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The Design of the Concert Hall of the Sydney Opera House

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Abstract – This paper deals with the Concert Hall only. It sets out initially the most important design criteria influencing the architecture of rooms for music, then deals with the Client Brief and its resolution in terms of volume, audience arrangement, ceiling design and choice of materials. The room is designed to seat 2,690 people with good seating and viewing conditions, to accommodate a large orchestra and choir and to have a reverberation time in the middle frequencies of the order of two seconds. In addition it is designed to satisfy the subjective criteria of musical quality. It describes the solutions chosen to achieve these ends. The hall embodies the attributes currently recognized as desirable in large concert halls.

Design Criteria Generally

I believe architectural design, or any other design for that matter, is impossible without constraints and without a set of requirements, the needs for which have to be resolved. Architects are trained essentially as problem solvers, consequently one must not complain at the complexity of the problem set. A building for music in itself is about the most complex modern architectural problem.

Plate I
1 – Concert Hall with the Sydney Symphony Orchestra

Plate II
2 – Long shot of eastern profile of the Opera House from Lady Macquarie's Chair
3 – Northern foyer to the Concert Hall

It was not always so. The designers of Concertgebouw, Amsterdam, or Musikvereinssaal in Vienna faced only some of the problems of the Sydney Opera House. Noise levels in the cities in general would have been much lower: no buses, no jet aircraft, much less efficient ships' sirens, no air conditioning, smaller audiences, fewer alternative entertainments. The large audience is a modern economic necessity; not always conducive to the best quality in a room. Neither, apparently, were people so critical about their bodily comfort. It was quite possible to sit them close together (e.g. in Concertgebouw, with 28.5 in row spacing and 20.5 in chair width) in hard, uncomfortable chairs, which probably rattled even when they were new when people moved in them. Sight lines and vision also would not have been nearly so critically looked at as they are now. Furthermore, the buildings were given time to achieve a reputation through the performances and the bad halls were torn down. Some of the world's great halls are great because great companies have performed in them and they have acquired reputation and glamour as they have aged and as the number of great performances has increased. Covent Garden, for example, would not be regarded as an ideal theatre. There are seats there, conspicuously the gallery slips, from which it is possible to see very little.

But if there is a notable performance (and most of the opera performances at Covent Garden have fallen into this category since the days of Sir Thomas Beecham) people are glad to be there, to see part of the stage, if any, but to hear, to stand when they really feel they must see, and, most important of all, to have been there while the event happened. Professor Cremer, the celebrated German acoustician, who worked for a time on Stage II of the Sydney Opera House, made exactly such a comment. He said he believed the reputation of the old Berlin Philharmonic had been made for it by the performances there, that Furtwangler made the reputation of the old Philharmonic Hall, and he hoped that von Karajan was about to do the same for his new Philharmonic.

Table 1

Typical Overall Noise Levels, Expressed in Decibels, Measured at a Given Distance from the Noise Source (Levels below 85dB are weighted)

(L. Doelle, 1965)

Noise Source	Noise level, dB, *re* 0.0002 Microbar
Ticking of watch	20
Quiet garden	30
Average residential development	43
Light traffic (100')	45
Average private business office	50
Accounting office	65
Average traffic (100')	67
Boeing 707-120 jet at touch-down (3,300')	70
Automobile (20')	74
Heavy traffic (25 to 50')	75
Average light truck in city (20')	77
Lathes (3')	80
Cotton spinning machines (3')	85
Inside sedan in city traffic	86
10 hp outboard (50')	88
Boeing 707-120 ject at take-off (3,300')	90
Inside motor bus	91
Train whistles (500')	92
Average heavy truck (20')	93
Subway train (20')	95
Sewing machines (3')	96
Looms (3')	97
Riveting gun (3')	100
Wood saw (3')	100
Inside DC-6 airliner	105
Chipping hammer (3')	108
Automatic punch press (3')	112
Car horn (3')	114
Pneumatic chipper (3')	123
Large pneumatic riveter (4')	128
Hydraulic press (3')	129
F84 ject at take-off (80' from tail)	132
50 hp siren (100')	138

But in a new hall one cannot expect to be allowed this ingredient of time to evaluate it. In the case of the Sydney Opera House (which had a formidable reputation when my partners and I took over from Jørn Utzon in 1966) there was every reason to expect that there would be a great focus of critical attention on the building, consequently every possible scientific means of prediction should be used to ensure that the building would meet high standards of quality. Neither the audience nor a professional critic could be expected to excuse any serious acoustical defect, however good the excuses offered by the designers.

Table 2

Vocabulary of Subjective Attributes of Musical-Acoustic Quality

(Beranek, 1965)

Quality		**Antithesis**	
Noun Form	**Adjectival Form**	**Noun Form**	**Adjectival Form**
intimacy, presence	intimate	lack of intimacy lack of presence	non-intimate
liveliness, fullness of tone	live	dryness deadness	dry dead
reverberation	reverberant	lack of reverberation	unreverberant
resonance	resonant	dryness	dry
warmth	warm	lack of bass	brittle
loudness of the direct sound	loud direct sound	faintness ... weakness ...	faint ... weak ...
loudness of the reverberant sound	loud ...	faintness ... weakness ...	faint ... weak ...
definition, clarity	clear	poor definition	muddy
brilliance	brilliant	dullness	dull
diffusion	diffuse	poor diffusion	non-diffuse
balance	balanced	imbalance	unbalanced
blend	blended	poor blend	unblended
ensemble	---	poor ensemble	---
response, attack	responsive	poor attack	unresponsive
texture	---	poor texture	---
no echo	echo-free anechoic	echo	with echo echoic
quiet	quiet	noise	noisy
dynamic range	---	narrow dynamic range	---
no distortion	undistorted	distortion	distorted
uniformity	uniform	non-uniformity	non-uniform

Let us look at some of the problems confronting the designer of any building for music and then let us multiply their complexity by some special Opera House factor arising from the peculiar internal geometry of the volumes under the shells, by the weight restrictions arising partly from the extraordinarily difficult engineering task of building those shells at all, and the statically indeterminate podium, designed on inadequate information about sound transmission and sound isolation, with the result that its load carrying capacity was less than desirable. Add to this the consideration that practically every surface or projection which is designed into a room has some effect on its acoustics. The audience must be arranged in such a way that it is comfortable, and that its relationship to other parts of the audience is satisfactory. The audience must see and hear the performers and the performers must be able to hear themselves. Both audience and performers must be brought in and taken out of the auditorium safely. The noise level inside the room must be low and the sound inside the room controlled and distributed so that there are no places where people do not hear well. Finally, both performers and audience should enjoy the whole experience. The solution of this design problem placed extraordinary demands on the consultants and client and all submitted patiently to the long period of investigation, testing and design development involved.

The Brief for the Concert Hall

The Concert Hall design was done first and was fundamental to the whole project, because from a decision on the use of this room all other decisions flowed in 1966. The basis for the brief was contained in a letter written by the General Manager of the Australian Broadcasting Commission on 7th June, 1966, to the N.S.W Government Architect, Mr. Farmer. The stated requirements of the ABC were a seating capacity of 2,800, with comfortable seating and good sight lines. The staging requirements for concerts should be sufficient to accommodate a large choir, preferably an organ of adequate proportions for concert work and capable of the performance of the large-scale works in the standard repertoire. The performers and the audience should be in the same acoustical space. Presumably this point was made to express the ABC's reluctance to have the orchestra perform on a stage with a proscenium opening between it and the audience. This produces the effect of the orchestra playing in a coupled room and does not give the audience the effect of actually sitting in the music which is desirable if the quality of intimacy is to be experienced. Aesthetically the acoustics required were stated as having a reverberation time in the middle frequencies in the region of two seconds when fully occupied and electronic assistance was specifically not required. The character of the sound considered desirable was such as is found in the Boston Symphony Hall, Concertgebouw, Amsterdam, Old St. Andrew's Hall, Glasgow, and the Grande Salle of Place des Arts in Montreal. Two other desirable attributes were stated to be the exclusion of all extraneous sounds from the Hall, and a quiet, well-designed system of air conditioning. In terms of Beranek's noise criteria this should be no greater than N.C. 25.

Fig. 1 – Ground Floor

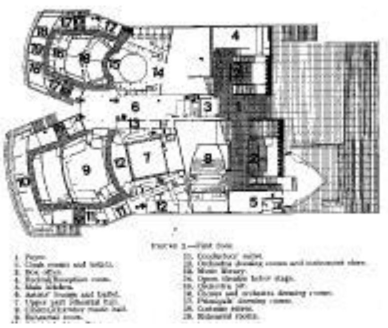

Fig 2 – First floor

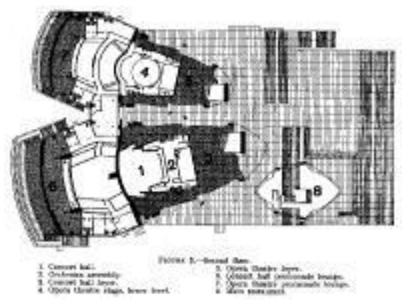

Fig 3 – Second floor

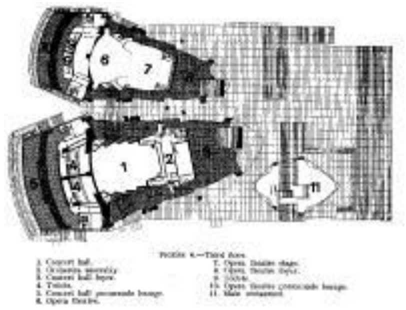

Fig 4 – Third floor

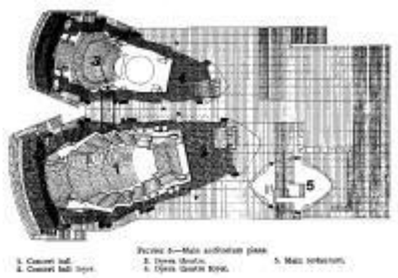

Fig 5 – Main auditorium plans

These requirements were formulated by the ABC's competent acoustic staff and present a good summary of currently accepted acoustic standards for large concert halls generally. A great deal of subsequent research, the findings of Beranek (1962) and Doelle (1965), the experience of Kosten and deLange in the new de Doelen Hall at Rotterdam, of Professor Cremer in the new Berlin Philharmonic, and the writings and views of many other authorities confirm this.

The two most readily identifiable objective criteria are clearly seating and reverberation time, since seats can be counted and reverberation time can be measured. Clarity, diffusion, brilliance, etc., form part of the subjective experience of the listener and the performer, and are not so readily identifiable. In fact, I believe there is as yet no satisfactory way of measuring these and it will be some time before they can be stated as design criteria, although it can be said that many of the attributes of a room capable of producing this good subjective response have been identified. In Christopher Gilford's article, he writes:

> "Thus it appears that the sound quality of a hall may be determined not only by the reverberation time, the diffuseness of the ,sound field, and the distribution of early reflections, but also on the height-to-breadth ratio and the shape of the ceiling zone. Clearly, this requires further investigation, but the general excellence of the Elizabeth Hall lends support to the idea.

Conclusions

The lessons to be learnt from the Elizabeth Hall are:

1. Reverberation time still remains the best indicator of the general acoustic quality and the fullness of tone : it is largely determined by the volume of hall per square foot of seating area, and accurate calculation on this basis is now possible.
2. Satisfactory tonal quality and definition is obtained without deliberate production of early reflections, provided that the diffusion is good.
3. The reason for the characteristic 'singing tone' of the best traditional halls is still not fully understood; it may require the existence of an appreciable height above the highest seating bounded by substantially vertical surfaces, as in this hall.

The 2,800 seat requirement of the ABC is, of course, a commercial one. Many of the great halls are smaller and the Berlin Philharmonic seats only 2,200. The classic way to achieve greater numbers of seats is to use'balconies which give in effect a multi-floor situation. The inward taper of the shells at the Sydney Opera House severely limited this possibility. In the case of the Concert Hall, where the number of seats clearly meant an enlarging of the seating axea already available, this was done by building out with cantilevered galleries over the side foyers and with a very large cantilever at the north end of the building which contains the terrace seating.

The Effect of Volume on Reverberation Time

In the case of reverberation time, it is well established that volume is the single most critical factor in achieving long reverberation time. Many of the concert halls built in the 1950's fell short of their target reverberation time because the effect of audience seating area in relation to volume was not realized. It is not only the number of people in the room, but it is the area they occupy which has to be taken into account in considering the volume-perperson ratio. Depending on the surfaces used and the shape of the room, the necessary volume per person would lie in the range of 320 ft3 to approximately 400 fts per person. In de Doelen the figure is as high as 400, but in Dr. Jordan's opinion this is a little too much volume. Beranek's table (Table 3) provides useful comparative data to which we can now add these figures for the Concert Hall in the Sydney Opera House:

V	Sa	So	NA	
Volume	Audience Area	Orchestra Area	Seats	V/NA
870,000 ft^2	13,590	2,000 ft^2	2,690	325 ft^2
T500-1000 (occup.)				
Reverberation Time		Seat Spacing - - - - - - - - - - -		Stage Height(in)
T mid 2.1	Row to Row		Seat to Seat	
	36”-38”		20”-22”	50

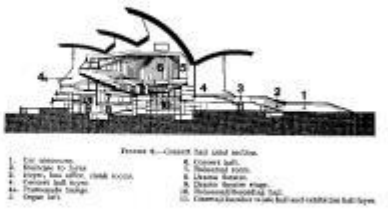

Figure 6 – Concert hall axial section

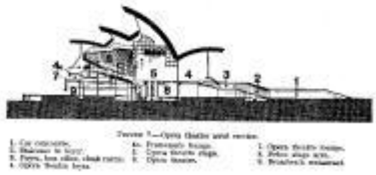

Figure 7 – Opera theatre axial section

Seating

A fundamental early decision taken was to use continental seating. When the seats are arranged in this way, there axe no longitudinal aisles. Obviously, when aisles run the length of the hall, in the centre they occupy some of the best area available for viewing. It is common sense to put seats in these positions. The second great advantage of continental seating is that better advantage can be taken of irregular shapes since the circulation space is located at the edge of the hall. The third great advantage is that there has to be room for people to get past those already seated, albeit at the expense of the possible.movement of their knees as somebody passes. But the rest of the time that a person is sitting in the chair, which is after all a much longer time than that taken by people to get past, there is more leg room available than is normally provided in multi-aisle arrangements. Further, continental seating offers a safety advantage. Ben Schlanger, our consulting theatre architect, had, shortly before we engaged him to work on the Sydney Opera House, recently completed a draft for a new code for places of public assembly for New York City. In the course of his research for this he had observed that the history of theatre disasters showed that loss of life was caused not by people being overcome by smoke or flames, but by being trampled because of poor exit and safety arrangements. He concluded that it was not desirable that a row of seats should quickly discharge into an intersection at aisles, neither was it necessary that a room be cleared instantly. What was impodant was that people should get, in reasonably fast time, from their seats to a safe area and that some control of the rate at which they reached the doors and entered that safe axea was desirable. Continental seating introduces virtually a queueing condition, and unless rows are spaced extraordinarily far apart people will not try to overtake other people, with the consequent risk that somebody will be knocked down, but they will proceed in an orderly manner to doors the width of which is calculated to be adequate for the number of people using them and to empty the hall quickly. The test concerts so far held in the Opera House have confirmed that the auditoria in fact emptied much faster than others in the city and that the audience dispersed through the foyers at a very quick and comfortable rate.

TABLE 4

Sydney Theatre Seat Spacing (1966)

Theatre	Row to Row	Centre of Arm Rests	Comments
St James:			
Stalls:	2’ 11”	1’ 7”	
Lounge:	3’ 0”	1’ 8”	Fairly comfortable
Dress Circle	3’ 0”	1’ 8”	” ” ”
Royal:			
Lounge	3’ 0”	1’ 8”	” ” ”
Phillip:			
Main Floor	2’ 11”	1’ 7”	
Rear	2’ 10”	1’ 6”	Tight, especially in width
Tivoli:			
Lounge	3’ 0”	1’ 7½”	Fairly comfortable
Gallery	2’ 8”	1’ 5”	Excessively tight, both ways
Town Hall			
Main Floor	2’ 11” (approx.)	1’ 9”	
Side Gallery	2’ 11”	1’ 9”	Reasonable, not much leg room
Back Gallery	2’ 9”–2’ 10”	1’ 9”	Tight for leg room
Barclay:			
Stalls	3’ 1½”	1’ 7”	New seating (four years old)
Gallery	3’ 2”	1’ 7”	Comfortable, especially as regards leg room
Her Majesty’s:			
Lounge	3’ 5”	1’ 9”	Very comfortable — Manager thinks these are the largest seats in Sydney
Stalls	3’ 2”	1’ 7”	Comfortable
Gallery	2’ 8”–2’ 9”	1’ 8”–1’ 9”	Too tight as regards leg room

The dimensions of the seats themselves range from 20 in to 22 in and the row spacing varies from 36 in to 38 in (Table 4). Special attention has been paid to the design of the individual chairs. A hydraulic tilting mechanism has been chosen because of greater quietness and reliability than springs and slower action than weights. One of the least satisfactory qualities of most theatre seating is that it is visually disorderly. Tip-up chairs do not all return to the same angle, and the individual chairs with gaps between look like a collection of postage stamps. An acoustic requirement of Dr. Jordan that there should be some exposed hard surface above the shoulders of the audience helped in the solution of this visual problem, which resulted in placing the upholstered back of the chair in a curved plywood shell. The same plywood as for the ceiling of the hall is used. This material is used extensively throughout the building, helping to achieve a unity of material difficult to attain in such a large and complex building as the Sydney Opera House. From both front and back the rows of seating take on the character of continuous arcs, not a collection of individual postage stamps. The upholstery material is a polyurethane foam chosen because of its firmness and because it could be well contoured to support the important areas of the small of the back and the popliteal muscles under the thighs. The upholstery does not readily yield when people sit on it, but most experience shows that this produces longer lasting comfort than soft upholstery, which compresses to the shape of the user's body and as a result does not give support. This thinking is now evident in the design of seating for motor and racing cars in which driver fatigue and comfort are critical. There are also modern classics of furniture design, for example by Breuer and Tobia Scarpa, which are very firm indeed. Although the fire risks associated with it are slight, the polyurethane is encased in a flameproof wrapper and then covered, in the Concert Hall (and all auditoria other than the Opera Theatre), in pure wool. In the Opera Theatre the covering is leather. The reason for the difference is that the absorption of the chairs in the Concert Hall is designed to be close to that of a person, whereas in the Opera Theatre, where there is a very much lower volume ratio per person, Dr. Jordan wanted empty seats to add to the reverberation through the use of a reflective upholstery fabric, hence the leather.

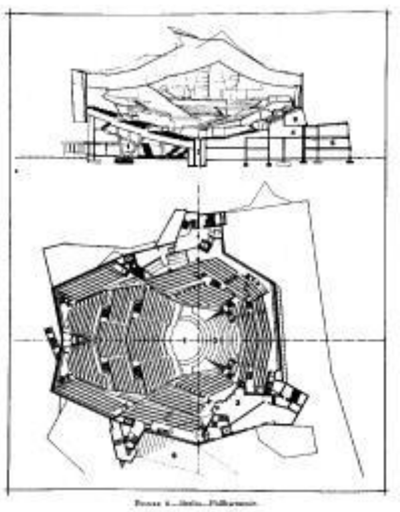

Figure 8 – Berlin Philharmonic

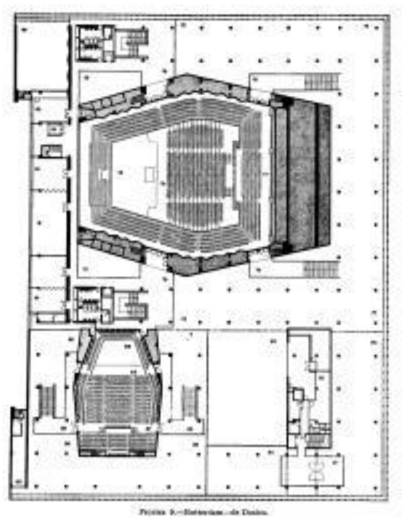

Figure 9 – Rotterdam – de Doelen

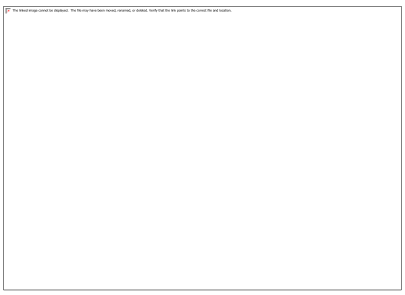

Figure 10—Cross section and long section, Rotterdam—de Doelen

The seats, arranged in this system, are subdivided into relatively small areas. This is made necessary partly by sight line considerations, because in the side terraces the closer one is to the platform the steeper the rake of the seats has to be, partly because subdivision of any audience of

2,700 into smaller groups is psychologically desirable and partly by the requirement that the furthest seat should not be too far from the source of sound, which is why there are some audience seats behind the platform. Provided the sound is good in such a location, these are not objectionable seats, giving an excellent view of the conductor.

The seating arrangement has some of the qualities of de Doelen and the Berlin Philharmonic, which has an even less regular arrangement of seats than we have and is a room which it is good to experience. The plan form at Sydney was of course largely dictated by what was already built during Stages I and II.

The Ceiling

While seating is determined by capacity, comfort and sight lines, the design of the ceiling is the area in which collaboration of architect, acoustician and engineer becomes of the greatest importance, since it is here that the acoustics of the room will really be determined. Within the limits set by the shells (some 1,000,000 cu ft in all) its overall volume is determined by the volume/audience area relationship and by the need to arrange surfaces in such a way as to allow a build-up of reverberation and a distribution of sound evenly over the seating area. The ceiling is supported from the shells by trusses hanging between the arches. On the outside is the layer of thin concrete referred to by Dr. Jordan. In the void between the outer and inner layers run the services. The inner layer is made up of ½ in plywood with a backing of 1 in plasterboard. Plywood was chosen because the steel trusses will inevitably flex a little and a continuous envelope such as plaster would not have been practicable, even had it been thought aesthetically desirable. Thin plywood by itself, however, would not retain the bass sufficiently well for the music to have enough warmth, hence the plasterboard backing, a system developed with Dr. Jordan to retain the bass without exceeding the very stringent weight restrictions. This material was capable of complete prefabrication off the site, and of the use of dry jointing techniques using plastic gaskets.

It is not easy to achieve a relationship between the ceiling of a hall and the audience because when the audience is broken up into its individual seats it is rather small in scale, whereas the ceiling of a hall with a volume of the order of 860,000 cu ft is of necessity very large. The plywood ribs have accordingly been arranged in a way related to Japanese paper folding, with two major bends in them as they radiate from the platform zone. They follow the audience's sight lines to the chosen arrival points of sight. On the way they have a number of protrusions, some of which accommodate lighting and which act like the coffering of a Victorian hall. The planes step in relationship to each other, and this stepping gives much the character of pilasters in the old halls, with resulting improvement in diffusion and sound quality.

Materials

Since heavy materials like off-form concrete or marble, as used at de Doelen, were out of the question the important lower surfaces surrounding the orchestra and separating the various seating groups had to be both reasonably light but retentive of the bass. For these surfaces and the floor solid thick timber, laminated brush box, was chosen. Like the ceiling, this could be prefabricated off-site, with the advantages of time-saving and improved quality control implicit in prefabrication in a factory. The result is an all-wooden room which is designed, because of the small number of materials used, to offer little to distract the observer from appreciating the volume, the forms enclosing it, and the bright facade of the impressive Sharp organ over the choir.

Conclusion

So far, objective and subjective assessment of the room has been good. Oddly enough, I believe the shells themselves, although a sort of restrictive straitjacket and the source of much design difficulty for architects and consultants alike, have contributed to this result. While their shapes, volume limitation and load capacity posed difficulties, they forced on us a long, narrow room with greater than normal height which is certainly contributing to people's visual experience and may well assist in producing Gilford's "singing tone". Certainly the room embodies much current philosophy on concert hall acoustics and shows promise of achieving in use many of the characteristics thought desirable. It is now for the performers, over an extended period, to find out whether it fulfils this promise.

Acknowledgements

Important contributions were made by all those acknowledged by Dr. Jordan. In addition much useful information and advice was given in the early stages by Warwick Mehaffey, acoustic engineer with the ABC, and Dean Dixon, then Musical Director of the ABC.

The realization of the design made necessary, because of the interaction of every component, an extraordinarily close collaboration between architects and consultants. Special mention should be made of Michael Lewis, Ian Mackenzie and Frank Manly (Ove Arup and Partners), Arne Larsen and Edvard Mortensen (Steensen and Vanning), Frank Matthews (Julius, Poole and Gibson), Dick Chappell and David McKellar (lighting).

In the execution of the work the subcontractors made every effort to achieve standards of workmanship and quality rare in building anywhere in the world. In particular, the work of Cemac Brooks, who tackled the job of building the ceiling on a firm price basis and performed splendidly, deserves special commendation. This sub-contract did much to dispel the then prevalent belief that prediction and planning were so difficult as to make firm prices and programmes impossible on the Opera House.

Phil Peach, of Co-ordinated Design and Supply, the seating suppliers, collaborated with us in developing the design of the chairs through successive prototype stages. Continental seating had not previously been used in N.S.W. and at the time of its design was not legal. Aden MacFarlane, of the Chief Secretary's Department, made a careful study of its advantages and formulated dimensional criteria resulting in its acceptance by his Department. Not only was this vital to us, but it will prove an important milestone in theatre design here.

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