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Model making at Arups

David Armstrong

Times have changed in the model room since last I wrote about it three years ago.* Gone are the solitary, but cosy, days of Stanley knife and steel rule. The dear old British craftsman has been hustled relentlessly into the age of automation and Parkinson: four new machines and two new pairs of hands have arrived, and consequently production has increased twelvefold. We all find this a bit bewildering at times.

In my last article I piously advocated a backwoods attitude towards model making, as opposed to the technological approach, on the grounds that it was more flexible and that really suitable machines were not to be had. This view was based largely on conservatism and ignorance and I must now change my tune. Our machines have various drawbacks but they do enable us to do many things impossible before and other things a lot more quickly.

We now buy our timber in large sizes and convert it ourselves. This frees us from the tyranny of Balsa and Obeche, the two woods easily available in finely graded thicknesses. Balsa has good qualities but soon becomes battered and dirty; it also brings on sneezing fits when sanded. Obeche is nasty stuff, smells like a chicken house and we are glad to be rid of it. Our new mainstays have delicious aromatic scents and also meet our other needs very well. These are Canadian Yellow Cedar, Western Red Cedar and Columbian Pine. They are very stable, not too hard on our circular saws and can be sawn to a very fine finish with hollow ground blades. This process cuts out hours of planing and sanding and means that we can produce quite awkward sections quickly without having to finish them by hand.

Yellow Cedar we use to represent concrete. It is probably too clean and precise for this purpose, except at very small scales, but designers and clients, alike, prefer to imagine that their concrete will really look like this. It makes a good contrast with Red Cedar which stands for brickwork: it does this very well varying in colour from pink to dark brown, and in annual ring width from 1/16 in. to 1/4 in. Columbian Pine, otherwise known as Douglas Fir, is particularly suitable for structural woodwork being strong, even-grained and unlikely to warp. For large, flat areas, baseboards and boxes we use 1/2 in. Douglas Fir ply, and Birch ply of various thicknesses down to 0.75 mm. and occasionally Gabon ply which, being French, comes in usefully capricious thicknesses. The last two of these are warped by Arups' rarified atmosphere, the Gabon to an unbelievable extent.

As well as wood we use sheet plastic and card. The plastic can be sawn and grooved in the same way as wood, though not so easily. We use it to represent glazing, and for invisible support in sectional models. Some model makers work almost exclusively in plastics but we think that their resulting models look rather dead, especially when painted. Card is used in models which do not need to last or to be amended.

ARM TWISTING

Another change which occurred some time ago is in the allocations of model making time. In the old days a prospective client would enter the model room armed with a bundle of drawings, would utter the magic word 'Foggo', and I would set to work to make him what he wanted. Two days later another man, similarly laden, would appear and pronounce the word 'Ahm'. Having found out how to spell this, I would rush to the Arup equivalent of Burke's Peerage, a piece of notepaper displaying the partners' names at its head, and having consulted it, would hastily put away the unfinished model and set about trying to propitiate the god 'Ahm'. This process would be repeated until, by the end of a fortnight, things would be fairly well out of hand. There would then be a confrontation between the deities concerned. This would involve the exchange of spells mounting in intensity, 'Hobbs', 'Dunican', 'Arup'. The first to say 'Arup' was, of course, the winner and his model would have an uninterrupted passage. Now, apart from the wasted fortnight, this system worked quite well as far as I was concerned. However there were those who were unhappy about it and we now have a new system. We are deaf to all spells but one, 'Sugden'. This makes the whole business much simpler for us, if not for Derek Sugden, who has to work out the priorities. Of course people still come to us with little jobs 'so simple' that it is not worth putting them through the administrative machine; like half a mile of elevated motorway with asymmetrically cambered road surfaces, a couple of tributary roads, all resting on a set of experimental columns whose shape would have given Euclid sleepless nights. The very mention of a tiny, simple job now makes us hesitate to do so much as sharpen a pencil for the most innocent looking visitor, in case it is used to draw up a little scheme which will hatch out into a monster to gobble up all our working time.

METHODS OF WORKING

This administrative streamlining, coupled with faster production, means that our clients often get what they want before they expect it: by the time they have decided they would like a thing or two changed, we have started a model for somebody else. Once upon a time I could begin a model with as vague an idea of what was required as the man who wanted it. Then as something took shape, more specific details would emerge together with suggestions for alterations and additions. It would then turn out that somebody thought it would be nice to put the model on an aeroplane and fly it out to Africa to show an interested party there, when all the time I had been making it specifically for home consumption. Of course models can still be made like this but it should be remembered that they cost at least four times as much as those for which

* In: The Newsletter, no. 14, pp. 25-34, 1963

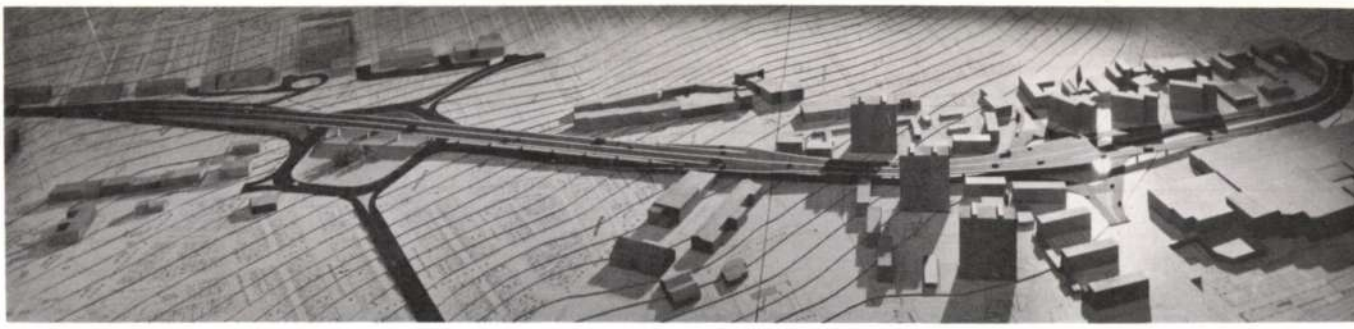


Fig. 1
Model to scale 1:500 of central area of Gateshead with the proposed new viaduct (photo: Henk Snoek)

precise details and requirements are supplied in the first place. If I describe the way we work it will make this clearer.
First a provisional date is fixed on which we will start the model. A week before this date we find out what materials we are going to need and what drawings are going to be provided; and if necessary we send site plans, which are seldom to the scale required, away to be blown up or down as the case may be. So on the starting date we should not have to hang around waiting for vital information or materials. One of us can start making a baseboard, another can convert timber into precise thicknesses for the third to cut up into the various components of the building to be modelled. The baseboard maker must know whether the model will stay at home or travel, and if so how; and what sort of lid, if any, it will need. The other two will want to know precise details of all components involved.
This is why the designer who tells us, half way through the second day, that there is a small strip of land to the NW to be added, just a couple of inches on the model; or that the beams are all six inches deeper than they were the day before; will be greeted with mutterings and hostile glances. The baseboard or beam manufacturer is wishing that he had spent the previous afternoon sunning himself in the park, instead of blunting blades and wasting timber. To this extent the new method is less flexible than the old but it is so much quicker that it is well worth the extra forethought which must be spent on it.
Once all the basic components have been made they can be fitted together, sometimes an agonizing process when each has to accommodate itself to the inaccuracies of the others. Then the subsidiary items such as roofs, chimneys, roads, trees and people may be added.
Of course we can still make experiments to show how some feature will look and to satisfy the designer that he is getting what he wants; but these must be made before work has begun on any part which might be changed as a result.
That is rather an idealized picture of the way we work: the course of true model making seldom runs so smooth. However, if you want a model you can help it to do so in the following ways.

SMOOTHING THE WAY

First, one man only should be responsible for liaison between design team and model room. Sometimes as many as four turn up one after another, each with his own idea of the purpose of the model and how it should be expressed. It would be better for our efficiency, and morale, if three of them came simply to gasp with admiration. So there should be initial agreement as to the model's precise function. This will determine its overall size, the degree and nature of detail to be shown, durability of materials and cost.
The size of the baseboard is often governed by portability. To move within the firm it must fit into a lift. If it is to travel it should go into the firm's van, or some vehicle which can be press-ganged for the purpose. Failing these, a van can be hired but this can be exceedingly expensive, almost doubling the cost of the model at times. I made an enormous model which had to leave by the window. It turned out to be too large to transport economically to the site for which it was intended. In the end it had to be broken up, half a day's work, and the council paid to take away the bits.
Some people want every detail shown, because they cannot bear to see anything left out. This has the same sort of effect as mixing too many colours together: the result looks like mud. Most models are intended to demonstrate some particular point and any detail which does not contribute to this point weakens the impact of the model. We try to avoid all unnecessary detail. Unkind critics may draw their own conclusions, but actually excessive detail is only appreciated by the designer himself and by those with very long sight or in unusual psychological states.
Points to be hammered home can be accentuated by variations of colour or texture and finer points can be shown on a larger scale, sectional model.
Durability is the next point. Some models have to last a long time, be amended once or twice, dropped by porters and architects, and generally maltreated without showing the scars too badly. One was actually sat on by an alcoholic admirer at a party: he must have mistaken it for one of Arup Associates' avant-garde furniture designs: it collapsed and with it any reputation he might have had for a knowledge of structures. Other models are intended primarily to be photographed. These can be made quickly of Balsa and card and impressive photographic results can be produced from a cheap model. Skilful photographing can do a lot towards creating an illusion of reality.

THE CORRECT PROCEDURE

At this point I would like to try and exorcise a ghost which has troubled us for years. This phantom, or rather figment, is the 'quick, rough model', and it has a lively existence in the minds of some of our less practical clients. The word 'rough' here refers rather to accuracy than to texture. The truth is that speed depends on accuracy. The less accurate the purveying of information to the model maker, the longer will he take to work out the construction of the model; the less accurate the making of the components, the longer they will take to put together. The only real aids to speed are a clear specification and absence of detail. A rough drawing may convey quite a lot but a rough model simply will not hold together.
When you have considered all this you should book model making time with Derek Sugden and persuade him that your project is more important than anyone else's on the list. Then you should come to us and if you tell us clearly what you want, we can tell you how long it will take to make. Then you go back to Derek and he dovetails it into our programme, according to the priority he gives it, and the time to be spent on it. The worst jobs are those which take a long time yet have a low priority and are always being pushed aside by more urgent ones. We can hardly bear to get out of bed on a morning when we know we will be faced by an awful box full of dusty bits, to try and relate to a set of drawings whose significance is just beyond the threshold of memory. On the other hand, a fresh and urgent project can be quite intoxicating.
Maps, surveys, or site plans are essential for any model showing landscape, grouping of buildings, or trees. These

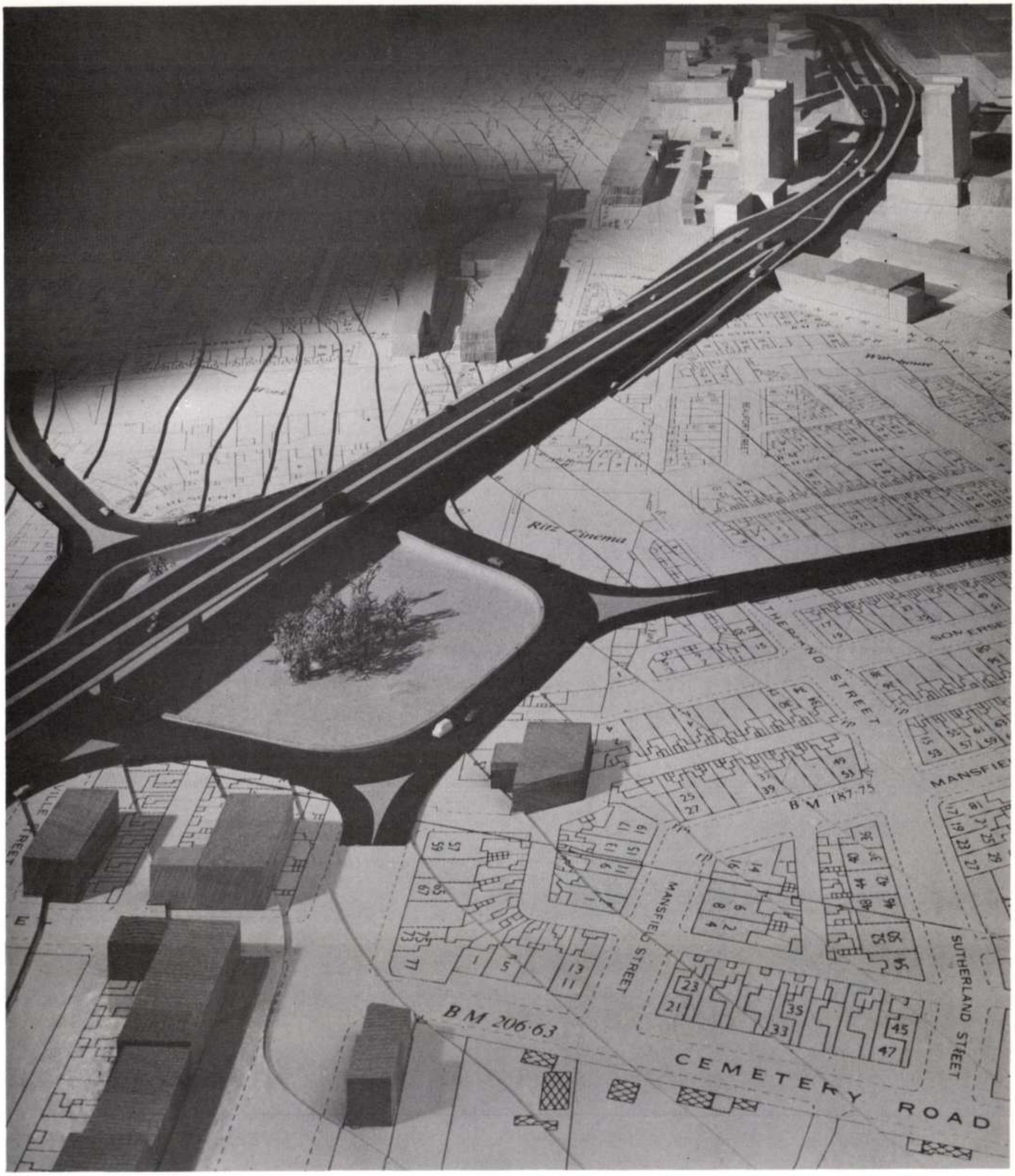


Fig.2
Model of Gateshead Viaduct
showing detail of photographically enlarged map
(photo: Henk Snoek)

Fig.3 Right
Technique using block models representing
existing buildings. N.B. Although the viaduct seems to end,
it won't. (photo: Henk Snoek)

must be of the scale of the model and adjustment of scale takes up to a week. With the model of Gateshead Viaduct, which we started last winter, we had the map of the site enlarged and printed on washable paper. This was cut along the contours, mounted on ply of appropriate thickness and built up into a 3D map of the site, on which was placed the model of the viaduct, and other buildings having relation to it. Less relevant buildings remained in 2D. Thus we had a half diagrammatic representation of a mile of built-up area, useful to the road designers, immediately recognizable by the layman and yet avoiding the cost of making hundreds of acres of tiny terrace houses, each with its backyard, wash-house and earth closet.

It is unlikely that drawings already in existence will be of much use to us without a good deal of supplementary information being added. Verbal instructions tend to be misinterpreted or forgotten, or both. The man who gets his model quickest, and he does exist, is the one who supplies minutely accurate drawings of each component to the scale of the model. We can then refer directly to them without recourse to dimensions or scales. If your time is not worth more than twice ours, this is probably the most

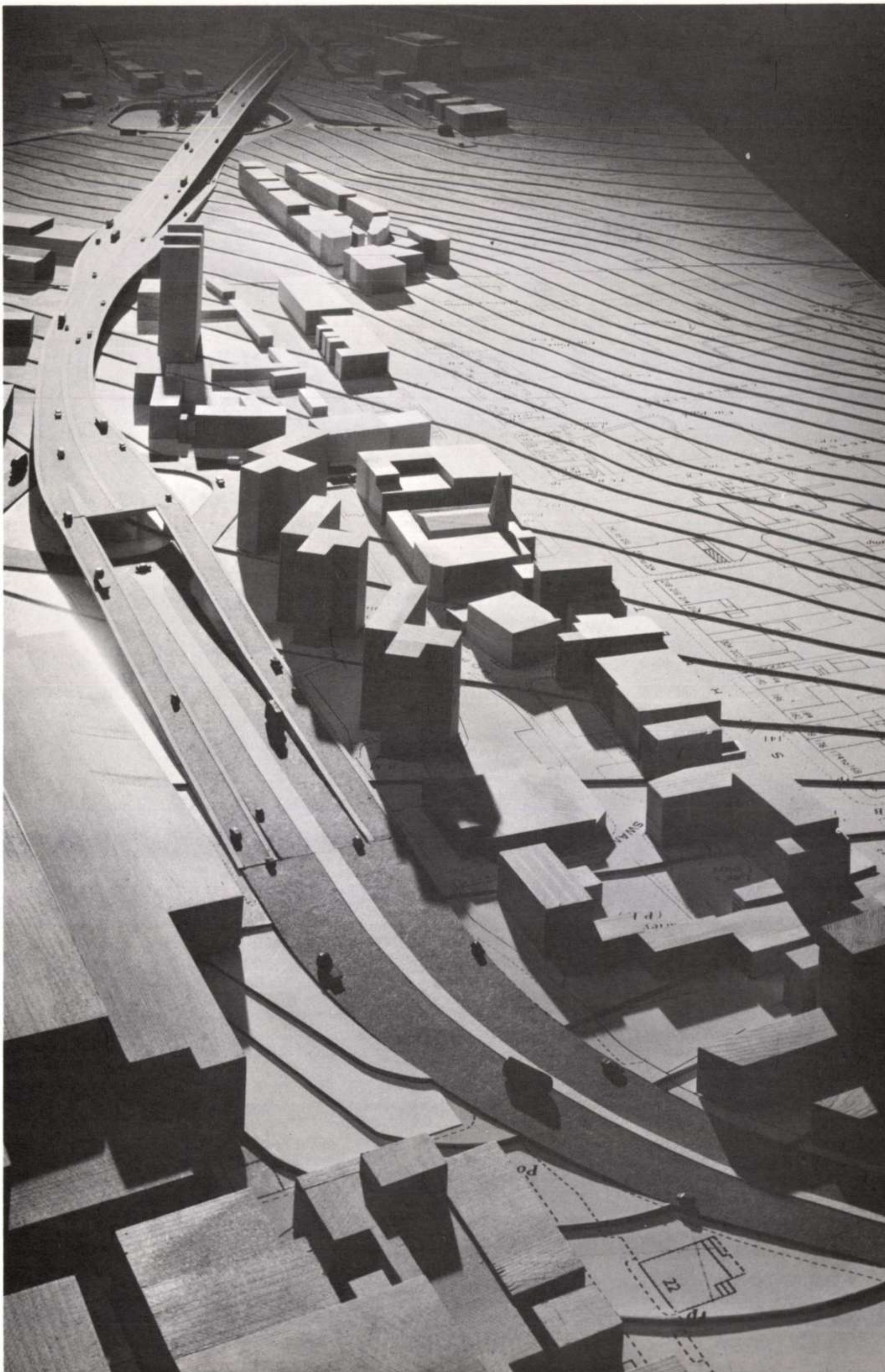


Fig.4
Leicester University, Attenborough Building
(photo: Harry Sowden)

efficient way of making a model. The relevant dimensions are, after all, printed on your imagination, whereas we may have to search for them amongst a mass of distracting and ambiguous detail.
The next best thing is a set of dimensioned sketches of the components and their relationships when assembled.
After this comes a set of architect's or engineer's drawings, suitably amended in colour to show the extent of the model, and what features to include and what to leave out.
Of course there are occasions when we model details to a quarter, half or even full size and then the full working drawings are all we need.
We may at times seem to be excessively fussy about this question of scale, but, unless you have the faculty of instant arithmetic, working with a variety of scales, too few dimensions, and prints which have stretched, can bring on a state of occupational paralysis. At the moment we are making a site model to 1 : 250 scale, from drawings of 1 : 500, 1 : 1000, and 1/32 in. to 1 in. scale, all containing conflicting information. The 1 : 250 scale enlargements were not thought of in time and will arrive too late to be of any use.
Often people want to make their own models, and here we can help by making baseboards, and fancy sections by the yard. A machine may do in ten minutes what would take a hardy backwoodsman half a day. All we need is a precise cutting list. We used this method with the Great Belt Bridge competition model, supplying Yuzo Mikami with a baseboard, rough sea, length of bridge section, ocean liner and components for piers which he glued, assembled and finished himself.
To end I would like to say a little about some of the more interesting models we have made in the last couple of years. There was Leicester University Attenborough Building: we had to make a rather detailed representation of the tall blocks to a small scale. This involved what almost amounted to the interweaving of strips of wood and perspex, to demonstrate the many faceted facade. It took us a whole day to work out a cutting and slotting programme with a sequence which had to be stuck to very strictly. I took the precaution of going on holiday next day, leaving my mate simply to carry out the programme. It worked with some amendments.
Loughborough University has been with us for two years, involving some seven models of various types, ranging from one of the whole site, to a typical floor system with services at 1/12 full size. We later added a couple of floors and various cladding designs. We had an interesting little excursion into solid polyester resin construction with this floor. It ended when a four ft. girder started to burn as it was setting in its wood and plastic mould. I had prudently gone to get my hair cut, and Mr. Arup chose that moment to bring Mrs. Arup to see what was going on in the model room. I returned to find that my mate had coped very well with the aid of some hurried excuses and a good deal of water. We made the floor of plywood.
In complete contrast was the hangar for the Zambian Air Force. It was made of Balsa and card; and it took us five days complete with sliding doors and a de Havilland Caribou to go inside. This was due to perfect drawings and no amendments. Photographs almost turned it into the real thing.
A model which fired our imagination and taxed our ingenuity,

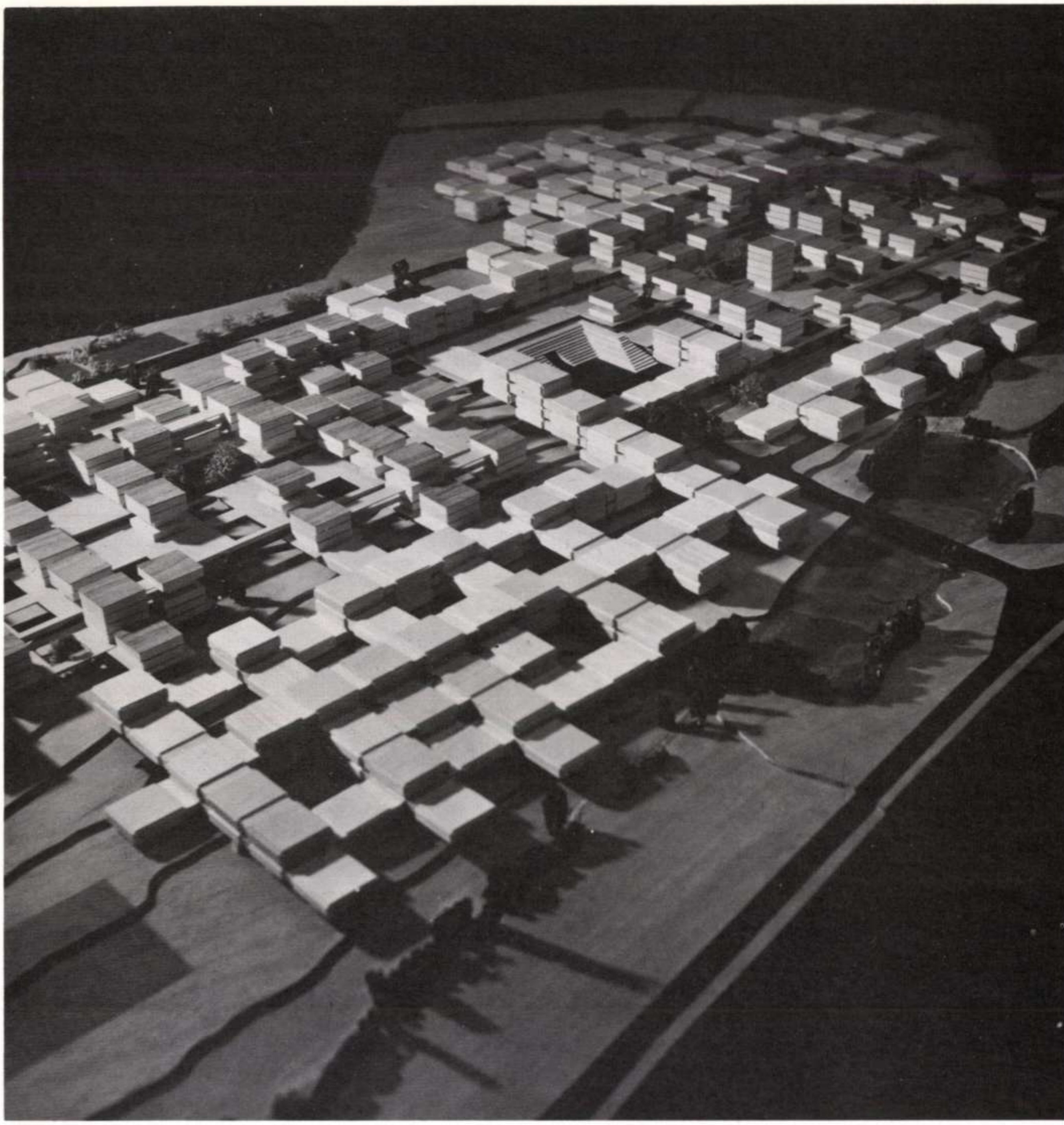
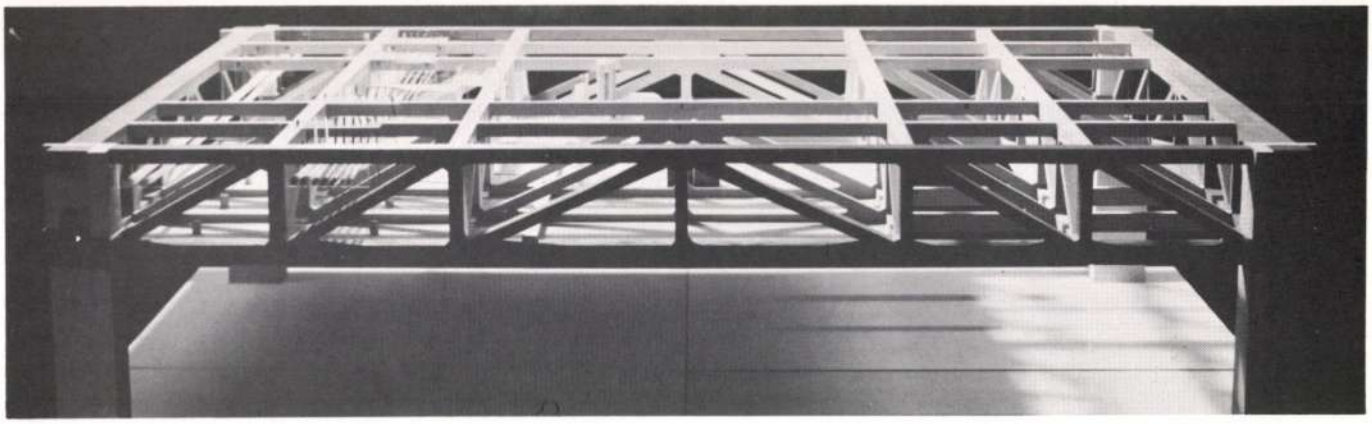


Fig.5
Loughborough University of Technology
General view of development
(photo: Harry Sowden)

was Alistair Day's radio telescope, a very simplified, but mechanically working model to a small scale. We used fibre glass reinforced polyester for the four concrete boats on which the structure revolves. We all three worked on this model one after the other, and each retired battered but unbowed to hand over to the next.
Lastly there has been the conversion of part of the Snape Maltings into a concert hall for the Aldeburgh Festival. Originally the model was to be of the interior only, but as time went on more and more external features were added until the outside was finished in as much detail as the inside. At the same time there occurred a gradual metamorphosis of function, from a design model into one which could be displayed in public without too many blushes. This was made possible by two factors. One was the set of beautiful and accurate survey drawings on which we based the model. The other was the fact that most of the parts which suffered from the vicissitudes of the creative process, were made of solid wood. This shows the scars of alteration much more gracefully than more artificial substances like plywood, hardboard and plastics. The same, of course, is true of the old brickwork of which the Maltings is built. We got as much of a bang out of this job as the contractors who are doing the conversion.
In fact we get a bang out of most of our jobs. We nag at people because we are idealists and would like what we do to be done more efficiently and without so much meaningless delay. I have not mentioned one of our chief impediments: this is shortage of space. Our three selves and four machines occupy a space just big enough for two people and one general woodworking machine. This means that we can only work efficiently on one model at a time, and even then we are continually getting in each other's way. With a big model one of us must either go on holiday or become a serious obstruction. We have received veiled hints that this state of affairs will be rectified one of these days. The danger is that when this happens we may become so efficient that one of us will become redundant. Perhaps it would have been better to keep mum. There must be a moral in this somewhere.



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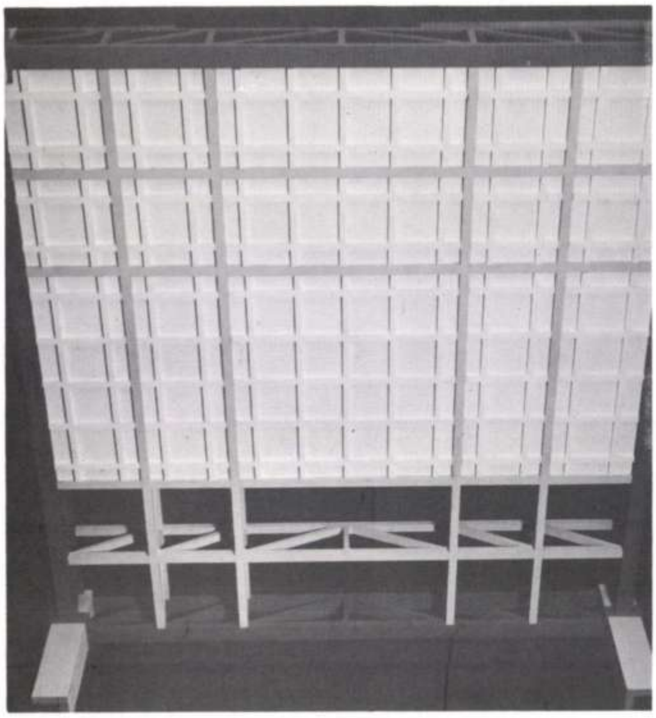

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Fig.6
Loughborough University of Technology.
Structure of the 50 ft. 'squares'
(photo: Harry Sowden)

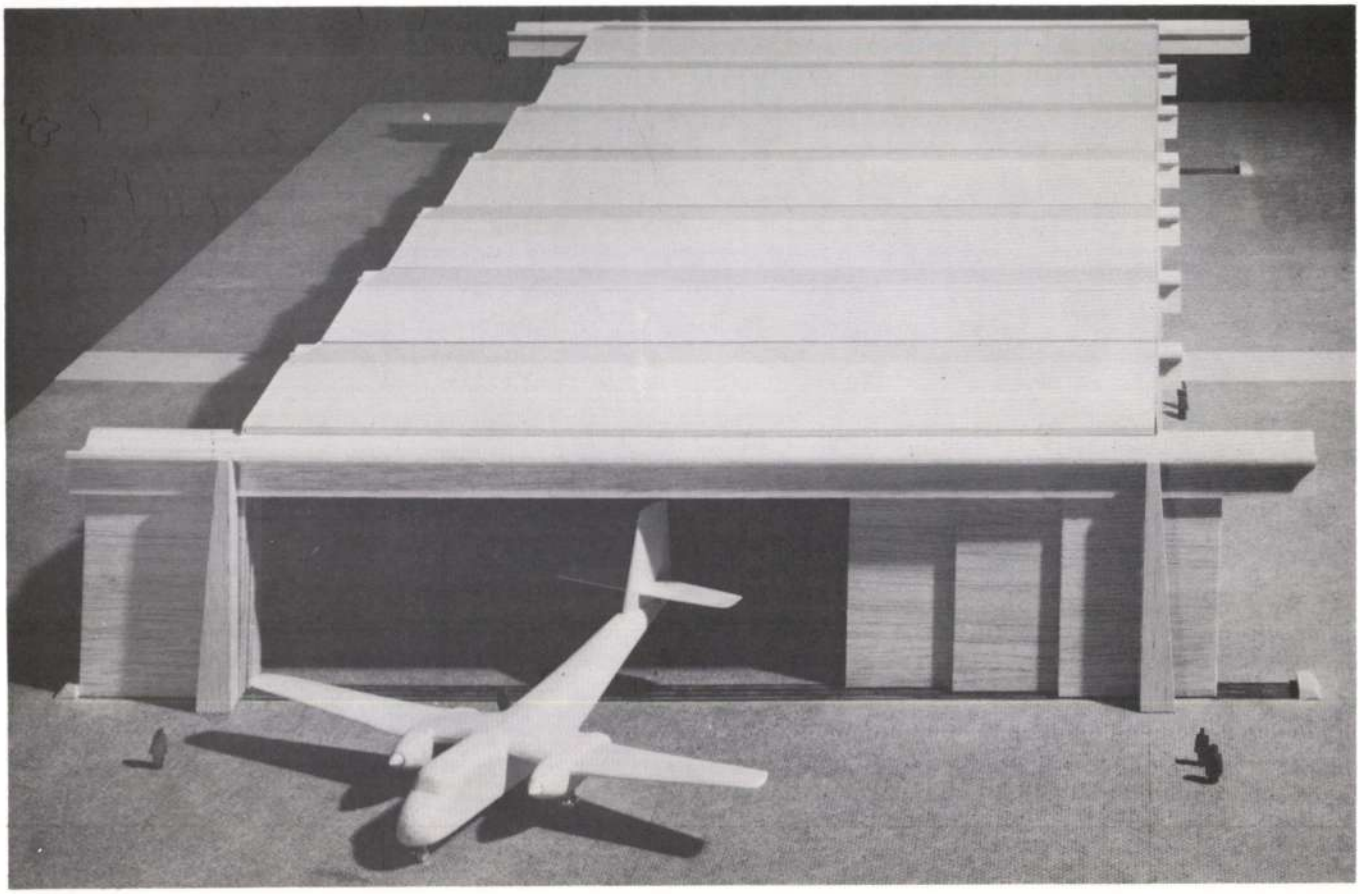
Fig.7
Loughborough University of Technology.
View of ceiling showing partition grids
(photo: Harry Sowden)

Fig.8
Zambian Air Force hangar
(photo: Henk Snoek)

Fig.9
Aldeburgh Concert Hall.
View of auditorium from stage
(photo: John Donat)

Fig.10
Aldeburgh Concert Hall. Main entrance
(photo: John Donat)

Fig.11
Aldeburgh Concert Hall. Main entrance
(photo: Harry Sowden)



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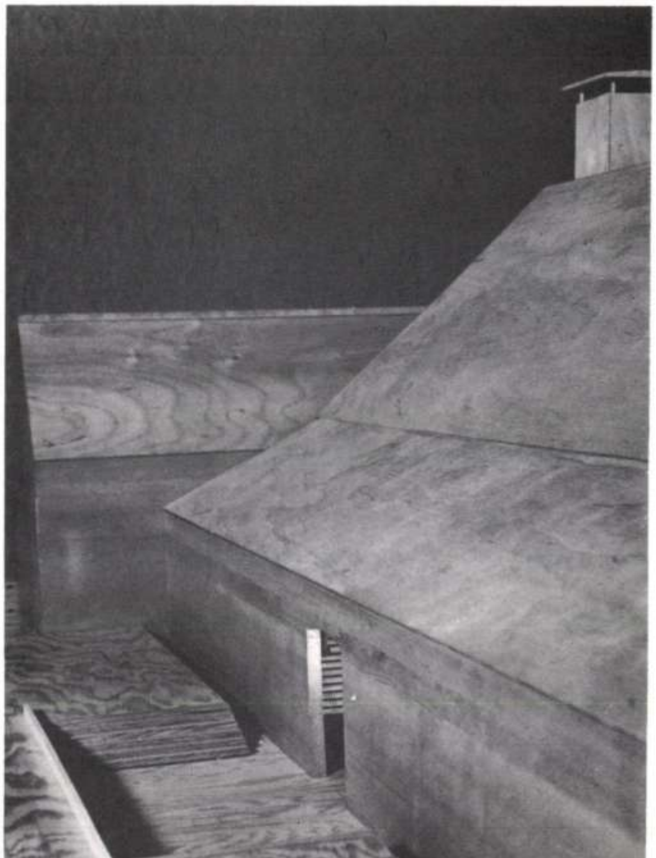
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*Editorial note:
This paper will be discussed at the first Technical Staff Meeting in December.
Everyone is invited to attend and to contribute to the discussion.

Random thoughts on durability*

Turlogh O'Brien

In his inaugural address as Professor of Building at University College, London, in February, Professor D.A. Turin pointed out that the cost of maintenance represents about 30% of the total expenditure on construction. This has been confirmed by the Ministry of Public Building and Works, at whose recent conference on maintenance a figure of £1,400 million per annum was given for the present cost to the country. This will rise to about £2,000 million per annum in 1970.
If it is accepted that this amount cannot be afforded, particularly in terms of labour, some very drastic reappraisals of the approach to building design are required, not only from the actual designers, but also from the clients and the Treasury - through the Inland Revenue. When put like this, the problems of developing a general durability-consciousness seem insuperable but every little bit helps.

At the design stage, distinction should be made between avoidable and unavoidable maintenance. The former should clearly be eliminated and the latter should be capable of being efficiently carried out. The idea of maintenance manuals being handed over with the buildings, is one way of ensuring that the requirements for unavoidable maintenance are fully understood. Designed maintenance will allow the concept of the 'life-cost' of a building to be used more effectively.
This article does not attempt to solve all the durability problems that arise in the structural side of building. Some of the technical aspects of the durability of concrete, steel, corrosion-resistant metals and paints are discussed, with reference to problems that have arisen on particular jobs.

SULPHATE ATTACK OF CONCRETE

Concrete which is sufficiently strong to cope with required loadings is subject to deterioration from four main causes:

1. Frost
2. Sulphates and acids in soils
3. Corrosion of reinforcement
4. Sea-water

Frost damage only occurs when the concrete can be saturated and air-entrainment (1) can prevent any serious trouble. Sea-water damage although put in a separate category, usually results from all the other three causes, with salt crystallization and mechanical impact of waves acting simultaneously. (2) (3)
Sulphate and acid attack of concrete foundations (4)

continues to excite a large amount of interest. It is probably true to say that one reason for the extent of discussion of the subject is the lack of real data. In view of the fact that failures of concrete due to sulphate attack are almost unknown and those few that have occurred have had other reasons for failure as well, it is worthwhile to examine the reasons for the degree of caution that is now taken. This is particularly necessary when it can be argued that as no concrete pile has failed through chemical attack, no chemical soil analysis or special cements can be justified for piled foundations.

The absence of evidence from the field other than from mortars and renderings, has meant that laboratory experiments have formed the basis for the recommendations. These experiments consist of immersing cubes of different cements and concrete mixes in solutions of sulphates of various concentrations and recording the visual appearance and cube crushing strength after various periods of time. The fact that complete disintegration of concrete cubes can occur in these experiments has led to the assumption that severe deterioration could occur on sites whose sulphates in groundwater could come into contact with the foundations.

It is hoped that the gap between present knowledge on laboratory tests and performance in practice will be partly filled by the results of a research project which is under discussion for the Northwick Park Hospital site in Harrow (Job no. 1705). This site showed sulphate concentrations up to 530 parts SO_3 per 100,000 in the groundwater, a figure which has only been exceeded on our jobs by Rayners Lane Site, Harrow (Job no. 2048/23) with up to about 650 parts SO_3 per 100,000. These concentrations are so great that they fall outside the limits of accepted recommendations for methods of dealing with the problem. However, it is still probable that the precautions being taken to use extremely dense piles on these sites, are more cautious than necessary. The research project, which will be a joint effort between various research bodies, proposes to bury various pieces of concrete, including piles, in ground which has been very thoroughly analysed. This concrete will be inspected over a period of up to twenty years and tested for retention of strength. This data will be correlated with the behaviour of similar concrete units immersed in standard sulphate solutions.

The results of this research are, of course, a long way off, and in the meanwhile buildings must be put up on highly aggressive sites. It is therefore necessary to have a site investigation procedure that is closely related to the state of knowledge of types of concrete for various degrees of exposure. Whilst this may seem obvious, close examination shows that the lack of information results in as many different recommendations as there are 'experts' in the subject. A comparison of international standards (5) shows the wide range of recommendations, the critical sulphate concentration before special measures are required varying from 7 to 120 parts SO_3 per 100,000 depending on the document used.

The classification chart in the Cement Manual* calls for a knowledge of the soil permeability, the total sulphate content - soil and groundwater - the magnesium ion concentration and the pH. As these properties can vary very widely over a site, a sufficiently large number of samples must be taken to give a valid picture of the site. It would seem that the numbers normally taken are insufficient for this. However, as the number of samples must be related to those that are taken for engineering purposes, there is little scope for adjusting this. In addition, there is inevitably a cost limit on the amount of chemical analysis that can be done. The introduction of automatic analysers as used by the Greater London Council laboratories, could, however, cut the cost from 32/6 for one sulphate determination to about 5/-, thus allowing a larger number of tests to be carried out within the usual budget.

A major problem remains on which very little work has been done. Once large numbers of analytical results have been obtained, which if it is a typical site, will show wide variations, it is necessary to determine from them what category of site it is, to enable the classification chart in the Cement Manual to be used. To date this has normally been done by individual personal assessment of results. No recommendations have even been tentatively suggested to rationalize this process, though the subject is now being discussed. It is hoped that all these aspects of the problem will eventually go into a code of practice for site investigation. The way in which the structure of the concrete affects the durability has been discussed in a recent paper (6).

CORROSION OF STEEL IN CONCRETE

The corrosion of steel in concrete is a more serious problem. Probably all structural engineers have grumbled at one time or another about the necessity of providing cover to reinforcement for corrosion protection. The current codes require a minimum of 1½ in. cover for external members. It has to be accepted, however, that even 1½ in. is not enough in certain circumstances. If all contractors succeeded in making good dense concrete with no flaws in it, ½ in. - ¾ in. cover only would be needed.

The origins of steel corrosion in concrete are similar for both reinforced and prestressed concrete but owing to the different composition of high tensile prestressing wire and to its greater surface to volume ratio compared to heavy reinforcing bars, the corrosion problems are more severe in prestressed structures.

The alkalinity of concrete ($pH \sim 12$) caused by the presence of free calcium hydroxide liberated from the cement during setting and hardening, has a passivating effect on steel and corrosion cannot occur if the concrete is uniform. However, regions of increased porosity, different additive concentrations, different concentrations of absorbed salts from the atmosphere, particularly marine ones, or any form of chemical contamination can lead to corrosion even at relatively high pHs. Differential effects in concrete enable minute corrosion cells to be set up, and that part of the steel that becomes the anode of the cell, corrodes. As the corrosion depends on the completion of an electrical circuit, the conductivity of the concrete is significant, and any factor which increases this will increase the risk of corrosion (7).

The problem of differential aeration cells occurring in post-tensioned structures may be illustrated by some difficulties that occurred in the grouting of the ducts in the ribs of the Sydney Opera House shell roof. The settlements - 'bleeding' - of grout that occurred in the filling of these 'vertical' ducts caused large voids to be formed, up to 20 ft. long, at the top of the duct. It was thought that the mechanism of settlement could give rise to voids along the length of the duct in addition to the large void, particularly where uniform settlement was hindered by the joints between precast rib-segments. The presence of intermediate voids, if they occurred adjacent to the horizontal ducts for cables and bolts that tie the ribs together, could lead to serious corrosion problems, as the cables passed from void to grout. It has now been shown that intermediate voids do not occur in the grouted ducts but the whole exercise raises again the question of how acceptable is the normal situation in post-tensioned structures where voids occur. There is no danger of corrosion if the voids are distributed along the length of a horizontal duct provided that there are no connections for the outside air, that the cover is adequate and that the concrete is sound throughout. The problems would, however, be further reduced if 'bleedless' grouts were developed, and work to find suitable additives to achieve this continues.

Corrosion due to differential salt concentration was best illustrated by the San Mateo-Hayward bridge in California (8). Built during the 1930s using a lean concrete, it has absorbed salts from the sea spray. The concentration of these varies

* Editorial note: Issued by Ove Arup & Partners and written by Turlogh O'Brien.

in different sections of the same members, due to the slightly different porosity and this has allowed corrosion cells to operate. Extensive spalling of the concrete cover ($1\frac{1}{2}$ in.) has occurred, and the whole structure is having to be progressively repaired with a dense gunite layer.
It is widely known that when using accelerating additives containing calcium chloride, the acceptable limit, to restrict corrosion of reinforcing steel, is 2% of flake calcium chloride-based on the weight of cement. This assumes a uniform distribution with thorough mixing. Whilst this can be achieved by adding the additive to the mixing water, the control exercised is often insufficient and the different chloride concentration may result in different parts of the concrete. As the presence of the additive raises the electrical conductivity of the concrete, a non-uniform distribution can cause corrosion by the same mechanism as that mentioned above on the Californian bridge.
The increased conductivity brought about by the use of calcium chloride-based additives has been shown to introduce corrosion problems if dissimilar metals are embedded in or in contact with the same concrete. This problem may arise with galvanized and non-galvanized steel in the same concrete, when the galvanizing will tend to be destroyed. The use of non-ferrous or stainless steel fixings may also lead to corrosion of the steel reinforcement. It is wise to avoid the use of calcium chloride at any concentration, if this danger exists.
A curious corrosion problem has arisen in connection with the galvanized steel reinforcing mesh in the tile lids of the Sydney Opera House roof shells. The method of manufacture is for the tiles to be placed face down in the mould, three layers of galvanized mesh are placed and a rich (1:2) mortar trowelled in to bind the whole together. Any tiles that were damaged or displaced during this process were subsequently replaced using a mortar containing an adhesion additive. These additives are usually pva - polyvinyl acetate - emulsions which are added to the mixing water in the proportion of one part additive to two parts of water (more dilute in many applications)[1]. Mortars containing these additives undoubtedly have improved adhesion initially. Their long-term performance, however, is questionable. This will be discussed more fully later.
It was discovered that when this type of mortar had been used for tile replacement, corrosion of the galvanized reinforcing mesh had occurred to the extent that rust stains were visible on the surface. As this occurred in about six months, it showed that corrosion was taking place faster than if the mesh had been exposed to the atmosphere. Examination of the mesh shows that it has only been attacked where it comes directly in contact with the pva mortar and that that part in contact with normal mortar is completely unaffected. The manufacturer of the additive maintains that corrosion of galvanized steel embedded in a mortar containing his material is impossible.
A completely satisfactory explanation of this reaction had not yet been produced. Various possibilities have been proposed. a) The pva mortar is very porous and hygroscopic - water absorbing - leading to differential aeration cells between the two types of mortar. b) The pva is hydrolyzed by the alkali in the mortar to give acetic acid which attacks the zinc. c) Some component of the pva emulsion - possibly the surface active agent which initially stabilizes the emulsion - prevents the formation of the usual tightly adhering protective film on the zinc.
The requirements for concrete cover to protect steel from corrosion conflict very sharply with other factors in the design of precast concrete cladding panels. To keep weight to a minimum they are normally required to be as thin as possible. Reinforcement is provided by steel mesh, with bars in the stiffening ribs. If normal steel mesh is used, a minimum panel thickness of 3 in. is required. The use of galvanized mesh allows a minimum thickness of 2 in. Stainless steel mesh requires no cover and can be used only $\frac{1}{4}$ in. below the concrete surface. High strength (cold-drawn) stainless steel mesh is now being used for cladding panels in one of the heavy precast concrete building systems. As stainless steel requires oxygen to maintain its protective surface layer, the minimum cover should be used.
The distress of cladding panels with inadequate cover to steel may be illustrated by the gable panels on one of the 11-storey blocks of maisonettes at Picton Street, Camberwell (Job no. 805) built in 1956. These ribbed panels have webs that are only $1\frac{1}{2}$ in. thick, providing a nominal 1 in. cover to the face and $\frac{1}{2}$ in. to the back for the galvanized mesh. However, the face has an exposed aggregate finish* which effectively reduces the cover to $\frac{3}{4}$ in. This is also the cover to the $\frac{1}{2}$ in. bars - ungalvanized - in the ribs of the panels. The corrosion of these bars is cracking the panels as shown. The reason why only one of the eight identical walls is suffering is not entirely clear. The degree of exposure is only marginally greater.
When the surface finish is to be a form of aggregate exposure, it is essential that the cover to reinforcement be calculated from the lowest depth of the indentations. It is also important to note that tooling or hammering to expose aggregate, tends to crack the aggregate particles, and that ideally the cover should be $1\frac{1}{2}$ in. plus the maximum aggregate size.

PROTECTION AND REPAIR OF CONCRETE

In certain situations, either initially or as remedial work, it is necessary to protect concrete by means of special surface coatings or treatments. An example is provided by the necessity to improve the durability of the tile lids on the Sydney Opera House where the cover to the galvanized mesh reinforcement beneath the recessed joint between tiles was only $\frac{1}{4}$ in. The use of a $\frac{1}{16}$ in. layer of an epoxy resin paste in all the joints has provided a continuous impermeable outer surface.
In passing, it is interesting to note that special care must be taken to allow concrete to breathe. The complete encasing of concrete in an impermeable skin can lead to bubbling when the temperature can rise sufficiently to produce a pressure of water vapour. This has occurred on the Sydney tile lids where the sprayed polyurethane foam on the inside has bubbled off in places.
Epoxy resin mortars [9] are now widely used for concrete patching. Their impermeability compared with normal mortar, has enabled them to be used with much reduced cover to steel reinforcement. A concrete lintel beam cast at Exeter 1 in. too low (Job no. 1500) has been cut back to expose the steel, and then made good with an epoxy patching mortar giving $\frac{1}{2}$ in. cover.
Where concrete has cracked for any reason, a number of resin treatments are available for sealing it up and providing full structural continuity. Before using any method it is clearly essential to establish the cause of cracking so as to be sure that it won't happen again in another place after repair. Cracks above $\frac{1}{16}$ in. can be repaired using low viscosity epoxy or polyester resins, injected under pressure. Normally the surface is sealed with a paste of resin before pressure injection. For finer cracks diluted resins or latex emulsions may be used but these cannot be relied on to give mechanical properties equivalent to the concrete. The more diluted they are the more they shrink on hardening and it is sometimes necessary to do a double application.
The cracked cladding panels at Picton Street will be repaired using resins of different viscosities, depending on the sizes of cracks. After this the whole surface will be spray-coated with a solventless epoxy resin coating to an average thickness of 0.010 in. in one application. This will provide a new weathering skin.
In addition to the use in mortars for repairing concrete, resins are also used as bonding compounds for patches of normal concretes.[9] The resin is painted on to the old surface and the new concrete cast before it has set. Bond strengths in excess of the tensile strength of the concrete may be achieved. This technique has proved useful for repairing precast concrete units at London Bridge office project (Job no. 1538) which had spalled due to the moisture

* See photograph by Poul Beckmann at beginning of article

expansion of timber inserts.
Bonding additives based on pva are also sold for concrete repair. They are used in the mixing water of the concrete or mortar. In addition a bonding coat of diluted pva emulsion may be brushed on the surface. Whilst very good bond strengths may be achieved by this method, the long-term durability, particularly when exposed to dampness or weather, is questionable.
Most manufacturers of pva additives claim that once the water is lost, the pva is non-re-emulsifiable. However, a small sample of a pva mortar stuck to a piece of glass, with the slogan 'BONDCRETE - it never lets go' at the interface, came apart after four days' immersion in water. It would seem, therefore, that in addition to the restriction imposed by the danger of reinforcement corrosion, a limitation must be placed on the use of pva for bonding or repair externally.
On two of the science buildings for Exeter University (Job no, 1237) extensive failures occurred when two courses of brick slip tiles were bonded to the edges of the boot lintels using a pva mortar. Several hundred feet of slip tiles were involved and although none actually fell, the majority were found to have failed in adhesion between the mortar and the concrete. The cause of the failure does not appear to lie in the moisture attack of the interface but seems to be due to the inadequate propping during curing. It does, however, reinforce the conclusion that the claims made for pva additives must be treated with caution.
A newer type of bonding additive makes use of acrylic emulsions instead of pva. Whilst this type would be expected to perform better than the pva's, they must still be regarded as unproven.

INORGANIC 'GROWTH' ON CONCRETE
Lime compounds may be leached from concrete and if the water is able to evaporate at the surface, deposits of calcium carbonate (calcium hydroxide reacted with carbon dioxide from the air) are formed. When this effect is associated with the initial drying out of concrete or with periods of wetting and drying on new concrete, it appears as a white bloom, called efflorescence.
During May on three jobs in Dundee, but particularly on the Ninewells Hospital (Job no. 1350), very severe efflorescence was observed. On long lengths of in situ concrete walls for the main service-way across the site, the efflorescence gave the appearance of a smooth, white coating. There seemed to be no possibilities of excessive salt contamination of the aggregate used. The cement was the same in all cases and the first time that cement from the new Dunbar works had been used on jobs. This raised the question of whether the unusually extensive efflorescence could be due to the cement. However, although the lime which causes the efflorescence originates from the cement, slight changes in cement composition that might be found between one cement works and another cannot make any significant difference to the efflorescence. The only explanation for the Dundee experience is that the wetting and drying cycles were particularly favourable for efflorescence. This was confirmed by the fact that on columns that were exposed on four sides, the efflorescence was severe on one or two sides only.
The extent of efflorescence may be reduced by careful attention to the curing conditions. If the rate of drying out is reduced, the rate at which the soluble lime is brought to the surface is also reduced. There is more chance of it being deposited below the surface instead of on it. Eventually, a semi-permeable membrane is formed, allowing evaporation of water but preventing the movement of lime.
A product is now available which when painted on to the surface is claimed to soak in and prevent efflorescence. Its composition is not revealed but the GLC laboratories have analysed it and reported that there appeared to be no reason why it should work. However, the manufacturers claim they have satisfied clients and so some site trials are to be conducted.
The leaching of lime to give white surface deposits may also arise from the percolation of water through badly compacted concrete, through badly constructed joints, or through other cracks. In these cases the deposits may be more concentrated and give stalactite growth. This occurred in the forecourt slab of the Hemel Hempstead Town Hall (Job no. 1297) and the highly alkaline water dripping from the construction joints severely damaged the paintwork of cars parked beneath.
Whilst it is usually acceptable on dams to allow water to percolate through the joints, until the movement of the lime slowly heals the crack by deposition, this cannot be allowed in the case of building structures, particularly when damage may be caused by the alkaline water. It is true, however, that the concrete itself is unlikely to be damaged by this and corrosion of reinforcement at the joints should not occur. If the autogenous healing does not occur for any reason, the concrete will be progressively weakened and once the majority of the lime has been leached out and the pH of the water falls, corrosion of reinforcement becomes a danger.
The simplest way to remove efflorescence and other calcium carbonate deposits from concrete is to carefully etch the surface with dilute hydrochloric acid.

CORROSION RESISTANT METALS
The mechanisms of metallic corrosion are now widely understood and have been fully reported [10,11]. Whilst some metals are inherently corrosion-resistant in certain environments, this does not mean, as seems to be believed by many people, that they do not corrode at all. It is more accurate to think that all metals corrode in various environmental conditions but at greatly different rates.
Although the approach given above would not be very helpful if metals such as gold, silver, platinum and titanium were being discussed, it is highly relevant to building metals. These are taken to include steel in all its forms, the sheet metals - copper, zinc - also zinc coatings - lead and aluminium and the fixing metals - brass, various alloys, bronzes and stainless steel.
The degree to which a metal may be corrosion-resistant depends upon its ability to form a protective oxide film on the surface, which stifles further reactions. If two metals are in electrical contact, enabling a corrosion cell to operate, their relationship in the electrochemical series, in addition to their inherent resistance to the particular environment must be considered. In normal atmospheres the corrosion products on mild steel are unable to prevent further corrosion as they are porous, whilst those of stainless steel are very impermeable and soon stifle the corrosion - being transparent they do not affect the appearance. In concrete, the initially formed corrosion product in the alkaline conditions is different from that formed in the atmosphere, and is able to 'passivate' the surface by forming a protective film. However, if mild steel and stainless steel were embedded in contact in the same concrete containing calcium chloride, at normally accepted concentrations, the mild steel would tend to suffer corrosion, despite the fact that both metals are passivated.
The resistance of stainless steels is provided by the oxide film formed by the alloying metals - chromium, nickel and molybdenum. Other alloy steels can also provide a measure of self protection at much lower concentrations of added metals. The best known of these weathering steels is COR-TEN, which was developed by US Steel in the 1930s and is made here by Colvilles[12]. It contains small quantities of manganese, phosphorus, silicon, sulphur, copper, chromium and nickel - 1.25% being the greatest amount of any. Copper steels (0.25 - 0.50%) are known to improve the corrosion resistances of steels, but the combined effect of all these is to improve it by a factor of 4-6.
COR-TEN is a high-tensile steel with mechanical properties only slightly below BS 968 steel, although its notch-brittleness is significantly worse above ½ in. thickness. The superior corrosion resistance is due to the formation of a more dense and more adherent oxide coating than on normal carbon steels. This effect is observed in all

atmospheres, except where the steel is in direct contact with salt spray.
The colour of the patina of COR-TEN is similar to that of normal steel rust and for it to be developed uniformly over the surface, shot-blasting is required to remove millscale. The patina takes about 6-12 months to form and during this time rust may be washed off by rain. Careful detailing to avoid staining is therefore required. The best known buildings using COR-TEN structurally and decoratively are the Deere Corporation headquarters and the Chicago Civic Centre in Illinois. It was proposed at one stage to use it for the microwave towers being built in Mexico (Job no. 2493) but the manufacturers do not stock structural sections and only roll them for minimum orders of 100 tons per section. This is so severe a limitation that COR-TEN is unlikely to be widely used, except in plate form, for many years.
The field of structural fixings has been dominated by the non-ferrous metal alloys in the brass and bronze groups. Confusion of terminology has been caused by the manufacturers referring to high-tensile brass as manganese bronze. This is unfortunate as the brasses are susceptible to stress- corrosion in industrial atmospheres, whereas the bronzes are not. The rule has therefore been to use the cheaper brasses for non-loadbearing, e.g. tie-back, fixings but either aluminium bronze or phosphor bronze for load-bearing fixings.
The changes in the relative prices of phosphor bronze and stainless steel, now make the latter metal competitive for certain types of fixings. In addition the recent introduction of cold drawn stainless steel means that if full use can be made of the increased mechanical properties, ultimate tensile 50-60 tons/sq.in., it should be cheaper than phosphor bronze. The stress corrosion problem with stainless steel has now been investigated and it was thought that chloride ion-containing environments could induce failures of this type. However, recent experiments under simulated building conditions, have failed to confirm this. The Building Research Station got no corrosion in stressed rods embedded in concrete containing 12% of calcium chloride based on the cement weight.
In the Wates system, the external wall units consist of sandwich panels with two concrete leaves separated by a foam polystyrene insulating layer. The leaves are tied together by crossed 3/8 in. bars of phosphor bronze. Investigation showed the equivalent performance could be achieved by 1/4 in. cold drawn stainless steel bars. However, it was considered undesirable to use smaller bars than the 3/8 in., largely due to damage and fixing problems.
When stainless steel is used in sheet form, as on the BP Moorfields building (Job no. 1405), it is important to consider the methods of fixing it, to ensure that there are no areas of oxygen starvation. In the absence of oxygen, the protective oxide coating cannot be maintained and corrosion can occur[11]. This is possible under washers, lap joints, etc. It is also necessary to wash down the metal at least once a year in industrial atmospheres, to prevent the build up of grime and dust, which could cause oxygen-impervious spots. The most weather-resistant stainless steel is the 18/10/3 chromium-nickel-molybdenum type (BS 58J) followed by the most common 18/8 type (BS 58E).
Aluminium has been widely used in sheet and extrusion form, following extensive publicity of its weather resistance. It is now time that careful attention be paid to the actual performance of the material in use. Examples of major projects using aluminium cladding and frames are the Picton Street development of 1956 (Job no. 805) and the engineering laboratories at Oxford of 1963. These two examples illustrate the condition of aluminium in industrial environments after three and ten years and the very bad state of the material at Picton Street must raise the question of whether it is appropriate in these conditions. Aluminium roofing in less severe environments has, however, weathered well, after developing its dull grey patina[13].
To improve the thickness of the protective oxide layer, aluminium is anodized - made the anode of an electrical cell. All aluminium for external applications should receive this treatment. However, even this does not prevent severe pitting where industrial grime can collect on the surface. The acidic nature of industrial atmospheres is aggressive to the oxide film and oxygen starvation under dirt prevents its healing. At Picton Street the surfaces of the vertical H-section balcony screen frames which are protected from direct rain are more severely corroded than the exposed surfaces. This illustrates the necessity for regular cleaning. It should also be noted that if dyes are incorporated into the anodizing baths so that the thickened oxide film is coloured, the resistance to corrosion is slightly reduced.
In addition to these factors, the corrosion resistance of aluminium is affected by the alloy composition. All alloying metals, except magnesium, reduce the corrosion resistance. Aluminium is affected by dripping water, particularly if the water is slightly acidic due to contact with vegetable growth (algae, moss, lichen) or with certain hardwoods (oak, western red cedar, Californian redwood). Alkaline water from Portland cement can also be detrimental, though the rate of attack is uncertain. It is clear, therefore, that a more restrained use of exposed aluminium is required with careful attention paid to the details of use.
The corrosion resistance of zinc is of interest mainly in connection with the protection of steel by zinc coatings. The increased atmospheric pollution has reduced the amount of zinc that is used for roof coverings. It is found that the durability of zinc as a protective coating is related to the environment and to the thickness of the film but is approximately independent of the method of application of the film,[14] (hot dip galvanizing, sheradizing, spraying, electroplating and zinc-rich painting).
Hot-dip galvanizing is the most used zinc coating process, although zinc-rich painting is becoming well established as the best priming treatment after shot-blasting. The main problem in galvanizing, that of dipping tank size, is generally appreciated. In the case of tubular steel structures, however, there are other problems as was illustrated in discussions on the tubular design alternative for the microwave towers in Mexico (Job no. 2493). If the tubes are sealed, the pressure of air and moisture inside may cause an explosion on dipping into the tank. The provision of vent holes to prevent this, results either in complicated apparatus using vent pipes or in galvanizing the inside of the sealed tubes. It is normally argued that the inside of sealed tubes requires no protection as corrosion cannot occur. However, if the outside is to be galvanized, it appears to be cheaper to galvanize the inside as well, than just to do the outside.

PAINTS FOR STEELWORK
Painting accounts for a large proportion of maintenance expenditure. It is necessary, when attempting to establish to what extent this can be reduced, to distinguish between repainting to maintain the protection of the steelwork and repainting to maintain a satisfactory appearance. With the older types of paint these two factors were effectively one, but the development of newer types, and particularly those which allow a greater film thickness to be built up in few applications, makes this distinction relevant.
The importance of the surface preparation in the success of a painting scheme is now generally appreciated and understood.[15] The presence of millscale on hot-rolled steel is never uniform and it does not normally cover the whole surface. If it did, it would provide a very good protective layer. However, any break in the scale will allow the development of a differential aeration cell,[11] which will cause the steel just under the scale to become the anode, and thus corrode, spalling off the scale.
The flaking of paint on balustrades and other decorative steelwork is a common sight and shows typical failure due to the lifting of millscale. A large scale example of this occurred at Swindon Hospital on the ward block (Job no. 1126) where the balustrade to the roof and upper ground floor and the window frames on the roof buildings, were showing signs of flaking and rusting before the block was handed over to the client, and only about 12-18 months

after painting. The specification called for wirebrushing, priming with RUSTOLEUM 769, two coats of undercoat and one gloss finishing coat of Hadfields HE-O-LIN paints.
Investigation into the causes of this failure, at the request of the architects, revealed that there were several factors contributing to it. Wirebrushing leaves a surface that is part covered with millscale, part covered with firmly adhering rust and part bright steel. RUSTOLEUM 769 is a primer specifically designed for surfaces with firmly adhering rust, as it contains an excess of oil which penetrates the rust, binding it together. If it is applied over millscale or bright steel, the excess oil rises to the top giving a glossy surface which encourages overbrushing of subsequent coats of paint. In addition, the primed steel was sometimes left for so long before painting that the primer was breaking down. Failure to clean these areas down and spot prime resulted in points of weakness being painted in. Finally, a check on the paint film thicknesses using an ELCOMETER gauge showed an average of about 0.003 in. with a range from 0.0015 in. to 0.005 in. for the four-coat treatment, when 0.0045 in. to 0.005 in. would be expected.
The protection of steel is achieved through a combination of a rust-inhibiting primer in contact with the bare steel and a coating of low air and moisture permeability above it. Clearly for any given paint the permeability depends on the film thickness. In the case of Swindon Hospital the thin coatings were simply not adequate to protect the steel satisfactorily. A lesson that springs directly from this is that in paint specifications the minimum thickness for each coat of paint should be stated, together with the overall acceptable minimum thickness.
Parallel with the increased use of zinc-rich epoxy or silicate primers, which have not less than 92% of zinc in the dried paint film, has come the development of primers that may be applied directly on to firmly adhering rust. The zinc primers only work as efficiently as their cost demands if they are applied on to shot-blasted steel. On surfaces with rust, red lead in oil, or metallic lead in oil are both more satisfactory, although difficult to use because of settlement. The RUSTOLEUM 769 primer referred to above, attempts to give a more positive reaction, by binding the rust together and to the steel underneath. There are, however, other primers which actually react with the rust and convert it into more stable and impermeable oxides. The best known of these are the Kingston KURUST and Allweather Paints CORROLESS[15].
In KURUST the active ingredients are metallic lead and phosphoric acid. Experience with it indicates good performance, provided that after it has been allowed to dry, the excess acid is thoroughly washed away with methylated spirits. Any that remains will attack the paint coats.
The ingredients of CORROLESS are not revealed but the action is to convert the iron oxides of rust - haematite - to another oxide - magnetite. Two coats of slightly differing compositions are used and no difficulties have been reported when the material was used on rusty surfaces during the phase 1 strengthening of the microwave towers in Nigeria (Job no. 2474).
The main problem connected with the increased use of this type of primer is the lack of knowledge on how the performance compares with other paint treatments. Ideally, all the possible treatments should be compared under simulated weather conditions in 'weatherometers'. Although accelerated tests do not predict life in the field, they are a valid way of comparing alternative systems.
Probably the most significant developments in steelwork protection in the last few years have concerned the high film build (occlusive) coatings. The principal types are the solventless epoxy, the pitch (coal tar) epoxy, the polyurethane and thixotropical chlorinated rubber paints. These enable thicknesses of 0.004 in. to 0.005 in. to be realized in one application. A three-coat treatment, including primer, should give film thicknesses of about 0.010 in., or twice that normally achieved with a four-coat treatment.
The techniques of applying these thick paints are slightly different from normal paints and require skill to achieve a constant thickness. This initially gave a little trouble in Nigeria where a thixotropical chlorinated rubber paint was used on top of the CORROLESS on the microwave towers. However, in many fields such as shipbuilding and bridges, a specification calling for shot-blasting, priming with zinc-rich epoxy and painting with two coats of pitch epoxy, is becoming standard practice. If a decorative effect is required on top of this, it is necessary to apply a sealing coat of a paint containing flake-metal pigment to prevent bleeding of the bitumen causing discolouration of the decorative surface. With this type of specification, even in severe industrial or marine environments, maintenance of the decorative paint, assuming it is a good one, would only be required every seven to ten years, with maintenance of the protective system at very much longer intervals.

CONCLUSIONS

What conclusions, if any, can be drawn from this? It is clear that the performance in time of materials, particularly composite materials is subject to a large number of variables. There is a general lack of collected information on the actual performance of materials, to compare with their theoretical performance. In addition, the problems of predicting the performance of new materials are very great, and although the new BRS Agrément system of test certificates will assist, intensive development of improved accelerating testing methods is used.

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