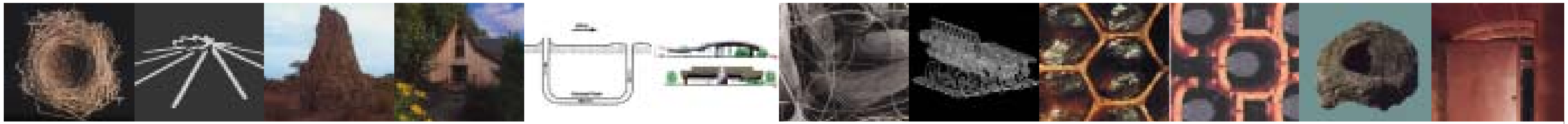
Anarchi

Animal Architecture



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The Edinburgh Zoological Society deserve special thanks for their willingness to act as a notional client for the demonstration building and to provide a site for use in the study.

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DETR
Department of the Environment, Transport and the Regions

Summary

The aim of Animal Architecture, a research project part-funded by the DETR Construction Directorate's Partners in Innovation Scheme, has been to bring animal building to the attention of the construction industry in order to encourage innovation. An area of particular interest has been to explore new ideas and research needs within the context of sustainability and to address biodiversity, environmental pollution and protection which are key aspects of Government objectives. The research has gone beyond traditional piecemeal approaches to innovation by undertaking an exploratory and wide-ranging review of opportunities in the field of animal construction which may offer guidance, advice, inspiration and stimulation to the UK construction industry.

The research team consisted of an engineer with a design background as the lead partner, a zoologist as principal project advisor and architects have been involved in developing practical application. The project is the outcome of a long held aspiration by the partners to bring the role of ecology, design and bionics in innovation to the attention of the construction industry.

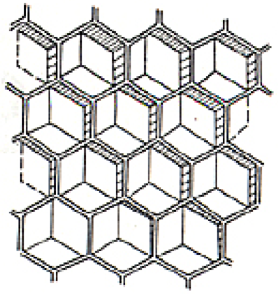
The project aimed to provide a scoping study of an immense field. Yet, the output has exceeded the original expectations. In the short term the project has identified and reviewed areas of ongoing research into techniques, materials and tools of relevance to human construction activity. It has also identified generic aspects of animal construction and a number of specific areas of specialist interest for longer term investigation and application. The outputs include creation of an inter-disciplinary network of interested parties. This has already begun to create a partnership between education, research and design professionals with construction industry interests. It will lead to further research in applied areas. A number of research ideas are being developed into research proposals. Aspects of the work has been investigated through a design feasibility study for an exhibition building for a notional client. The project may lead to development of a demonstration building. A significant amount of media interest has been generated and this has resulted in journal articles and technical lectures, a Radio 4 programme and participation in a programme for the Discovery Channel. The development of concept designs for a demonstration building based on the principles of animal architecture is a particularly high profile output.

It is evident that we still know very little about animal builders and their achievements, the underlying physical principles, and how we might apply them. However, it is also apparent that animal architecture has the potential to radically change our thoughts about the world we live in and hence our perception of, and approach to, the built environment. The field is developing rapidly and it is hoped that the work that has led to this report, and that which will now follow, will be a fundamental driver in developing enquiry and subsequent solutions as a contribution to sustainable construction. The implications for building design and the built environment are profound. Animal building behaviour is only a subset of the wider field of biomimetics which might, when investigated, offer further opportunities for innovation.

Contents

Introduction

Animals are responsible for some impressive, experienced and environmentally sensitive architecture. Their achievements in structural form and strength, microclimate creation, material exploitation, membrane design, ventilation and pest management are immense.

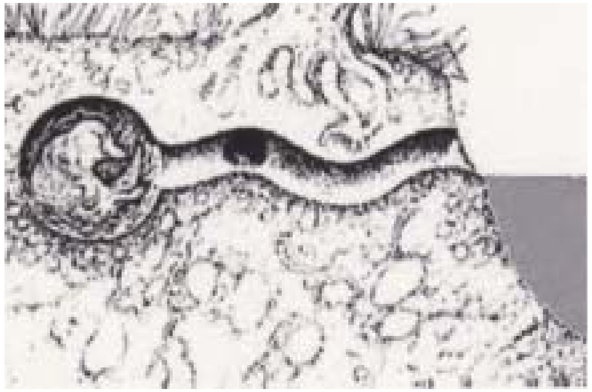


In contrast to animal builders, humankind uses significant mechanical and chemical resources to create and transform our habitat. It is argued that use of these resources has been a principal element in our species success, but how optimised is our performance? How significant and predictable are the problems which we are introducing for future generations? Whilst resources were abundant and adverse impacts of pollution largely dispersed the approach was understandable, but how well adapted are we now that generic and specific toxicity is apparent? Can we use our intellect, and our knowledge of the natural world and physical and biological principles to design a safer, more hospitable and sustainable future built environment? What information do we need to create a culture shift in relation to place, process and product?

Gaia Group, an Edinburgh based architecture, planning and building research company, are specialist designers & consultants in ecological design. They have been using elements of animal architecture to develop concept designs for a building to address biodiversity, environmental pollution and environmental protection which are key themes in sustainable construction. The approach has involved:

1. investigating the achievements of animal builders in environmental and structural terms.
2. developing an understanding of the context in which animals build and its relationship with human building behaviour.
3. identifying precedents, where principles which may have corollary with animal architects have been used.
4. developing new design concepts based on this research.
5. creating links between those with existing knowledge base of animal architecture (in fields such as physics, biology and zoology) and construction professionals. Of the latter the focus has been particularly designers with a practical and an investigative approach.
6. undertaking an inter-disciplinary design exercise, in collaboration with a notional client and site, to develop the concepts into a building project.
7. examining the outcomes to determine the potential benefits for the construction industry and the wider environment, and future research and development needs.
8. taking forward research ideas with project partners.

Context



The project boundaries have been identified as involving the ways in which animals build. Study of how animals themselves are made is outside the scope of this project. Neither is the project about animal buildings constructed by humans, a popular misconception, although it may be that the work finds expression in a related field. Homes for a wide range of animals - ants, bees, birds, beavers, sea life (fish, coral, etc) - are included if they are identified as modifying and adapting their environment including responding to change in temperature, dynamic forces etc. But the structure of the tail streamers of swallows, for example, which act as an automatic aeroelastic control device deploying a leading-edge vortex flap are, albeit interesting, not of relevance here. Neither is the study of teeth, eyes, bones or wings unless they have specific building related features. The study includes the techniques, tools and construction methods used in animal construction, including bonding materials and the manipulation of materials.

Animals build to avoid enemies, catch food, store food, to protect themselves from inclement weather and to raise young. Theories concerning the nature and motivation for animal building activity are diverse. To some the mounds, hives, nests and other dwellings produced by animals are useful artifacts. Others take a radical view and see them as organisms in their own right perceiving that the structures themselves are alive and able to take energy, water and oxygen from the environment and to self-regulate in a manner akin to conventional organs. This principle of self-regulation is similar to that propounded in the Gaia Hypothesis which maintains that this self-regulation occurs on a scale which makes the Earth itself a living super-organism which has biological and physical systems co-operating in such a way as to keep it healthy.[1] It was first proposed as a consequence of a study by NASA to identify how to recognise the existence of life in the universe. Having established the parameters for life, including the existence of atoms and compounds in an excited state, the study team were surprised to find that the earth itself met them. The Gaia hypothesis remains controversial, and is invoked to support a wide range of sometimes diametrically opposed arguments.

Evidently the constructions animals make are inextricably linked with the evolutionary processes of the animals which build them and they are entwined in a co-evolutionary process. They build in order to transform their environment in a wide range of ways and by so doing they create a co-dependence on the materials they require and the environment which they create. Earth burrowing worms have evolved changes in their senses which make them distant cousins of the non-burrowing descendants of their common forebears. Termites cannot exist in the natural environment outside their complex mounds for any length of time. However, builders also increase their own survival chances by climate moderation, protection from predators, increasing food supply etc, which justifies the expenditure of energy which is then unavailable for other tasks.

[1] Lovelock J E, Gaia, A New Look at Life on Earth, Oxford University Press, 1979

The range of human experience in the built environment varies tremendously, from the expectations of corporate business development throughout all major cities to the unsophisticated and sometimes extremely basic housing of peoples in these same countries. Evidence of human co-evolution with their indoor and built environment is limited. Although it has been known for some time that preferred indoor temperature in winter has steadily increased in the last 40 years. Where wealth facilitates it, humans evolve more ambitious needs, requirements and aspirations of which comfort, cleanliness, function, flexibility, status, security and aesthetic delight might take a part. Where poverty prevails, these are luxury items.

Humankind uses mechanical and chemical resources whilst animals use physical principles and their own energy. It is argued that our use of these resources to transform our environment has been a principal element in our species success but it raises a number of questions. It is appropriate that we ask ourselves how optimised is our performance and whether we are introducing problems in extended timescales. Whilst these resources were abundant and their adverse impacts were unappreciated the rationale was clear but we need to address how well adapted we are now that this is evidently no longer the case. Our systems can also seem extremely fragile as evidenced by recent problems with fuel shortages, whereas natural systems are seemingly more robust. Importantly, a fundamental and conspicuous difference is in changing human aspiration. It is generally believed that animals are seeking to maximise their reproductive capacity. Humankind is moving towards a situation which suggests optimal rather than a maximum reproduction. At the present time those countries with the lowest reproductive rates consume a disproportional amount of resources/capita.

So given some significant discrepancies in objectives and aspirations, it would be useful if we could identify any commonality which would form the foundation of a transfer of information. It would be particularly valuable if such information could enhance our knowledge of the natural world and physical principles such that we can we use our intellect to design our built environment to deliver a safe, hospitable and sustainable future.

Initial forays into the field of animal architecture can be frustrating as the subject area is frequently marginalised as being of interest to children or naturalists. The potential for application and utilisation by construction professionals is rarely a consideration. Three principle areas were considered worthy of investigation:

- ongoing research
- precedents where animal principles may be considered to apply, and
- new applications which may be generated as a result of the above.

Project Development

Background

If innovation is genuinely desired then progressive, imaginative and radical approaches are required to deliver genuinely new information to the appropriate sector to meet future needs. It is important to go beyond traditional, confined expectations and identify new sources of inspiration.

It was determined at an early stage to look specifically at animal building behaviour which is a subset of the wider subject area of bionics. Bionics is the science of systems whose functions are based on living systems, or which have the characteristics of living systems or which resemble them. The focus on learning from nature makes it also a subset of the field of biomimetics which aims to literally mimic biological systems. The range of these disciplines were considered too vast to deal with in a small research project. It was felt that the active creation of enhanced environments would be a useful starting point having a close affinity with the construction industry.

We are aware that animals have been making structures in order to transform their environment, improve their quality of life and provide safety and security for their young for hundreds of thousands of years. They have used the readily materials available to them including their own bodily secretions as well as "as found" materials and they have co-evolved their own bodies into tools, and even use and adapt the material around them to form tools. Our own experience of building is relatively short and it has been remarked that given our ancestry amongst the great apes, whose building skills are very limited, our own achievements are notable.[2]

A few extraordinary examples of techniques employed by the natural world include:

- sand grain structures of amoeba
- climatic moderating behaviour of termites
- air-open structures to moderate internal air quality
- weaving and hollow beam construction techniques of birds, as well as in-built elasticity to allow for an expanding family.

The natural world also offers the most sophisticated of materials:

- tensile strength of spider silk
- durability of wasp paper
- selective use of mosses and earth to provide appropriate structural and tensile strength, ventilation and thermal insulation.

[2] Byrne R, From Unpromising Beginnings

In additional spatial organisation and planning by the social insects may offer guidance. Some of these have been written about, and research projects exist in various fields. The study of animal building is very new and has been described as "*a country road compared with the motorway of molecular biology*".[3] Importantly, this research project aims to be truly interdisciplinary and to overview the implications for innovation in the built environment and target construction professionals.

Detailed biological research is beginning to produce results in a few applications, for example the study of spider silk[4], wasp paper[5] and nest engineering[6], although progress has been tortuously slow. The study of spider silk has uncovered new ways of generating strong polymer fibres from aqueous solution. The study of 'earthquake resistance' has also been looked at in depth using wasps nests as model systems (some wasps build nests in houses which are stable, others in hedges/bushes which blow in the wind). There has been some detailed study of the nature of air movement in termite nests but the results are, as yet, inconclusive. As yet there has been no transfer of a building principle or material to the construction sector as a result of detailed research into animal architecture. It is hoped that this scoping study will make it more likely to be in the domain of the practising architect/engineer in the near future.

The subject matter provides a rich and largely unexplored seam by which to understand the role of human construction in response to environmental pressures. Research in the area is now particularly timely as the animal world offers us opportunity to explore techniques used in construction directly within the context of sustainability, which is implicit in animal architecture, dealing as it does with biodiversity, environmental pollution and environmental protection. This project provides an opportunity for participants from the UK construction industry to identify principal issues and some specific relevant opportunities through analysis of animal builders.

[3] Hansell M H, Reilly M, & Parry S, Animal Construction Company, Hunterian Museum and Art Gallery, 1999
[4] Vollrath F, 1992 Spiders Webs & Silks. Scientific American, March, 70-76
[5] Collias N E, 1986 Engineering aspects of nest building in birds Endeavour 10, 9-16
[6] Hansell M H, 1989 Wasp Papier Mache Natural history 8/89

Work Done

A literature and research review has formed a significant part of the research. This sought to identify the building behaviour of animal builders and existing research in this area of relevance to architecture, engineering and building science. It produced a number of design concepts and precedents, where principles which may have corollary with animal architects have been used. Applications were identified in fields of morphology, joints, structures, environmental control and materials. These were presented and discussed at a seminar and workshops open to research professionals in bionics, biomimetics and related areas with a view to creating links between those with existing knowledge base of animal architecture (in fields such as physics, biology and zoology) and construction design professionals.

It was determined at an early stage that the project could move from being desk based research such that a major outcome of the research could be the production of design concepts for a demonstration building. The concept designs would then be rooted in practical application and be more likely to act as an exemplar of a number of the principles to the intended audience than if the limited resources were applied only to a written report.

The practical application of the work meant that Gaia Architects were asked to become involved in the production of ideas and designs based on principles gleaned from research into the way in which animals build. Having identified a notional client willing to consider proposals for a potential building Gaia Architects, along with structural and services engineers, were approached to work on ideas in parallel with desk studies, reading and briefing in general. Through a series of interdisciplinary meetings ideas started to form into generic groups and these have subsequently become an integral part of design ideas for a notional building. The outcomes have been developed as the basis for future research.

Literature Review

Summary

The literature review has been extensive. From this a number of ideas considered worthy of further investigation were identified. Following is a short review of some of the principal texts on the subject written from a diverse range of professional perspectives. It was felt appropriate to look in detail at a topic as an indication of the potential direction of further study. Termite building behaviour has therefore been reviewed in detail. An additional bibliography reviews some of the principle research papers.

In addition to these mentioned below, Collins's *Empires in Anarchy*[7], Davey's *History of Building Materials*[8] and Thompson's *On Growth & Form*[9] are useful background reading for architect, sociologist or engineer. Some well known texts have evaded all attempts to find them including von Frish's *Animal Architecture*[10],Turner's *Insects in Houses in Connecticut*[11] and Owing's *Animal Architecture*.[12] Research has brought forward extremely valuable new information on termite nests. Some publications, such as Lee & Wood's *Termites and Soils*[13] and Chilton & Choo's *Reciprocal frame, long span structures*[14] will inform further investigation of principal areas of interest such as reciprocal frame construction and microclimate controlthrough building materials. Whilst Lane's *The Kingdom of the Octopus*[15] must in all its specificity, breadth and depth be one of the best examples of the one book that is in all of us, but it offers little to our project.

Inevitably the literature search has generated much by way of primitive and vernacular architecture including Rudofsky's *Architecture without Architects*[16], Fraser's *Village Planning in the Primitive World*[17], Schapera's *The Khoisan People of South Africa*[18] and Beazley & Harveson's *Living with the Desert*[19]. Some, such as Tinbergen's *Animal Behaviour*[20], were a divergence; containing general animal behaviour but little or nothing on building activity.

Some exemplars of Animal Architecture promised much on practical experience and implementation principles but delivered little. Examples are those which pertained to the East Gate Centre in Harare, Zimbabwe, which is apparently based on animal architecture but the link is tenuous.[21] No publishedinformation has been found on the Web of Life building at London Zoo, which also claims an animal architecture pedigree. A visit found its use of ground source cooling and air to air heat exchange not a particularly noteworthy contribution to development of the subject.

[7] Collins W B, Empires in Anarchy, London 1967
[8] Davey N A, History of Building Materials, London 1961, New York 1971
[9] Thompson D'arcy, On Growth & Form, Cambridge 1942
[10] von Frisch K, Animal Architecture, Hutchinson 1975
[11] Turner N, Insects in Houses in Connecticut, Agricultural Experimental Station Circular No. 224(revised) June 1970
[12] Owings J, Animal Architecture, Orchard Books
[13] Lee K E & Wood T G, Termites and Soils, Academic Press 1971
[14] Chilton J & Choo B S, 1992 Reciprocal Frame, Long Span Structures. Proceedings of 14th International Association of Shell and Spatial Structures, Canadian Society of Civil EngineersCongress Vol 2, 100-109
[15] Lane F W, The Kingdom of the Octopus, London 1957, New York 1965
[16] Rudofsky B, Architecture without Architects, New York 1965
[17] Fraser D, Village Planning in the Primitive World, London and New York 1968
[18] Schapera I, The Khoisan People of South Africa, London 1930
[19] Beazley E & Harveson M, Living with the Desert, Aris & Phillips Ltd 1982
[20] Tinbergen N, Animal Behaviour, Life Nature Library 1965
[21] Anon, School of Hard Rocks, Building Services Journal, February 1999

Principal Texts

The Naturalist

The oldest traceable and available text on the subject of animal builders dates from 1866. *Homes withoutHands*[22] (pp 632) by Reverend J G Wood and subtitled "*being a description of the habitations of animals,classed according to their principles of construction*". The available text is an 1898 reprint of the original. Reverend Woods was already an accomplished author on natural history when he penned the text andevidently was a man of considerable investigative, leisure pursuits.

He classifies the constructions as follows:

a) burrows
b) suspensions in the air
c) buildings using mud, stones, sticks and similar
d) underwater building
e) structures by parasites
f) buildings on branches
g) miscellany

Within each type, rules of classification presumed common at the time are followed, giving precedence to higher order followed by lower order mammals, and then birds, reptiles, invertebrates and crustacea.

It is a dense, well illustrated text - much is given over to habits of eating and reproduction, as well as building. Dated attitudes distract from its title subject matter, making it less of a pleasure than an enthusiast for the subject might hope. Occasional reference is made to the works of seemingly noted natural historians and ornithologists, but there is no reference in the index to works or publications. There is an indication that the British Museum has a significant collection of physical objects dating from this period.

[22] Woods Rev J G, Homes Without Hands, Longmans Green 1986

The Architect

David Hancocks *Master Builders of the Animal World*[23] (pp 144) published in 1975 may be the first thorough overview of the subject matter by an architect. It is altogether a more zesty, coherent and readable text than its predecessor, and the influence of an architectural mind is apparent. It is in many instances a revisiting of the work of Reverend J G Wood, sometimes presenting new and contradictory evidence. There is no reference to the work by Lee & Wood.

Hancock claims for his book a desire to remind us of the achievements of animals other than man and,by association, of the skills and innate abilities of vernacular human architects. Hancock, like Hansell after, is concerned to emphasise those abilities, economies and achievements that surpass our own. In Hancock's case this is threaded with an identification of the egalitarian aspect, which means that all animals of a species are empowered with the skills and resources to create their own, largely adequate, means of shelter.

We cannot realistically pursue this as a parameter of the work. Specialism is a fact of human life and the work would be intolerably limited if the techniques and skills were to be those available to all. However, we can be conscious of building budgets - a feature common to animal builders. None are so greedy with resources as to deny others the ability to build, and all are involved in a delicate balance between budgetfor building and budgets for reproduction, which mitigate against extravagance.

Hancock's Chapters (Building by Addition, Building by Subtraction, Co-Operative Builders, Colonists andImperialists, Parasites and Partnerships) give away his architectural and humanist values, and stay clear of traditional classifications.

[23] Hancocks D, Master Builders of the Animal World, Hugh Evelyn Ltd 1973

Soil Biologists

This 1971 publication, *Termites and Soils*[24] (pp 251) by Australian Soil Scientists, K E Lee & T G Wood, is a specialism in its own right. Its uniqueness in 1971 lay in the attention to the biology of soils, and the role that flora and fauna play in the transformation of soil organic matter, rather than the traditional geographical and morphological characteristics. This brought with it a significant degree of study into siteselection, architectural variations according to climate, construction materials and methods, ventilation, insulation and internal climate. It is dealt with in detail later alongside new information on termites and nest building.

The Zoologist

Mike Hansell's *Animal Architecture & Building Behaviour*[25] (pp 324) follows in the tradition of Wood's learned document but in a much updated and accessible format. It is perhaps the most extensive review of animal building yet written and the first to establish animal architecture and building behaviour as a discipline. Hansell's objective as a zoologist is to "pass on to others my own sense of wonder that the, often, minute minds of animals can conjure tangible, complex and functional objects". However, this is undertaken in the context of seeking generalisations and patterns as a means of scientific discovery. The book is in two parts:

1. a study of builders, the function of building, materials and methods of construction and the nature of the resulting structures

2. an examination of the potential of artifacts and artifact builders to investigate evolution, function, causation and development.

What the publication, like all others in the field, fails to address is the potential relevance of this knowledge to the built environment and it remains a challenge to identify what, if anything, can be applied to human builders, the building process and buildings.

[24] Lee K E & Wood T G, Termites and Soils, Academic Press 1971
[25] Hansell M H, Animal Architecture and Building Behaviour, Longman, London 1984

The Journalist

Animal Architects[26] (pp 104) is a National Geographic Society publication. It is not listed in any of the reference documents and does not appear on any searches. It is a lay person's summary of the earlier work with exceptional graphics and photographs. The habitats are divided into:

- Mound builders
- Weavers & platform Builders
- Users of Silk, Saliva and Foam
- Animals that Build with Mud
- Makers of Wax and Paper
- Excavators

The Exhibitionist

Elainten Arkkitehtuuri (Animal Architecture)[27] by Juhani Pallaassma (pp 128) is the book of the exhibition in 1995, held at the Finnish Museum of Architecture. Pallaassma describes his subject as ecological functionalism. It covers all of the subjects embraced in Hansell, as well as the generic trends, and looks in detail at specific aspects from insect, bees, wasp, ants, birds and mammals. It is probably best summarised through the foreword:

"*We humans are proud of our inventions. But can we discern greater merit in our capabilities than in those of the master builders who unconsciously follow their instincts? The evolutionary roots of human behaviour reach far back into the behaviour patterns of animals. Those who are fascinatedby these connections need only fasten on one such puzzle, the architecture of animals perhaps, find an absorbing interest for a lifetime. Gradually they may learn to understand a great deal that at first sight appeared incomprehensible, and to people of an inquiring cast of minds, this will afford deep satisfaction. And yet the sum total of unsolved mysteries will always remain immeasurably greater than the sum of our discoveries.*
There are biologists who are convinced that they, or future generations of scientists, will ultimately find the key to life in all its manifestations, if only research perseveres. They are to be pitied. For they have never experienced that sense of profound awe in the face of the workings of nature, some of which will forever elude comprehension, even by the mind of man."

K von Frisch, Nobel Prize (1973) in physiology and medicine for pioneering work in the field of ethology.

26 National Geographic Society, Animal Architects, National Geographic 1987
27 Pallaassma J, Animal Architecture, Museum of Finnish Architecture, Helsinki 1995. ISBN 9519 229 884

The Text Book

External Constructions by Animals[28] is an overview of work in animal building. It is one of a series of Benchmark Papers in animal behaviour which was generated in response to the rapidly expanding and 'sometimes overwhelming volume of information' in the field. It consists of a collection of significant research papers, from Charles Darwin onwards, and covers historical and philosophical aspects, evolution of behaviour, habitat control and the actual mechanisms of building behaviour.

The Animal Construction Company [29]

In 1996 Hansell was approached to give a plenary lecture[30] to the building services community at the CIBSE Technical Coference within the overall conference theme of Learning from Nature. The remit provided by the conference chair (Halliday)[31] was to address how animals build, and the manner in which they deal with climate protection, air quality, ventilation, pest control and materials, and all manner ofother aspects. This led to a number of conversations about the relationship of animal building behaviour to human building, and the potential for increasing understanding by a network of people interested in developing knowledge through interdisciplinary research. Subsequently an exhibition was organised by Hansell and others as part of Glasgow 1999 City of Art & Architecture. It was possibly the first time that any real link had been made between animal building behaviour and construction activity.

The book of the exhibition is an adequate overview in its own right of much animal building behaviour and therefore no attempt has been made to further summarise it.

[28] Collias N E & Collias E C, External Constructions by Animals, Dowden Hutchison Ross Inc 1976
[29] Hansell M H, Reilly M, & Parry S, Animal Construction Company, Hunterian Museum and Art Gallery 1999
[30] Hansell M, You Don't Need Brains to be a Builder, keynote lecture, CIBSE/ASHRAE Technical Conference, Harrogate 1996
[31] Halliday S P (Editor), CIBSE Technical Conference Proceedings Vols 1 & 2, CIBSE, 1996

Ideas for Further Investigation

Sand Dollar	Bernoulli's Principle	Air filtering /heat recovery
" "	" "	Water filter
Beehive Honeycomb	Versatile structures	Structural strength
" "	" "	Urban form
Garden Warbler Bird's Nest	Reciprocal Frame	Free spanning structures
" "	" "	Assembly methods
Compass Termite Nest	Building Orientation	Climate control
" "	" "	Gas exchange
Nest of the Macrotermes bellisosus termite	Air Conditioning	Ventilation
" "	" "	De-toxing
Apicotermes Lamani Termite Nest	Climate Control	Internal ventilation
" "	" "	Water deflection
House of Caddis Larva Lepidostroma Hirtum	Modular Building	Standardisation
" "	" "	Out of phase construction
An Opened Wasp Nest	Paper in Construction	Paper in compression
" "	" "	Paper Insulation
Burrow System of the Black-Tailed Prairie Dog	Natural Ventilation	Dynamic insulation
" "		Culvert Ventilation
Deporaus Betulae (Beetle)	Leaf rolling	Rolled structures
" "	" "	Cost effective building
Megapodiidae Birds Nest	Controlled Incubation	Natural Heat Production
" "	" "	Alternative Heating Systems
Cliff Swallow's Nest	Natural Reinforcement	Natural building materials
" "	" "	Breathing walls
Duckbill Platypus	Earth Compacting	Rammed earth foundations
" "	" "	Excavating with minimal impact
Marconema Transversum Caddis Larva	Filters	Natural ventilation
" "	" "	Air filtration
Spiders orb web	Spiders Web Construction	Energy absorbing structure
" "	" "	Structural integrity
House Martin's Nest	Building techniques	Ground stability during earthquakes
Spiders web construction	Order of construction	Alternative construction sequence
Pupae	Fire protection of dense silk	Natural fire protective materials
Swift nests	Saliva hardens when exposed to air	Quick hardening liquid building material

Termites, Soils and Air Flows

The vast majority of termites live in tropical and subtropical regions but they extend from 45° N to 48° S. Termitaria house and protect a colony, facilitate storage of food and allow termites to maintain an optimum environment. All termites live in communities within a nest system. Social behaviour plus the structure creates a self-regulation of optimal conditions for development, reproduction and maintenance of a social order. Nests provide extraordinary examples of the ability of termites to modify their environment and, as such, are useful material for studying of the evolution of behaviour.

The nest and associated mounds, galleries and covered walkways are a closed system which is isolated from the external environment except to allow foraging parties or seasonal flight. In exceptional cases,the termites might open up the nest in response to a stimuli such as excess heat, moisture or gas concentration. The ability of the nest system to create a controlled micro-climate seems to be a significant contribution to their success.

Materials

Most termites live off rotten or decaying wood. Some heartwoods are toxic and repellent and it would be useful to know what the repellents consist of. Many are quite specific about what they will eat. Some termites are pests and are known to attack plant debris, dung, living plants and stored products and materials as well as wood. Fungi are important in the breakdown of food, but particularly to Macrotermiitinae which construct 'fungal combs' in their nests which support various fungi and which are continually being eaten and renewed. Opinion varies but the combs are believed to consist of macerated but undigested plant or faecal material and to have a nutritional and an environmental control aspect. The fungi is only a small part of the diet but may contribute particular essential nutrients. Construction materials depend onfeeding habits and availability, but include soil, excreta, saliva and plant remains.

- The degree of soil selection varies enormously.
- Plant material is usually used after digestion or mastication. Some such as grass may be incidental.
- Saliva is used as a cement. Some use it in considerable quantities.
- Excrement is used as a cement and as a structural component
- It is mainly pasty although some have pellets. Carton is the name given to the faecal material used by termites to construct part of their nests. It generally consists of lignin and cellulose. It is consumed by those termites which enlarge their nests by a process of reorganisation. Humus feeding termites have excreta very similar to soil.
- Excrement is also used as wall lining and to fill in empty galleries.

The information for this section is principally taken from Lee K E & Wood T G, Termites and Soils,Academic Press 1971, and other texts, as stated.

Structure of Nests

Termites have a wide range of nesting habits from simple to complex. They include nests underground, in trees or tree stumps with covered walkways and galleries; small diffuse nests with no distinct structure in damp wood or soil and highly complex structures. The more complex will have a number ofdistinguishable components:

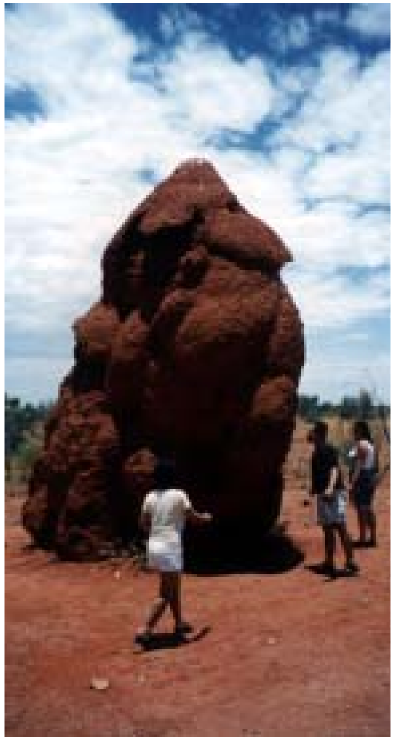
1. Central chambers for royal pair + eggs + nursery + food store and food cultivation in some species which is sometimes a distinct inner region.
2. Peripheral galleries and chambers which act as a protective barrier.
3. Perhaps a further protective wall from a few centimetres to one metre in thickness. The network of peripheral galleries may contain food and building materials and subterranean galleries which might be sources of food, covered runways and sheets.
4. A further external system, of cavities open to the exterior but having no permanent connection tothe inside.

There is also sometimes an open space between subterranean nests. Great structural complexity is evident in some nests. The simplest forms are chambers sub-divided by thin walls, and the nest may consist of several such chambers connected by subterranean galleries. Generally, concentrated nests are single-unit structures and may be subterranean, epigeal (i.e. mounds), arboreal, or in wood. Two types are distinguished:

- those with a homogeneous structure consisting of chambers which are almost all alike and which lack important differences between the peripheral and internal regions.
- those with a heterogeneous structure.

The different regions of the latter often serve different functions, and may be constructed of different materials or different proportions of materials.

Construction Methods



A large termite mound in central Australia

Building activity occurs in response to a stimulus which may be air movement, odour, light or temperature and which upsets the colony environment. The attempt to remove the stimulus explains the initial activity and the variation in architecture, but not the complexity.

Nest Morphology

Nests tend to enlarge as a colony grows. Some achieve this by excavation, which may be associated with feeding or repacking of soil, or selective removal of some soil or particles. Some add new structures leaving the new ones as they are. Others have a complete reorganisation so that the nest grows from the inside to the outside.

Shape

The most complex structures are built by certain members of the Termitidae, among the most intricate being subterranean nests. These nests are sub-spheroidal, and divided internally into a number ofhorizontal, parallel storeys, separated by thin lamellae. Communication between the different floors is either by direct or spiral ramps. The walls of the nest are perforated by a series of holes or slits for ventilation and these holes may communicate with peripheral circular galleries within the wall. The architecture is very constant within species and species diagnosis is sometimes easier by examination ofnests than termites.

The relationship between evolution and architectural complexity of nest construction is unclear. Certainly primitive families have simple nests (a notable exception being Mastotermes darwiniensis), but among the Termitidae there is every level of building behaviour from diffuse subterranean galleries to arboreal nests, even within a single genus. In addition, building behaviour is often influenced by the environmentand this is particularly obvious in the case of mound-building termites. It is probable that termite mounds represent a balance of material, behaviour and climate.[32] It has been suggested that a species which is restricted in its distribution to a particular ecological niche or to zones where environmental factors, such as soil and climate, are relatively uniform, will build mounds of a uniform shape. On the other hand, aspecies occurring in a wider range of habitats will build mounds of variable appearance.

The “magnetic ant-hills” built by Amitermes meridionalis in northern Australia are an outstanding example of uniform mound-building. These mounds are restricted to a small area south of Darwin where they are found only on grey soil flats subject to summer flooding. Several species of Amitermes in northern regions of

Australia build tall mounds, elongated in a roughly north-south direction, but Amitermes meridionalis invariably builds these elongated mounds. The most plausible explanation is that the shape minimises heat gain in the middle of the day and controls diurnal variations in mound temperature. Other amitermes sometimes build mounds of similar form, but not always with a north-south orientation. In seasonally flooded areas on Cape York Peninsula, Amitermes laurensis, which normally builds more or less regular conical mounds with rounded tops, builds mounds of the meridional form.

Convergent evolution of nest-building behaviour among unrelated species occurring in a similar habitat is well-illustrated by the rain-shedding devices constructed by various species of Amitermitinae, Termitinae,and Nasutitermitinae in rain forests, where protection from flooding and excessive erosion may be important. In addition, rainfall erodes away turrets and pinnacles, and in areas subject to heavy rain there is a tendency for mounds to be domed. On the other hand, in South Africa mounds of Trinervitermes trinervoides, which are normally domed, are conical or turreted in wet regions.

The extent of variation in form of mounds are illustrated in Figure 3.1, all of which are common forms built by Nasutitermes triodiae in northern Australia. They include:

A) which attains a maximum height of about 4m and a basal diameter of 3m
B) irregular cone- or dome-shaped structures
C) variation on B
D) variation on B
E) a smoothly contoured, domed structure
F) Irregularly turreted mounds, up to 2.5m high, surrounded by many smaller ones
G) There is a rapid change to the “fluted” or columnar” type, which commonly exceed 4.5m in height and reach up to heights approaching 9m

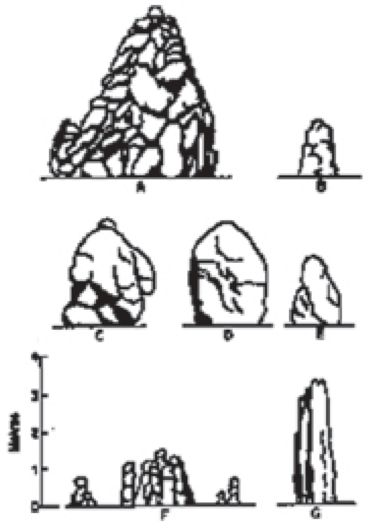


Fig. 3.1 - Variations in Nasutitermes triodiae mounds

The variation in form is not consistently related to variations in climate.

Variability in mound-building behaviour is exhibited by species and it has been shown that variability in shape of mounds of M.subhyalinus is related to the sand to clay ratio of the soil used for construction. Tall thin mounds had sand to clay ratios of 1:1 to 1:3 while larger dome shaped mounds had ratios of 2:1 or 18:1. Soil type appears to influence the shape of mounds of Amitermes vitiosus in northern Australia. On shallow soils with a uniform sandy or sandy-loam profile the species is either absent or builds small conical mounds up to 0.5m high. As the amount of clay in the soil increases so does the abundance of taller mounds, up to 1.5m high.

Where silt and clay tends to accumulate, alongside watercourses or in depressions, even larger mounds are built. However, there are some species in which the variability in form of the mound does not appear to be related to obvious features of the environment. The mounds range from small domed or conical structures to 9m or more in height and 20-30m in diameter at the base. The mounds are not static but are continually being eroded away by rainfall. Occupied mounds are repaired and enlarged.

Galleries and Runways

All termites construct a system of galleries or covered runways which they use in searching for food, moisture and soil particles. Some species excavate their nests and galleries solely within their food supply (wood) and rarely have any contact with the soil. Other species with similar habits excavate galleries within, and feed on the carton of their hosts' nest. Other termites construct galleries in the soil or make covered runways or sheetings on the soil surface, low-growing plants, fallen logs, or on the outside of standing trees. Subterranean galleries appear to be constructed in two ways, not necessarily mutually exclusive.

- by compressing soil away from a central starting point to form a compact layer around the gallery. However, there is obviously some excavation of soil as the logs and tree stumps utilised are often filled with copious quantities of soil.
- Excavation has already been noted as a method of constructing subterranean nests.

Subterranean galleries are often lined with excreta which may have a characteristic appearance peculiar to the species. A uniform lining, "freckled", consisting of a mosaic of dark and light brown faecal material.

The construction of covered runways appears to follow a similar pattern to nest-building. Depending on the species, runways are constructed of excreta or of soil particles cemented together with excreta or salivary secretions. The construction of covered runways follows odour trails laid by secretions of pheromones. Where the trail is distinct, soldiers line the edges with their heads pointing outwards. If the food source is too small these trails are only temporary, but if the food source is large (such as a log) workers deposit pieces of chewed wood and excrement along the edges of the trail. Eventually two walls, on which the soldiers mount guard, are formed and these bend towards each other and are eventually joined to form a covered runway. Special purpose galleries are built to avoid drought, to obtain clay, for moisture, but mainly for food.

Some termites forage above ground without the protection of covered runways or sheetings. In general, these species appear to feed on materials which, in contrast to concentrated sources of food (logs, tree stumps etc.), do not occur in sufficiently large quantities at any one place to promote the building of semi-permanent covered runways. Among such species are the various grass-harvesting termites and the lichen-feeders. Extensive covered sheetings are constructed by certain species. In contrast to covered runways, which protect the termites moving between the nest and the source of food, sheetings cover the source of food itself and several dung-feeding species envelop dung pads with sheets of soil.

The Environment in Mounds, Nests and Subterranean Galleries

It has been proposed that termites do not merely occupy a niche, but model it within the dimensions of their tolerances and preferences. The composition of the atmosphere within nests and mounds, their temperature and moisture content, are related to those of the external environment, but there is abundant evidence that many termites exercise some control over them. Control results from the cumulative effects of various adaptations of behaviour and methods of construction, and varies in its effectiveness.

Oxygen & Carbon Dioxide Concentrations

Few measurements have been made of oxygen and carbon dioxide concentrations in termite nests. Experiments with oxygen consumption concluded that ability to withstand high carbon dioxide concentrations is probably a characteristic of all termites.

Luscher[33] (1955) found the volume of air in a mound of Macrotermes bellicosus to be about 500 litres. He estimated that there were about two million termites in the colony, and that their oxygen requirement would be about 240 litres per day (i.e. 1200 litres of air). Carbon dioxide concentration is related to the intensity of metabolic activity of termites within mounds, and this in turn depends on temperature. Ruelle(1964) recorded diurnal fluctuations in the nest chambers of M. bellicosus. Concentration rose to a maximum of about 3% in the middle of the day and fell during the night to a minimum of 0.6% in the dry season and 1.0-1.5% in the wet season. Fluctuations in carbon dioxide concentration closely paralleled diurnal temperature fluctuations recorded in the wall of termite mounds and in adjacent soil at 20 cm depth. Skaife (1955) found that in mounds of the South African Amitermes hastatus carbon dioxide concentration was usually about 4-5%, but reached 15% in mid-summer when colonies were very active.

[33] Luscher M, (1961) Air Conditioned Termite Nests, Scientific American 205, 138-45.

On hot days some termites make temporary openings at the top of their mounds to promote ventilation. Ruelle (1964) covered a mound of M. bellicosus with a sealed plastic dome. In less than 48 hours the termites built a large porous addition to the top of the mound, apparently in an attempt to promote airflow. One day after the dome was fitted, carbon dioxide concentration in the air inside the mound was 4.5%. When the dome was removed carbon dioxide concentration fell very rapidly to about 0.5%. The termites then sealed the porous top of the mound.

Temperature

The temperature inside termite nests varies diurnally and from day to day. Holdaway and Gay [Nasutitermes exitiosus] found that the temperature in the central nursery chamber was always higher than soil or air temperatures, but varied less than temperatures in other parts of the mound. Occupied mounds were always warmer (8.6 - 10.3°C) than unoccupied mounds, apparently due to metabolic heat. The presence of alates results in an increase of 5.6 - 7.2°C above the temperature of similar mounds without alates.The mean daily temperature in the nest was approximately 30°C and did not vary more than 0.5°C throughout the year, but diurnal fluctuations paralleled ambient temperature variations and sometimes exceeded 3°C.

Air Movement

It has long been considered that limited control over the gaseous environment in mounds and nests maybe exercised by some termites. Two passive ventilation systems, driven by temperature and velocity gradients, have been identified:

a) open ventilation systems where the walls of a mound have holes through which air can move in and out due to differences in wind velocity at different heights
b) closed systems where the surface of the mound is the exchange area between inside and outside.

Luscher described two patterns of air circulation and exchange with outside air. In both cases the air circulation was driven by convection currents, induced by heating of the air in the fungus combs, but the geometry of the air spaces in the mounds differed, and he considered that the two types of mound might reflect behavioural differences between two morphologically indistinguishable geographical races of M.bellicosus. Ruelle (1964) made casts of the space inside mounds of M. bellicosus and showed that the arrangement of interconnecting spaces above and below the central nest and their connections with openings to the exterior favour massive air flow through the mound. Loos (1964), using small anemometers located in the air spaces within M bellicosus mounds, demonstrated convection currents and also showed that air currents within mounds are related to, but are much less than, outside wind speeds and directions.

Luscher proposed that in the closed cathedral shaped, thin walled mounds with many ridges of the savanna dwelling M belicosus the central nest has an air humidity near saturation and a constanttemperature of about 300°C. He proposed that the air rises from the central nest inside the central shaft to the top of the mound driven by convection currents. Because the air channels at the edge would be below the temperature of the core the air would then descend into the ridges and in doing so exchange respiratory gases with external air through the mound walls. Hence the ridges were proposed as the mound lung.

More recently Korb & Linsennmair[34] have undertaken field research into the ventilation of two types of Macrotermes bellicosus closed termite mounds - that investigated by Luscher and and the dome-shaped mounds with thick walls and no ridges found in the forest. They identified two types of ventilation depending on environmental temperature and resulting from convection currents and diffusion of CO_2.

During the day, in the cathedral shaped mounds examined, the sun heats the exposed surface and hence the air inside the exposed channel. The increase in temperature increases the diffusion of CO_2. Warm air rises inside the peripheral channels from a medium mound height which tends to be warmest (possibly because of combination of lower mass and greater exposure to solar radiation than other parts of the mound) pulling CO_2 rich air into the ridges. These respiratory gases are then exchanged through the mound walls. The existence of air rising upwards in the peripheral channels did not conform with the Luscher hypothesis. A second ventilation mechanism was identified in the cathedral shaped mounds at night and in forest mounds at all times. This was internally driven from temperature gradients generated by the termite metabolism and the fungi. The temperature profile increased from outside to the nest core. The air channel temperatures were lower than the core and no upward air movement was detected.

Site Selection

In very hot climates the mounds of some termites, for example, Tumulitermes tumuli in central Australia, are commonly built in the shade of trees or woody shrubs. Large mounds of Nasutitermes longipennis, were similarly situated. For the distribution of mounds of four species of Trinervitermes; 75% of mounds of T oeconomus and T occidentalis were located in the shade of trees, while 90% of mounds of T geminatus were located in full sun. All these are grass-feeders, so the selection of sites near trees is not due to food preferences. In the Sahara desert, some species build subterranean nests with chambers deep in the soil, apparently to minimise the effects of diurnal temperature fluctuations. In cooler climates some species have a preference for sites exposed to the sun. In dry forest, on the hills east of Adelaide, Nasutitermes exitiosus mounds are numerous on slopes with a northerly aspect and low-growing vegetation and are rare or absent on adjacent shaded southerly slopes with tall trees. Many species show a strong preference for sites under stones exposed to sun, compared with stones in shaded areas.

Architecture of Mounds

Variation in the proportion of mound-nest construction above or below ground level also appears to be related to climatic variation in some wide ranging species. Where winters are mild, Nasutitermes exitiosus, builds nests that are almost wholly above ground level, while where winters are more severe, about half of the nest is below ground level and mounds are correspondingly smaller. Macrotermes bellicosus builds its mounds in a variety of places. The nest is entirely above ground in the swamps of Gabon, while in some of the dry savanna areas of Oubangui the nest is largely subterranean. The differences may be due to differences in environment or they may reflect, over such vast areas, differentiation of geographic races with differing mound architecture.

Temporary modifications of mound structure to promote air flow are discussed above in connection with oxygen and carbon dioxide concentrations. Dissipation of excess heat appears to be accomplished inthe same way, and may be more important to a mound population than reduction in carbon dioxide concentration, since many, if not all, species can tolerate high concentrations of carbon dioxide.

Insulation

The mounds and nests of termites insulate the central regions of the nest from variations in ambient temperature. Many species construct insulating layers around the periphery of their mounds. Many fill the outer galleries of their mounds with loosely packed fragments of grass, which would provide insulation as well as food storage. In Nasutitermes magnus harvested grass is often concentrated in a zone of galleries surrounding the central nursery chamber.

Insulation is not necessarily the primary purpose of such placement of stored grass, but some insulation of the inner mound galleries results. Some species construct their mounds with the inner nest separated by an air space from the outer soil wall. A similar separation of outer wall and inner nest is noted in the earth mounds of Macrotermes bellicosus. The subterranean nests of Apicotermes spp and some fungus-growing termites have a sharply defined outer casing and are almost entirely separated from the surrounding soil, or may have a surrounding space filled by the termites with loose sand.

Metabolic Heat

Crowding together of large numbers of termites in the central portion of the nest during cold weather is acommonly used device for maintaining high nest temperatures. The numbers of termites in mounds are low when ambient temperatures are high, and vice versa. The metabolic rate of individual termites is higher when ambient temperatures are high than when they are low. A smaller numbers of termites can maintain an elevated nursery temperature when ambient temperature is high than when it is low. Thus the mound temperature, particularly in the nursery, is probably buffered by movement of individuals between peripheral galleries and the mound.

It has been suggested that a primary function of fungus gardens in mounds of Macrotermes bellicosus is to maintain constant temperatures for the raising of young by production of metabolic heat. Fungus garden temperatures are shown not to follow diurnal fluctuations of ambient temperature and there is little difference between temperatures of fungus gardens in mounds exposed to the sun compared with others built in shaded situations.

Mass Movements of Mound Populations

At the end of the dry season in the hot savannas of Northern Guinea and Upper Volta mounds [Cubitermes] are almost devoid of inhabitants, which take refuge in underground galleries at the base of the mound, or deeper in the soil. This may be to escape desiccation or a direct response to high temperatures, but the two are related. Vertical migration of mound populations can be correlated with diurnal temperature fluctuations.

Moisture

Termite species differ in their moisture requirements, some being able to live in dry wood above ground in deserts while many are restricted to wetter regions, or to subterranean nest and gallery systems. Various sources of water are used by African termites including water produced metabolically, free water in the soil and from the water table, even when it is very deep, water from rain, and condensation within nests or other termite structures. Reabsorption of water from faeces before they are voided is practised by termites living in dry wood.

Some species which feed on dead wood, build their nests in living trees immediately adjacent to living tissue, apparently to take advantage of the moisture available. In general termites are very susceptible to desiccation, because their cuticle is exceptionally soft and its water-retaining properties are poor. A few species could not live in very humid atmospheres, but most prefer relative humidities of 90-97%, hence, the maintenance of high humidity in nests, mounds and galleries is an essential requirement for the survival of most species of termites, especially for those that live in arid and semi-arid regions. Mechanisms that contribute to humidity control include:

1. Active transport of water.
2. Use of absorbent materials for construction of nests.
3. Metabolic water.
4. Protection from excess water.

Active Transport of Water

Termites that live in arid or seasonally arid regions frequently have vertical galleries descending to the water table and transport water to the nest to maintain suitable humidity. Several Sahara species [Psammotermes] bring water from a depth of several metres to humidify shallow subterranean nests. While West African termite galleries have been observed going to the water table at a depth of 70m. During the dry season

[Macrotermes subhyalinus] maintains high humidity in the inhabited parts of its nest, especially in the vicinity of the royal chamber, while the remainder of the mound is allowed to dry out. Some termites [Odontotermes magdalenae] have been observed rebuilding mounds at the end ofthe dry season with moistened soil, and maintaining a trail of moistened soil for the columns of workers involved in rebuilding. Galleries have been found [Anacanthotermes ahngerianus] descending from nests about 1.5m below the ground surface to moist soil at 10-15m, which are considered to allow moist air to ascend to the nest.

Absorbent Material in Nests

By introducing absorbent materials into their living space many termites are able to store water. The absorbent materials are of three main kinds, i.e. clay, “carton”, and “fungus gardens”.

Clay is used as a structural and cementing material, but sometimes its distribution in mounds indicates that it is important for water conservation. In Macrotermes subhyalinus the central portion of the nest, including the queen’s chamber, contained up to 70% clay, transported from deep soil layers, and this portion was maintained during dry seasons at 25-32% moisture content with water transported from below by the workers; outer regions of the mound were predominantly sand, cemented with clay, and were not kept moist.

Carton consists largely of the excreta of termites, usually incorporating some mineral particles and often undigested fragments of wood, grass or leaves of trees. It is formed into a labyrinth of laminar or alveolar structure and makes up the galleries of the central portion or sometimes the whole of mounds and nests of many species of termites. In many other species similar material is used to line earthen galleries within the mound or to line galleries that provide access to food supplies.

Fyfe and Gay measured the absorptive capacity of mound material (N. exitiosus) from various layers at 26°C and 36°C and at a range of relative humidities, l00%-10%. Material from the nursery absorbed about twice as much water/unit dry weight as that from the outer alveolar region, at all temperatures and relative humidities. For a short time on hot days the outer layers reach temperatures similar to the nursery; subsequent relatively rapid cooling could lead to temporary dew formation in outer galleries, but not in the nursery and adjacent regions of the mound where the termites are concentrated. Water loss from mounds to the outside air is further inhibited by the relatively impervious outer soil covering. The contribution of carton to water conservation has not been studied in detail for any other species of termite, but it may reasonably be inferred that processes operating in mounds of N. exitiosus are paralleled in similar mounds built by many other species.

Fungus Gardens The cultivation of fungus gardens is confined to one species. It has long been observed that the fungus are inadequate as a food source and moisture control is one possible function. RH in the air around fungus gardens [Odontotermes obesus] varied only between 85% - 95%. It differed little from relative humidity of the soil air immediately adjacent to the fungus gardens but differed markedly from that of soil air at a distance. It is possible that fungus gardens (which present a very large absorptive surface to the air) function primarily to control humidity by taking up excess moisture or by releasing water to a drying atmosphere in a similar way as attributed to carton, with the additional advantage that the metabolic heat of fungi would contribute to temperature control.

Metabolic Water

Decomposition of cellulose, which is the principal food resource of termites, results in release of water. It has been calculated that most of the water required to maintain high humidity in mounds of Nasutitermes exitiosus could be produced from carbohydrate metabolism. No reliable measurements have been made of production of metabolic water by termites in the field, but extrapolation from the results of laboratory feeding trials indicates that metabolic water may be important in replacing losses by evaporation.

It has also been found that the moisture content of inhabited mounds of three East African species of Macrotermes was higher than that of adjacent uninhabited mounds, and inferred that metabolic water was largely responsible for the difference. It seems likely that the fungi in fungus gardens of Macrotermitinae supply metabolic water to the environment in the mound, but no information on their significance is available.

Protection from Excess Water

For species that inhabit regions of heavy rainfall, especially rain forests, maintenance of high humidity presents no problems, but protection from flooding and excessive erosion may be important. Many rainforest termites build arboreal nests, often with covered runways descending to the soil and some have special structural features, apparently for shedding water. Some build nests consisting of “half hats” spaced down tree trunks; or overlapping sheet-like flanges projecting outward and downward from tree trunks with their edges prolonged into finger-like projections from which water is shed. Some build a herring-bone pattern of covered ways on tree trunks above their nests, apparently to divert water running down the trunk away from the nest. Not all species that live in the same environment build such “rain-shedding” structures but on the

other hand some species construct nests with “hats” in the wetter parts and without “hats” in the drier parts of their range.
Where widespread seasonal flooding temporarily prohibits access to the soil for termites in low-lying areas then, during the wet season, grass-feeding termites retreat into their mounds and apparently live on grass collected and stored during the dry season.

Termite Nests as Environments for Others

The physical protection and equable environmental conditions provided by termites in their nests, mounds, and other structures attract many animals, mostly insects, to spend part or all of their lives in association with termites. Many species of termites are parasites in the nests of other termites. Reptiles, birds, and mammals frequent termite mounds, both as permanent living places and as nest sites. Armadillo, foxes, lizards and rattlesnakes live in termite mounds in Guyana; some species using mounds as incubation sites for their eggs. It is a fair assumption that termitaries are well developed ecosystems and that reptiles, such as geckos, living in nests and preying on termites will themselves become prey to snakes.

Fundamental Principles

Animal construction appears to follow a number of basic principles:

- Structures are simple to build
- No complex structures are used
- Specific building materials are chosen which are fit for their purpose
- Standard units are chosen from which to build
- There is standardisation brought about by repeat behaviour
- Use of local materials, materials that are available[35]
- The number of materials are limited
- Through their architecture animals can impose control in two ways:
    - ◊ Climate control (keeping rain out and water in)
    - ◊ Biological control (keep predators out)
- Animals incur their own ‘building costs’, ie.time spent on building relative to survival and procreation
- There is an aspect of social building, for example in large ant or termite colonies
- There is evidence of a progression in materials used and building techniques within certain species.Wasps, for example, have progressed from mud burrowing, to mud shaping, to paper building.
- There is evidence of animal agriculture found in leaf ants growing fungus on leaves in chambers.
- Much of animal architecture shows that ‘builders with no brains’ can still create something verybeautiful.
- Animals use camouflage to:
    - ◊ make themselves blend into the background
    - ◊ look like something obvious but not good to eat
    - ◊ make something look ‘broken’

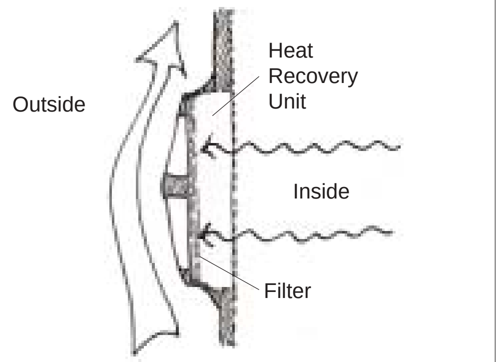
[35] It is unclear whether animals choose sites because of the materials they wish to use or if they build according to the materials available. For example, Song Thrushes do not breed in some places where there is a lack of water required for plastering their nests.

Concepts

From the earlier list a number of concepts were developed in detail.

Air Filtration, Heat Recovery

The method in which the sand dollar uses the elevation it has created to extract food from the sand could be applied to air filtration and membrane-based heat recovery.

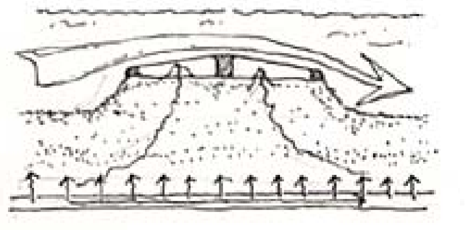


Air filtration unit fixed to outside face of building

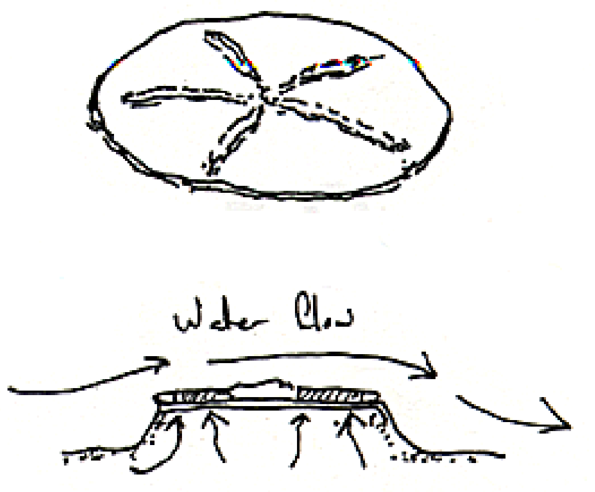
Water Filtration

The extraction principles of the sand dollar could be used to produce a natural grey water filtering and heat exchange mechanism.

Direction of flow of clean water over slotted discs



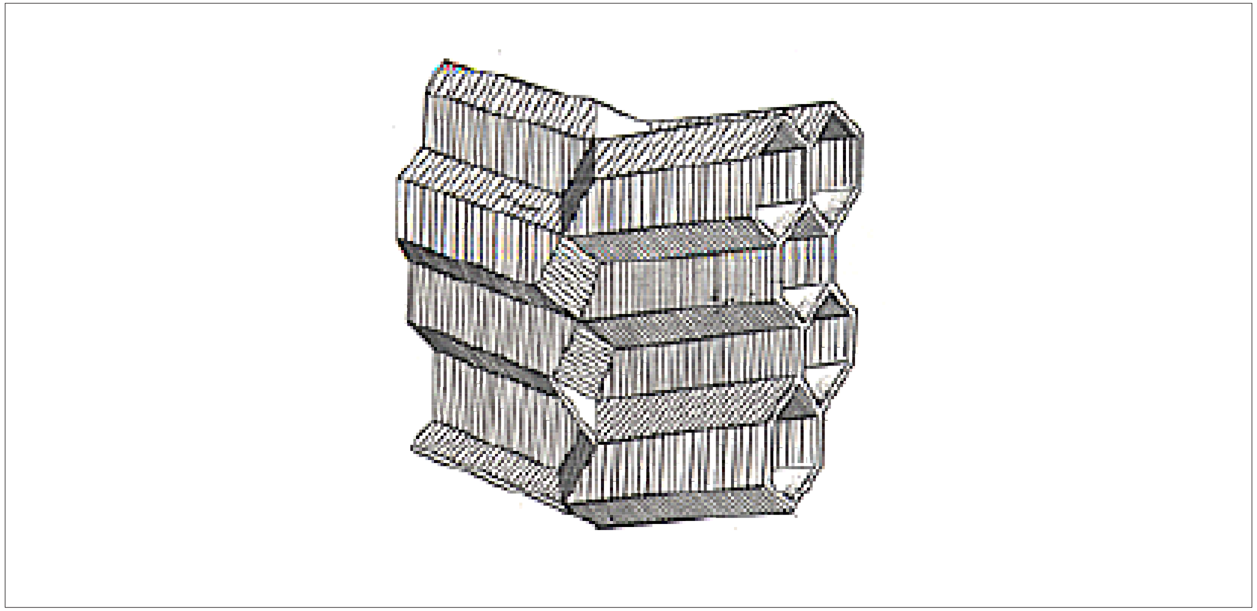
Grey water flowing below through perforated pipes gets drawn up through a filtering layer of sand



The Sand Dollar

Bernoulli's Principle

Slotted sand dollars form slight elevations on sandy bay bottoms, so water flowing across them draws water and edible particles up through their slots from interstices in the sand.



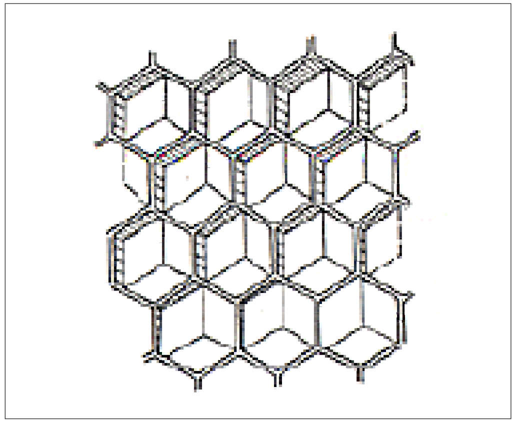
The Honeycomb

Versatile Structures

"A comb of hexagonal cells is a very versatile structure; it has the properties of surprising strength and stiffness while also being very light. It is indeed these very properties which led to waterproofed paper 'honeycomb' sandwiched between sheets of plywood or other materials being used in aircraft construction during World War II."

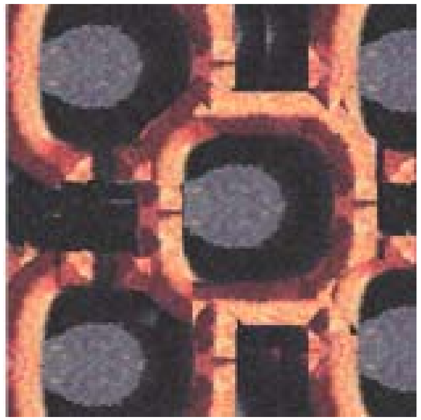
Structural Strength

The honeycomb is intrinsically strong as a form and can have many more applications in construction than as just a flush panel door core material.



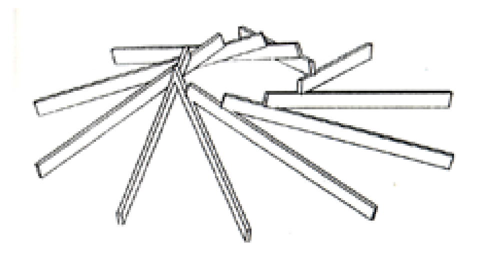
Urban Form

The efficient enclosure of space has been researched by Leslie Martin and others, and the lessons to be learned from this form in nature go from microcosmic to macrocosmic.



Free Spanning Structures

The polygons which are stacked up around the centre of the nest create a deep cup with a wall that incorporates some of the virtues of a reciprocal frame structure.

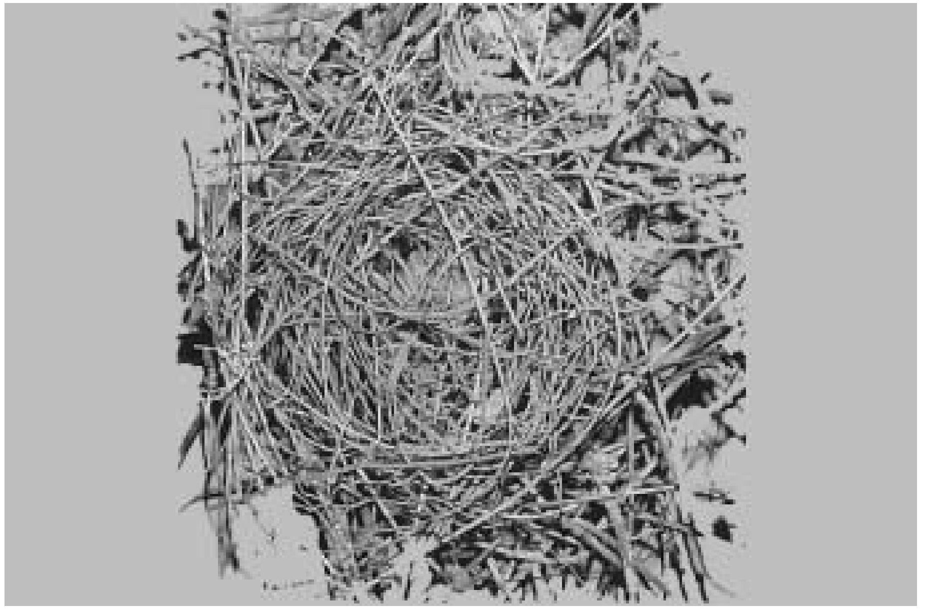


Reciprocal frame roof structure

Assembly Methods

Mutually supported beams represent a valuable source of investigation as a simply assembled structural system.

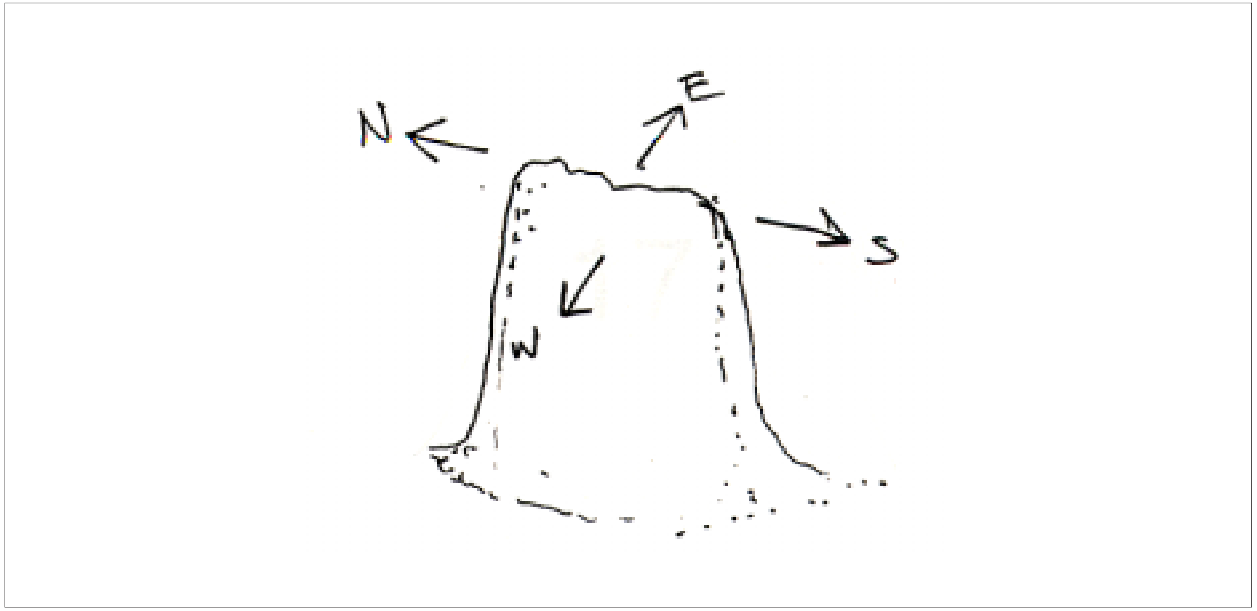
Plan view shows anchoring points



Blackcap Bird's Nest

Reciprocal Frame

At first glance the neat cup nest of a Blackcap does not seem to be a beam structure. It is in fact made from grass stems which are hollow tubes, light and strong. However, a closer look reveals that the bird is not able to bend these stems around the nest cup but has instead buckled each hollow beam at fairly regular intervals. This creates a polygon, hinged at the buckling points.



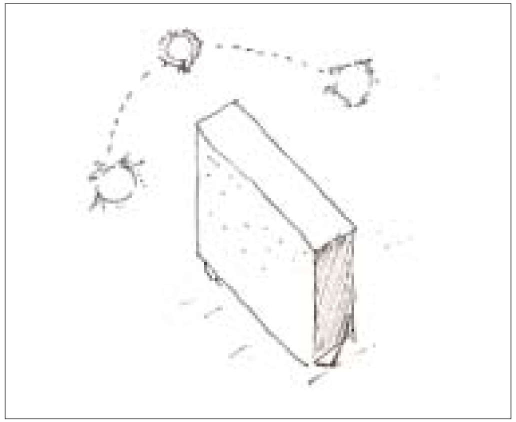
The Compass Termite Nest

Building Orientation

Compass Termites build their slab-like nests (up to 3.7 metres high, 3 metres wide, and 1 metre thick) orientated exactly in a north-south direction to minimise noon heat and to maximise early morning and late afternoon warmth through shape and orientation. They move from one side of the nest to the other to maintain optimum temperature in their immediate surroundings.

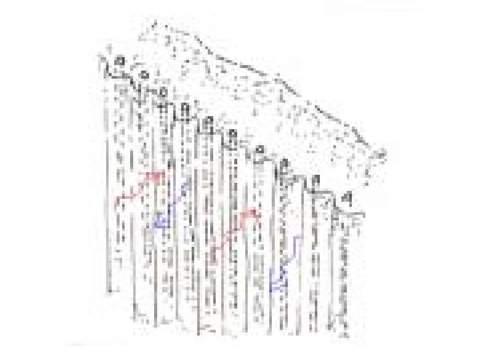
Climate Control

The way in which a termites' nest uses shape and orientation to control internal climate is worth investigation in seeking to control thermal gain.



Gas Exchange

Gas exchange may be a primary reason for the nest's shape as it increases the ratio of surface area to mass.



Increased surface area allowing greater exchange of Carbon Dioxide and Oxygen

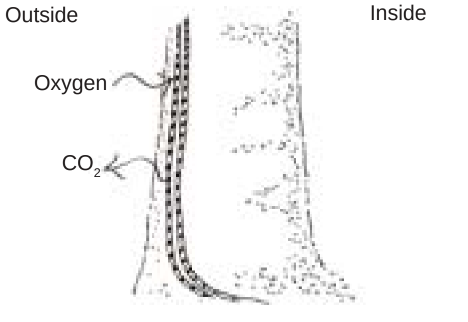
Ventilation

Perforated ducts within earth walls could channel stale air down out of a building exchanging it for fresh air through an air permeable skin.

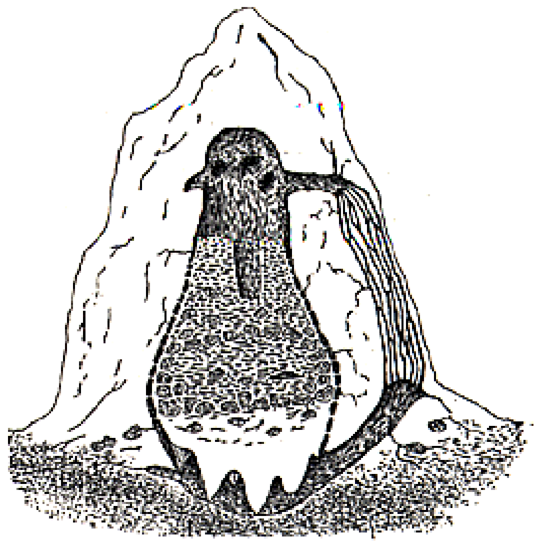
Perforated ducts bring stale air from the innermost parts of the building

De-Toxing

The mound wall has a gas exchange before the air passes down in to the basement.The wall itself could act as a detoxing agent, filtering the air in and out of the building.



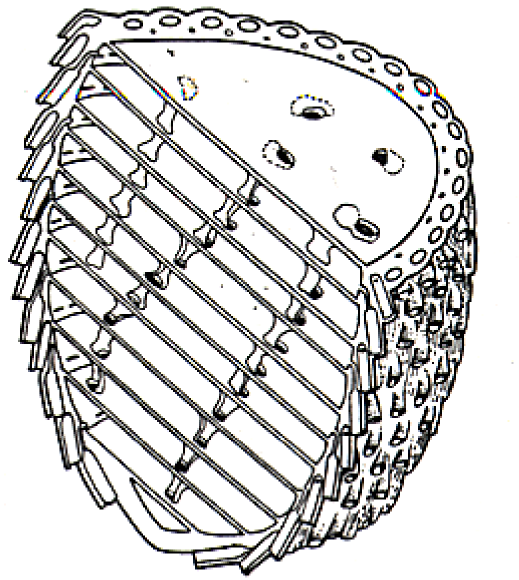
Earth walls containing these ducts act as natural filters while exchanging gases



Macrotermes bellicosus Termite Nest

Air Conditioning

“Metabolic heat causes air to rise through the nest from a basement and be pushed out into fine channels, which run superficially in prominent ridges down the side of the mound, before returning to the basement. The whole structure incorporates an ingenious circulating air system which regulates temperature, humidity, and gas exchange.



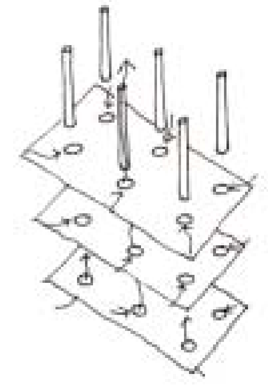
Apicotermes Lamani Termite Nest

Climate Control

“...a massive, thick wall, perforated only by vertical channels, surrounds a central cavity in which the dwelling area is built. It stands on pillars over a large basement cavity which is below ground level.”

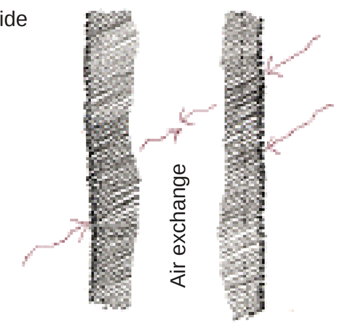
Internal Ventilation

The vertical channels which run through each floor of the nest could similarly be used to ventilate spaces within central areas of buildings.



Water Deflection

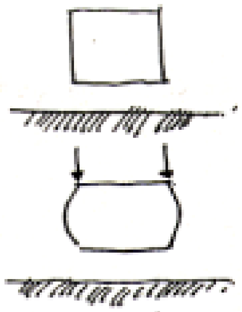
Ventilating louvres within a thick wall membrane could offer an alternative method of ventilating a space efficiently.



Section through “thatched” breathing wall

Standardisation

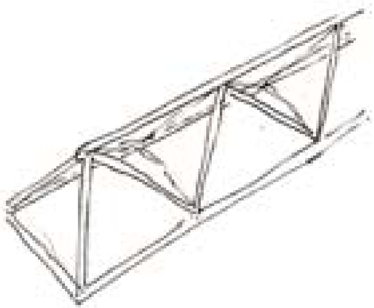
Of interest are organic materials that are standardised but not to high tolerances, as there is give in the connection mechanism



Panels cut from leaves are able to carry load and help form a rigid structure

Out of Phase Construction

A bonding system in a brick wall is essential for its strength, but to form a structural unit in 3-D with the use of Out-of-Phase units is innovative



Repeated modules linked together to form a rigid structure as in this steel truss

Caddis Larva Lepidostoma hirtum House

Modular Building

"...panels in neighbouring sides are half a panel length out of phase and, at the anterior end, the roof projects half a panel length in front of the sides and a whole panel length in front of the floor." Rotated through 90 deg - wall becomes roof etc. "The normal house is square in section but external loading directly over both vertical walls simultaneously causes these to buckle outwards... The ability of the house to sustain repeated deformation without fracture shows that, although not rigid, it is rather tough."

The Wasp Nest

Paper in Construction

"The nests of Polistine and Vespine wasps are mostly supported from above, sometimes from the side and almost never from below. They must therefore, principally be structures capable of bearing the load in tension."

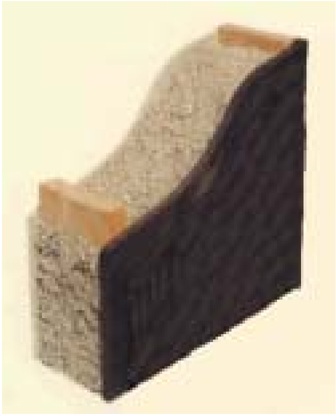
An opened wasp nest shows how the insects build an outer wall of paper several layers thick. Bits of wood are chewed up into a pulp and mixed with saliva which then hardens in to tough walls of paper. The layers create pockets of air, which insulate heat efficiently.

Paper in Compression

It is intended to make an investigation into paper/ cellulose based structures capable of bearing load in tension or compression

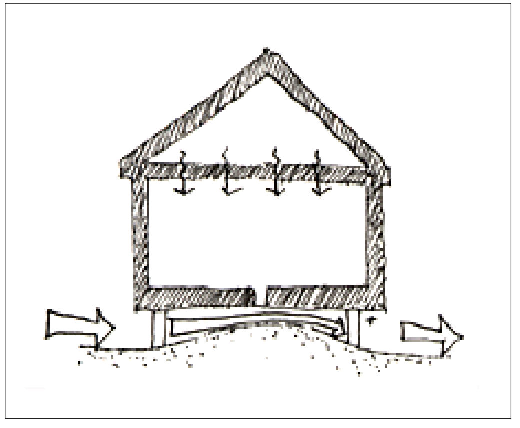
Paper Insulation

An investigation into expanding the potential for paper as a breathing and air-pocket forming insulation material



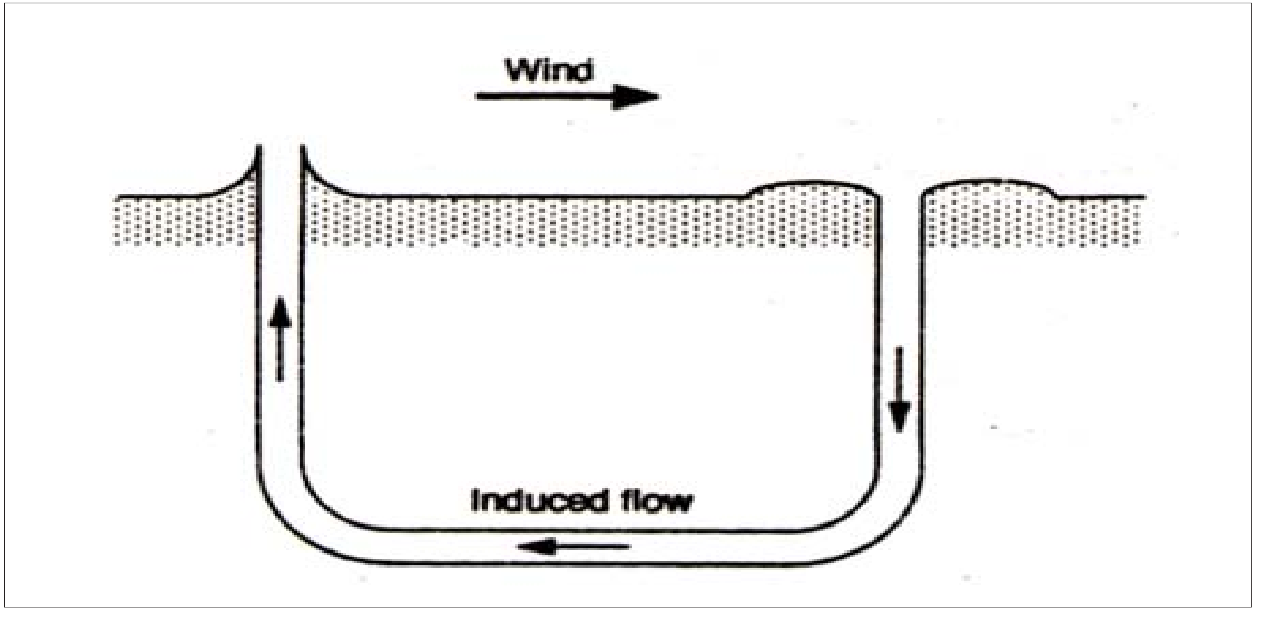
Dynamic Insulation

The essential for Dynamic Insulation is the creation of pressure differences - to substitute a fan with a natural drawing effect would be beneficial.



Culvert Ventilation

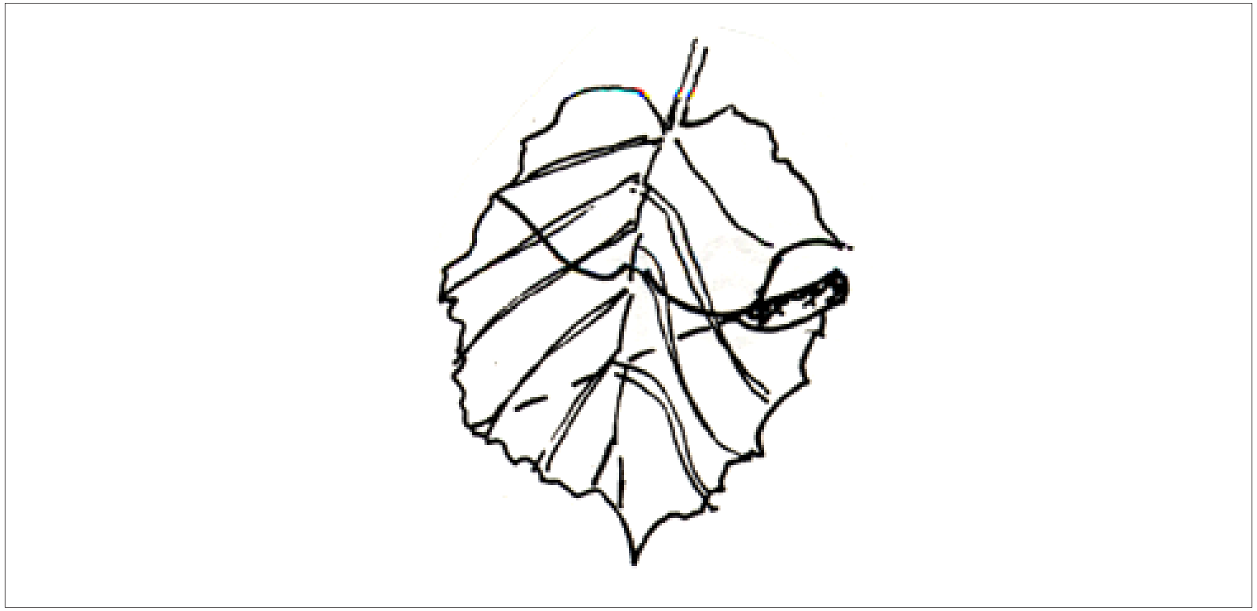
The development of a sports Centre at Drumchapel leans on Swedish experience of culverts to create a tempering of the incoming air



Black-Tailed Prairie Dog Burrow

Natural Ventilation

"The black-tailed prairie dog burrow emerges to the surface through two different exits: low wide mounds with rounded tops (dome mounds) and narrower steep-walled, sharp-rimmed craters (rim craters). The average height of craters is nearly twice that of mounds. The wind over the top of the crater is faster than that over the top of the mound; the lowering of pressure at the top of the crater draws stale air out of the burrow through the rim crater and fresh air enters through the dome mound."



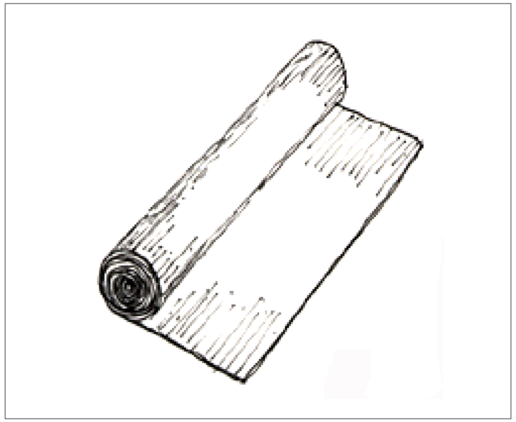
Deporaus betula Beetle

Leaf Rolling

Leaf rolling by the beetle Deporaus betulae. The principle of this type of construction is to create a three dimensional structure by rolling a plant leaf. (Solid line indicates the direction of the cut. The dotted line indicated the axis of the roll.)

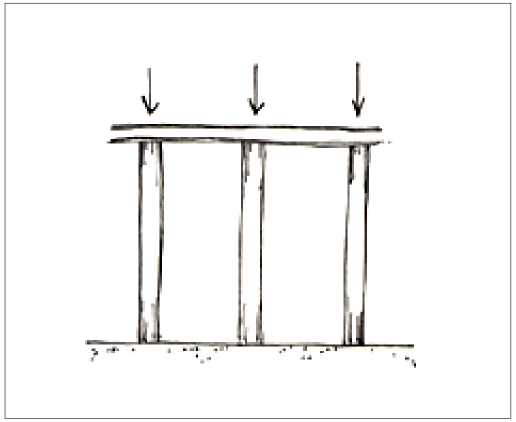
Rolled Structures

Rigid load bearing structures fabricated from rolled flexible material, eg. paper.

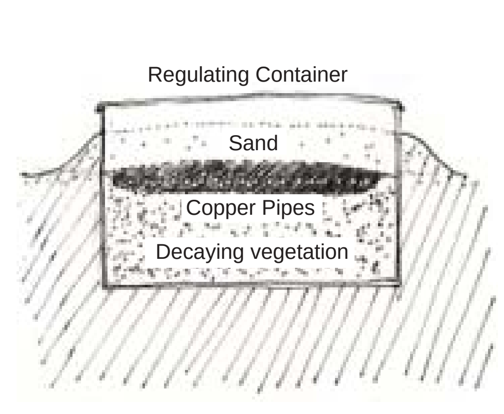


Cost Effective Building

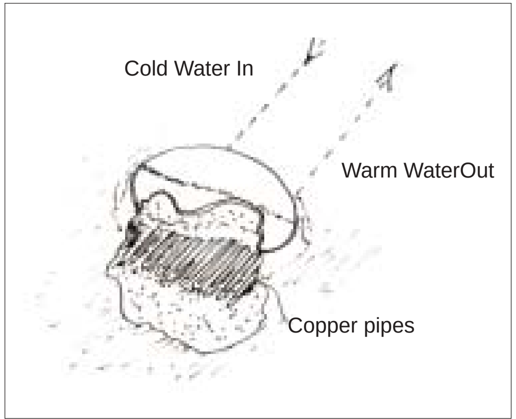
Research into alternative building materials could produce new and varied types of more cost effective construction methods.

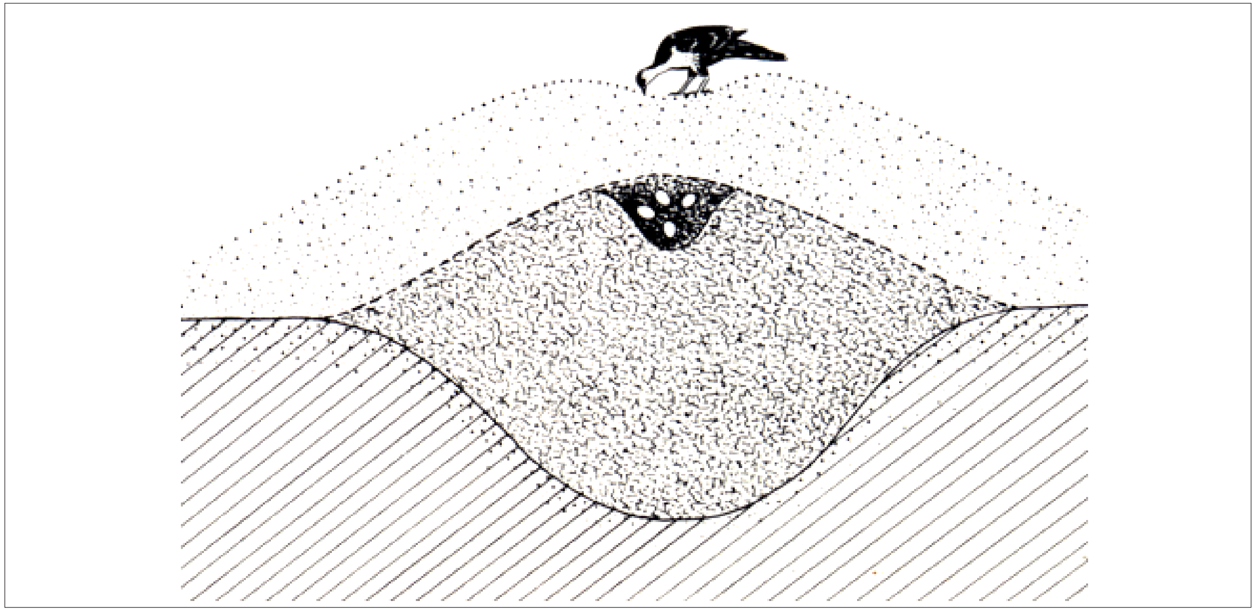


Natural Heat Production
Just as the birds use heat produced by decaying matter to incubate their eggs, a similar technique could be employed to aid a radiant heating system.



Alternative Heating Systems
This technique could perhaps be applied to aid or replace a conventional boiler system.

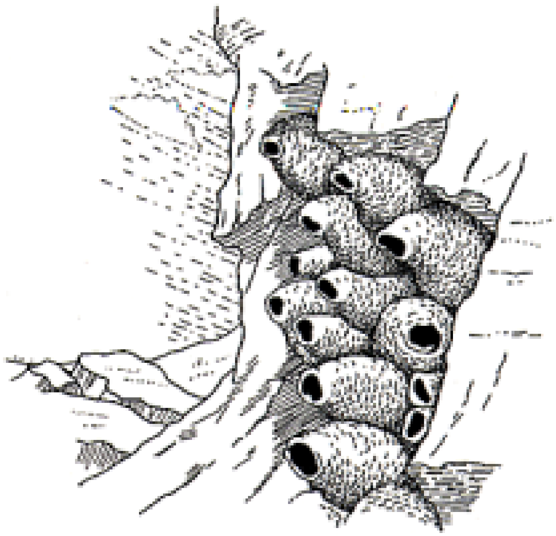




Megapodiidae Bird Nest

Controlled Incubation

The Megapodiidae birds incubate their eggs in gigantic earth nests by heat generated through a process of fermentation. In winter they pile leaves and twigs in the pit. After each rain, the birds cover the vegetation with sand, sealing in the moisture. As the moist vegetation decays it produces heat. The bird regulates the temperature by either ventilating the nest chamber or piling more earth on the nest.



Cliff Swallow Nest

Mud & Straw Structures

"...the cliff swallow, whose retort-shaped nest is attached to the underside of a rock overhang indicates that the nest material is not simply mud but has grass incorporated into it; the latter probably contributes to the tensile strength of the material... The bracket-shaped nests of the crag martin and the blue swallow also have grass mixed with the mud; this is further circumstantial evidence to suggest that the grass does have a structural role."

Natural Building Materials

Straw and mud are currently being used as alternatives to traditional block and brick walls as seen in this private office in Perthshire.

Breathing Walls

The walls of the building are made of straw bales combined with mud and coated with lime to add strength.

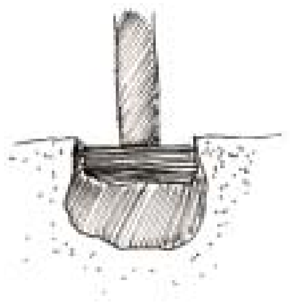
Rammed Earth Foundations

This technique could perhaps be applied in construction wherever earth is normally excavated.

Soil is either compacted into the ground or taken away, filtered to remove debrix and then compacted and replaced

Excavating with Minimal Impact

By compacting soil rather than extracting it its inherent load bearing qualities can be exploited, and the need for additional supporting building materials can perhaps be avoided.

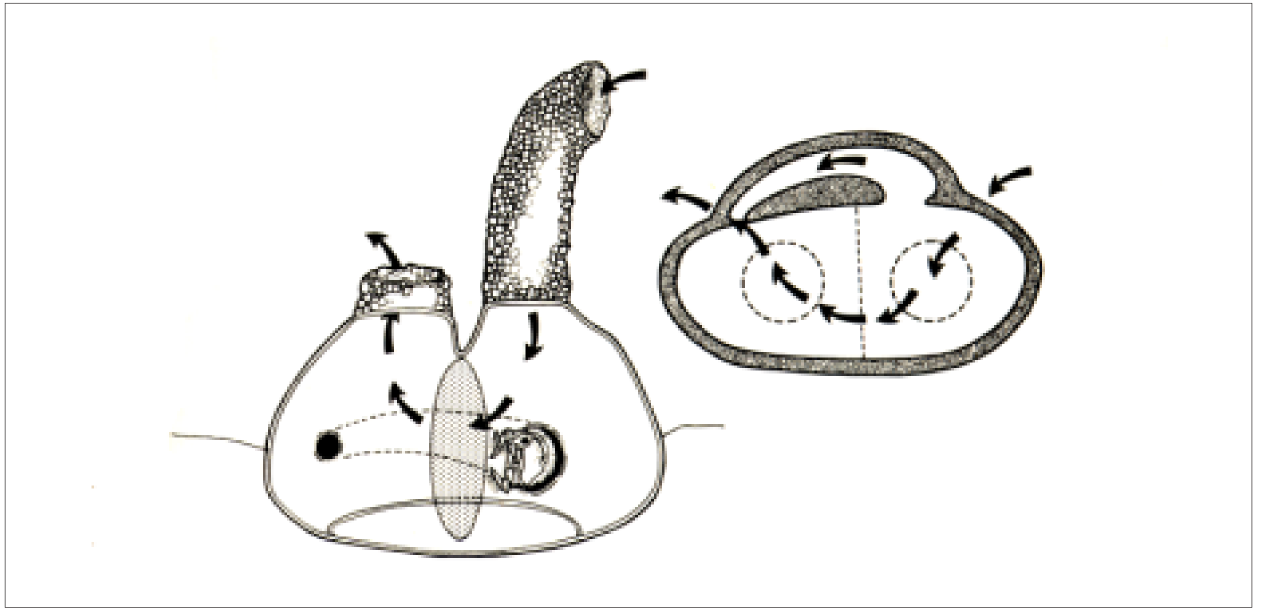


The firmly compacted soil acts in much the same way as traditional concrete foundations, allowing load to be spread from the structure being built

Duckbill Platypus

Earth Compacting

“...a platypus, in digging its extensive burrow, carried almost no soil to the outside but created space by compacting excavated material in to the walls behind the work face.”



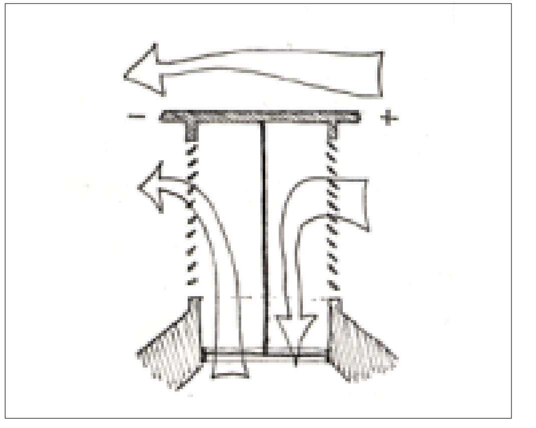
House of the Macro Nema Transversum Caddis Larva

Versatile Structures

Combines living quarters and capture device constructed by Marconema transversum caddis larva. Water is directed into and out of the chamber through funnels. The larva waits for its prey in a side chamber next to a vertically positioned fine net.

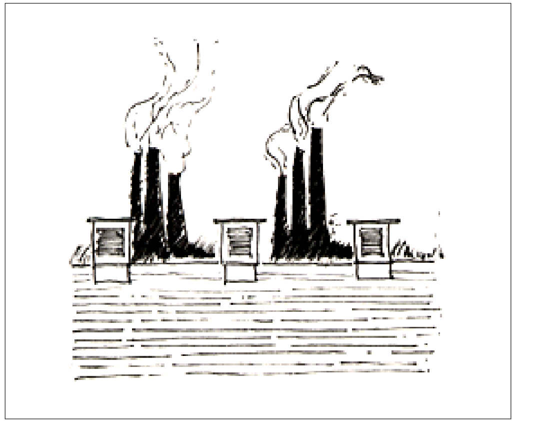
Natural Ventilation

The idea of using funnels to naturally re-direct currents into and out of a dwelling could be adapted for use in aiding natural ventilation



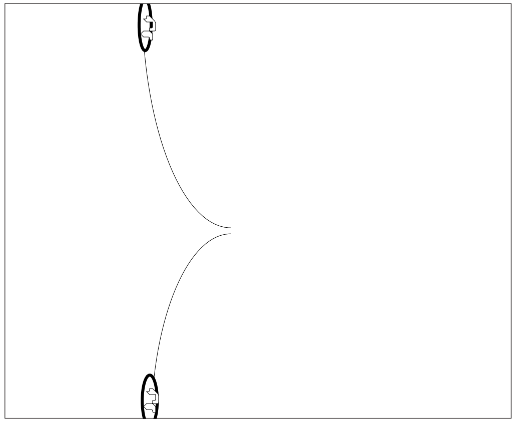
Air Filtration

It could also be beneficial to explore the use of filters in growing areas of high air pollution.



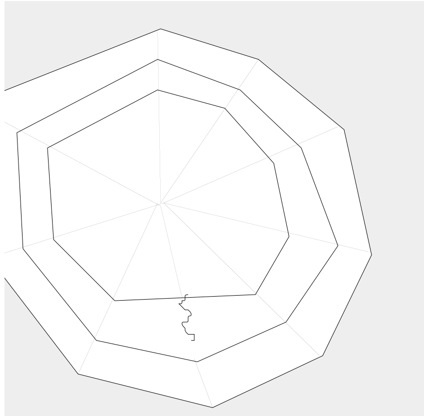
Energy Absorbing Structures

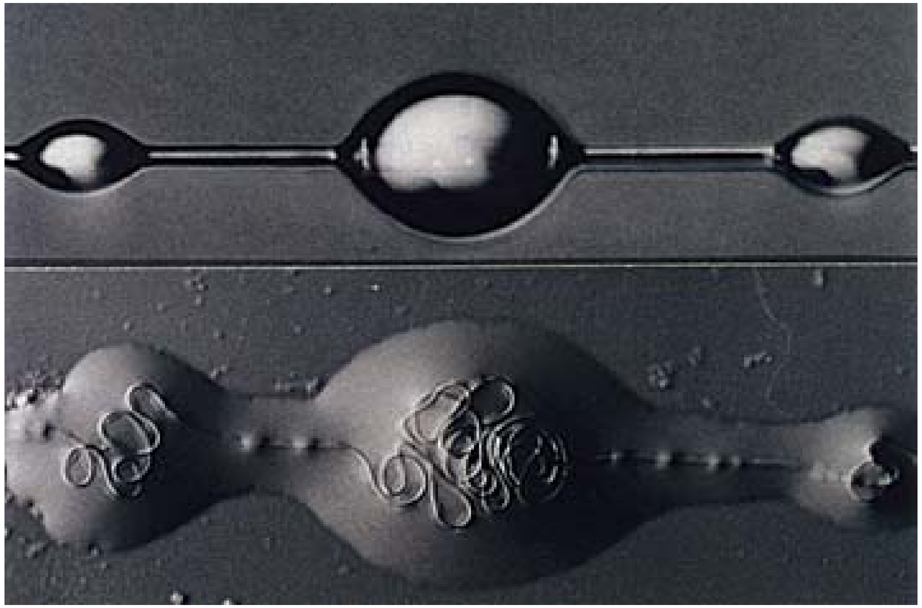
The phenomenon of a structure absorbing impact without breaking (as when a fly hits a web) is one which has applications in buildings or elements of buildings where constant or high impacts are likely.



Structural Integrity

The maintaining of the integrity of a structure after the loss of a member in that structure (as in a web after impact) is a principle which would have an application in certain construction circumstances





Spider Orb Web

Spider Web Construction

"...tension acting on a section of capture thread secured between radii by zero junctions resulted not only in the elastic extension of the capture thread but also in thread slipping through the junctions from the neighbouring segments of capture thread. The result of this is an increase in the length of the thread between the two junctions and therefore an increase in its capacity to absorb energy.... If the capture thread broke, the junction sealed and (web) damage was thereby confined."

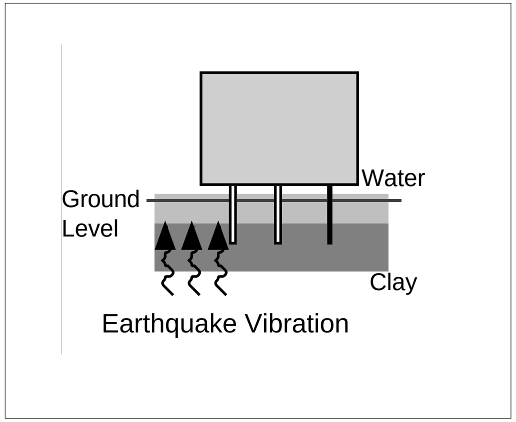
Mud Dauber Wasp

Building Techniques

“A parallel to this welding technique is in the nest building of the Mud dauber wasp... The wasp presses the mud onto the nest rim and agitates it with a vibrating movement -many times per second. The soft mud, which contacts the rim first, forms a weld between nest and new material... the rapid vibration makes use of thixotropic property of mud which results in it becoming temporarily liquid. This allows the whole load to be shaped more easily and evens out concentrations of stress in the final structure.”

Ground Stability During Earthquakes

This phenomenon has been responsible for buildings collapsing during eathquakes. Its further investigation has two potential outcomes - preventative and creative.



Animal Architecture in Existing Buildings

Some building projects can be readily identified as having similarities with animal building behaviour which may be due to:

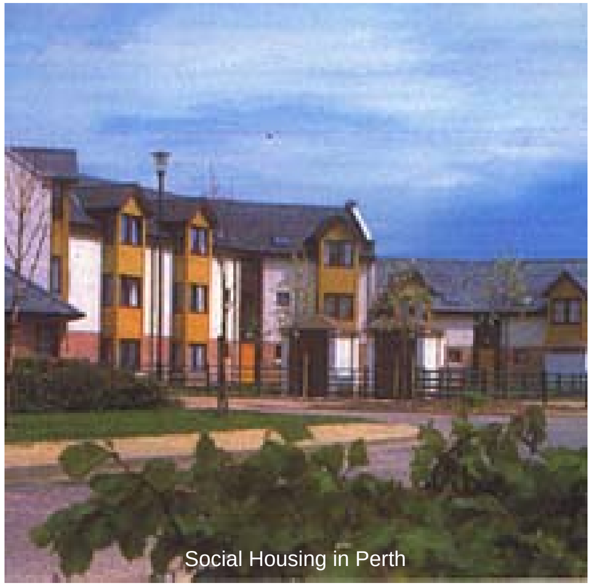
a) the applications of fundamental principles such as gas exchange, air flow or similar
b) observation and subsequent replication of animal builders
c) inspiration
d) a combination of the above

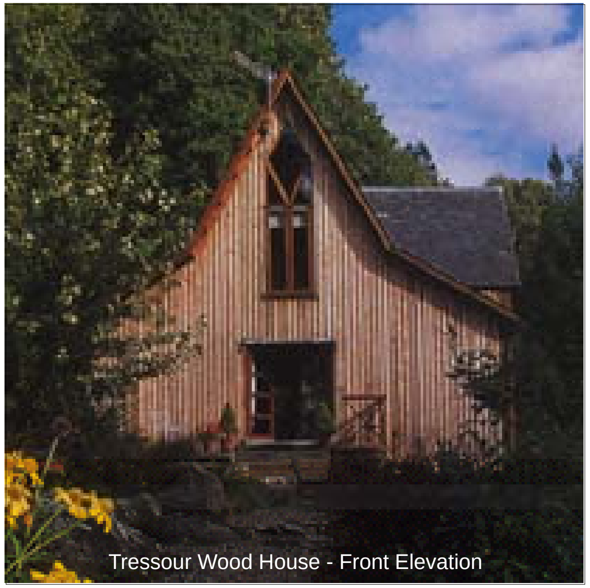
Some of these are detailed on the following pages.

Case Study 1

Fairfield Housing Cooperative

Perth, Scotland


Social Housing in Perth


Tressour Wood House - Front Elevation

General Description

Breathing wall construction was first used by Gaia Architects (Norway) in 1983 in a house in Stavanger. It was also used in the Tressour Wood House in Weem, Perthshire, built in 1992, and voted the UK House of the year in 1993. It was then developed for the whole of Phase 7 of the Fairfield Housing Coop Development at Perth, as part of an overall environmental specification for all 18 houses. Phase 8 will take this further to low allergy specification

Principle Related to Animal Architecture
Breathing Wall Construction

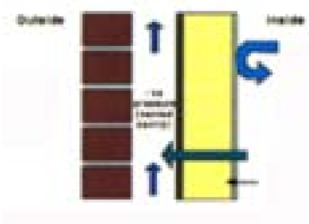
Creating a healthy indoor environment in the context of high numbers is something which termites achieve by constructing the walls of their nests such that unwanted indoor pollutants permeate through the wall structure.

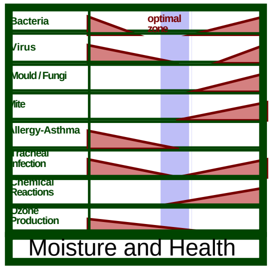
In buildings for Human habitation a basic principle in maintaining comfort and health is in the control of Relative Humidity. Energy conservation measures - notably the quest for air tight construction - has led to the introduction of vapour barriers, which retain moisture indoors. But this has implications for comfort and health.

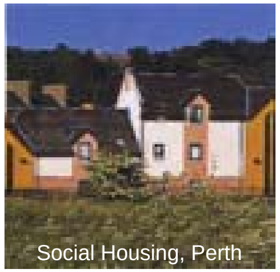
Areas for Further Investigation

Gaining a greater understanding of the Physics/Biology of the ventilation, moisture control and gas exchange in termites nests will assist in the better understanding of breathing wall construction


Termite Nest


Breathing Wall Principle


Moisture and Health


Social Housing, Perth

Case Study 2

Urban Design

Forli' (Italy) – Bergen (Norway) – Viikii (Finland)

General Description

The most effective way to house people at high densities in cities has been the subject of much study and debate. However there are certain geometric forms which can be demonstrated mathematically as being the most efficient shapes for the enclosure of space in terms of the wall to floor ratio.

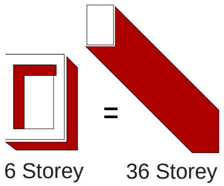
Leslie Martin at the Centre for Urban Studies (Cambridge) showed that the traditional city block was a very effective way of achieving high density - due to the fact that it built at the perimeter of a square rather than the centre.

Principle Related to Animal Architecture
Urban Form

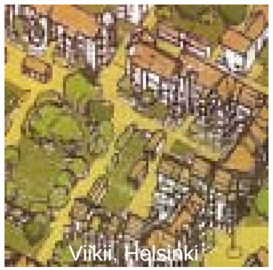
In Projects in Italy, Norway, Scotland and Finland, the Gaia Group has developed urban forms which are of a human scale, yet achieve high densities whilst also providing a healthy, productive and useful outdoor environment, based on the principles of Permaculture. In Forli', Italy we adapted the form further to take on the efficiencies of form shown in the enclosure of space in the honeycomb structures made by bees.

Areas for Further Investigation

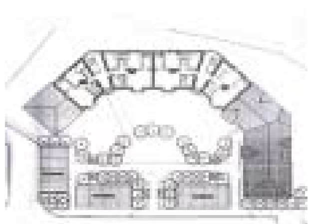
There are a number of complex forms developed for communities which could hold lessons for Urban Design including: termite mounds, badger setts, etc.

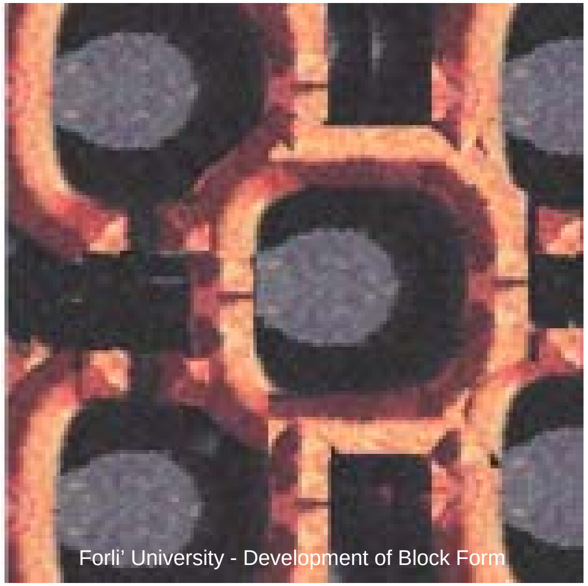


City Block v Skyscraper


Viikii, Helsinki


Bergen Eco Suburb '94


Fairfield, Scotland


Forli' University - Development of Block Form


Honeycomb Structure

Case Study 3

Drumchapel Sport Centre

Glasgow, Scotland

General Description

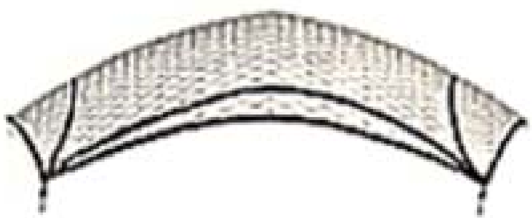
Gaia Group worked on a European roundpole construction research project. The Drumchapel Roof Mk1 and 2 were both from this form of timber. In the first (1994) version of the Drumchapel Sports Centre project (main illustration) the use of roundpole construction was in a lattice system which was not only dependent on the lateral displacement of forces over the whole of the structure but also gained strength and rigidity from the curved shape.

Principle Related to Animal Architecture Structural Form

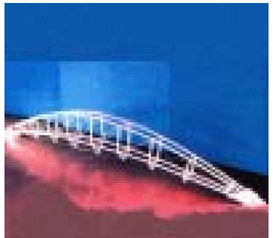
A man-made structure lattice framework is operating under very similar structural circumstances as many birds' nests. The principles underlying a garden warbler's nest, for example are seen as the displacement of downward forces to a lateral plane (see reciprocal frame). An example of the reciprocal frame in practice is in the roof structures of the Whisky Barrel houses at Findhorn. The bottom right illustration shows an application of the same principle in a traditional Lappish fence.

Areas for Further Investigation

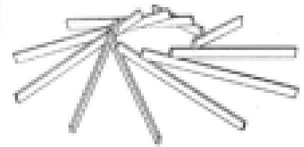
Structural experimentation in terms of both random and extrapolated forms of roundpole construction would be worth pursuing. There could be a variety of applications which might turn out to have different viabilities dependent on context (availability of materials, remoteness etc).



Proposed Roof Structure for Drumchapel Mk1



Drumchapel Roof Mk2



Reciprocal Frame

Reciprocal Frame

Fence in Lapland

Case Study 4

Drumchapel Sport Centre

Glasgow

General Description

One of the key Environmental Design strategies for Drumchapel was to reduce energy consumption and to question assumptions in terms of conventional solution to dry sports activities - notably the use of air conditioning for fitness suites. The use of a natural ventilation system in summer will obviate the use for energy intensive mechanical ventilation and air conditioning. Fitness suites have become more and more energy hungry as they have raised their cooling requirements - often in inappropriately glazed settings.

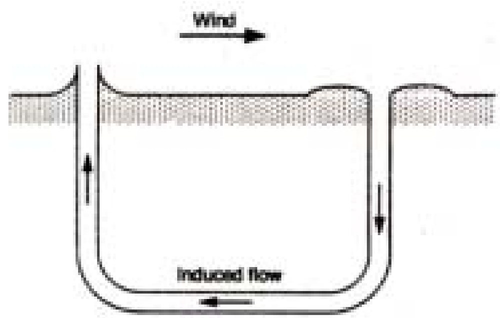
Principle Related to Animal Architecture
Natural Ventilation

The natural ventilation strategy at the Drumchapel Sports Centre (Mk2 design) is based in a culvert which causes the air to become a constant temperature as it flows underground. The air is induced naturally through the culvert by means of stack effect - or induced ventilation. This process is precisely what is occurring with the Prairie dog burrow.

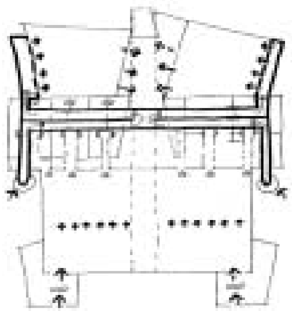
Areas for Further Investigation

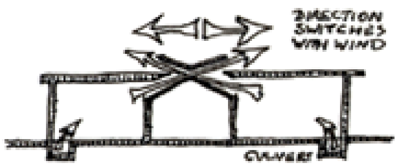
The Culvert system has been developed primarily to achieve even summer and winter supply air temperatures. The Prairie dog burrow system is a development of this in that the different dispositions of inlet and outlet assist the induction of air. This design principle would be a further development in the Drumchapel project.


Drumchapel Sports Centre Mk2

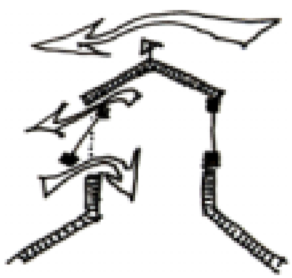


Prairie Dog burrow with induced ventilation


Drumchapel Culvert Plan



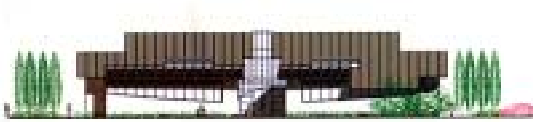
Drumchapel Ventilation Section


Drumchapel Ventilation Detail

Case Study 5

Drumchapel Sport Centre

Glasgow, Scotland



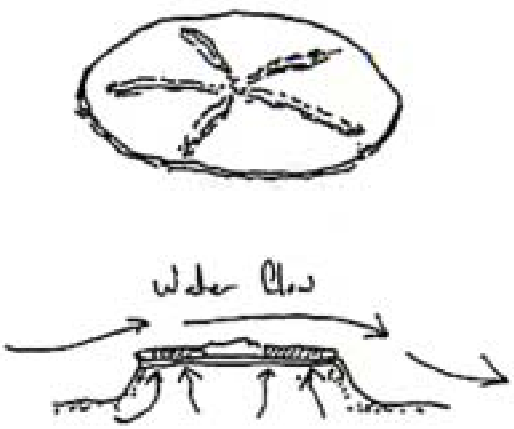
Drumchapel Sports Centre Mk2

General Description

The conservation of water is a general objective at the Drumchapel project. The use of grey water to feed to the plant system in the environmental Garden for the first Version of the project has now been changed to a more targeted approach. The use of waterless urinals and low flush cisterns are the primary strategies on the cold water side, but innovative techniques on the hot water side are perhaps the most interesting and innovative.

Principle Related to Animal Architecture
Water Conservation

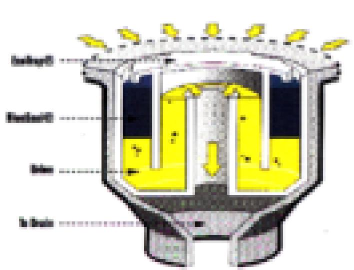
The heat recovery system at Drumchapel uses a spiral of fresh water outsider the hot water exit drainpipe for the showers, thus creating a preheat (diagram 2). The further development of such exchanges and 'smart' membranes is a key to the effectiveness of these systems, since it has been acknowledged that a number of previous grey water heat recovery systems have been discredited because of a build up of grease etc on the exchangers.



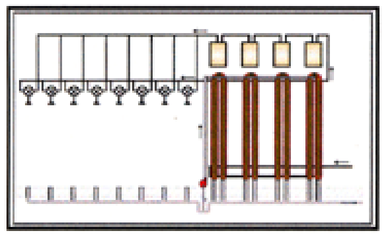
Sand Dollar Exchanger

Areas for Further Investigation

The way in which the sand dollar uses/creates/adapts its context to gain benefit (in this case through food) is one possible area of further investigation - in terms of the encouragement of flows of air or water, and the creation of induction forces that can draw air/water through a membrane.



Waterless Urinal Waste Trap



Shower Waste Heat Recovery

Case Study 6

Private Office

Dunning, Perthshire

General Description

The Office at Dunning designed by Gaia has walls that are unconventional but which work well for the indoor climate. The Straw bales which form the wall depth are covered in lime plaster both inside and out. The use of organic materials is always subject to potential attack from moisture, mould and vermin. (This is nevertheless, also true of inorganic buildings and often to an equally significant level of impact). Careful detailing is essential.

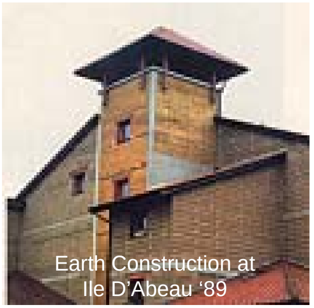
Principle Related to Animal Architecture
Earth & Straw Construction

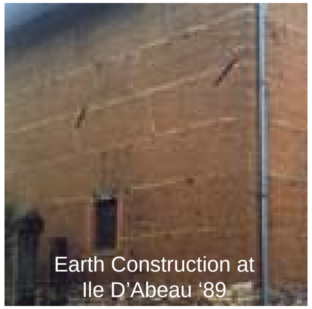
This building is sealed both sides with lime - the key property of which (as with earth) is its hygroscopic nature, which allows moisture to breathe out of the construction. The structure also has good heat retention properties.

Birds which use mud for an internal nest lining will also find it copes well with both moisture and heat.

Areas for Further Investigation

The way in which earth construction works and particularly cob (earth straw) is being re-investigated after a number of projects have revisited and reused this technique - not just in refurbishing old buildings (eg at Cottown) but also in new building (eg as at Ile d'Abeau).


Earth Construction at Ile D'Abeau '89


Earth Construction at Ile D'Abeau '89


Earth Construction at Cottown, Perthshire


Office at Dunning

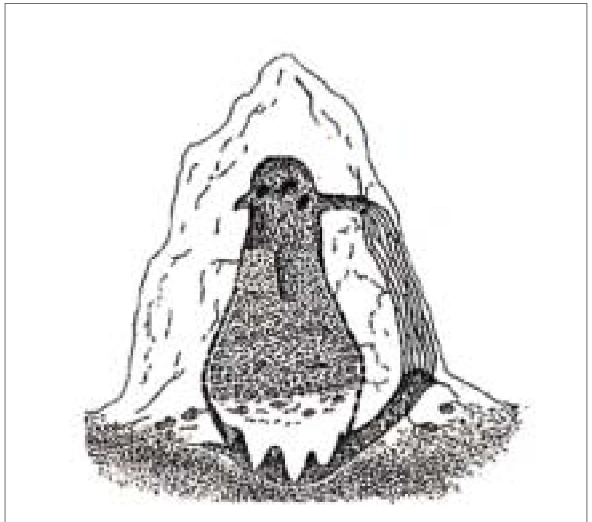

Nest from mud and straw

Case Study 7

McLaren Leisure Centre

Callander, Scotland


McLaren Leisure Centre


Termite Nest

General Description

The McLaren Leisure Centre is the largest example of the application of Dynamic Insulation worldwide. The diagram (below centre) shows the way in which there is an exchange of air and temperature in the ceiling. The system is also designed such that there is a tempering of the moisture in the indoor climate, which along with careful materials selection, makes for a contribution to the healthy indoor climate.

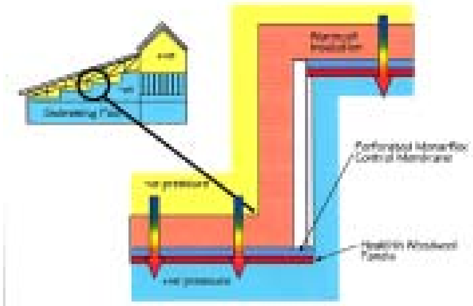
Principle Related to Animal Architecture
Pore Ventilation

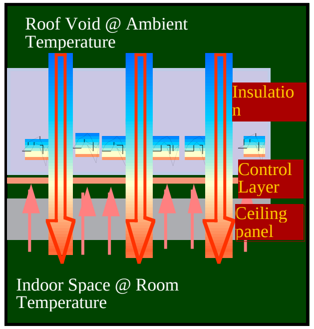
The principles related to Dynamic Insulation can be found in a number of Animal Architecture examples. Termite nests have a gas exchange at their external walls and also have an internal flow of air that helps modify the indoor climate. Both of these have a resonance in the principle applied in the McLaren Leisure Centre.

Areas for further Investigation

The current monitoring at McLaren has established that the moisture control filtering and energy benefits have all been demonstrated. The difficulty and expense of monitoring toxicity levels means that this aspect of the project remains as yet unproven. There is much to be gained from laboratory research in controlled conditions, and the human replication of termite nest membranes could be very fruitful area of further investigation.


McLaren Pool Ceiling


Section through ceiling



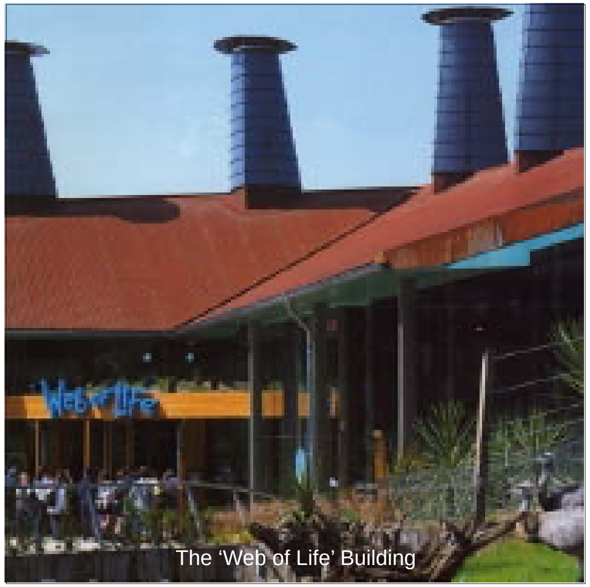
Case Study 8

The 'Web of Life' Building

London Zoo

General Description

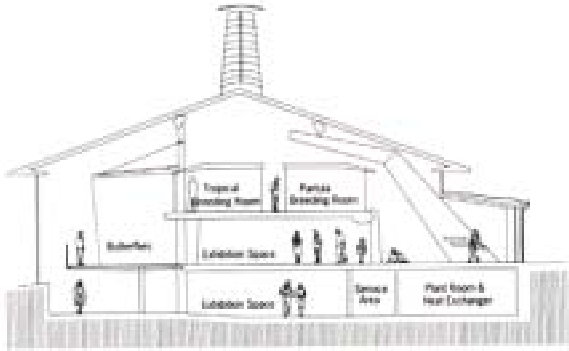
Designed on 'environmentally progressive' principles, the zoo building has relatively simple construction but sophistiacted methods of natural ventilation. A row of five ventilators along the ridge draws air out of the building. The height and volume of the ventilators and the position and shape of the cowls above were calculated to maximise stack effect. Inside each ventilator a pair of insulated flaps (designed like butterfly wings) open and close on motorised hinges.



The 'Web of Life' Building

Principle Related to Animal Architecture
Natural Ventilation

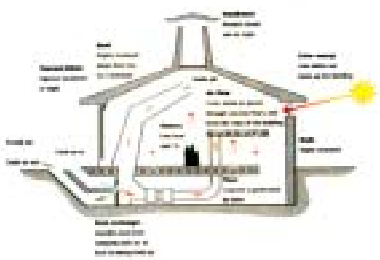
Similarities can be seen in the 'stack effect' method of natural ventilation utilised in the Web of Life building with the technique adopted in certain termite mounds. The shape of the mounds aid in creating this chimney effect to great advantage as in the Web of Life. Further complexities lie within the termite nest, however, given the suspected gas exchange which occurs the the wall memebrane.



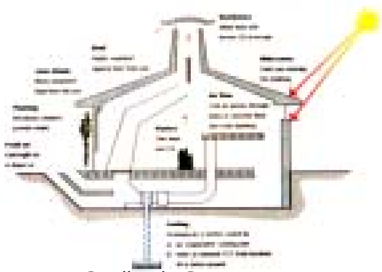
Short section along diagonal axis

Areas for further Investigation

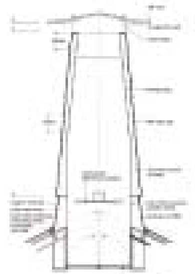
The extent to which natural ventilation can be controlled to give reasonably constant indoor climate conditions utilising as minimal technology as possible. In this case there are fairly sophisticated means of manipulating the air flows through dampers, heat exchangers and various duct routes.



Heating in Winter

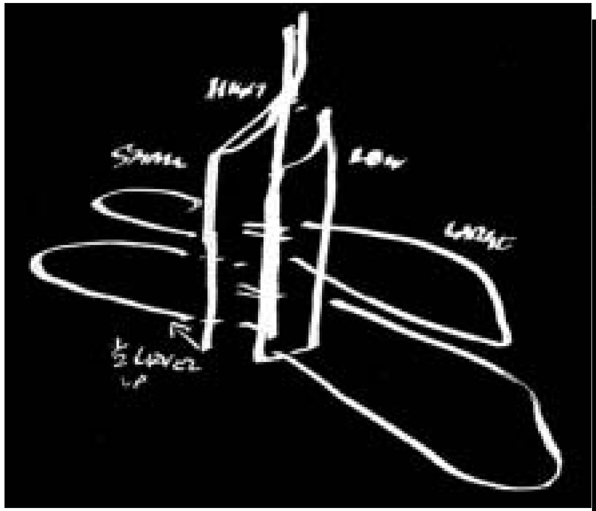


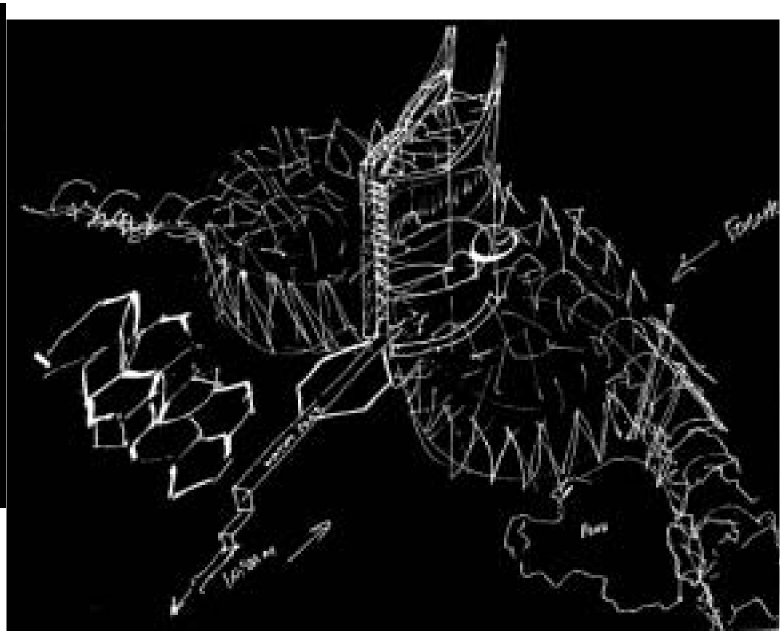
Cooling in Summer



Detail section of vent

A Proposed
Animal Architecture Centre
for Edinburgh Zoo





Introduction

Building Location

The proposed site locates the building at the very top of Corstorphine Hill, giving way to spectacular views across the Pentlands, to Edinburgh and out towards Glasgow. With a slight incline to the south there is potential for taking advantage of solar gain possibilities. At the moment the building can be approached by footpaths either from the east or west, however as part of a proposed re-masterplanning of the Zoo a monorail system may be introduced which would take visitors directly to the site.

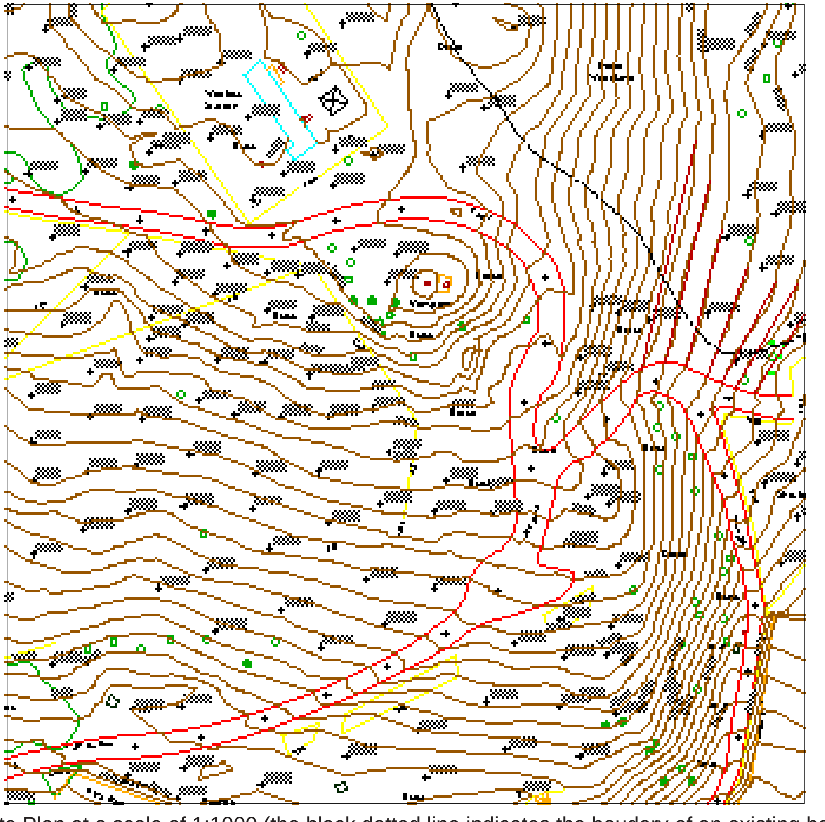


Fig 6.1 - Site Plan at a scale of 1:1000 (the black dotted line indicates the boudary of an existing badger sett)

Schedule of Accommodation

The building consists of four levels each dedicated to four main areas of interest.

Level 1: Exhibition Space 1
Monorail Station
Lifts
Ramp up to Milling Space

Level 2: Exhibition Space 2
Main Entrance
Reception/Milling Space
Lifts
Ramp up to Cafe, ramp down to Exhibition Space 1

Level 3: Cafe
Kitchen/Servery
Service/Secondary Entrance
Lifts
Ramp up to to Restaurant & WC's, ramp down to Exhibition Space 2

Level 4: Restaurant
Male, Female, and Disabled WC's
Lifts
Ramp down to Cafe

Fig 6.2 - View towards the proposed site at the top of the hill

Fig 6.3 - The existing viewpoint marks the spot where most ideal views can be gained

Fig 6.4 - Panoramic view acquired from the top of Corstorphine Hill

Morphology

Spatial Arrangement

Exhibition spaces and eating spaces are located either side of a multi-functional central core which provides structural, climatic and natural lighting functions in addition to acting as a general milling space, entry point and cross over area between levels.

Two wings of exhibition spaces are located in the lower, darker areas of the building. It is intended that visitors will primarily enter these spaces via the monorail system on the lowest level, and progress up through the building via a series of perimeter ramps, or by glazed hexagonal shaped lifts located in the central atrium space. By containing the exhibition spaces in these darker spaces a degree of flexibility can be achieved in controlling light levels and room temperature levels in order to create the desired atmosphere.

Both cafe and restaurant spaces are intended to be, by direct contrast, light and open spaces and are located in the upper parts of the building to take advantage of the unique views on offer.

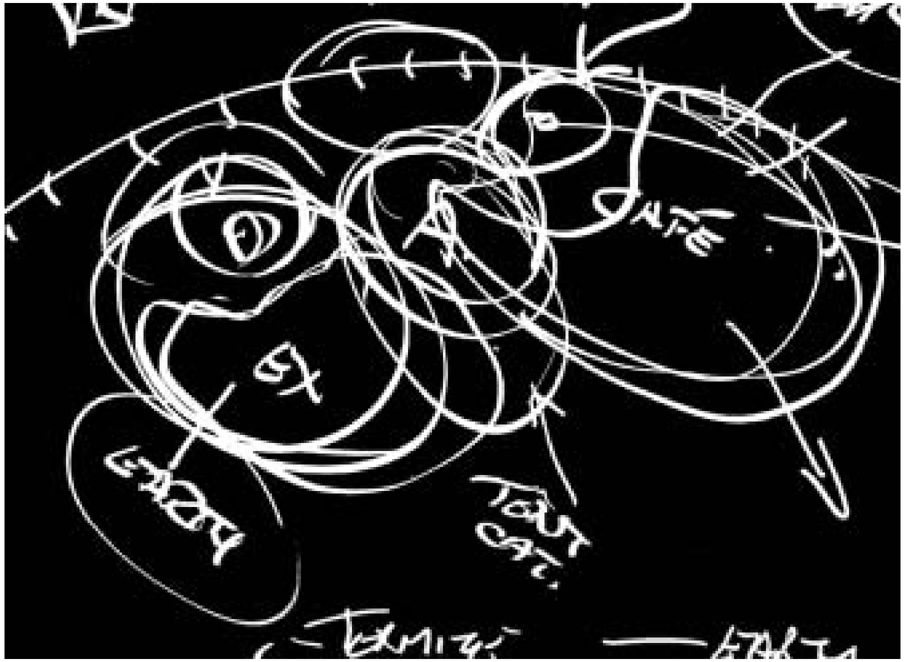


Fig 6.5 - Conceptual plan showing 'two wing' arrangement about the atrium in the middle. The monorail wraps around the back of a building through the station which is connected to the atrium.

Access & Circulation

The building can be accessed by one of three ways. Direct entry to the exhibition spaces by the monorail system, located on Level 1, or alternatively by foot via the main foyer space on Level 2, entering from the front of the building. From there visitors may go down into the larger exhibition space or next door into a smaller exhibition space.

Direct access to the two eating spaces can be reached by a secondary foot entrance on Level 3, also intended for use as a service entrance for delivering goods. This allows the building to be approached either by foot or more quickly and directly via the proposed monorail system.

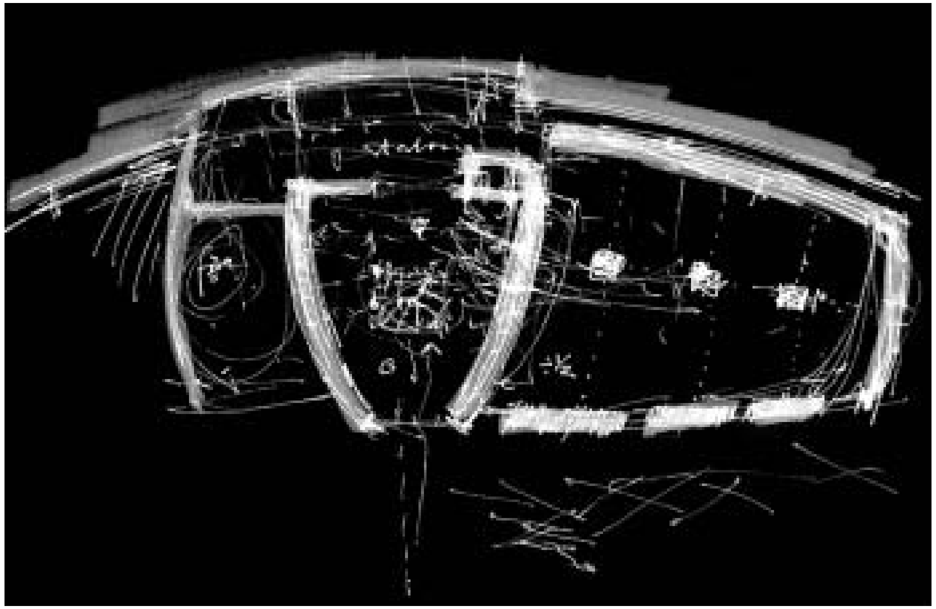


Fig. 6.6 - Early sketch plan showing smaller exhibition wing on the right and monorail station located behind the central circulation space.

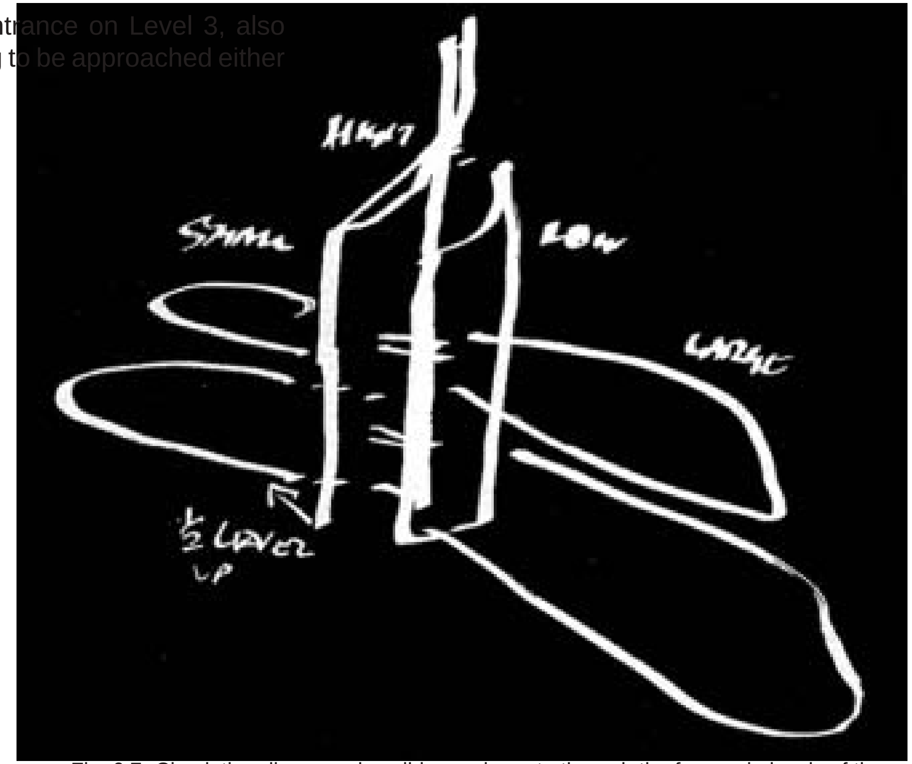


Fig. 6.7- Circulation diagram describing main route through the four main levels of the building via curved ramps. The massing arrangement was later reversed so that the larger spaces are located on the west side of the building.

Central Core

A prominent feature of the design is the large earth tower, located in the centre of the building. The tower acts in a number of ways to help serve the building.

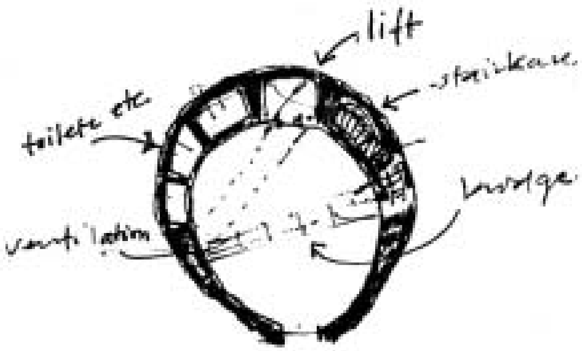


Fig. 6.8 - Alternative to design of the termite inspired central core with the services, including lifts, stairs, and toilets located within the mass of the earth walls.

Visual Marker & Entrance/Milling Space

The tower acts as a visual marker for the building and accentuates its position at the highest point within the Zoo. It also marks two entrances, one at the front and one at the rear of the building, on two different levels. Similarities can be seen in the nest entrance of the Trigona (Partamona) testacea (fig 6.11), whose funnel shaped entrance allows access in and out of the nest.

The core also acts as a cross-over point, connecting the various levels of the building at a central point.

Natural Ventilation

The material and form of the tower is derived from the earth nests of the Macrotermes termites, who build their nests in a similar shape primarily to aid in controlling the internal environment. The design of the central tower aims to mimic this effect in aiding the natural ventilation of the building.

Atrium

A large atrium space is created within the centre of the tower allowing natural light to be brought to all levels.

Service Containment

Alternative designs show the tower as two separate elements and as a single connected funnel. Both allow for service runs to be housed within the earth walls and lift shafts within the space, while the latter design also accommodates the lift, toilets and stairs within the walls themselves. This could perhaps aid with absorbing moisture more directly from the wet areas in addition to keeping all services, including horizontal circulation, within a central area.

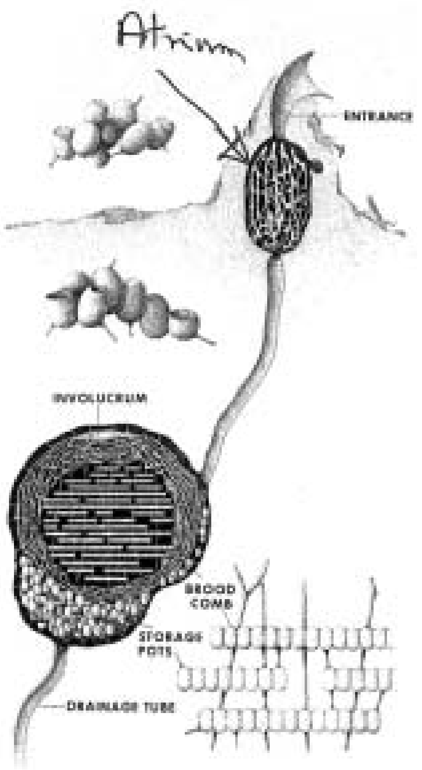


Fig. 6.9 - Atrium entrance of the nest of the tropical stingless bee Trigona (Partamona) testacea connected to the brood comb deeper underground via a tunnel.

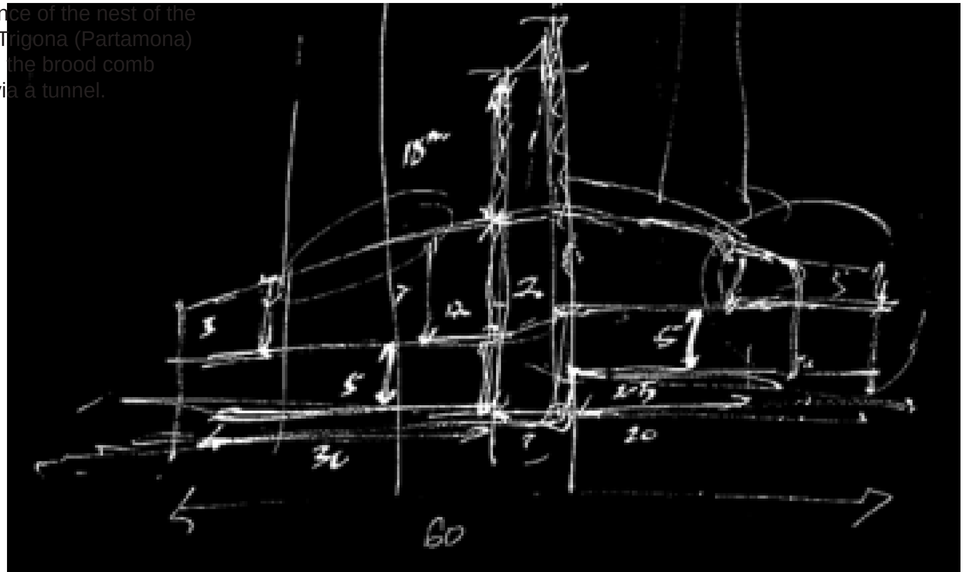


Fig. 6.10 - Long section through the building locating the central tower and indicating proportions of scale.

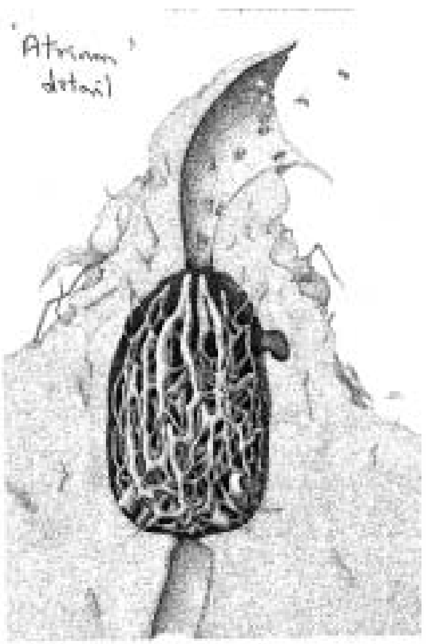


Fig. 6.11 - Detail of the nest entrance of Trigona (Partamona) testacea, showing funnel-shaped entrance and cavity within, in which anastomising rods presumably provide resting space of the defence force of the colony.

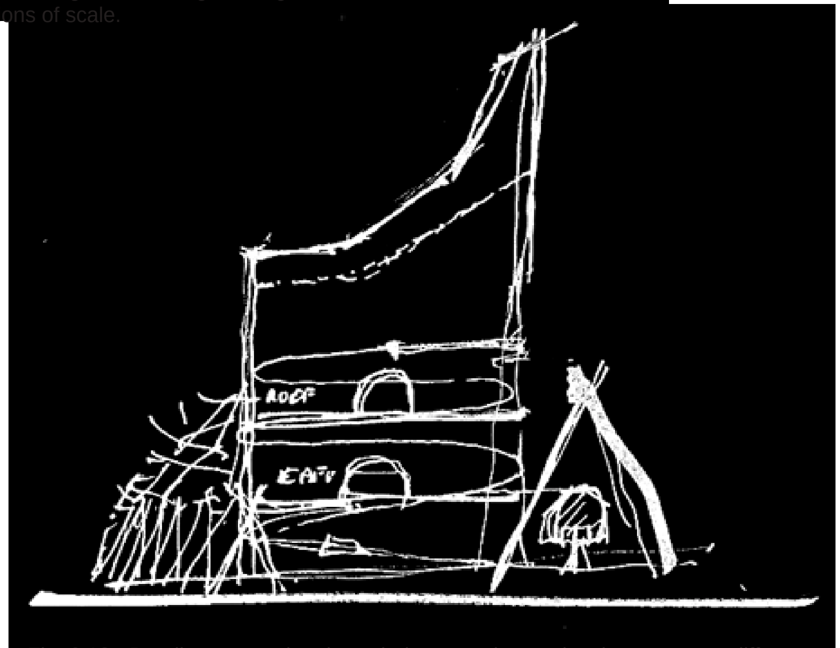


Fig. 6.12 - Detail cross section through the central core showing access to different levels and monorail station at the back.

Day & Night Use

The Centre is intended for use both during the day, as an exhibition space, cafe and conference facility, and at night as a quality dining restaurant facility. Panoramic views from the top of the hill give added incentive to make the journey to the top, both during the day and at night. Due to foliage and natural cover further down the hill it is only at this highest point that the views can be fully appreciated.

An underground station within the building is proposed as a half way stop for an intended monorail system which would take visitors around the Zoo. This gives the added advantage of allowing the building to be directly accessed at night time, after the rest of the Zoo has closed to the public, while keeping the rest of the Zoo secure.

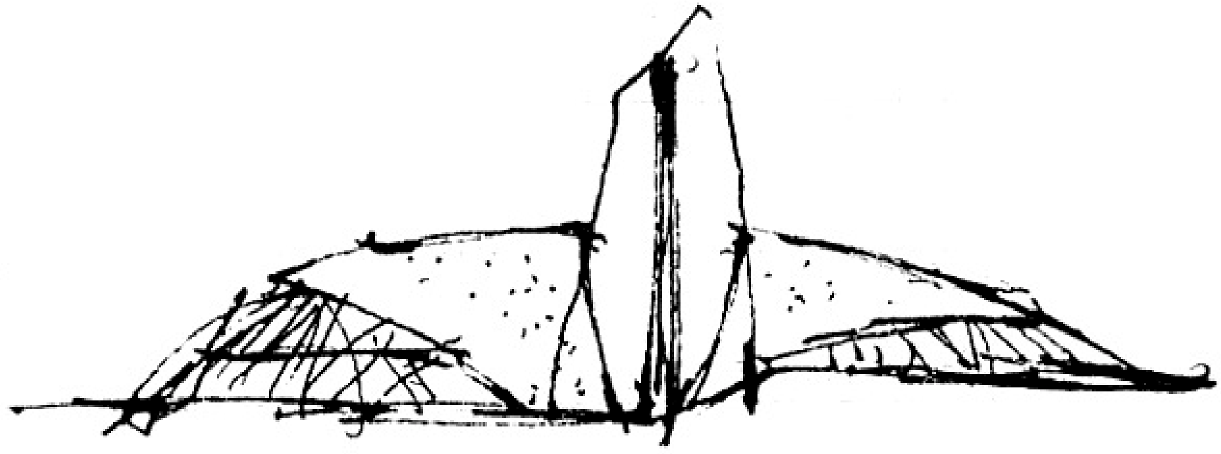


Fig. 6.13 - Sketch elevation of how the building might look. The main entrance is located at the foot of the central tower giving access to both lower and upper floor of both wings. Breaks in the external fabric of the shell allow views out of the building at key points.

Ancillary Provision

A kitchen is provided on the third level adjacent to the cafe space which will serve customers in both the Cafe and Restaurant spaces. It is assumed that the Cafe space will primarily be in operation during the day, serving light snacks and refreshments from a service counter, with the restaurant space located on the adjacent floor above reserved primarily for evening a la carte meals.

Male, Female and Disabled WC's are located directly above the kitchen serving the immediate cafe and restaurant spaces and the remainder of the building. A further set of WC's may be located below serving the exhibition spaces.

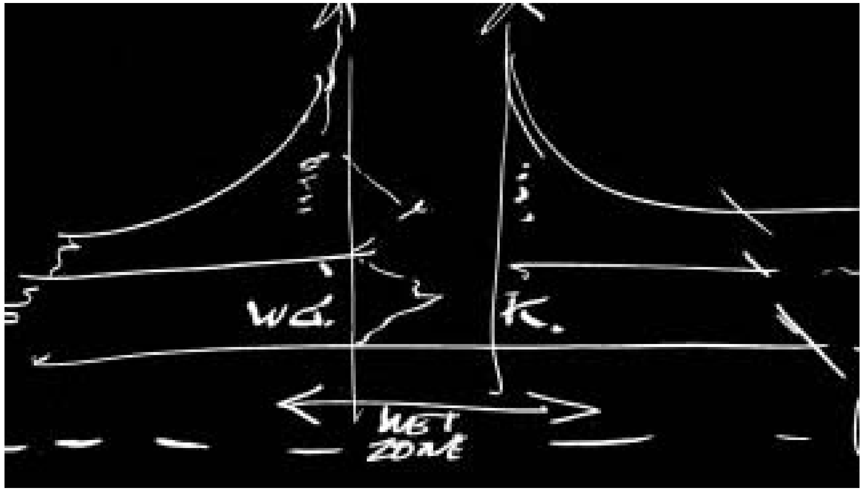


Fig. 6.14 - 'Wet' areas of the building are located next to or within the earth walls of the central core establishing a 'wet zone'. The built-in ducts within the walls allow for efficient ventilation while the walls themselves aid in absorbing and de-sorbing moisture built up in the air.

Fig. 6.15 - Early sketch section showing possible arrangement of eating and exhibition spaces stacked on top of one another. This design included outdoor terraces to the restaurant and cafe .

Structure & Materials

The overriding form of the building results from a combination of a number of factors based on animal architectural principles including circulation and spatial requirements, ideas for natural ventilation, lighting, heating, structural systems and choice of building materials. Five main principles have been highlighted as possible indicators in the creation of the building's structure, materials and its resulting form.

Birds' Nest

Fig. 6.16 - Piece of wooden sculpture by Andy Goldsworthy who uses interlocked pieces of branch in forming a ‘nest’ type structure, similar in process and appearance to that of a bird’s nest.

A lightweight roof structure, based on the nests of various bird species, sits over either wing of the building forming a lightweight outer shell. By interlocking together short spans of timber or recycled hollow cardboard tubes-layer upon layer - it is intended that a structure incorporating principles found in birds nests will be achieved.

This method of roof construction offers a number of advantages and new opportunities. By utilising short lengths of material, large spans can be produced where perhaps only smaller ones were thought possible, giving way to large uninterrupted spaces. Its lightweight structure would also reduce the need for foundations while the construction elements and the shell, to some extent, retain a degree of portability.

Like some birds nests it is intended that the surface of this shell, whether internally or externally, be lined with natural materials, such as earth and moss, while much of the inner layer be left uncovered to display the roof structure to the spaces below.

Fig. 6.17 - Nest of the village weaverbird Ploceus cucullatus, showing both the outer basket-work and the section through both middle rooting layer and the inner lining of fine grassheads.

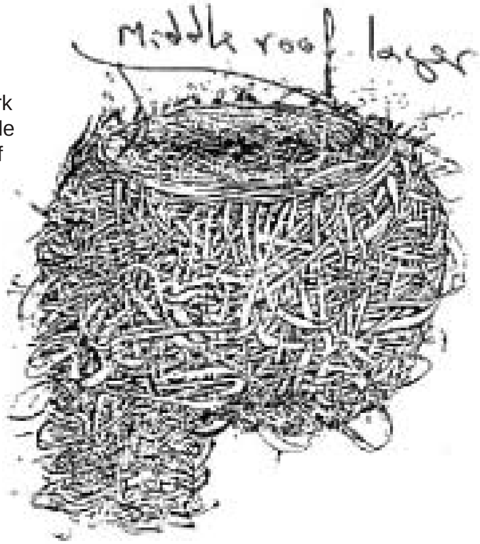
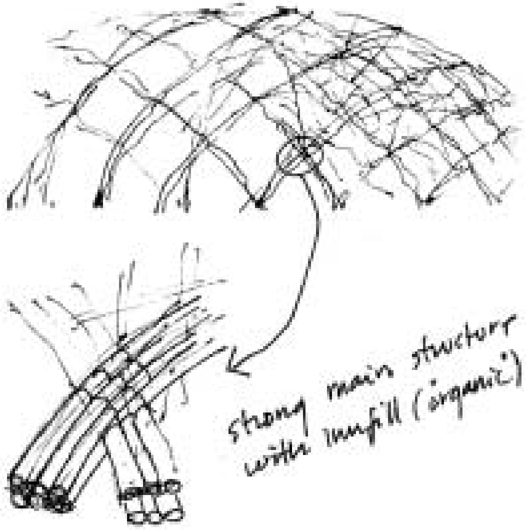


Fig. 6.18 - Sketch showing how a frame work structure might be constructed using hollow tubes, lashed together. Like the weaver bird's nest, additional layers could then be added in order to build up an external skin.



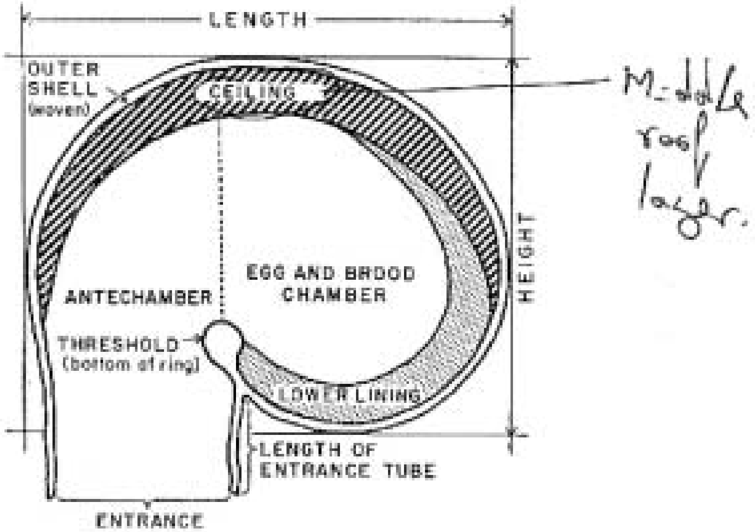


Fig. 6.19 - Ploceus cullatus. Longitudinal section through the nest of a village weaverbird. The lined ceiling prevents the egg chamber being penetrated by heavy rain showers. This inner lining is made up of short, wide strips of grass, broad leaves, and pieces of fern, etc. A special layer of dead leaves may also be incorporated into the fabric.

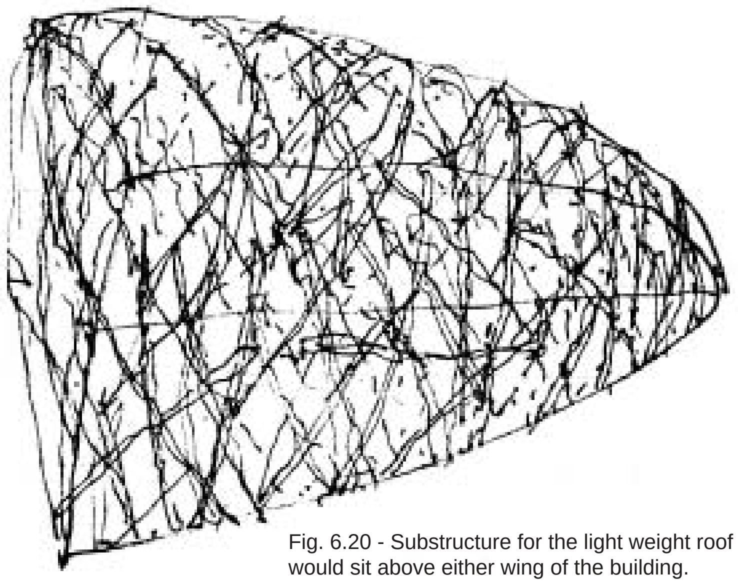


Fig. 6.20 - Substructure for the light weight roof which would sit above either wing of the building.

Termite Mound

Analysis of termite nests shows how earth can be used successfully to create a self supporting structure with integrated environmental and thermal controls. The advantages of using earth as opposed to other more widely accepted materials such as concrete are clear. It is a non-toxic material, with far less embodied energy, which may be locally sourced. We know that the inherent properties found in the types of soil selected by termites play an integral part in the nest's climatic control, allowing gas to be exchanged through its surface, in aiding thermal and ventilation control, and in absorbing and desorbing moisture from the internal spaces.

With these properties in mind, earth would seem an ideal material for use in several key parts of the building:

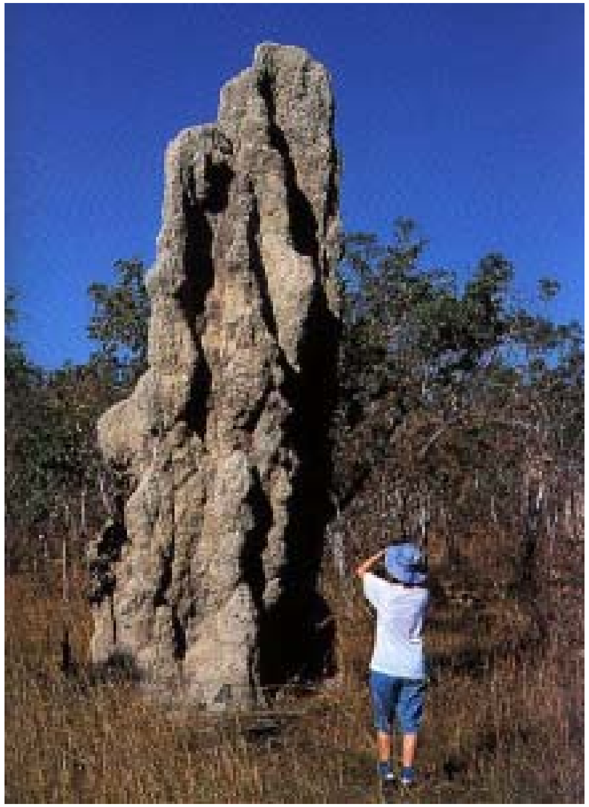


Fig. 6.21 - A large mound of the Australian termites Amitermes which may reach up to 6.7 metres tall.

Earth walls to Circulation Core

A large earth tower, mimicking the nest of the Macrotermes termite, is placed within the central core of the building. In addition to providing structural support to the floors at their points of attachment its thick walls act as part of the building's ventilation and moisture control. To achieve the required stack effect the tower will need to be of a sufficient height. Currently the highest earth walls in existence measure approx. 7 metres. Building higher would offer some interesting structural and practical challenges, for instance in its reinforcement, and in the method of construction itself.

Further comparisons can be drawn to the way in which the duckbilled platypus constructs and stabilises the walls of its home by compacting earth into the walls to stabilise its burrows, similar in principle to the construction of rammed earth walls. (M H Hansell, The Animal Construction Company)

Fig. 6.22 - Sketch showing how the earth walls may perform in providing gas exchange aided by passive ventilation.

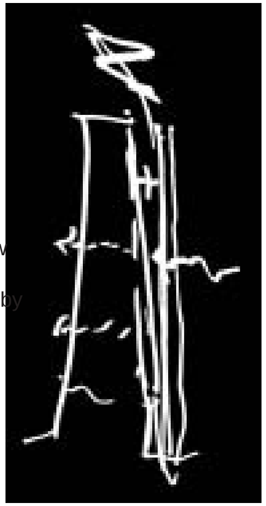
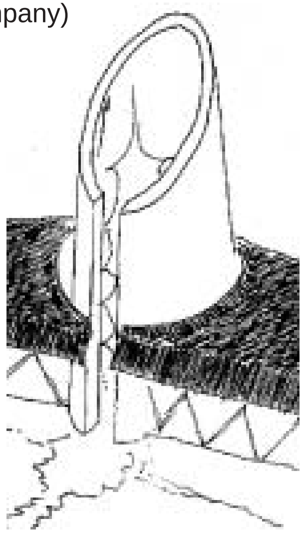


Fig. 6.23 - Centrally placed this rammed earth cone shaped tower could provide interesting challenges, pushing existing boundaries for earth wall construction.



Vaulted Earth Columns to Exhibition Spaces

Other species of termites build earth vaulted structures, joined together to form arches. This principle has been adopted in creating the vaulted structures throughout the exhibition spaces which support the floors of the café and restaurant above. Columns could be constructed either by a similar method to the walls with rammed earth or by building with earth bricks.

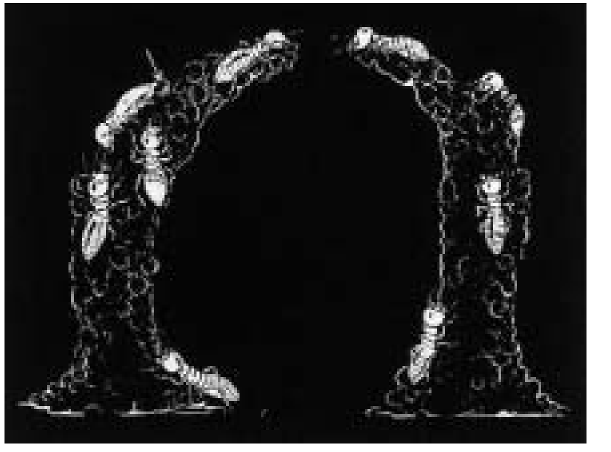


Fig. 6.24 - Macrotermes natalensis building an arch, the two halves of which are about to be joined. The building material consists of soil particles and droplets of excrement, possibly substituted with natural glues in human scale.

Compacted Earth Floors & Walls to Exhibition Spaces

The building is designed in such a way that the north sides of the exhibition spaces are submerged below ground level, with the south walls more exposed. This maximises opportunities for solar gain while exploiting the earth's inherent ability to act as thermal mass, aiding the passive control of the environment.

There is a natural link between the earth used in the vaulted columns and the compressed earth used in the floors above and below which suggests a possible overlap, not only in materials but also in appearance. It may be appropriate for a more vernacular approach to be considered in the construction of these areas, rather than a typical 'blueprint' approach, lending itself to an element of 'self-build'.

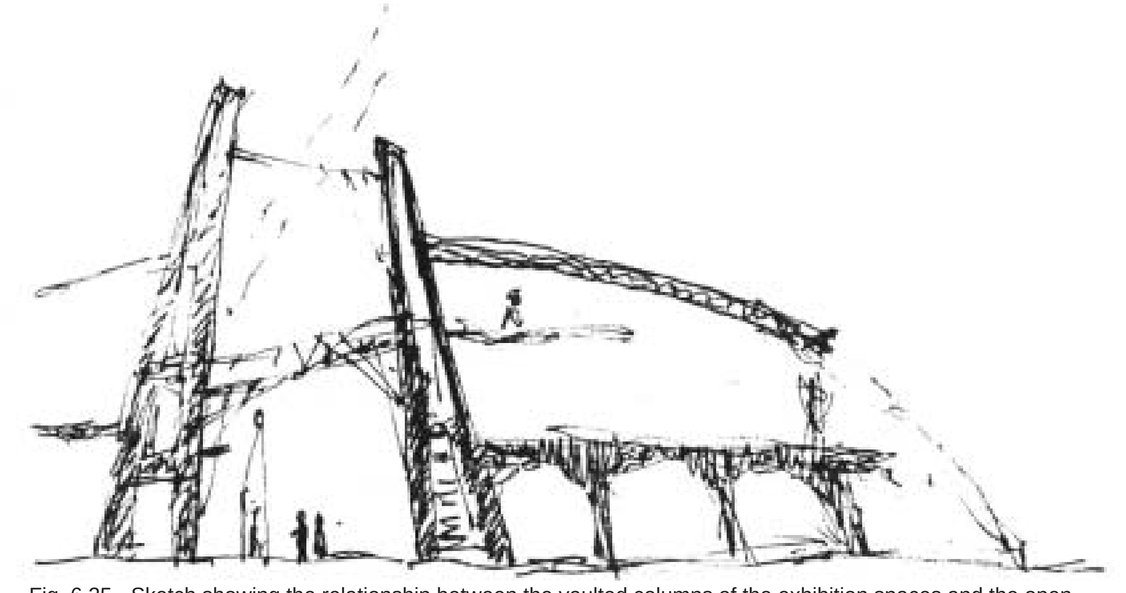


Fig. 6.25 - Sketch showing the relationship between the vaulted columns of the exhibition spaces and the open plan eating spaces above.

Honeycomb

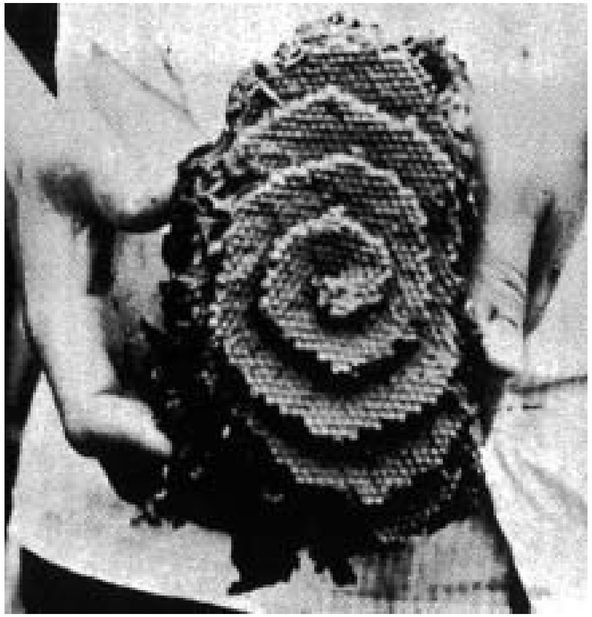


Fig. 6.26 - The spiralling ramp of the Trigona (Oxytrigona) tataira, bee brood comb

The inherent geometry found in the cells of bee and wasp honeycombs is clearly something that can be employed in a number of ways within the building, as it is already in many buildings today. The strength of these structures in relation to the amount of material used lends itself to the efficient generation of flat, horizontal planes in addition to three-dimensional structures.

Floor

The floor structure to the main foyer space and upper balcony spaces within the circulation core is made up of a repeating hexagonal pattern to form a stiff, light horizontal framework in which panels can be filled, in this case with glass or a similar translucent material. As a great deal of weight would be experienced on these floors the depth and type of material used to make up the grid structure would have to be taken into consideration. It is likely that, in order to achieve the desired strength, metal may be required. At different points around the space individual hexagons can be extruded vertically to create shelves, podiums, a reception desk or lift shafts.

Roof

The domed roof over the circulation space could also be created from hexagons with a mixture of pentagons in order to give it a three-dimensional form. As lighter load requirements would be needed the structural elements could be possibly made from recycled cardboard, or timber. The panels would be in-filled with glazing to allow a maximum of natural light into the space.

Circulation Ramps

Some species of wasps create three-dimensional spiralling forms with their honeycombs and a similar method could be used in the construction of the ramps around the perimeter of the building, particularly in the 'light weight' upper eating spaces of the building.

Spider's Web

The main structural interest of the spiders web is in its inherent elasticity, in its ability to take up an irregular form, and in its jointing mechanisms. It is proposed that within the Animal Architecture Building the web's built in redundancy could be used to generate a vertical framework from which to suspend glazing or translucent fabric. This would be most likely located at the front of the building down the centre of the circulation space. It is possible that the web's elasticity and flexibility may be incompatible with fixed glazing. It has very elastic capture threads intended to take the force of collision but less extensible frame and radii threads. Webs do have great strength, lightness and ingenious pad like attachments which, when fully understood, could lead to the development of new types of lightweight economic structures and fixing methods.

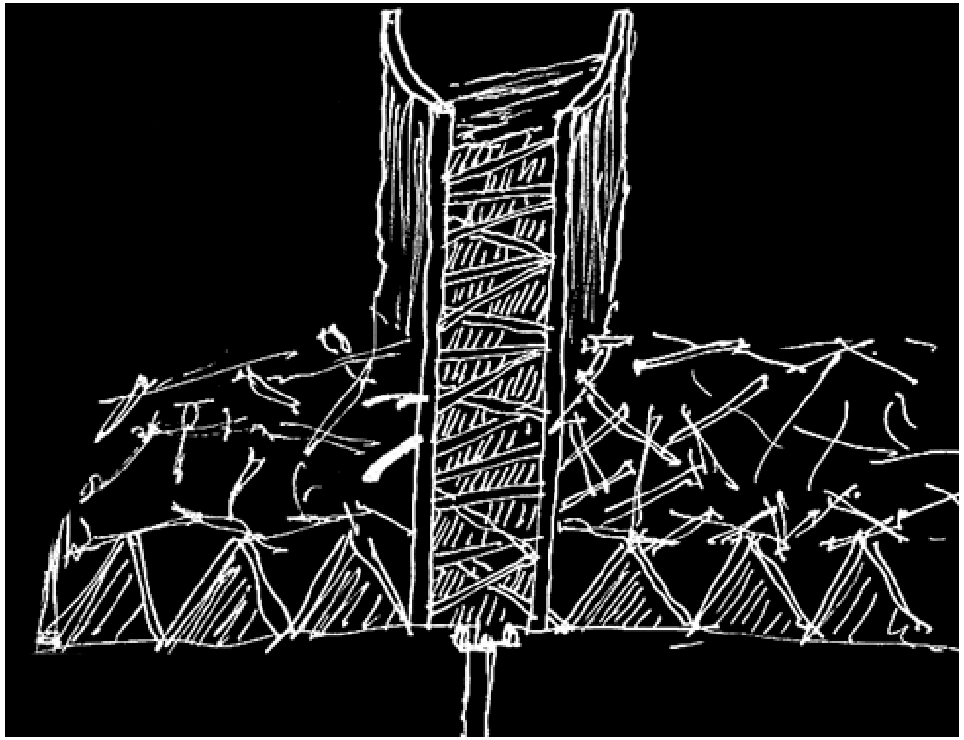


Fig. 6.27 - Sketch elevation with 'web' supported glazing suspended from the edges of the tower walls.

Fig. 6.28 - The silk orb web of a garden spider Araneus suggests a flexible vertical framework which could provide a stable support structure while absorbing movement.

Tent Caterpillar

Fig. 6.30 - Communal silk tent of the Eastern Tent Caterpillar

Elements found in the free formed translucent tension web created by the tent caterpillar could be applied to the building wherever a constant quality of light is required without necessarily providing views in or out of the building. A three-dimensional structure in tension could perhaps be suspended in the central atrium space to diffuse glare from direct light entering from above. Literal translation of materials would utilise silk for the translucent membrane thought it may be possible to substitute this with some form of coated paper.

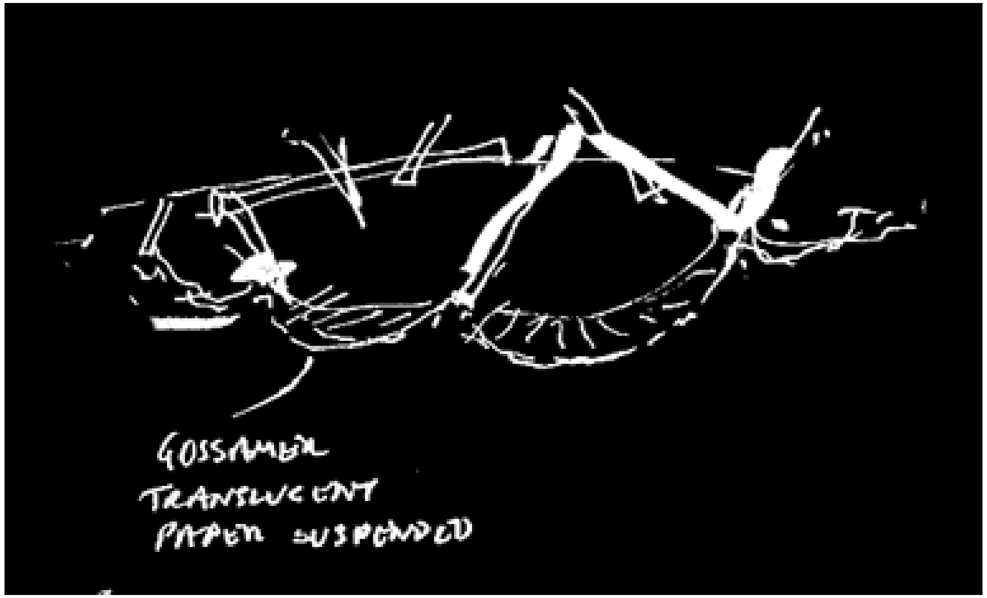
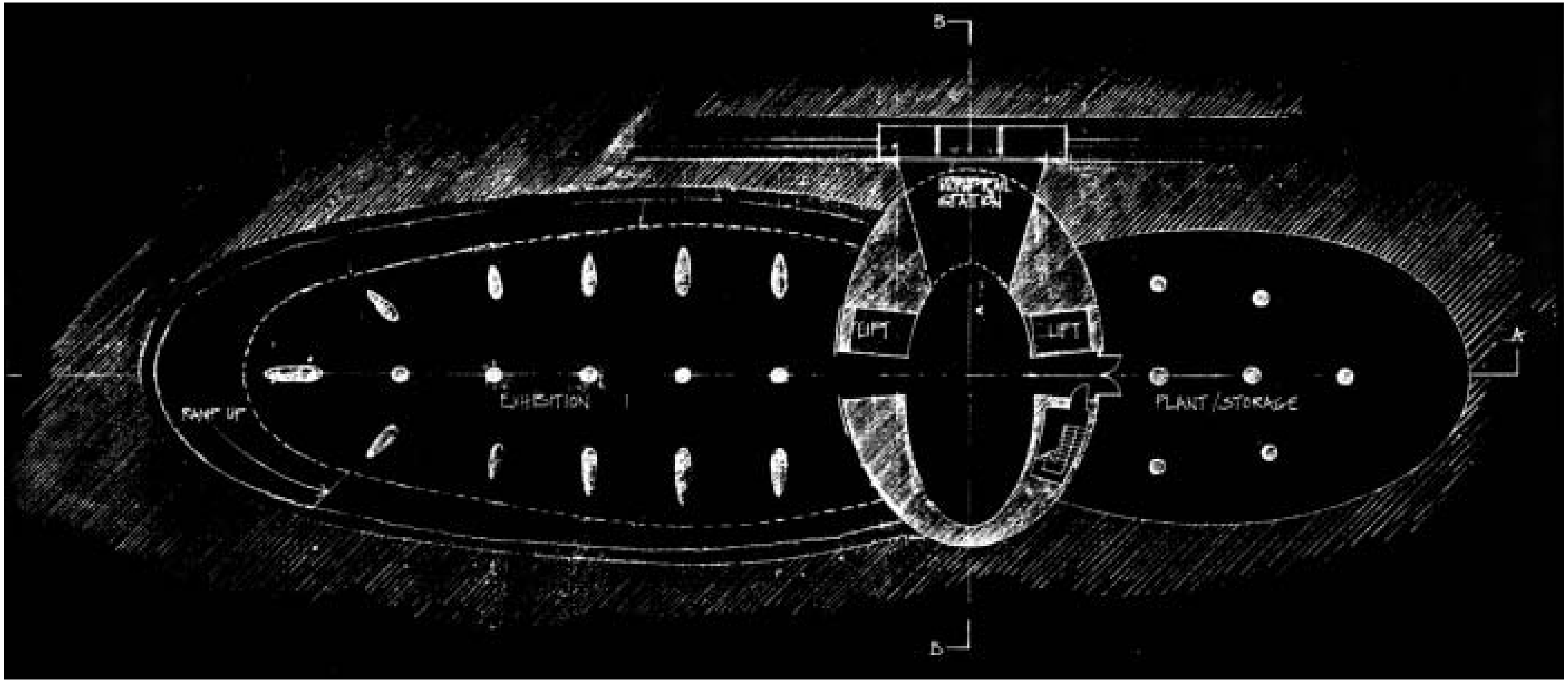


Fig. 6.29 - Suspended membrane made from translucent paper hung from the internal framework of the weaved roof structure.

Design Development

Basement: Level 1



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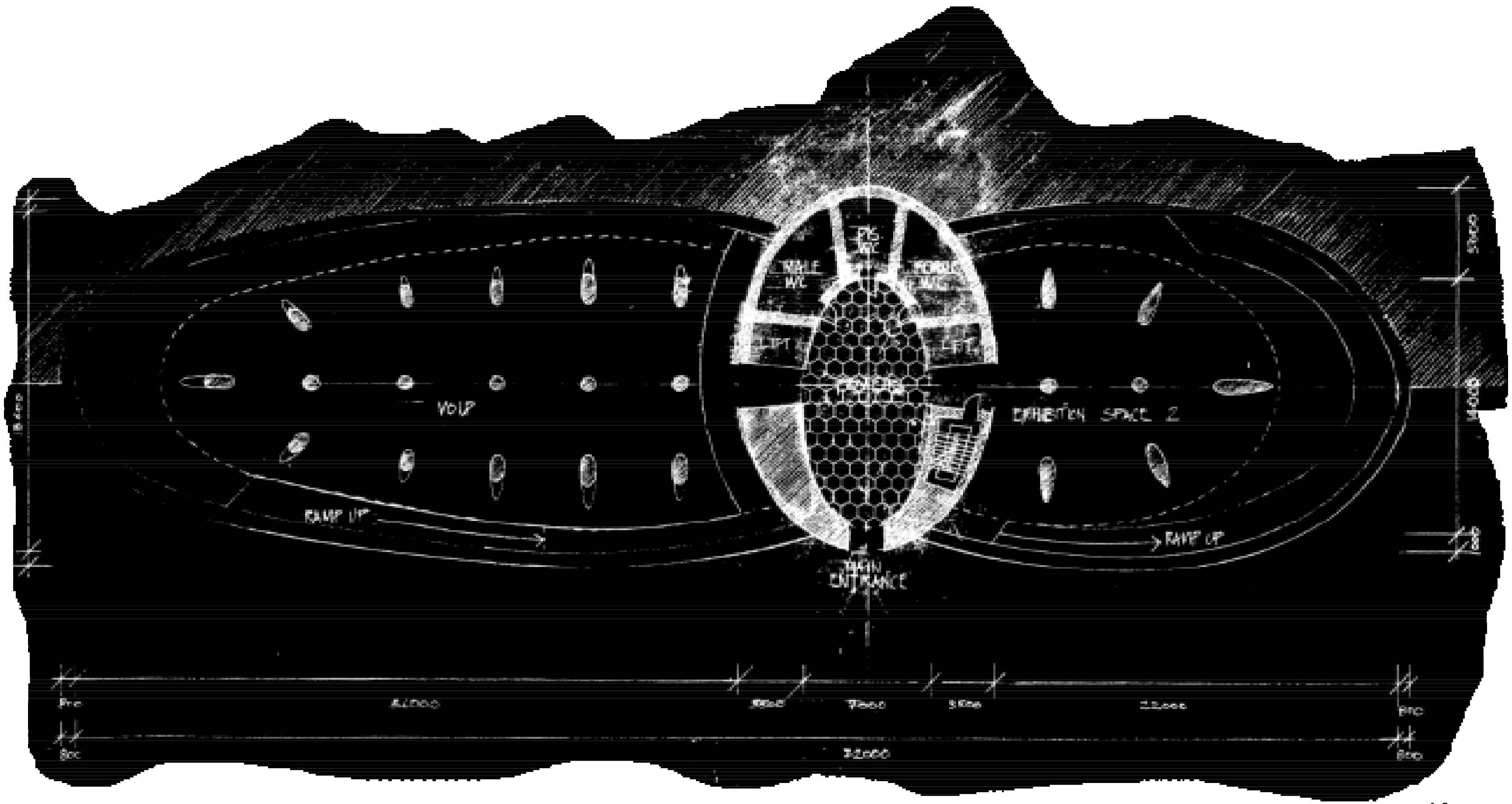
Ground Floor: Level 2



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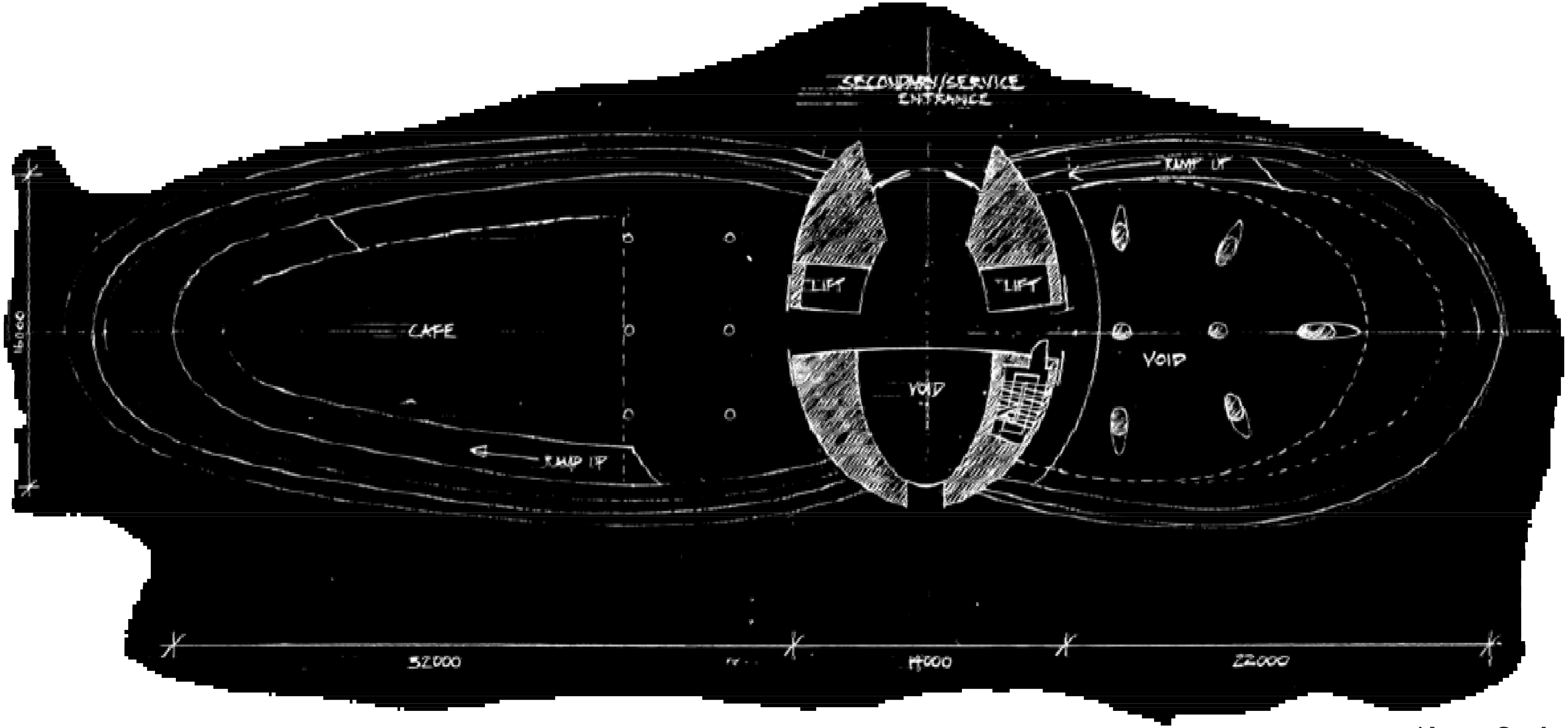
Café: Level 3



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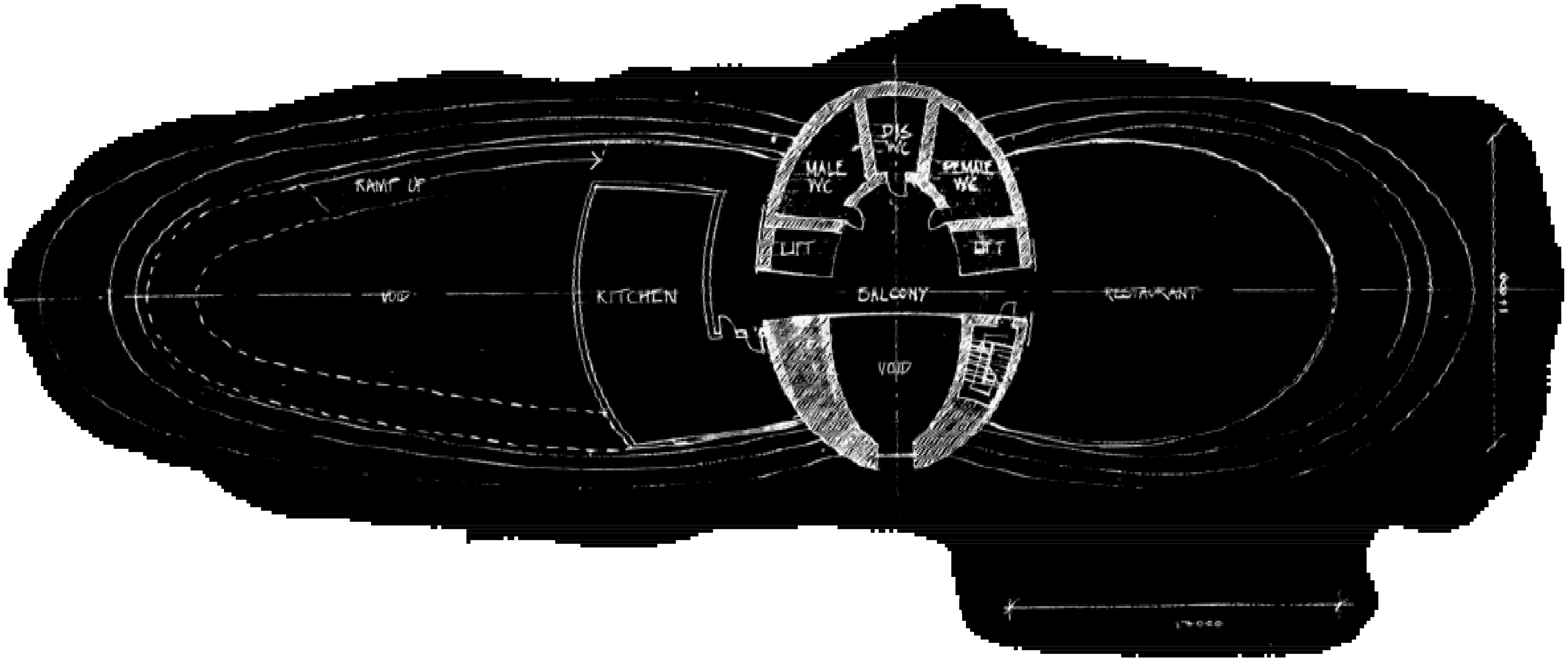
Restaurant: Level 4



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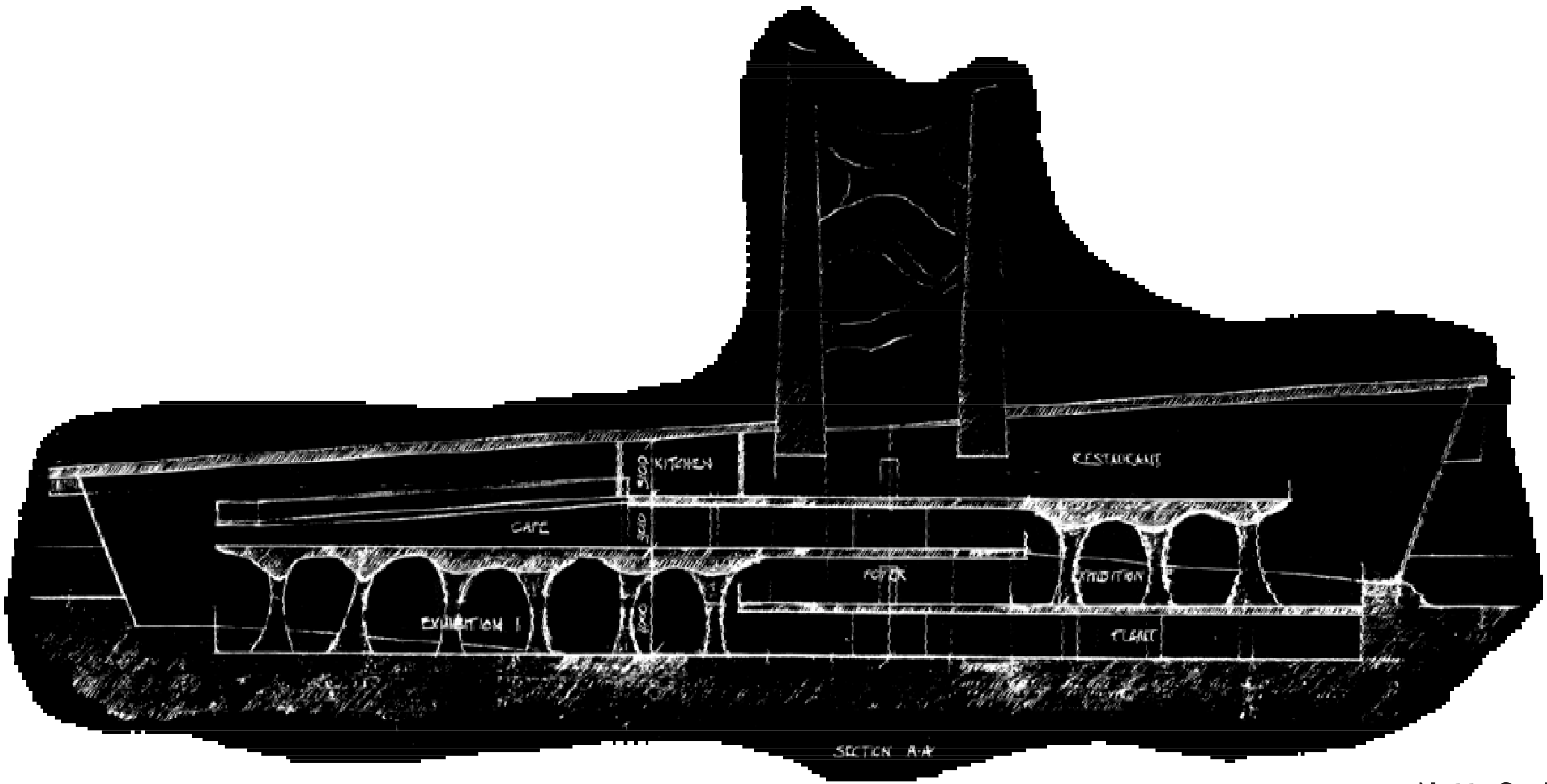
Long Section



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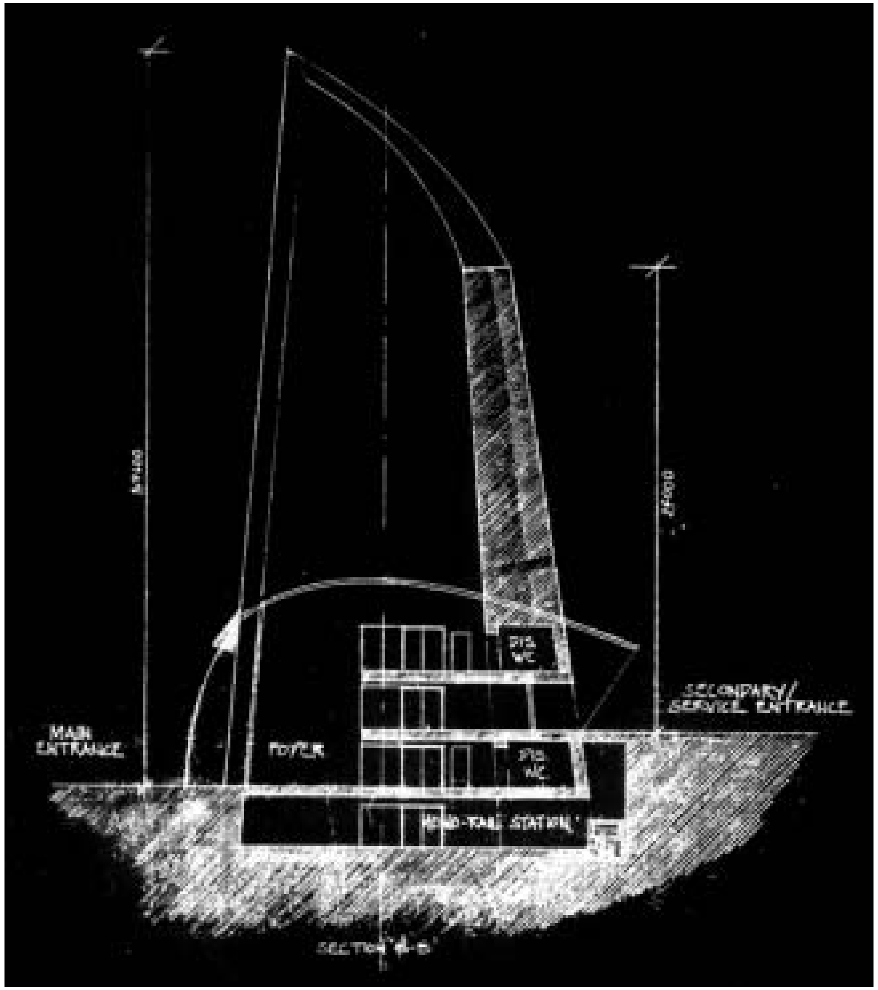
Cross Section



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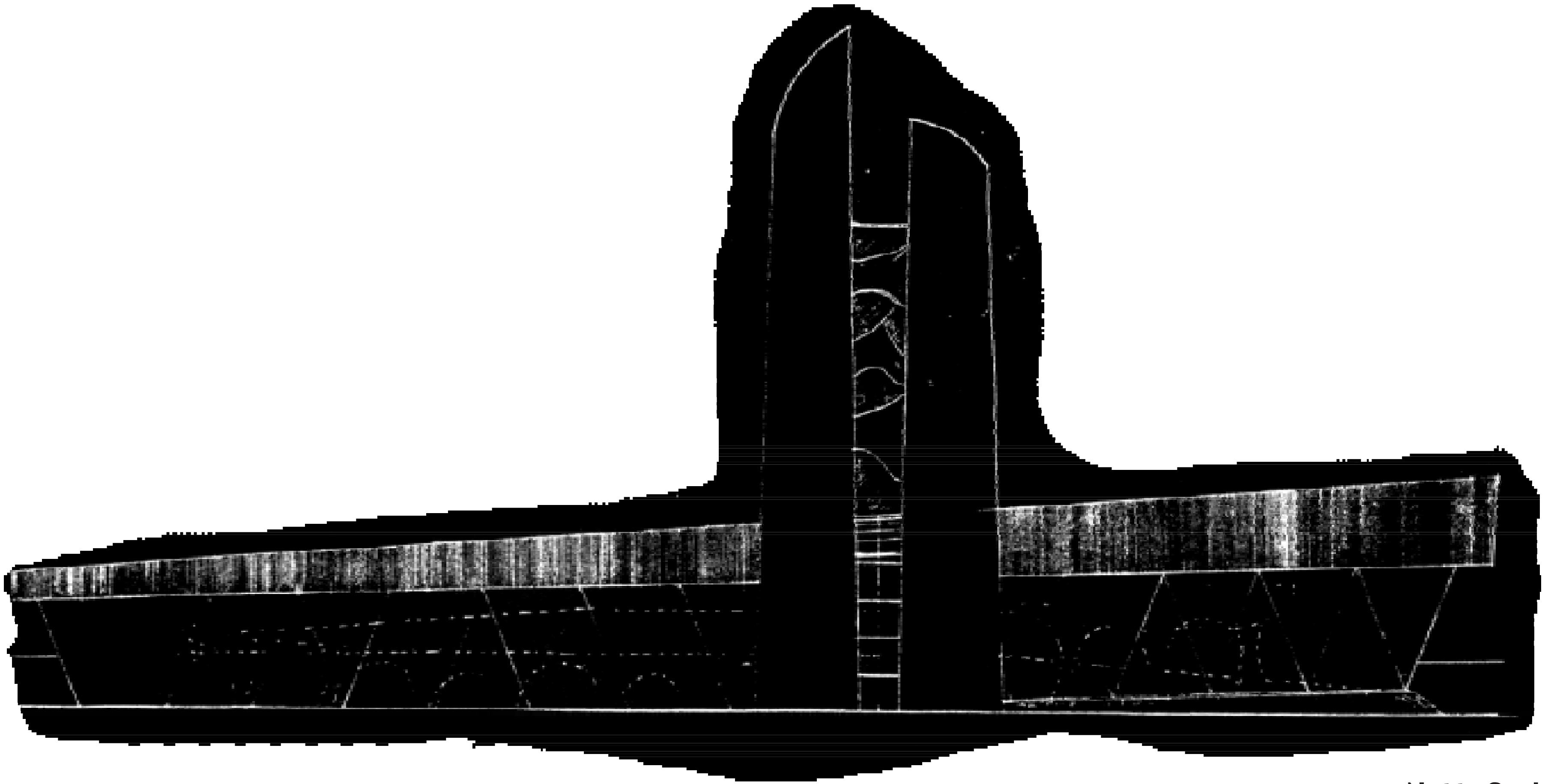
Front Elevation



Not to Scale

Proposed Animal Architecture Centre

Credits

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Images

- Fig 6.1, Gary Wilson, Edinburgh Zoo
- Fig 6.9, Fig 6.11, Michener C D
- Fig 6.16, Goldsworthy A
- Fig 6.17, Fig 6.19, Collias N E & Collias E C
- Fig 6.21, Hansell M H
- Fig 6.24, von Frisch K
- Fig 6.26, Michener, C.D.
- Fig 6.28, Hansell M H
- Fig 6.30, Hansell M H
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Servicing Strategies

Introduction

This chapter highlights the concepts proposed for servicing the Animal Architecture building, provides some thoughts on the principles involved and discusses those aspects which have no direct Animal Architecture corollary.

Summary of Main Concepts

Concepts that mimic animal architecture:

- Termite towers provide stack ventilation and thermal massing.
- Atrium as an assembly place, solar gain opportunity and for additional stack effect.
- Earth construction to pillars, towers and walls to allow moisture control.
- Orientation of entire building to aid ventilation and solar gain.
- Composting as a source of heat and farming nutrients.
- Shaping of the side building pods to facilitate Bernoulli effect.
- Provision of underground tunnels and catacombs for tempering of ventilation air and for a source of air to the stacks.
- Shallow and wide plan to assist cross ventilation .
- Daylighting to give a pleasant environment and save on artificial lighting requirements .
- Hollow core floor slabs and walls for ventilation paths and air tempering.
- Waste water treatment and filtration by reed beds, where there is no AA corollary and composting, where there are many.
- Optimise natural circulation for ventilation and water supplies.
- Transient heat and moisture loading by visitors and staff.

Additional Requirements

The areas which appear unresolvable using animal architecture principles directly include:

- Providing adequate ventilation for kitchens.
- Cooking methods and construction of kitchens.
- Lighting of exhibitions, underground areas and operation after dark.
- Clean drinking water provision.
- Heating of domestic hot water.
- Pressurisation of water supply.
- Electricity for plant, lighting and IT.
- Transport propulsion methods (monorail, lifts, deliveries).

Each of these may have corollaries with the wider fields of biomimicry and would be worth investigating.

Main Concepts

Termite Towers

The proposed twin (or single, hollow) termite towers are envisaged to perform at least three main roles:

- Structural supports for adjoining floors.
- Provide thermal massing and moisture control.
- To contain internal ventilation stacks and service ducts.

All these principles are related to the performance of termite nests. Fig. 7.1 shows a cross-section through the Cornitermes bequaerti termite nest and Fig. 7.2 shows an exterior picture of the nest. The ventilation system works by using the height of the hollow tower to draw air through the main living quarters. It uses the stack effect and differences in wind speeds between ground level and the top of the tower to operate. The stack effect principle relies on temperature variations in a vertical space or shaft, with warm air rising and drawing in fresh air at ground level.

The height of the proposed towers (approx 30 metres in the initial architect designed model) means that they have to be capable of supporting themselves and the attached structures. This would give the opportunity of giving the towers mass, in the form of an earth rendering. Internally the tower should be as massive as possible, without having to resort to extensive steel framing and overuse of concrete - both have high embodied energy.

Ventilation for the building will be aided by the substantial height of the towers and its location at the top of a hill. A series of vertical shafts are positioned within the width of each tower, see Fig 7.3. These are then linked into the various rooms as extract ventilation ducts. Lower down in the tower, the shafts can perform as air supply routes; ducting the air from underground. The sketch in Fig 7.4 shows the principle routes for air through the centre of the building. The height of the towers is intended to provide sufficient suction to draw air through earth tubes and interstices in the walls and floors without the need for fans.

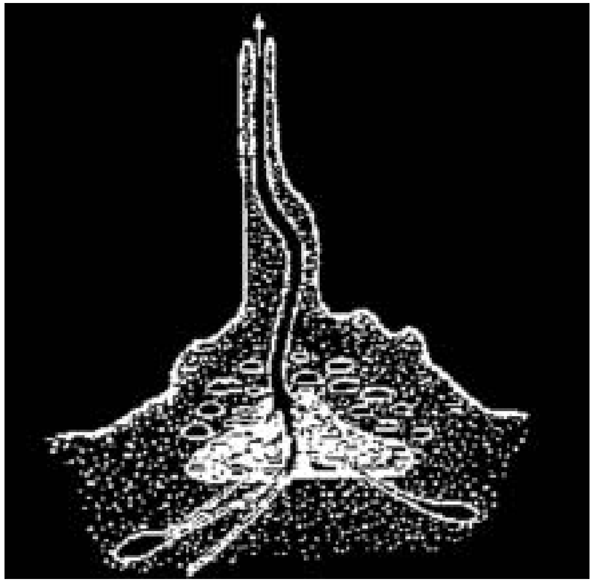

Fig 7.1 - Cornitermes Bequaerti termite nest cross-section

Fig 7.1 - Cornitermes termite nest ventilation tower

It will be important to expose the building mass, be it earth walls or other materials, directly to the occupied spaces so as to make the most of both the thermal and the moisture mass and thereby aid internal climate control. The vaulting will increase the heat transfer surface.

The partial "burying" of the Level 2 galleries in the earth replicates animal architecture and it inherently provides temperature stability. Subterranean nests, burrow, dens, caves etc, all use the thermal stability of the ground/earth.

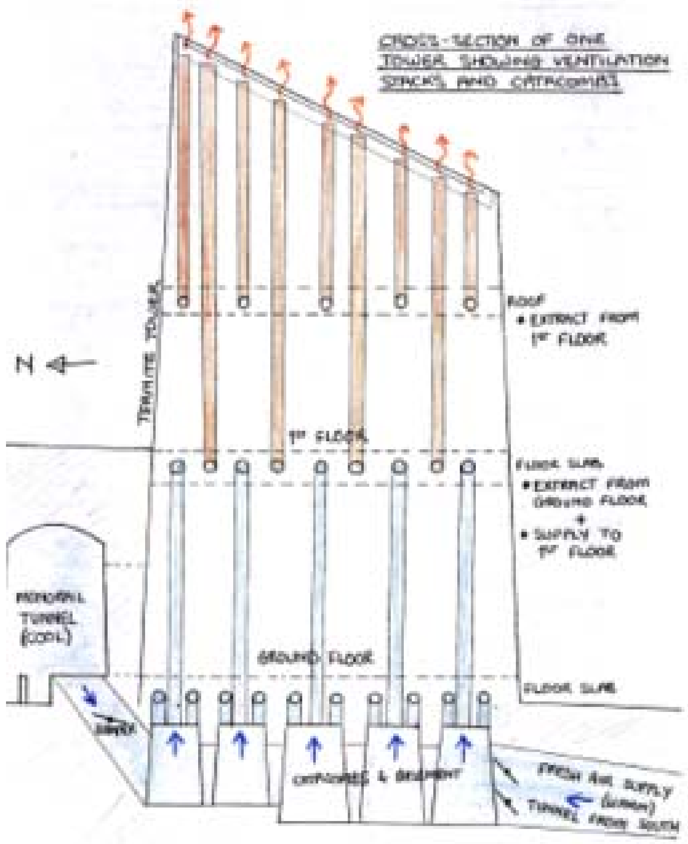

Fig 7.3 - Cross-section of central tower

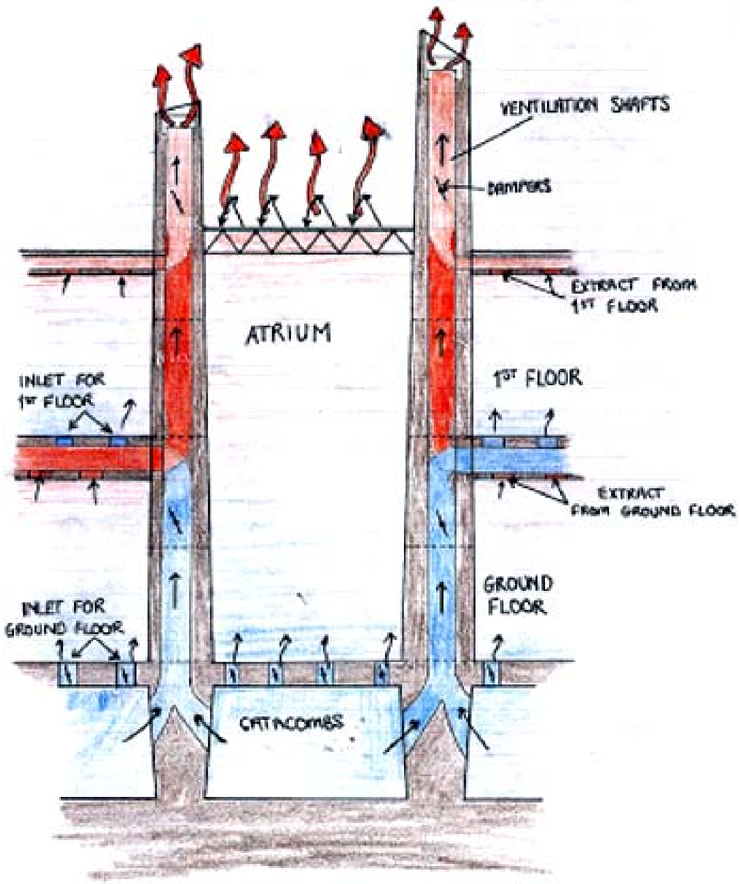

Fig 7.4 - Principal ventilation routes through building

A system using earth tubes has been applied in a school theatre.[1] Concrete tubes 50 to 75mm thick, 80m long and 900mm in diameter were used. The tubes were run in parallel to reduce the overall length, see Fig. 7.5. There would be a considerable advantage for the zoo project over the theatre in using this system. As it is located on a hill it would aid both the buildability of earth tube construction and the resulting wind driven ventilation.

Using hollow core floor slabs, such as TermoDeck (a commercially available hollow core slab) would mean that the ventilation air from the towers can be diverted through the floors and into the rooms. This is an elaboration on the termite ventilation strategy. The air will be tempered as it passes through the mass of the floor. Fig. 7.6 shows the idea behind Termodeck operation, with airflow through the slab. Construction of these floors will probably need to be of concrete, for strength and mass. Concrete made using recycled aggregates would ensure that the concrete is at least partially sustainable in construction. Recent developments in the use of limecrete would be of interest to research further. Care in design and construction is necessary to ensure that the resistance to air flow is not too great, as this could affect the effectiveness of the natural ventilation. The air flow through the building is largely governed by the height of the ventilation stacks; increasing the power of the stack effect. Experiments and modelling will be necessary to determine the exact height of the towers and the allowable resistances to air flow in the building structure.

The design of the Anarchi building will need to take into consideration that there will be large numbers of visitors entering and leaving it. This will lead to transient heat and moisture loading that has to be absorbed and managed by the building structure and its services. Animals use a wide range of strategies to change the conditions inside a structure including adding or closing openings. The proposed thermal massing will provide some form of thermal stabilisation and the use of moisture open materials will contribute moisture stability. However, there will inevitably be some hysterisis. The ventilation strategy will also have to take into consideration the requirements to cope with sudden cooling loads. This could involve simply opening windows, or adjusting dampers in the towers to allow an increase in stack induced extract.

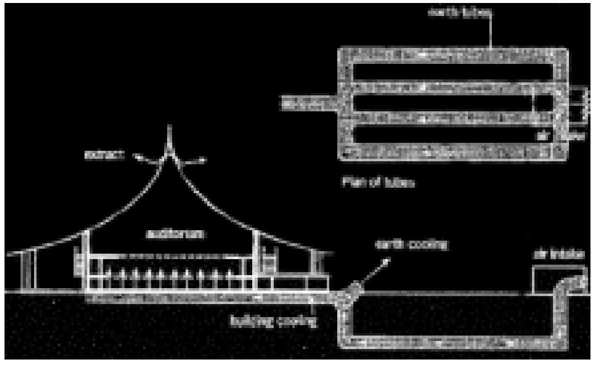

Fig 7.5 - School auditorium with ground-cooled ventilation

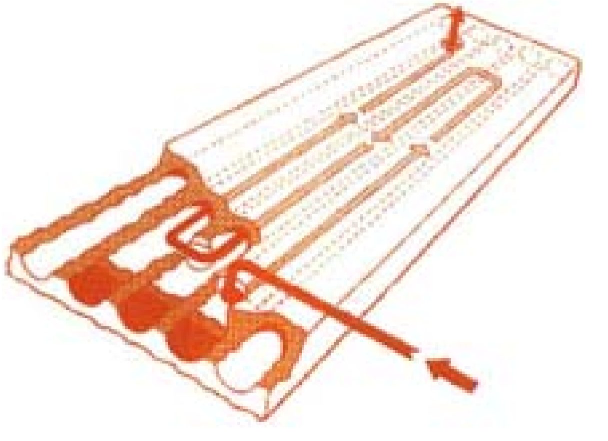
Fig 7.6 - TermoDeck, showing a possible air flow route through the slab

1 Architects' Journal, 7 April 1993

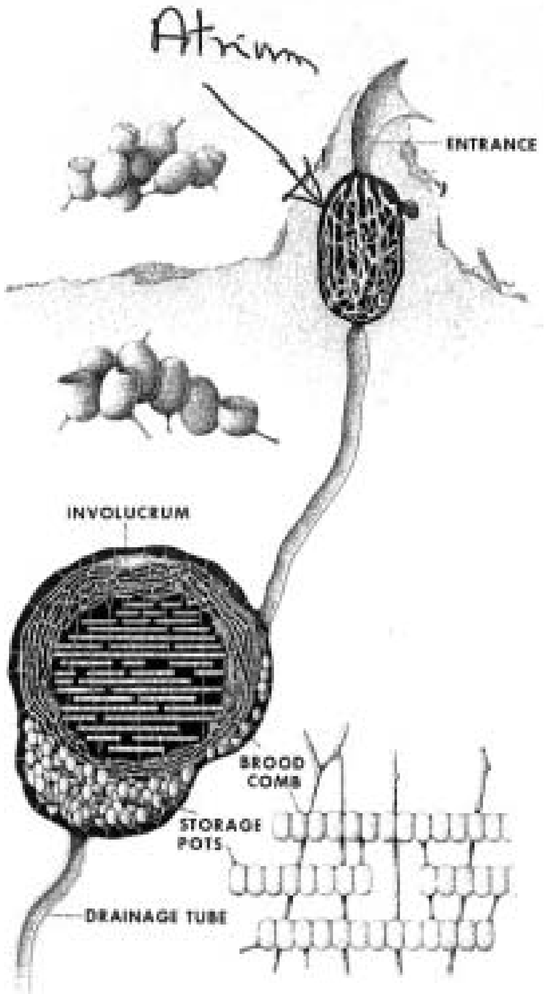

Fig 7.7a - Trigona testacea bee nest with atrium

Atrium

The Trigona testacea, tropical stingless bee has a form of atrium as an assembly area in the entrance to its nest, see Fig. 7.7a. However, the silken tents of the social caterpillars are probably a closer analogy to how atria are used in buildings to provide buffer zones for light and ventilation assistance, as well as circulation space. An atrium will perform a useful function in the operation of the building. It is to be situated between the towers, Fig. 7.4, providing a circulation space and route for daylight and natural ventilation. Fig. 7.7b shows a typical atrium.

Louvres or doors in the bottom of the atrium and high level openings will create a stack effect, which can be used to ventilate the space and, when linked to the adjoining rooms, provide extra ventilation for these. The ventilation can also be fed from the catacombs below the building, through adjustable dampers to provide ground cooled air.

Fig 7.7b - A typical atrium

Earth Rendering

The earth rendering on the towers and walls of adjoining spaces will serve several purposes, including:

- Controlling moisture in the air due to its hygroscopic properties.
- Regulating and stabilising the thermal environment due to its high thermal capacity and hygroscopic properties.

Orientation

The tower and atrium are intended to operate along the principles of the compass termites; reducing overheating by orientation, Fig 7.8. The flattened mounds of the compass termite are found in tropical yet open country in Australia. By being flattened, tapering towards the top and orientated with their axis North-South, they expose large surfaces to the morning and evening sun to make use of solar heat for a longer time during daylight. However, to avoid excessive heating in the middle of the day, they present a minimum profile to the sun positioned overhead or rather to the North (southern hemisphere).

The building is envisaged to be positioned so that the tower has its long sides facing east and west. The exhibition and facility wings have their greatest width facing south, with the north sheltered by the hill. See fig. 7.9 for a photo of the model, showing the initial concepts. A narrow, glazed opening between the towers will allow solar radiation into the atrium at around midday, whilst the east and west towers will absorb and re-radiate the heat gathered in the morning and evening.

The exhibition and facility wings face south, but will have solar control devices, brise soleil, positioned above windows to protect the interior from direct sunlight in the summer, whilst allowing for low level passive solar gains in winter and interseasonally. These could be constructed from woven natural materials, similar to the way that a weaver bird builds its nest, see Fig. 7.10, as an animal architecture aesthetic rather than a direct corollary of animal building behaviour. It was noted earlier that animal buildings attract other animals to live in them and this encourages co-evolution and a robustness in ecological system dynamics. It would be interesting to provide these along with other features to attract animals to live in them. These can be either fixed, moveable or demountable, for optimum control of solar gain throughout the seasons. The ventilation in the building will be assisted by the solar gains in the atrium and towers. The warming of the towers by the sun will assist the stack effect in the internal ventilation shafts.

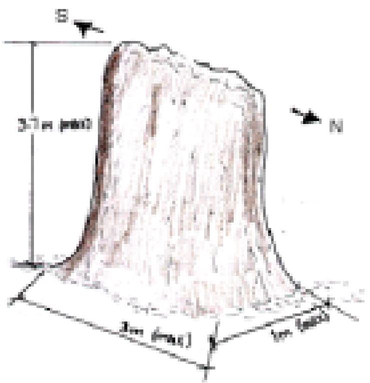

Fig 7.8 - Compass termite nest orientation


Fig 7.9 - Model of proposed Animal Architecture building

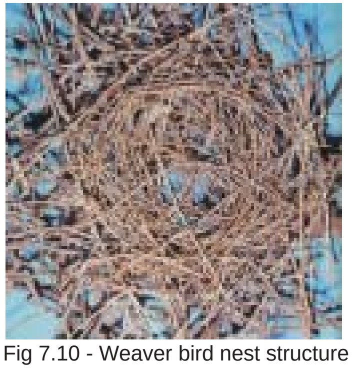
Fig 7.10 - Weaver bird nest structure

Composting

Based on the Megapodiidae bird nest, the composting system will generate heat to provide warm water, warm air and compost for vegetable growing.

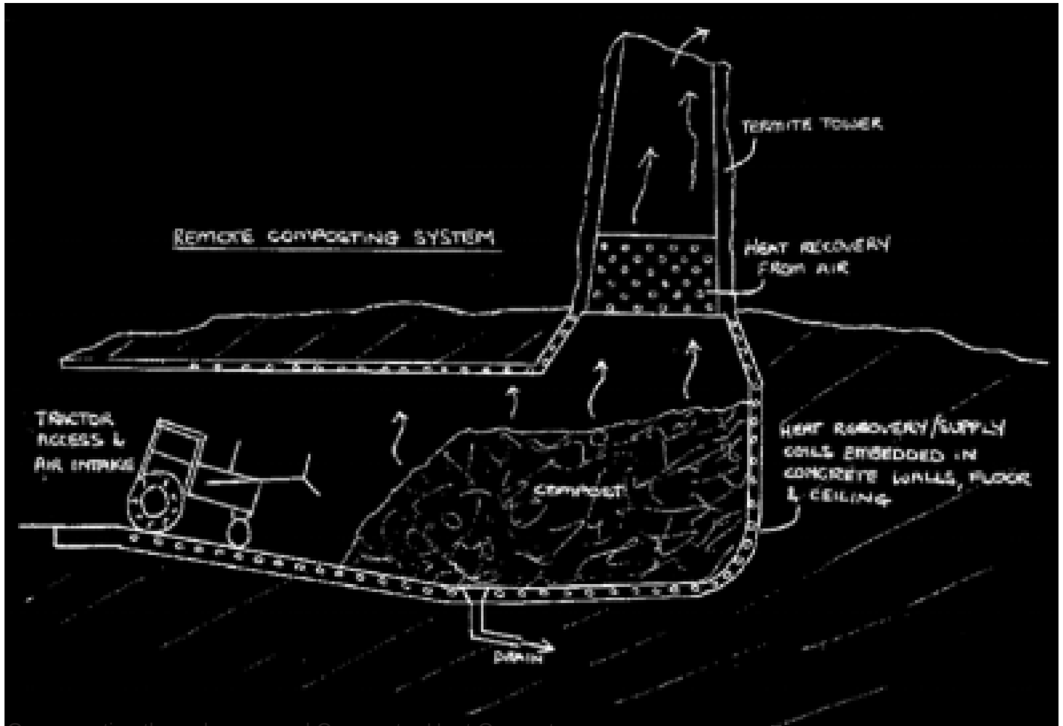

Fig 7.11 - Cross-section through proposed Composter Heat Generator

Some means of heating will be required to supplement internal heat gains in winter. The use of aerobic composting could be a real possibility. The sustainable output temperature of up to 40˚C is ideal for underfloor heating. The link to animal architecture is "fungus gardens" and also the behaviour of some birds in using composting techniques to maintain nests at a temperature adequate for incubation. An alternative to a composter could be to use an anaerobic digester for composting and use the gas in a combined heat and power plant. There are several plants like this producing biogas on farms in Ireland. However, the scale of these plants is much greater than that required here. There may be a link to animal architecture in the natural production of methane in termite and ant nests, although it is not clear if and, if so, how they use it.

Underground Tunnels

The prairie dog utilises the Bernoulli effect to provide ventilation through its tunnels - by having one entrance to its tunnel at a higher level than the other. The Bernoulli effect occurs when a faster flowing liquid passes over a slower moving liquid, creating a pressure difference. The water is thus dragged into the faster flowing liquid. This principle could be used to boost removal of warm air, if internal temperatures become uncomfortable, by incorporating adjustable dampers in the roof spaces.

The faster flowing air, at the higher entrance, draws air through the tunnel, see Fig. 7.12. The location of the Anarchi building will allow air to be drawn through tunnels at low level and out through the towers and roof. The tunnels and catacombs below the building could be used to stabilise the temperature of the supply air, by exposing it to the earth walls. A temperature of around 8 - 12˚C can be expected, which may be boosted by solar gain or left as a cooling medium for the warm exhibition spaces - perhaps through displacement.

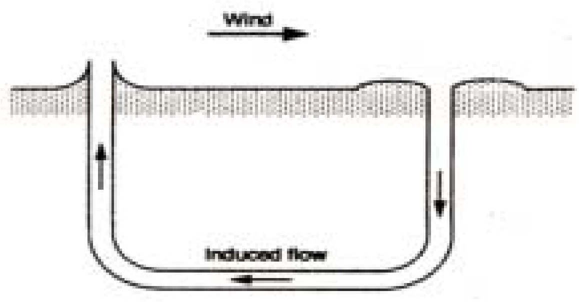

Fig 7.12 - Cross-section through Prairie Dog tunnel

Several routes for the intake of air have been discussed. Some will depend on the final design of the building, especially concerning the monorail:

- Intake low on hillside, through earth passages (as in Fig. 7.5) and catacombs to building.
- Intake through monorail tunnel.
- Openings in lower areas of building - louvres, doors, windows, etc.

The exhibition, restaurant and facilities wings can be shaped so that they utilise the Bernoulli principle to extract stale air from the rooms.

Narrow & Wide Plan

Compass termites utilise the geometry of their nest to reduce solar gain, by having as small an area as possible facing north (southern hemisphere). This factor has already been considered, but the use of a similar geometry for the building could also encourage cross ventilation, by having openings on the north and south sides to allow air to flow through. This would be particularly useful during the summer, when all forms of natural ventilation might have to be exploited to keep internal temperatures at a comfortable level.

Daylighting & Lighting

Animals do use various elements of transparency and daylighting to see as, other than luminescent bugs and fish, they do not have artificial means of generating light. This is likely to have a security element. Some animals might use it in their architecture to allow them to see inside their nests, such as weaver bird nests being constructed using a fairly open mesh - letting light through the structure.

The Polybiine wasp from Brazil (Pseudochartergus fuscatus) constructs a nest from the leaves of living trees and surrounds them witha semi-transparent envelope of hardened granular secretion see Fig. 7.13.

Use of daylight in the Anarchi building will help save energy and provide a pleasant environment. Elements such as the atrium and large window areas in the exhibition and restaurant areas will give the opportunity to use daylight to its maximum benefit.

Daylighting is to be used for most of the time in circulation spaces and the cafes. However, exhibitions tend to require controlled lighting, which has to be provided artificially. The spaces underground will also require lighting by artificial means. Some ideas from the discussion include:

- Fibre optic distribution of daylight, using a collector to focus light onto a bundle of fibre optic cables - this light is then distributed throughout the building.
- Fibre optic distribution of artificial, high-efficiency lighting, such as induction lamps or similar, high intensity lamps.
- Use of mirrors, light pipes, and other transmittance methods to direct daylight into exhibitions or underground spaces.
- Glow worms for demonstration purposes.

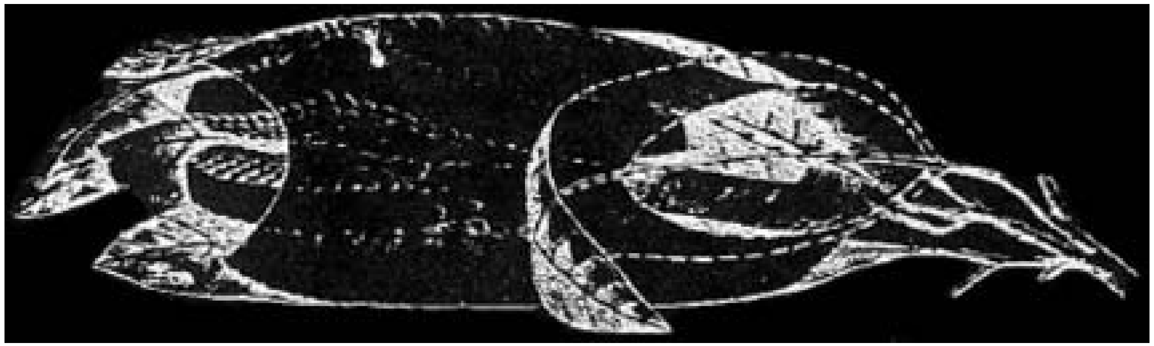

Fig 7.13 - Polybiine wasp nest with transparent ‘windows’

Waste Water Treatment

Very few animal architecture based ideas are available for the treatment of effluent. Other options, using natural technologies, can also be applied:

- Caddis fly filtration principles can be used to trap particles, see Fig. 7.14.
- Nest structures, from natural materials, can be used as biological filtration media in a sewage treatment plant, such as the weaver bird nest in Fig. 7.10.
- Reed bed filtration should be considered as a major means of treating sewage, as opposed to sending it to the public sewage works.
- Some or all of the sewage effluent can be diverted to nourish the composter.

One feature of social animal shelters is the recycling of bio-waste. This could be replicated by using composting toilets, which are an increasingly common feature in buildings. It would also be interesting to demonstrate the filtering techniques used by animals in various ways, which could provide a source of non-potable water.

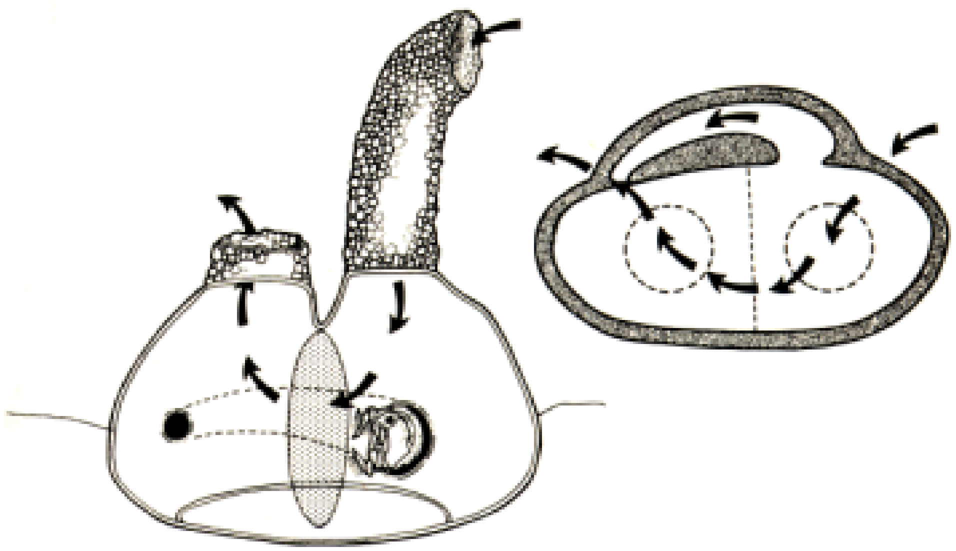

Fig 7.14 - Caddis fly larva sand grain food filtration pod

Additional Requirements

Kitchens

Discussions highlighted the desire to provide a gourmet restaurant and a cafeteria in the building. Kitchen facilities have no equivalent in animal architecture although there are parallels with hot, humid conditions in the tropics. The problem, therefore, turns to the task of designing catering facilities that will be innovative, of sustainable construction and energy efficient.

Ventilation

A major consideration for commercial kitchen design is the provision of effective extract ventilation and a fresh, clean air supply. Combustion by-products - from gas burners and burning food; steam, heat, air-borne grease and cooking odours, requires a substantial extract rate. To achieve all of this using purely natural ventilation could prove to be an impossible task.

Standard commercial kitchens have ventilation systems incorporating fire-proof materials, grease filters, fire-extinguishers, fans and high air flow rates. The Anarchi building's kitchens would require, at least, grease filters - to prevent contamination of upstream ducting. Incorporating these into a natural ventilation system would be extremely difficult, as they would introduce a high air flow resistance, rendering the system ineffective. Some form of extract fan will probably be necessary to provide adequate ventilation.

Domestic scaled kitchens do achieve satisfactory natural ventilation extract through use of stack effect ventilation or the opening of windows. However, the rate of production of air-borne grease and steam in a commercial kitchen would be too great for a natural ventilation extract.

Cold Storage

Many animals use storage as a survival mechanism. Certain species of owl take advantage of cold weather to store frozen meat. They also store desiccated seeds and grasses. Refrigeration, especially freezing, has become a ubiquitous part of food storage for humans and it is unlikely that it could be avoided. However, it is important that any refrigeration plant is designed to fit with the overriding objectives of sustainable design:

- Non ODP refrigerants.
- High levels of thermal insulation.
- Use of waste heat from the condenser coils in other areas of the building, eg water heating, ventilation heat exchangers.
- High-efficiency compressors, with variable speed control.

- Minimise size of plant by using passive design where possible. eg pantries of stone construction to store non-perishable food - preferably facing onto an outside, north facing wall and ventilated to the exterior.

Cooking

The means of cooking in the Anarchi kitchens would be, preferably, by methane from waste or natural gas. Electricity is not an option that should be considered as it has a high CO_2 penalty and is not liked by professional cooks as a means of cooking. It might be interesting to see if hydrogen could be used, though this might not be considered a safe option. Research into this field has not brought up any existing examples of cooking with hydrogen.

Novel methods of cooking, on a demonstration basis, could include a solar oven to produce home baking for the cafeteria. A solar oven is a small metal box with large, reflective “petals” that collect and concentrate the sun’s energy into the box. The resulting temperature increase is enough to bake food.

Dishwashing

Dishwashers save a great deal of time, are hygienic and can be relatively efficient if well designed and used correctly. However, their construction and operation is often not of a particularly effective design. Most heat their water by electricity, from cold. An option is to consider machines that use hot and cold water supplies and heat recovery, which save electricity, as they do not need to heat up water from cold.

Waste Disposal

Kitchens produce a large amount of organic and non-organic waste. Care should be taken in ensuring that purchasing of produce is sustainable and that disposal of non-organic waste is given consideration. All organic waste (apart from meat) can be used in the composter or to feed zoo animals.

Construction Materials

Commercial kitchens tend to be constructed of stainless steel. This is a robust and hygienic material, but requires substantial amounts of energy to produce. The use of wood and recycled metal and plastics should be a major feature of the kitchens, although there will be toxicity implications to consider from leaching of chemicals, resins and tannins.

Drinking Water Provision

There is an artesian well near to the proposed site and it is intended that this be exploited if possible, see Fig. 7.15. Water can also be provided by rainwater or public supply. The most effective, reliable and efficient solution will be investigated. Discussions have pointed to several uses for the water:

- The supply for the building might be able to come from the well, depending on pressure and head of the water in the well.
- Pros and cons of pumping (if insufficient supply) might indicate that the well is a better source of water than the public supply. It is cheaper and could be of a better quality.
- A source of cooling water for circulation in some form of structural or air cooling system, perhaps similar to underfloor heating coils, see Fig. 7.16.
- Supply for a water-balanced funicular railway, similar to that found at the Centre for Alternative Technology in Wales.
- Drinking water.
- A beaver dam feature in or near the building, see Fig. 7.17.

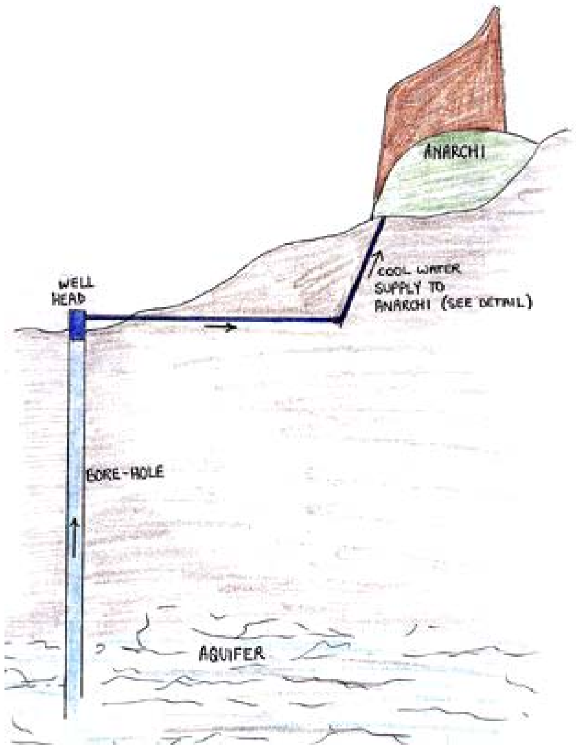

Fig 7.15 - Cross-section through Artesian well, showing supply route to building

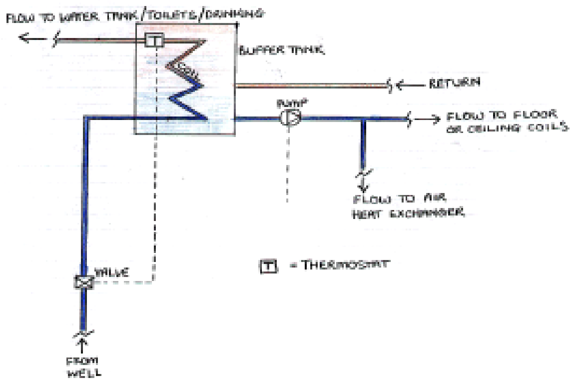

Fig 7.16 - Simplified diagram of well water use inside building

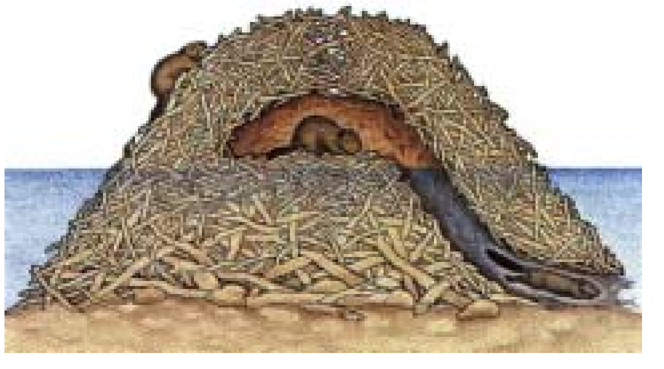

Fig 7.17 - Cross-section through a beaver dam

Water Pressurisation

Most non-domestic buildings require the storage and subsequent pressurisation of water. It would be desirable to avoid this, if possible. Some ideas on this are:

- Using a hydraulic ram, powered from the well, to drive water up to a tank - see Fig. 7.18.
- To supply the building directly, provided that the well has sufficient head.
- Collection and storage of rainwater at a high level (between the towers).
- Wind driven pumps.
- Solar powered pumps.

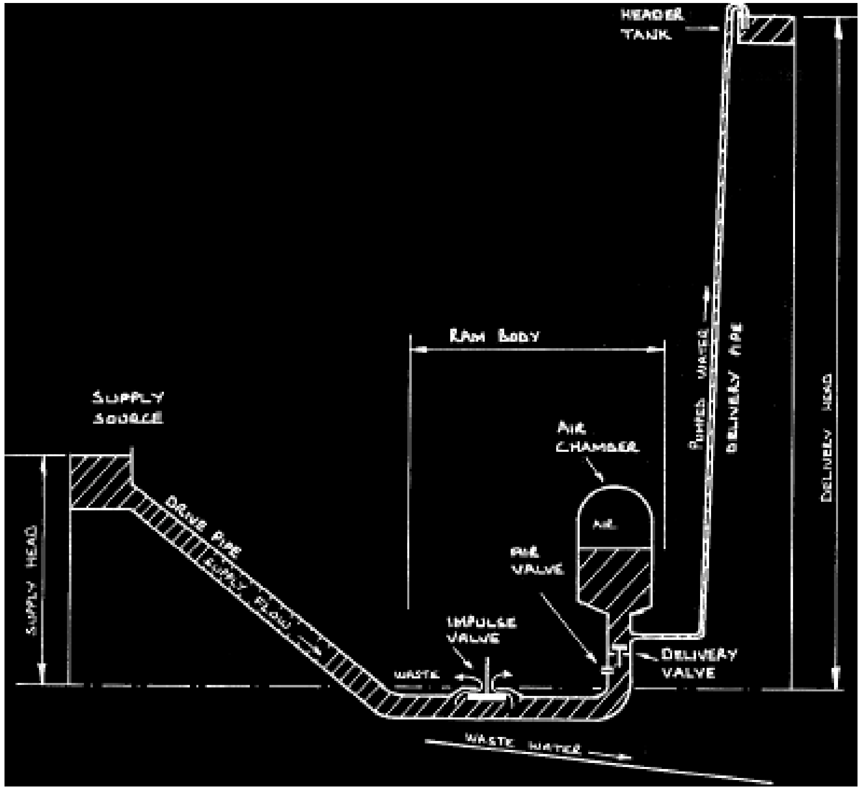

Fig 7.18 - Operation principle of the Hydraulic Ram

Main water flow is through impulse valve, which shuts in a regular sequence (approx 75 times per minute). Each time impulse valve closes, a small amount of water is forced up the smaller delivery pipe. The system is automatic and requires no electricity supply.

Domestic Hot Water

The requirement for hot water only extends to humans, so it is impossible to find a direct link between hot water production and animal architecture. However, this does not mean that provision of hot water cannot be energy efficient. Solar panels, of either standard or vacuum design, can be mounted on the roof and hillside. The water can then be put to a variety of uses:

- Domestic hot water.
- Underfloor heating.
- Perimeter/convector heating.
- Boosting of the compost generator during start-up.

The underfloor heating and compost generator booster would be ideal opportunities for solar heated water as they operate at relatively low temperatures (40 - 60˚C). The domestic hot water could be heated in part or wholly, depending on the output from the solar panels, to reduce the energy requirement for heating the water from cold, if conventional heating systems are used.

Electricity Supply

Efficient ways of producing electricity on site should be investigated, including:

- Photovoltaics.
- Wind turbines.
- Small-scale hydro, using the hill as an opportunity to create a small dam.
- Fuel cells[2] - soon to become a realistic alternative.
- Combined heat and power - possibly using bio-mass or hydrogen.
- Public supply.

[2] A fuel cell is an electrochemical energy conversion device with two oppositely charged electrodes that produce electricity, water and heat from a fuel and an oxidant. The fuel typically used is hydrogen and the oxidant is air. Hydrogen can be produced locally from methane (from the composter). Fuel cells discharge zero, or extremely low, emissions of greenhouse gases.

Transport

The proposed monorail will present a significant challenge, in terms of providing a means to drive it. A cable driven system is not possible, due to the curves in the track and length of route; water power will be difficult for a curving track, as it requires cabling. Large amounts of electricity would be needed to power the monorail, which could not be provided on site. Fuel cells, bio-mass or hydrogen could be used as a self-contained propulsion system.

Lifts are required for disabled access and movement of supplies. Novel methods of propulsion should be investigated, including:

- Manual operation, by a pulley system.
- Water powered counter-balancing, see fig. 7.19.

Deliveries to the building, both during construction and operation, should be given careful consideration to ensure that vehicles are used efficiently.

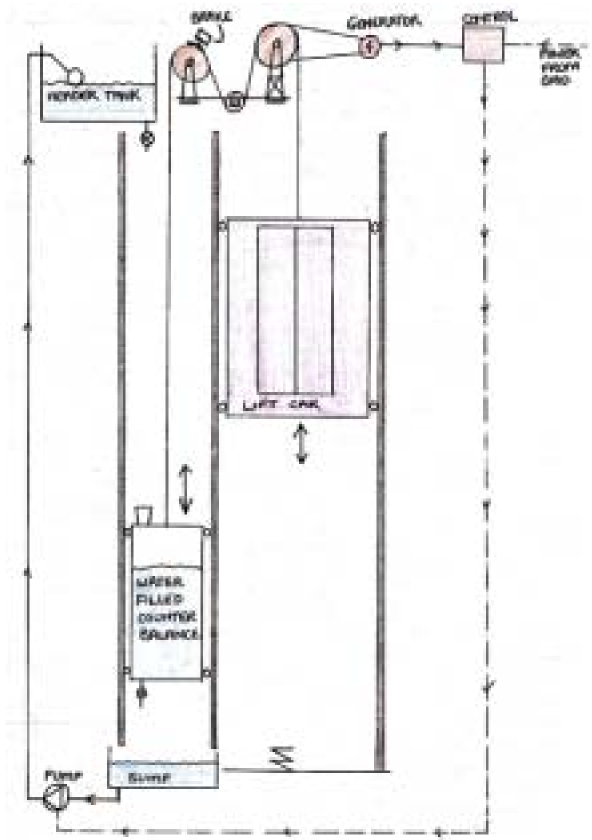

Fig 7.19 - Water balance lift

Servicing Strategies

Credits

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Images

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- Fig. 7.2 Hansell M H, Reilly M, Perry S, The Animal Construction Company, Hunterian Museum and Art Gallery, 1999.
- Fig. 7.5 Architects' Journal, 7 April 1993.
- Fig. 7.6 Termodeck website, www.termodeck.com.
- Fig. 7.7a Hansell M H, Animal Architecture and Building Behaviour, Longman, 1984.

- Fig. 7.7b Trade literature.
- Fig. 7.9 Malone S & Liddell H.
- Fig. 7.10 The Animal Construction Company (as above) & CBS Trade Literature.
- Fig. 7.12 Vogel S, Cats Paws and Catapults, Penguin 1998.
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- Fig. 7.17 Animal Architects, National Geographic Society, 1987.
- Fig. 7.18 Watt S B, A Manual on the Hydraulic Ram for Pumping Water, Intermediate Technology Publications, 1994.
- All other figures by S Downie - Gaia Research

Issues & Future Needs

The natural environment is a subject of increasing interest and one which we aimed to investigate in pursuit of important issues and specific opportunities for designers in the UK construction industry. In particular we sought to identify how principles derived from animal architecture techniques can be applied to establish a sustainable contemporary architecture.

Animals employ astounding examples of selectivity, repeatability of operations and standardisation of components to the creation of structures. It became clear in the course of the research that while isolated research projects exist territory is largely unexplored. Only in a very limited number of areas have the skills and techniques employed by animals in transforming their environments been studied. Where research into the natural environment does exist it tends to be dominated by the study of natural structures such as bone and plant forms and fibres as models for structures and machines, and the field of cybernetics and actuation. The research which does exist tends to be scientific rather than applied, and to be targeted at a limited audience of zoologists, biologists, scientists and research engineers. The existing outputs of biological and zoological research in building behaviour are not adequate to answer even the most basic questions posed by the construction industry. The most simple and ubiquitously cited example of animal building behaviour is the termite nest. Yet, although we know that termites behave in certain ways and achieve certain conditions, we know practically nothing about them. We do not even know how, or indeed why, open and closed systems are used by different species. This paucity of information is everywhere.

It is clear that if animal architecture is to produce generalisable principles then we need to identify the basic rules and systems of animal building in detail. These are wide ranging and diverse. Some relate to the abilities of particular species to use materials or create structures, environments and joints with remarkable attributes. Others relate to vernacular architecture, to construction processes and skill development and yet others to the overall context of building within environmental limits and what this would mean for future radical responses to the design of the built environment. The issue of scale requires additional analysis.

Specific Attributes

Among the possible research opportunities identified are:

- Structural analysis of spiders webs and connections
- Analysis of the mechanical design and safety factors in simple birds nests , including development of a series of timber structural forms based on:
    - materials as near “as found” as possible
    - spanning areas (floors, roofs) greater than lengths of individual elements
    - abandoning conventional triangulated frames and arches
- Material, structural and safety factors of wasp nest (paper) and chemical properties
- A study of the ways in which animals make joints in nature eg, spit and leaves in nests etc, and also the shapes of the structures around joints to optimise stress distribution
- Investigation of the use of microbes inside buildings to achieve a habitable internal environment (eg internal composting)
- Activities of termite nests make them a principle area of interest because of the potential contribution to knowledge on passive design. They evidently integrate structure and function in passive control strategies to control CO_2, moisture, temperature and ventilation. Research needs includes detailed analysis of processes occurring in the termite nests such as humidity, temperature and ventilation control through:
    a. varying apertures
    b. use of porous /semi porous membranes walls for environmental regulation including gaseous interchange[1]
    c. Choice of materials for water shedding
    d. use of different sorts of material (Mud, carton, fungi etc) in different areas of termite mounds for moisture/humidity control[2]
    e. site selection as a fundamental aspect of habitat management
    f. response to rising water in wet season
    g. social interaction.

It would be valuable to identify precisely how these work and to model and scale these in order to assimilate them into human architecture. A detailed investigation should look at why are there so may different forms of termite ventilation system, how a termite mound wall acts as a part of a system, what is it made of and what are its properties. It could offer an efficient means to ventilate buildings and removing air pollutants. It could be combined with investigation of structural design principles of cobb/mud/straw construction.[3]

[1] Presently being developed into an EPSRC research proposal
[2] This is the subject of research application to DETR CIRM
[3] This is the subject of research application to DETR CIRM

Systems

It is clear that there are basic rules from which complex systems emerge. It would be valuable to investigate building from the bottom-up, which requires repeated application of the same principles and processes, and results in exquisite adaptation to a site. The aesthetics would also be an area of interest.

Vernacular Design

Inevitably the study of animal buildings raises questions about structural and environmental design principles of vernacular buildings such as cobb/mud construction and the role that the materials play structurally and in terms of environmentally control. There are similarities with aspects of vernacular and pre-industrial architecture where minimum mechanical and chemical transformation was possible and materials, site, orientation and form were used to their best potential. It may be that revisiting these in a post-industrial, low embodied pollution context may highlight possible opportunities especially as we realise that radical global solutions are required. This could fundamentally influence the nature of our approach to construction activity.

Environmental Limits

Aspects which relate to environmental and ecological context may assist in defining rules for sustainable building. These include:

- Passive control of temperature, moisture, air quality
- User Involvement in management and construction, labour intensive
- Waste management
- Plasticity/Robustness of structures
- Selection of materials and their utilisation in a non processed or naturally processed state

Others

A diverse range of other research opportunities were identified including:

- Relationship between how non-human animals make use of and modify human built structures how humans use animal built structures.
- Sensory qualities of buildings in terms of light, sound, touch
- Autonomous structures adaptive to energy change / function
- An on/off glue bond to allow every element of a construction to be used again.
- The effects of buildings on sleep and how bedrooms can provide the best environment for sleep.
- The possibilities inherent in the combination of glue and common materials.
- Ways of extending living and working space architecturally, behaviourally and functionally
- Socio-economic and related aspects of taking building inspiration from biogenic structure: aesthetics, cost and user acceptability since most biogenic structures may be considered to be 'rough finished', are often irregular in shape and may be ramifying [spatially inefficient re-cost].

Discussion was raised on the fact that much animal architecture and services is effective on the scale that it is used. However, there might be problems when it comes to scaling up the systems to cater for humans. A building of similar design and construction to that used by termites, scaled to human needs, would be several hundred metres tall.

It is clear that further research in the area is particularly timely as the animal world offers us opportunity to explore techniques used in construction directly within the context of sustainability. This is implicit in animal architecture, dealing as it does with environmental pollution and protection and with maintaining biodiversity.

Conclusions

In view of the environmental challenges that it has now been acknowledged that we face, radical approaches are required to deliver genuinely new information to the construction sector to meet future needs. If innovation is really desired then thinking needs to be progressive, imaginative and to go beyond traditional, confined expectations and horizons in order to identify new sources of knowledge and inspiration. The DETR Technology & Performance Business Plan embodied the aim to improve the competitiveness of the UK construction industry by enhancing codes and standards, applying technical knowledge and adding value through new technology and techniques. This research project addresses a key priority within the Business Plan which is to develop a better understanding of new and improved technologies and techniques. This project comprised a short feasibility study to identify opportunities for the use of new and improved techniques and technologies based on an investigation of animal builders. It aimed to overview the implications for innovation in the built environment and to target construction professionals. The project was designed to have both short term and longer term deliverables.

An interdisciplinary gathering provided an opportunity for a creative exchange of views between a small group of invited construction industry professionals and researchers in animal building behaviour from the biological and zoological sciences. Prior to the seminar the research identified a number of principal issues and opportunities based on existing research and a number of key areas for further investigation in fields such as membrane science, fastenings, tool design, structures and climate control through the analysis of animal builders.

It was evident that biomimicry provides a rich and largely unexplored seam by which to understand the role of human construction in response to environmental pressures. But, whilst biomimicry shows us how animals use materials and natural processes to work for them, designers working with ecological design of buildings have already developed principals which rely on making similar sorts of choices. Design concepts were identified alongside precedents, where principles which may have corollary with animal architects have been used. It became evident that only in a very limited number of areas have the skills and techniques employed by animals in transforming their environments been studied in any degree of useful detail by those in either the natural or the biological sciences. Those construction industry professionals who engaged in the project (including planners, architects, structural engineers, building services engineers, quantity surveyors) did so with an evident enthusiasm for genuine research, multi-disciplinary activity and innovation.

The participants from a wide variety of design and research areas identified key areas of interest derived from animal building behaviour. These were developed in a series of workshops to generate a number of specialist, interdisciplinary groups keen to pursue further research and a large number of topics were identified.

The workshop debates also raised issues of a philosophical nature which reflect contemporary debate on the nature of organisms and their ability to self-regulate. For example it was thought that many of the lessons to be learnt are in the holism rather than the reductionism. For example, understanding the contribution of the termite (individually and collectively) to the successful maintenance of the nest at a steady 86˚F is likely to be as important as understanding the microscopic composition of the mud they use. The outputs of that seminar are available as a short guidance note and the information is summarised on the Gaia Group web-site. Along with this report and the guidance note produced at the seminar the research has been the subject of a Radio 4 programme and the work is also to be included in a programme on the discovery channel in 2001. It is therefore likely to attract greater interest in the coming months.

Subsequently a small interdisciplinary design team have developed some of the principle aspects into designs for a building based on principles of animal architecture. A major outcome has been the production of design concepts for a demonstration building. The project has raised many questions which themselves require more study and interest groups will take forward particular areas of interest and develop these into proposals for further funding so that the work will be able to extend the knowledge gained from this project into further work eg., demonstration projects, university curriculum development, and CPD on specialist applications. The network of interested parties provides an excellent framework from which to pursue further research.

The project has already led to development of a number of further research proposals to take forward aspects with potential near market benefits to the construction sector, indoor environment and overall environmental impact. Research proposals have been drafted on passive moisture control, straw/clay construction and further plans are afoot to develop proposals for timber construction and also to investigate termites in more detail. It will improve the level of construction industry innovation and its ability to take advantage of existing knowledge and experience and be a positive and proactive approach to benign construction. The project will in time deliver innovation of new and improved products, approaches and further innovative research. It has provided opportunities to better understand the opportunities and limitations of construction activity with benefits in indoor, local and global terms.

The project was only a short fact finding exercise, tiny in relation to the field of study, but we have sought to identify implications and applications for the built environment and to disseminate these in a way which engenders enthusiasm for the opportunities. The potential to cross traditional boundaries and translate this knowledge into design, building science and applied engineering in architecture and construction is enormous. The subject is relevant to manufacturers, architects, structural, controls and services engineers. It is hoped and anticipated that the project will be a stepping stone in gaining critical, rigorous understanding and insight into the practical application of lessons from animal builders and the natural world.

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