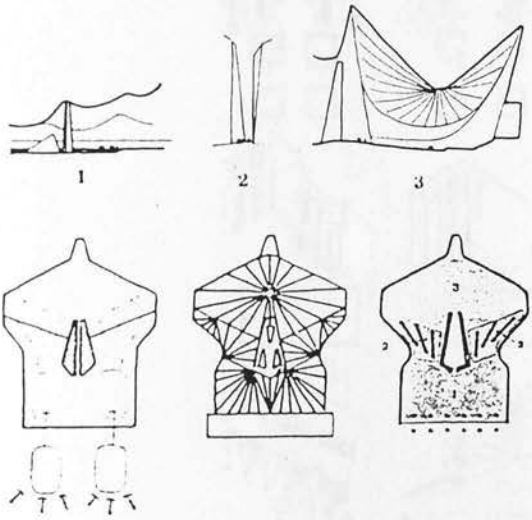
this point, we drew sketches of the roof as a symbol of a crane with outstretched wings. This image was selected because it symbolizes the universe and the hopes for the world held by religious people.



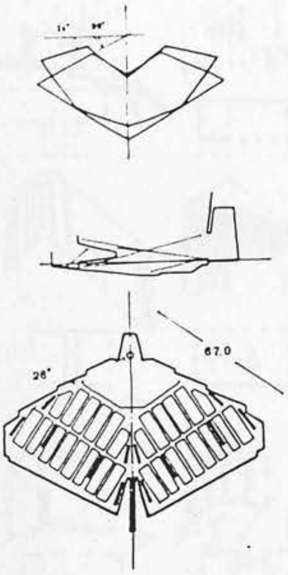
Spring, 1966

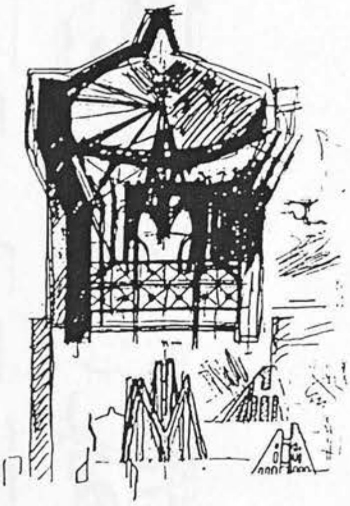


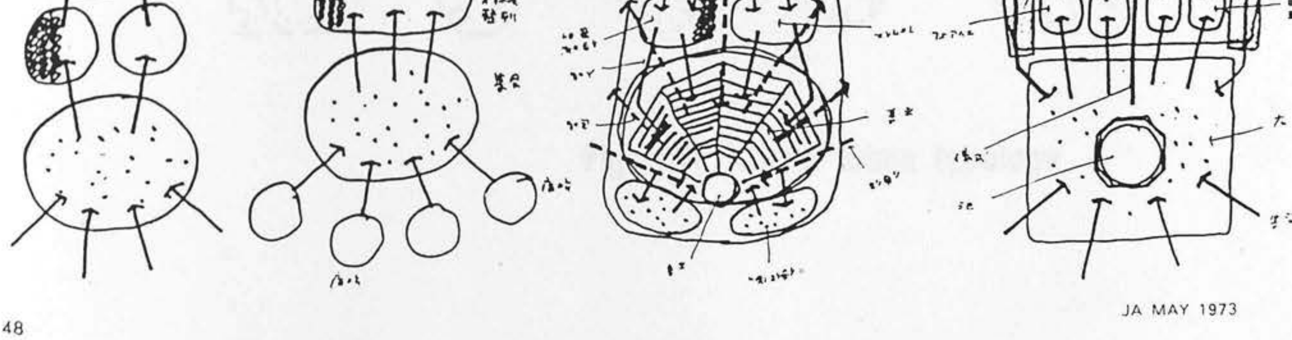
Interior space



Placement of the rows of seats







Fiq 1C SKETCHES FOR SHO-HONDO SANCTUARY

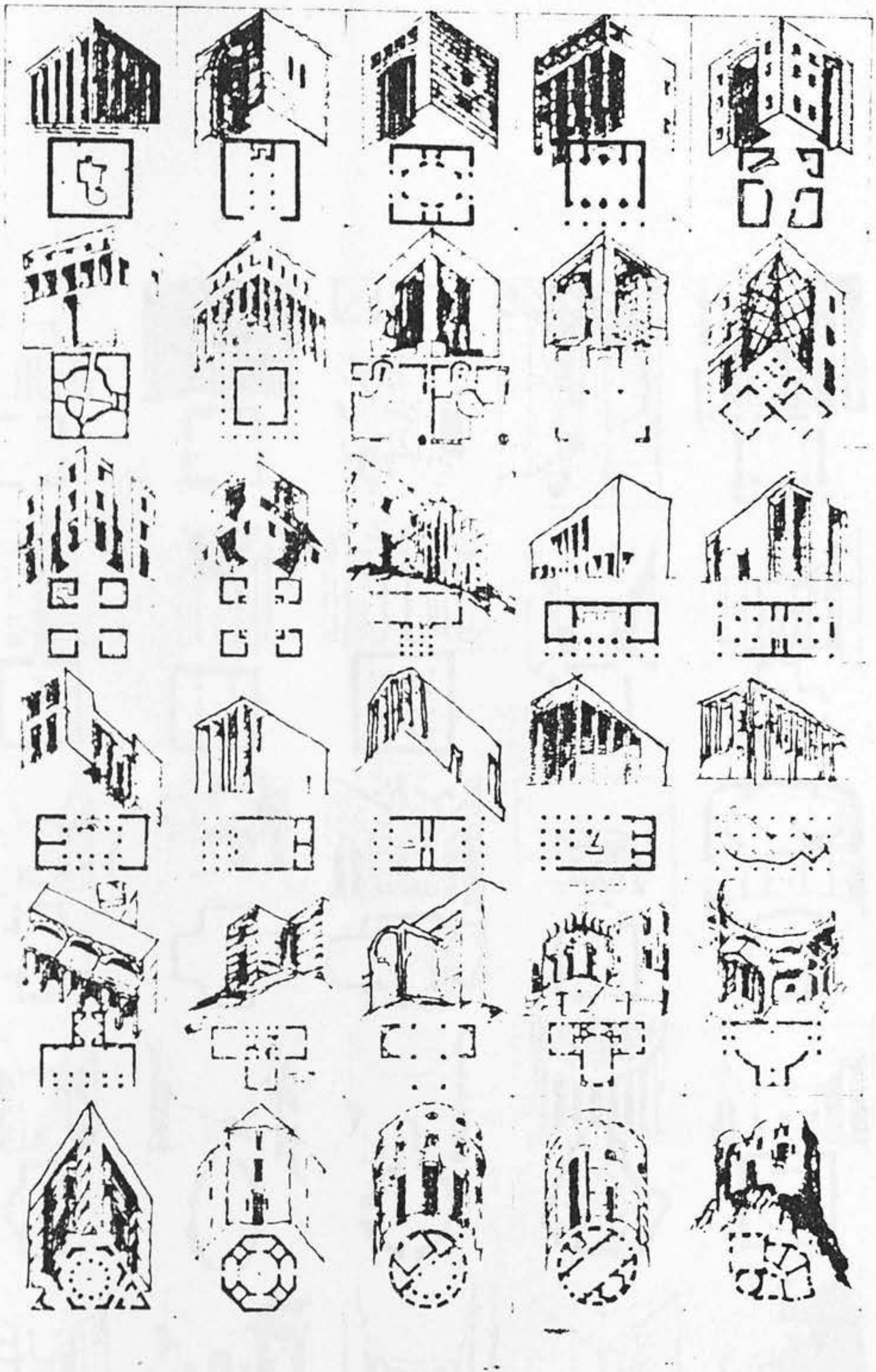


Fig 2A Krier's urban typology

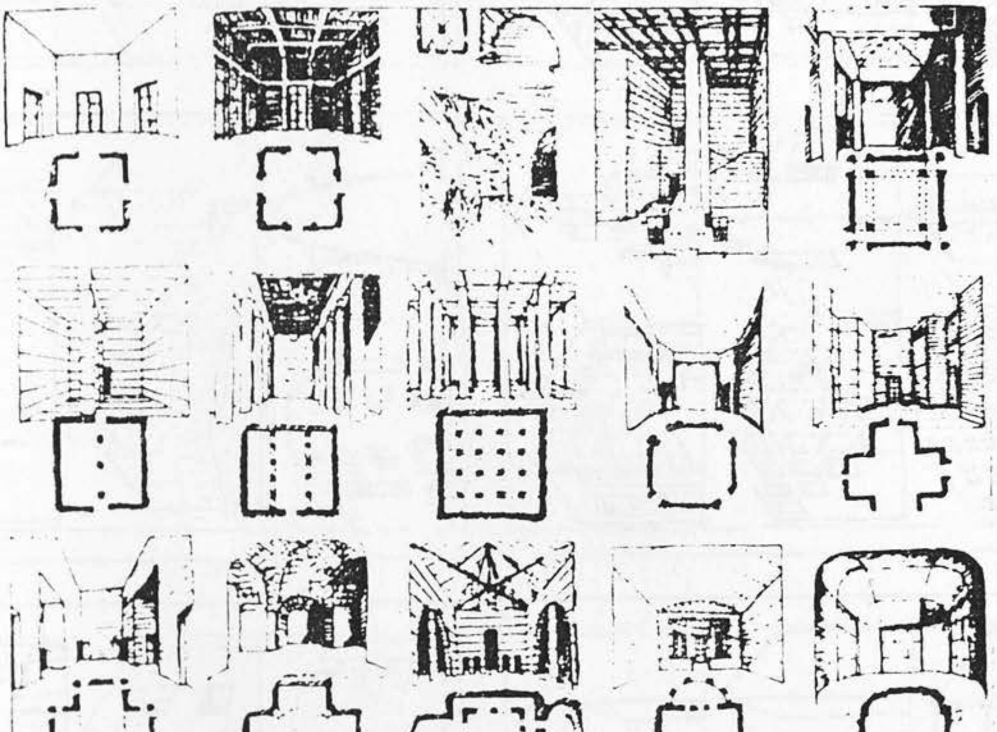


Fig 2B

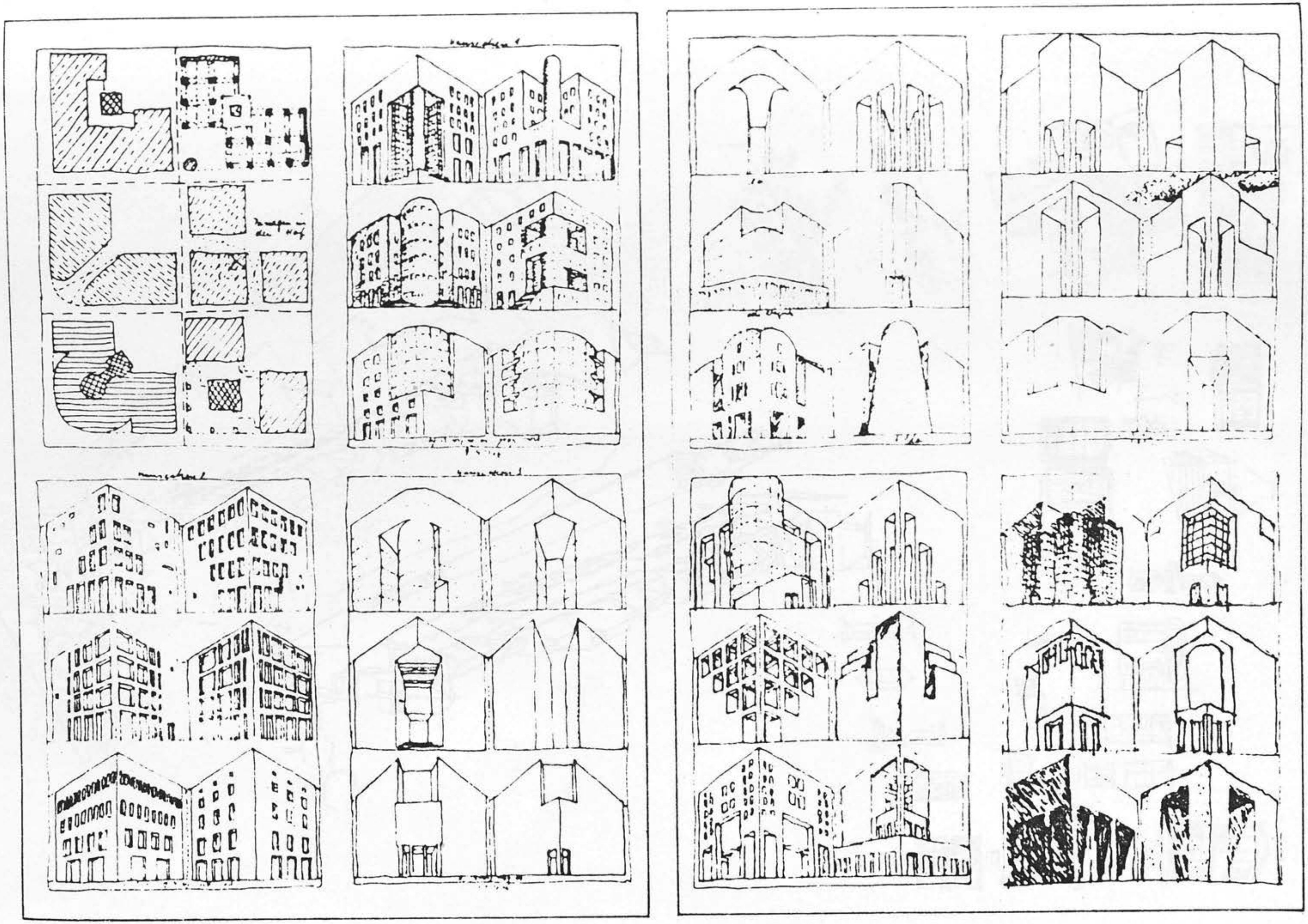
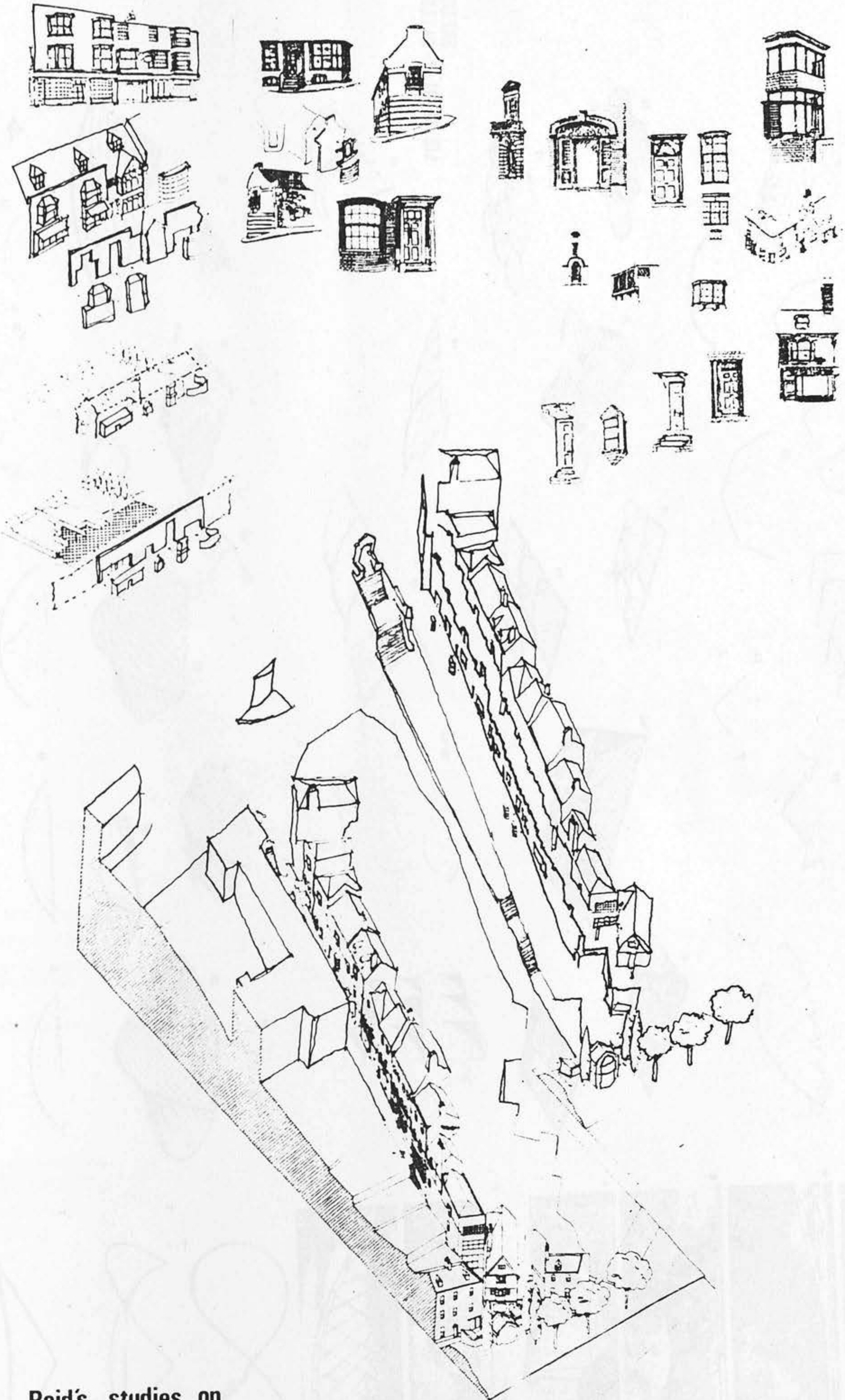


Fig 2C

Rossi's studies on facade elements



Reid's studies on facade elements

Fig 2d

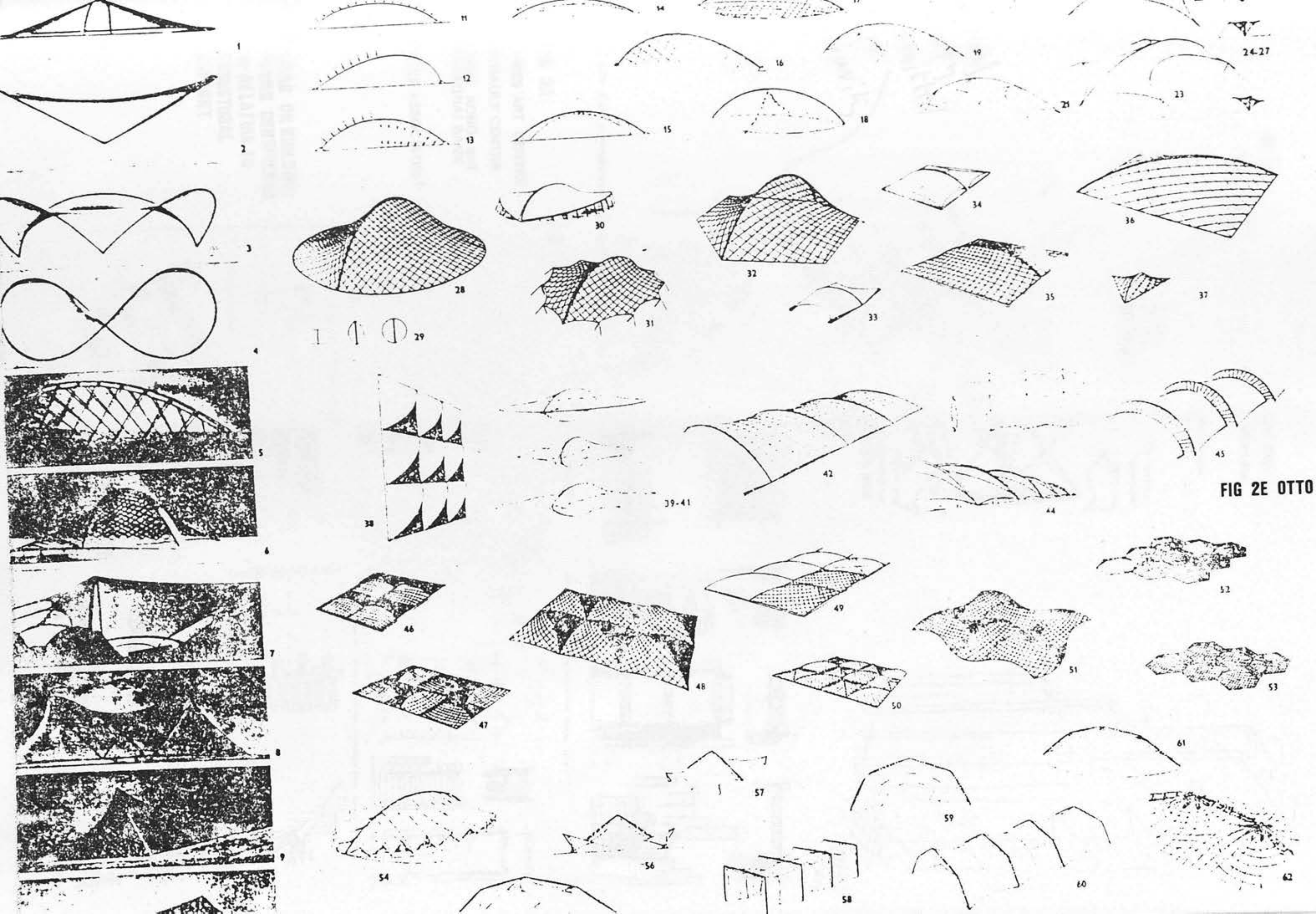
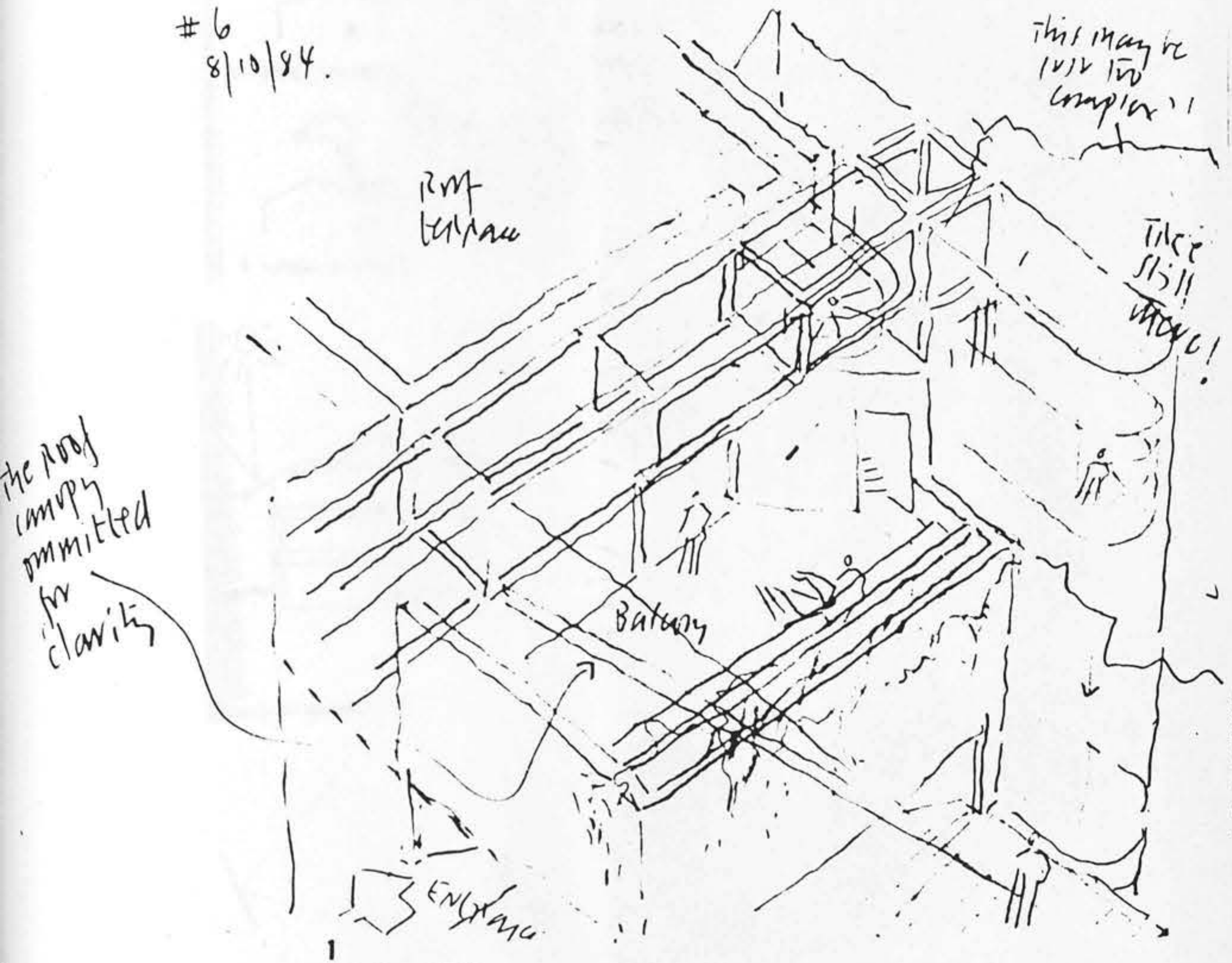


FIG 2E OTTO-SYSTEM SKETCHES

', the generative ideas: Foster's sketches of the suspended structure and the stack of villages in the tower.



1

isse pour le Centre d'art contemporain et la médiathèque de Nimes.

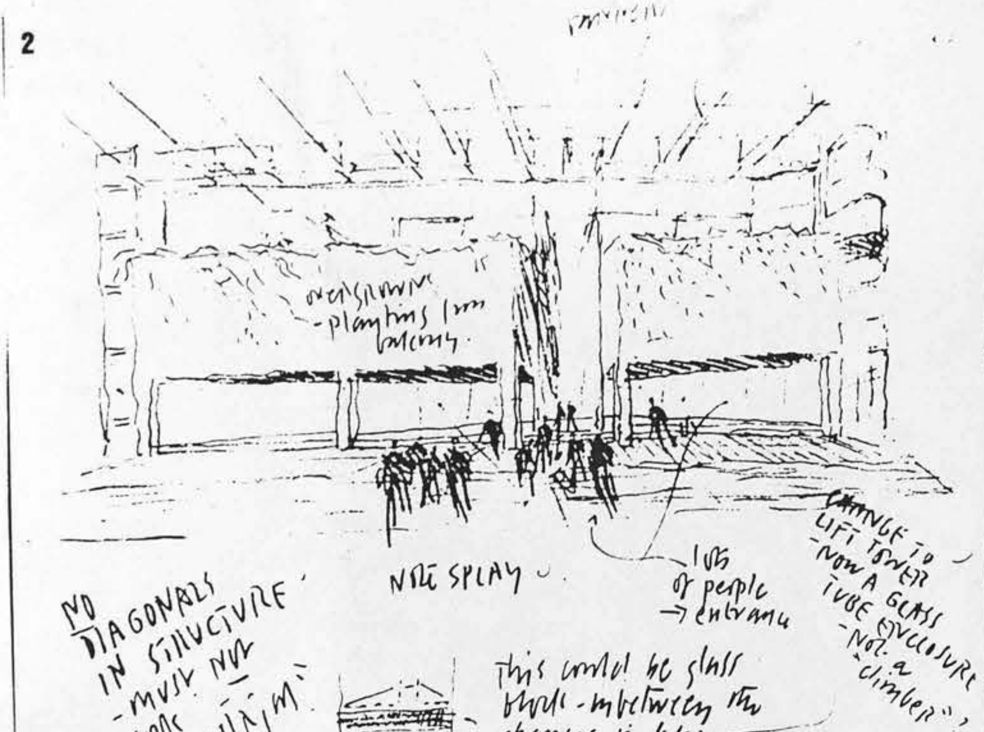
FIG 3A

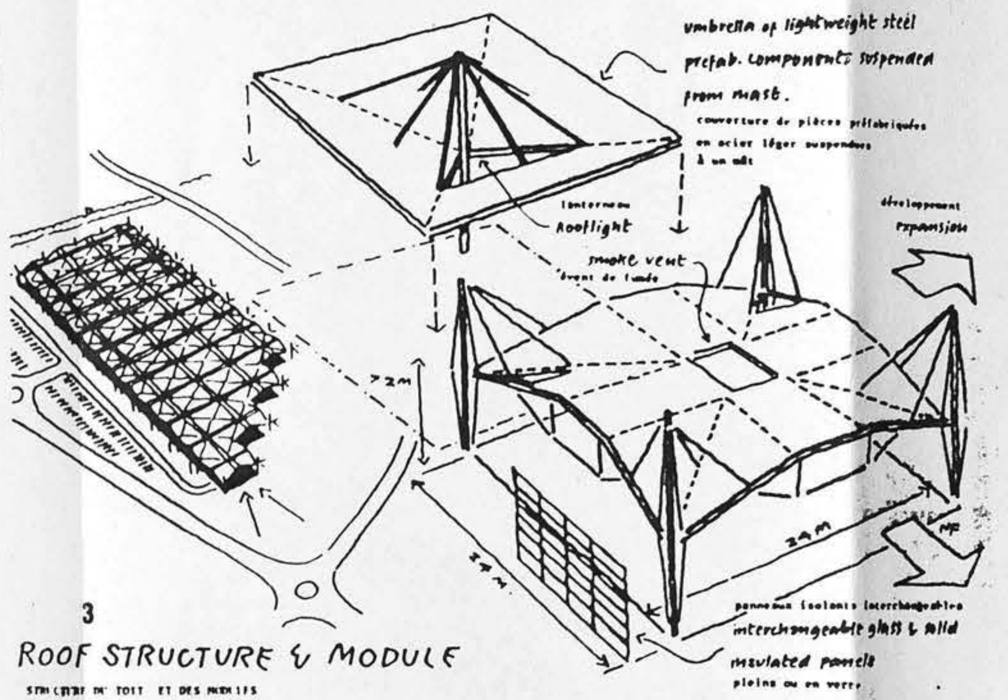
1,2 NIMES ART CENTRE
3 RENAULT CENTRE
4,5 HONG KONG and SHANGHAI BANK

(FOSTER ASSOCIATES)

3A-D IDEAS ON BUILDING FORMS CONSIDERED IN RELATION TO STRUCTURAL SUPPORT

2

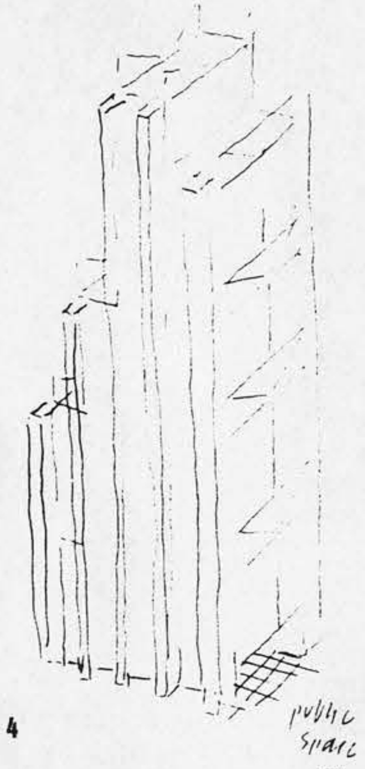




3

ROOF STRUCTURE & MODULE

STRUCTURE DU TOIT ET DES MODULES



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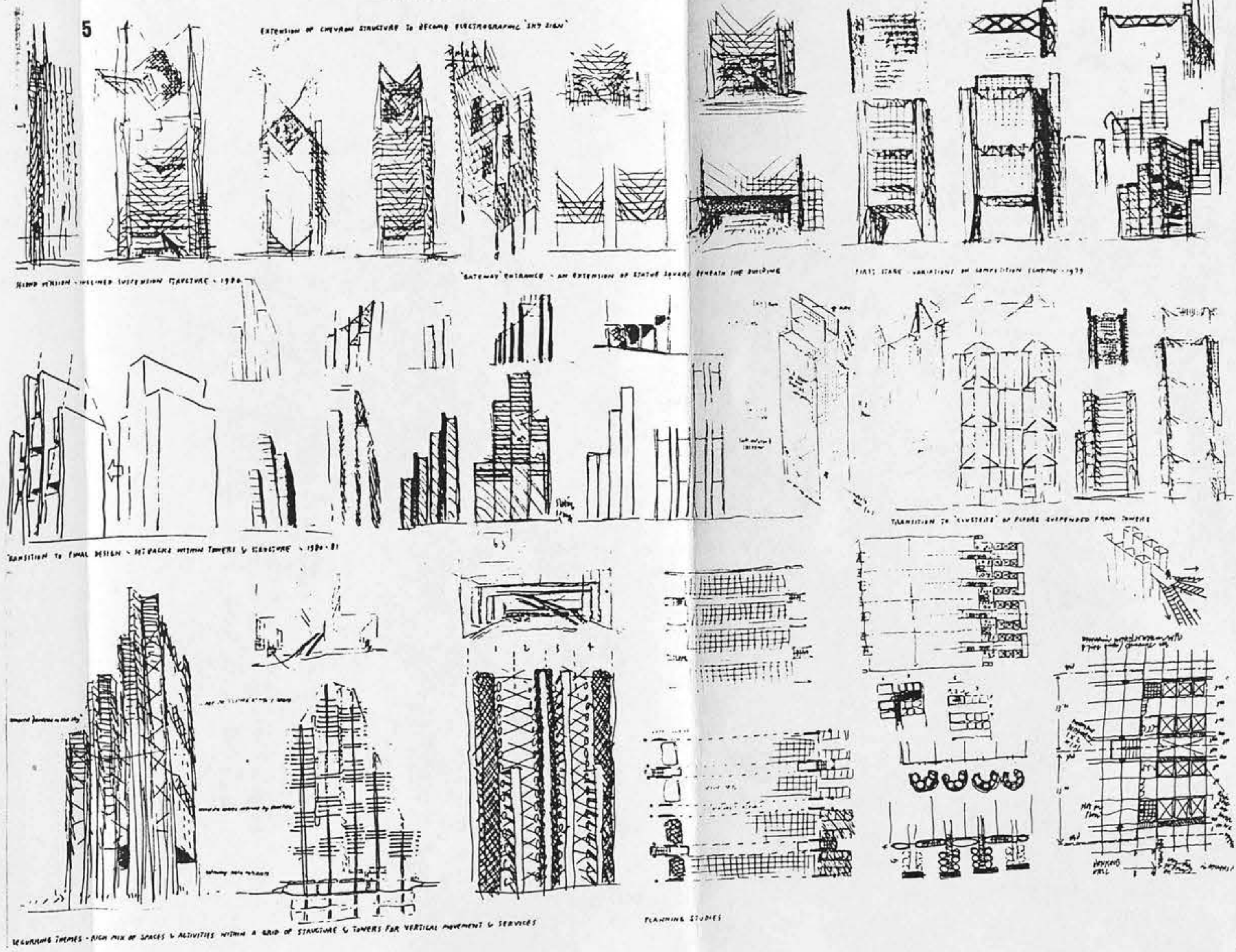


FIG 3B

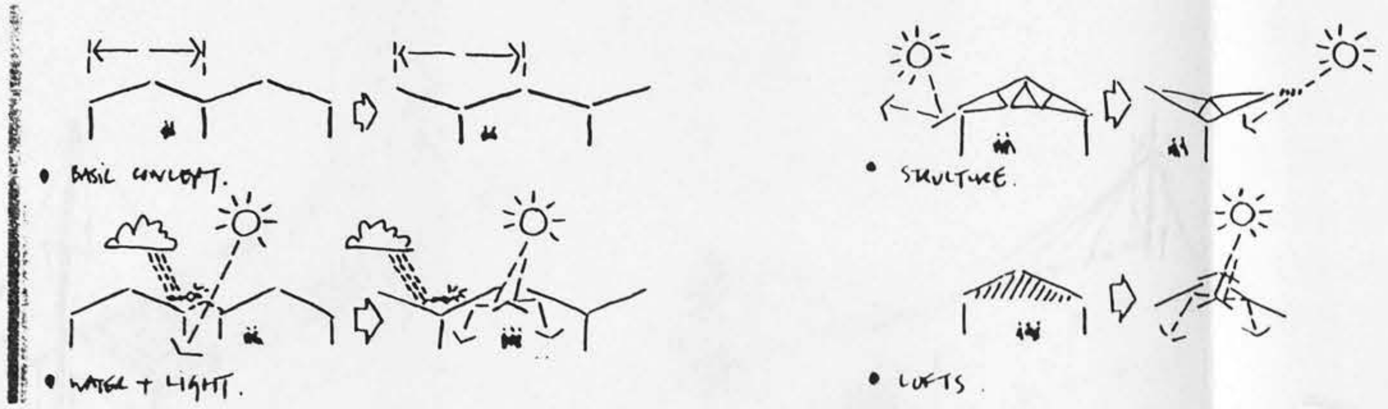
1-4 STANHOPE OFFICES

5 MENIL COLLECTN MUSEUM

6 B&B ITALIA OFFICES

7-9 IBM TRAVELLING EXHIBITION

10-11 SAINSBURY VISUAL ARTS CENTRE



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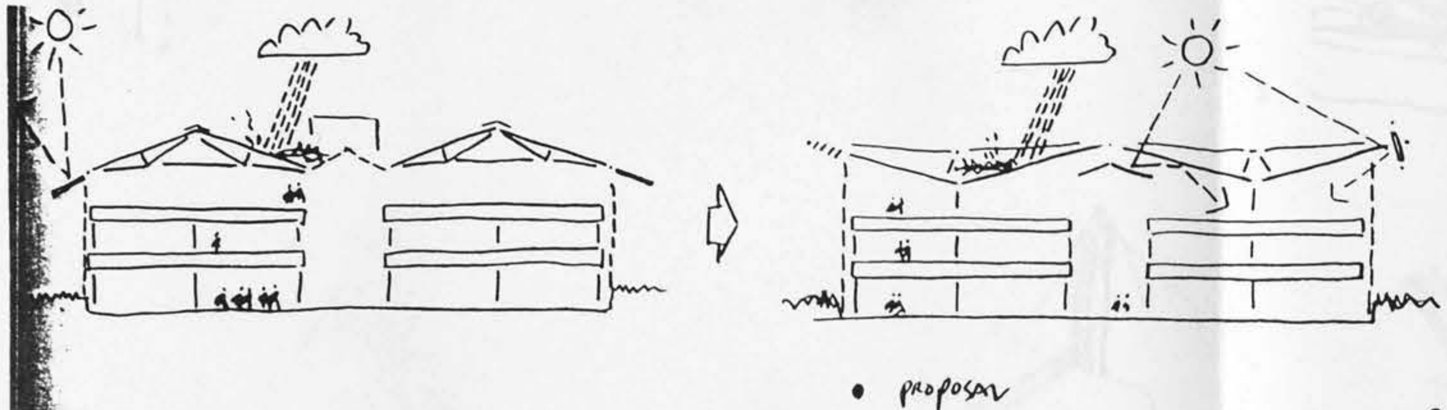
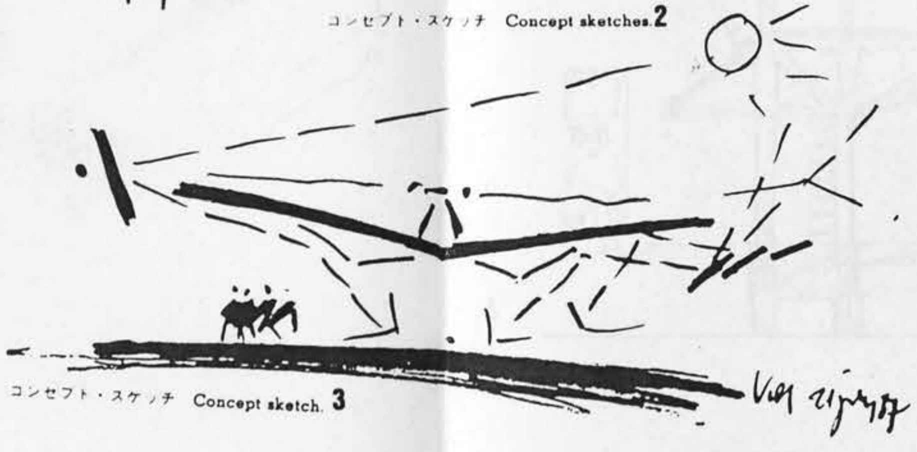
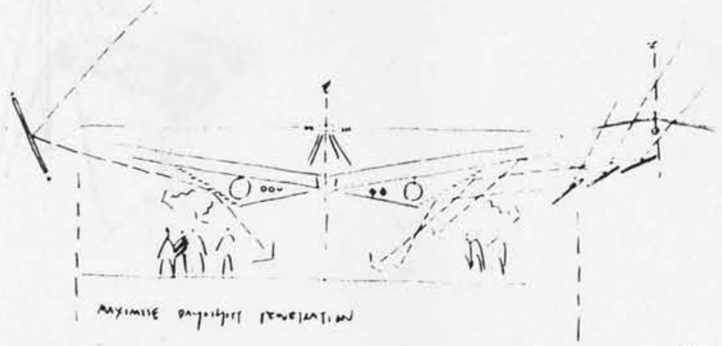


tch by Ken Shuttleworth

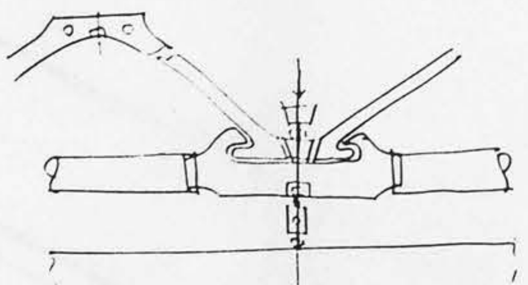
コンセプト・スケッチ Concept sketches.**2**



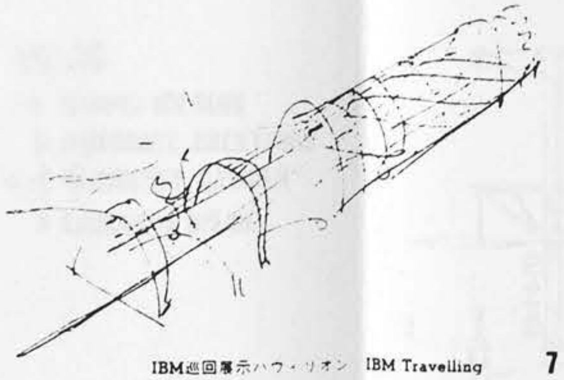
コンセプト・スケッチ Concept sketch. **3**



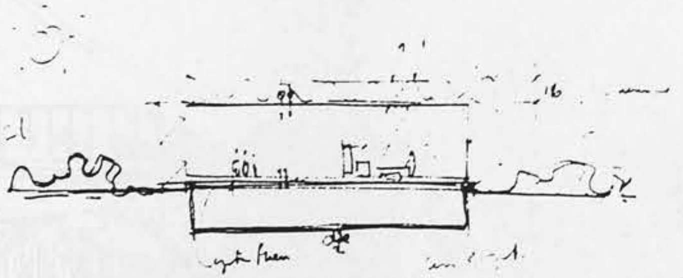
コンセプト・スケッチ Concept sketch. *Sketch by Ken Shuttleworth* **4**



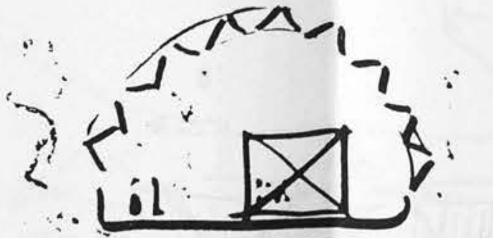
メニル・コレクション美術館 The Menil Collection Museum, 1981. **5**



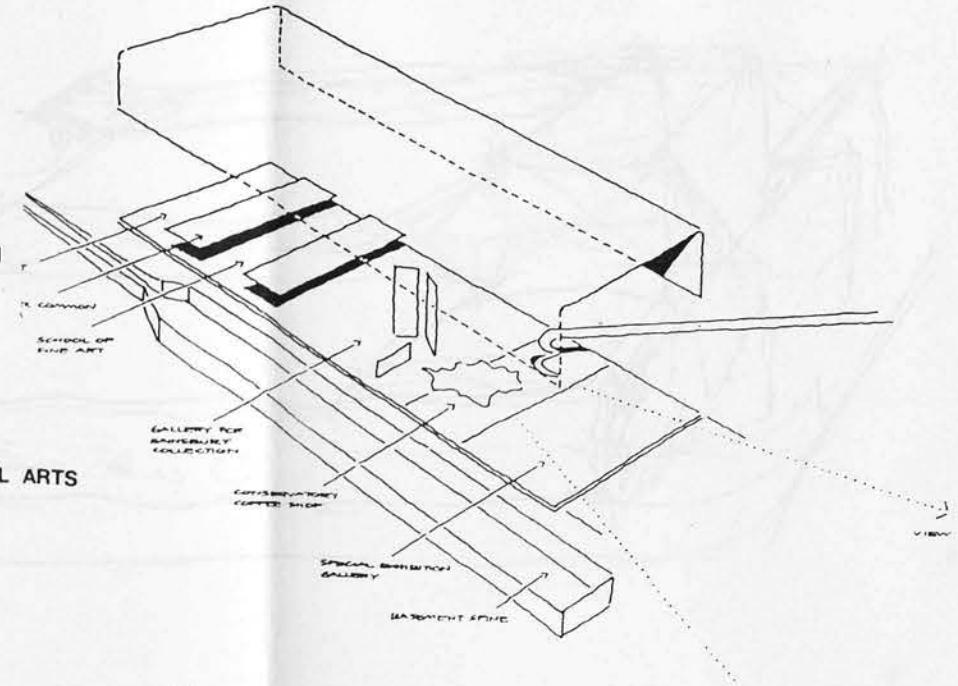
IBM巡回展示パヴィリオン IBM Travelling **7**



B&B イタリア・オフィス B&B Italia Offices Building, 1971. **6**



IBM巡回展示パヴィリオン IBM Travelling Pavilion, 1982. **8**



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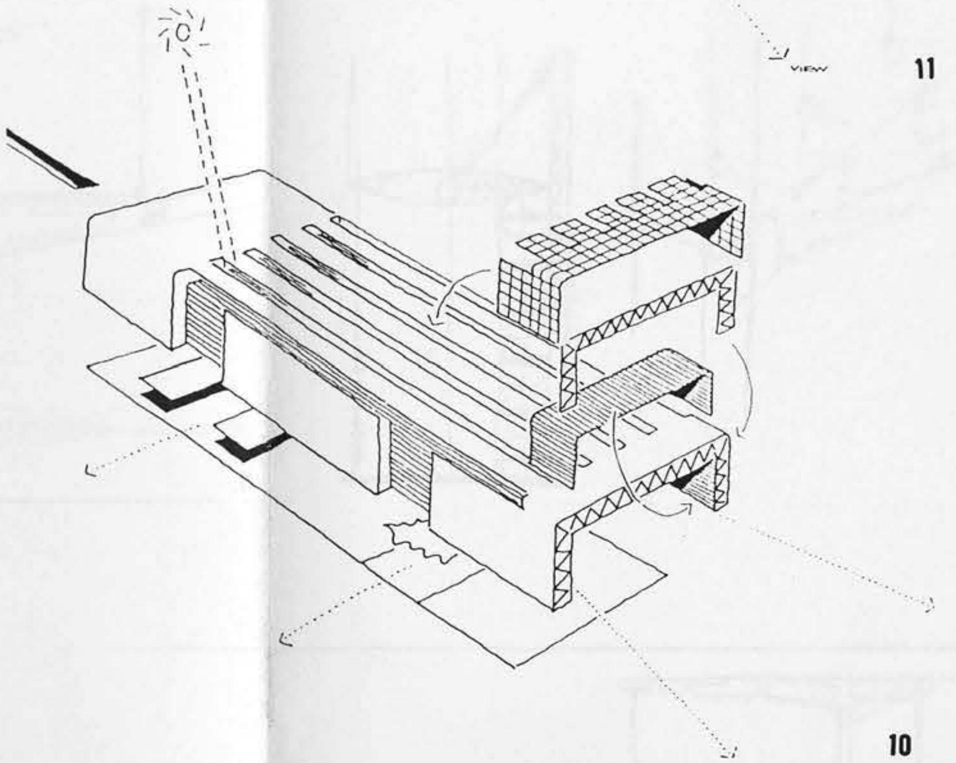

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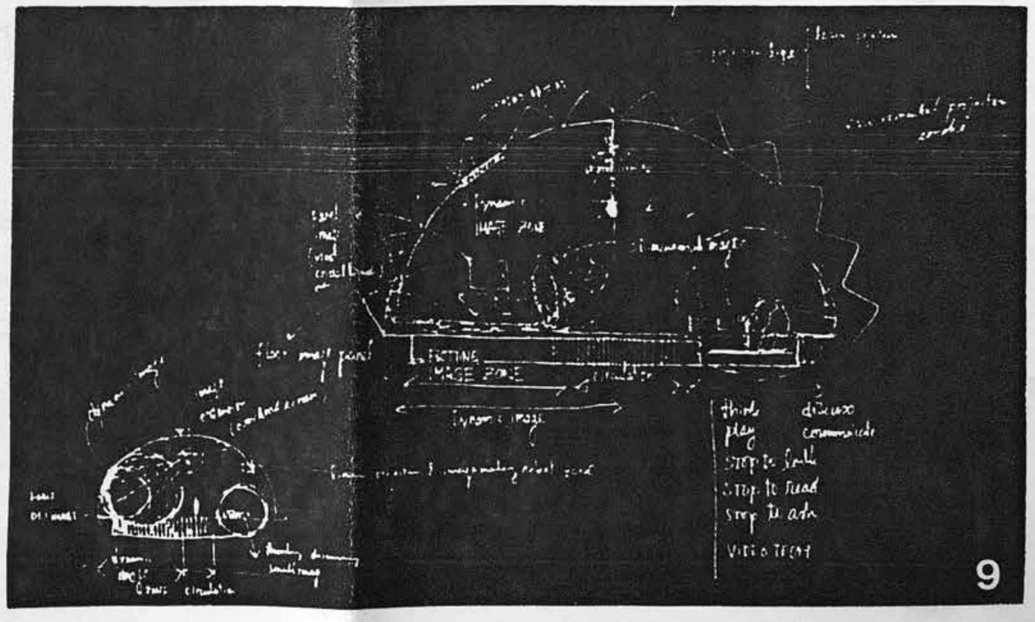

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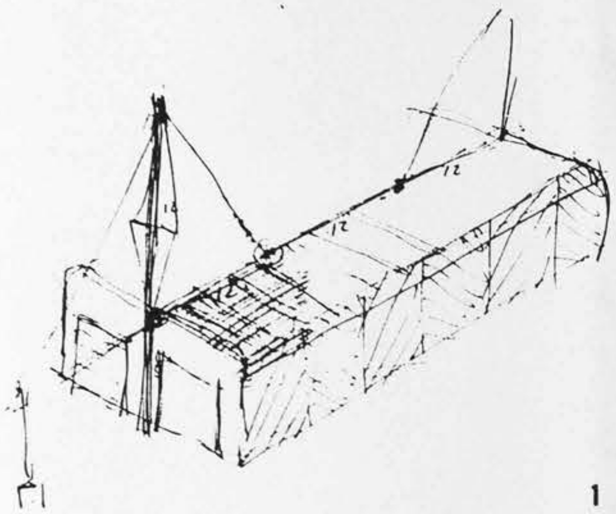

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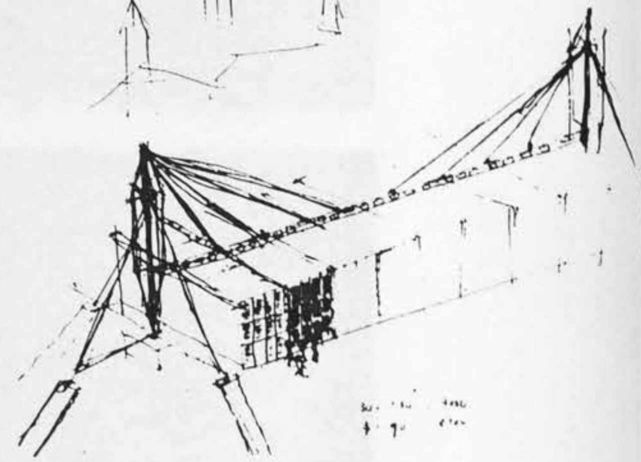

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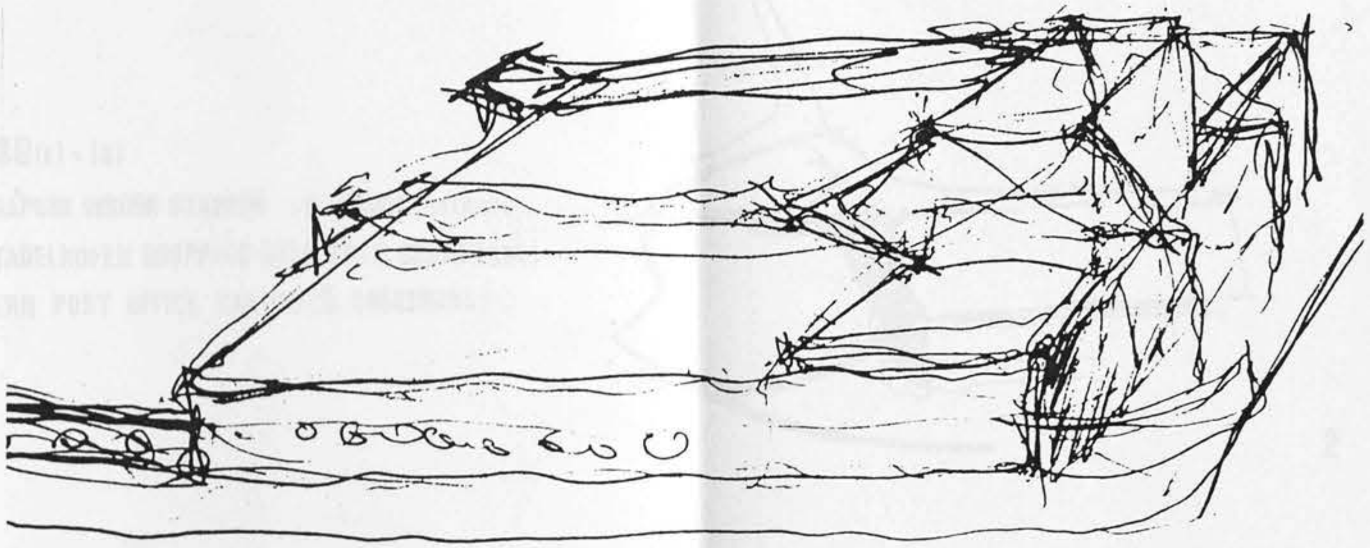

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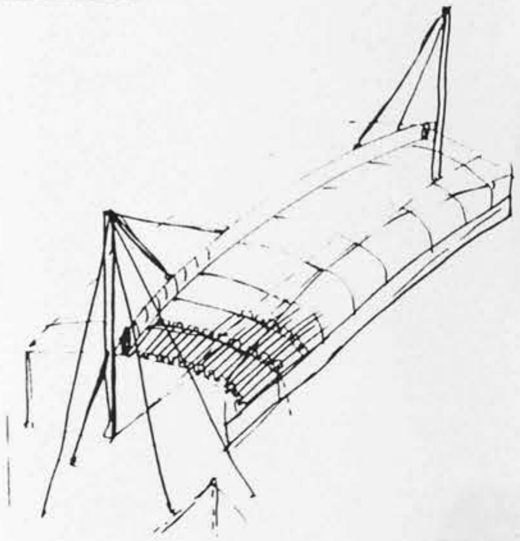

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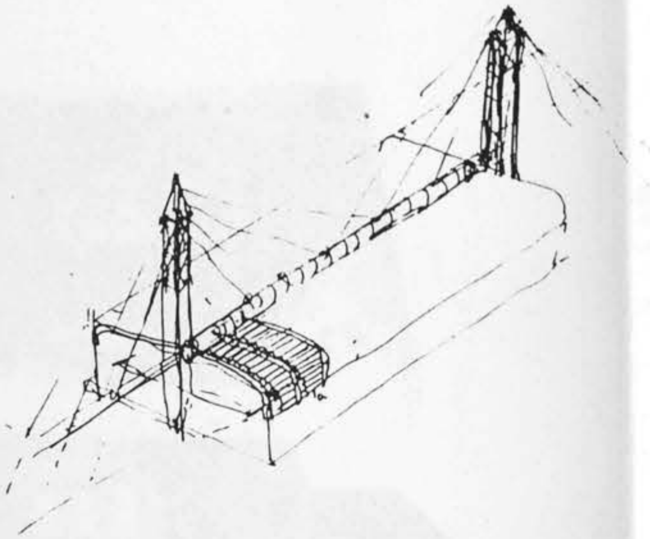

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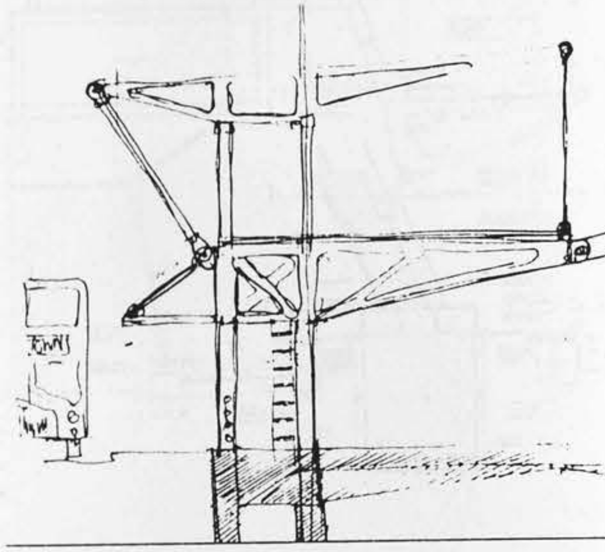

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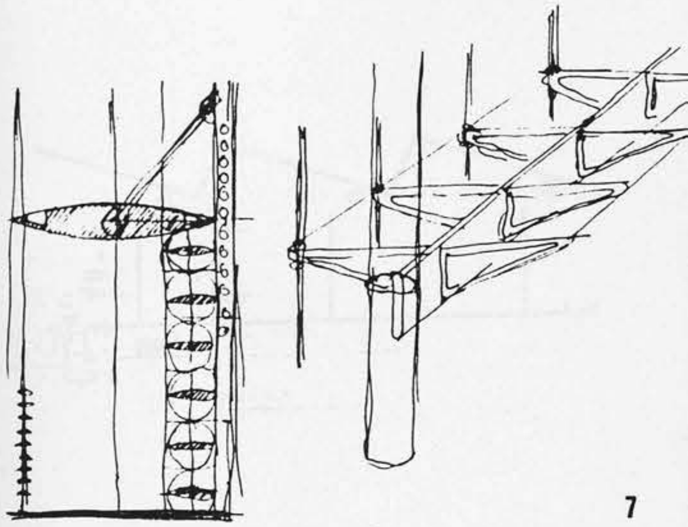

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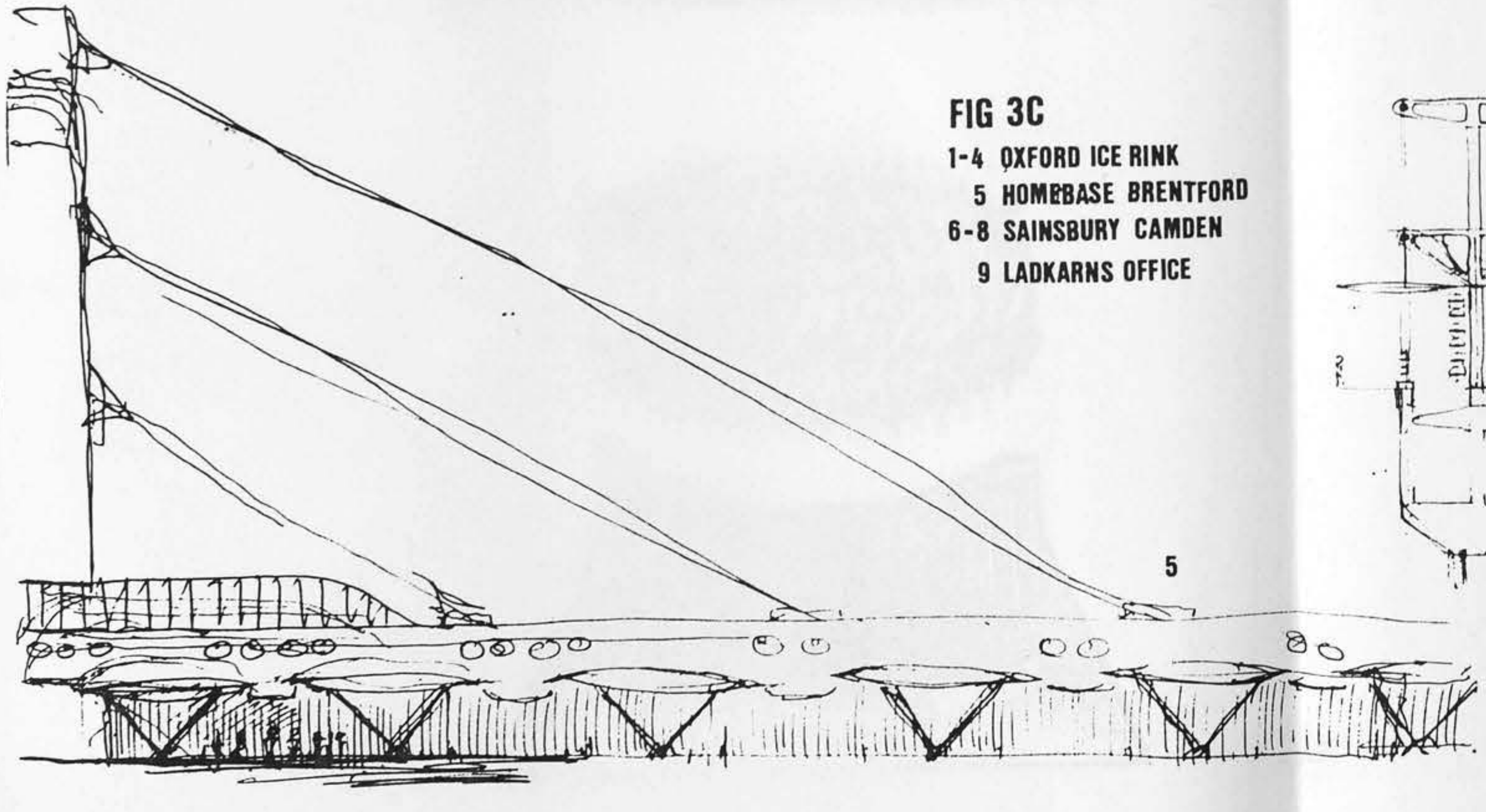
FIG 3C

1-4 OXFORD ICE RINK
5 HOMEBASE BRENTFORD
6-8 SAINSBURY CAMDEN
9 LADKARNS OFFICE



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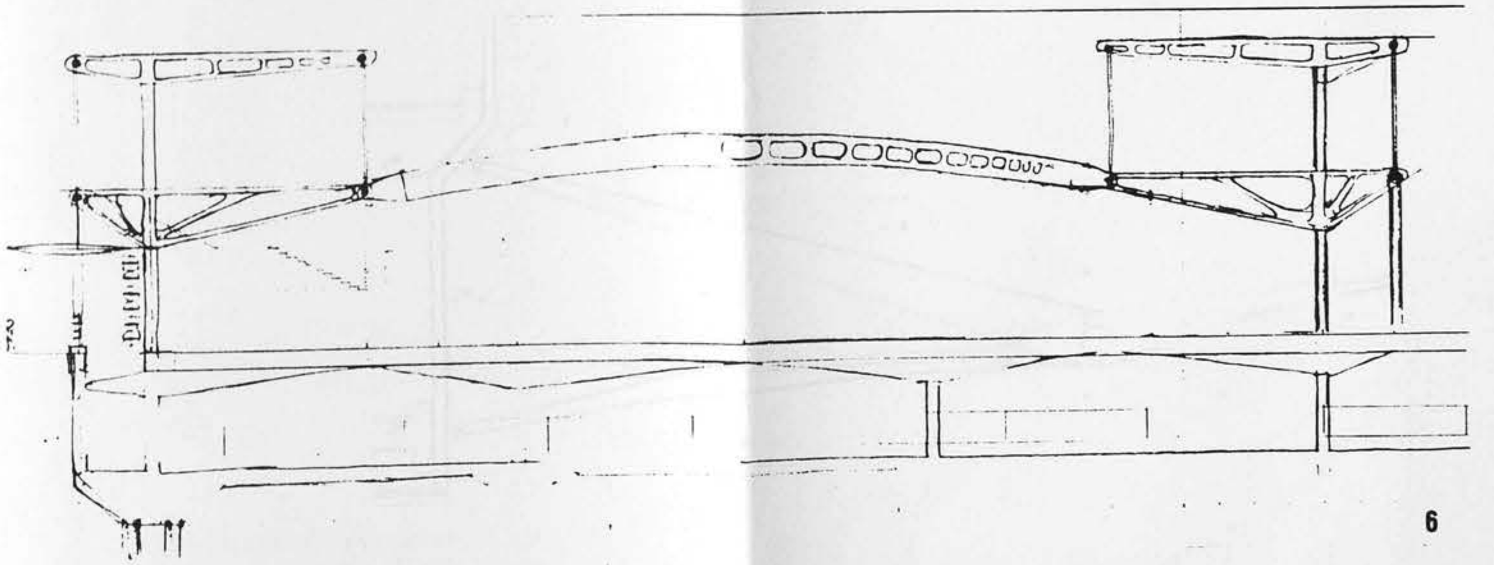

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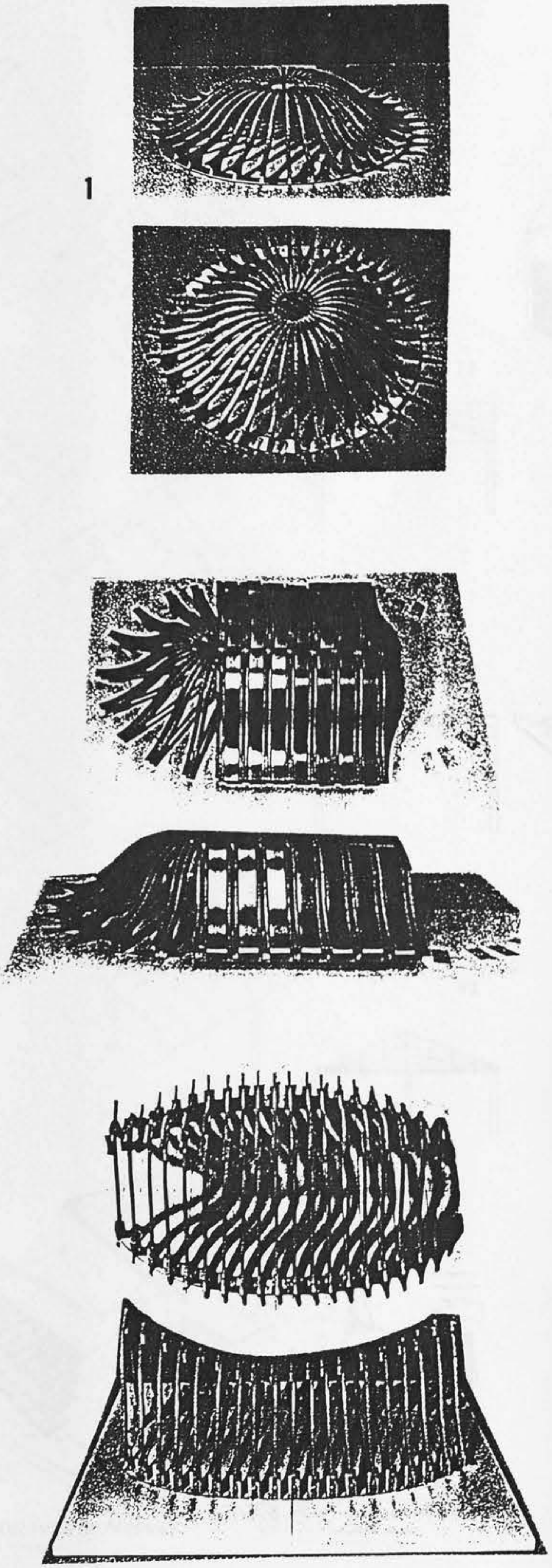
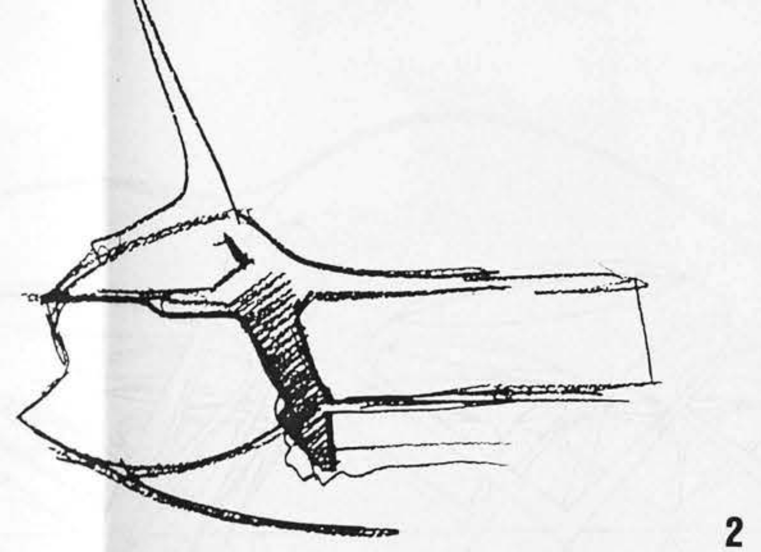

1

FIG 3D(1) - (4)

1. SINGAPORE INDOOR STADIUM (K. TANGE) STUDIES
2,3. STADELHOFEN SHOPPING GALLERY (S. CALATRAVA)
4. LUCERN POST OFFICE CANOPY (S. CALATRAVA)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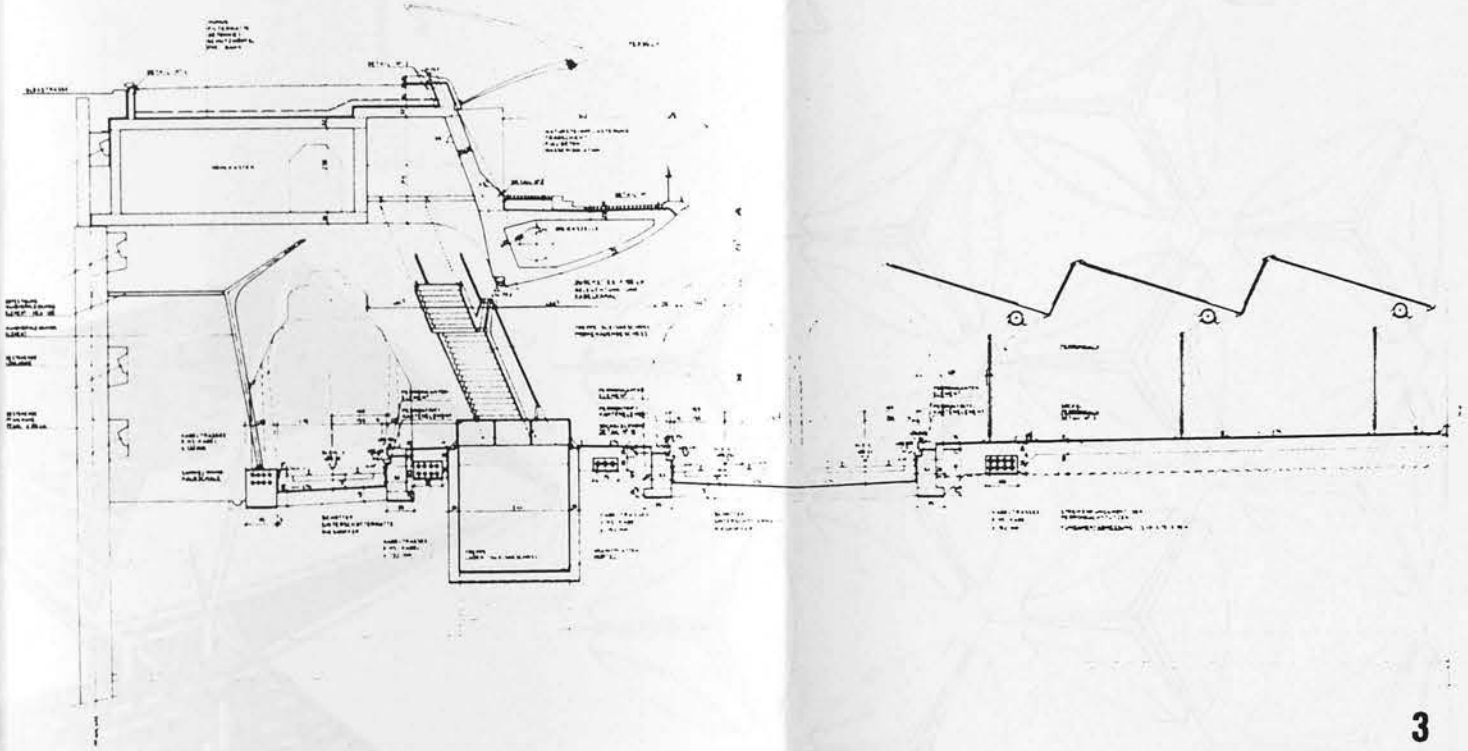
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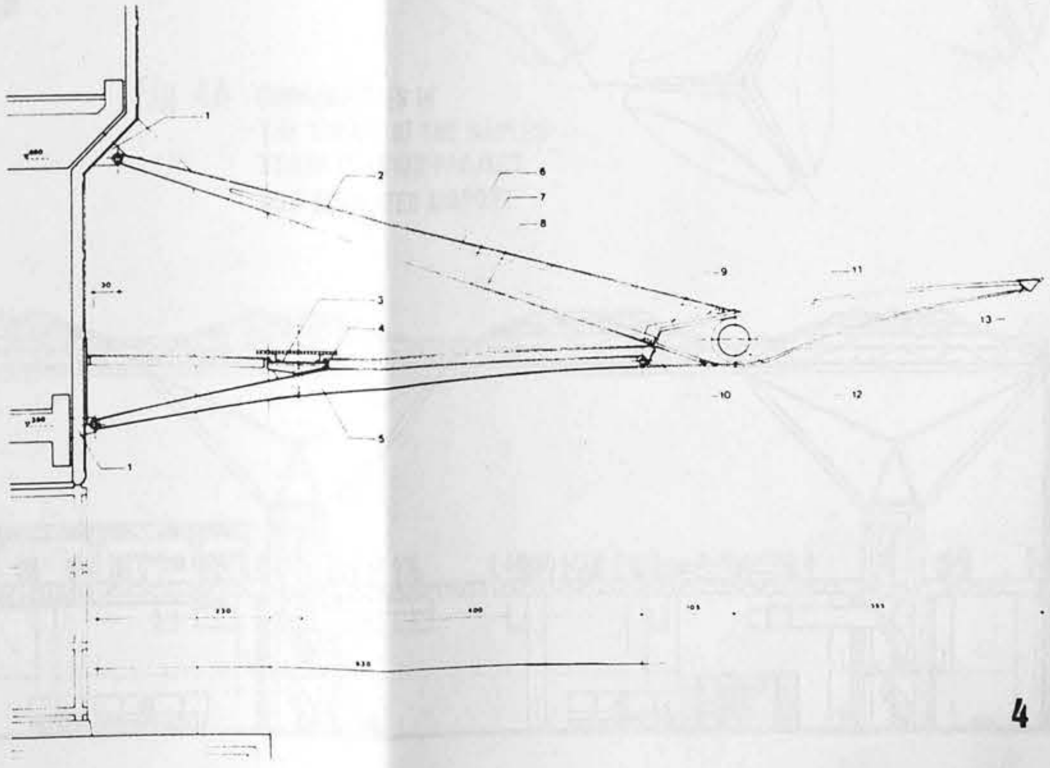

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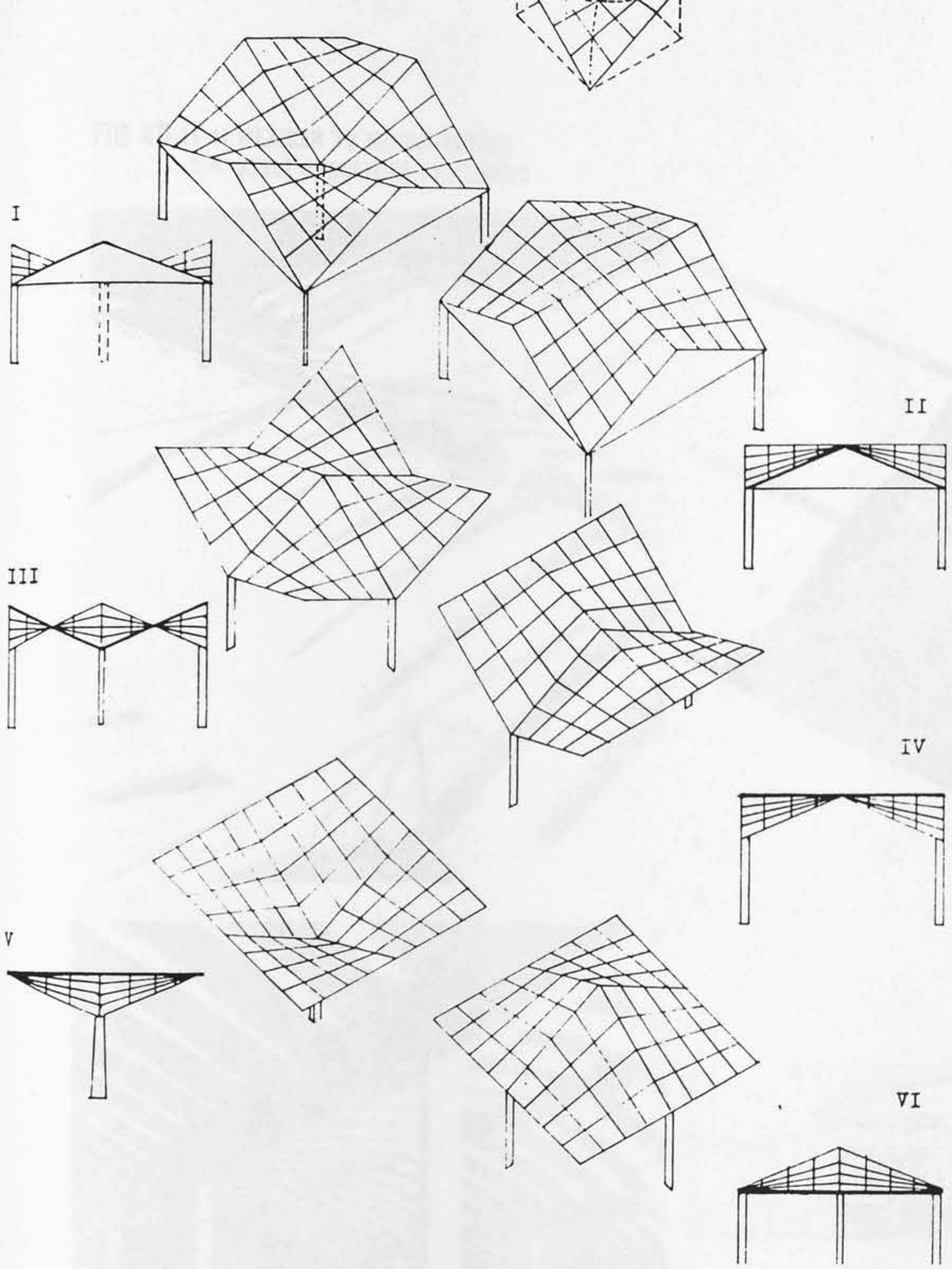
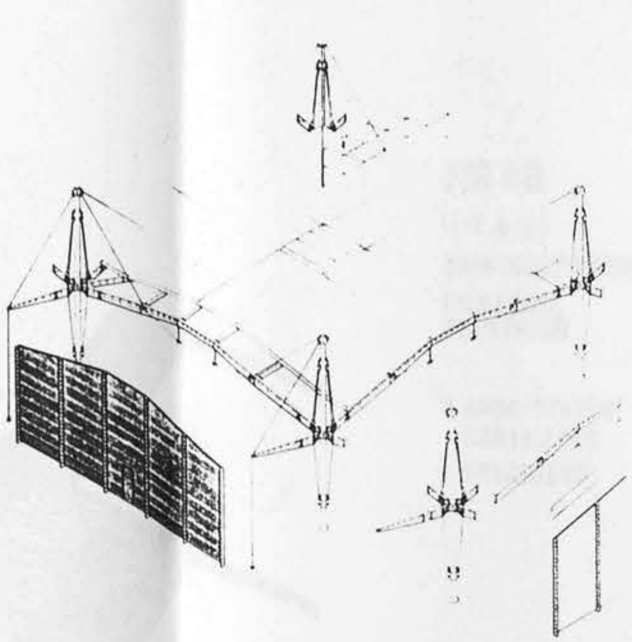
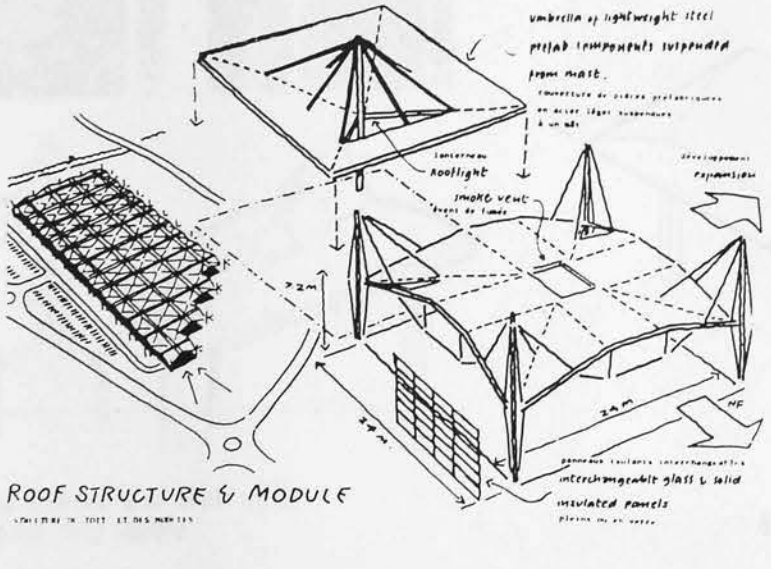


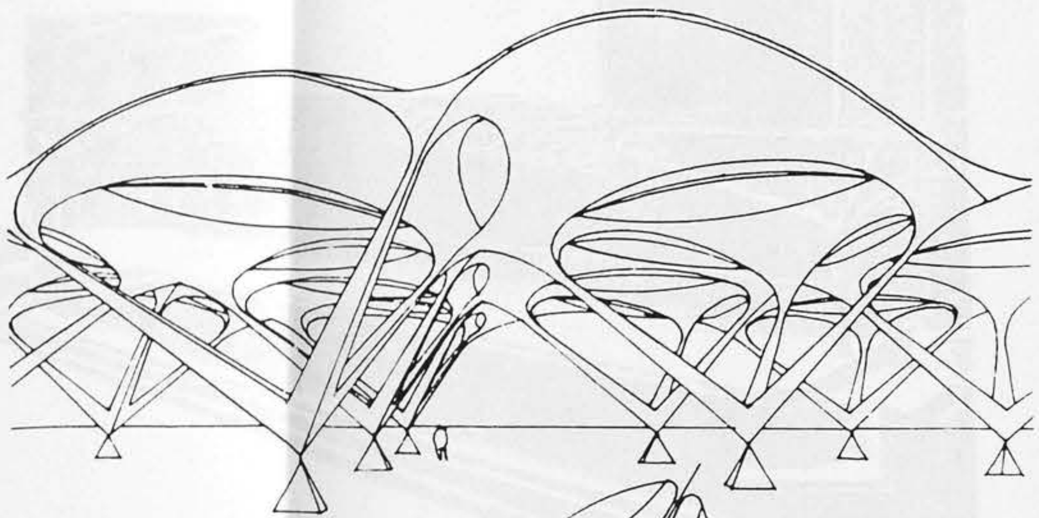
Fig 4C THE PRECEDENT HP SHELL FORMS OF THE RENAULT CENTRE STRUCTURAL MODULE

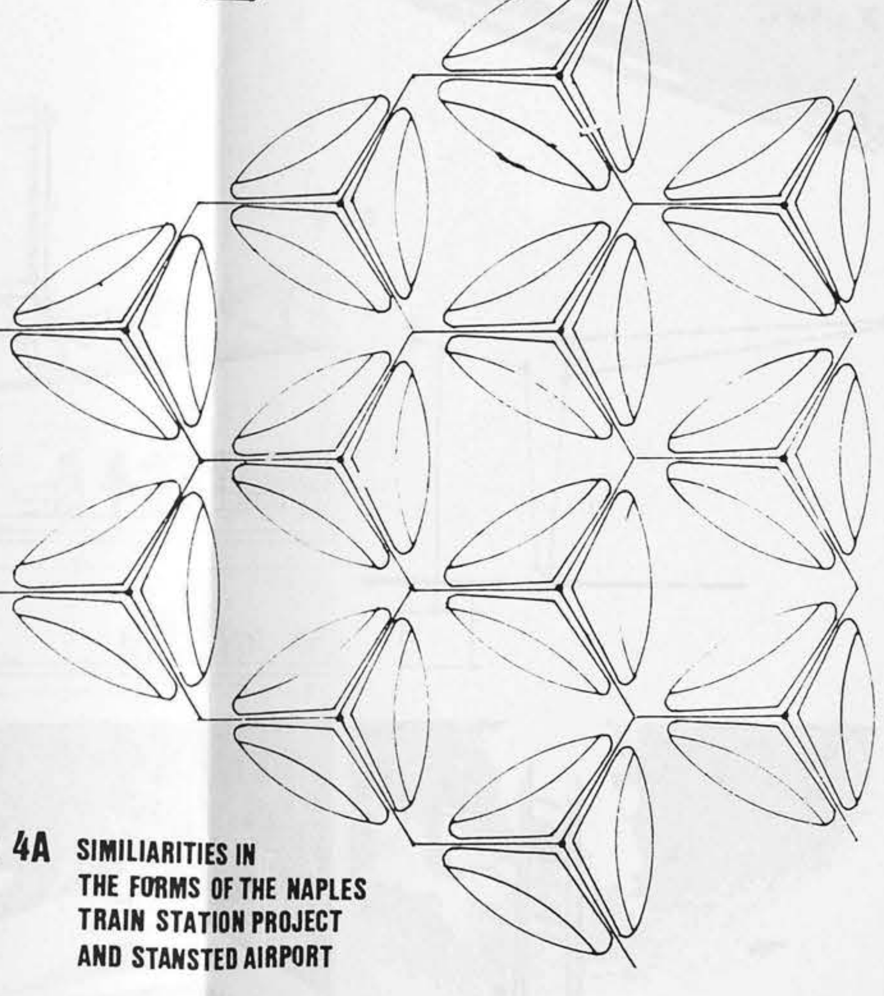




ROOF STRUCTURE & MODULE

STRUCTURE DU TOIT ET DES MODULES





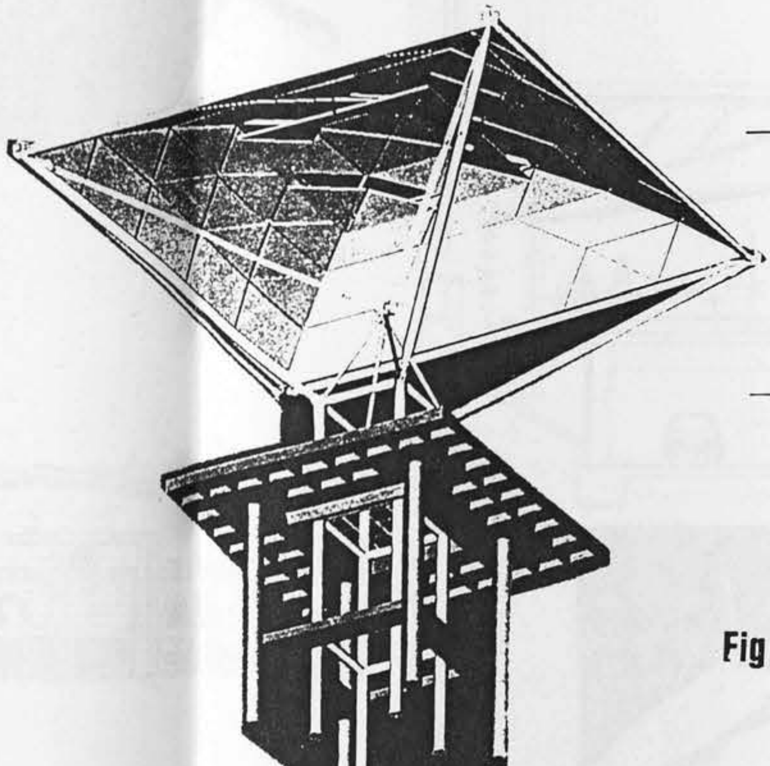


Fig 4A SIMILIARITIES IN THE FORMS OF THE NAPLES TRAIN STATION PROJECT AND STANSTED AIRPORT

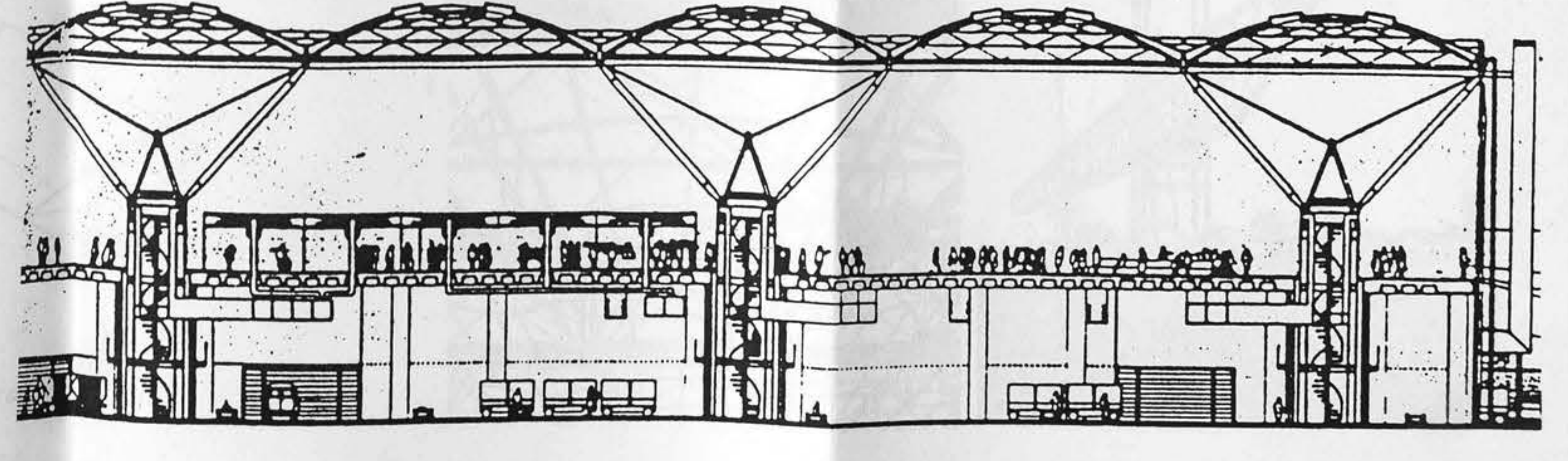
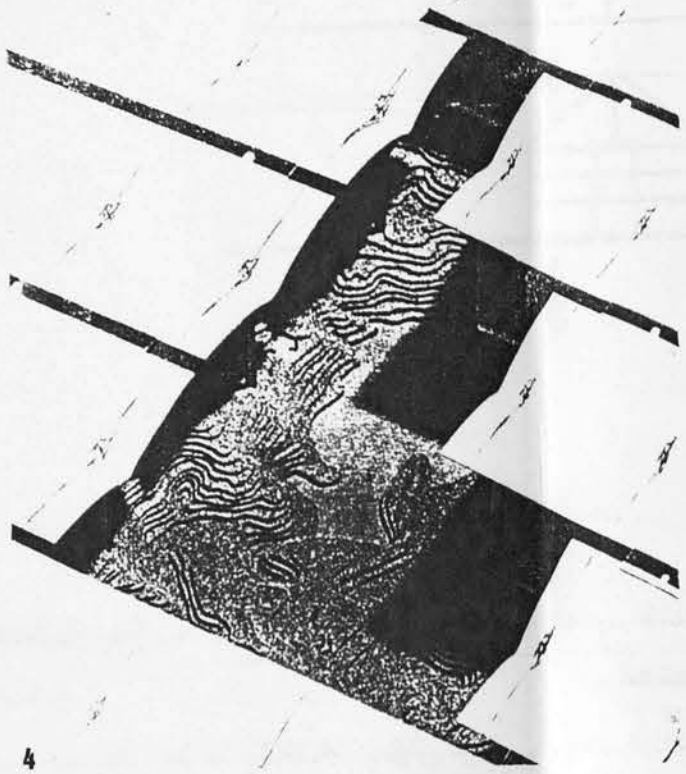


FIG 4B (1-4) **MEXICAN TV HEADQUARTERS**
5,6 SHELL STRUCTURE PRECEDENT

1



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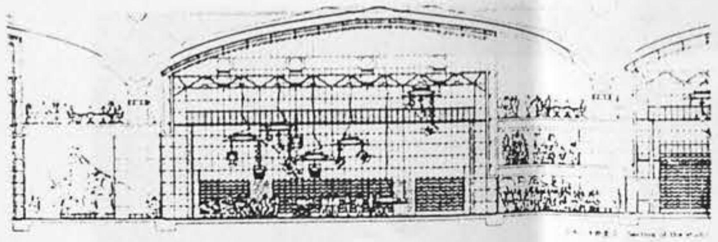
3



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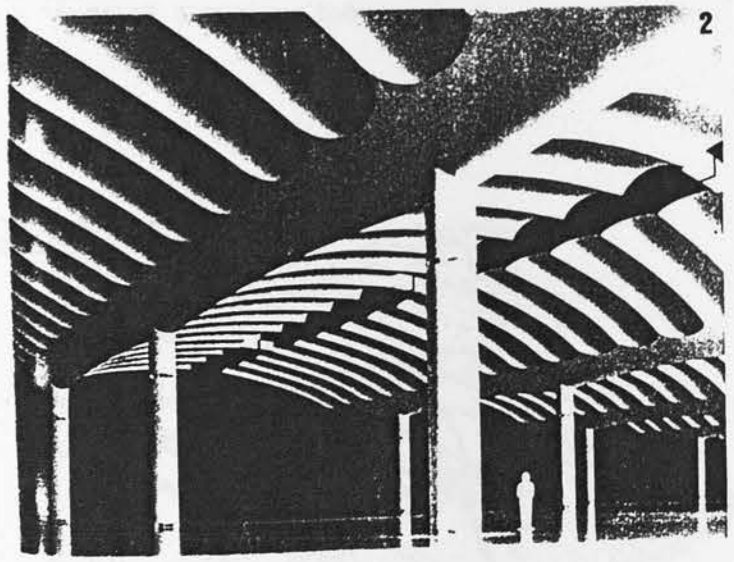
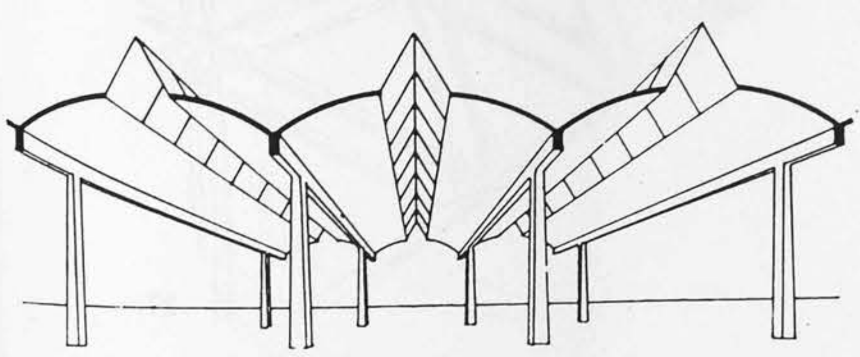
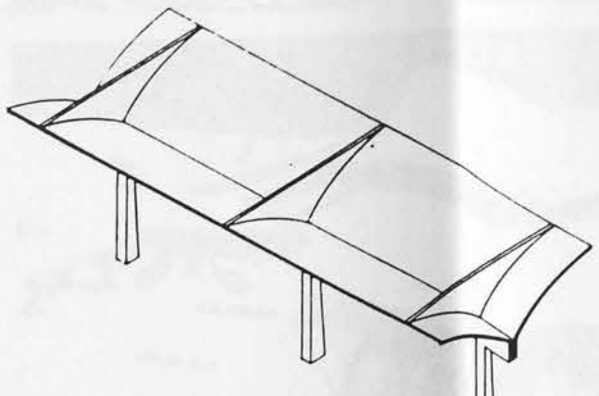




5 *Cantilevered cylindrical shell with interspaced roof lights*

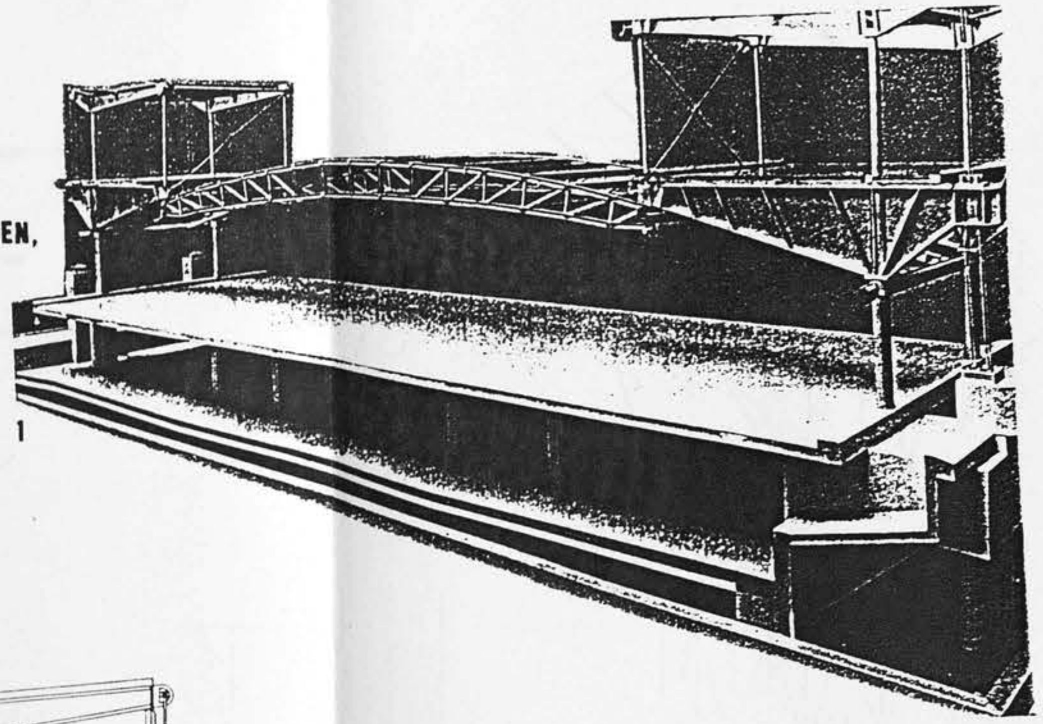


6 *Station roof*

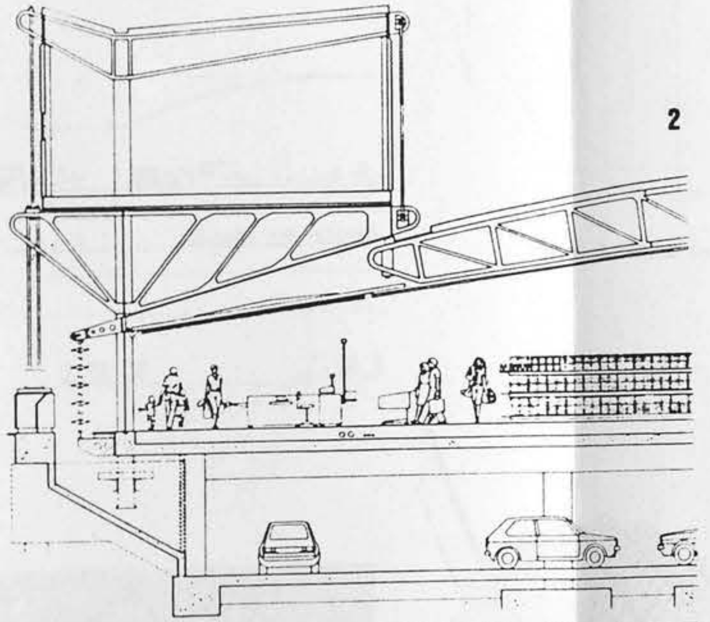
FIG 4D
(1-2,4-6)
SAINSBURY CAMDEN,
HOMEBASE
BRENTFORD

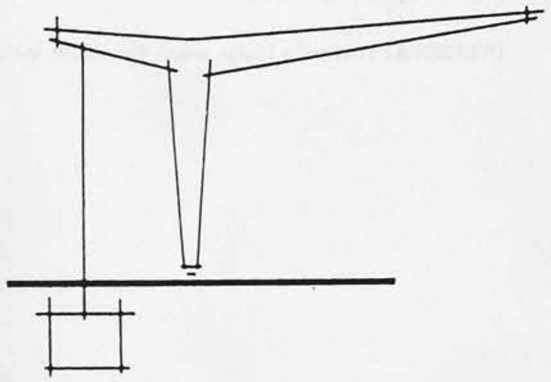
3 BACK-STAYED
CANTILEVER
PRECEDENT

1



2 3





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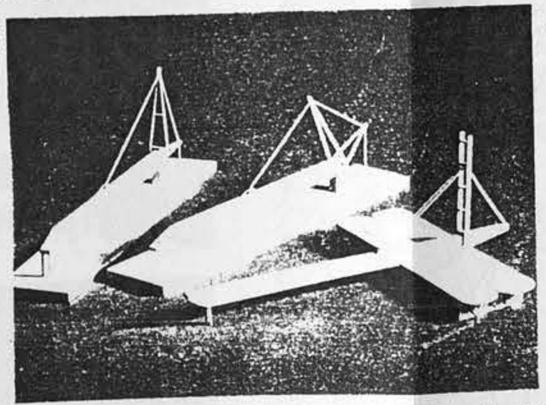

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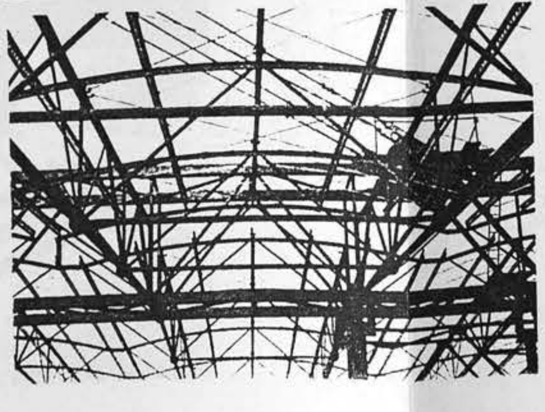


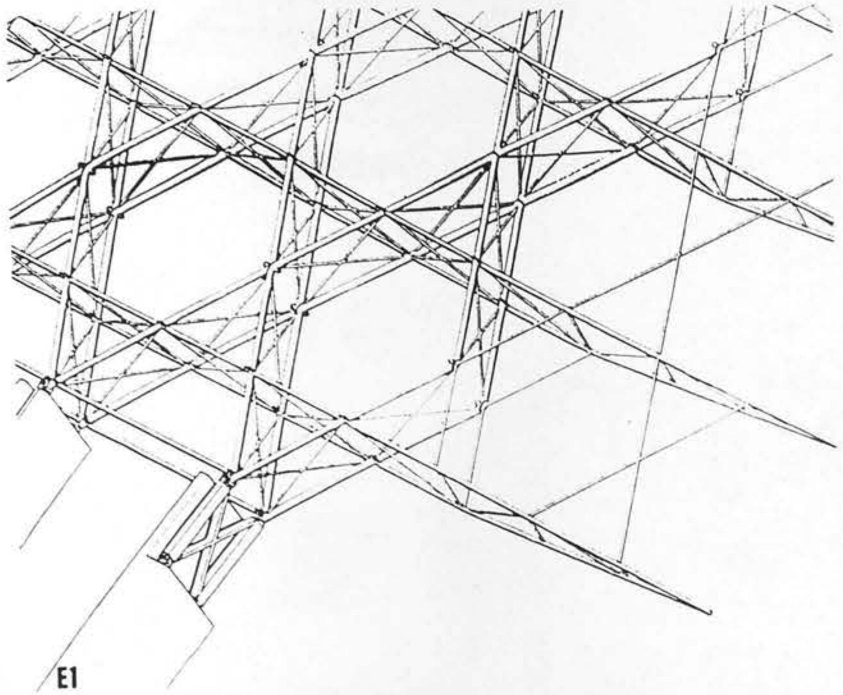

E1

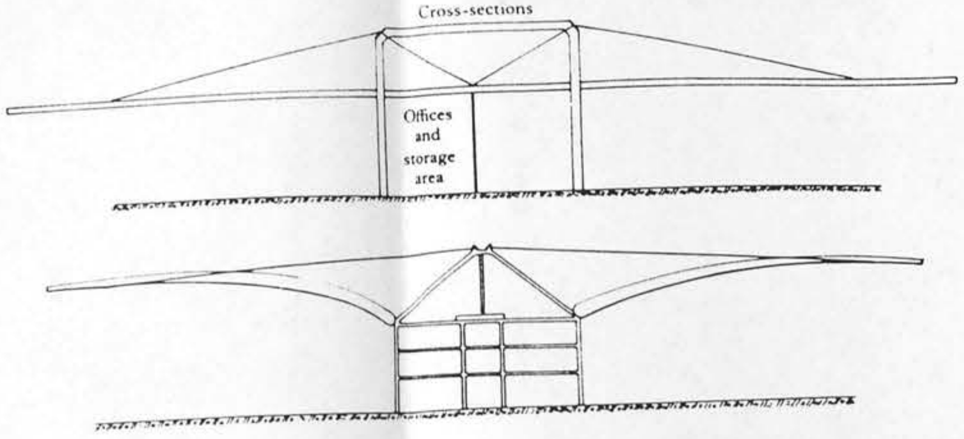
FIG 4 (E - G) PRECEDENT FORMS

E1,2 FRANKFURT STADIUM, STEEL LAMELLA PRECEDENT (MAKOWSKI)

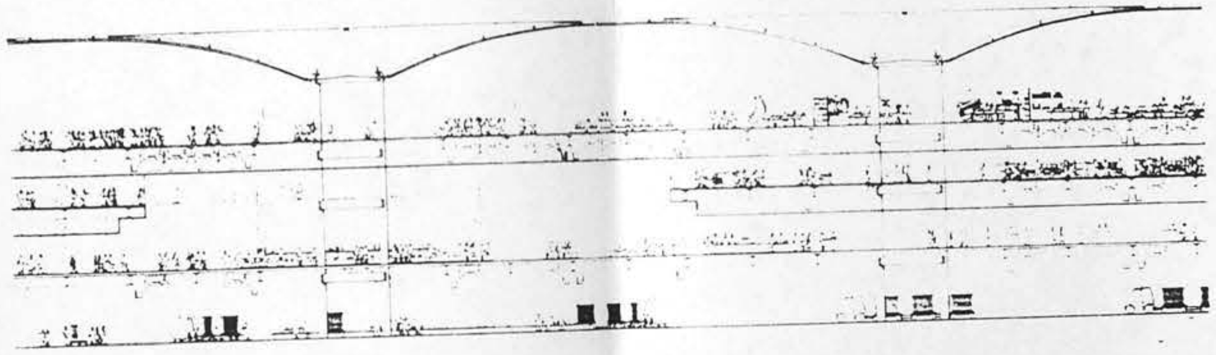
F1,2 FOSTER'S ENTRY FOR THE KANSAI AIRPORT COMPETITION

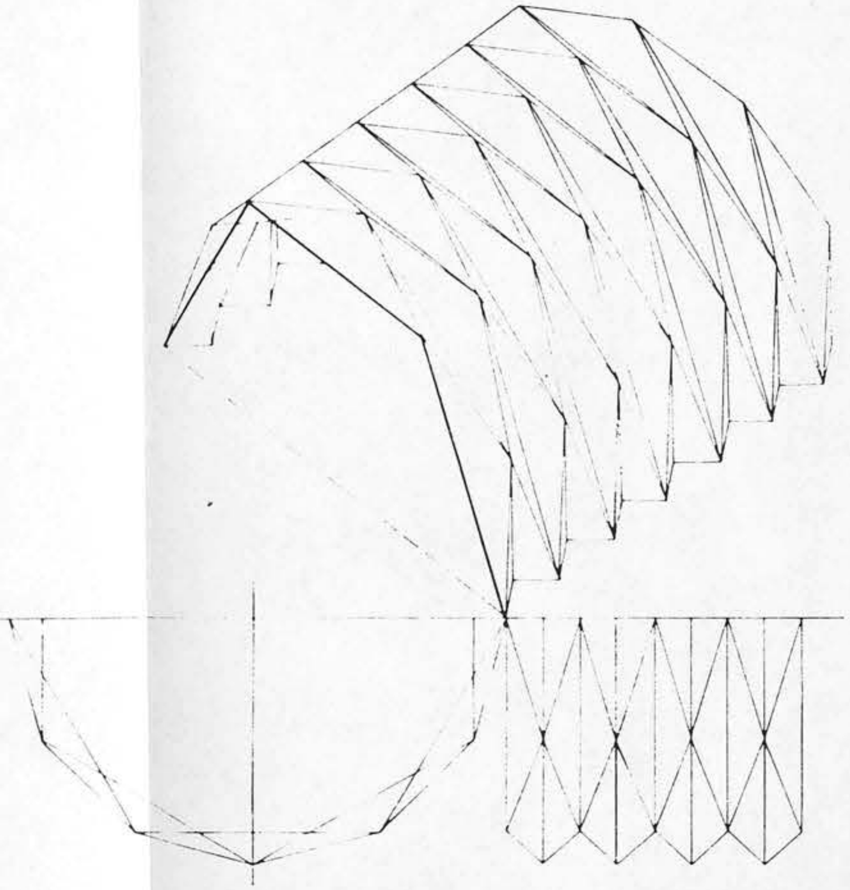
F3 CABLE-STAYED PRECEDENTS (MAKOWSKI)

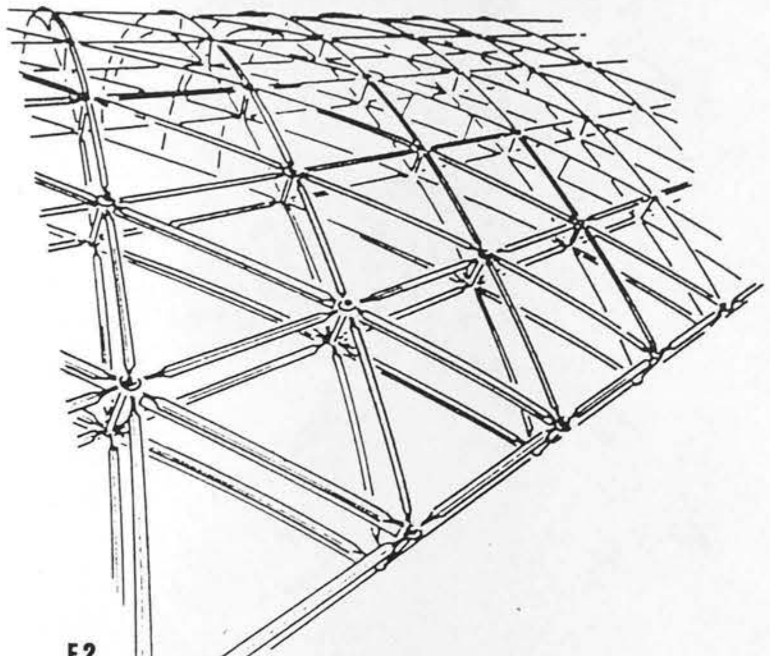
G1,2 IBM EXHIBITION VAULT, SURFACE STRUCTURE PRECEDENT

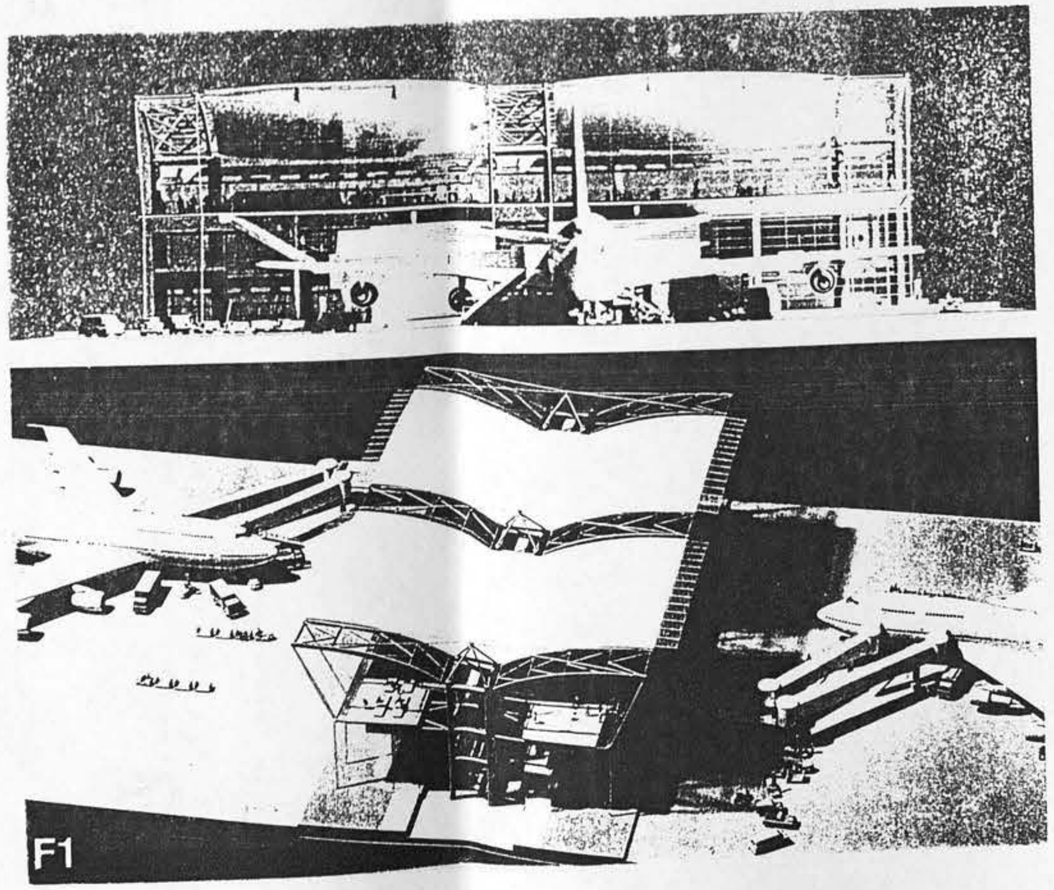


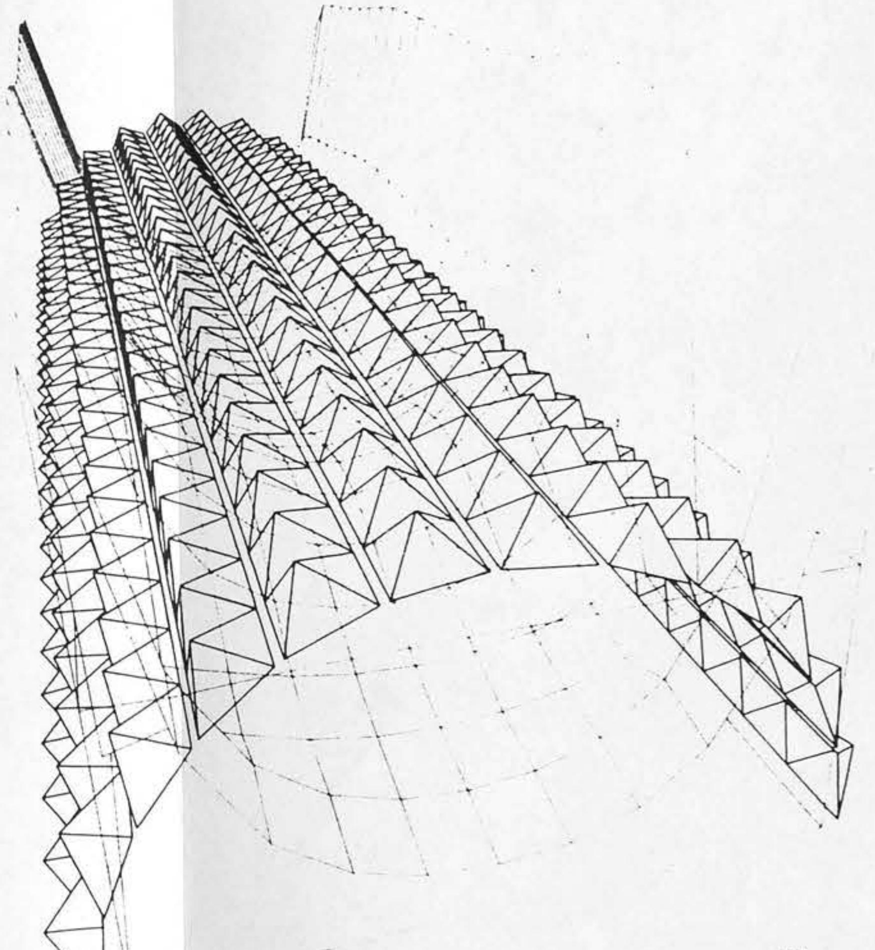
F3

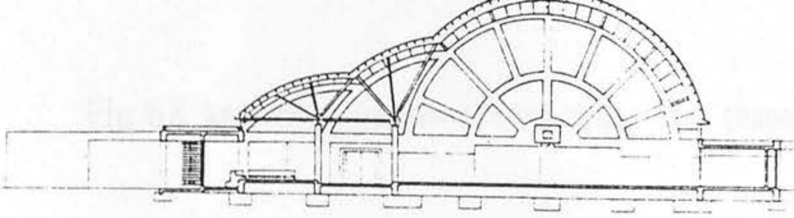

F2

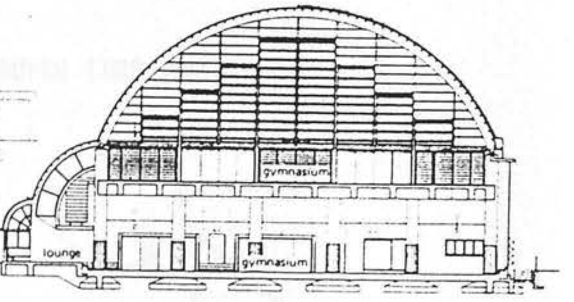

G2 *A folded barrel made up from equal elements* (ANGERER)


E2


F1

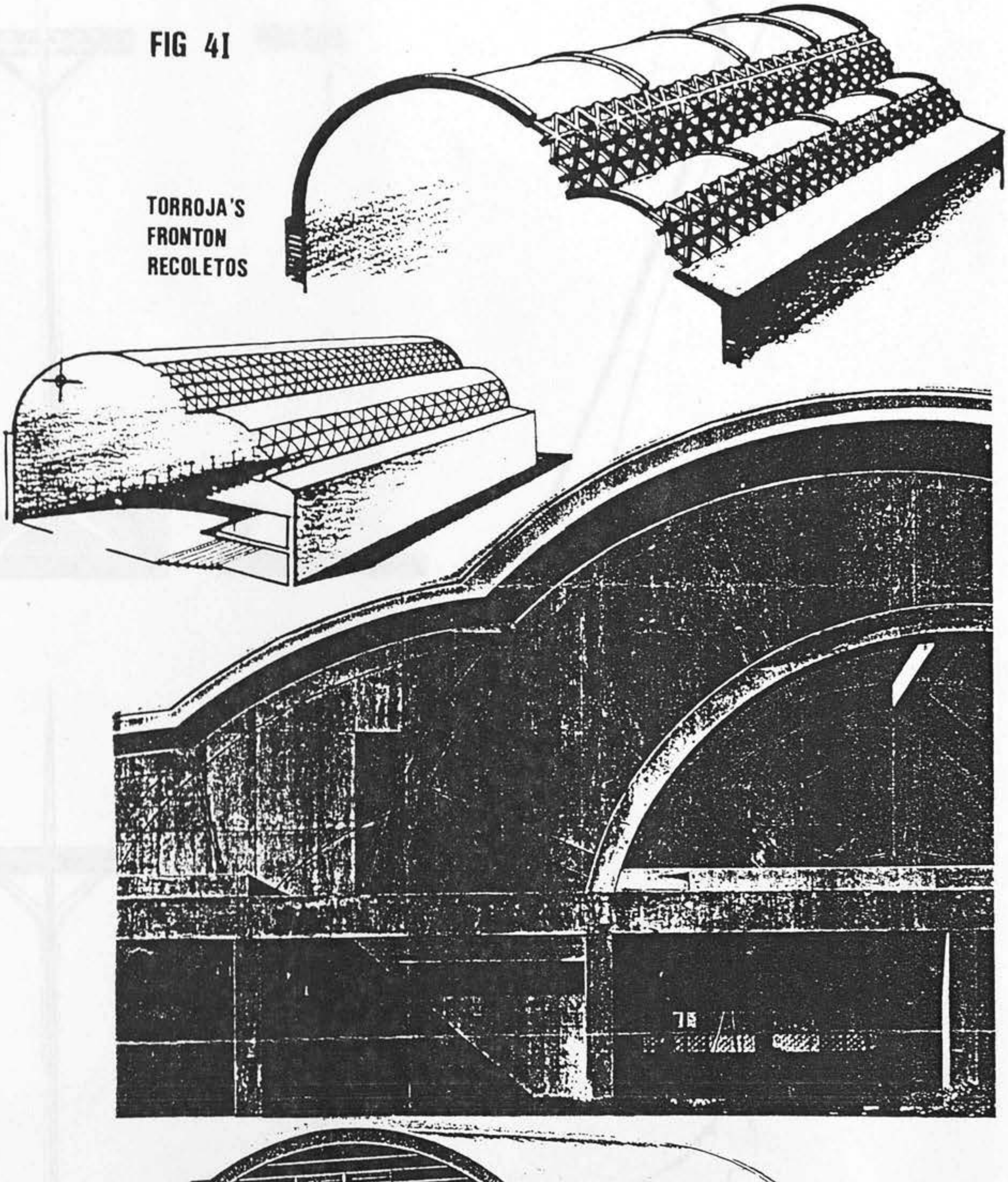

G1





NAGASHIMA'S GYMNASIUMS

FIG 4I



TORROJA'S FRONTON RECOLETOS

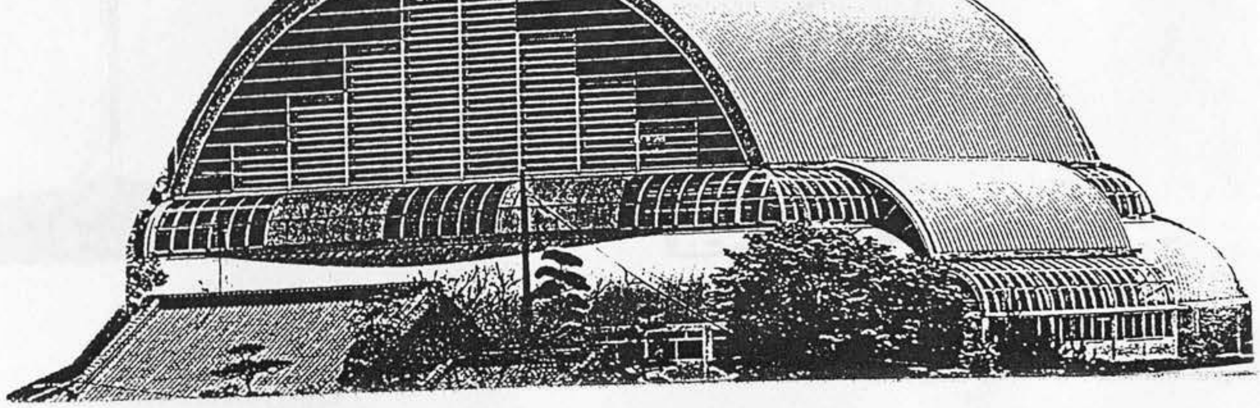
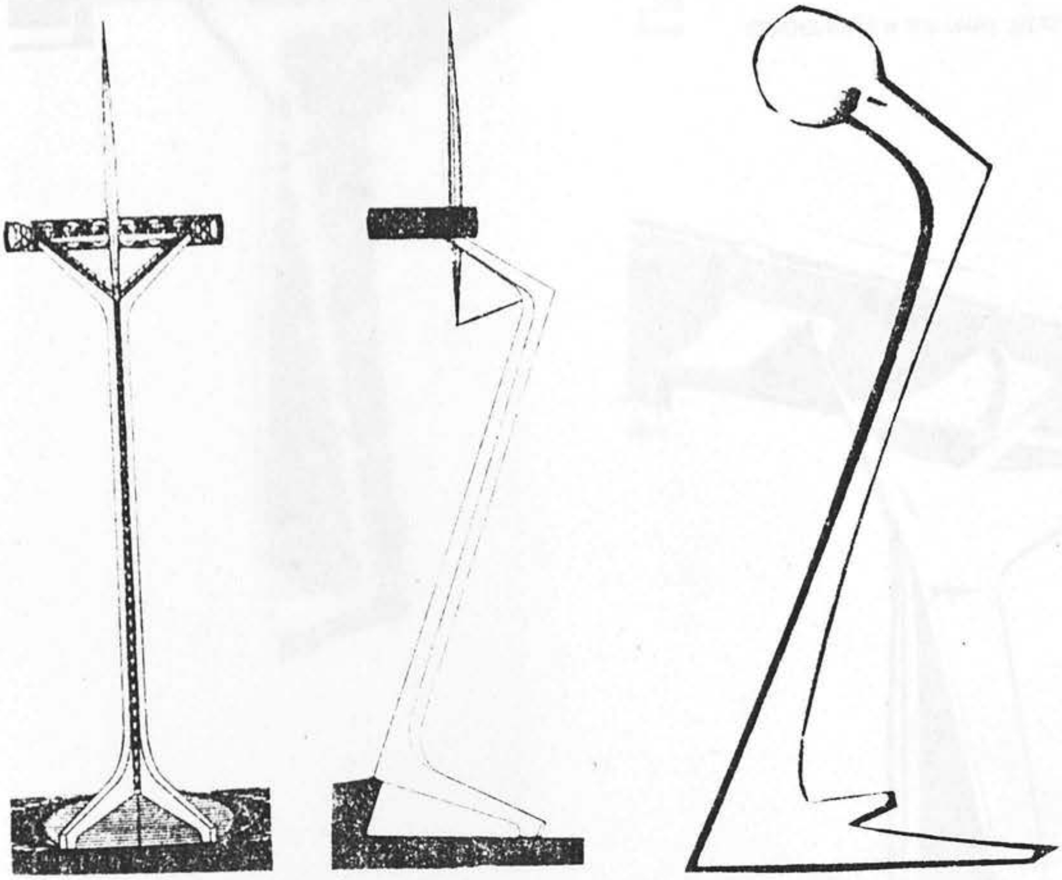


Fig 6A BARCELONA COMMUNICATIONS TOWER AND QUADRUPED LIMB ANALOGY



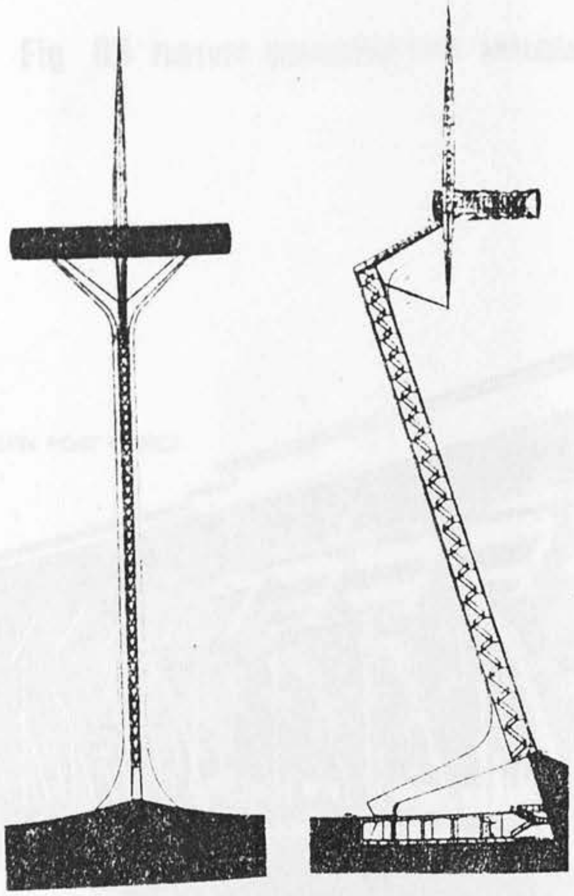
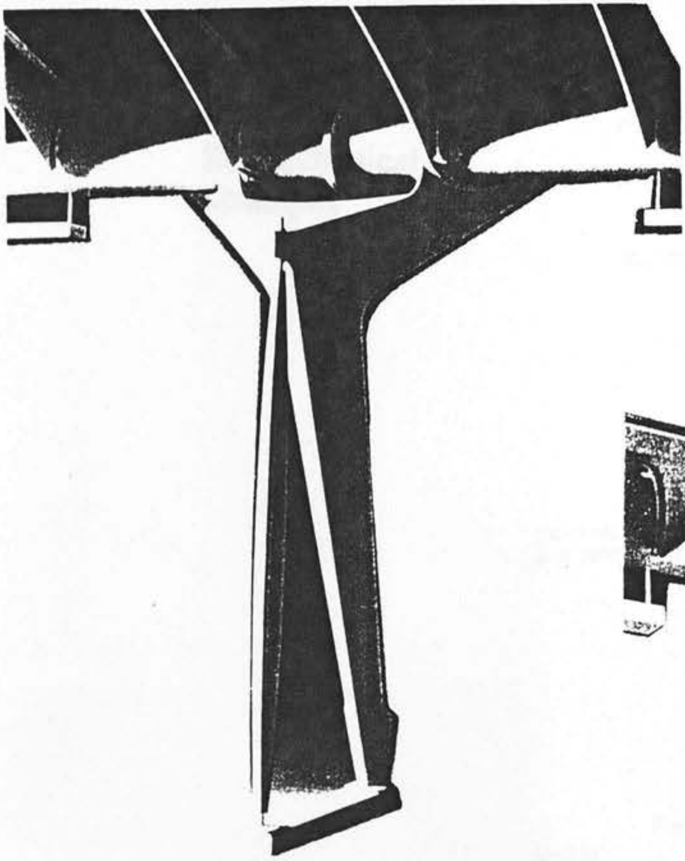


FIG 5



STADELHOFEN RAILWAY STATION

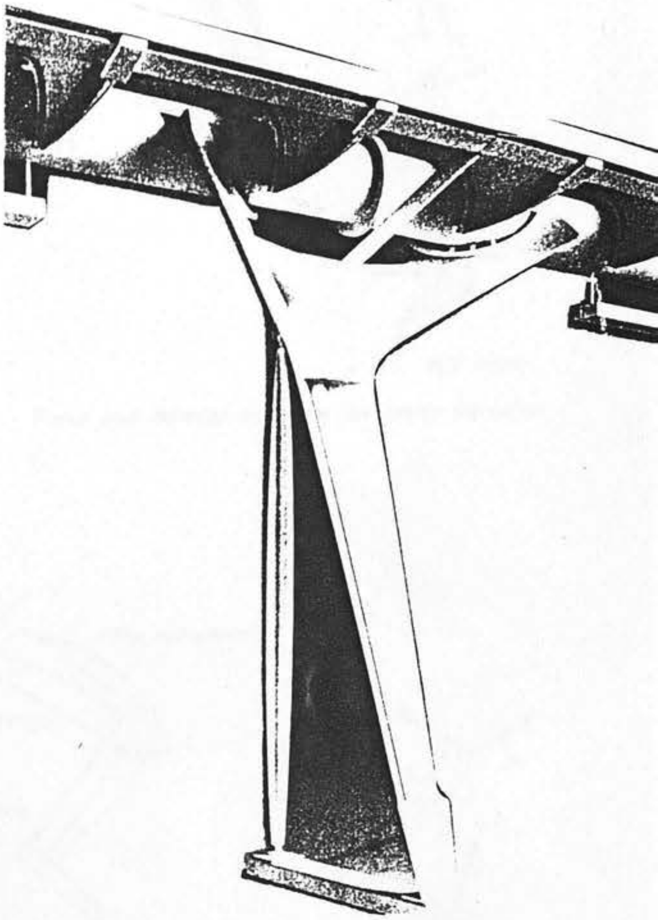
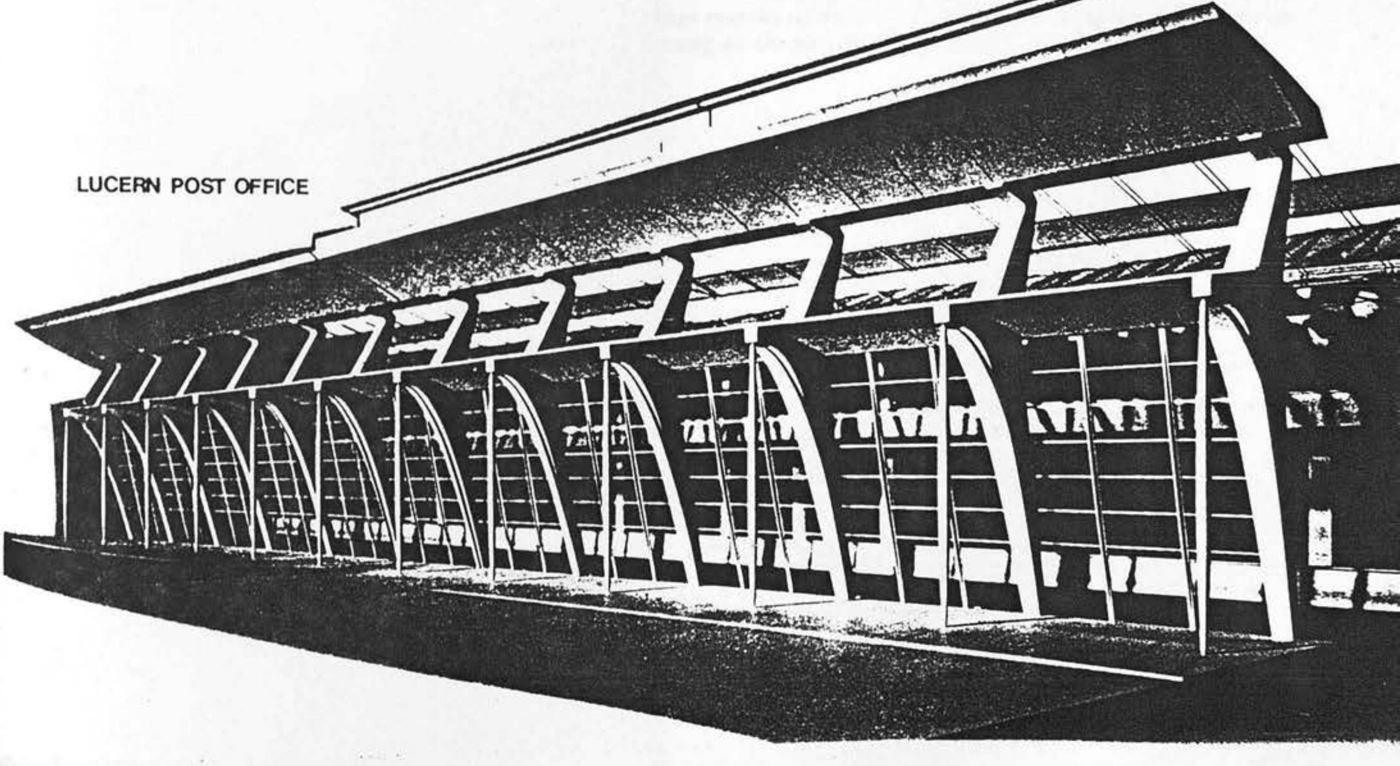
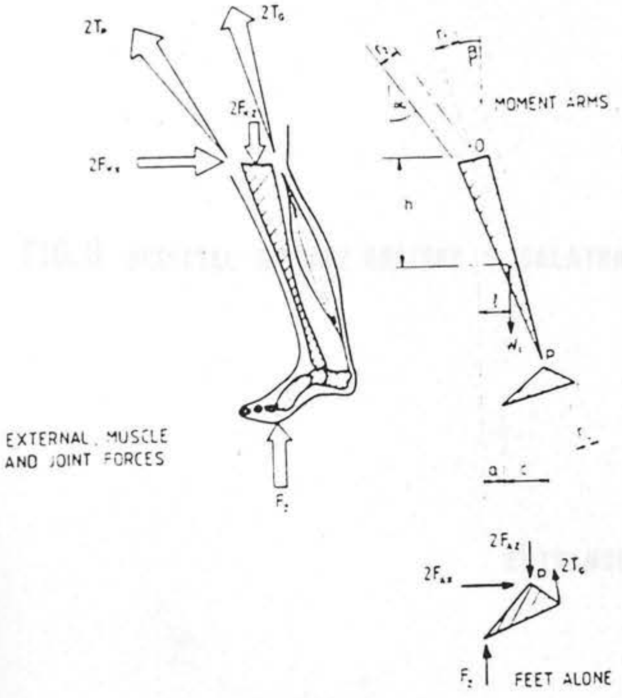


Fig 6B FURTHER QUADRUPED LIMB ANALOGIES

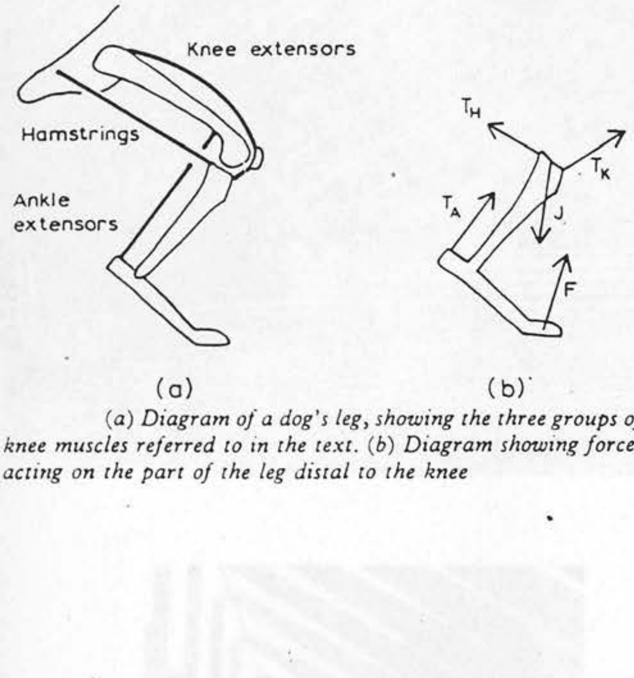
LUCERN POST OFFICE



Fiq 7 Biomechanical analogies



Force and moment diagrams for lower leg (after Smith)



(a) Diagram of a dog's leg, showing the three groups of knee muscles referred to in the text. (b) Diagram showing forces acting on the part of the leg distal to the knee

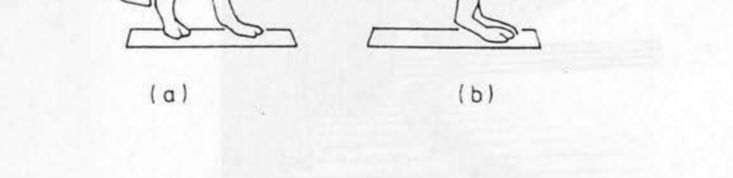
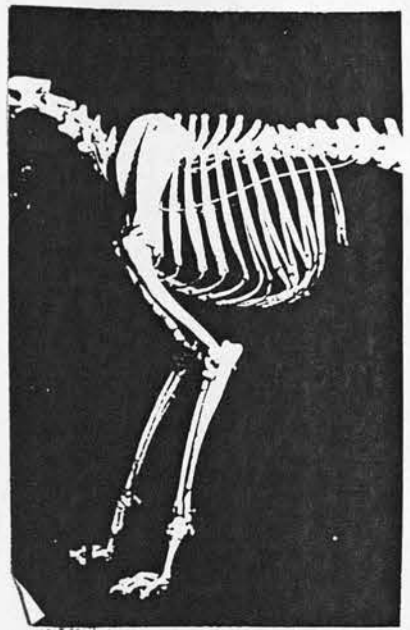
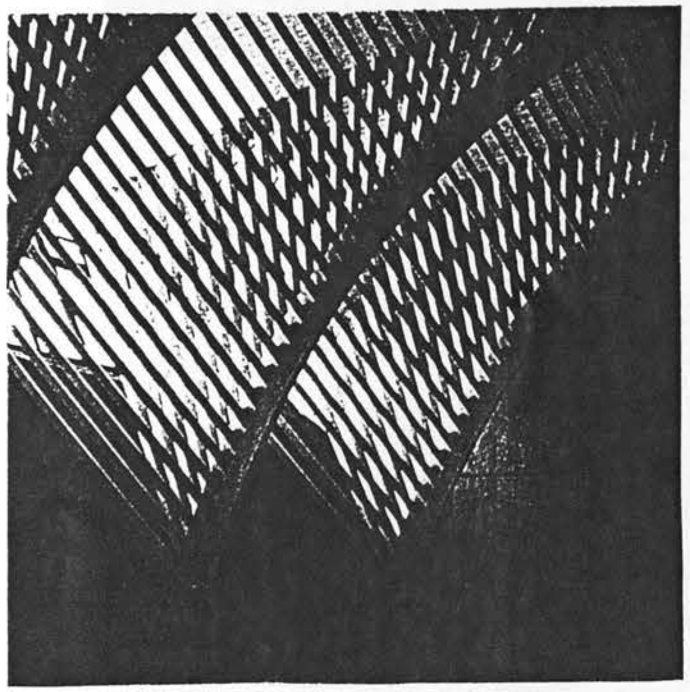
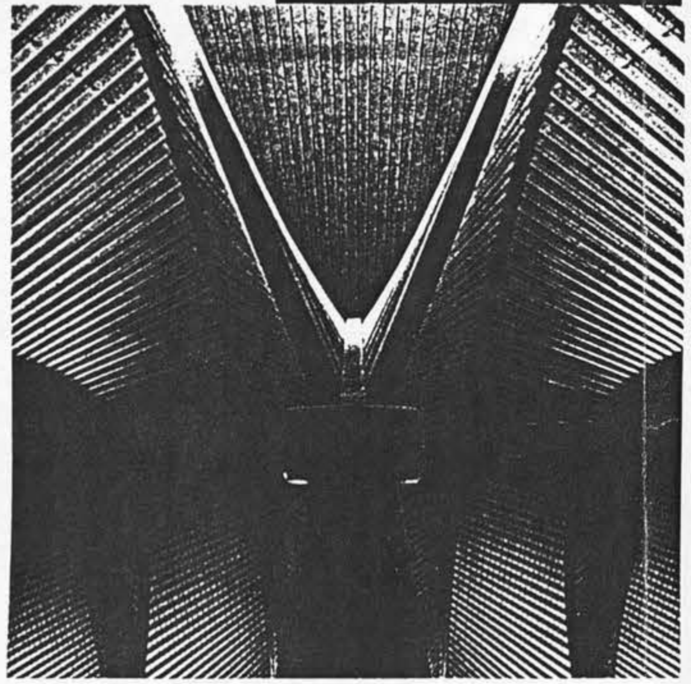


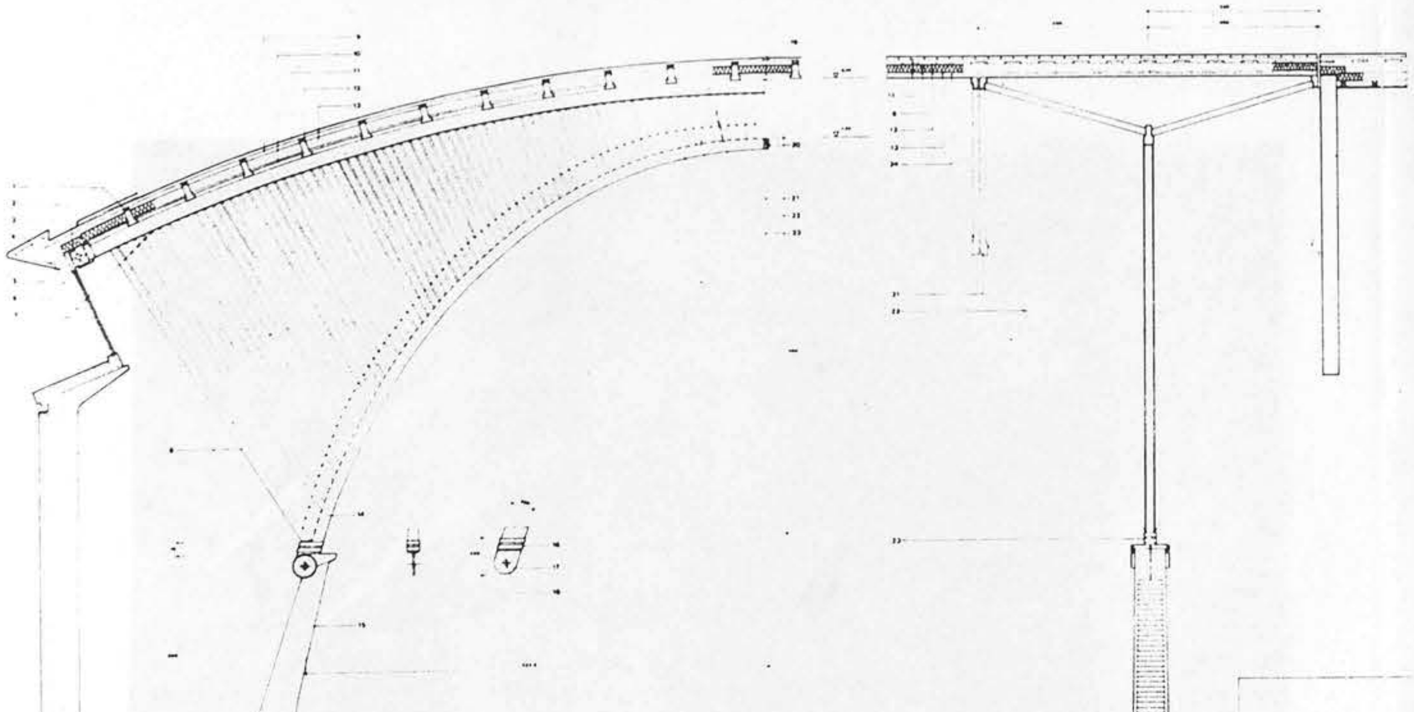
FIG. 8 SKELETAL RIBCAGE ANALOGY (S. CALATRAVA)



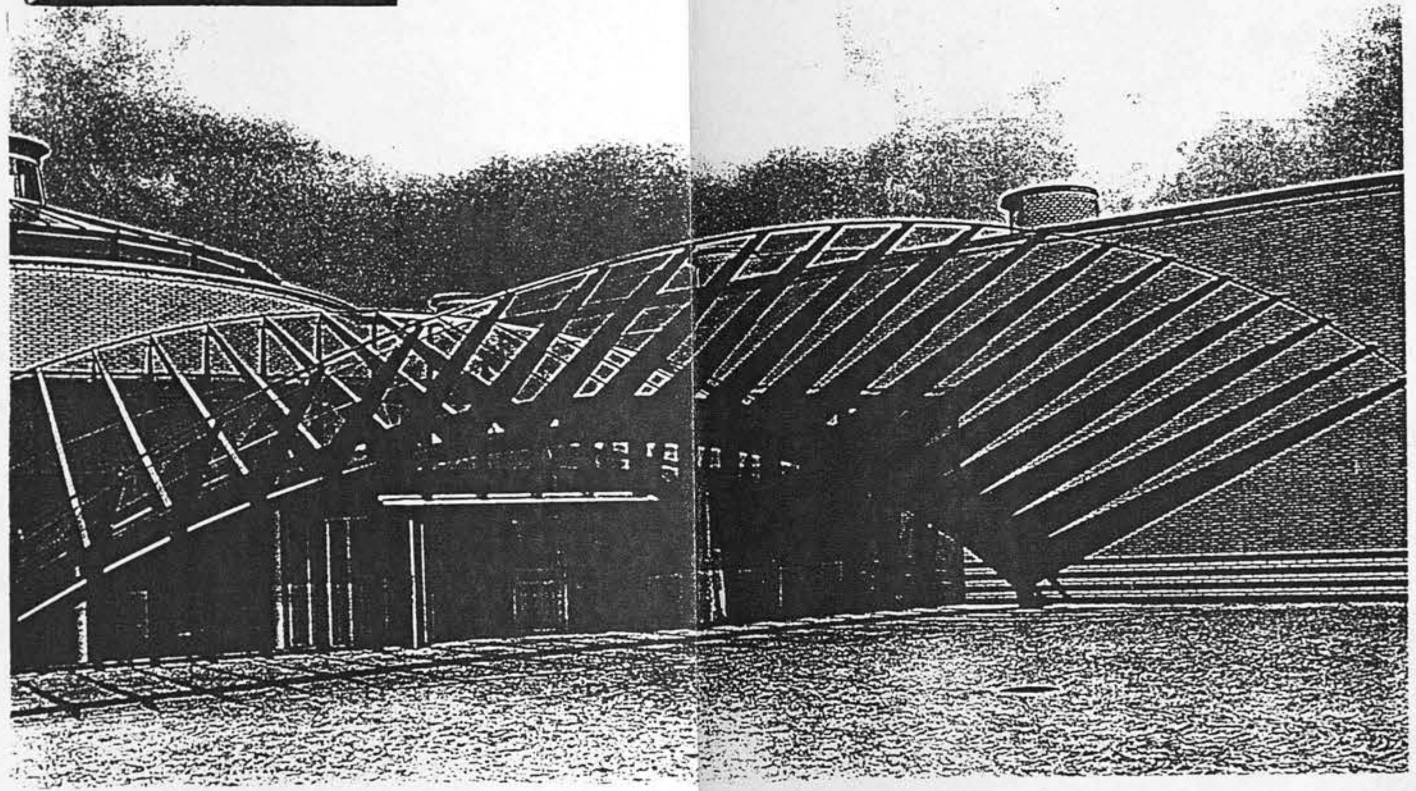
WOHLEN HIGH SCHOOL ENTRANCE HALL

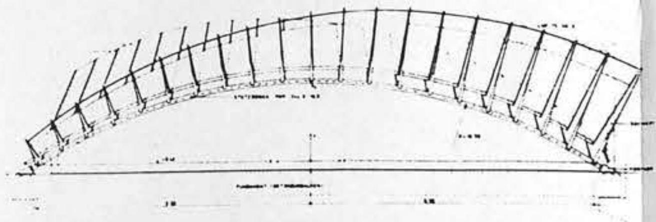




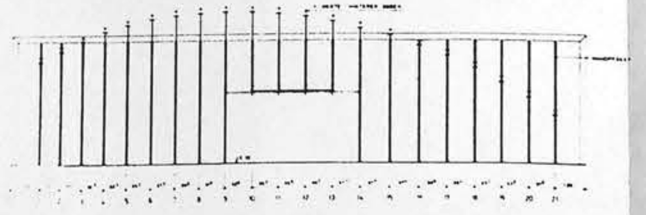


ENTRANCE CANOPY



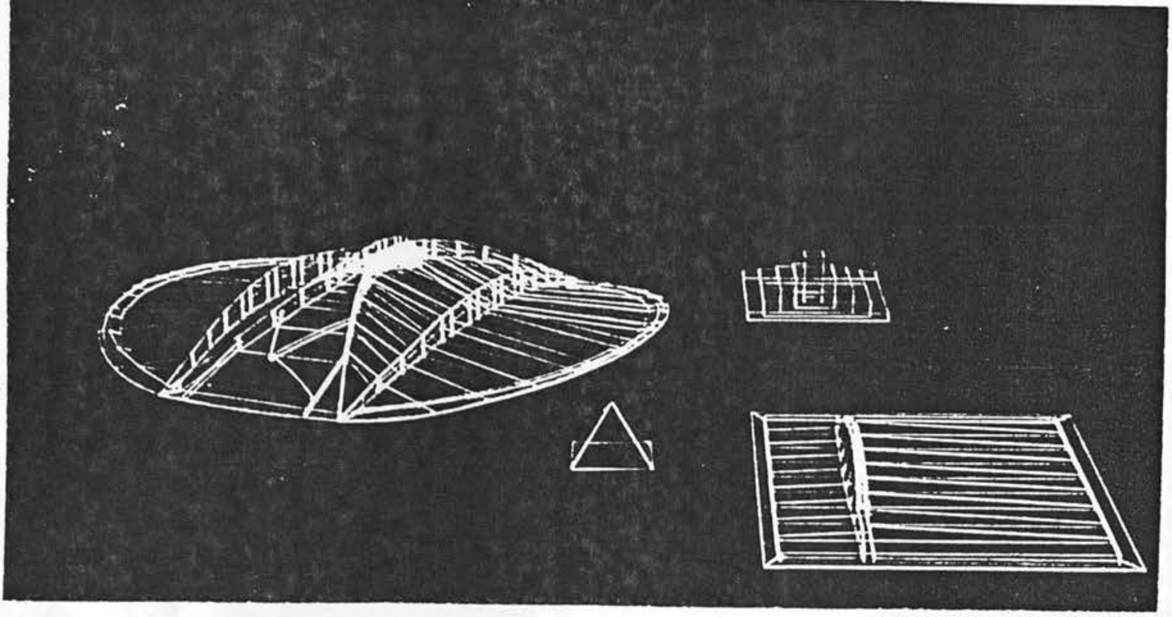


Alzado frontal / *Front elevation*

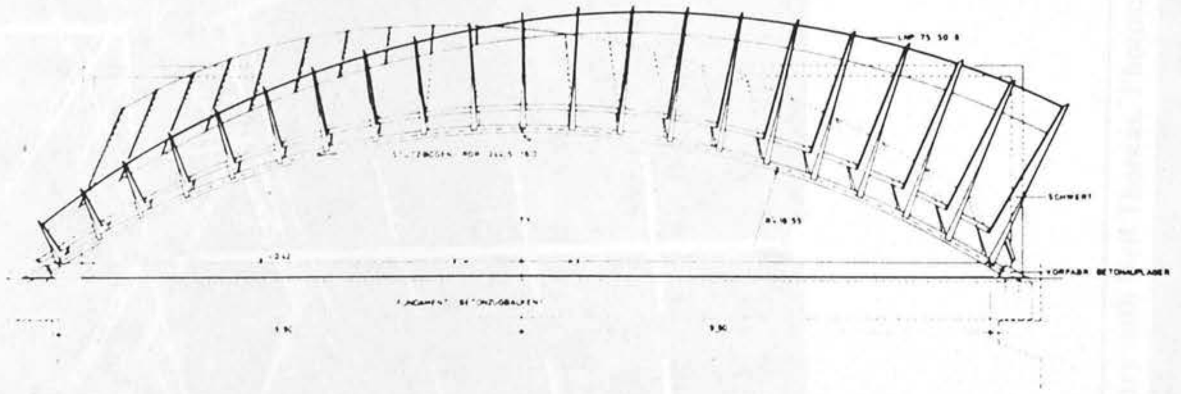


Alzado de la estructura de fachada / *Structure elevation of the facade*

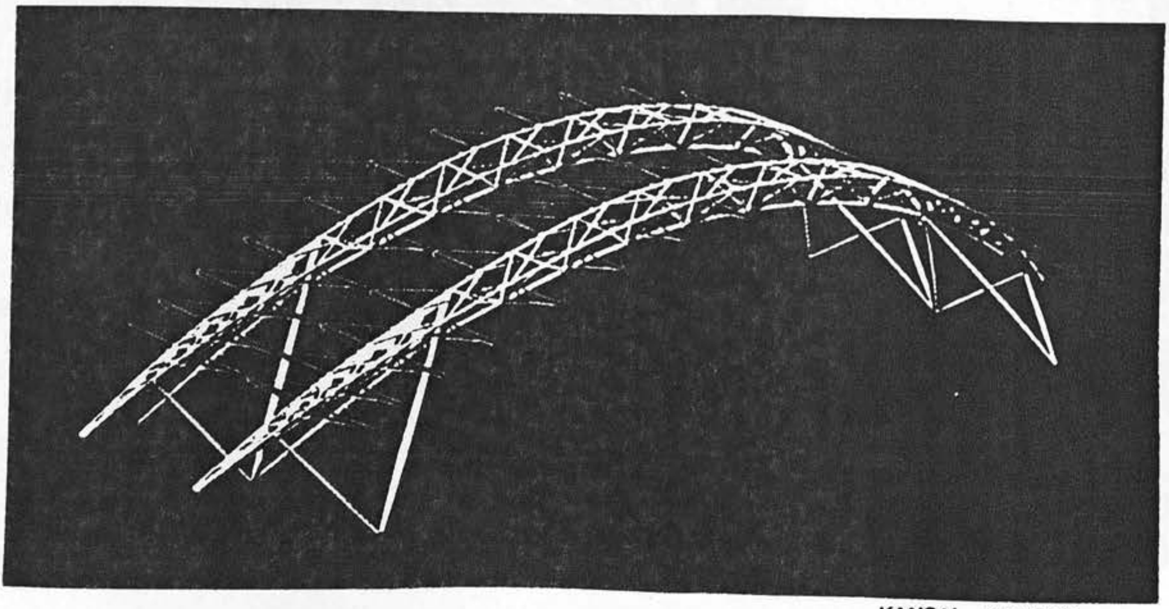
Fig 9A



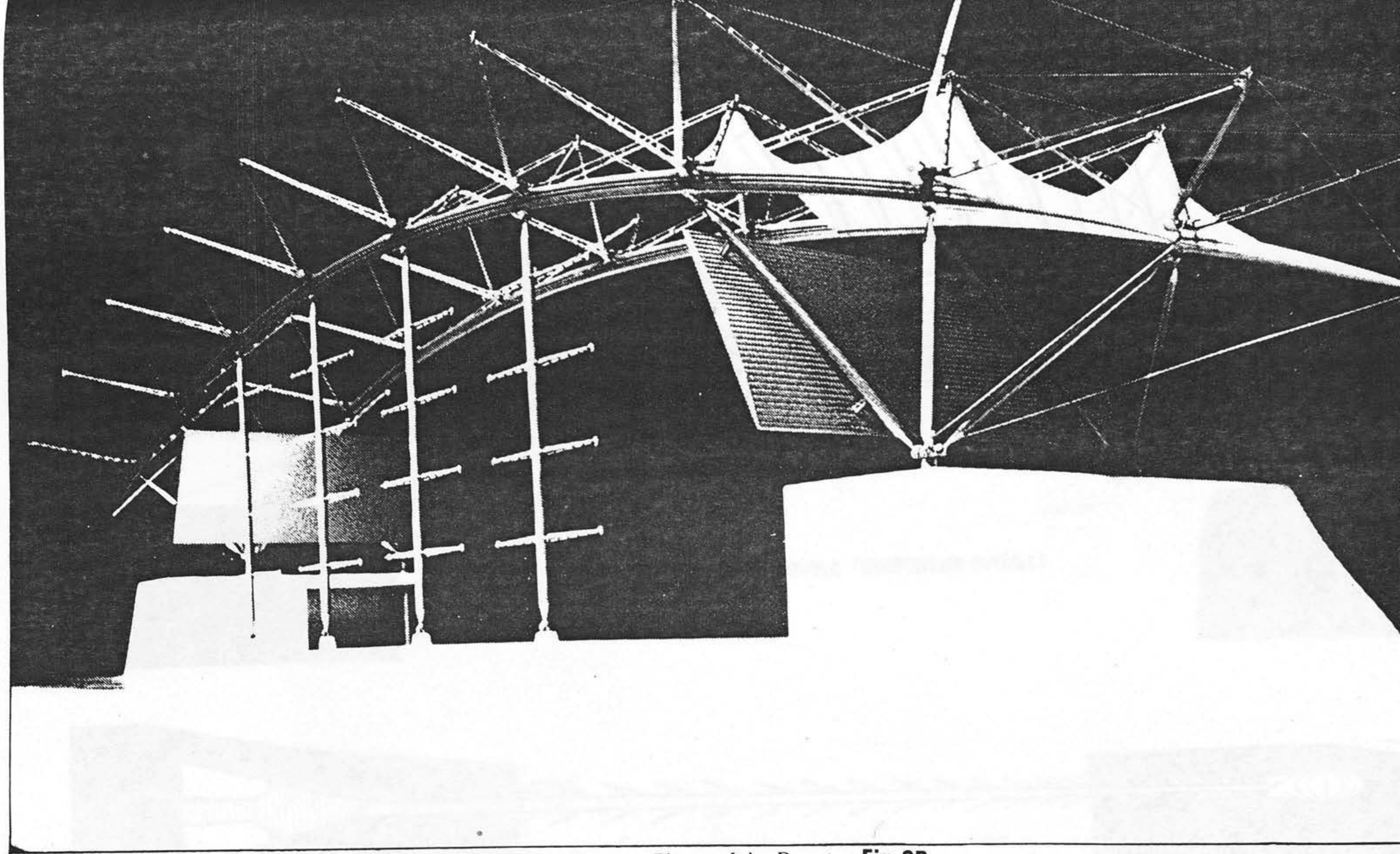
METROPOLITAN STADIUM



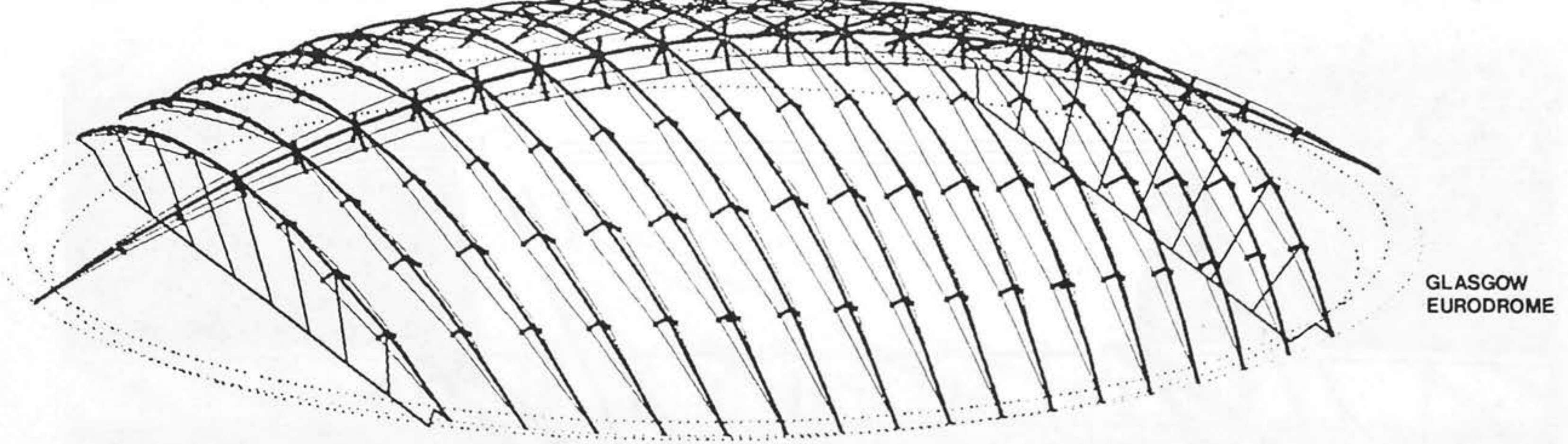
WOHLEN HIGH SCHOOL ENTRANCE CANOPY



KANSAI AIRPORT



Model of the Glasgow Eurodome competition entry with Neil Thomas. Photos: John Donat. **Fig 9B**



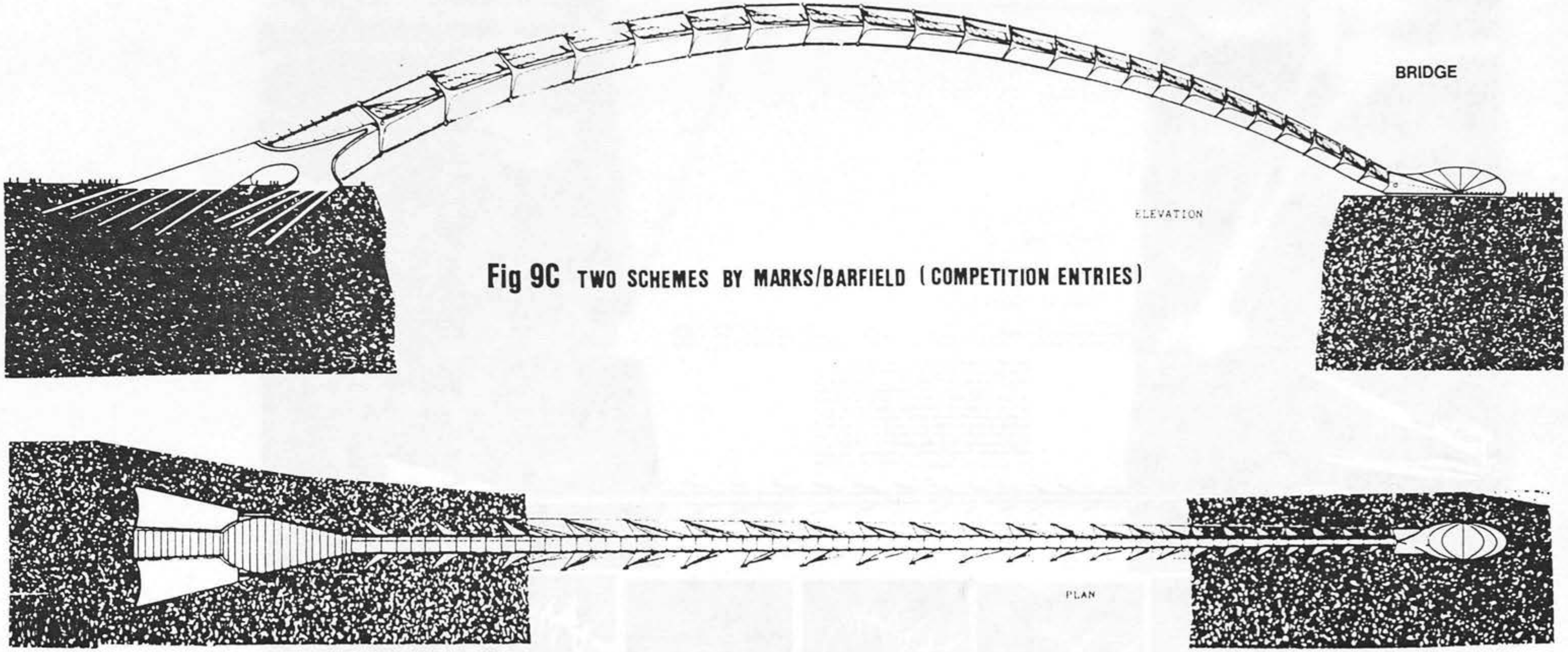
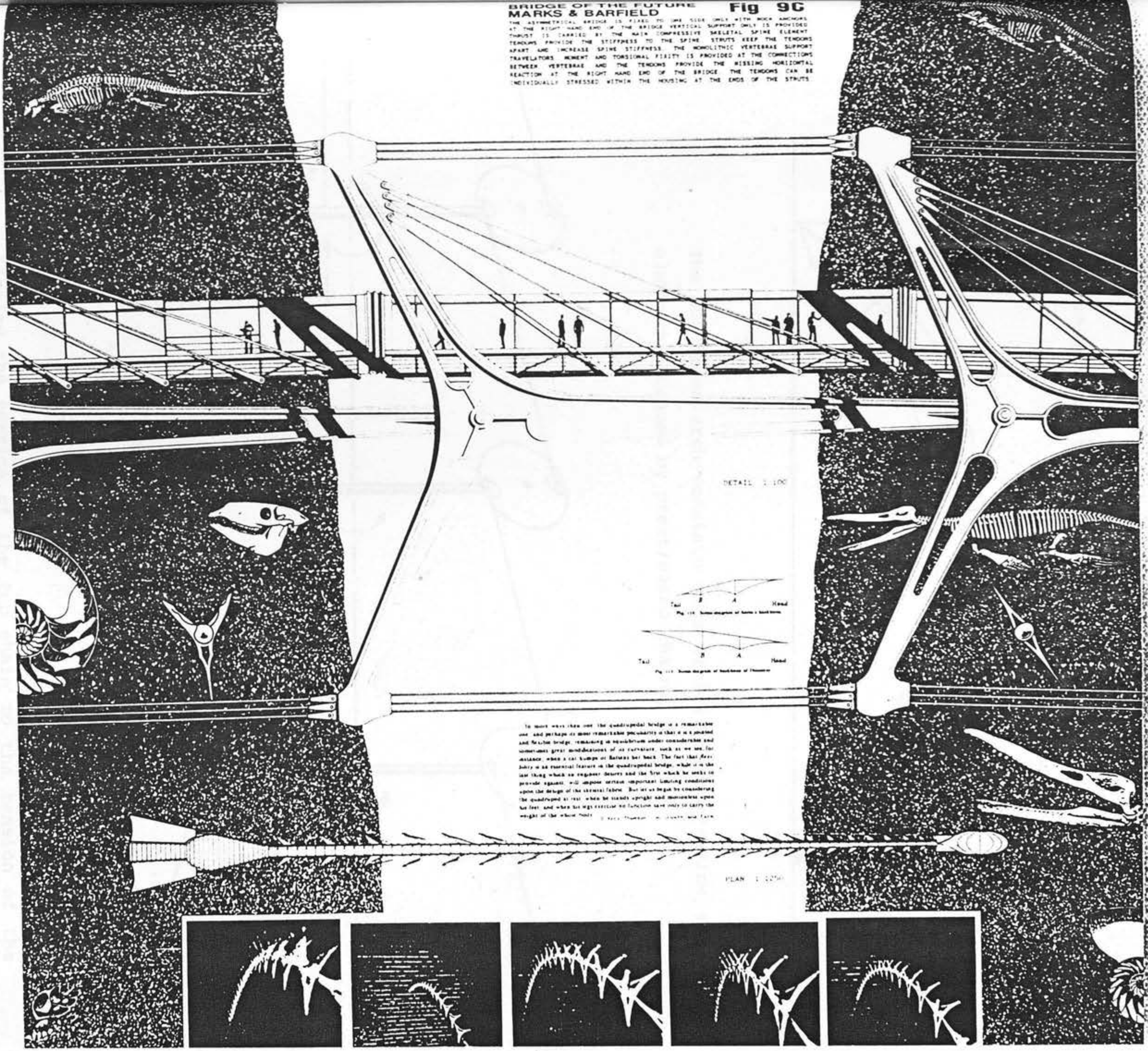


Fig 9C TWO SCHEMES BY MARKS/BARFIELD (COMPETITION ENTRIES)

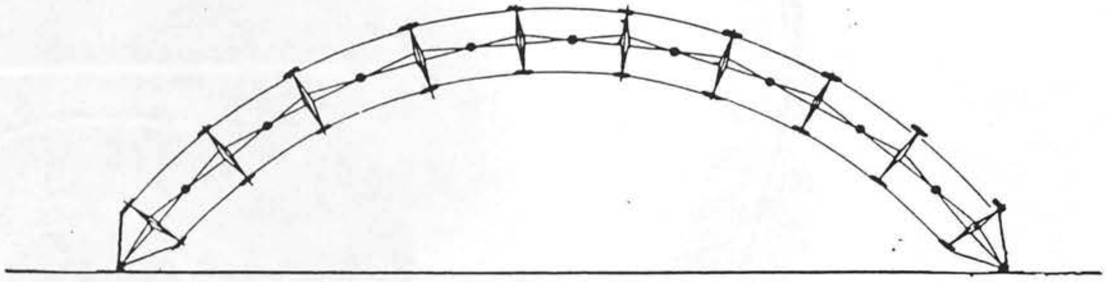


BRIDGE OF THE FUTURE
MARKS & BARFIELD **Fig 9C**

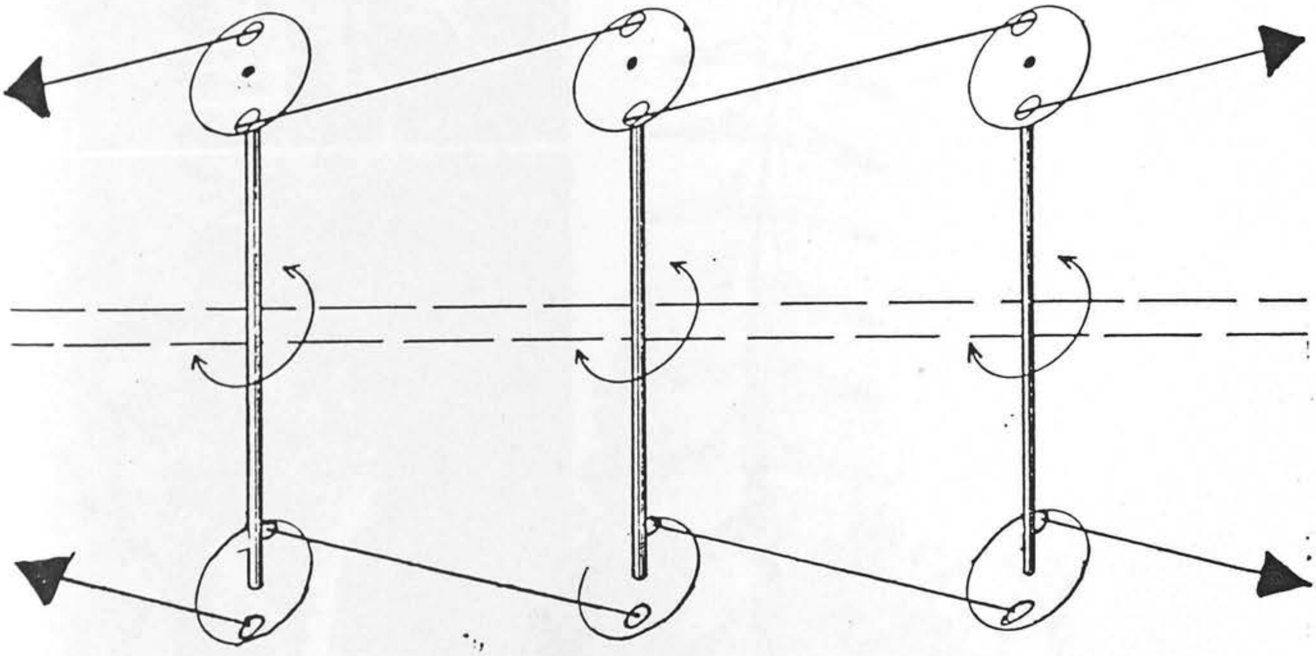
THE ASYMMETRICAL BRIDGE IS FIXED TO ONE SIDE ONLY WITH ROCK ANCHORS AT THE RIGHT HAND END OF THE BRIDGE VERTICAL SUPPORT ONLY IS PROVIDED THRUST IS CARRIED BY THE MAIN COMPRESSIVE SKELETAL SPINE ELEMENT TENDONS PROVIDE THE STIFFNESS TO THE SPINE. STRUTS KEEP THE TENDONS APART AND INCREASE SPINE STIFFNESS. THE MONOLITHIC VERTEBRAE SUPPORT TRAVELATORS. MOMENT AND TORSIONAL FIXITY IS PROVIDED AT THE CONNECTIONS BETWEEN VERTEBRAE AND THE TENDONS PROVIDE THE MISSING HORIZONTAL REACTION AT THE RIGHT HAND END OF THE BRIDGE. THE TENDONS CAN BE INDIVIDUALLY STRESSED WITHIN THE HOUSING AT THE ENDS OF THE STRUTS.

In more ways than one the quadrupedal bridge is a remarkable one, and perhaps its most remarkable peculiarity is that it is a jointed and flexible bridge, remaining in equilibrium under considerable and sometimes great modifications of its curvature, such as we see, for instance, when a cat humps or flattens her back. The fact that flexibility is an essential feature in the quadrupedal bridge, while it is the last thing which an engineer desires and the first which he seeks to provide against, will impose certain important limiting conditions upon the design of the skeletal fabric. But let us begin by considering the quadruped at rest, when he stands upright and motionless upon his feet, and when his legs exercise no function save only to carry the weight of the whole body. D'Arcy Thompson 'On Growth and Form'

Fig 10 Responsive Arch(**Chris McCarthy**)



The Eurodrome arch consists of a series of compression star elements balanced by prestressed chains.



Linking the tension of the top chain to the tension of the bottom chain by the means of a vertical axle produces an interesting result. The tension in both the top chain and bottom chain will be maintained to be equal for all load cases.

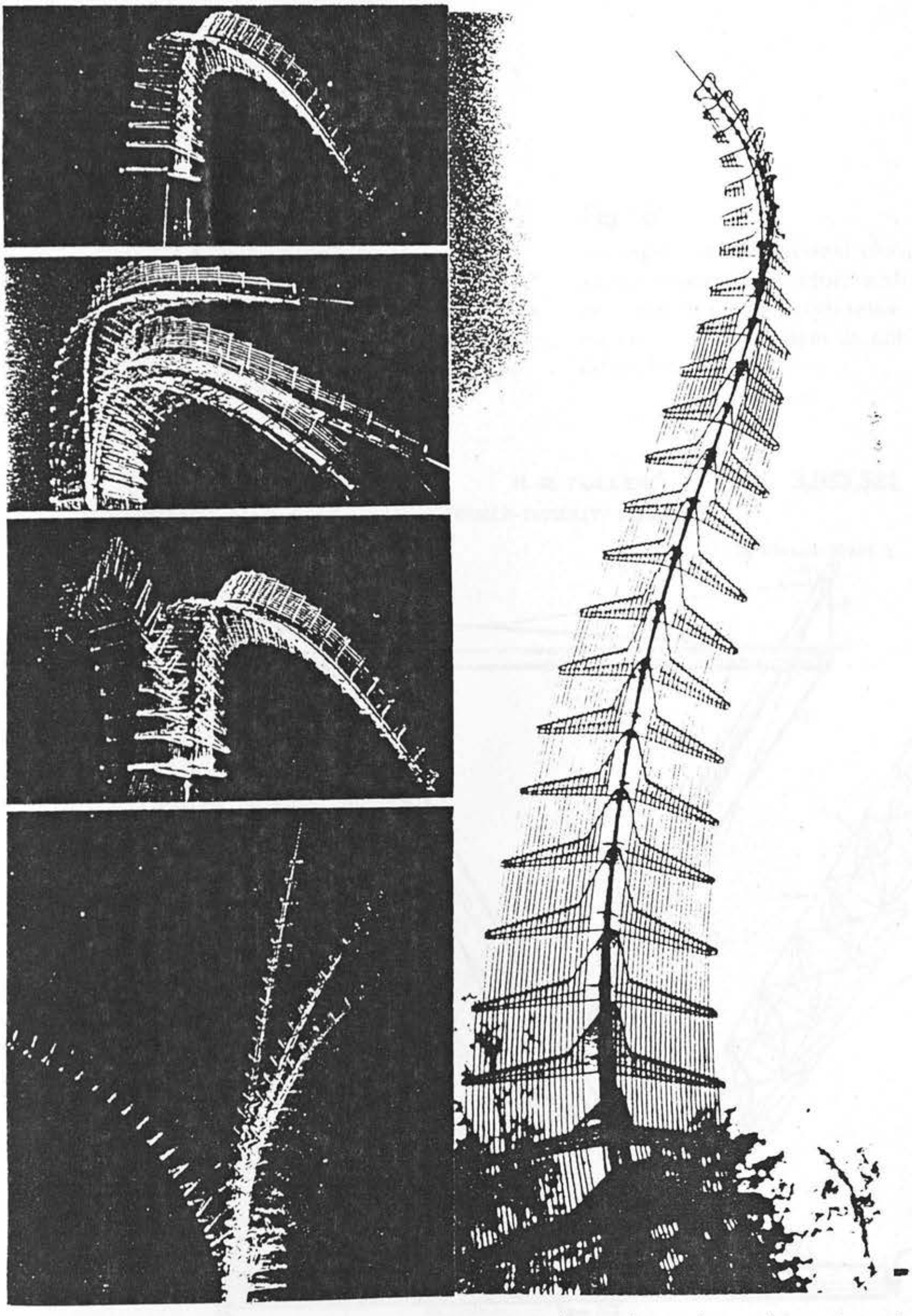


FIG 11 Otto's flexible column

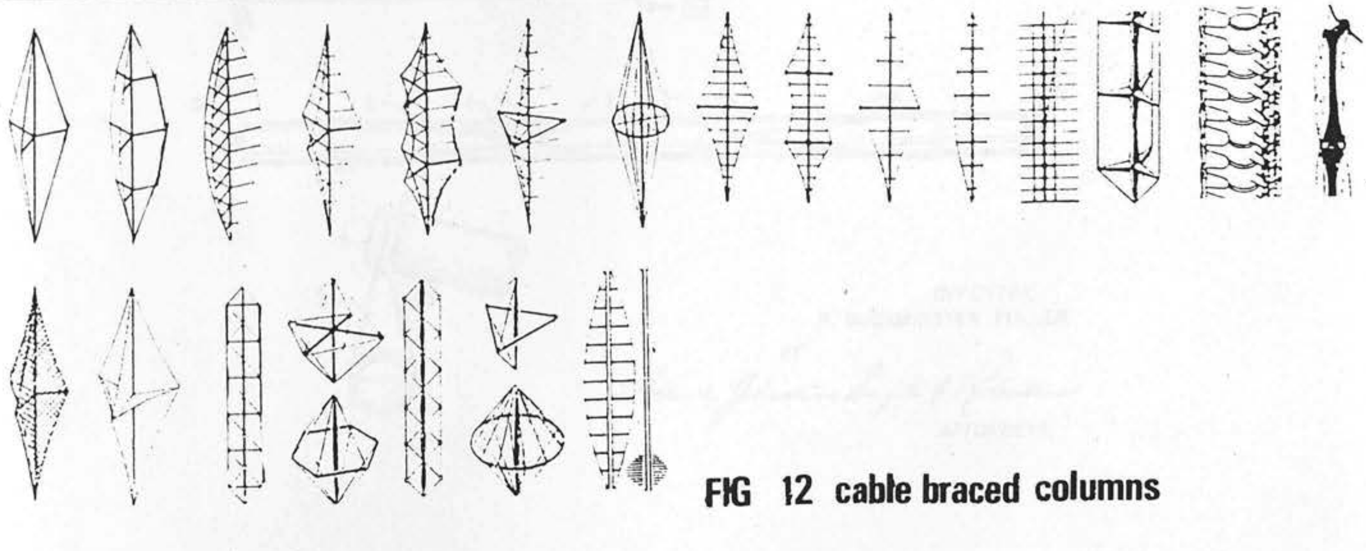


FIG 12 cable braced columns

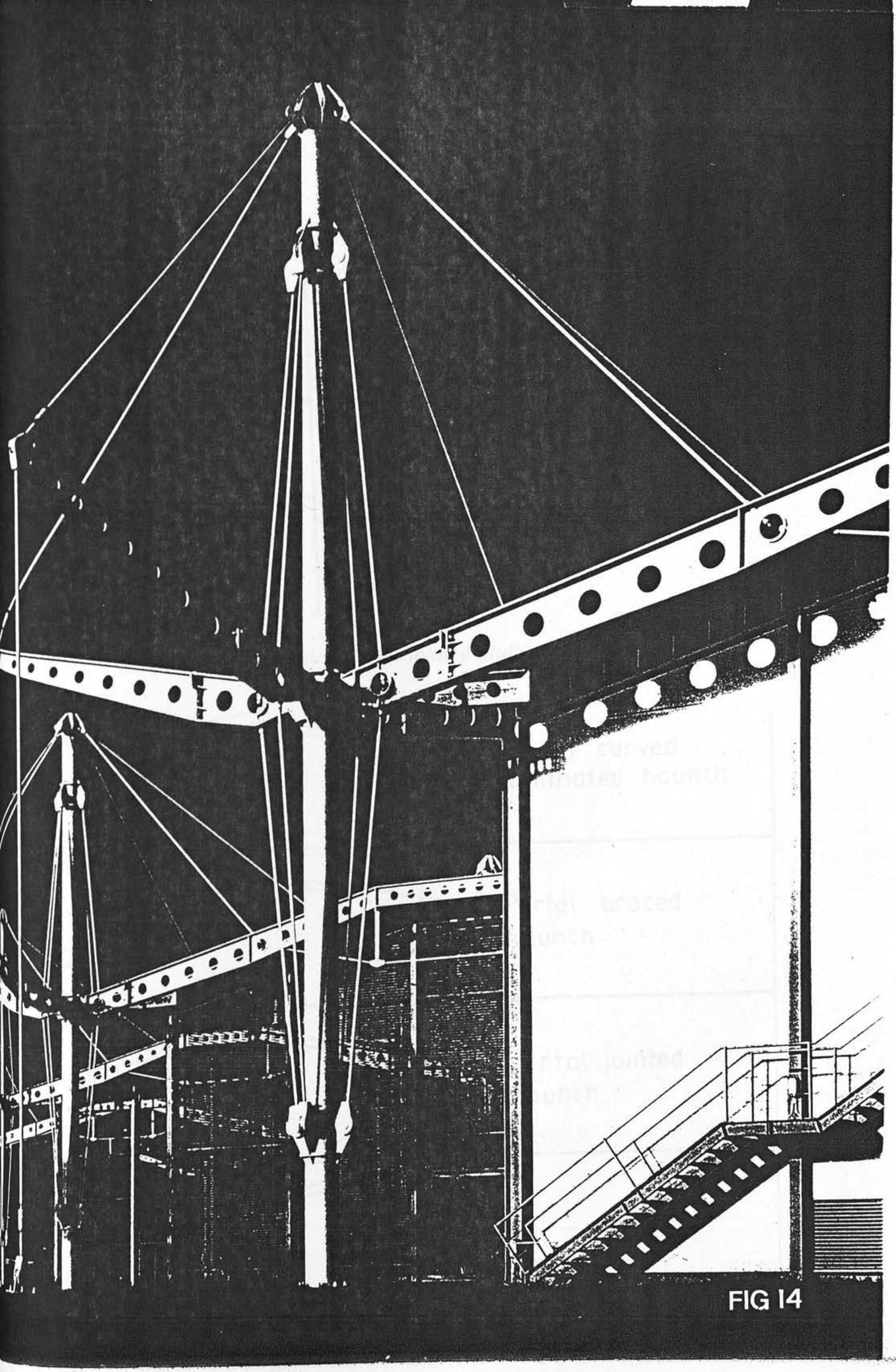
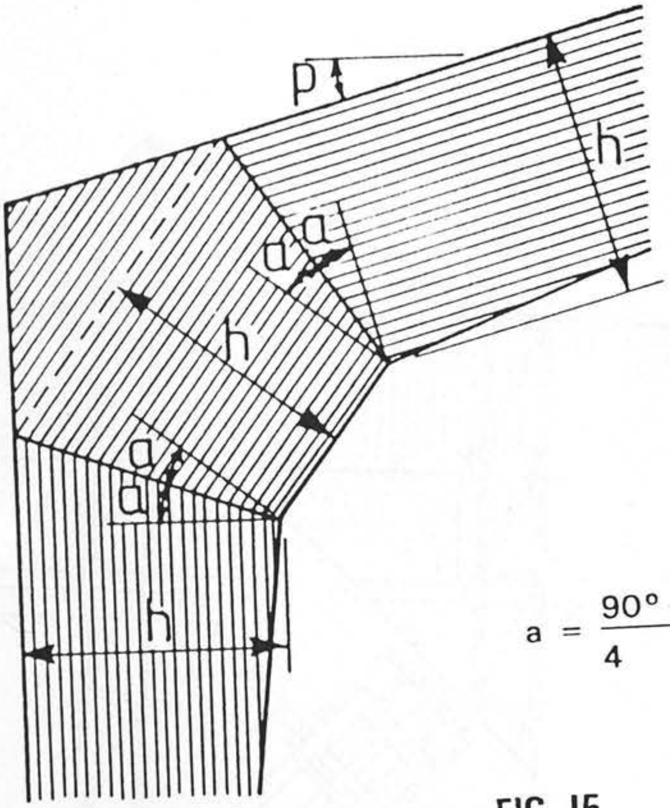


FIG 14



$$a = \frac{90° - P}{4}$$

FIG 15

A typical finger-jointed glulam portal haunch

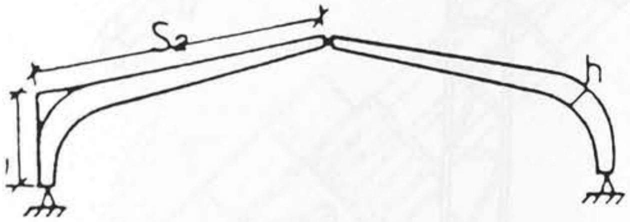
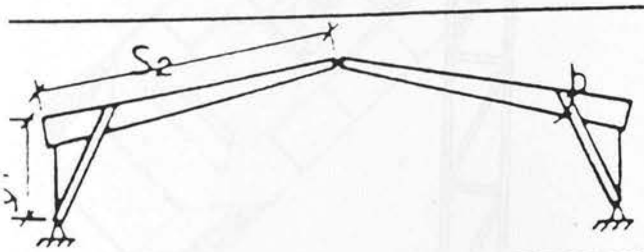
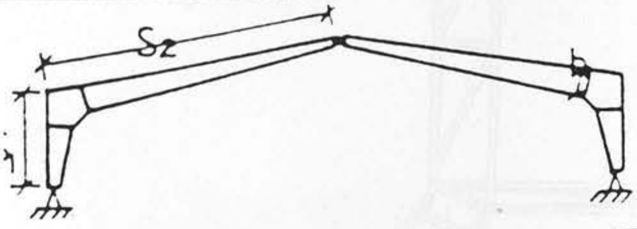
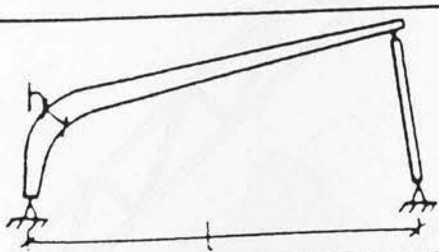
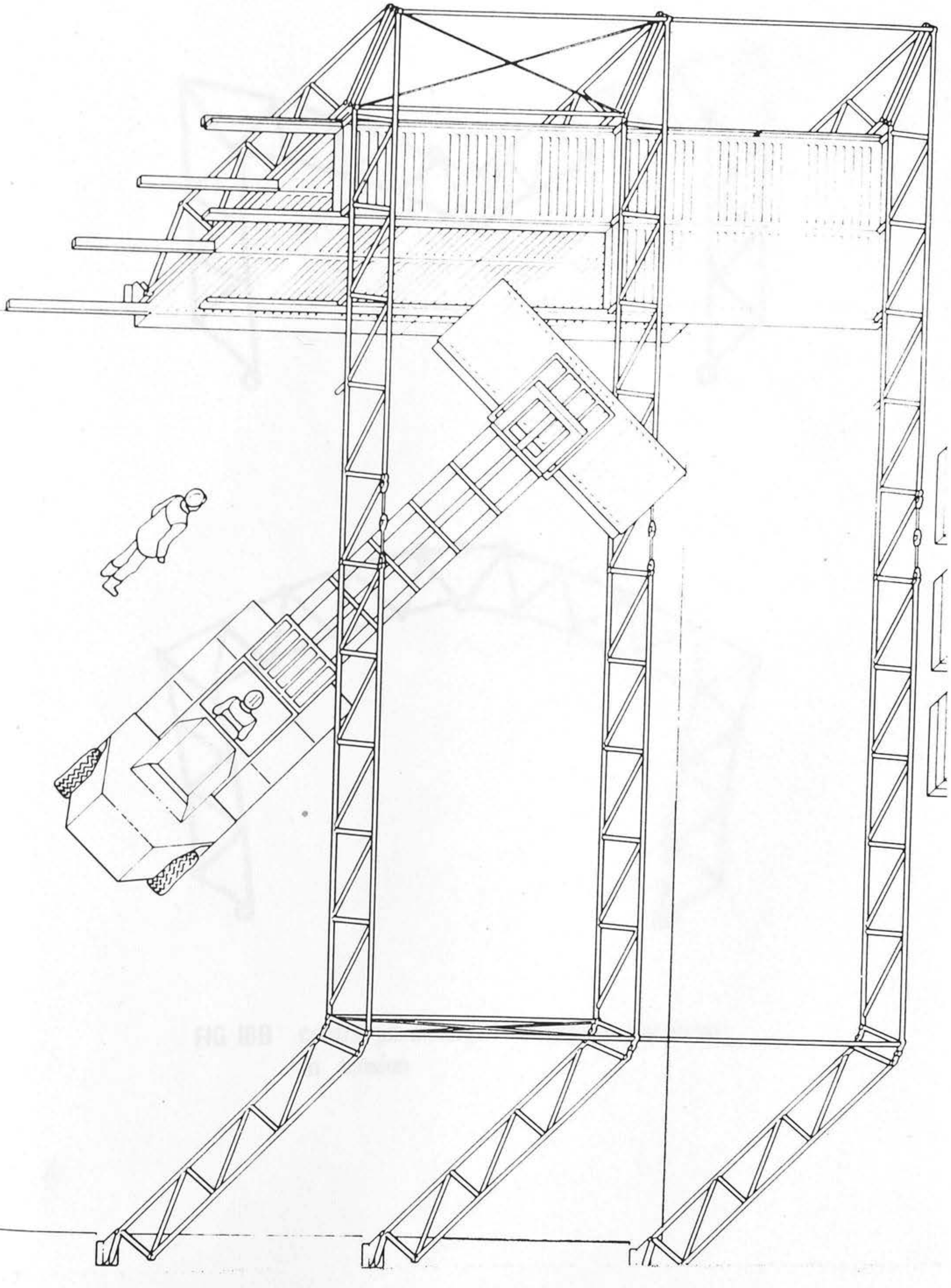
	Portal curved laminated haunch
	Portal braced haunch
	Portal jointed haunch
	Half – portal propped

FIG 16A



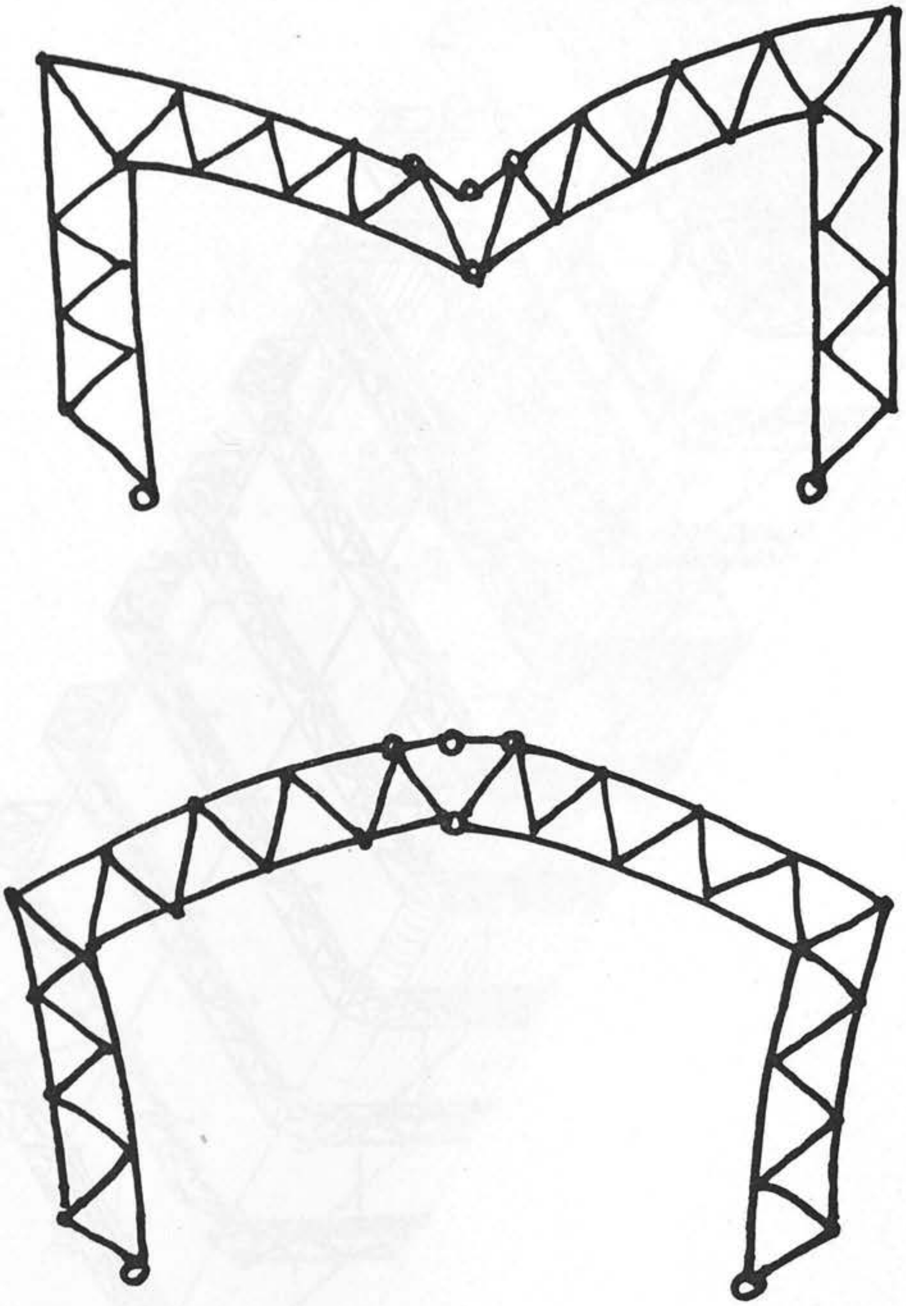


FIG 16B central pin arranged to maintain top boom in tension

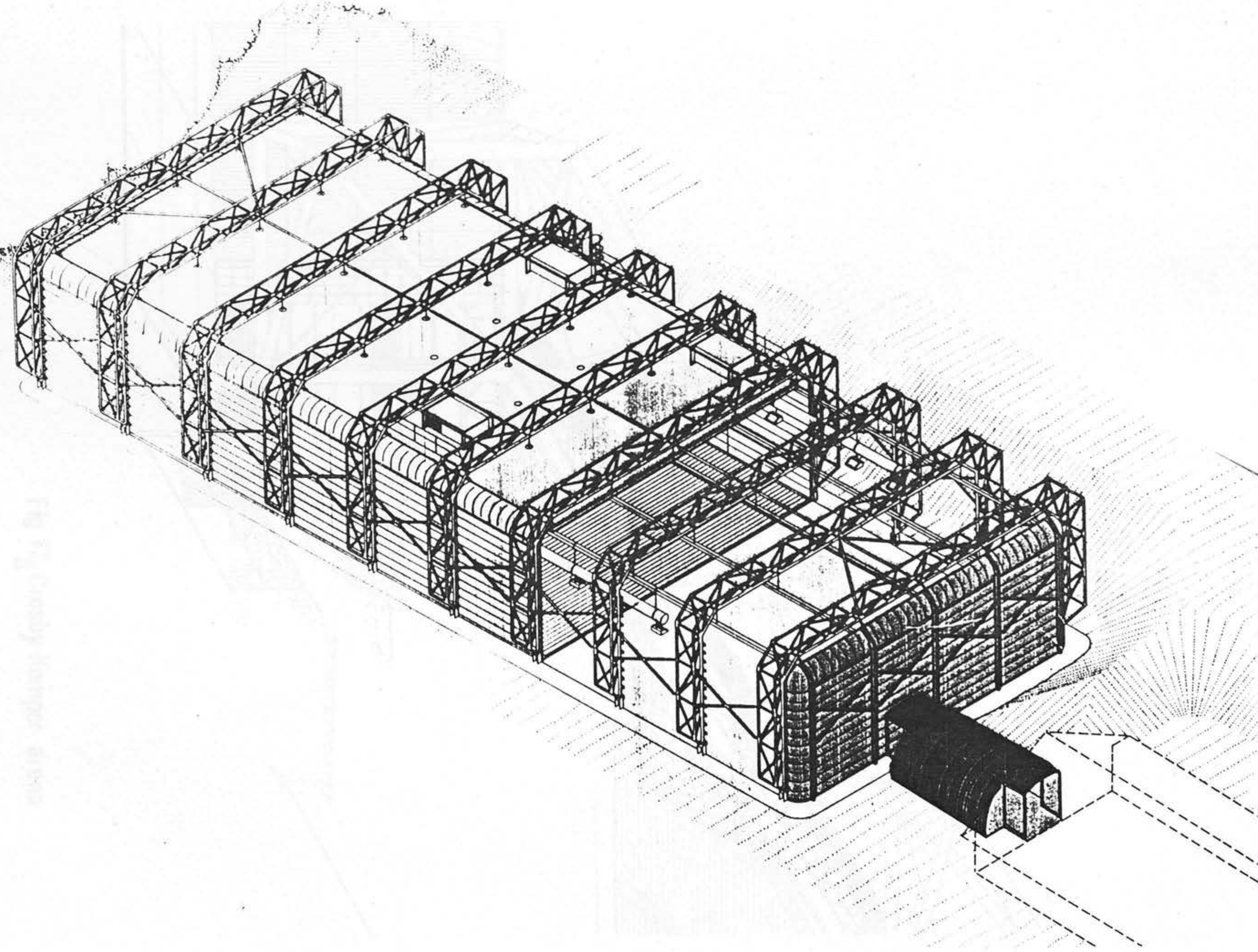


FIG 17A IBM SPORTS HALL
right: axonometric from south-east: grey tint indicates completed portion

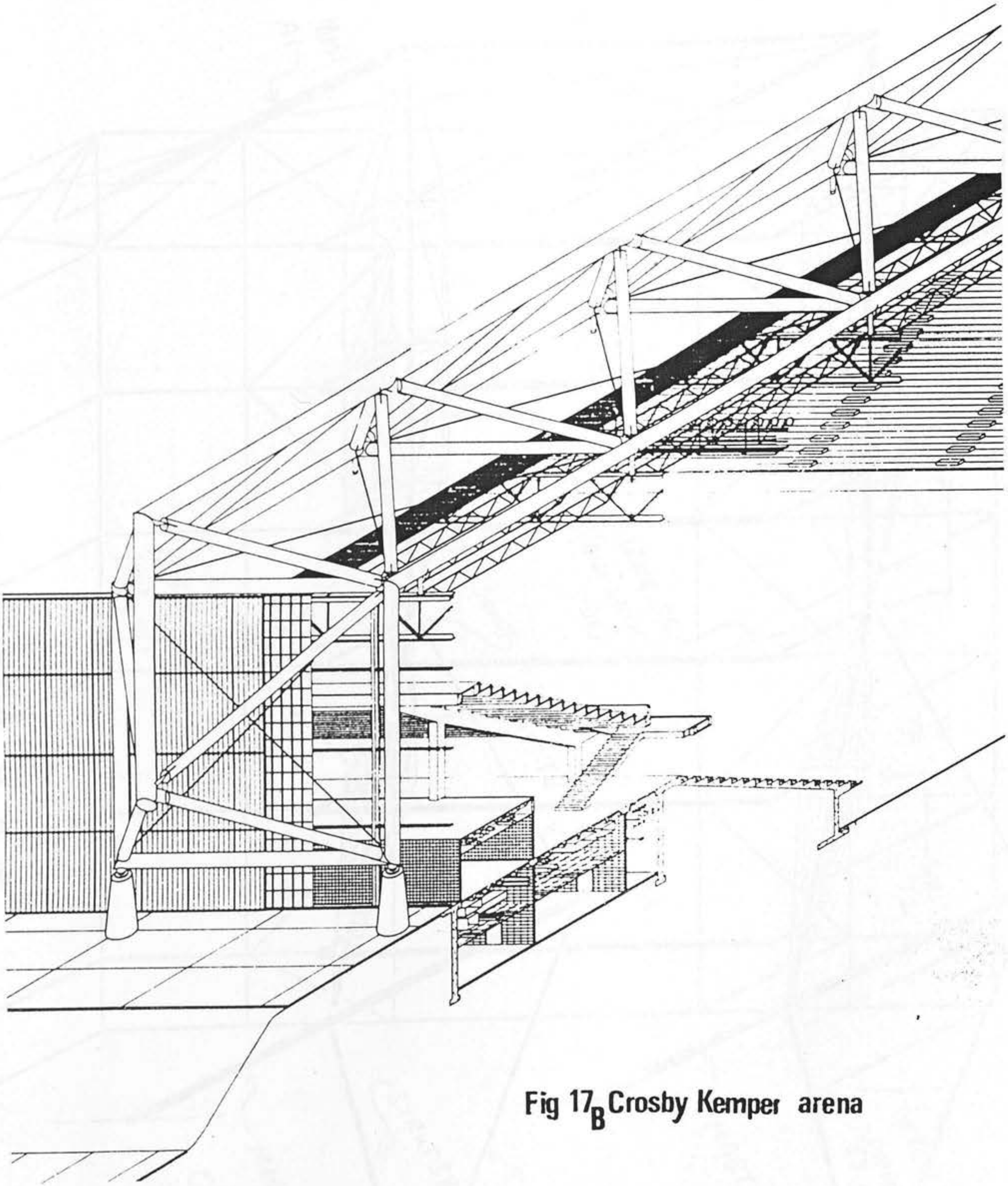


Fig 17_B Crosby Kemper arena

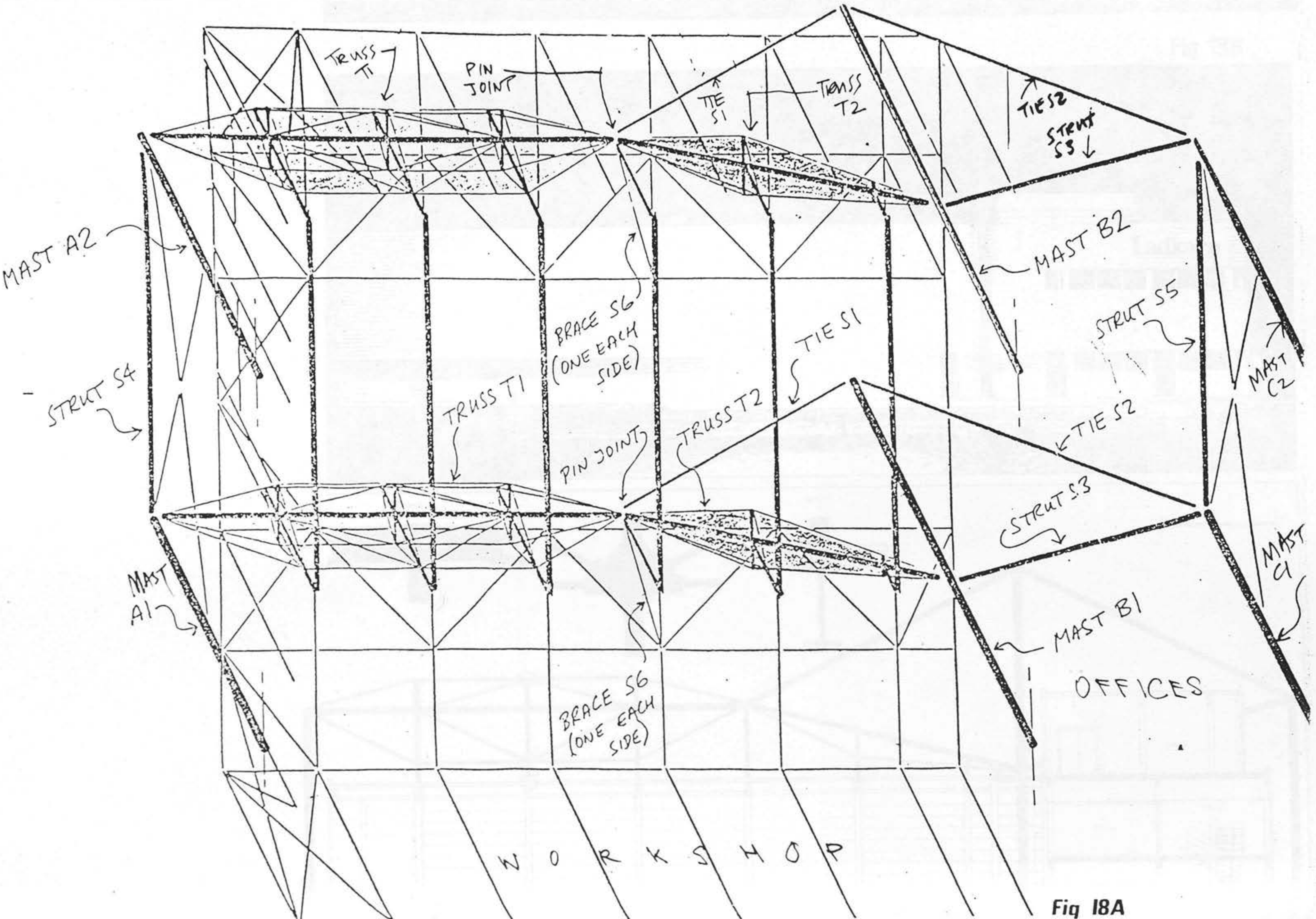
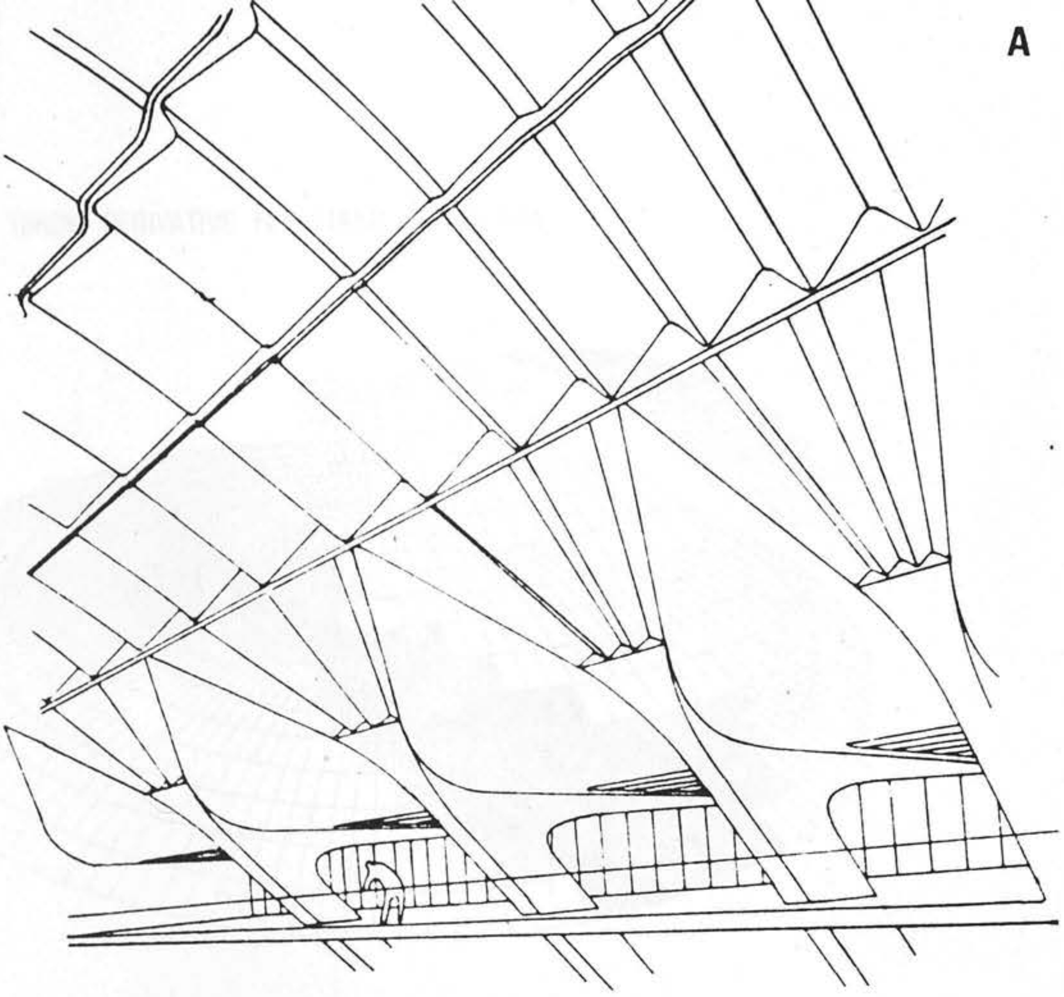

TRUSS T1
PIN JOINT
TIE S1
TRUSS T2
TIES2
STRUT S3
MAST A2
MAST B2
STRUT S5
BRACE S6 (ONE EACH SIDE)
TIE S1
STRUT S4
TRUSS T1
TRUSS T2
MAST C2
PIN JOINT
TIE S2
STRUT S3
MAST A1
MAST B1
MAST C1
OFFICES
BRACE S6 (ONE EACH SIDE)
WORKSHOP

Fig 18A

Fiq 18B


Ladkarn
Detail 1
Detail 2
Detail 3
0
5m
1
2
3
A
Office
Office
Office
Office
Office



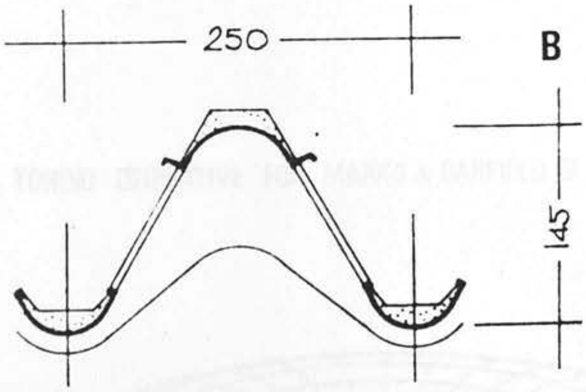


Fig 19

A NERVI'S TURIN EXHBTN HALL

B FOLDED FERROCEMENT SECTN

C,D MAINSTONE'S COMPARISON OF RADIOLARIA CORAL PATTERNS WITH NERVI'S SPORTS PALACE STRUCTURE

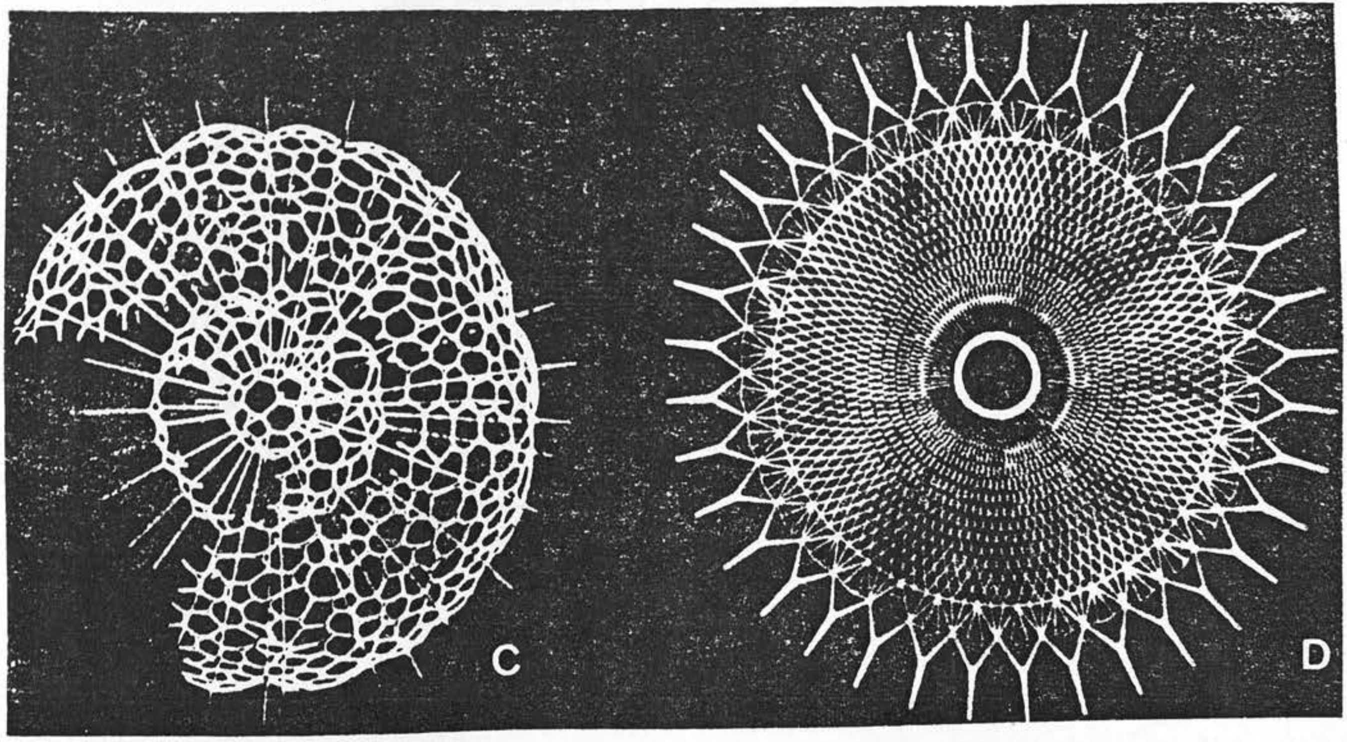


Fig 20 TOROID DERIVATIVE FOR PIANO'S RAVENNA

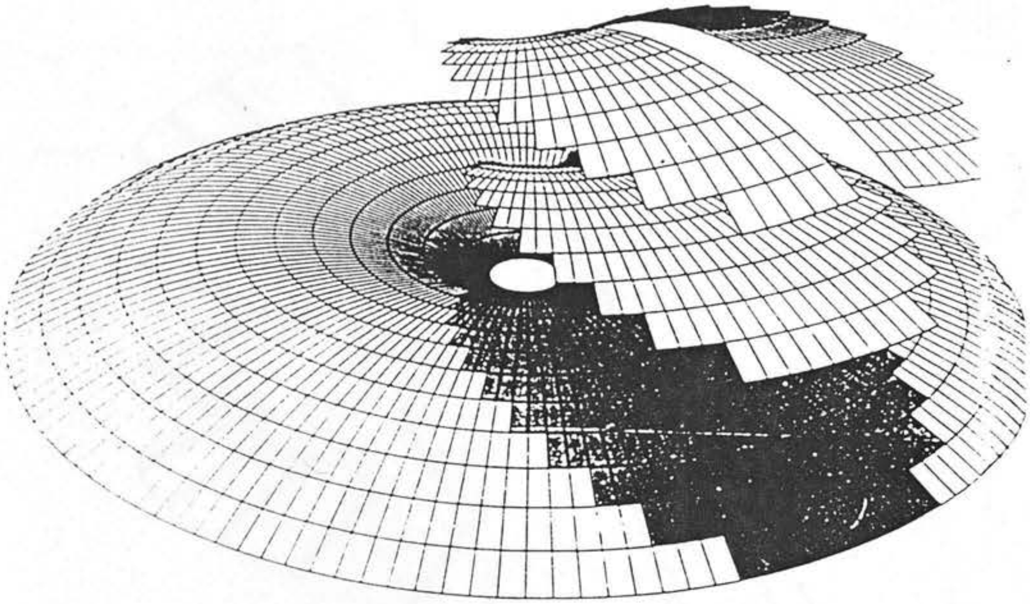
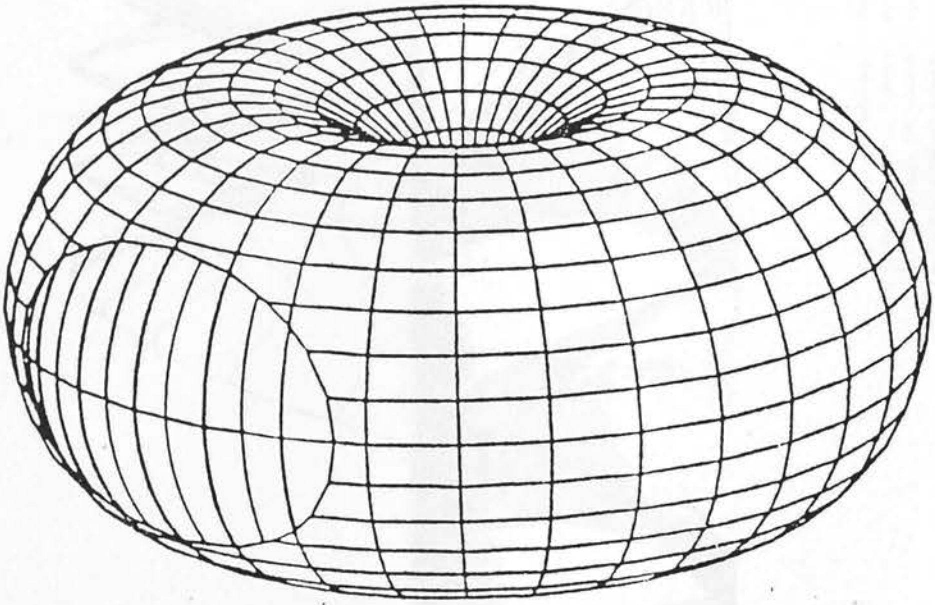


Fig 21 TOROID DERIVATIVE FOR MARKS & BARFIELD 'S EURODROME



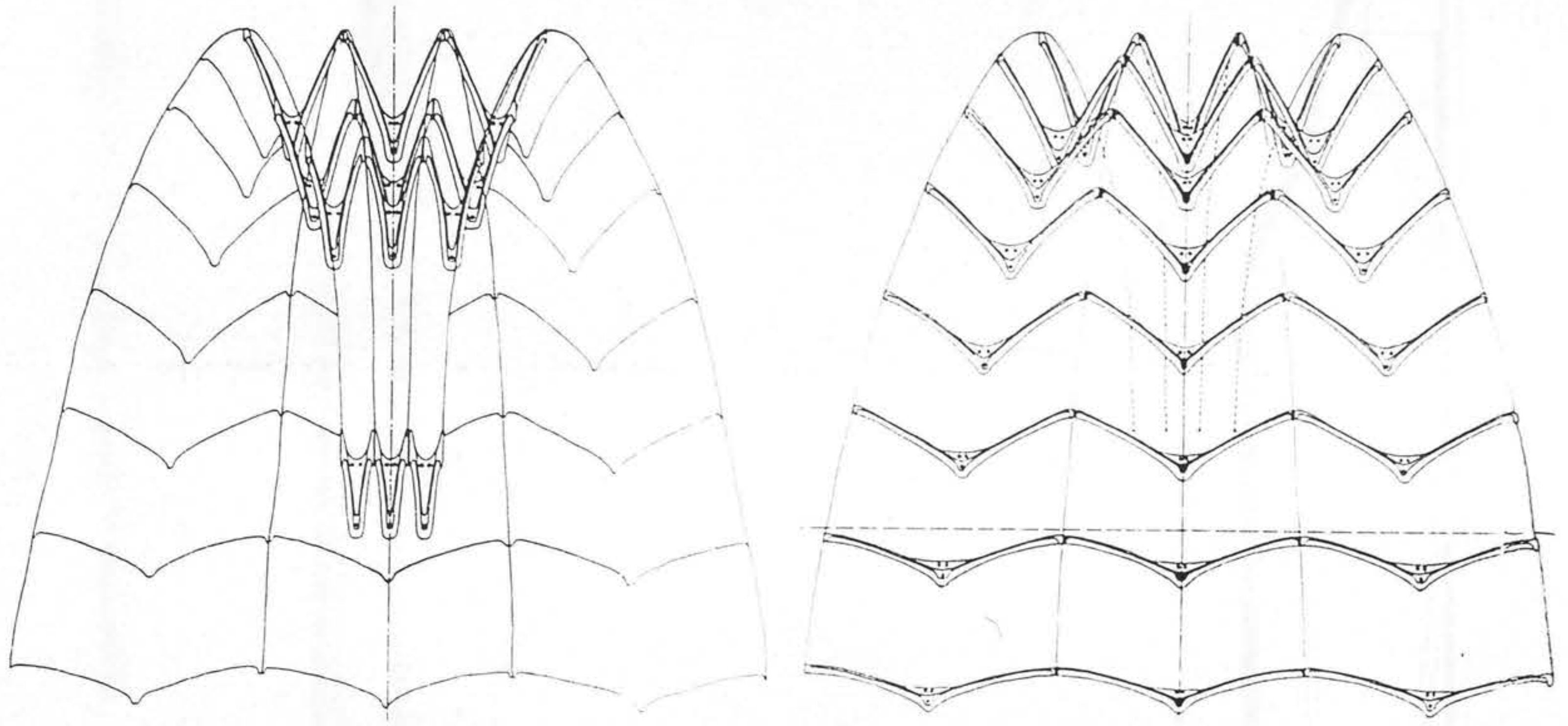
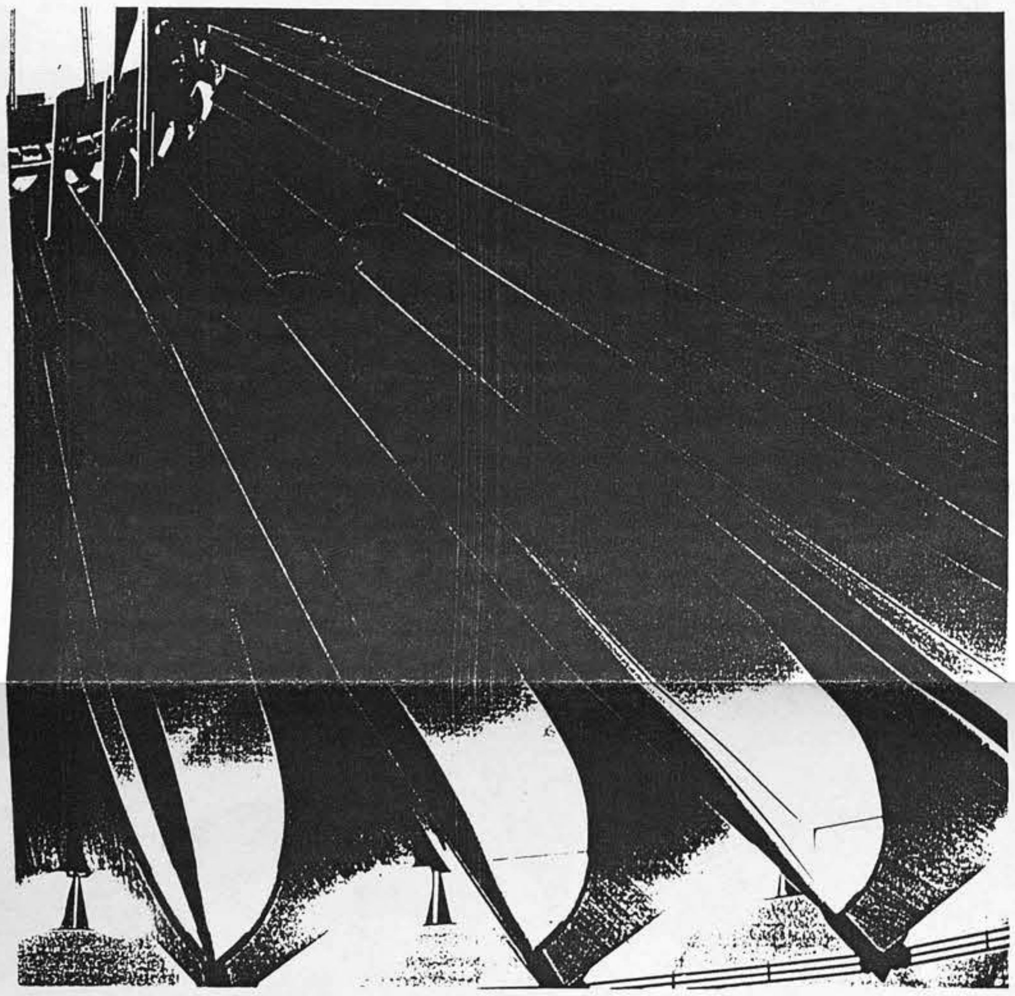


FIG 22 A THE DEPTH OF THE SHELL SECTION DECREASES TOWARDS THE OUTER EDGES AS BENDING MOMENT DECREASES, (RAVENNA)

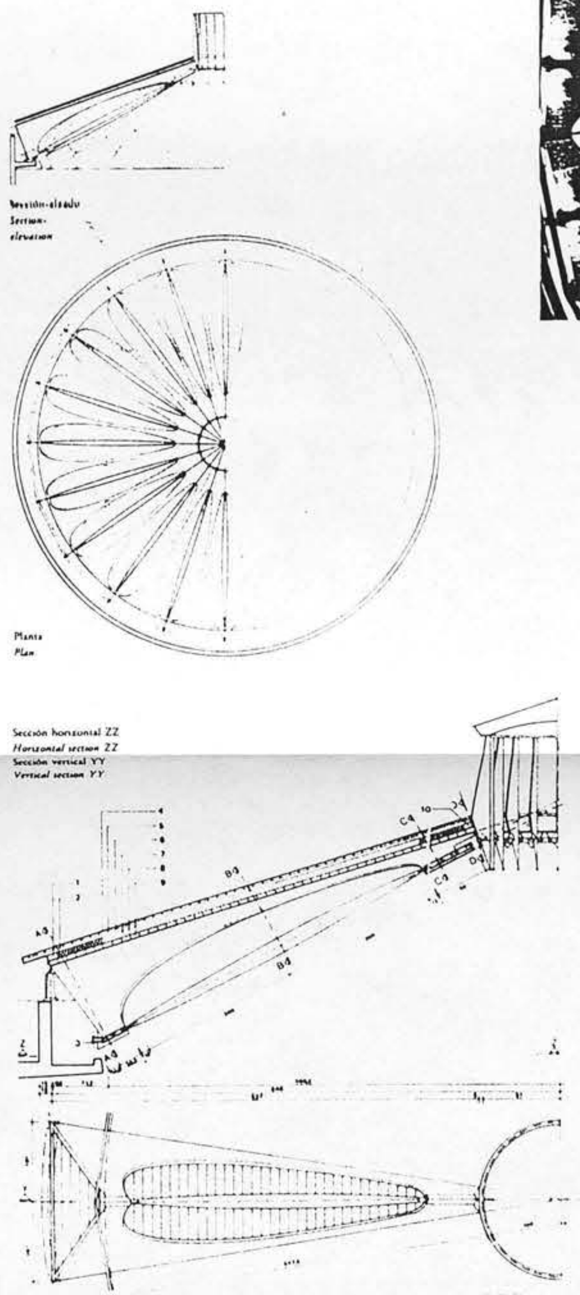
FIG 22 B FOLDED SECTIONS PROVIDE RIGIDITY, (WOHLEN SCHOOL HALL)

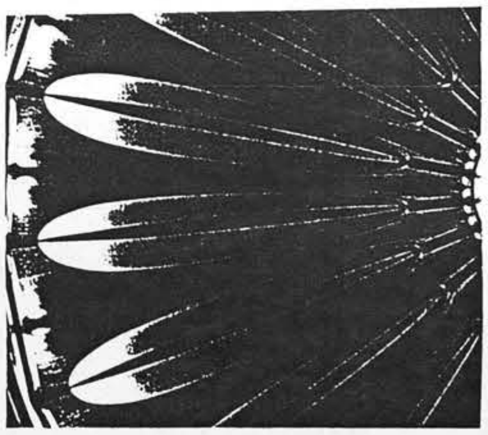
te queda desligada de la cubierta, filtrando, de esta manera, la luz al interior.

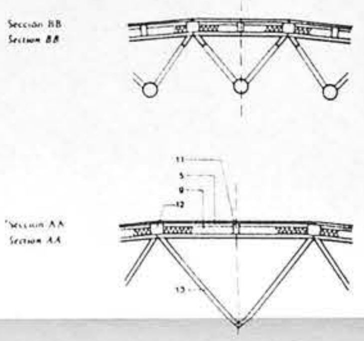


The roof of the *great hall* is another variation of the use V-shaped structural elements. The individual wood girders are linked together by means of an articulated structure

The exterior roof is separated from the load-bearing structure so as to allow natural light to filter into the hall below







Detalle de jácena

1 Viga de borde de madera 10/16 cm, solidaria con estructura en V
2 Alero 4/16 cm
3 3 FLA 10/40 cromados
4 Chapa de zinc titanio
5 Capas de cubierta 30 mm (22 mm)
6 Ventilación 4 cm
7 Lana mineral 10 cm
8 Barrera de vapor
9 Acabado interior 40/120 mm madera cepillada por una cara
10 Viga de madera 10/16 cm, solidaria con estructura en V
11 Madera intermedia 8/14 cm, en combinación con acabado interior y capas de cubierta
12 Estructura radial 14/16 cm, solidaria con estructura en V
13 Estructura en V de 3 capas 6 cm

Detail of girder

1 10/16 cm edge wood beam in combination with V-shaped structure
2 4/16 cm gable-end
3 Chromium-plated 10/40 3 FLA
4 Zinc titanium plate
5 30 mm (22 mm) roof layers
6 4 cm ventilation
7 10 cm mineral wool
8 Steam barrier
9 40/120 mm inner finish. Wood planed on one side
10 10/16 cm wood girder in combination with V-shaped structure
11 8/14 cm intermediate wood in combination with V-shaped structure
12 14/16 cm radial structure in combination with V-shaped structure
13 6 cm three layered V-shaped structure

FIG 23

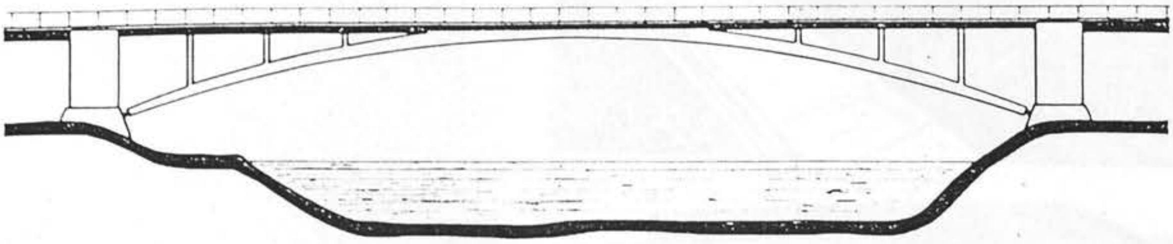
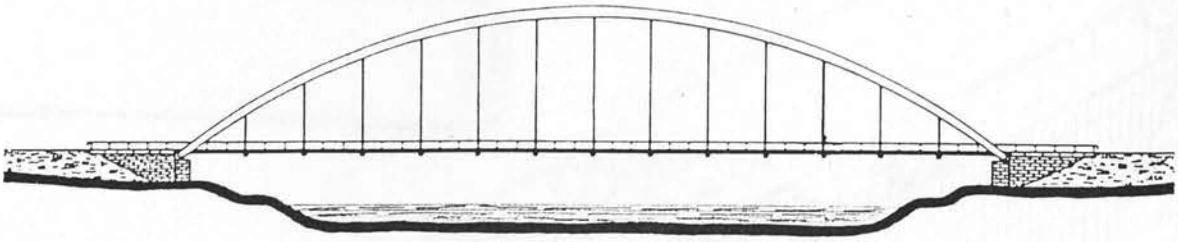
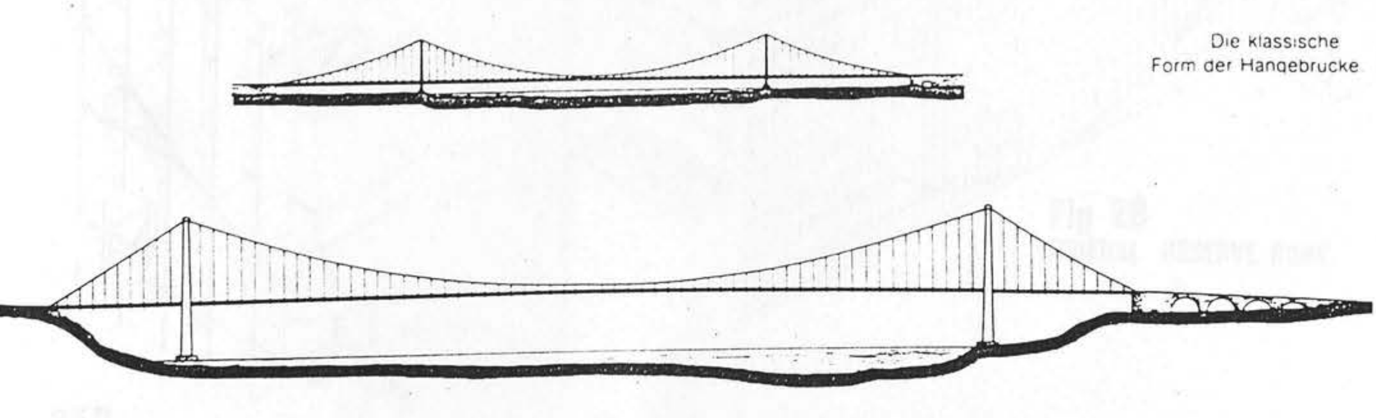


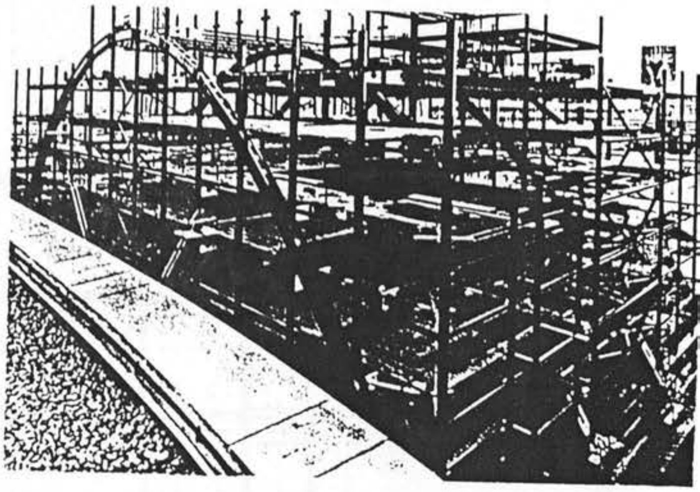
FIG 24

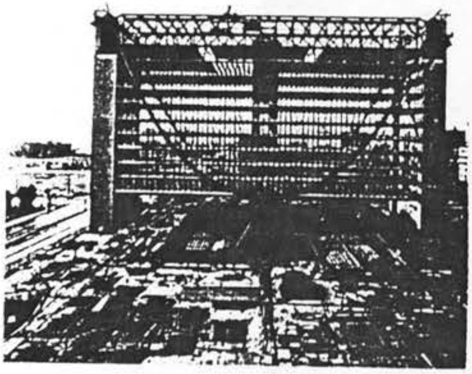


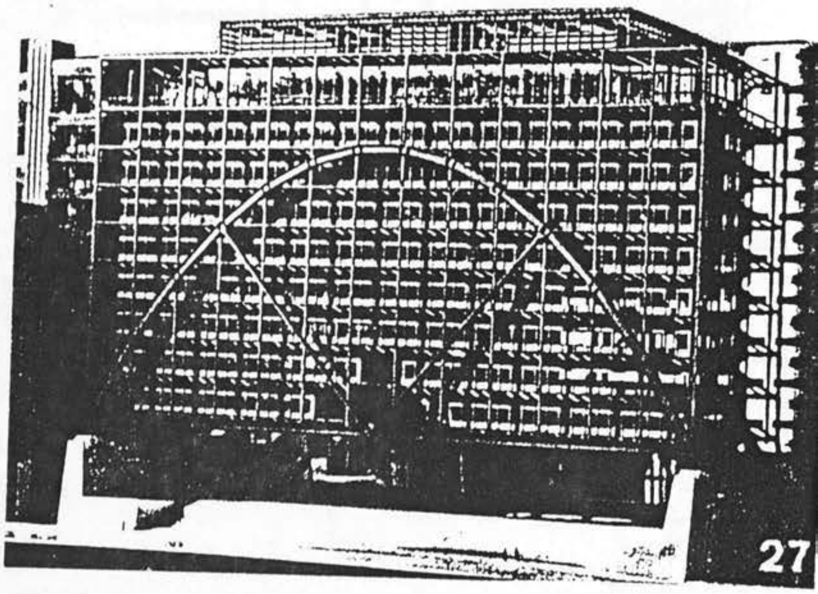


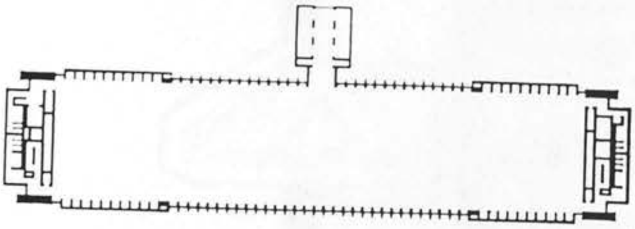
Die klassische
Form der Hangebrucke

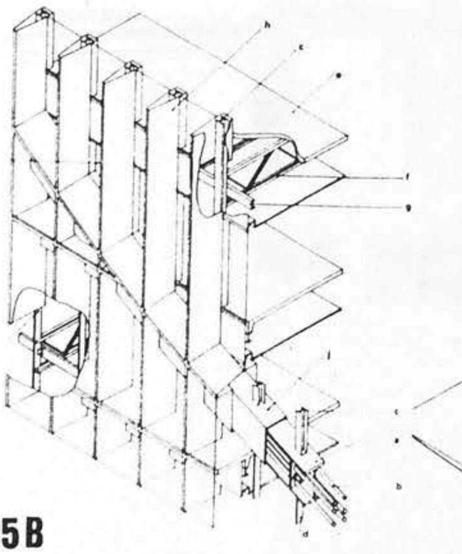
Fig 25A
BROADGATE
PHASE 11






27





25B

tenary member b 4" strand cables c 8" wide column d 1" × 8" hanger e concrete slab f 3' 0" deep
I g 10" deep channel cross member h steel fin i 1" double glazing j fireproofing
ce wall

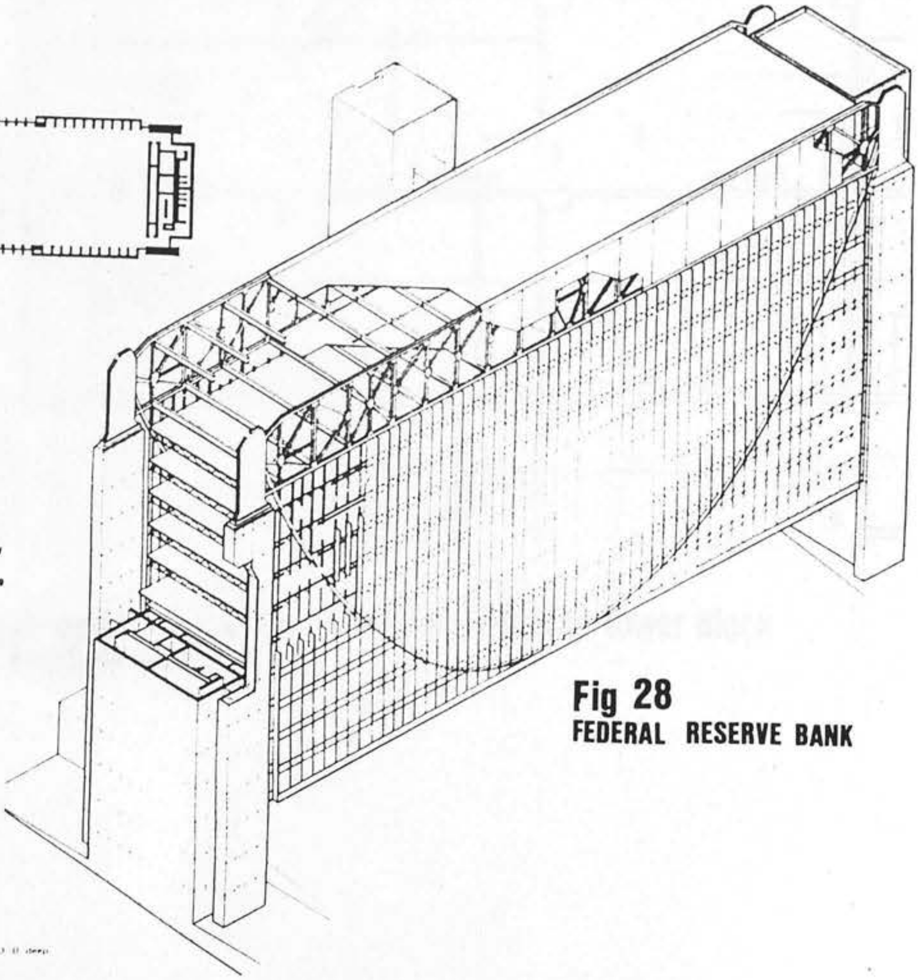


Fig 28
FEDERAL RESERVE BANK

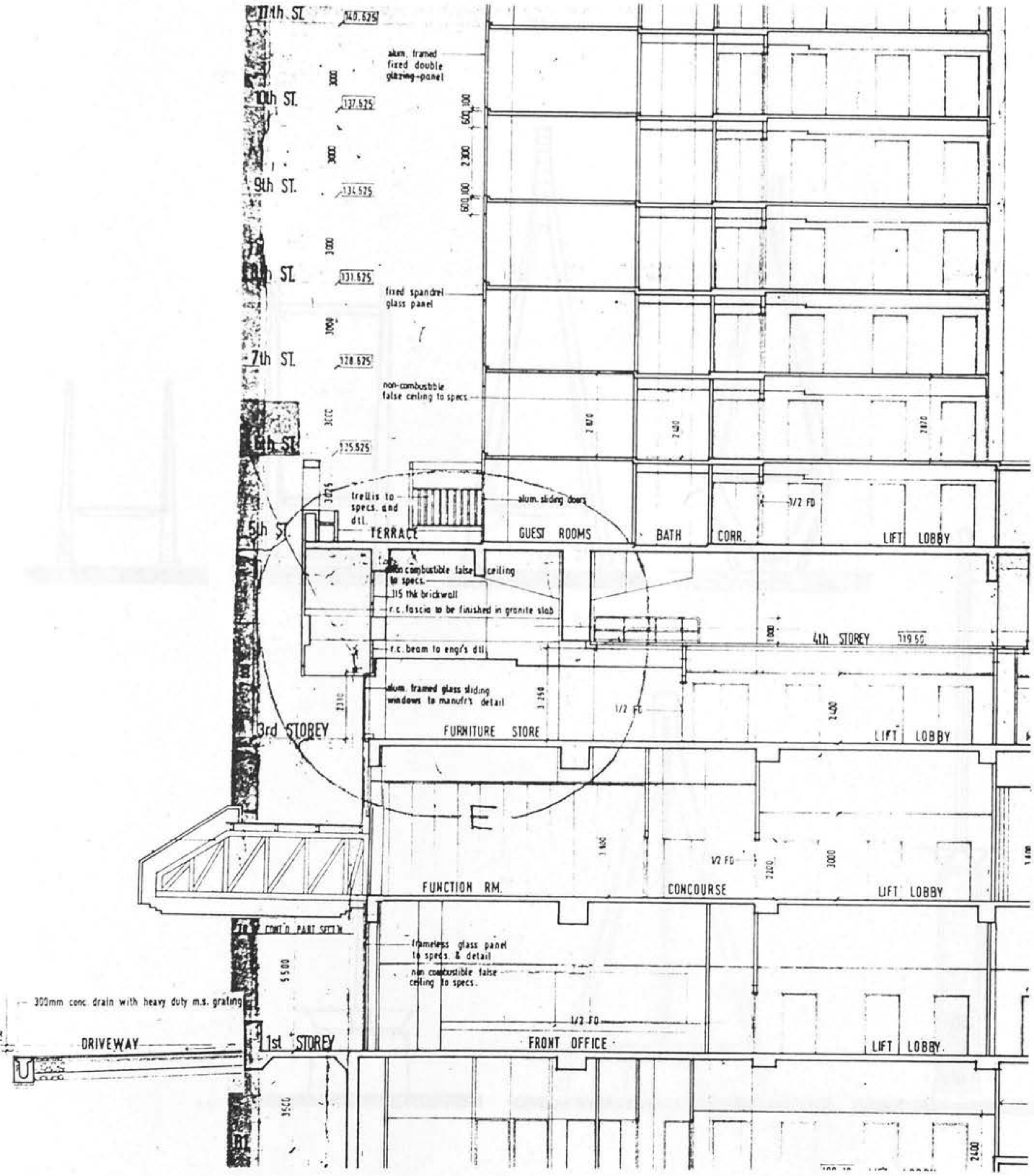


Fig 26 Prestressed rc transfer beam in 17-storey tower block on 4-storey podium

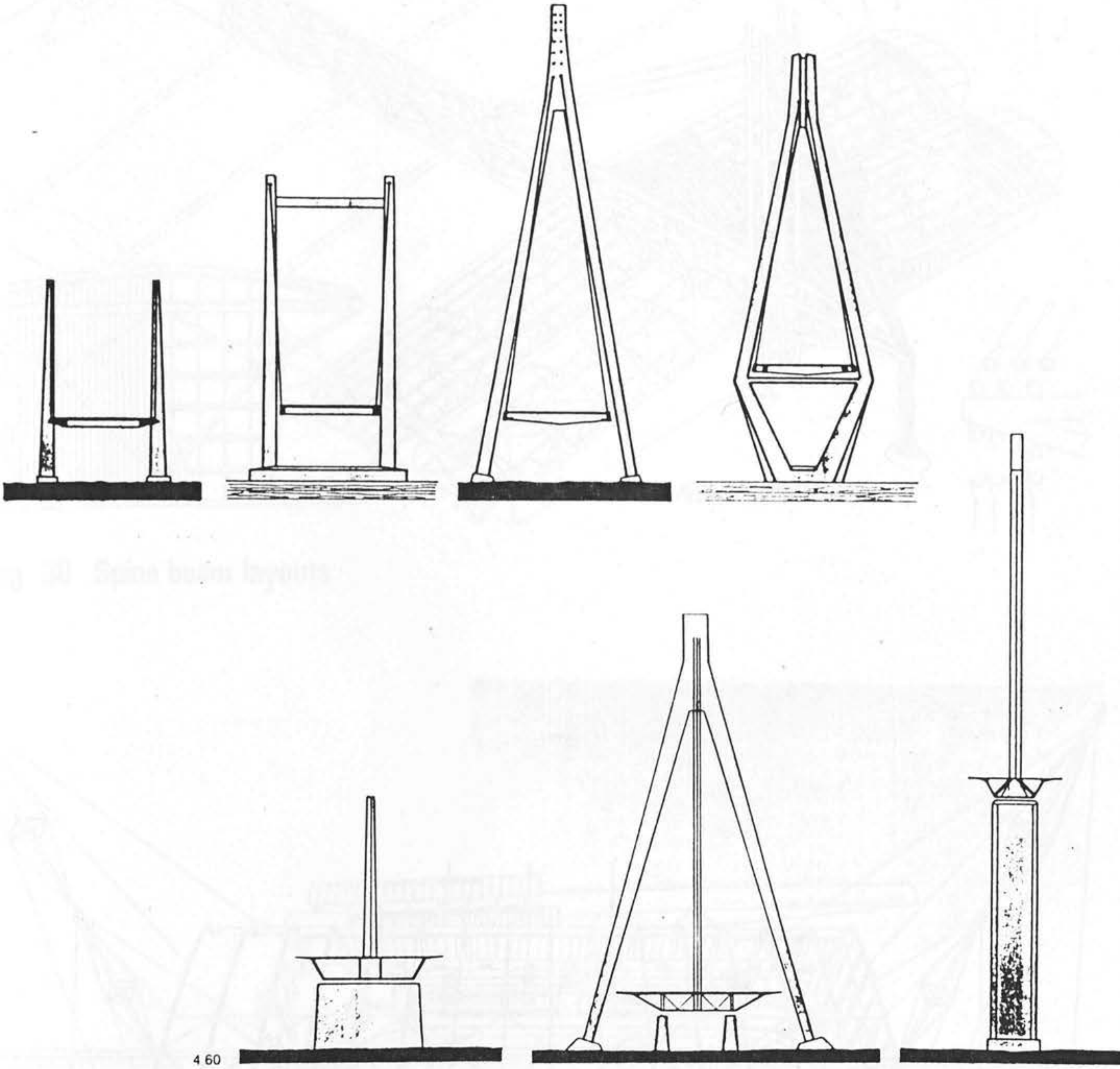


FIG 29 EXAMPLES OF SUPPORTS TO CABLE-STAYED BRIDGES

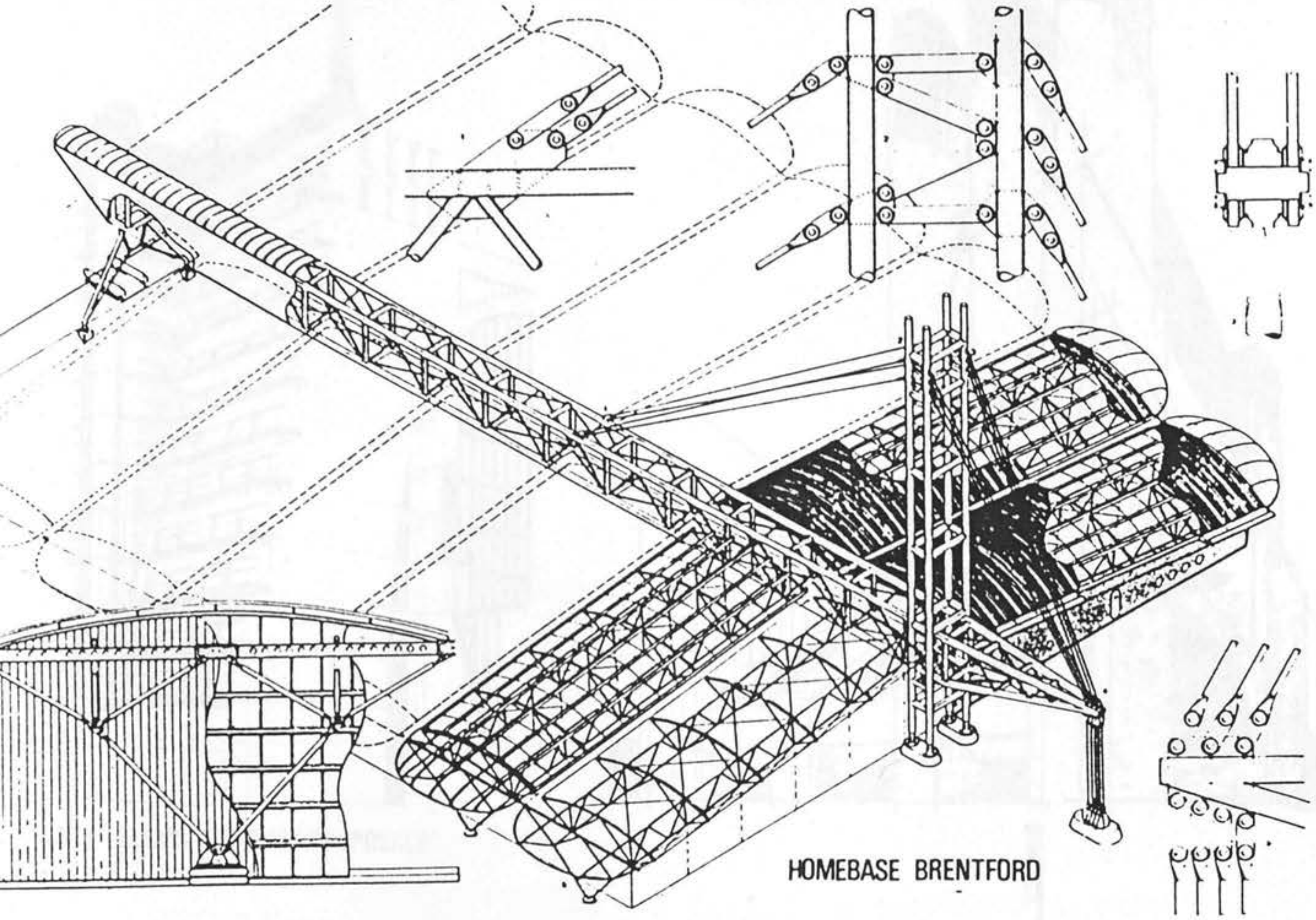
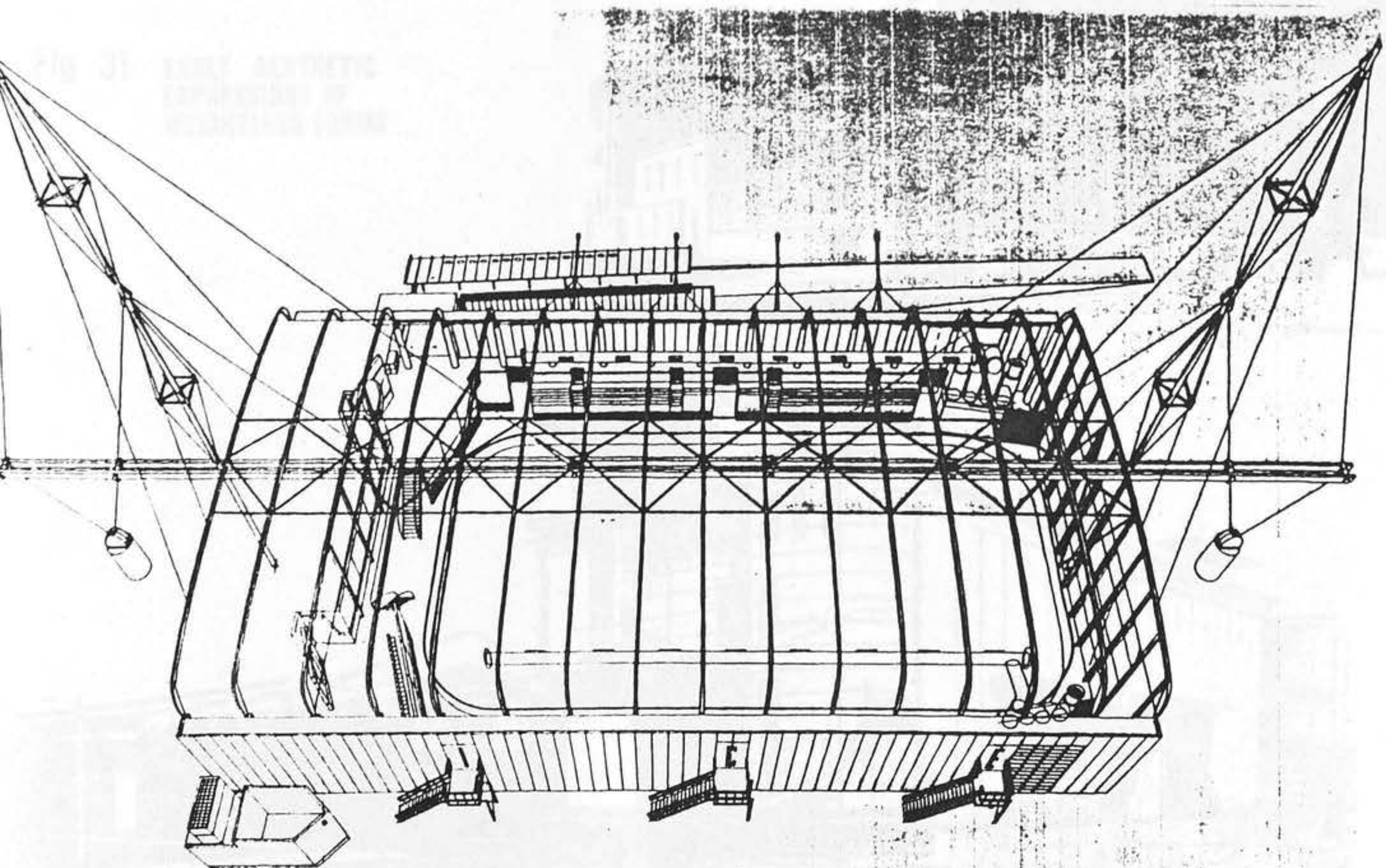
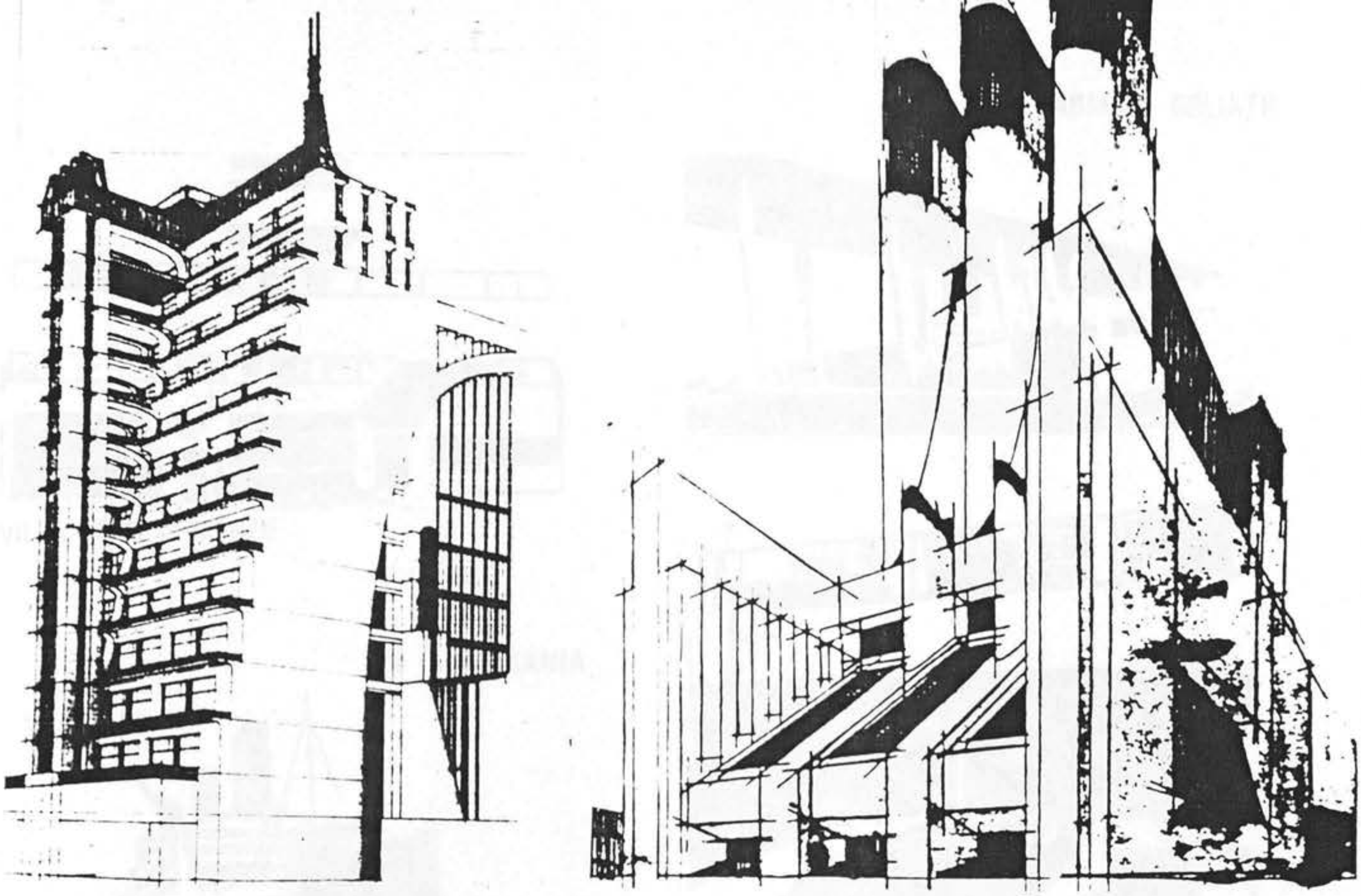


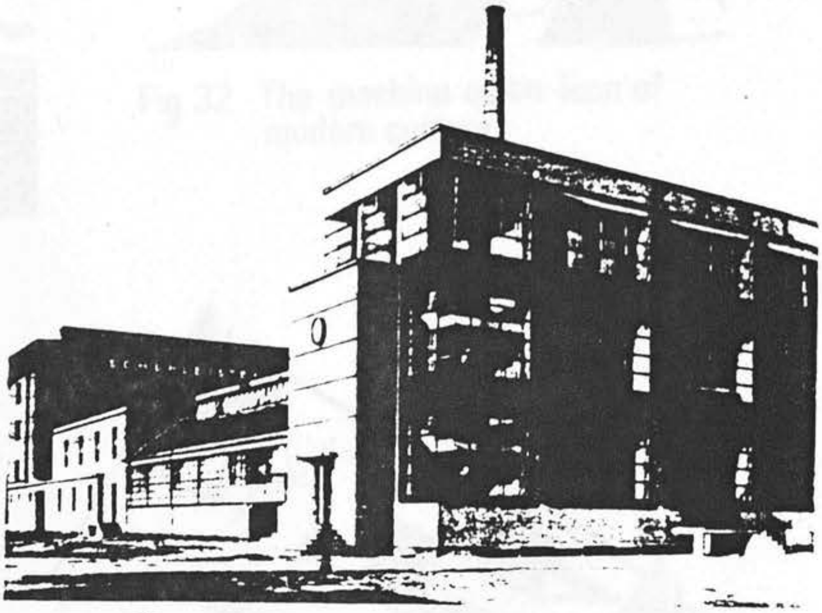
Fig 30 Spine beam layouts

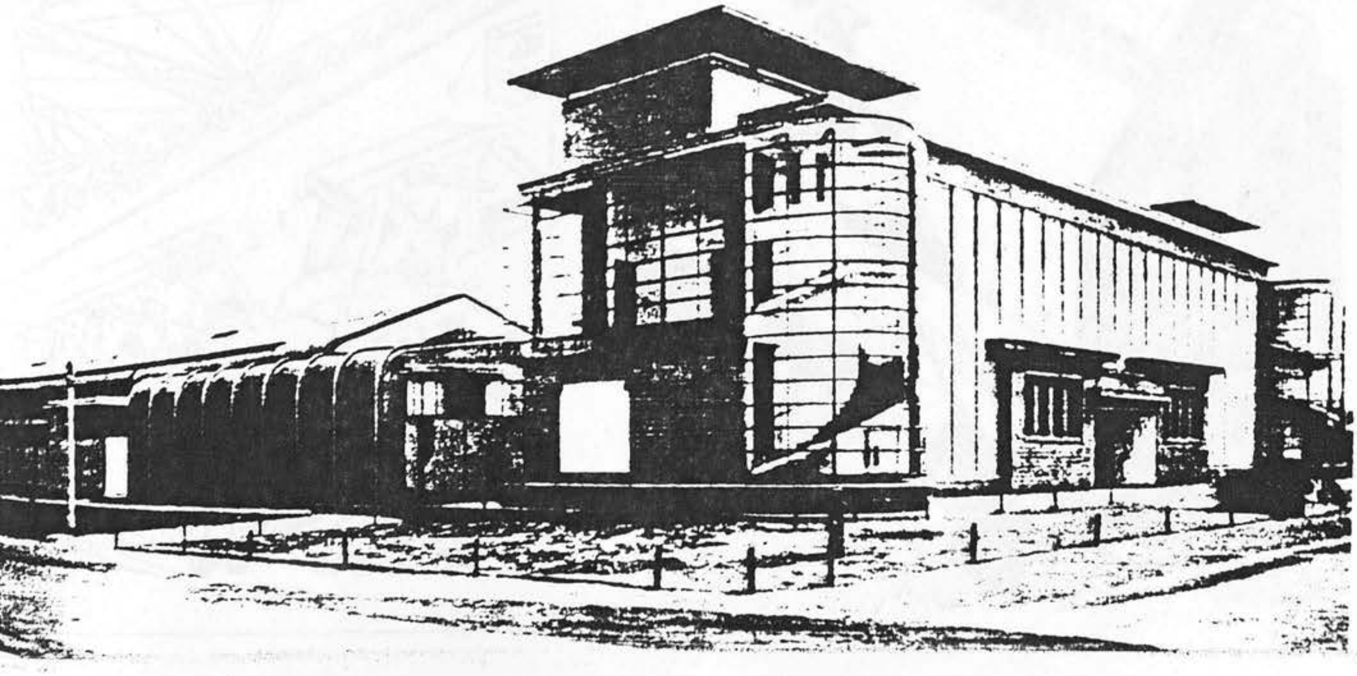


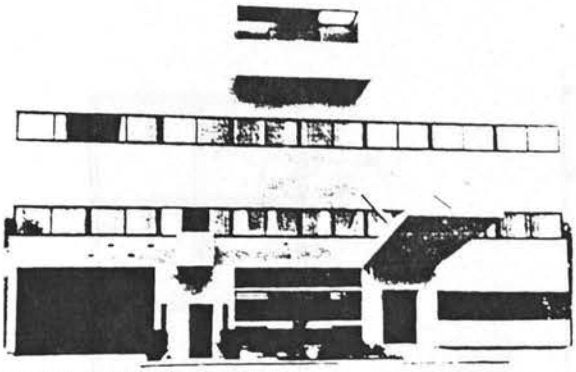


SANT' ELIA'S FUTURIST PROPOSALS

Fig 31 EARLY AESTHETIC EXPRESSIONS OF WEIGHTLESS FORMS

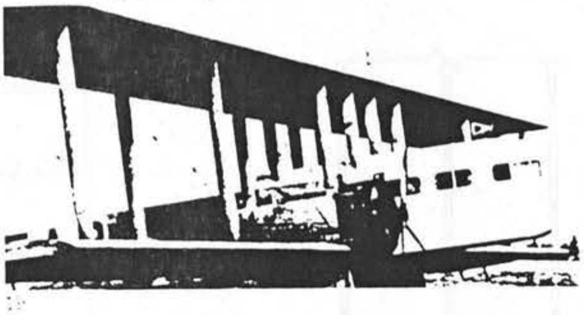


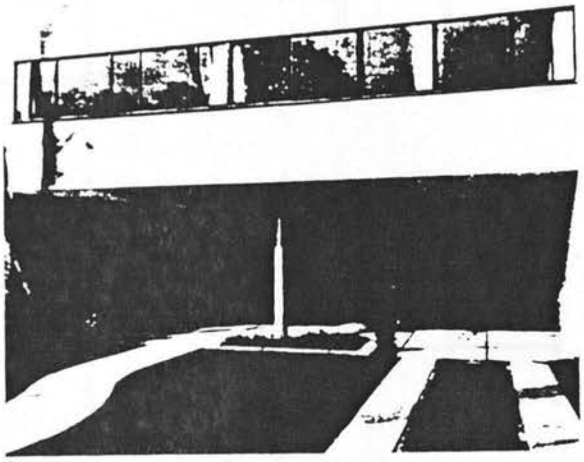




VILLA STEIN de MONZIE

The FARMAN GOLIATH





20

The AQUITANIA

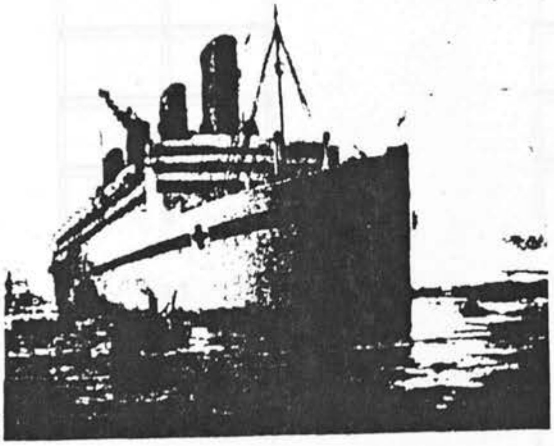
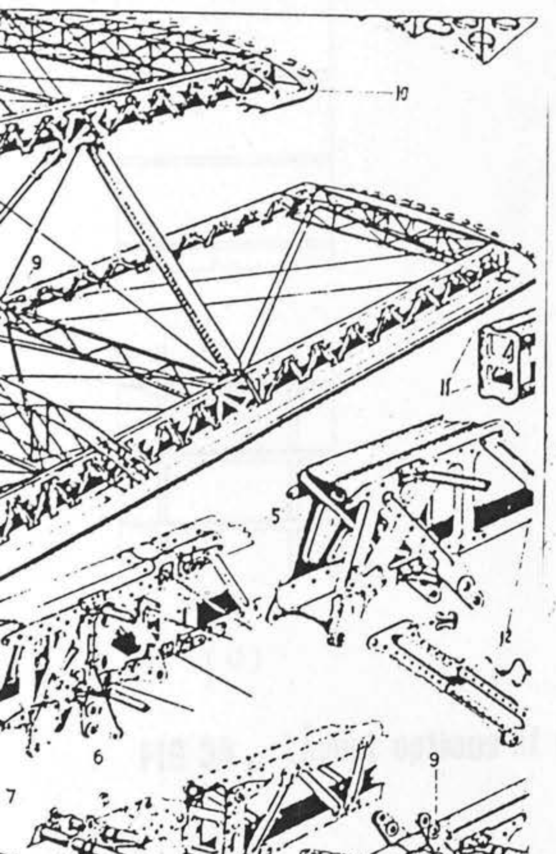
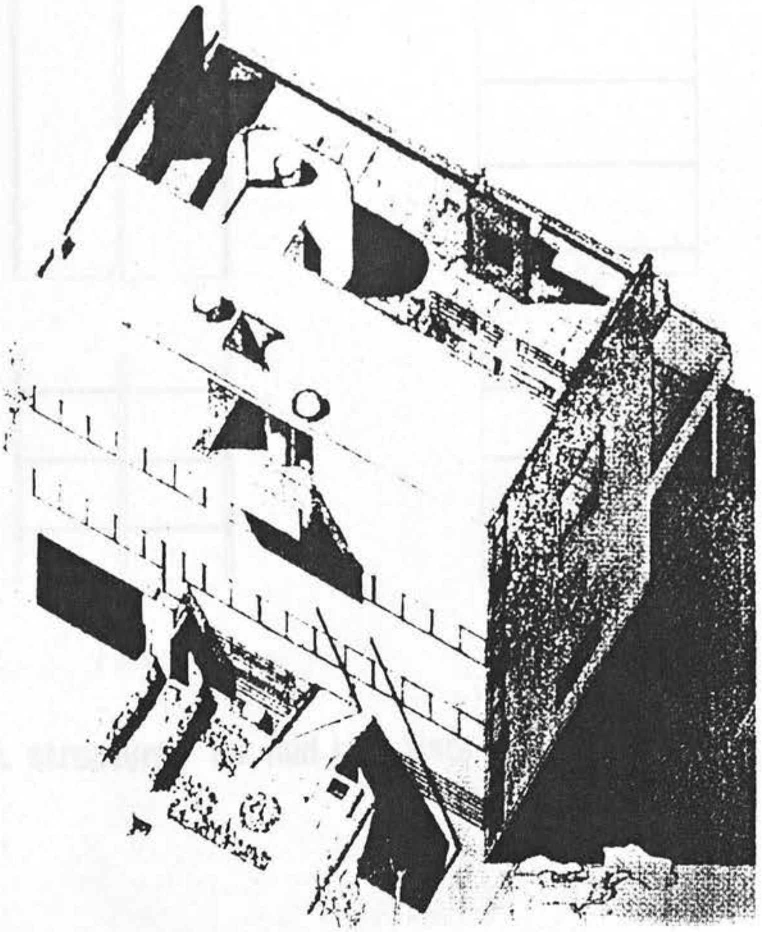


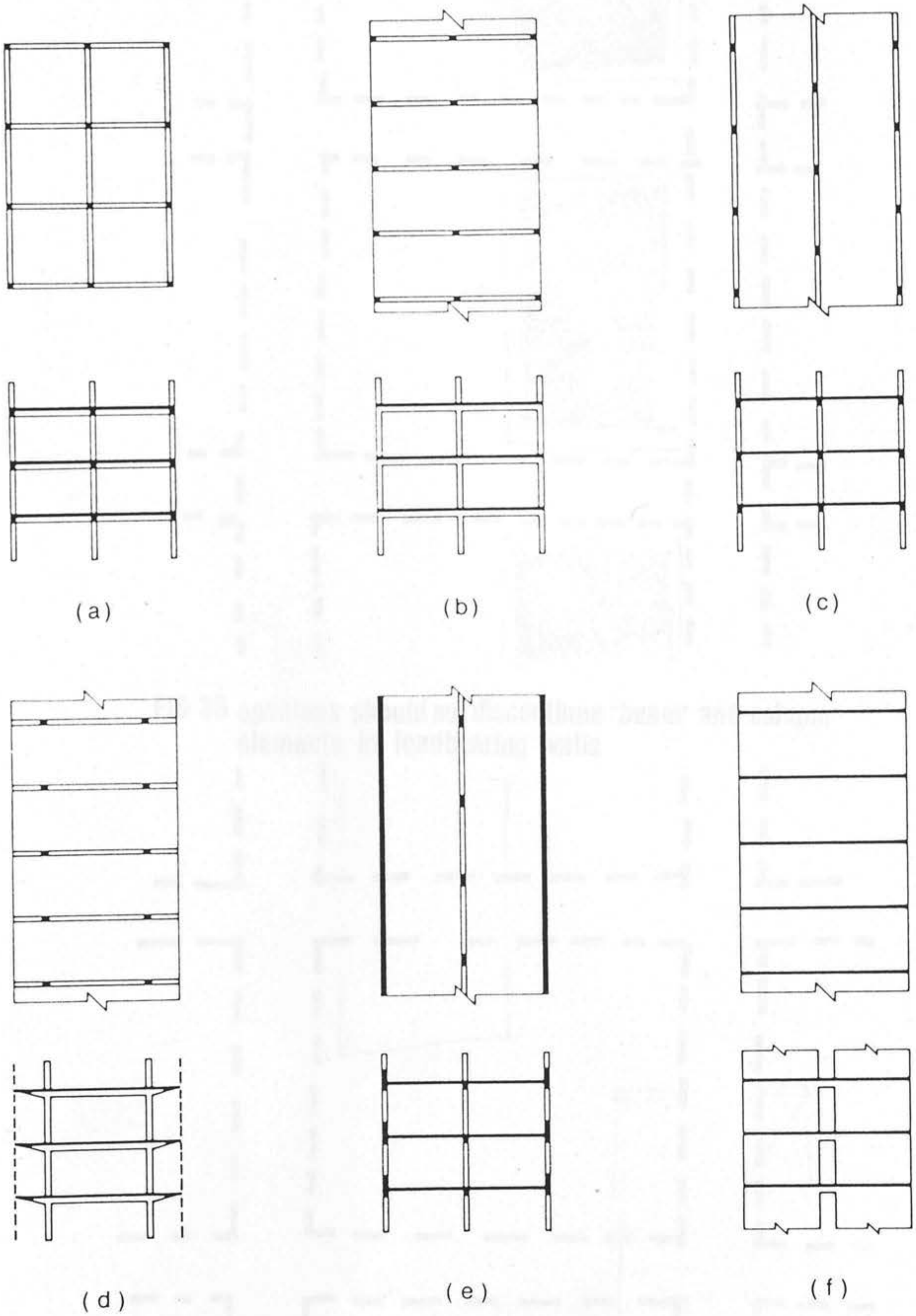
Fig 32 The machine as an icon of modern culture

Fig 33 Caproni Biplane



VILLA STEIN





(a) (b) (c) (d) (e) (f)

FIG 34 Layout options of r.c. structures for mid-rise flats

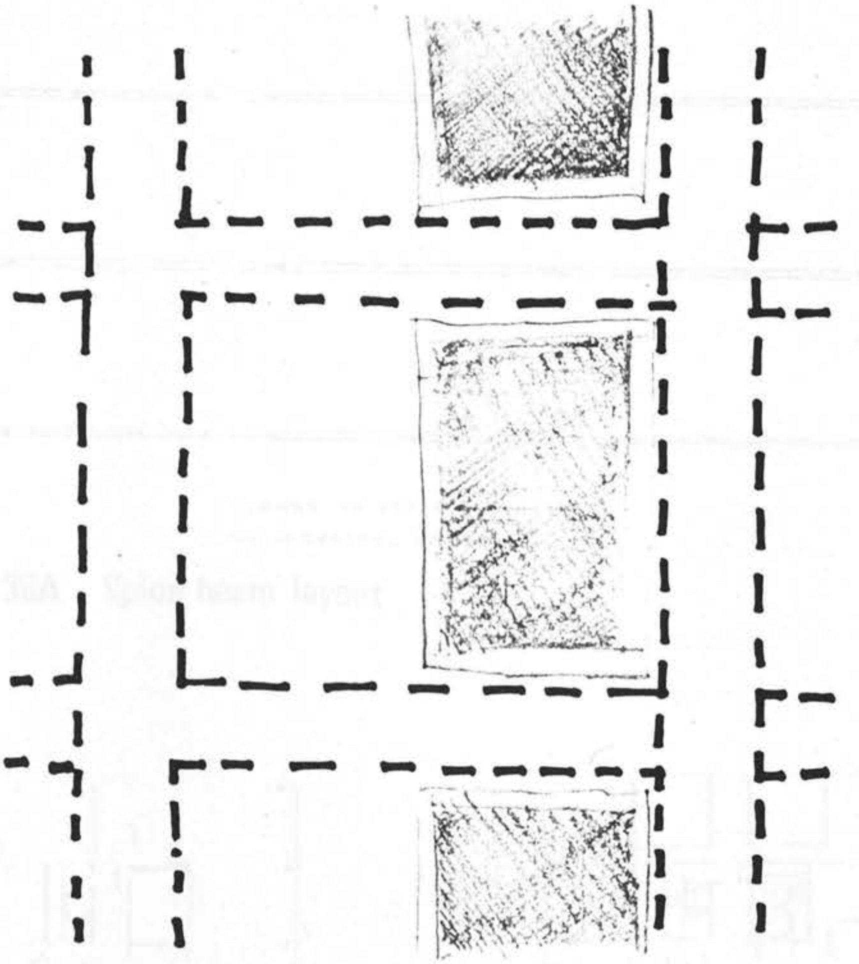
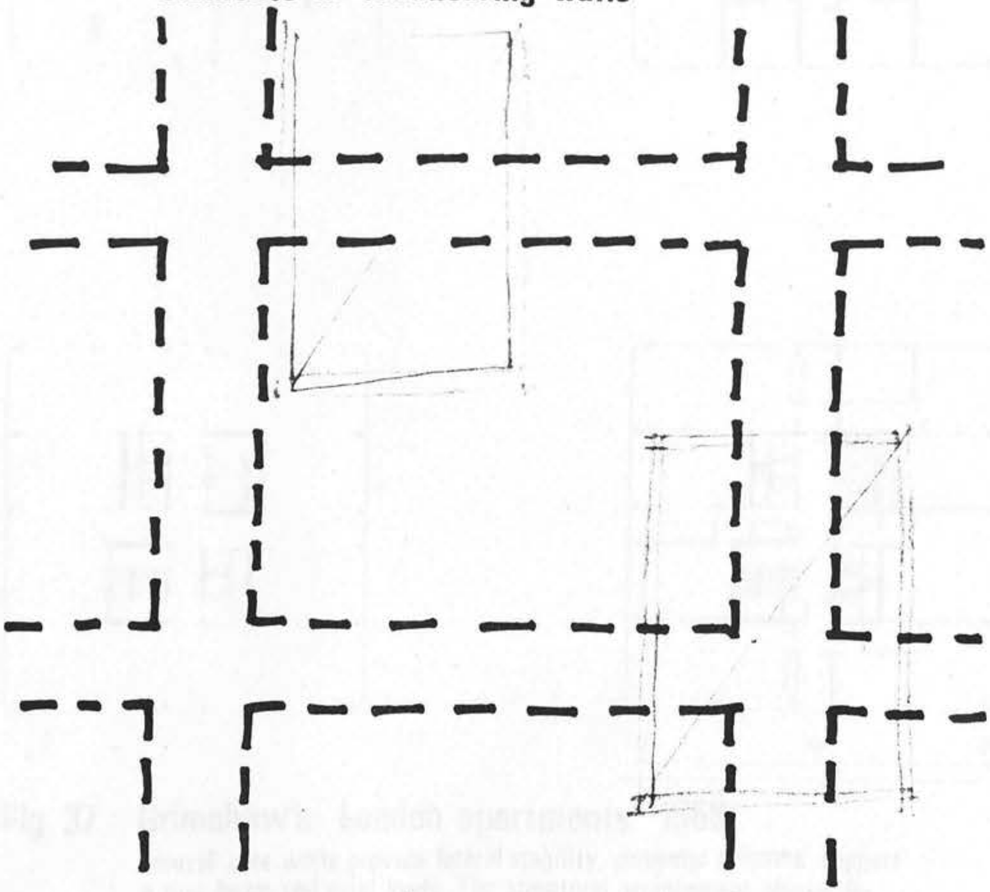


FIG 35 openings should not discontinue 'beam' and 'column' elements in loadbearing walls



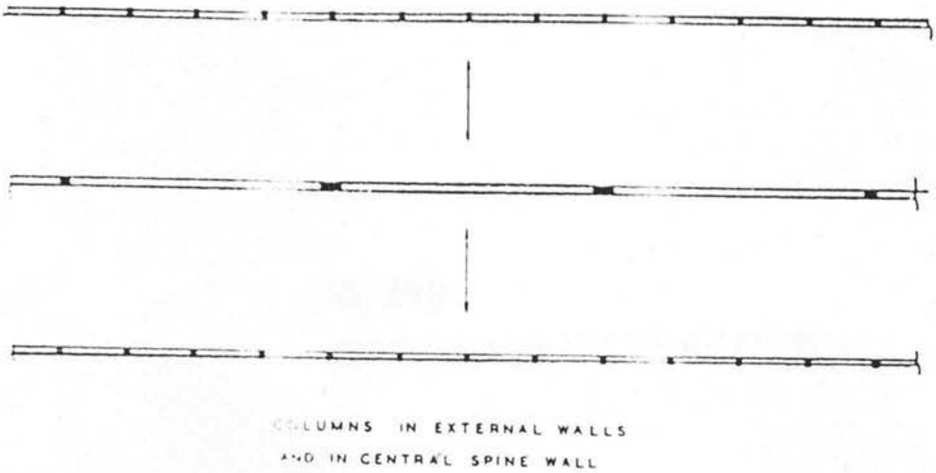


Fig 36A Spine beam layout

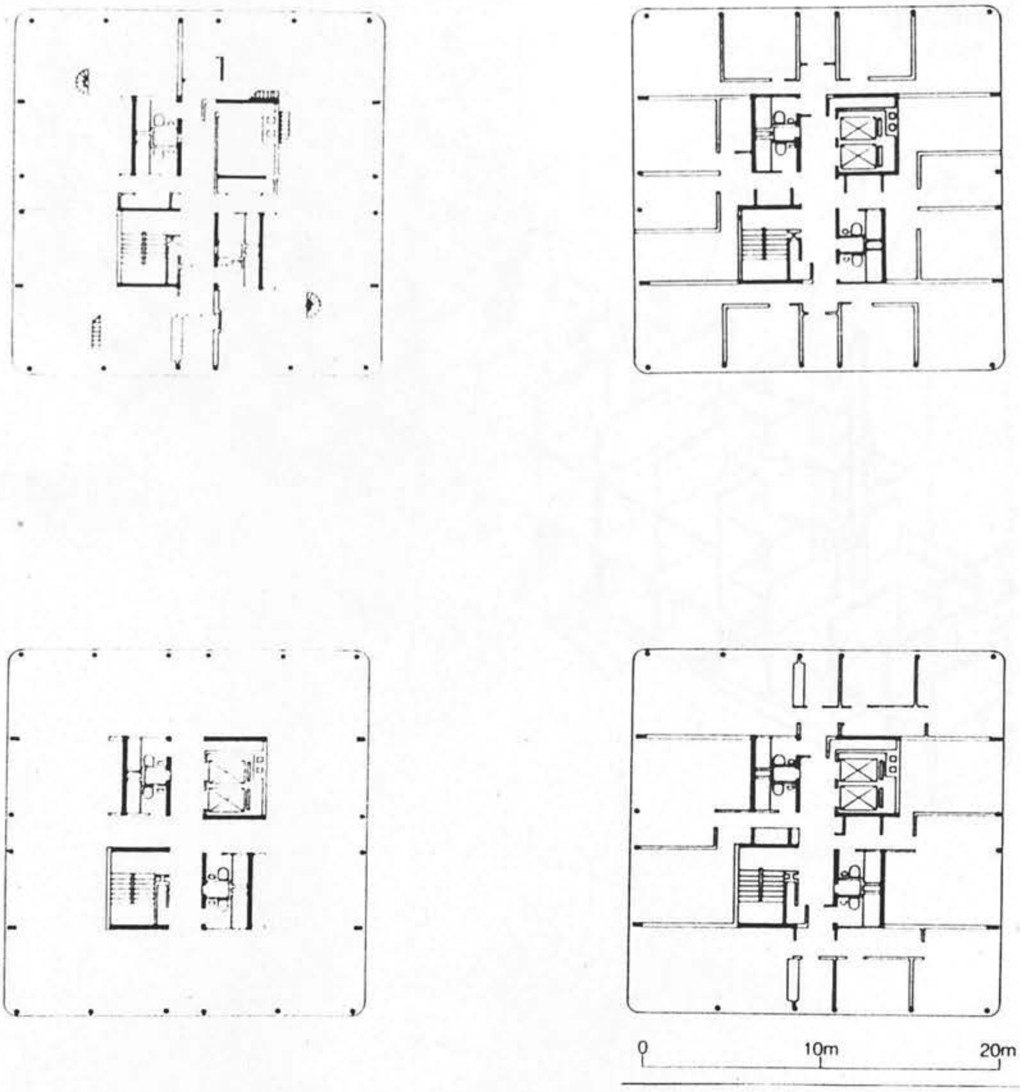
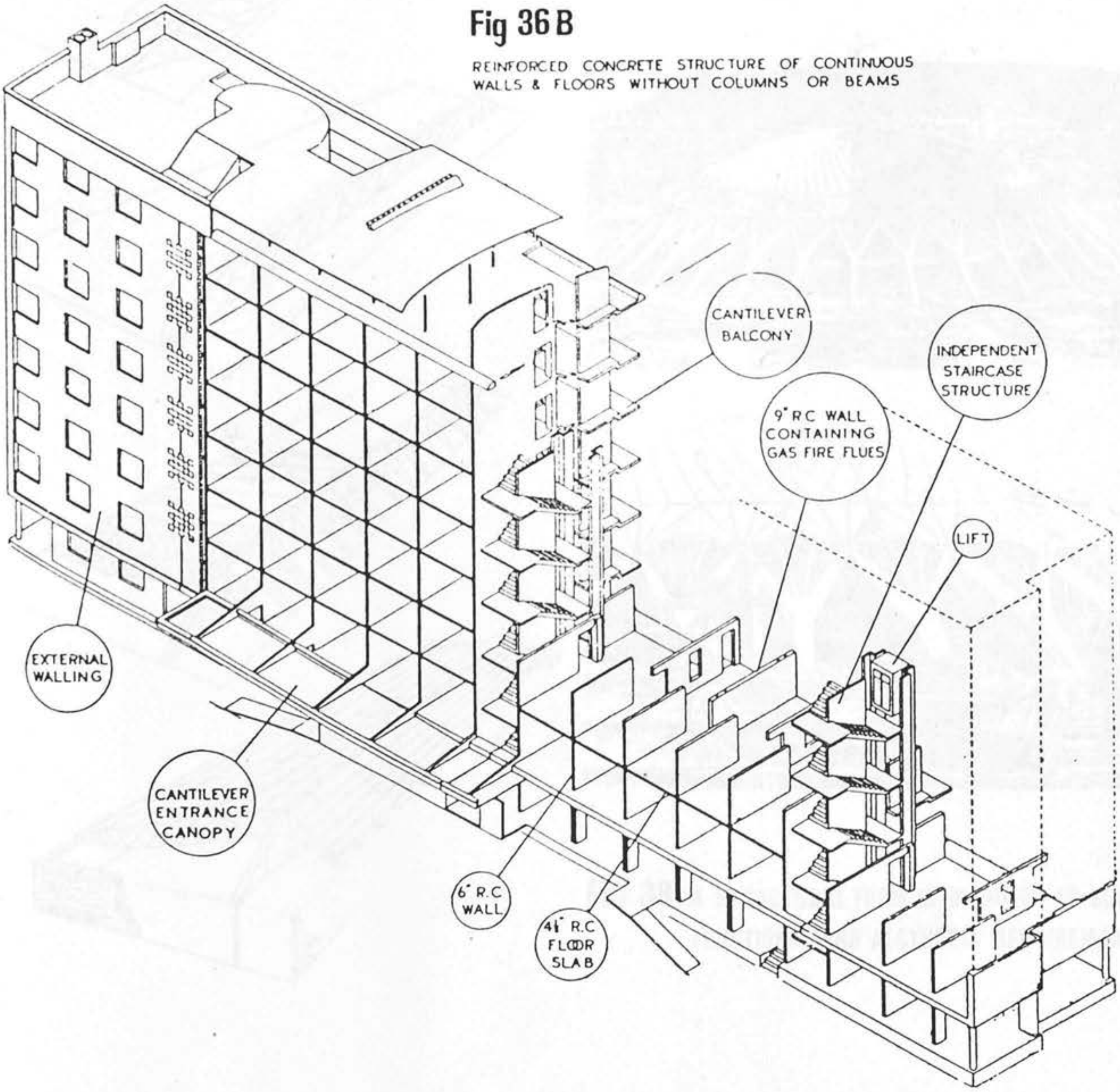


Fig 37 Grimshaw's London apartments 1968

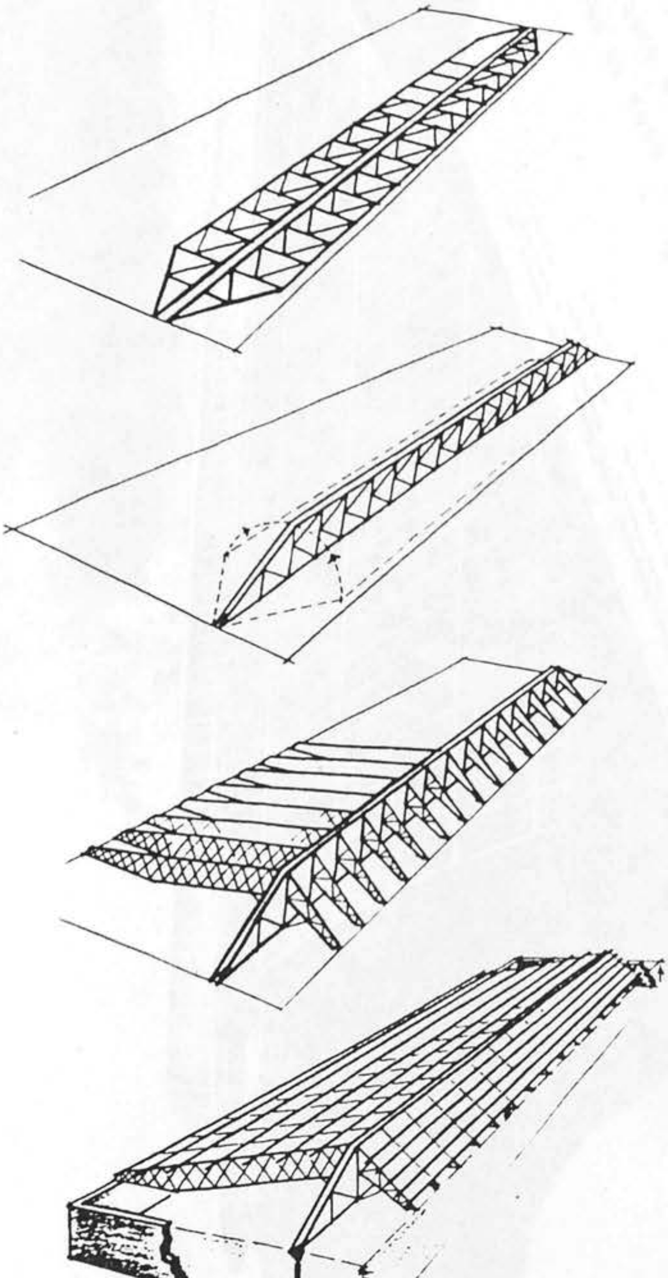
central core walls provide lateral stability, perimeter columns support a ring beam and axial loads. The structural arrangement allows for flexibility in architectural layout

Fig 36 B

REINFORCED CONCRETE STRUCTURE OF CONTINUOUS WALLS & FLOORS WITHOUT COLUMNS OR BEAMS



Torroja's Barrajas Hangar



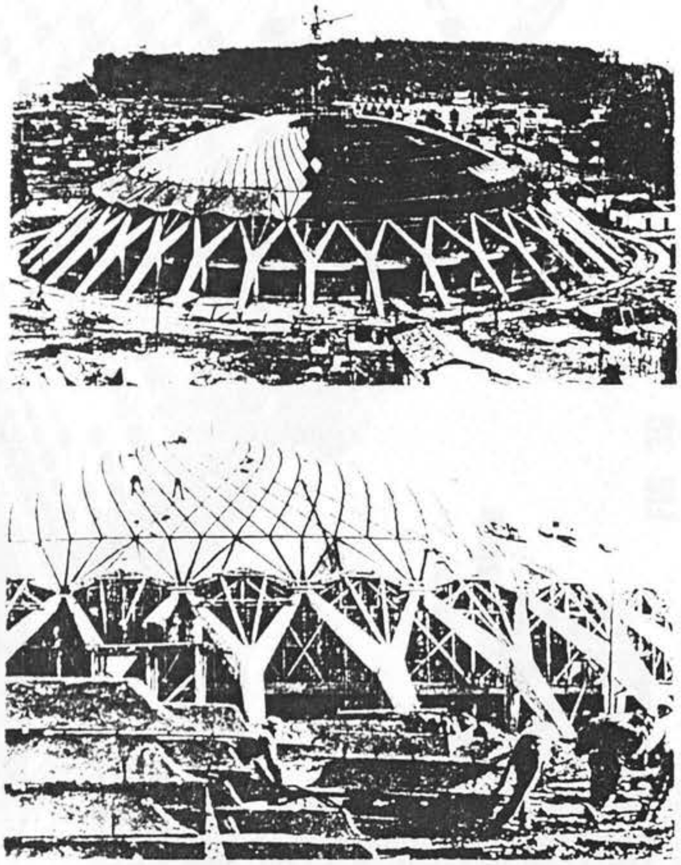
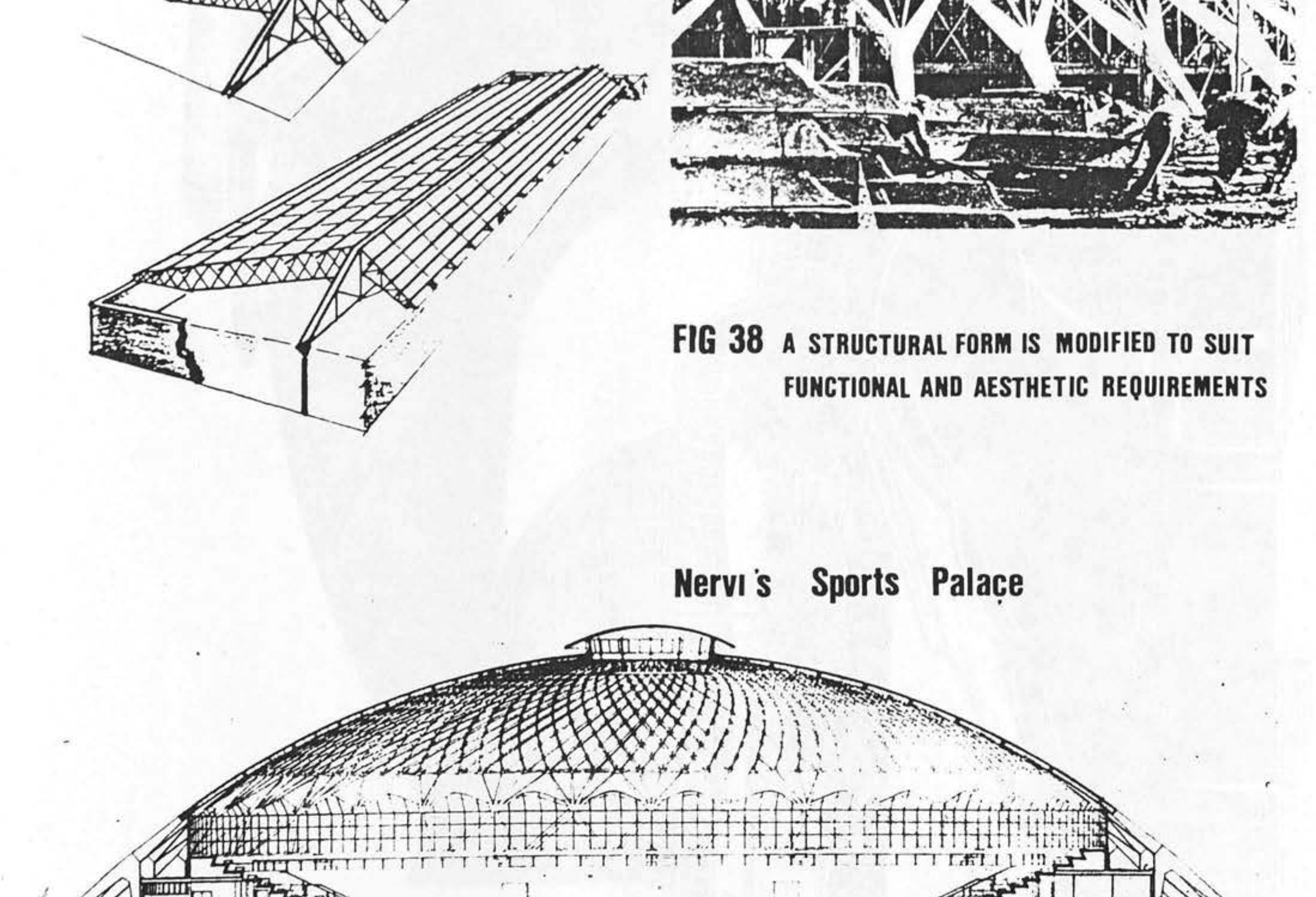


FIG 38 A STRUCTURAL FORM IS MODIFIED TO SUIT FUNCTIONAL AND AESTHETIC REQUIREMENTS

Nervi's Sports Palace



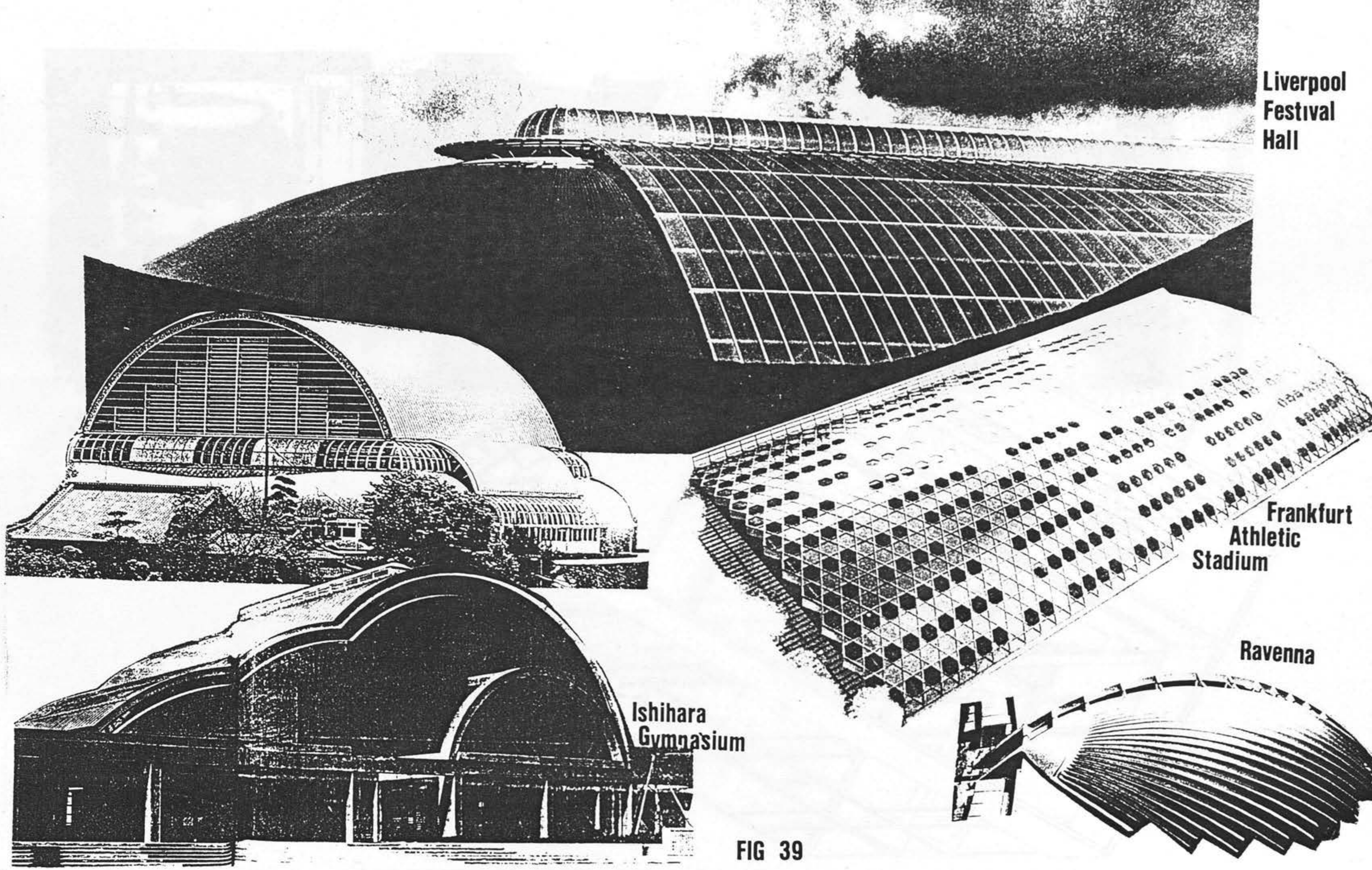
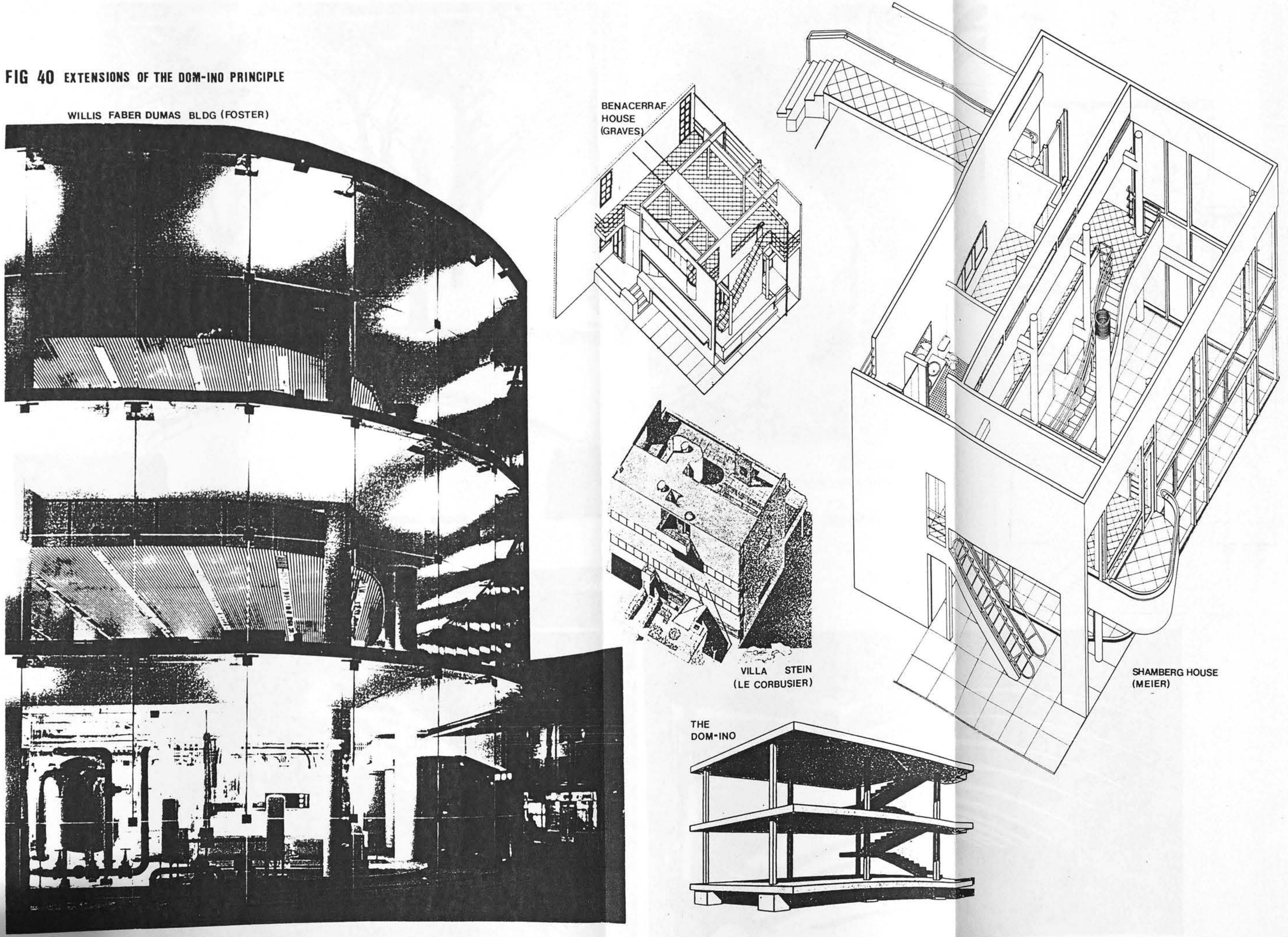

Liverpool
Festival
Hall
Frankfurt
Athletic
Stadium
Ravenna
Ishihara
Gymnasium

FIG 39

FIG 40 EXTENSIONS OF THE DOM-INO PRINCIPLE



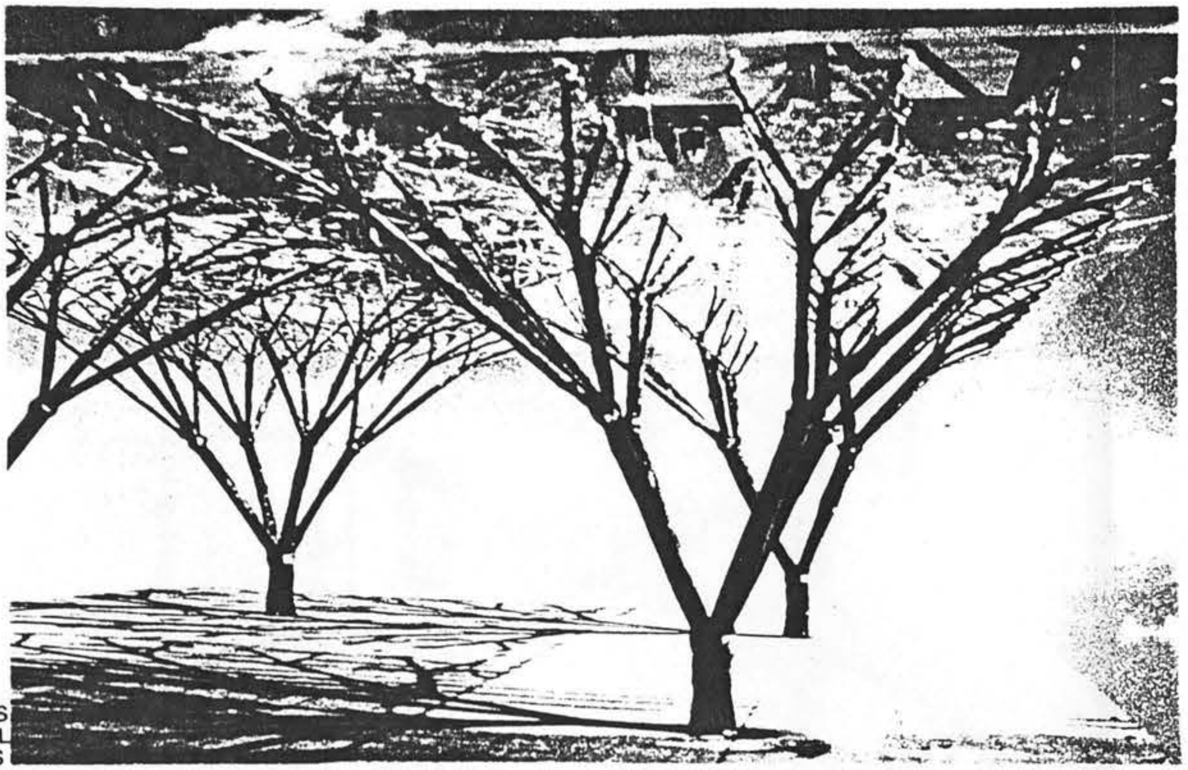
WILLIS FABER DUMAS BLDG (FOSTER)

BENACERRAF HOUSE (GRAVES)

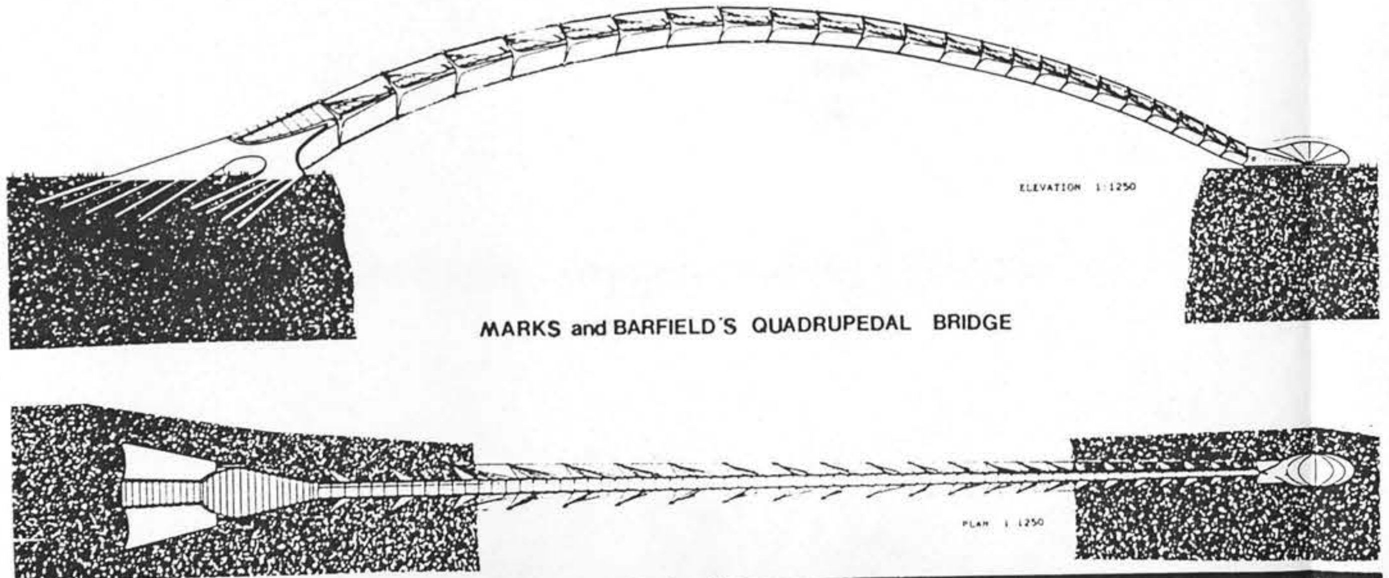
VILLA STEIN (LE CORBUSIER)

SHAMBERG HOUSE (MEIER)

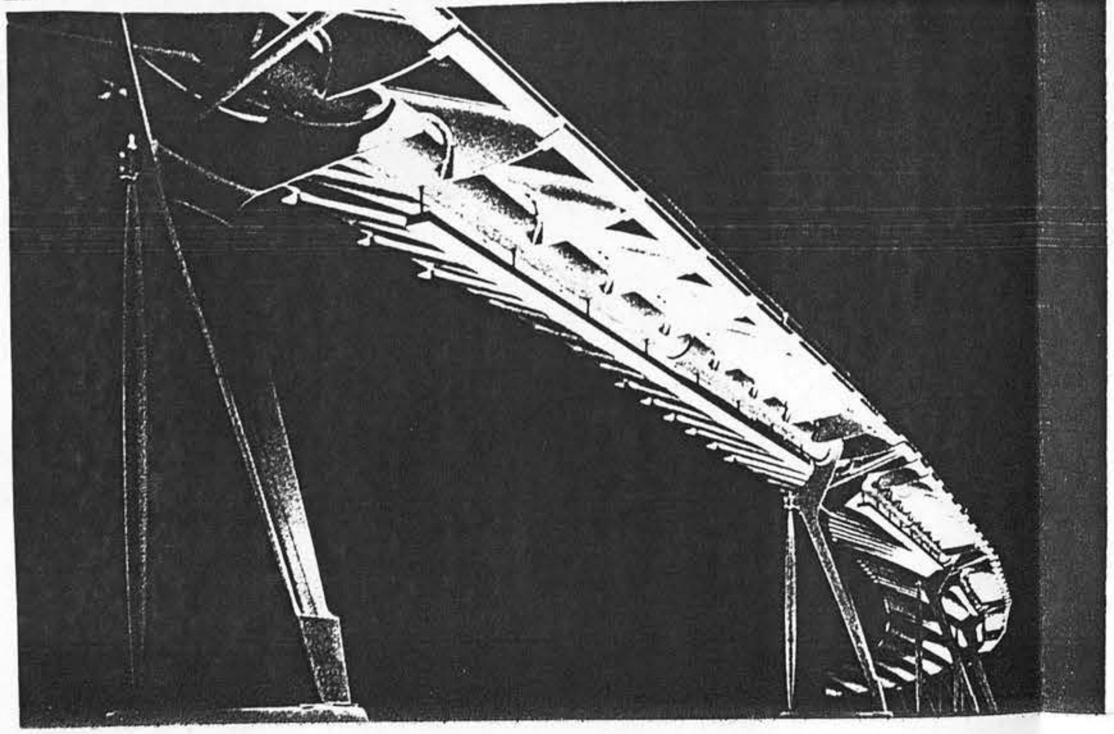
THE DOM-INO

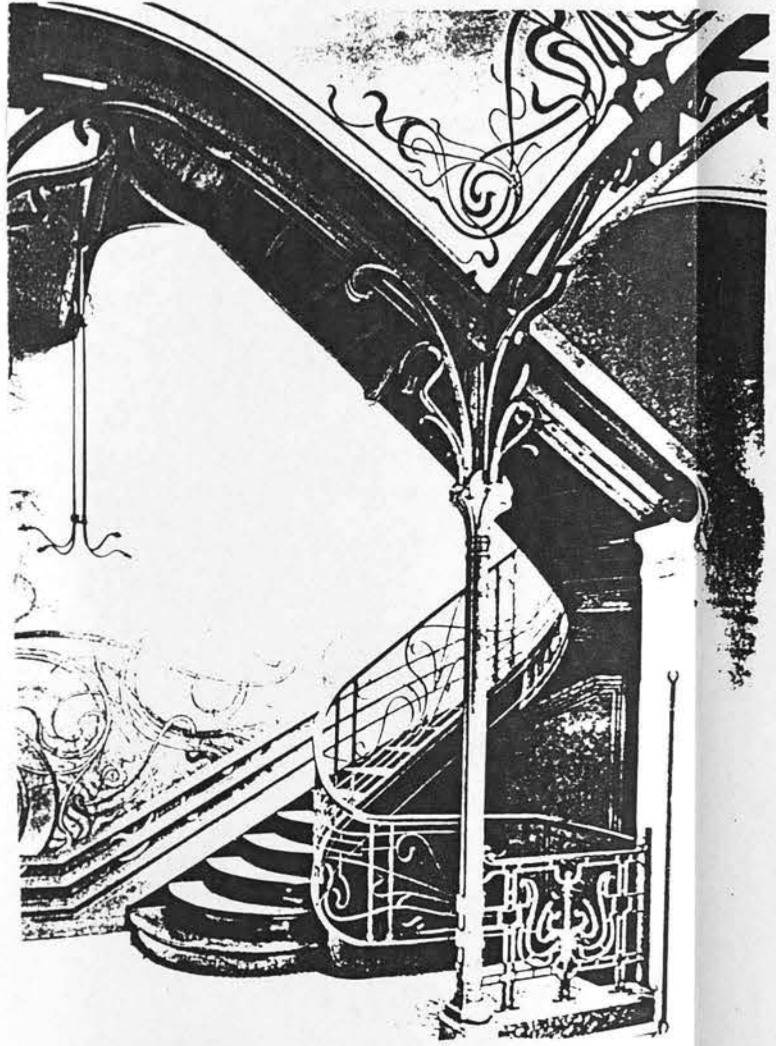


OTTO'S STRUCTURAL TREES



MARKS and BARFIELD'S QUADRUPEDAL BRIDGE





ART NOUVEAU EXPRESSIONS. V. HORTA

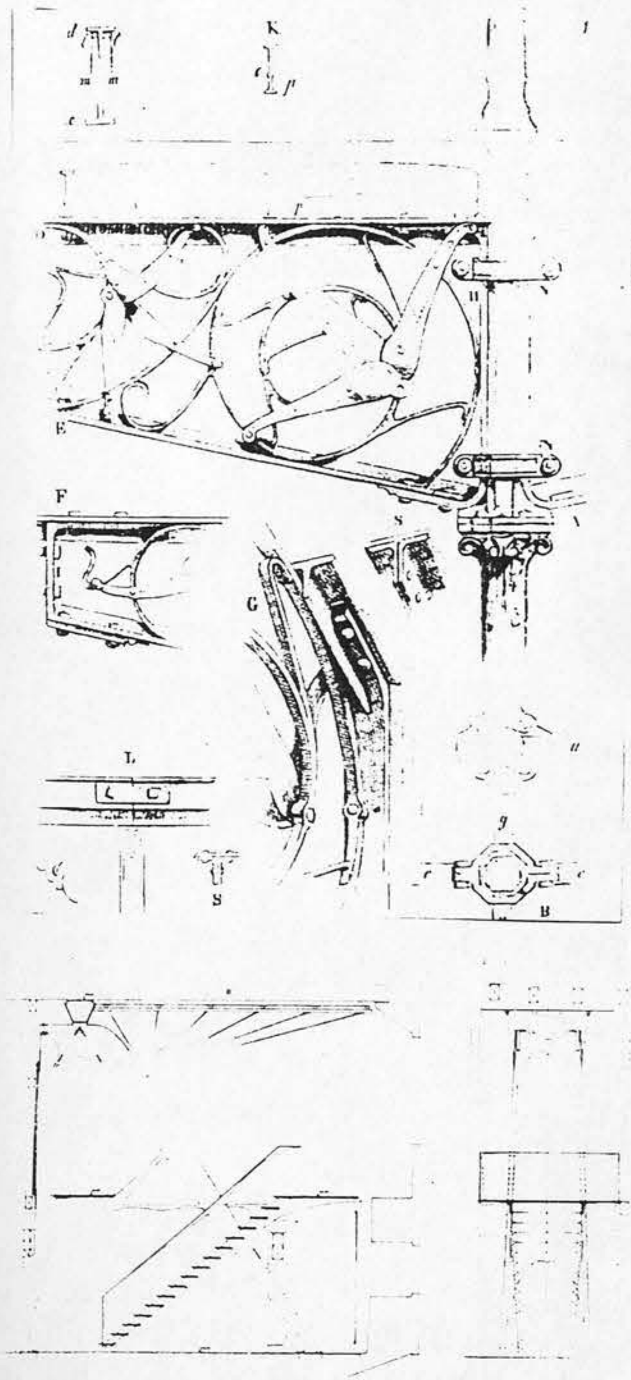
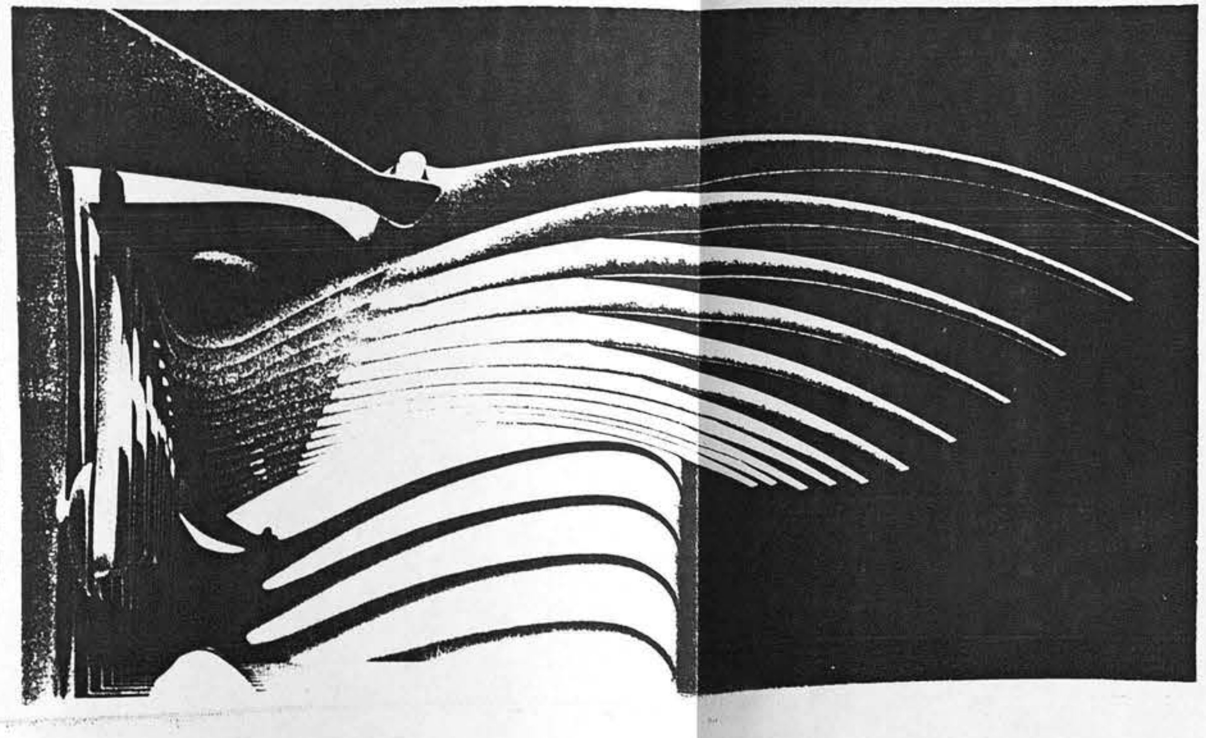
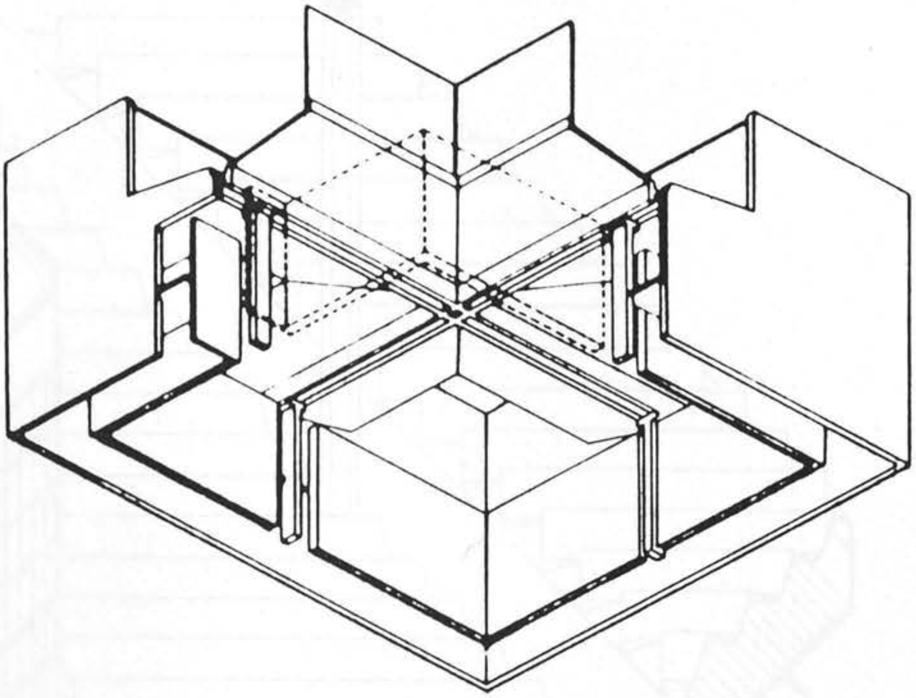


FIG 41 STRUCTURAL FORMS ANALOGOUS TO THOSE OF NATURE





AN APPROPRIATE FUNCTIONAL STRUCTURE IS DEVELOPED TO MAINTAIN A SCULPTURAL FORM

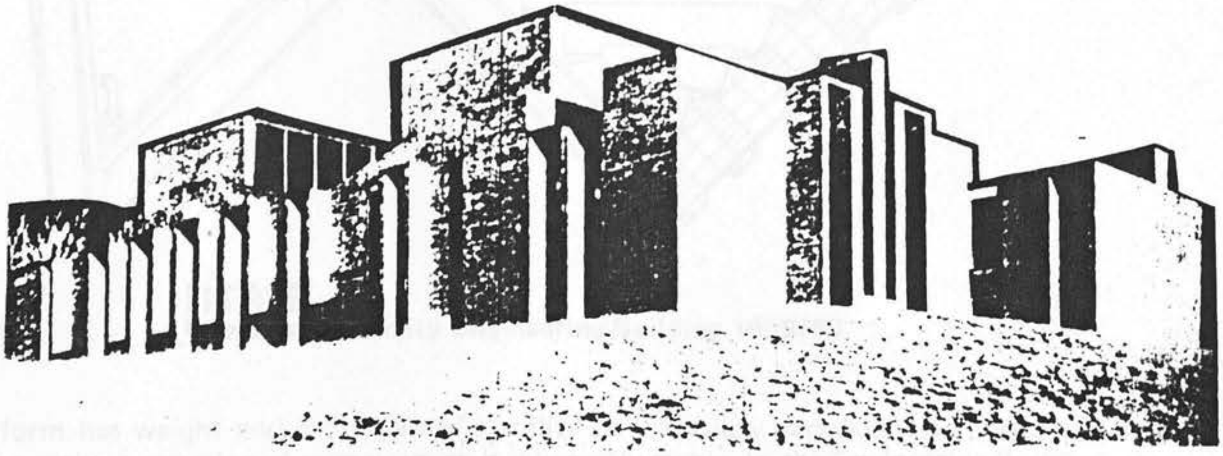


Fig 42A Kahn's First Unitarian Church embodying a sense of space, structure, and light

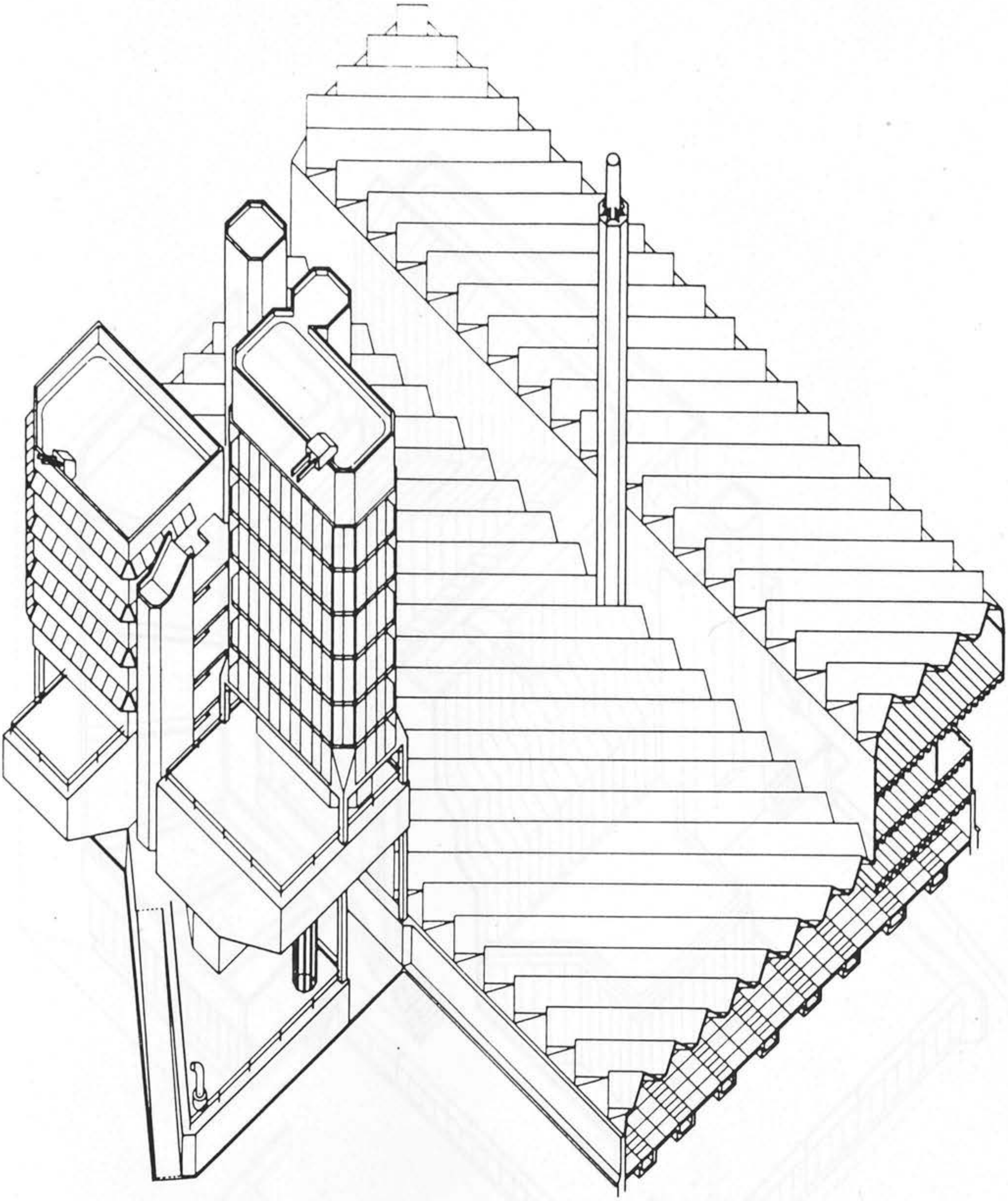


FIG 42B
Leicester University Engineering Building 1959/63

'All built form has weight and properties of stability or instability dependant on shape and it is necessary to make a grouping of masses which is inherently stable. In the Engineering Building, the weight of the towers above counterbalances the overhang of the lecture theatres under, or to say it another way, the extent of the cantilever of the lecture theatres is dictated by the amount of weight over; if you removed the top floor the building would overturn. No doubt there is a certain architectural quality inherent in the composition of stable masses particularly when they are asymmetrical.'

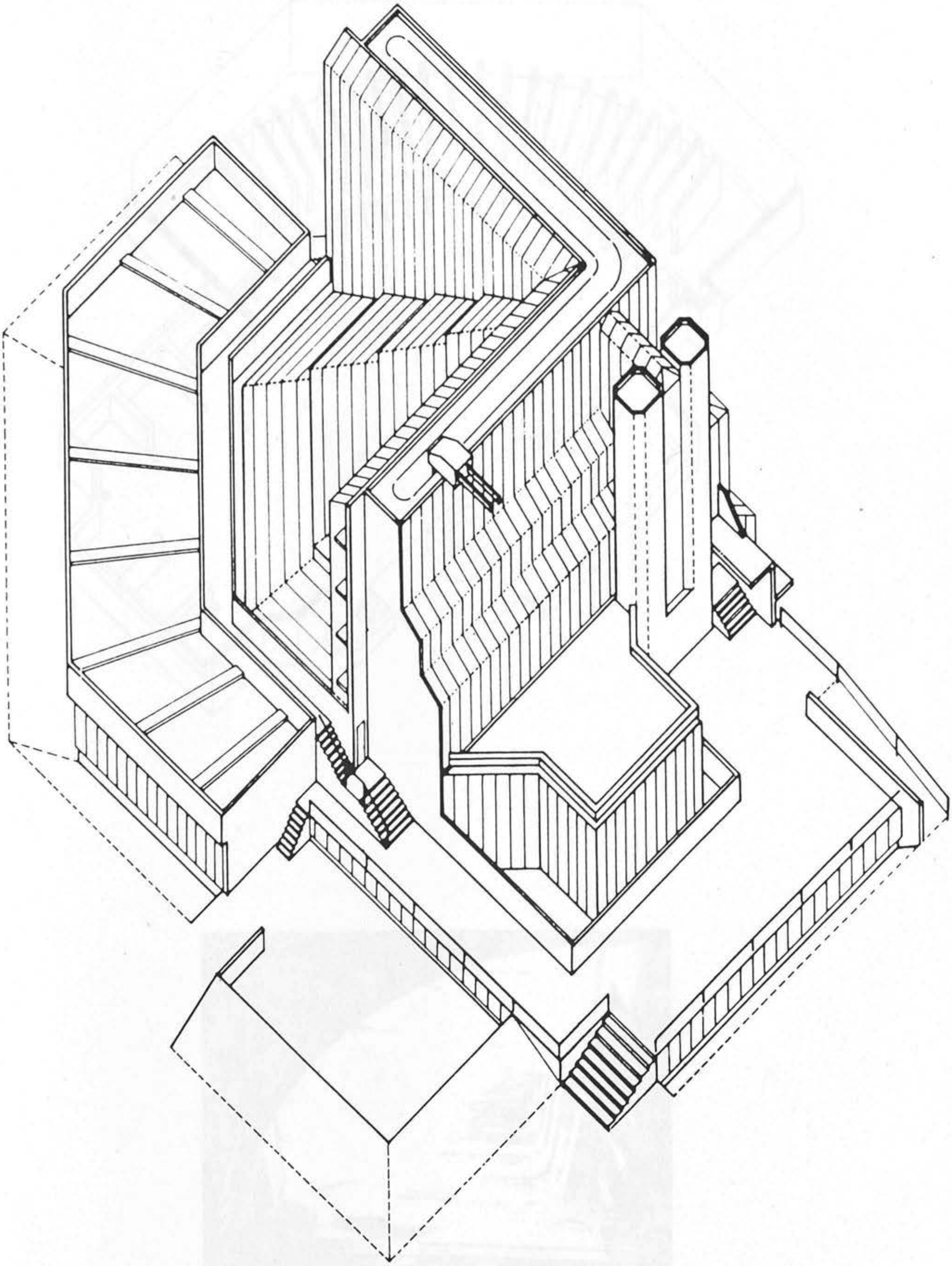
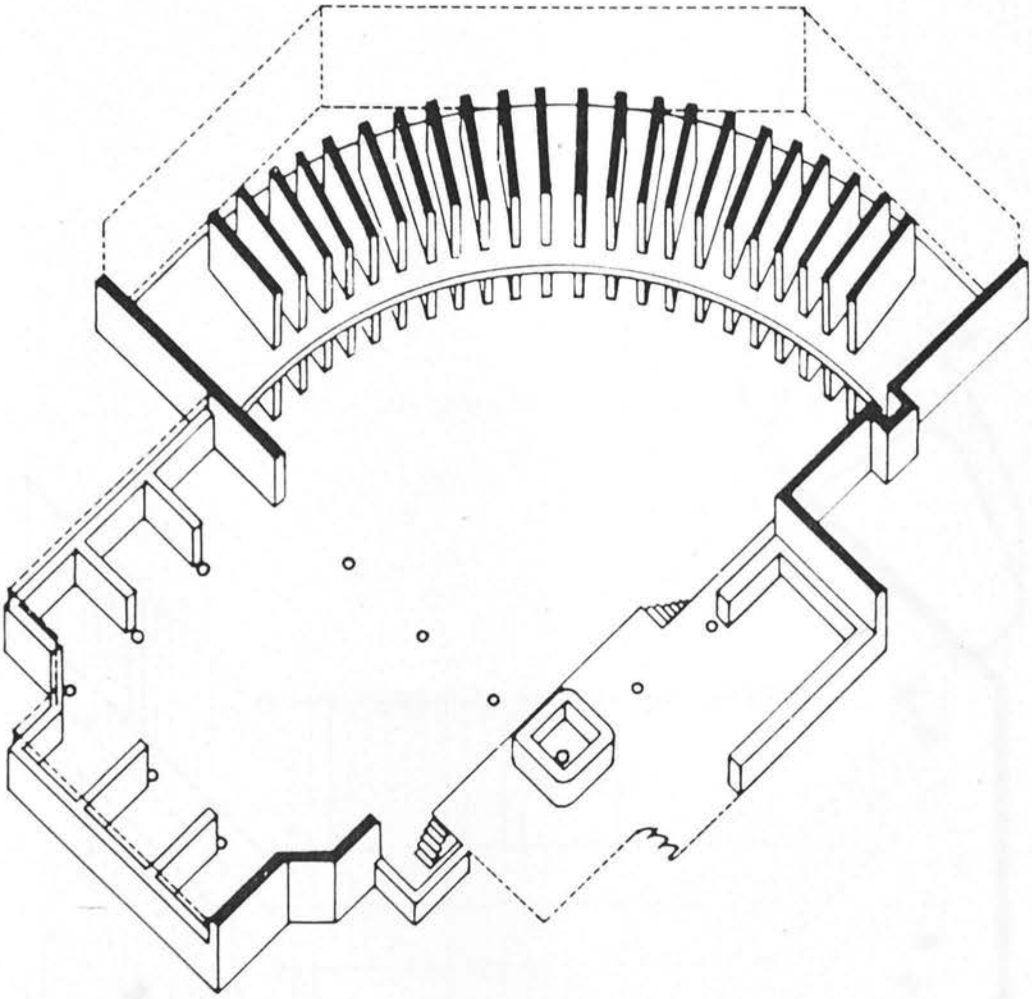
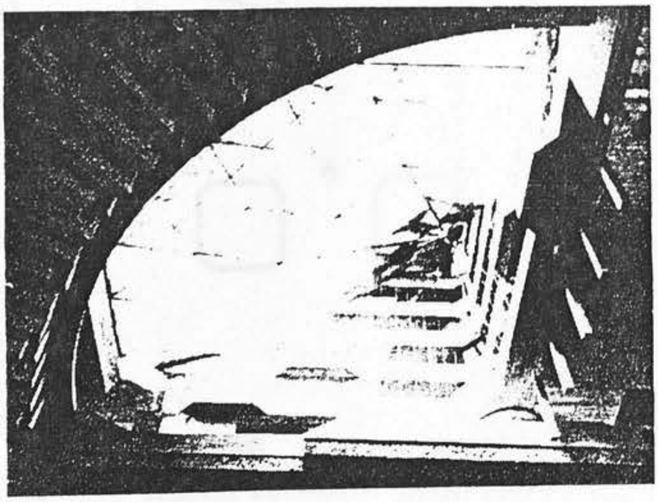


FIG 42C Cambridge Univ History Bldg





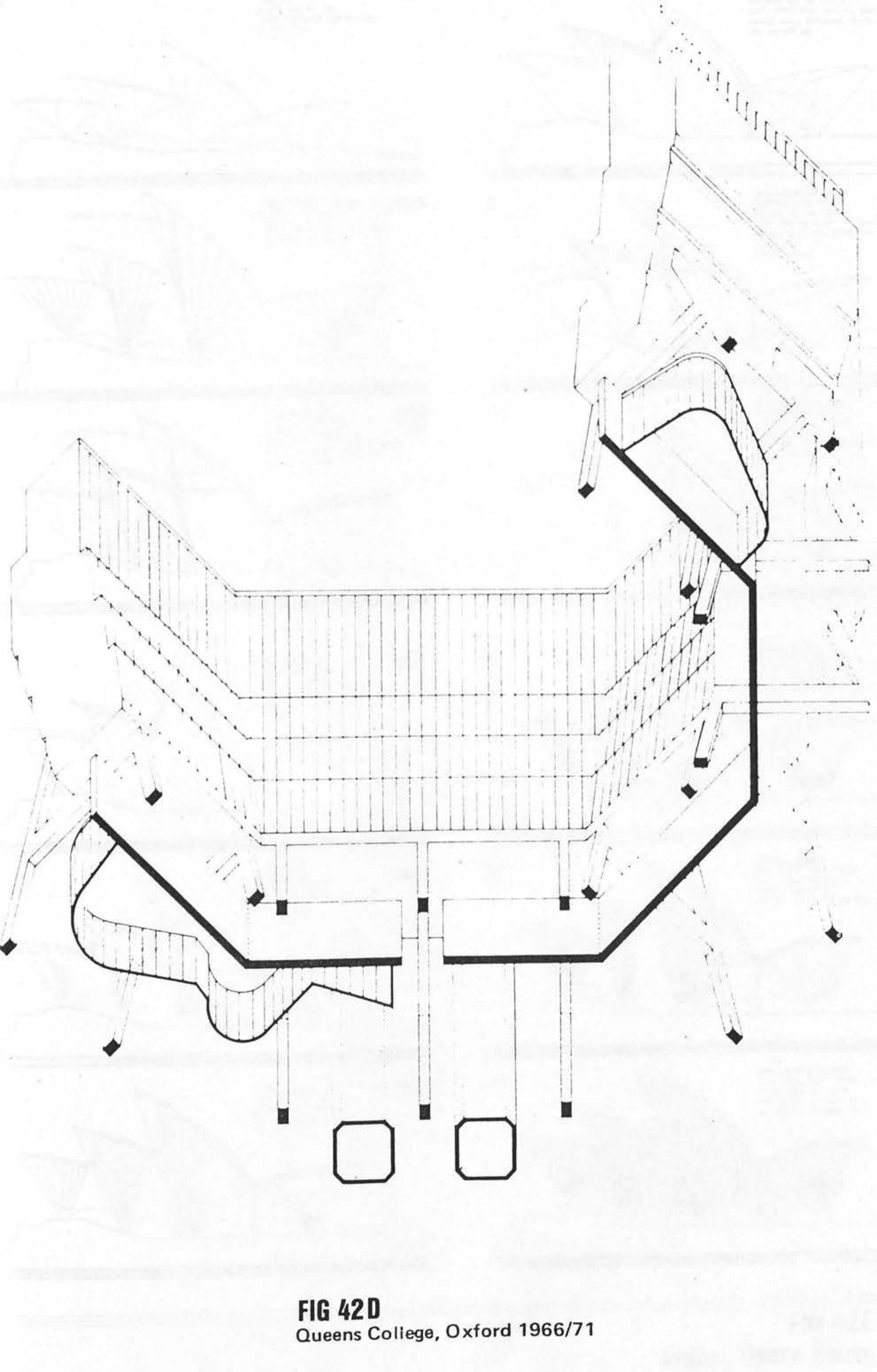


FIG 42 D
Queens College, Oxford 1966/71

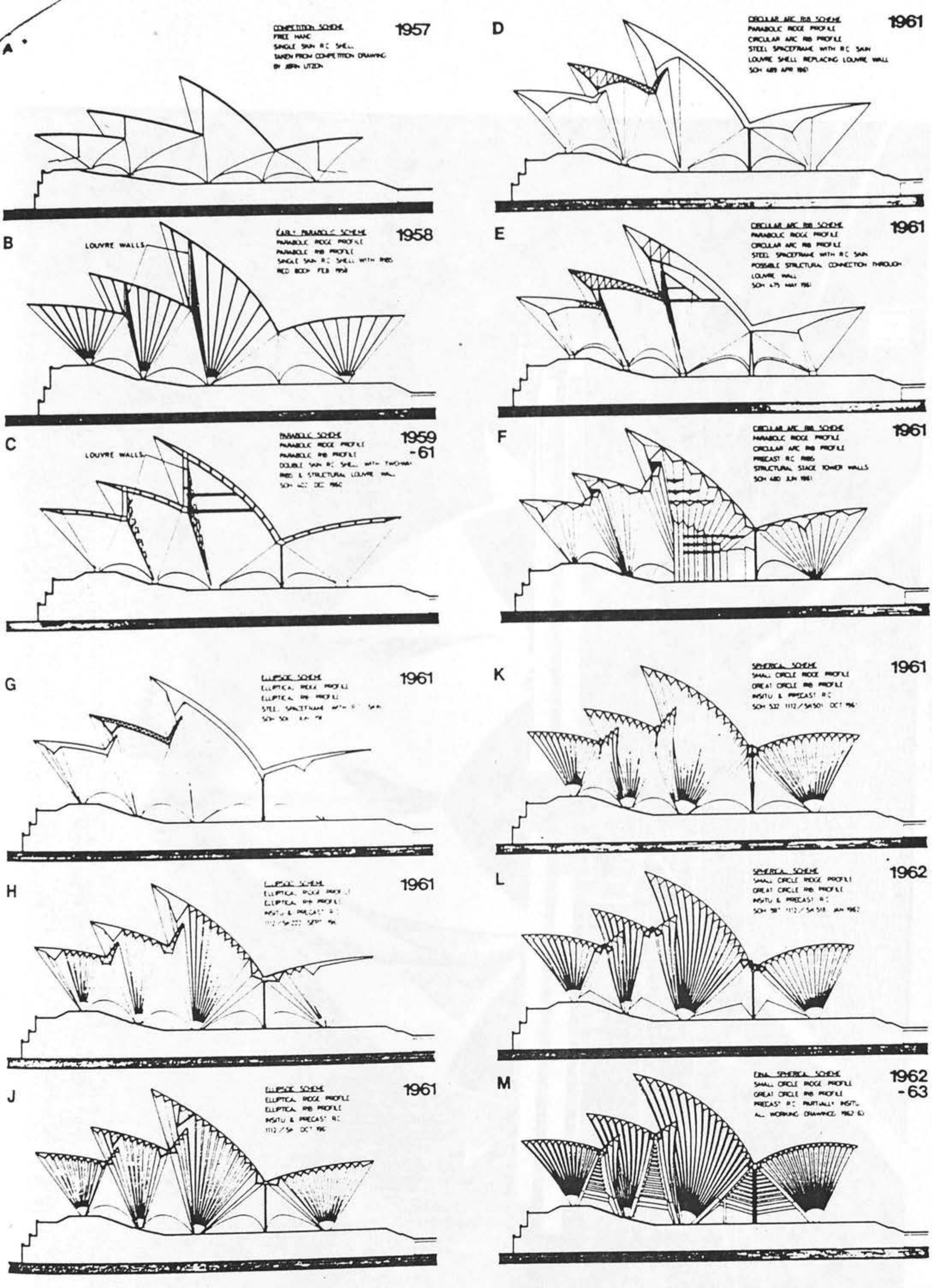


FIG 42E
Sydney Opera House

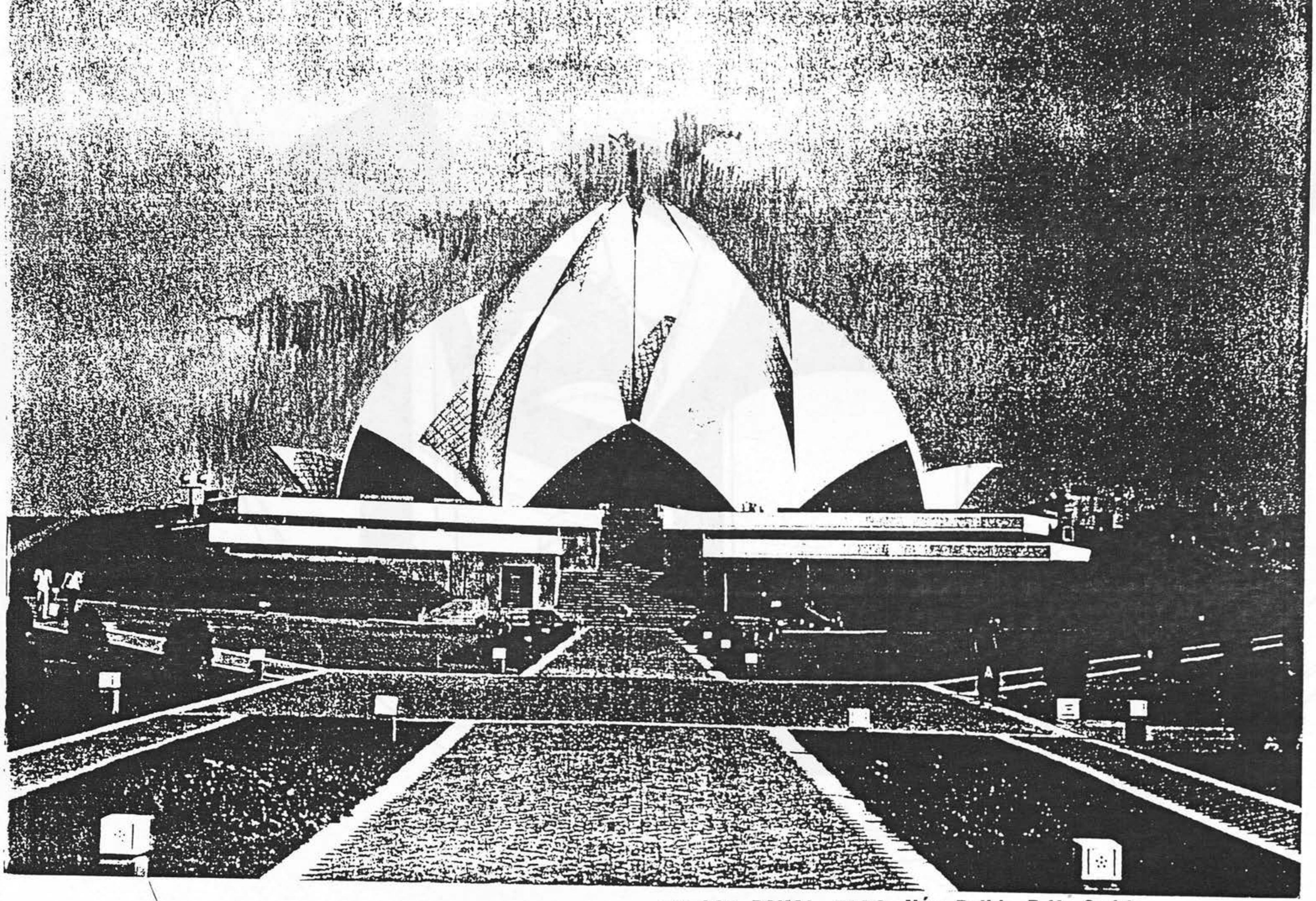
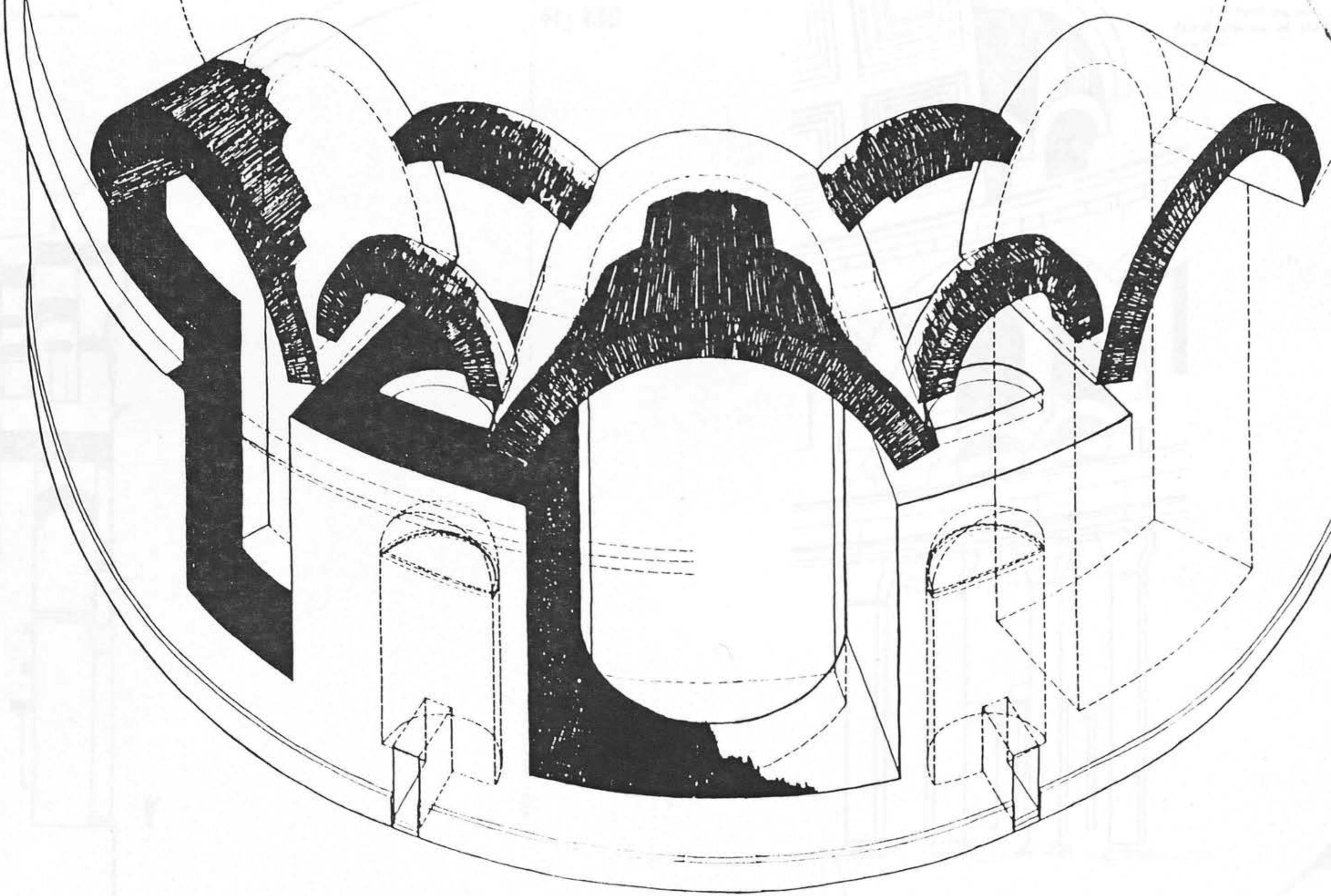
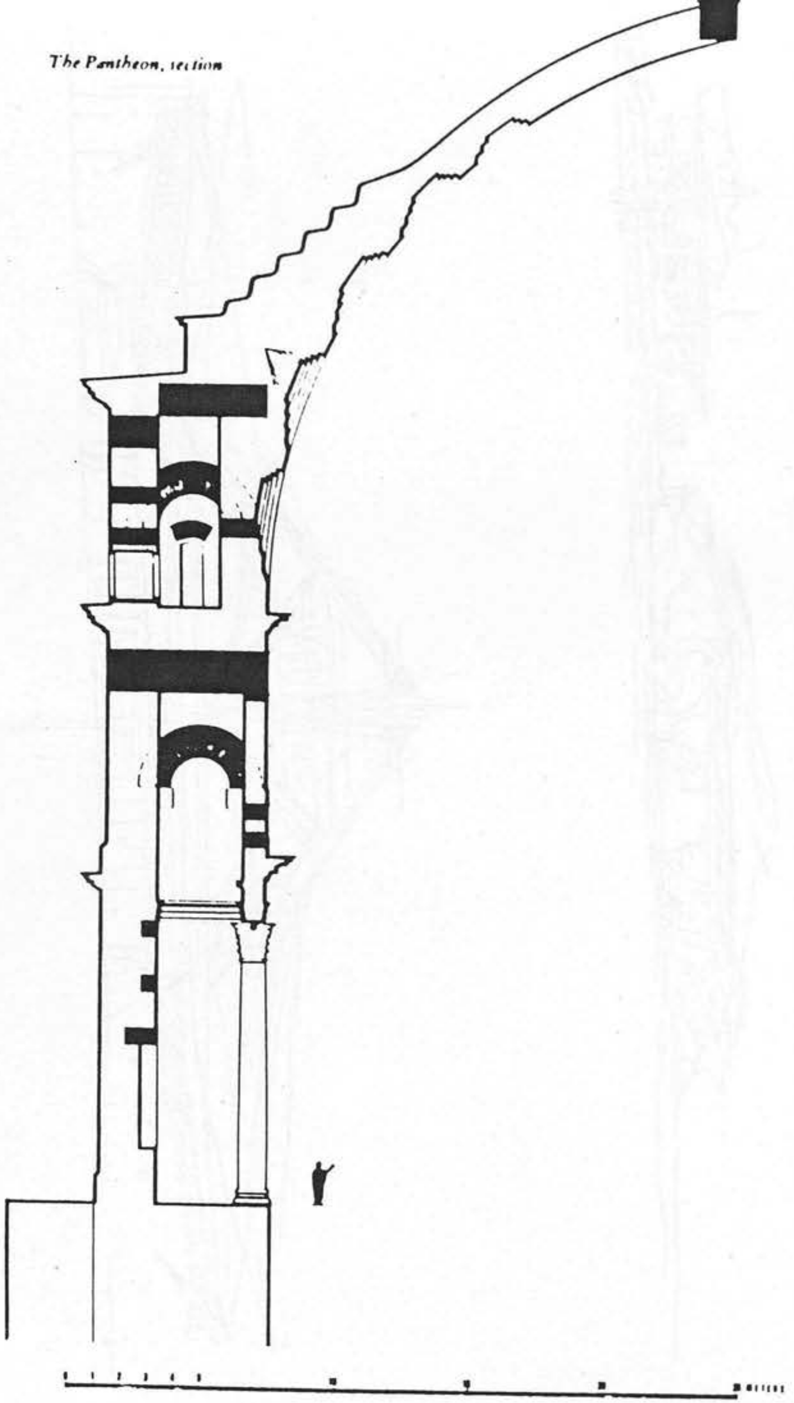


FIG 42F BAHAI BLDG, New Delhi, RJL Smith

Fig 43A The structural system of the Pantheon between levels II and III



The Pantheon, section



Fiq 43B

The Pantheon, analytical drawing of the structure

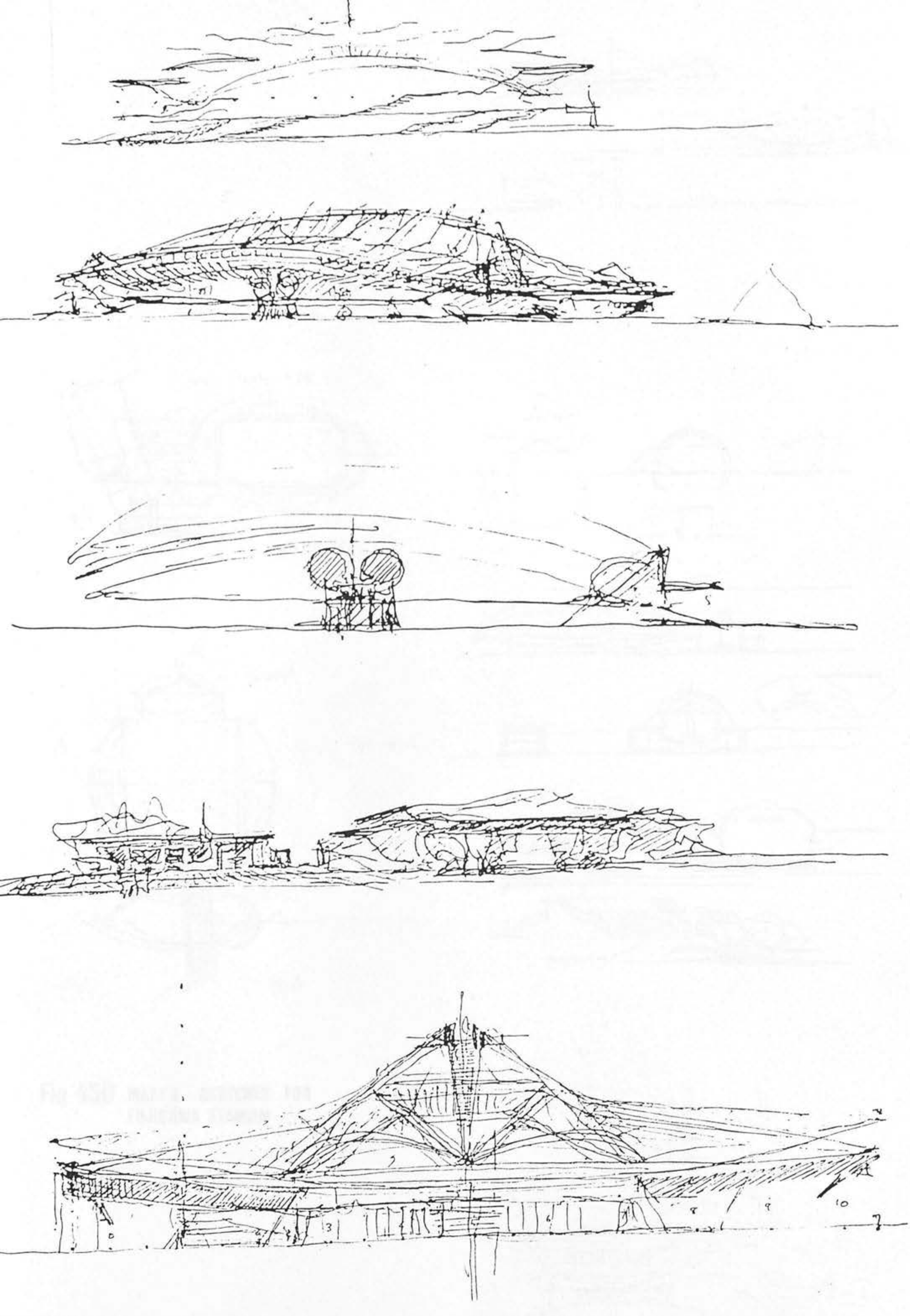
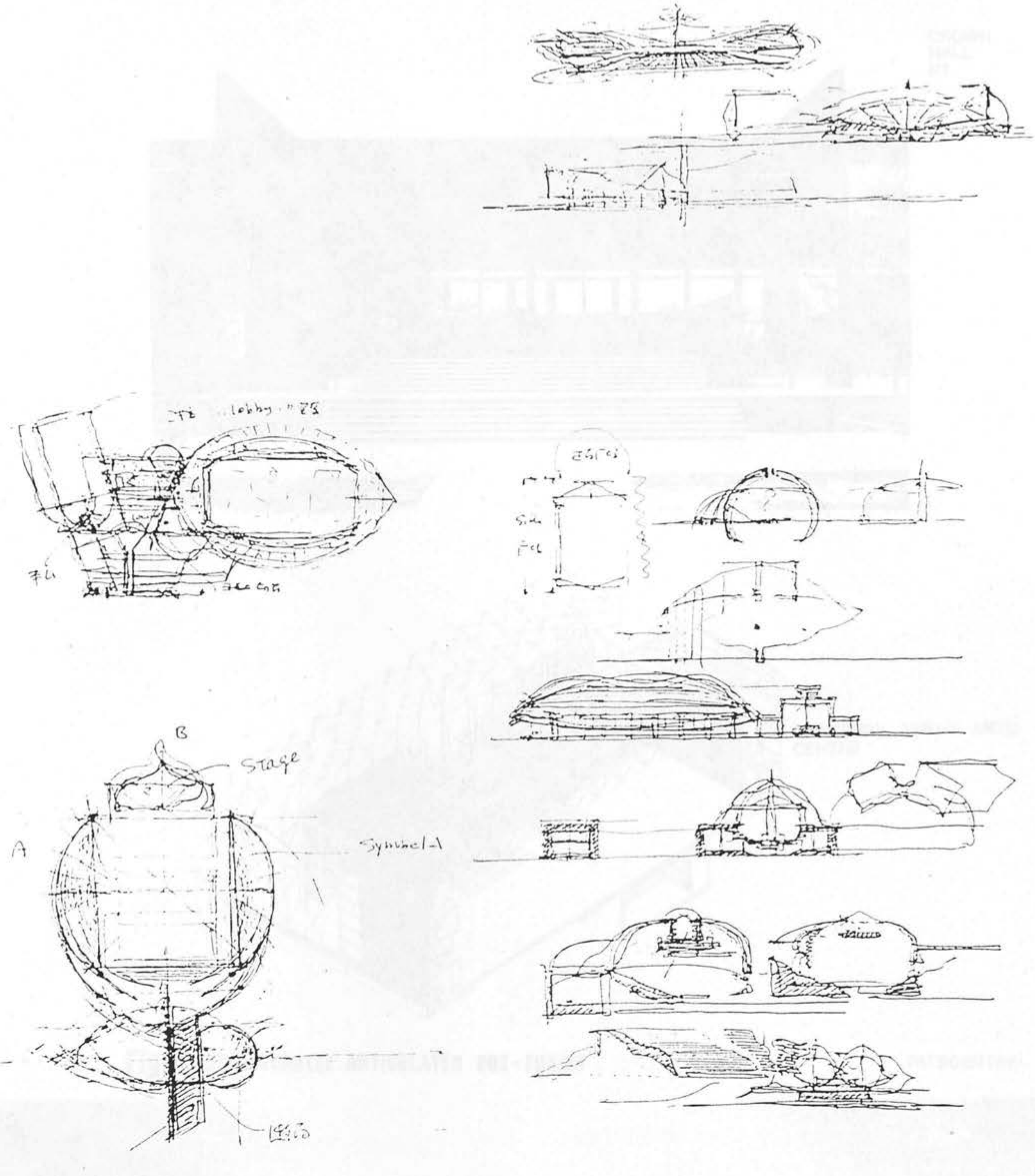
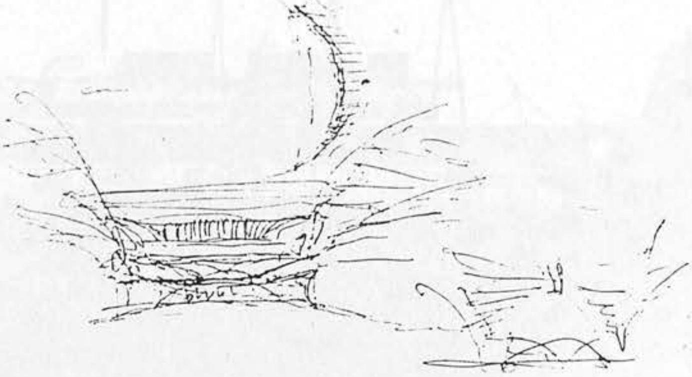


Fig 43C MAKI'S SKETCHES FOR TOKYO METROPOLITAN STADIUM



Fiq 43D **MAKI'S SKETCHES FOR FUJISAWA STADIUM**



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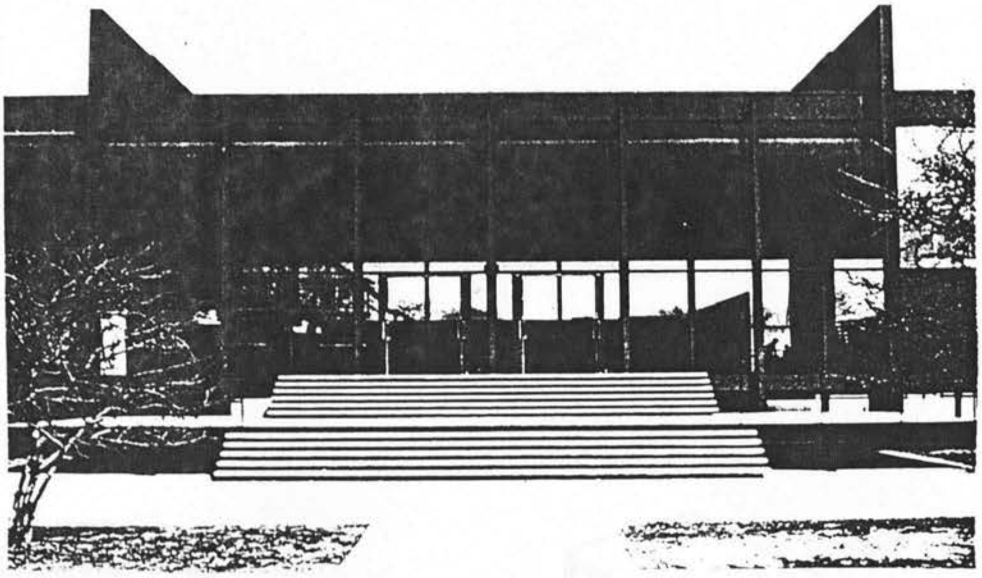

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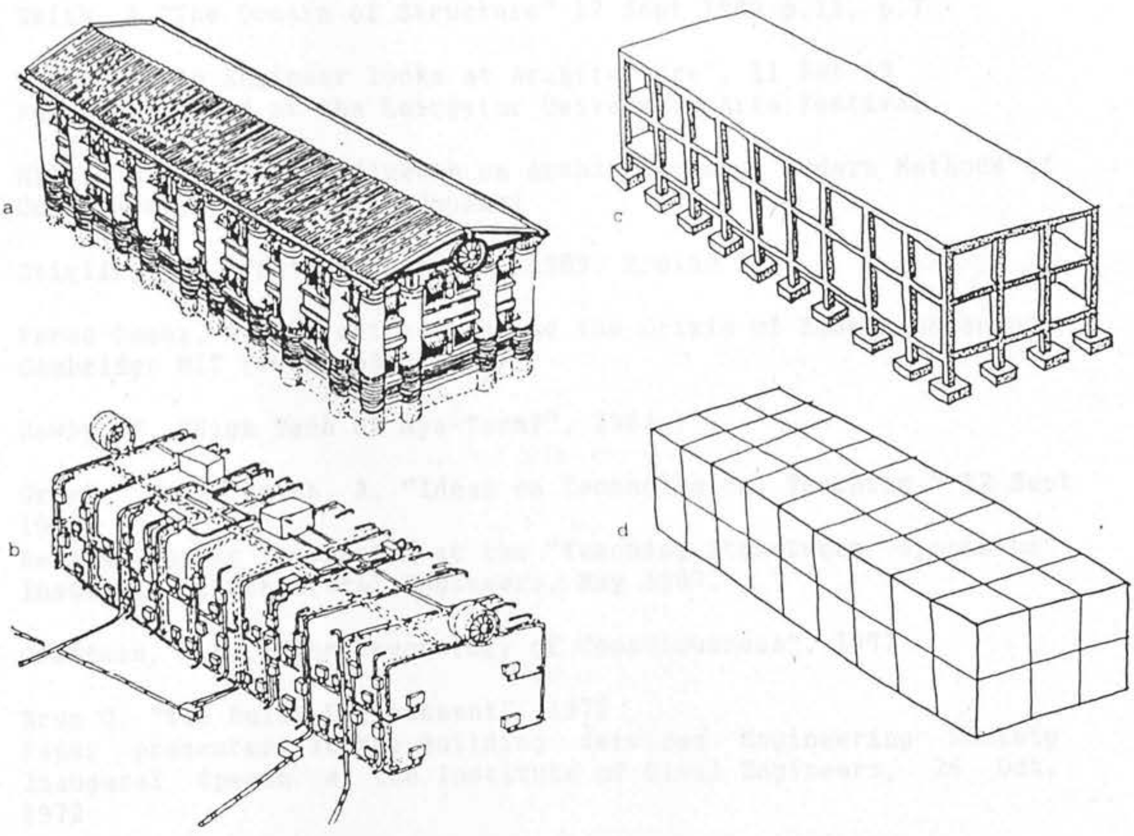

Fig 45: Offices at Swanley, Kent, John Outram

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