The art in
structural design
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Preface

Design and philosophy in structural engineering

There is an old saying which goes something like this: 'An engineer is a man who can do for a dollar what any fool can do for two.' Its emphasis on ingenuity is praiseworthy, but it has been seen too often as a justification for much that is cheap and nasty in engineering. It has been taken to mean that engineering is nothing more than the achievement of clearly specified technological objectives for the lowest possible cost in cash. This view has been reinforced for engineering students by the fact that with a few notable exceptions, textbooks entitled 'Design of Structures' are predominantly concerned with the techniques of computational analysis. This contrasts strongly with the situation in mechanical engineering, where much thought has been given to the mental processes involved in design and to the development of creativity.

When one looks at the architectural field, the contrast is even stronger. Many books are available, written *by* architects *for* architects, on the selection of structural form and the understanding of structural behaviour, two fields which have traditionally received little attention in engineering texts. In addition there is a vast literature devoted to the philosophy of architecture, and to the architect's place in society and in the professional design team. Naturally, this literature represents a wide range of viewpoints. There is no definitive text giving *the* recipe for a philosophy of architecture, but a student architect is able to work out a philosophy for himself which suits his own personality and ideals, giving him a perspective with which to view his studies.

Although some such material does appear in the engineering journals, especially the 'Engineering Issues' section of the Proceedings of the American Society of Civil Engineers, the available literature is limited in comparison to that in other disciplines. Discussion of the merits and demerits of particular designs, which is quite common in the architectural world, is definitely discouraged. As the impact of technology on society and on the environment becomes more apparent the resulting image of the profession must dissuade many intelligent people from entering or even considering a career in this field.

There are, however, some signs of improvement in recent times. Engineering news magazines such as the *New Civil Engineer* (U.K.) are willing to provide the background information on projects even when this may involve them in controversy. Authors of texts on 'design' are including more discussion of issues behind the simple calculations. White, Gergely, and Sexsmith (1972–1976) and Schodek (1980) are good examples of this new approach and the aim of the present book is to contribute to the closing of the gap which has been left in engineering studies by the almost exclusive emphasis on computation.

The need for this book

It may be that a proportion of students are drawn to engineering precisely because they see it as an entirely rational discipline. Such people imagine that to every problem there is a 'right' answer and that it is possible to work steadily and logically towards this goal by a process similar to that of a proof in Euclidean geometry. Some also imagine that when disagreements arise amongst technologists they are settled by recourse to purely dispassionate, logical discussion, free of the problems that normally beset human relationships. These people are destined for a rude awakening and it is doing them a great disservice to leave them with their misconceptions.

Students who are struggling to assimilate a vast range of new concepts in analytical subjects may not appreciate having their cosy image of well-defined technique shattered and may wish to forget about the 'art' of engineering for the time being. They may have a justifiable pride in their new-found ability to choose the correct size of beam to carry a given load and may wish to enjoy practising this for at least a few years before worrying about the complications. This is an understandable attitude, but there are a number of good arguments for avoiding it if possible.

There is some evidence that traditional engineering courses reduce the creativity of students. One reason is, no doubt, the vast amount of information which has to be assimilated; but perhaps the main difficulty is that one cannot teach standard clear-cut answers to problems without implying that there are standard clear-cut problems. Once the mind becomes set in this view of the world it becomes very difficult to break out of the mould at a later date. As a result, the possibility of improving on existing techniques and adapting them to changing needs is diminished.

The practising graduate soon becomes aware that the knowledge and techniques available are quite limited compared with the complexity of the problems encountered. There are many areas where science can give little guidance or where quantitative techniques are not applicable. Rules are necessarily generalized and hence rarely apply exactly to any particular situation. Thus even in the technological sphere the engineer must face problems to which the only answers are subjective and as anyone who has worked in a design office knows, they provide grounds for a great deal of lively discussion.

Then there is the question of personal satisfaction. Once the basic techniques have been assimilated, the joy of mastery begins to wear off, and the repetitive application of rules and formulas becomes tedious. Such work can often be carried out more efficiently by a computer. There is thus less intellectual satisfaction in the display of technical virtuosity than in the 'art' of design.

As the new graduate soon realizes, there is no clear-cut order of progression to the solution of a problem. Before a 'problem' can exist, someone must first have perceived a need and prepared a subjective formulation of what he thinks needs to be done. Quite often this person is not an engineer and is thus unaware of the full range of technological options available and of the full advantages and disadvantages of each. As a result he has not been able to balance the strength of the perceived needs against the costs and difficulties of satisfying them.

Hence, after initial investigations it may be advisable to revise the original definition of the problem. This interaction is rarely mentioned in undergraduate courses. As a result, the recent graduate often feels totally bewildered when painstaking calculations made over a period of weeks are suddenly discarded because a new approach has been adopted, or awkward anomalies are found to have crept into the design which somehow cannot be eradicated. Thus it is important for engineers to have some idea of how their objectives are defined for them, how they may be changed, and to what extent engineers can influence this process themselves.

About this book

The title of the book was inspired by two sources: Mr P. Dunican's paper (1966) on 'The art of structural engineering', and Mr C. B. Stone's Presidential Address to the Institution of Structural Engineers, London (1969), in which he said:

> We are, by definition, duty bound to care for the *science* and the *art* of structural engineering: we cope very well with the *science*, but what about the *art?*; this embraces not only the choice of form, the technique of structure, the

> related processes of production and the fabrication of building units, but above all the humanities of our profession . . .

The need for this is reaffirmed in the section of the '*Handbook*' of the Royal Institute of British Architects (RIBA 1980) which deals with multi-disciplinary design teams. This states that:

> . . . it is vital to bring together a sufficient number of members of the main professions, each of whom has a perceptive awareness of the nature of their fellow designers' contributions along with deep knowledge and professional competence in his own field.

and later:

> It is not the system, but the people who operate within it, who produce results . . . all disciplines may have to make concessions.

It would be an impossible task to survey the entire range of non-computational factors which influence the daily work of the structural engineer and the form of the structures he designs. Of the larger issues, only a brief mention is made here of the influence of politics and organizational behaviour. On the technological side little is said of the important subjective decisions which the engineering profession makes on behalf of society by defining the criteria for design and the levels of safety factors. Only a mention is made of the qualitative technological knowledge required in fields such as fabrication and construction techniques.

The emphasis in this volume is on those fields which lie mid-way between the very broad issues such as politics and the subjective technological issues listed above. These are: the nature of the design process and especially of creativity; the formal organization of design; and functional requirements and economic criteria.

A large part of this book is devoted to studying the architect: his *modus operandi* and his philosophies, since in many projects his is the single most important influence on the work of the structural engineer. This knowledge is of direct practical value to the structural engineer, but at the same time provides an example of the difficulties of co-operating with any other member of the design team who has a different outlook and training, be he a mechanical engineer or a lawyer, economist or sociologist. The constant themes, which culminate in the final chapters, are the questions 'what are the true aims of structural design?' and 'what relative influence should be accorded to all the relevant factors in determining the form of structures?'

It can be seen that this is not the sort of book to which engineering

students are accustomed. There are no formulas and little technology. It is hoped that students will find it pleasant reading for the sake of the light it throws on broader issues which are not normally included in their undergraduate course, but which will concern them immediately they graduate.

Because the book covers so many broad topics it is impossible to survey them in depth. For those readers who wish to delve further into particular topics copious source material is provided, although the average overworked engineering student may not have time to follow this up until he graduates. Since many engineering schools schedule some part of the timetable for studies in the humanities and the development of English expression, a number of questions are supplied at the back of the book, related to various topics covered. These provide suitable material for assignments and are designed to give practice in critical appraisal of source material in descriptive subjects, and the assembly, testing and presentation of theses in essay form.

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A. H.

1

The art of structural design

Art in technology

In the *Oxford English Dictionary*, the first meaning attributed to the word 'art' is 'skill, acquired as the result of knowledge and practice'. Design of structures as taught in undergraduate courses tends to consist of guessing the size of members required in a given structure and analysing them in order to check the resulting stresses and deflections against limits set out in codes of practice. Where then is the 'art' in structural design in the sense of a skill which goes beyond the limits of precise logic?

Structural design can be seen as the process of disposing material in three-dimensional space so as to satisfy some defined purpose in the most efficient manner possible. To do this we must have philosophies of 'purpose' and 'efficiency'.

An engineer might see the purpose of the structure as being to carry the imposed loads to the foundation in the most direct manner possible. The word 'possible' recognizes that in doing so it should not interfere with the function for which the structure is intended. The structure of a building must be accommodated to the needs for clear space within the envelope, that of a bridge must allow for passage of water, or forms of transport beneath it. When these needs conflict with directness of structural action one or both must be compromised in some way. Already the designer finds himself attempting to balance the relative certainties of structural logic against the qualitative properties of interior space.

What is structural 'efficiency'? An engineer might define it as the ratio of benefit (output) to cost (input). It is possible to measure cost quite precisely in terms of the quantity of material used in a structure. Unfortunately this is of no practical use because it ignores the relative cost of different materials and most importantly the costs of fabrication and construction. A truss with intricate web tracery may do the same job as a solid plate girder while requiring far less material, but the high cost of labour involved in cutting and assembling its many parts may far outweigh the saving in material cost. Again the designer must balance precise savings in material against his qualitative knowledge of the problems of fabrication and construction and the uncertainties of cost prediction in these areas.

The designer must use skills and imagination in envisaging the types and combinations of loads and internal forces that may arise in the life of the structure and in estimating their likely magnitude. Guided by the committees who write the codes of practice and the building regulations and in discussion with the owner, he must make many subjective decisions about the performance which is to be demanded of the structure. Should the building be designed at enormous cost to withstand the most severe earthquake it is possible to imagine, or the impact of crashing aircraft? If not, should it at least afford some protection, ending up bent but more-or-less whole?

Looking at more common types of loading the designer must decide what intensity of wind and occupancy loading he must allow for. His decisions must be based on the life of the structure, its importance to the community and on possible changes of ownership and usage, as well as on meteorological data and surveys of typical loadings.

All structures are designed with a factor of safety which may be defined briefly as the ratio of strength to reasonably expected load. This may be as low as 1.1 for slip-circle analysis of earth dams, but is typically of the order of 1.7 to 2.0 for structures. In arriving at such figures a large number of qualitative and probabilistic factors have been taken into consideration including quality of fabrication, variability of materials and loads, and accuracy of the theories employed in analysis. These figures also involve an assessment of the amount of risk which is acceptable to the owner, the users, and the community.

When the time comes for analysis, skill is required in the application of theoretical concepts and analytical techniques to the mathematical modelling of structures. All theories are approximations and the designer must choose with care the theory most closely approximating the reality of the structure, and encode its geometry and material properties into his mathematical procedures and computer programs in such a way as to achieve a valid analysis.

In order to do this he should be aware of the background to the development of the theories and the code rules which he applies. What are the approximations and assumptions inherent in the theory and especially in the computer program that he is using? What shortcomings should he expect in the picture they give of stress and strain in the structure, and how may he compensate for these?

The rules which are found in codes of practice for the analysis of reinforced concrete floor systems and the stability of beams and columns are gross simplifications of very complex phenomena. They incorporate decisions about which parameters may be ignored, what are the likely dimensions and form of the structural elements under consideration, and in the case of stability what are the likely magnitudes of geometrical imperfections and of residual stresses in steel. Code rules governing fatigue, brittle fracture, and corrosion and other problems of weathering again give only patchy guidance on very complex and qualitative issues.

In order to apply these rules with any intelligence the engineer should be aware of their origin and the procedures through which they have been developed. Once he has analysed the structure the designer must with the aid of codes make further decisions concerning performance requirements. All structures deflect under load. How much deflection is 'too much'? How much sway may be permitted in a multistorey building under wind load? At what levels of vibration does the average person become uncomfortable and then alarmed? Should the designer cater for the most sensitive person or the average?

It is of course possible for the designer to be lazy and depend for most of these decisions on the unthinking application of codes of practice and compliance with the letter of building regulations most if not all of the time. Such an approach is unprofessional and at times dangerous. Designers of office buildings have for some years been allowing for much higher floor loads than required by law in order to cater for the weight of proprietary types of compact filing systems. A few years ago it was realized that the current dance craze was imposing dynamic loads with a static equivalent equal to several times the regulation design load.

It is obvious from this brief survey that sufficient skill, cunning, and imagination are required in the 'design' of structures, even in its most narrow technological sense, for it to be properly described as an 'art'. The greatest part of this art lies of course in envisaging a suitable form for a structure: the disposition of material in space to perform the required function most efficiently. Our theoretical tools can provide us only with analyses of structures whose basic geometry has already been defined. At present our commercially available computer programs can do little more.

Space limitations prevent further detailed consideration of the qualitative and subjective aspects of the engineer's input into structural design. It is hoped that sufficient has been said to caution the engineer against a too arrogant assertion of the objectivity and precision of technology in comparison with other disciplines. On the other hand there is no need to adopt the defensive stance taken by some that engineering is all 'rule of thumb and fudge-factors'! Coping with the variable and the ill-defined is a challenging and a perfectly respectable occupation.

The art of working in the design team

The structural engineer does not of course work in isolation. Politicians, executives in private and public organizations, and architects often play the major role in the definition of 'purpose'. In addition the structural engineer is usually involved in projects which are so large and complex that they must be conceived and designed by a team rather than an individual. To work effectively the structural engineer should know something of the concerns of these other participants in the project. It can thus be said that the art of structural engineering includes the art of communication, of relating successfully to the other members of the team, and of sharing in or leading the administration of the design process.

This is rarely an easy task because of certain conflicts inherent in the aims and limited viewpoints of the various participants. As a simple example, if the structural engineer increases the depth of floor in a multi-storey building in order to provide greater leverage between the flanges of his I-beams, he may add considerably to the area, and hence the cost of the external cladding. If he designs his floor too tightly with regard to depth or stress levels he will add to the problems of the services engineer who may wish to cut holes in the webs of the beams for water pipes.

In the wider context there is liable to be conflict between the structural engineer's desire to minimize the cost of the structure by providing regular and reasonably closely spaced supports and the architect's desire for appropriate clear spaces to suit the function of the building. In minimizing the direct cost of construction the engineer might choose a slower form of construction thus involving the investor in higher interest charges which could easily outweigh the saving in capital cost.

The moral of this is that all parties involved in the project should attempt to take into consideration all relevant factors. Obviously this ideal is unattainable. Given that no one can 'know everything' it follows that many propositions must be put forward and many binding decisions made in the early stages of the design process in ignorance of the relevant facts. As we shall see shortly a classic example was the action of the architect of the Sydney Opera House in sketching the shell-like forms of its roof without the benefit of an engineer's understanding of the mechanics of thin shells.

As the implications of the original decisions become clearer the question arises of whether to attempt to overcome the difficulties imposed by the earlier decisions or whether to take advantage of other possibilities which were envisaged or have been revealed by the investigation. To what extent should the earlier decisions be modified? Should they be abandoned entirely? What relative weight should be given to the conflicting objectives and values of the various parties?

At this stage the personalities and social skills of the participants become as important as whatever objective facts may be to hand. As the architect who designed the Munich Olympic Stadiums wrote, 'often the louder, the stronger, the quicker will win' (Behnisch 1980). The roots of what may be quite heated conflict lie in the varying objectives and value systems of the participants in the project. To simplify the situation to the point of caricature, the goal of a private client, say a property developer, is to make a profit. The politician wishes to achieve credit so that he will be returned at the next election. The architect might want fame for an outstanding design, leading to further commissions. All of these people are concerned with different aspects of the project. Their goals are different and possibly contradictory, and conflicts of values are inevitable.

Of course, people are far more complicated than this. They have a need for self-esteem and for public recognition of their significance. Competition and the ruthless pursuit of profit are limited by convention and personal beliefs. Some people seek public recognition directly, either from the public or their peers, while others are satisfied to earn a high salary and demonstrate their status by the way they spend it. It is important for some to establish bureaucratic 'empires' while others prefer the anonymity of 'back-room' jobs. It is necessary for all consultants to convince others of their competence in order to ensure a continuing livelihood.

However, even the less contentious motives may give rise to friction. The architect may see himself as an artist, bringing warmth and humanity to a staid and colourless environment. The engineer may pride himself on his practicality and his ability to conserve capital and resources. A local government engineer may gain satisfaction from his roles as a sort of policeman of the building industry. The potential for conflict is obvious. Furthermore a person's system of beliefs is also usually influenced by his personality rather than rational analysis.

Fortunately, all the participants also have motives for banding together to form a team and this normally overcomes the divisive effects. Consultants would be lost without clients and vice versa. Architects would, one hopes, be lost without engineers and regulatory bodies would be out of a job if there were no one to regulate!

An interesting point concerning motivation is that salary earners on the whole have a different outlook from the self-employed, particularly regarding the importance of money *vis-à-vis* perfectionism in the search for solutions, in computation and detailing, and in aesthetics. Contrary to popular belief, government engineers may be more innovative than privately employed ones because they run less personal risk in trying out new ideas.

As previously mentioned, these matters are beyond the scope of the book, except for the difference in attitude between engineers and architects which is of immediate importance to most structural designers. The manner in which people interact in groups as a result of personality factors has been researched by sociologists and psychologists under the headings of 'group dynamics' and behavioural psychology. In the final chapter of Middleton (1967), Professor Sir Misha Black provides a very interesting account from an engineer's standpoint.

The influence of politics in the community

Although this book concentrates on the middle ground the influence of the politics of the general community must be given at least a passing mention. Politics may have a considerable influence on the work of the structural engineer, the ultimate being the cancellation of a project to which he has devoted several years of his life.

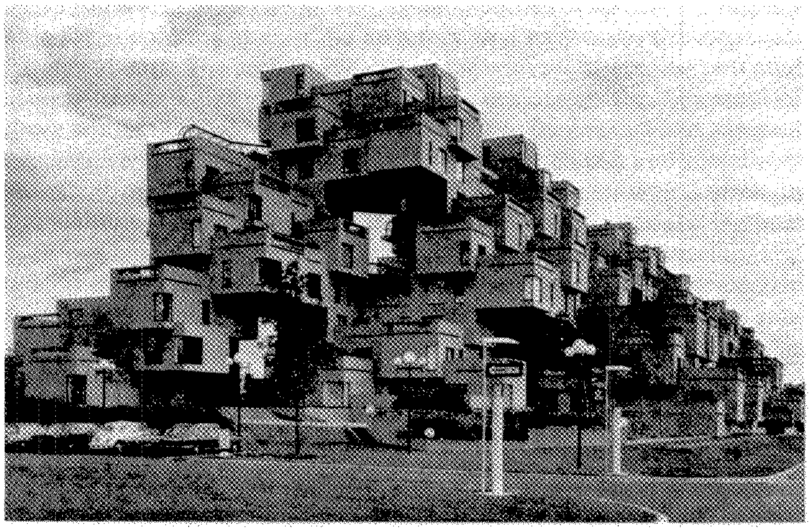
We shall see in the section on aesthetics the influence which pressure groups concerned with enviromental protection may have on the design of structures in both the country and the city. Applications to the local authorities for planning permits may be opposed by local interest groups who are capable of obtaining major modifications to, or even complete abandonment of proposals. With publicly funded projects there may be similarly strong resistance to the basic concept and there is the added problem that taxpayers' money is being spent. It is always difficult if rises in cost occur (an apparent rise is impossible to avoid in times of inflation) or if completion does not occur on schedule.

The Snowy Mountains Hydro-Electric Scheme in Australia was a politically sensitive project in its early days and there was much debate about its economic viability. As a result great attention was paid to public relations. The design of above-ground power stations was considerably affected, and the Authority became a pioneer in the aesthetic design of industrial structures. In the Murray River stations, one side

of the machine hall was fully glazed to allow visitors to see into the station, despite the resulting problems in structural design. Areas were provided for visitors to observe the machines at close range, and in the M2 station this facility was incorporated in a two-storey building spanning a 15 m gap—an expensive requirement. Such decisions are entirely political; but involving as they do considerable additional expense they tend to make the cost-conscious engineer wonder just why he struggles so hard to save a few millimetres on the diameter of his reinforcing bars or to cut a few centimetres off the thickness of a concrete slab.

National, state, or city prestige often becomes tied up in structures, with consequences for those involved in their design and construction. In the following chapter we shall see how politics hastened the start of the Sydney Opera House project, compounding the difficulties of the design and how they entered into the final resolution of the conflicts within the design team.

The city of Montreal was host to Expo '67 in an attempt 'to put itself on the world map'. One of the major exhibits was 'Habitat', a high-density housing project whose designer, Moshe Safdie, wished to prove the practicability of mass-production methods in the building industry. This aim became entangled with the desire of the city to prove it could 'produce the goods' on time (Safdie 1970). Private industry is also affected



1.1 Habitat, Expo '67, Montreal. A prototype for an industrialized building concept, which became entangled in politics. (Archt: Moshe Safdie. Engr: initially A.E. Komendant.)

by the desire for prestige and this may in turn affect the instructions given to the architect, particularly in the case of banks and head-offices.

It is hoped that by now the reader will be growing aware of the very human side of structural design and has begun to realize that while technical competence is very valuable it is only a part of the overall skill required for the successful design of structures. In the hope of confirming this impression and giving some taste of the nature of the design process, a part of the story of the design of the Sydney Opera House is provided in the next chapter as a case-study.

2

Case-study of the Sydney Opera House design

Introduction

This case-study highlights the problems of interaction between clients, architects, and structural engineers, and the influence of politics both within and outside this group. For reasons of brevity it does not cover the contribution of the services engineer or of the contractor (builder) who after appointment worked closely with the design team.

It is assumed that the reader has some idea of the roles of the various parties mentioned above. If not, it is probably sufficient to explain that the client is the person or organization which pays for the project and obtains advice as to the nature of the building that will best suit its purposes. In this case its advisers would include people from the worlds of opera, music, and theatre as well as the architect. The client is responsible for appointing at least the architect, and sometimes the engineering consultants. The architect in discussion with the client, the potential users of the building, and the engineers, decides on the allocation of space within the building, its overall form and its internal and external appearance. The various engineers advise the architect and sometimes the client on the requirements of the building for structural strength and stability, heating, lighting, and ventilation, and acoustics. As final decisions are reached the architect and engineers prepare drawings and specifications defining the work to be carried out in their respective spheres of responsibility. Normally tenders are called, contractors submit quotes for the work and the architect and other consultants advise the client on the choice of builder. During construction the professionals supervise construction in their respective spheres to ensure that what is done complies with their requirements and to make any modifications that appear necessary when unforeseen difficulties arise or for some reason requirements are changed. There are other approaches to the organization of the industry but these will be discussed in a later section.

The background to the Opera House project

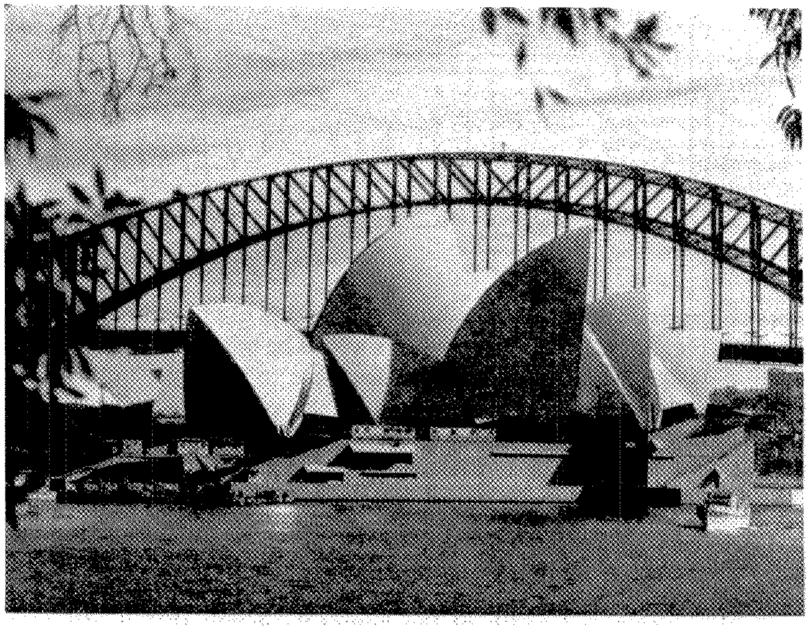
The sources available fall into two categories: accounts written by the structural engineers for the project, Ove Arup and Partners, and presented as papers to learned institutions; and books written in a journalistic style, for instance Baume (1967), with emphasis on the human side of the problems and intended for the layman. In general, papers written for engineering journals observe the convention that the influence of non-technological factors is an unfortunate aberration which should not be mentioned in polite technological circles. Arup's papers make a refreshing change. However, they come nowhere near the laymen's books in detailing the interpersonal conflicts that arose. Indeed Arup admonishes the other authors for describing in 'vivid and often exaggerated and incorrect detail the more sensational aspects of the project'. The events they relate must certainly be placed in perspective within some fifteen years of steady application to the task. On the other hand, the human conflicts they describe have a familiar ring to anyone who has been involved in practical design.

The form of the Opera House is the result of an architectural competition held in 1956–7 for the design of an arts centre for Sydney. The centre was to incorporate two main auditoria and numerous other facilities for the performing arts, such as rehearsal rooms. Bennelong Point, a narrow peninsula jutting into Sydney Harbour had been chosen for the location.

As a result of the advocacy of Eero Saarinen, a world-renowned architect and member of the panel, the judges (all architects) chose an entry submitted by Jørn Utzon. This was despite the fact that his drawings were in a very rough form and that the details had not been thought out to the extent required by the competition rules.

Although opera was only second in importance in the list of priorities for both halls, the building came to be known as the Sydney Opera House. In Arup's words this was an embarrassing anomaly which 'became established'. Baume, however, attributes it to a takeover within the Executive Committee by an 'opera clique' which was prepared to overlook the original requirements.

The New South Wales Government appointed an 'Opera House Executive Committee', composed of part-time honorary members to act as client. The structural engineer, although recommended by Utzon, was made directly responsible to the client. This arrangement is quite common in Britain, but unusual in Australia where the engineer is normally responsible to the architect, who is thus very clearly the leader of the design team. In addition, the other specialist consultants (for acoustics, mechanical services, etc.) were made contractually responsible to the client through Arup, rather than through the architect. It is thought that the Government adopted this arrangement because Utzon's ability to organize a project of such magnitude was untried by any similar previous experience.



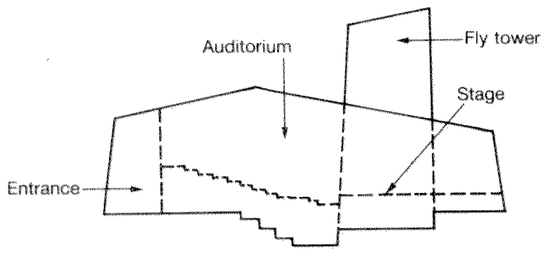
2.1 Opera House, Sydney, Australia. In fact, a complex arts centre crowded onto a narrow peninsula in the Harbour. (Archt: Jørn Utzon. Engrs: Ove Arup & Ptnrs.)

The project was divided into three parts. Stage I comprised the foundations and podium; stage II the 'shells'; and stage III the cladding, paving, glass walls, and interiors.

A characteristic problem of theatre design is the architectural treatment of the 'flytower'. A large space is required above the stage so that scenery and other effects can be hoisted out of view of the audience and quickly dropped into place when required. Some architects actually express this volume as a separate tower adjoining the auditorium (Fig. 2.2). However, most attempt to integrate the two into a unified form.

The majority of entrants in the competition handled the 'tower problem' by placing the two halls back-to-back so that the towers adjoined. However, this had the disadvantage that the two foyers were then at

2.2 Alexander Theatre, Monash University, Melbourne, Australia. An alternative expression of the spatial requirements of a theatre. (Archts: Eggleston MacDonald Seccombe. Engrs: Irwin Johnston and Breedon.)

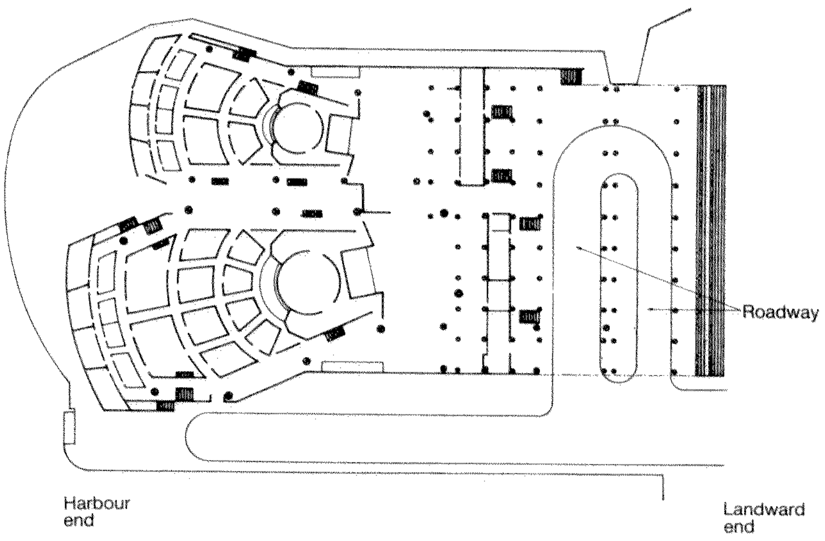


opposite ends of the peninsula. Utzon's idea was to place the halls side-by-side (Fig. 2.3) so that the entrances would be at the same end. However, he felt it was aesthetically undesirable to have the bulk of the structure (the towers) at the far end of the peninsula, so he placed the entrances at the far end and provided circulatory galleries around the sides.

In his report to the New South Wales Government in January 1965, Utzon emphasized the architectural experience which he expected this arrangement to provide for the visitor as he circled the auditorium through the galleries with their inspiring views of the harbour. However, the constricted width of the peninsula meant that it was now impossible to place wings either side of the stage in the traditional manner. The required space was therefore placed beneath the stage, and complex machinery was devised for raising and changing scenery.

Utzon had first approached Arup in 1957 and in March–April of 1958 the pair visited Sydney. There they were informed that the Premier wanted work to start well before March 1959 when there was to be a state election for New South Wales. He feared that if the then Opposition gained power the whole project would be abandoned. It was therefore necessary to achieve a *fait accompli*. As a result, despite their advice to the contrary, the two were forced to 'start the job without a single correct drawing'. Foundation sizes were estimated before the weight of the roof was known and were continually revised as excavation revealed unexpected site conditions. As we shall see, the weight of the roof turned out years later to be much greater than the initial estimate.

The decision to press on before proper consideration had been given to design was responsible for a great deal of chaos throughout the entire project. It resulted in drawings being fed to the contractor on a hand-to-mouth basis as construction proceeded, and a great many alterations as later decisions affected earlier ones which had been made too hastily. Sometimes portions of the structure actually had to be demolished because of such changes. The preoccupation with Stage I meant that less forethought could be given to Stages II and III, and so affected the whole project.

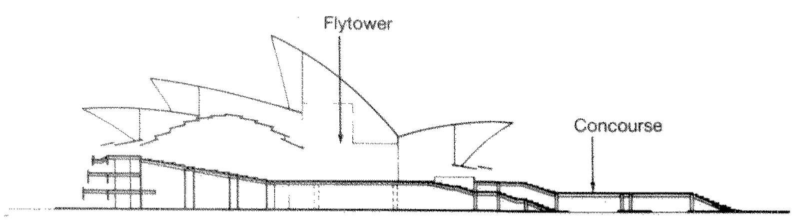


2.3 Sydney Opera House; main floor plan (competition entry): two auditoria side-by-side with foyers at the seaward end and access round the sides.

Design of the concourse

The design of the concourse, a part of the project which has received very little attention from the public, provides an excellent case study in architect–engineer relations. It is seen on the right in Fig. 2.4. It consists of a series of broad steps leading to a large flat area. Beyond this are more steps leading to the top of the podium. (This concept owes much to a visit Utzon made to the Mayan monuments of Mexico.) A roadway runs under the concourse to allow vehicles to deliver patrons to the lower entrance halls.

Originally Utzon allowed for columns under the centre of the concourse, a reasonable decision seeing that the resulting spans were still of the order of 18 m—a healthy span for a bridge. In the initial discussions with the engineers, however, he asked if it would be possible



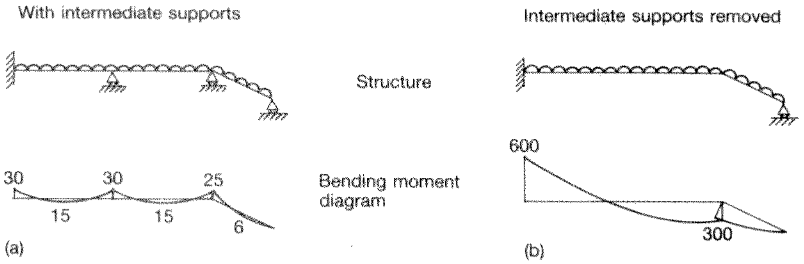
2.4 Sydney Opera House; longitudinal cross-section (competition entry) showing how the shells envelope the fly-tower and acoustic ceiling.

to omit not only the central columns, but even those under the junction of steps and concourse.

As Arup and Jenkins put it (1968), this was 'a typical question' for an architect to pose to an engineer and it 'received the typical answer': it would be possible to omit them, but much more expensive, and since the columns offered no obstruction to traffic, very hard to justify. If this answer was typical of an engineer, Utzon's response was that of a pure architect. He was going to omit applied finishes such as tiling or render under the concourse in order to 'express the structure' honestly. Having saved money in this regard he felt entitled to spend it elsewhere on achieving a bold, impressive form.

The span was now some 50 m and the beam depth was required to be a minimum because of clearance requirements over the roadway. Figure 2.5 shows, using a highly simplified idealization broadly similar to the concourse and first flight of steps, the sort of increase in bending moment which would result from this decision.

The response of the engineers was to prop the bottom of the steps against the sandstone substrata to prevent horizontal movement. In this way axial forces would be developed in the structure, relieving the bending moments shown in Fig. 2.6. It was later found that the sandstone dipped away at the southern end of the steps. Also Utzon decreased the slope of the steps with the result that a greater horizontal reaction was required for equilibrium. For these reasons the engineers inserted tie-beams under the road to tie the bottom of the steps back to the main structure. To gain an added advantage the tie-beams were extended out past the bottom of the steps and the superstructure was prestressed by jacks which pushed inwards against the bottom of the steps and forced the ends of the tie-beams outwards, placing these in tension before the connection was made rigid. The problem posed by the removal of the central columns was thus solved at considerable expense in design effort and construction cost.

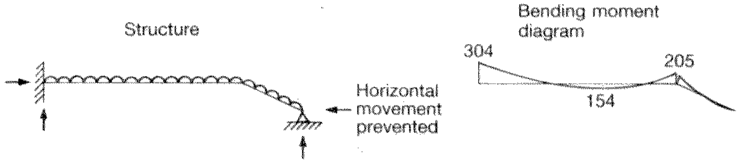


2.5 A simplified mathematical model of the concourse beams of the Sydney Opera House: (a) bending moments with supports as originally proposed; (b) increase in bending moments due to removal of interior supports.

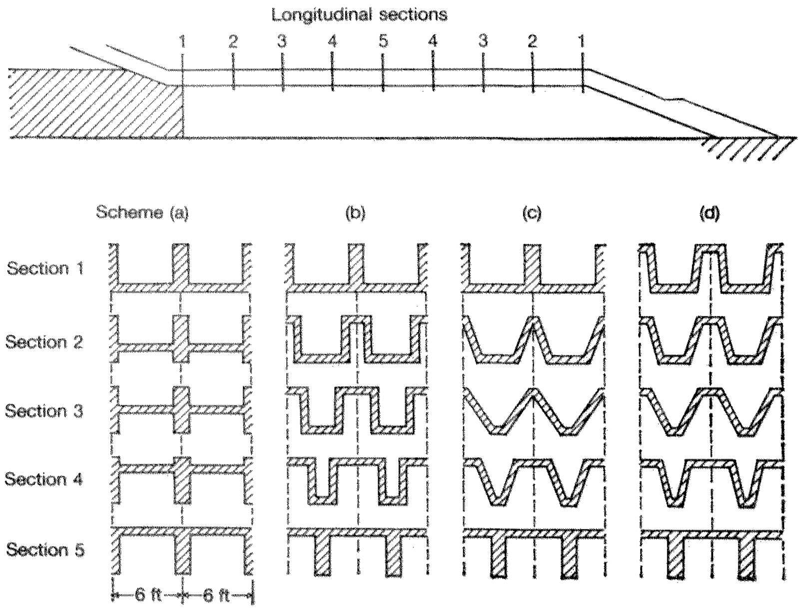
Utzon was also keen to see the design of the beams express their mode of structural action and to dispense with the slope normally provided for drainage. He proposed to use perfectly flat, precast paving slabs, 1828 × 1441 mm, supported so that rainwater would drain through the joints and be carried away underneath. In addition the depth of the concourse was to be constant and keep to a minimum.

These constraints led the engineers to propose a series of webs at the appropriate spacing supporting the edges of the paving slabs, with a horizontal flange varying in position so that it would be near the top of the webs at mid-span and near the bottom at each end. Figure 2.7 shows the variation in height of the flange at different positions along the beam. The idea developed through a number of stages to result in the scheme shown on the right which cunningly provided the required drainage channels, while disposing the material in the locations required for efficient resistance to the bending moment.

The question then arose of the geometrical definition of the transition from one section to another. The architect did not like the harshness of the scheme originally proposed and illustrated in Fig. 2.8(a). He wanted to round off all the sharp edges. This would have made fabrica-



2.6 A model of the concourse beams of the Sydney Opera House showing a reduction in bending moments due to horizontal propping force at right-hand support.

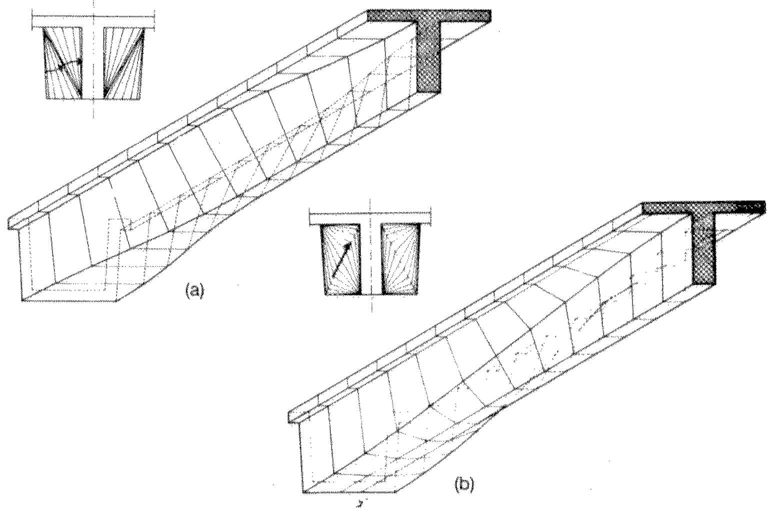


2.7 The cross-section of the beams for the concourse varies in accordance with the magnitude and sign of the bending moment. The initial proposal 'a' with vertical webs and horizontal flange was developed into scheme 'd' with warped webs transforming a double-trough into a double-T.

tion difficult and expensive. After much debate, the proposal shown in Fig. 2.8(b) was adopted as providing 'the roundness or voluptuousness which the Architect was looking for . . . while still being reasonably easy to fabricate'.

Another problem arose when the architect wanted some of the beams which run under the restaurant raised, because the restaurant floor was higher than the general floor level. In keeping with his philosophy of structural honesty and expression he was against the idea of building a raised platform over the beams to accommodate the change in level. This posed enormous engineering problems because five non-standard beams would have had to be inserted. As they would have been unsymmetrical, their prestressing would have created torsional moments which would have had to be absorbed by adjoining, already highly stressed, beams. To quote Arup and Jenkins:

> . . . the very considerable cost, and the disturbance it would cause to an already critical situation would be too high a price to pay for something which after all would not be missed by anybody.
>
> However the Architect was insistent and the Engineers were bracing themselves to attempt a solution to the problem, when the Heating Engineers intervened with a demand for space over the slab in which they could accommodate their pipes and services.



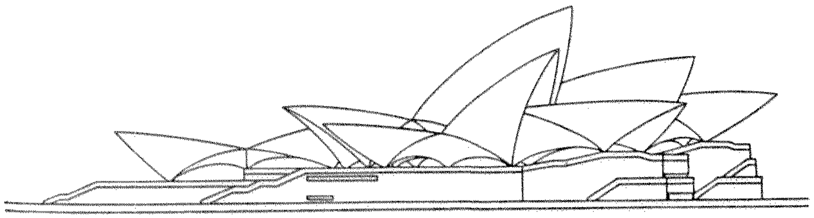
2.8 Aesthetic refinement of the concourse beams: (a) hard-edged original proposal; (b) final solution—a compromise between artistic goals and cost of fabrication, providing considerable softening of form.

This allowed all concerned to justify building a platform over the slab and saved the day for the engineers.

So much for the minor question of the Concourse! It would be interesting to know just how many visitors appreciate what is going on under their feet when they stand on the concourse, or over their heads when they enter the rather gloomy cavern beneath.

Design of the shells

The 'shells' of the Opera House inspired infinitely more awe and controversy on the part of the public. Arup is, as usual, on the side of the architect. He says that although 'many architects allege that form has dominated function to the detriment of the scheme', the 'unusual roof was really only the outward expression of an inner plan which provided an ingenious solution to the competition problem'.



2.9 Sydney Opera House roofs: Utzon's original conception showing softer outlines of the roof-scape.

Even so, Utzon had conceived the scheme with little or no engineering advice and with 'the then prevailing faith amongst architects in the omnipotence of shells'. He failed to realize that in order to ensure membrane action a shell must follow a definite form so that all forces produced by distributed loads, in particular the weight of the shell itself, are transmitted in the plane of the membrane. There is a range of possible forms which meet this criterion, but any deviation from the disciplined form imposed by statics introduces bending moments which the thin shell is unable to resist.

Not only were Utzon's shells drawn freehand and therefore unlikely to correspond at any point to a suitable form, but they had a ridge along the centre (Fig. 2.9) which made it impossible for forces to be transmitted smoothly across the top within the plane of the shell. They could not therefore be described as 'shells' in the engineering sense of the word. Another difficulty was that the 'shells' were not balanced longitudinally and so had a tendency to fall over end-on-end.

The first thoughts exchanged in early meetings thus included the use of non-pointed arches, doubly curved shells covering each hall, or even a single roof over both halls. Arup says that to design a dome-like structure covering both halls would probably have been easier than persevering with the original concept. However, it was agreed that such changes would destroy the sculptural quality of the original scheme and that all efforts should be directed towards reproducing it as closely as possible.

The shapes of the shells as originally drawn were not defined by simple mathematical formulas. This meant that, at the time, it would have been almost impossible to analyse them mathematically and very difficult to fabricate them. After much debate, agreement was reached to define the curves as parabolas.

In an attempt to cope with the bending moments, ribs were added to the inside of the skin. These, however, proved insufficient and a double skin was proposed with two-way ribs in a four-foot (1.22 m) space between. At the same time the louvre walls enclosing the ends of the shells (Fig. 2.10(a)) were designed to transmit load from one shell to another, to ensure longitudinal stability and provide all possible support for the edges of the 'shells'. The shells originally sprang vertically from their supports, but it was soon shown that a slight inward inclination would greatly reduce the bending moments.

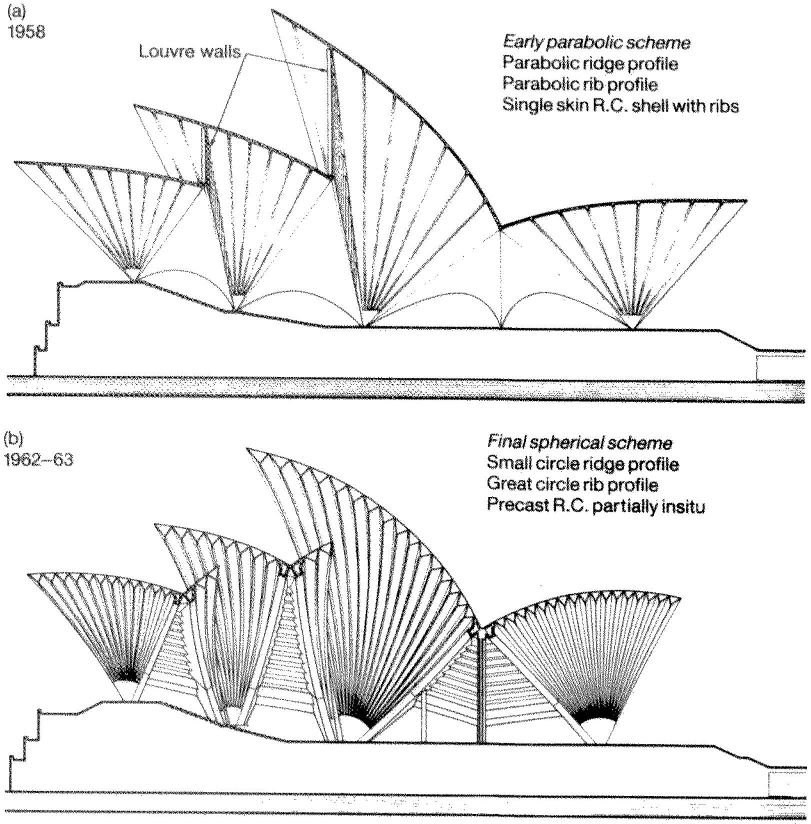
Further options for the structural scheme were examined, including the 'rib' pattern fanning out from the supports which was finally adopted (Fig. 2.10(b)) and is described as like a pair of hands with the fingertips pressed together. However, the alternative which became most attractive to the engineers was a skeletal steel space frame covered by two concrete skins about four feet apart.

In mid-1961, however, the situation became fluid for a number of reasons. Results from model tests suggested that the system of load-transmission originally envisaged produced foundation loads which could not at that time have been predicted analytically. The bending moments and shear forces in the roof itself also appeared to be higher than had been anticipated. To increase dimensions to cope with these effects would increase dead loads still further and result in a possibly endless spiral of increasing size and weight.

At this juncture Utzon, who had been preoccupied with keeping abreast of Stage I found himself able to turn his attention to the roof. He expressed dissatisfaction with certain aspects of the current scheme, particularly the louvre walls and the internal appearance. He wanted a ribbed surface under the shell and an improved means of closing the gap, because trouble was being experienced elsewhere in the world with glass walls meeting shell roofs.

As a result the whole scheme was reviewed and after much thought it was decided to abandon the initial structural concept. Improvements were made by moving the centre of gravity of each shell closer to its points of support, thus reducing the overturning moment. The flat louvre walls were largely replaced with curved surfaces ('shells') facing the other way (Fig. 2.10(b)). Finally, the articulation of the roof was entirely changed so that the three sets of shells were structurally independent and stable, the remaining louvres being non-load-bearing.

The architect was then presented with two versions of this scheme; the double-skin with internal steel space frame, or the series of arched ribs springing from the supports like fans. The former was preferred by many in the structural design team as being much easier to analyse and construct and providing the outward appearance of Utzon's initial



2.10 (a) An early version of the structural scheme for the roofs; (b) the final structural scheme.

scheme. However, Utzon was now keen on the idea of a ribbed internal surface and considered the steel skeleton to be structurally dishonest. Arup therefore agreed to pursue the design of the ribbed alternative. Arup's version of this decision is recorded in his 1965 paper. The double-skin proposal was 'heartily disliked by Utzon and I did not really like the idea either'. In his 1969 paper he simply says 'faced with the choice the architect had no doubt what he wanted'.

Utzon's version, contained in a letter to the Minister for Public Works in 1965 and quoted by Baume is somewhat different.

> After a long period I succeeded in convincing the engineers that the first scheme was absolutely hopeless, and that together we had not been able to achieve honest structure at the same time as we had not been able to fulfil the expectations of the competition scheme had promised. My new scheme which I developed in my office as the last of a whole series of schemes was brilliant enough to stand up to any criticism the structural engineers could bring forward . . .

Internal and external politics

The change involved the abandonment of some three years' work on the analysis and design of the original concept. To quote Arup:

> it is quite a sacrifice for a man at the height of his power to dedicate five years of his life to one job which demands so much and to see so much of his work thrown aside because of altered disposition or because the difficulties ahead are insurmountable.

Baume's account is that the decision caused a split in the Arup organization. He claims that Arup had some difficulty in persuading the engineers to return to the beginning once more and that there were some resignations.

Despite Ove Arup's personal efforts in this regard Utzon's relationship with him began to deteriorate seriously in 1963. Baume explains how Utzon began to feel that Arup was attempting to take over the running of the project in conjunction with the Public Works Department and capture an unfair share of the glory. The Minister had asked Arup for a report on the shells and had been given the engineers' version of their development. Utzon's previously quoted letter continues:

> You might have been misled by Arup's recent report . . . to the extent that you do not really understand that every detail in the existing work carried out, and in the whole scheme down to the last dimension and shape, has been formed by me.

Utzon's relationship with the Government also began to deteriorate. There had been a change of power in New South Wales and the new Minister had begun to shift control away from the part-time executive committee towards the Public Works Department. This process ended with the Minister taking over the authorization of payments to the architect, thus giving himself total control. The reason was basically public concern over the rising cost of the project. The full blame was attributed to the chaotic state of organization and for this Utzon was held by many to be totally responsible.

This was probably unfair as many problems were inevitable due to the forced early start, and the part-time nature of the large committee. This had made it difficult to organize meetings and so obtain decisions.

Communication was also hampered by the fact that Arup's were contractually responsible direct to the committee, and so could not resolve important matters directly with the architect. The result was that attempts were made to obtain quick decisions from individual members who were considered to be influential, with resulting problems when this faith proved to be misplaced. Utzon's constant striving for perfection, and his willingness to abandon an old idea if a better one turned up, undoubtedly added to these organizational reasons for confusion.

The situation led to complaints from Arup's to the Minister and appeals for a more rational organization. The Public Works Department was also recommending changes and was beginning to vet more and more of Utzon's proposals. In conflicts of opinion, Arup's and the Department usually found themselves on the same side in opposition to Utzon.

A particularly strong controversy developed over Utzon's desire to use structural plywood for the acoustic ceilings of the auditoria. The engineers questioned both the structural integrity of his scheme and his proposal to give the order for the plywood, without tender, to a bankrupt firm which he asserted was the only one in the world capable of fulfilling it. The Sydney representatives of Arup's, being perhaps more typical of engineers in general than Ove Arup himself, failed to show the same exceptional sympathy for the architect's aspirations and changeability. The client, advised by the Public Works Department, entered the dispute over the soundness of the proposition and a complex political situation developed with Utzon accusing Arup's of further bad faith. In February 1966 Utzon resigned.

There was still a considerable amount of work to be done on Stage III of the project and architectural control was handed to a committee of four with Peter Hall as the design architect. The story of the design of the interiors and of the glass walls enclosing the ends of each set of shells provides yet another interesting episode in this lengthy saga. Hall claims that his committee adhered to the intentions of the designer as far as was practicable, but this has been hotly contested by those who continue to support Utzon.

Conclusion

In spite of events, Arup continued to be sympathetic towards Utzon and to champion his cause. In his 1969 paper (after the resignation) he talked of 'an unprecedented collaboration between architect, engineer and contractor'. This is all the more intriguing because Utzon believed

in the integration of structural form with architectural expression and was a keen proponent of 'structural honesty'. Arup with his partners on the other hand, did not believe that there is necessarily any connection between the two. They described the Opera House as 'one of those not infrequent cases where the best architectural form and the best structural form are not the same'. After his resignation Utzon wrote to Arup complaining of his firm's 'whole attitude of dividing structure and architecture'.

The reader might think that the Sydney Opera House is a very atypical example to choose to illustrate the wider problems of design and that Utzon is an atypical architect. On the contrary, while the engineering problems, the personality clashes, and the political manoeuvring were certainly on a grand scale, they are quite similar in nature to those which occur on many smaller projects.

Unfortunately, it is only where the glare of publicity is cast, because a public project greatly exceeds its budget or a major structure suffers total collapse, that the human side of engineering is revealed. It is ironic that much of the public outcry that was directed at the Sydney Opera House and those concerned with it must have arisen because the public was under the impression that normal engineering projects are totally devoid of personality problems and organizational confusion. It would be better for everyone if we did not feel a need to delude ourselves and others that the application of technology is an entirely objective and rational undertaking.