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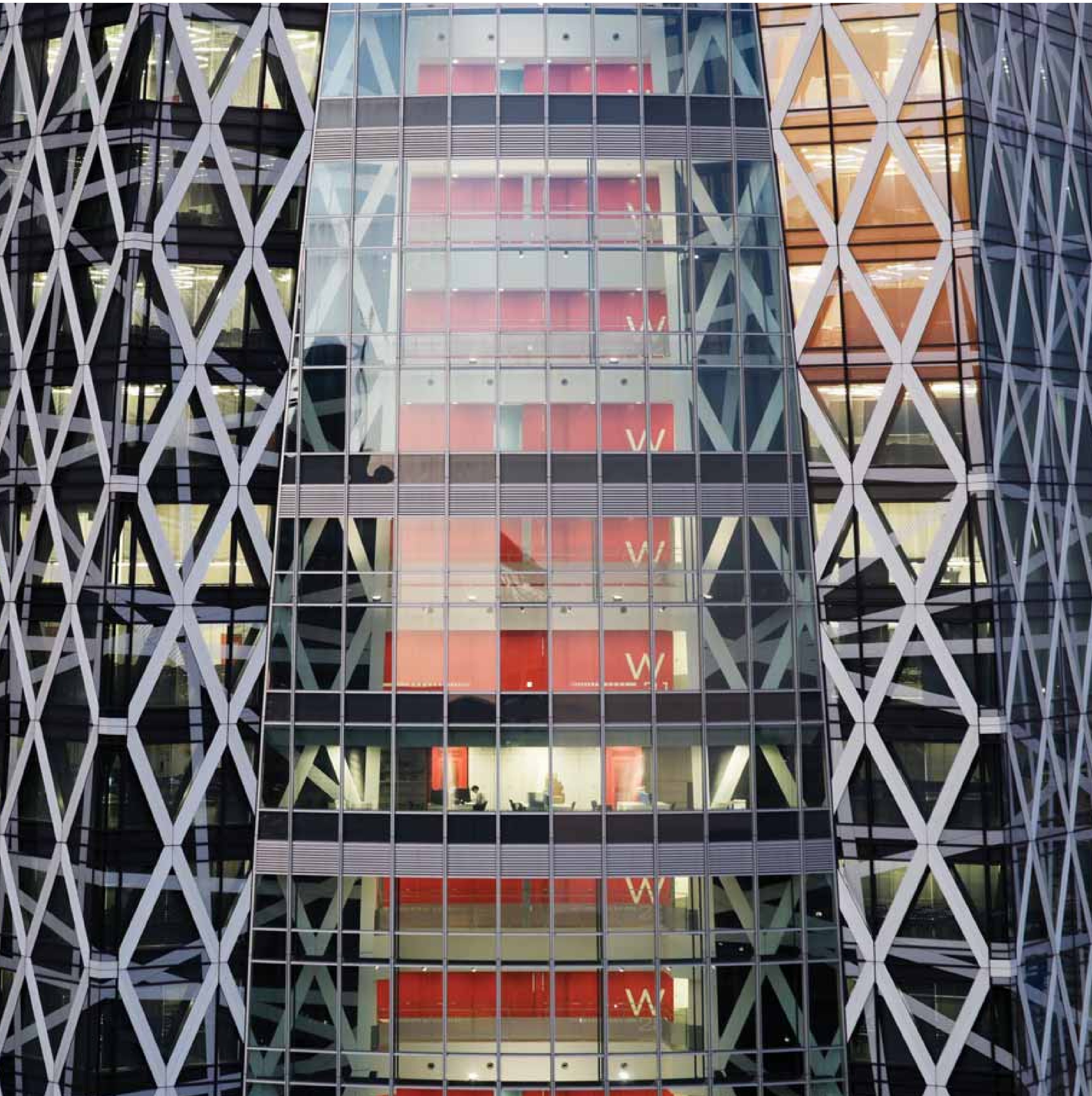
The Arup Journal



Contents

Sir Ove Arup: The design of bridges

Foreword

Jørgen Nissen*

Ove Arup (1895-1988) once said in a BBC interview that the two structures that had given him most satisfaction were the Highpoint flats in North London (1935) and the Kingsgate footbridge, Durham, Yorkshire (1963), as "both are rather perfect examples of the complete integration of architecture, structure and method of construction".

But before Kingsgate Ove had designed other bridges. Although they were for real none was built, for reasons unconnected with their design, but he wrote about them. The article that begins overleaf appeared in the Arup *London Newsletter*, nos 21 and 22, February and April 1964, though it was written a few years earlier so that Kingsgate only comes in with a few final lines, almost as an afterthought.

In 1961 Ove had shown sketches of some of his bridge designs to his CIBA friend the Italian architect Ernesto Rogers (1909-1969), who was then editor of the architecture magazine *Casabella*. The article "*Cinque ponti*" duly appeared in June 1961. Ove changed it slightly two years later, and a shortened version, "*Trois projets de ponts*", appeared in the October/November 1963 issue of *L'Architecture d'Aujourd'hui*. The *London Newsletter* editor, Rosemary Devine, reverted to the longer English original for the Arup publication (but to a then very small internal audience).

It is a fascinating article, well worth studying even now almost 50 years later, and not only by bridge engineers. In it Ove lucidly describes what he meant by what he would later call "total architecture" – which, whatever we call it now, is very much what we are about. He wrote extensively about "total architecture" throughout his career, but usually in the abstract, almost philosophically. Here, uniquely in his writings, he is addressing the subject in specific contexts, with real if unbuilt examples, revealing step-by-step how his thoughts progressed.

He says it all at the start, emphasising that he is writing about bridges – "… a more rewarding field for the study of unity between architecture and structure. A bridge is architecture with a clear and simply formulated function. All one has to worry about is the stability, durability, cost, and appearance." And as for appearance: "there will always remain a number of more or less arbitrary decisions, which have to be made on purely aesthetic or sculptural grounds. I suggest, however, that the best result is obtained if there are very few of such arbitrary decisions to be made, in other words, if decisions affecting proportion and form at the same time make structural and constructional sense".

Kingsgate footbridge, Durham.

In spite of writing for an audience of architects – or perhaps because of it – he did not offer any thoughts on how these decisions should be taken. He did not need to. He was writing about the engineering. In the earlier *Casabella* version he had included a small footbridge at Bowring Park, St Johns, Newfoundland, but he almost apologises for it at the end of the paper: "it does not really belong in this series because the method of construction is not in any way out of the ordinary and in fact, the whole object is small and insignificant and presents no structural and constructional difficulties. But the appearance was important – it always should be anyhow. This is therefore a case of satisfying function and structure in a pleasing and neat manner – construction is of lesser importance."

And when he refers to Kingsgate at the end he adds: "Although appearance was of major importance in this case, the form was largely influenced by structural and constructional considerations". He did work with the architect Yuzo Mikami on this bridge and it is a great pity that he could not include a full account here and so close the argument.

A few years later, in 1971, Ove was asked by the Institution of Civil Engineers to advise on "how to improve the appearance of engineering structures… if architects are not to muscle in on the Engineer's domain" (sic!)… and "please write a paper which will teach engineers how to design beautiful and efficient structures". True to character, he wrote a fairly long paper explaining why he could not write such a paper, concluding: "you cannot make rules or principles for what is beautiful, but you may be able to learn by examples of good design – by studying it *in statu nascendi*". He does just that in this article.

All four bridges were to be built over water and therefore called for particular engineering expertise. Ove had that expertise; he had been chief designer for contractors specialising in marine structures for nearly 20 years: "We were designers and contractors in one, design and construction were naturally integrated. Now the bulk of designers are mostly unacquainted with the problems on site."

The construction methods he proposes are complex, but as ever Ove explains them in simple direct language. He is aware of the danger of writing *ex post* but he writes about it as it is, not leaving out ideas that had to be aborted and only including the successful ones. The construction methods are all quite sophisticated and would have been innovative at the time but feasible. His partner Geoffrey Wood (1911-2007), who had a great deal of experience of working in Africa, did argue that the Ghana bridges required technology not then available in Africa. But Ove insisted that they had been "designed down to the last detail". So they had, but then maybe the local contractors did not yet have an Ove.

Would we do the same today? We might. But technology has moved on; we now have at our disposal stronger and more durable materials, more precise controls and better methods of analysis and forecasting, more sophisticated construction methods, etc. The limits of what we can now do have expanded. And society has greater expectations; environmental and social issues are significant and Ove's "more or less arbitrary decisions" now weigh heavier in the balance sheet.

He would have approved. His approach is as relevant now as it ever was, even if the input to the process and therefore the outcomes may be different. It is a pity that these four bridges were never built, but he did at least leave us the best: the delightful Kingsgate bridge and our approach to "holistic design".

After the article was written, the Ministry of Transport, then England's main client for bridges, announced its first-ever design competition, for the Calder Bridge in Yorkshire. 110 designs were submitted, five of them from Arup (*London Newsletters* 19-22, January-May 1964). A team from Povl Ahm's group including Yuzo Mikami as architect won a special prize. This led directly to the award in 1965 of our first bridge project by the Ministry, the Gateshead Viaduct, and the Highways and Bridge group in London was born. Ove took an interest – and sometimes more than an interest – in some of our subsequent bridges, particularly the Jesmond Dene Bridge in Newcastle, close to his birthplace. The design was almost ready for tender when the project was cancelled following public pressure not to demolish the existing wrought iron Armstrong Bridge built in 1878. This is in fact a striking bridge and is now listed.

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*Jørgen Nissen joined Arup in 1962, at first designing shell structures. He was one of the prize-winning Calder Bridge competition team and later in attendance at the birth of the Highways and Bridges group. He was made a director in 1977, a main board director in 1984 and a trustee in 1992. He retired from the board in 1999 and as a trustee in 2004. He is now a consultant to Arup. Throughout his career Jørgen has maintained his interest in bridge design. Of his many bridge projects his favourites are, from the beginning, the Bishopthorpe and Berry Lane bridges in England, in the middle the Kylesku Bridge in Scotland, and at the end the Øresund Bridge between Denmark and Sweden.

The design of bridges

Sir Ove Arup

This article is about the design of bridges, and tries to show why in a number of cases certain designs were chosen, and how they were developed. That most of these bridges will probably never be built is regrettable but does not defeat my main purpose, which is to probe into the nature of architecture by showing how in the case of bridge design the architectural form results mainly from the choice of structure and the method of construction.

I say mainly, because there will always remain a number of more or less arbitrary decisions about proportions or detail design which do not greatly affect economy or functional efficiency, and which have to be made on purely aesthetic or sculptural grounds. I suggest, however, that the best result is obtained if there are very few of such arbitrary decisions to be made, in other words, if decisions affecting proportion and form at the same time make structural and constructional sense.

When everything thus “comes naturally”, there will be the greatest possible unity between architecture and structure – they will in fact be one and the same thing, which is as it should be. I know that this kind of unity is not always possible, and that it can be perfectly justified to do violence to the structure or to add to the difficulties of construction in the interest of architectural values, but most people agree that such unity is worthwhile striving for. As is well known, what in the end “comes naturally” is the most difficult thing to attain. It has the best chance of emerging if one mind controls the design process. That is why the great bridges are created by engineers with a feeling for form, but thinking mainly in engineering terms.

Unity between architecture and structure, or perhaps rather “Unity” in general, has since Aristotle been valued as a mark of great architecture.

However, in the case of buildings filled with technical equipment and housing a multitude of human activities – as for instance a teaching hospital – such unity is difficult to obtain or even define. The needs to be harmonised are multifarious and perhaps even conflicting, and structure anyhow comes rather low on the list of priorities. That is why bridges and large engineering structures seem to me a more rewarding field for the study of architectural unity. That a bridge is a form of architecture will probably be conceded; in fact it can have a very powerful architectural impact. But it is architecture with a clear and simply formulated function: to carry traffic of a certain kind from one place to another. All one has to worry about, then, is the stability, durability, cost, and appearance. Or to put it in another way, structure, method of construction, and architecture.

It is, of course, the architectural past which for the engineers may be the most difficult to come to grips with, and this explains my interest in exploring the issue. Architectural theories, I am afraid, do not help much. Unity, harmony, balance, proportion, scale, pattern, truth, structural honesty, fitness for purpose, economy of materials; all these guiding principles are much too general, and can all be violated with impunity in particular cases. They give practically no guidance to the designer who has to resolve an alternative on the drawing board. Fortunately bridge design is fairly immune from infection by warring and ephemeral architectural issues.

It is generally accepted that to impose a preconceived “style” would be out of place. This leaves us basically with a structure with certain sculptural qualities. But this is not the same as a piece of sculpture with certain structural and spatial qualities enabling it to carry traffic from A to B. If an architectural critic looks at the finished result he may be tempted to judge it from the latter point of view. He has a right to do so, of course, but it would be like judging a car by its appearance only. To judge the quality of a bridge – the whole bridge and nothing but the bridge – one should not only appraise its form, but should understand why it has that form.

“That a bridge is a form of architecture will probably be conceded... in fact it can have a very powerful architectural impact.”

This brings me to the crux of my argument, which is that to study architecture – I am talking about bridges, but suspect that it applies to all architecture – one should study it *in statu nascendi*.* One should be privy to the working of the minds of the creators. Creating architecture – good or bad – consists of making a great number of choices. One should get to know what these choices were, what was rejected as well as what was adopted, and why. If one selected as example designs of acknowledged merit – and there is much more agreement about what is good, once it has been created, than about architectural theory – then one would come nearer to an understanding of how good architecture was produced and one might perhaps even get an inkling of what good architecture was. One would derive a benefit akin to that accruing to the pupil who watches his master at work. It would serve the dual purpose of exploring the nature of good architecture and of teaching the making of it.

It would be nice to think that that this was generally conceded and that henceforth we would be spared the tedious descriptions of what the work looked like, how many tons of cement and acres of glass were used, how the contract was administered and so on, and that we instead would witness through information “straight from the horse’s mouth”, the exciting battle going on in the designer’s mind to find the right answer amongst the scores of possible solutions. But I am afraid these are pipe dreams, and that for several very good reasons.

The main reason is this, that it is extremely difficult to get hold of what exactly happens during the largely intuitive process of designing. The material would at any rate have to be edited and drastically reduced. It is also difficult to remember unless immediately recorded. Designers are not authors; they are bent on designing, not on recording. When much later, a reconstruction of the process is attempted, the result is probably a rationalisation more *Dichtung* than *Wahrheit***. And then in order even to attempt to describe the design process to the reader, it is necessary that he should understand the problem as it presents itself to the designer. The latter will have spent some time and effort getting acquainted with the problem as it relates to the site and other conditions, and only when it has been thoroughly absorbed into his system will be able to survey the field of three-dimensional possibilities in his head.

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* “In its original form”. **From Goethe’s autobiography Aus meinem Leben: Dichtung und Wahrheit (“From my Life: Poetry and Truth”).

What he can then see in a flash will need a lot of explanations and 3-D sketches or models to put across to a reader.

I am afraid, therefore, that this *statu nascendi* business will have to be dropped, at least if taken too literally. But I still think that the main idea has validity, and that designers could make a contribution to informed criticism if they could bring themselves to give an account of the path followed – including some of the blind alleys – to reach a particular solution.

This then, is what I am going to attempt, but I am immediately up against two difficulties. One is lack of time and space which will make my effort very sketchy in any case. The other, more serious, is, that in the nature of things I can only talk about my own experiences. What we really want is an eye-witness account of how great architecture is produced, and unfortunately I am far from being a great architect. My only hope is that my example will inspire someone better qualified to make a more valuable contribution on these lines.

Perth Narrows Bridge

The first design, for a bridge over the Narrows at Perth, Australia, never got further than an early sketch stage, but the fundamental decisions about how to build the bridge had been taken and, as will be seen, these decisions, logically applied, resulted in a bridge of a somewhat unusual form.

The task, as presented to us by the clients at the time, was to build a low road bridge 92ft wide and 1300ft long – of which 900ft were over water – between the mainland and a large island. The special feature of this bridge was its skewness – the line of the bridge formed an angle of 60° with the channel it had to span, and consequently with the current. The clients at one time expressed the hope of spanning the bridge in one span, but that could only be done by having the main structure above road level – suspension bridge – and that was not considered desirable for other reasons – landscape. The best that could be hoped for with the construction height available was three spans: a long middle span with two cantilevers and a floating span, and two shore spans.

Considering the method of construction, however, it was very soon found that to provide a temporary staging for the whole bridge would be far too expensive. The best method seemed to be to drive piles from a floating plant for the construction of the piers and then cantilever both ways from these piers, delivering all the materials or precast units to these piers by barge (Fig 1). This would not be easy, considering the depth of water and the skewness of the pier; at the least it would require very heavy and expensive piers. It would obviously facilitate matters enormously if each of the two piers was replaced by two narrow piers relatively close together (Fig 2). These two twin piers would then form natural harbours for supplies by barge and would, when connected, form a stable base from which to cantilever in both directions. Further, it would then be possible to arrange floating spans connecting the bridge with the shore, thus diminishing the height of construction over land, and solving the problem of temperature changes.

However, there was still the skewness to consider. The narrow piers would have to follow the direction of the current, forming an angle of 60° with the centreline of the bridge (Fig 3). If we, in order to preserve the symmetry and the logic of the system, were to cut the floating spans on the skew as well (Fig 4), all sorts of problems would arise. The system would work if the bridge consisted of parallel strips, but that would be wildly uneconomic because each

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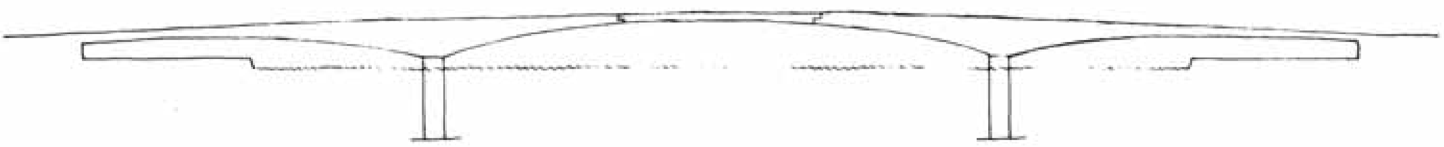

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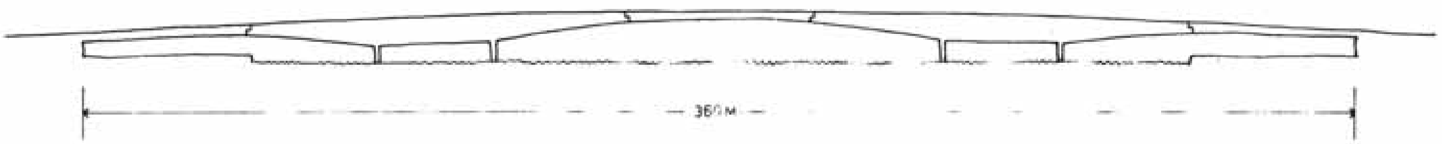

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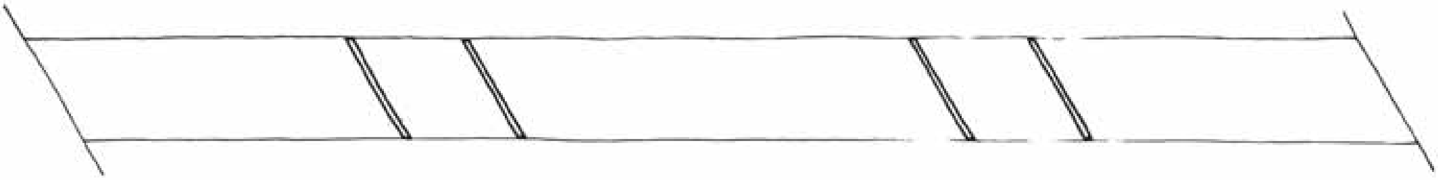

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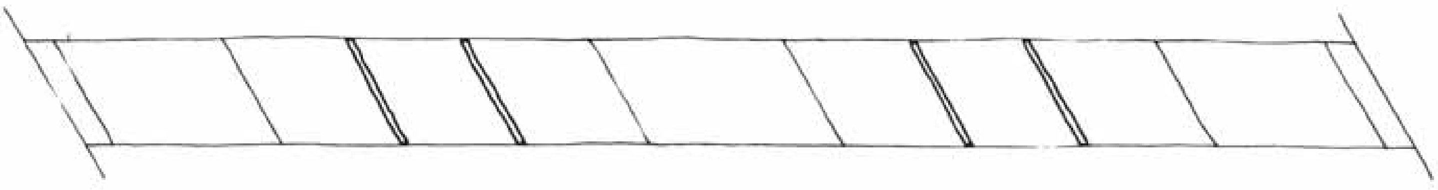

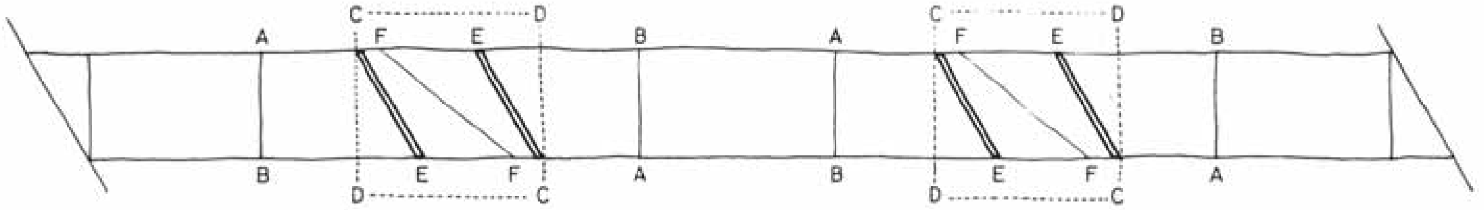

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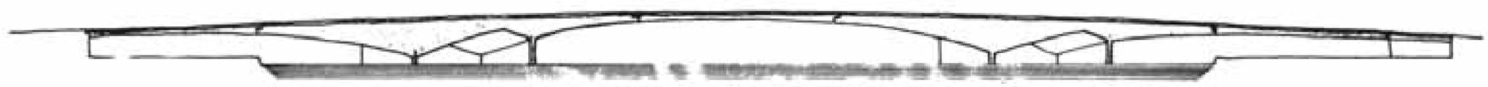

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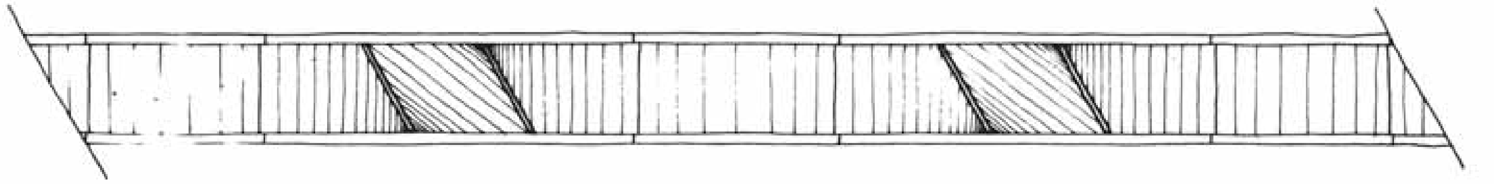

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strip would then have to support the maximum point load on its own. Tying the strips together to form a monolithic structure would, however, cause havoc with the orderly distribution of moments, certain points would be overstressed in relation to others, in other words, shape would not any more correspond to the forces acting on the bridge. To overcome this, it was proposed to cut the floating spans at right angles to the bridge along the lines A - B (Fig 5). Now everything is normal outside the areas CDCD around the two twin piers, or at least almost normal, because there is still a small extra deflection of the points D compared with points C which rest on the pier, and this would cause a small torsion in the "normal" areas. This can be rendered insignificant, however, by making the deflection of D sufficiently small, and this is achieved in a simple way if the curve of the cantilever from B to D is continued downwards to a lower point on the pier at E.

The elevation of the bridge will then look like Fig 6, with short cantilevers AC and long cantilevers BE, the latter following an identical curve to AC on the stretch BD and then dipping down further to E. From E to C, that is between the twin piers, the soffit is formed by two curves, each being symmetrical to the corresponding cantilever curve and meeting in F. The resulting contour lines of the soffit are shown in Fig 7. The soffit in the area between the piers will then consist of a vault with horizontal lines running parallel to F - F, a direction still more skew than the piers.

It will be seen that the elevation is not symmetrical about the centre of the bridge but follows a rhythmic but syncopated movement from left to right of deep dip, low dip, deep dip, low dip. Seen from the other side, the movement is again the same from left to right, not from right to left, as one would expect. A perspective is shown in Fig 8. This is as far as we got.

There were of course hundreds of questions left to consider – whether to construct the bridge in situ as a hollow box section or a ribbed construction, of precast and prestressed units – probable – and the size and shape of units, the treatment of the joint between bridge and pier, cantilevered footpaths, if any, railings, lighting, etc, all of which would have influenced the architecture in varying degrees, but none as much as the basic design decisions described above, taken on purely structural and constructional grounds, which really determined the architectural character of the bridge for better or worse. I must confess I felt a bit doubtful myself, when I had drawn an outline of the elevation resulting from my structural thinking, and an architect friend, who came in and saw the thing, thought it looked awful. But after a few days of looking at it I came to like it more and more, and I was very grateful for the skewness of the bridge that made it possible and even sensible to produce something with a distinct character, different from the ordinary run of bridges. But that feeling may of course be peculiar to me.

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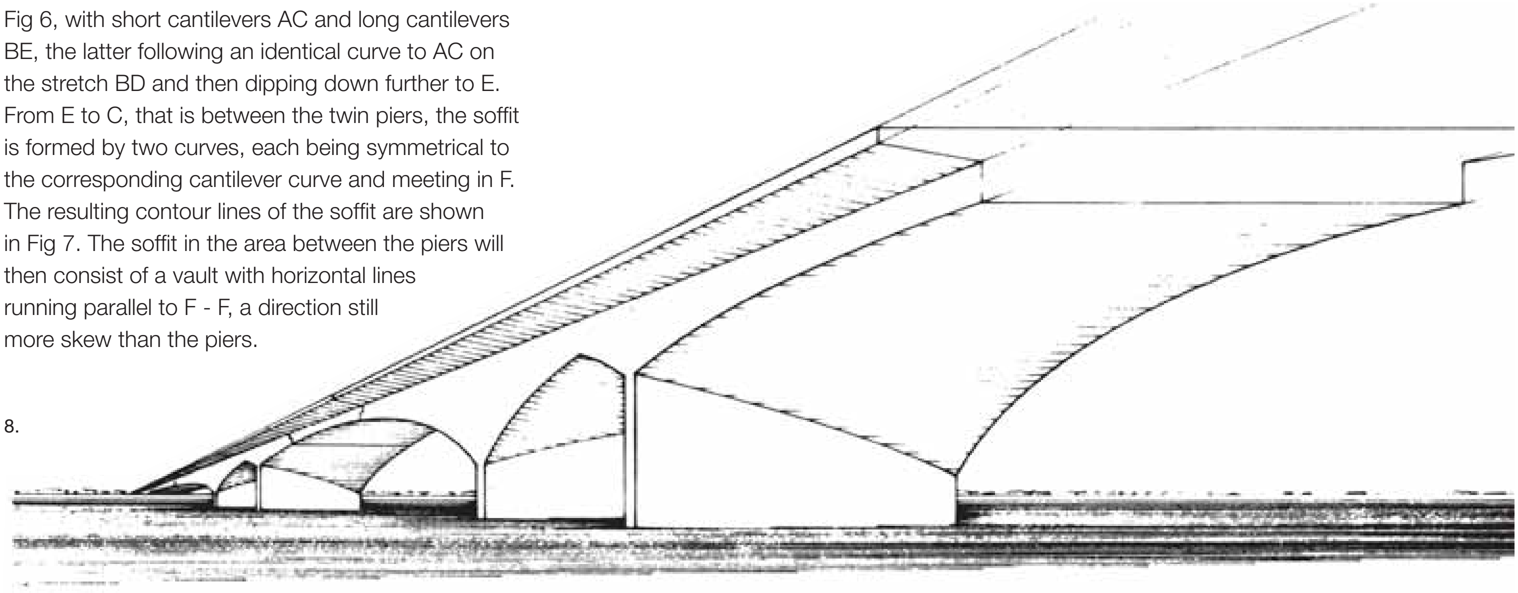

Bridge in Scotland – over the Tay

The next sketch design is for a bridge in Scotland (Figs 9-11). The bridge is about 8070ft long, of which 5510ft is over not very deep water. The roadway is about 110ft above high water level, because the roads on both sides of the firth are at that level, and because shipping requires a free height of 82ft. There are 11 piers in the water, spaced 475ft apart.

The main consideration in this case was to keep the cost down. It was thought that the height of the bridge above water level would make this very difficult, but in the proposed design this difficulty has been largely overcome by extracting the greatest possible advantage from this extra height. Greater height means of course that there is more room available for the supporting structure, which makes it possible to employ arches, deep cantilevers, or raking struts thus reducing moments, increasing spans, and reducing the number of supports. But the fact remains that more structural material has to be used to raise the road level to this height, and more important still, work at this height and far out over the sea is very expensive.
The aim of the designer must therefore be to reduce this extra material to a minimum, and to avoid work in situ.

In this case conditions for prefabrication were favourable, insofar as the length and uniformity of the bridge involved a lot of repetition. This would make it economically possible to invest a fair amount of capital in specially designed floating cranes and other plant that could be used for sinking cylinders and landing prefabricated units. There was also available, near the site, a rather underemployed shipyard, which could be used for constructing and launching floating units, if structural steel were used for the bridge.

These considerations led to a form of cantilever-construction almost on the lines of the old Forth Bridge, with floating spans between balancing cantilevers supported on central piers. Arches were considered, but rejected because of the one-sided thrust they would exert on the piers during construction, but mainly because the chosen system seemed to offer greater opportunities for almost complete shore-fabrication.

The first problem was to establish stable bases from which to work without going to the expense of constructing heavy solid piers. This led to open piers, consisting of four cylinders placed at the corners of an 18.5m square, and connected by precast concrete bracing, as roughly indicated on Fig 10(a) (next page). The lower “ring” would be cast or assembled at the top and lowered down, the diagonal bracing lowered into pockets at the connection of the piers with the lower ring, and fixed by pouring concrete in the pockets under water, etc – enough to say here that it would be possible, at a reasonable cost in view of the repetition, to provide 18.5m wide bases able to resist forces and moments in all directions, and therefore each able to support a portion of the bridge independently of the other piers. The next problem was then to use the available height to spread out the support as much as possible in the most economical way, and the method chosen, with four A-frames that together with the deck provide maximum stability with a minimum of material and minimum wind resistance, could hardly be improved upon.

Having established a desirable static system, there still remained the question of how to build it and what materials to use. I am not suggesting that this happened exactly in that order. When you are designing, the mind is let loose amongst a lot of possible combinations of statical systems, methods of construction, until an idea emerges for closer examination. Anyhow the idea emerged, based on the preferred statical system, to form the bridge of floating units - which I will call “barges” - which could be completely finished with paving, lighting, railings, etc, on shore, and which could be lifted up to their final position by making use of the supporting structure of A-frames. If the main A-frames supporting the barges are hinged top and bottom by simple open hinges and the barges are pulled towards each other, they will automatically rise from the water at high tide to the required level, and can be secured to the other A-frames which provide the longitudinal stability (Fig 9).

It would take too long to describe in detail the various problems involved in this operation, but the forces were all calculated and the necessary plant designed in principle. The winches and hoisting gears were to be fixed to a temporary steel frame formed as a pyramid, which from a couple of barges could be transferred to each pier in turn. A floating crane would transfer the A-frames to the piers and the bridge barges would be guided towards each side of the pier by temporary guides fixed to the piers.

It is obvious that the use of structural steel for the bridge would favour these operations, as the weight of barges, etc, would be much less. There was actually no time to investigate a prestressed concrete scheme as well, but had it been decided to proceed with the construction of the bridge, this should have been done. It would have reduced maintenance problems - but actually these were not too bad in the case of the steel structure, because it was to be constructed of hollow units presenting a smooth surface to the outside.

Actually, later a probably somewhat better way to erect the bridge was thought of. According to this the lifting up of the barges from the sea would take place at the dockyard, and the whole section of bridge resting on one pier, including A-frames but excluding the floating spans, would be brought to the bridge pier on two large barges or ships,

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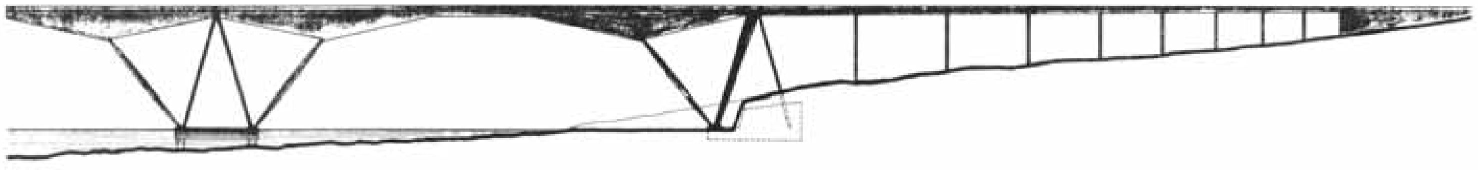

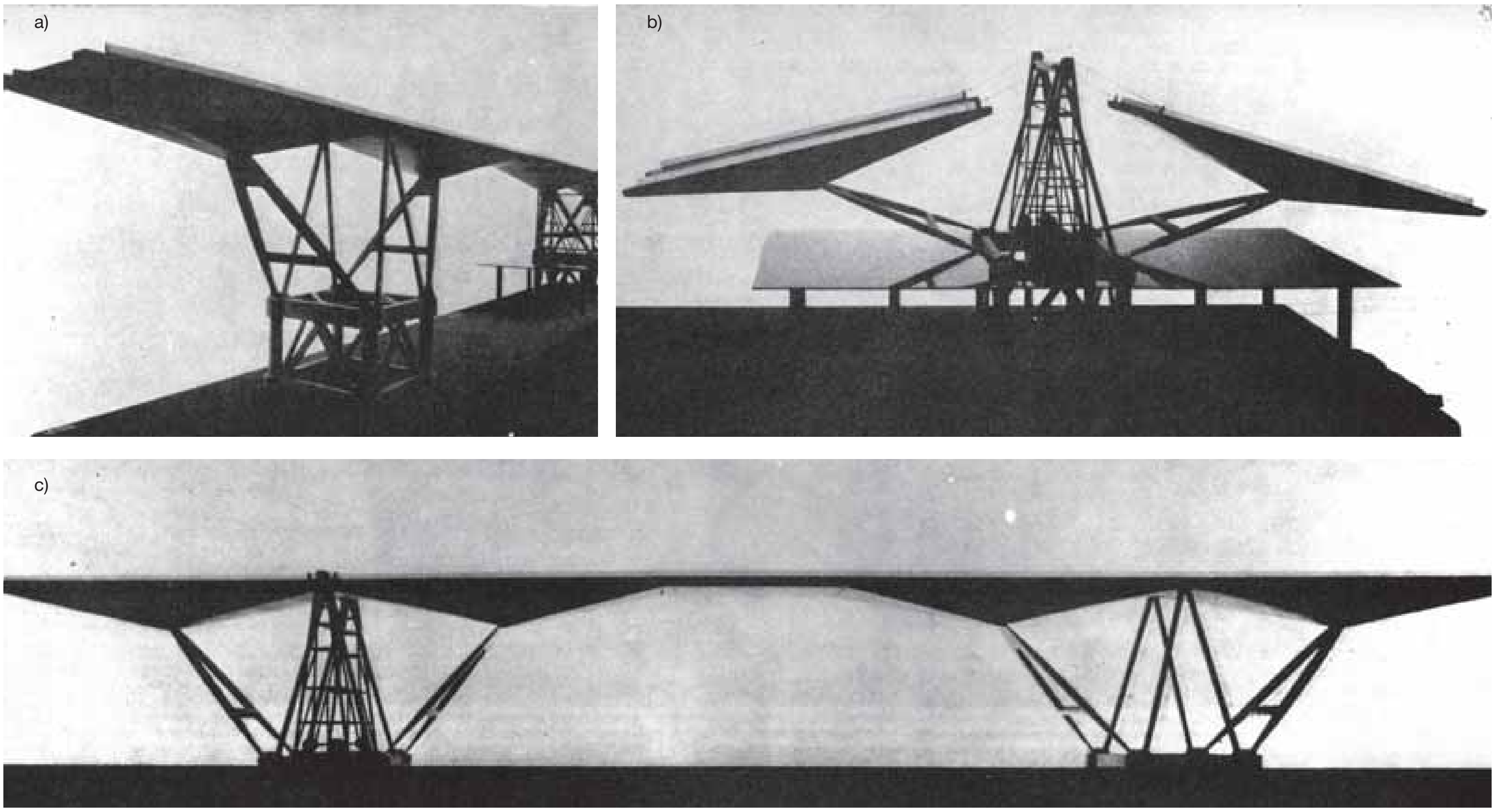

10. Stages in the bridge erection.

total weight about 900 tons. This would mean that the steel pyramid including hoisting gear could remain in one position all the time and would not have to be transferred from pier to pier. The bridge section would be brought to the pier at high tide and guided so that when the tide went out it would come to rest on the pier.

The "floating span" would of course also be floated out and lifted up in position.

How to design the railing is always a most perplexing problem for the engineer – and I suppose the architect too – because of the danger of its becoming a mere additional ornament not logically or organically part of the bridge. In this case this problem was solved very neatly and naturally by making the railing part of the hull of the barge (Fig 11), thus assisting the floating and acting as a useful windbreak protecting cars and pedestrians.

Also in this case, the "architecture" is essentially dominated by the structural and constructional idea. What remains is to look after the main proportions, the detailing of the structural members and their joints, and the design of the two land approaches at each end.

As far as the main proportions go, these are actually largely dictated by the need to strike a reasonable balance between the forces in the members and the distance between piers, but this balance is in my experience arrived at more by eye than by calculation. In other words what looks right, both structurally and aesthetically, is likely to make structural sense. But of course such judgments must be checked by calculation.

The two land approaches were difficult to deal with, because these portions of the bridge, which would best be built in concrete, would be entirely different in character, and the junction between the steel structure and the concrete abutments was obviously of the greatest importance from an aesthetic point of view – in fact it is on points such as these that so many bridges go wrong. To obtain a satisfactory transition it seemed best to complete the "arch" in steel (Fig 9). This meant, however, that the last "barge" and A-frame would not balance against another barge, as in the case of the 11 centre piers, and it would be necessary to provide a counter-thrust to take the reaction from the cantilevered "barge". This was done in the simplest possible way (Fig 9). The concrete approach was designed as a completely plain hollow slab, on plain walls which were spaced closer together as the height became less. This is logical enough – although it may not lend itself so easily to prefabrication – but at any rate I think it is justified aesthetically. This slab was bent down at an angle to form the front leg of an A-frame at the junction with the bridge proper, which automatically enabled the bridge to resist a pull from the "barge" at this point.

This account is of necessity very brief, dealing only with the basic idea. In fact, all the many detail problems were only solved to the extent required to make sure that the scheme was workable and economic.

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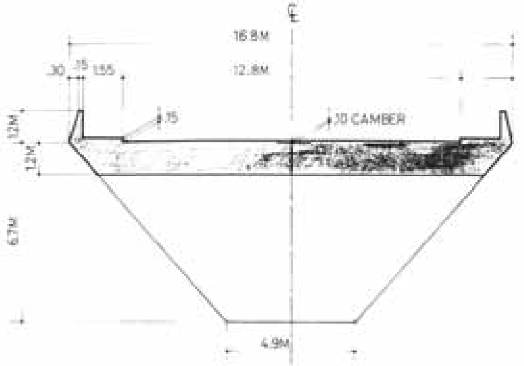

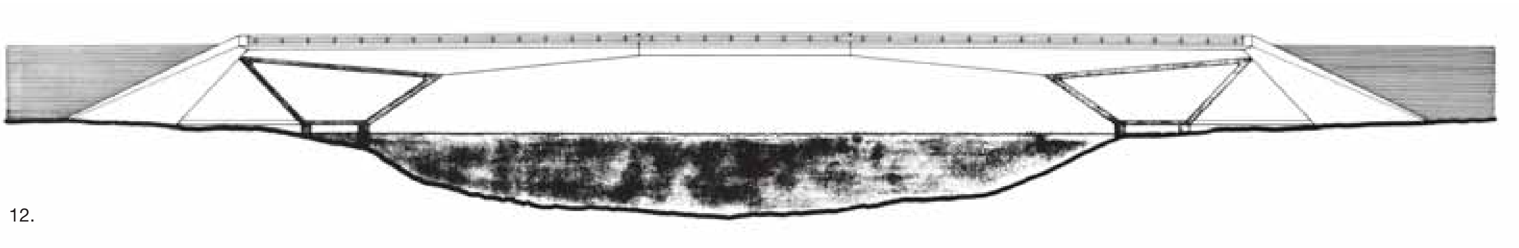

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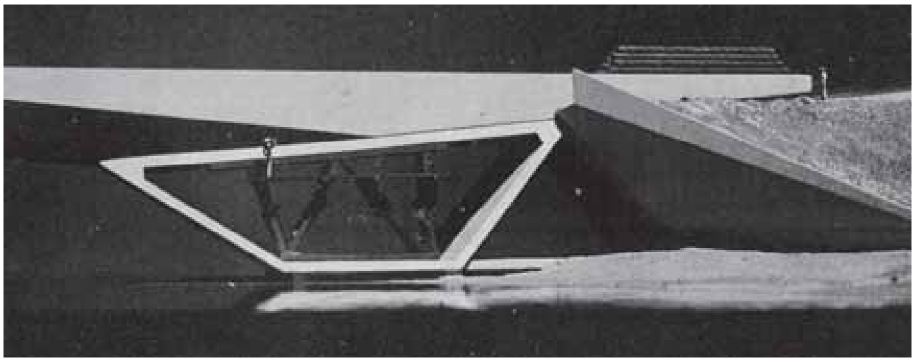
Ankobra bridge, Western Ghana

The next bridge on the list is the Ankobra bridge in Western Ghana, over the river Ankobra, close to the sea. This bridge has been designed down to the last detail, including the temporary staging and apparatus for sliding the main units into position, and tenders have been received, but owing to lack of funds the bridge has not yet been built and it now looks as if it never will be.

The conditions we have to deal with here are: a road, 24ft wide, with two footpaths of 6ft each, to be carried over about 302ft of river, giving a clearance at the centre of about 24ft over high water. Subsoil is poor, until rock is reached 90ft down on one side, and about 33ft down on the other. To provide temporary staging in the river would be expensive and should if possible be avoided.

There is often a salt spray from the sea nearby, and this salt, humid, and warm atmosphere would corrode steel, aluminium, and even concrete, unless the latter were in fairly smooth, solid sections of high-grade concrete, preferably compressed to avoid cracks. So prestressed concrete was the obvious material to use, especially as it would not be justified to rely on proper maintenance in this fairly remote spot.

The desire to produce a bridge which would withstand the ravages of time without maintenance was therefore a major factor in the design. Another was the desirability of avoiding staging in the river. And not least, there was the expressed wish of the government that this should be a beautiful and impressive bridge worthy of the new era in Ghana. A design on the lines of many of the Public Works Department bridges with frequent pile trestles supporting steel or concrete girders was definitely not wanted.



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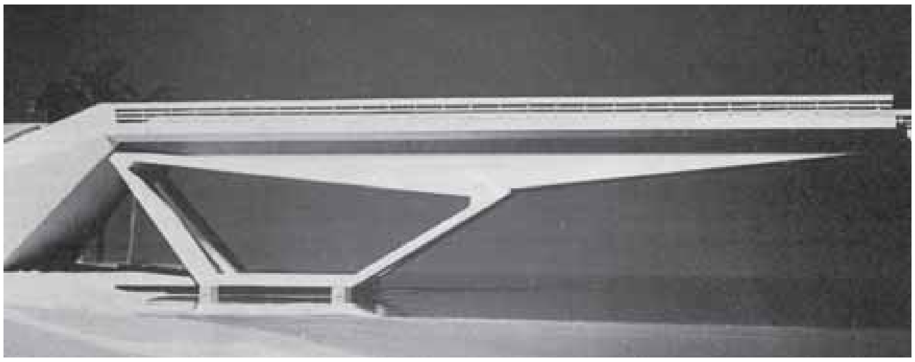
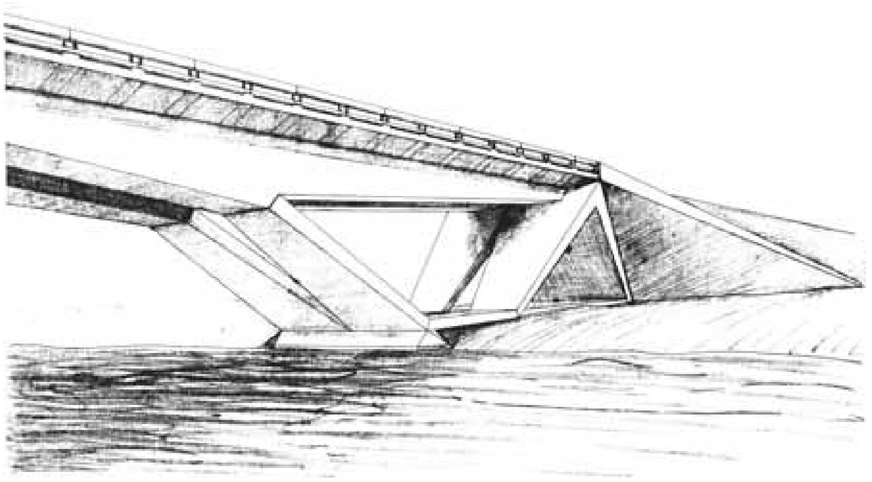


The need to avoid staging suggested cantilevering out from the two shores. The normal method of cantilevering by adding small sections and tying them back did seem to be rather complicated, making high demands on constant good workmanship to ensure that the many joints would not be sources of weakness. I did not feel certain that this procedure would in the given circumstances yield the high quality that I was after. So I was groping for an idea on the lines of the previous bridge with the “barges” constructed in prestressed concrete instead of steel, but in this case there was not the same height to play with, and there were no two balancing barges. The structural system could easily enough be envisaged, with inclined struts supporting the “barges” in the centre, so as to reach as far out into the river as possible and an A-frame with a counterweight at each shore end (Fig 12) but how to get the “barge” into position?

Sliding them out seemed a possible solution, and that is in fact the solution which was finally adopted, but it proved to be much more difficult than at first realised, and the design went through many stages before reaching its final form. It would be very instructive to retrace the many alterations made and the reasons for making them, because it would show very clearly that aesthetic conceptions must not be imposed at a too early stage; the final form cannot be determined before the structural and constructional requirements have been met in a direct, clear, and simple manner. But it would require a book rather than a short article to bring that out.

The first scheme (Figs 12-14) was completed in outline before the structural problems had been properly resolved, because the model was needed for presentation to the clients. Visually, this scheme is satisfactory enough, and brings out very clearly the main components of the scheme: the cradle along which the “barges” are slid out, the counterweight, and the suspended span in the centre. And this appearance of the bridge could have been kept, the details were actually solved, but the solution was too complicated to be really satisfactory. In this scheme, the inclined forward strut was permanently anchored back to the A-frame and counterweight, and afterwards the three barges on each side were slid out, using the ties as tracks. Naturally the ties would have to be supported during the sliding, and that



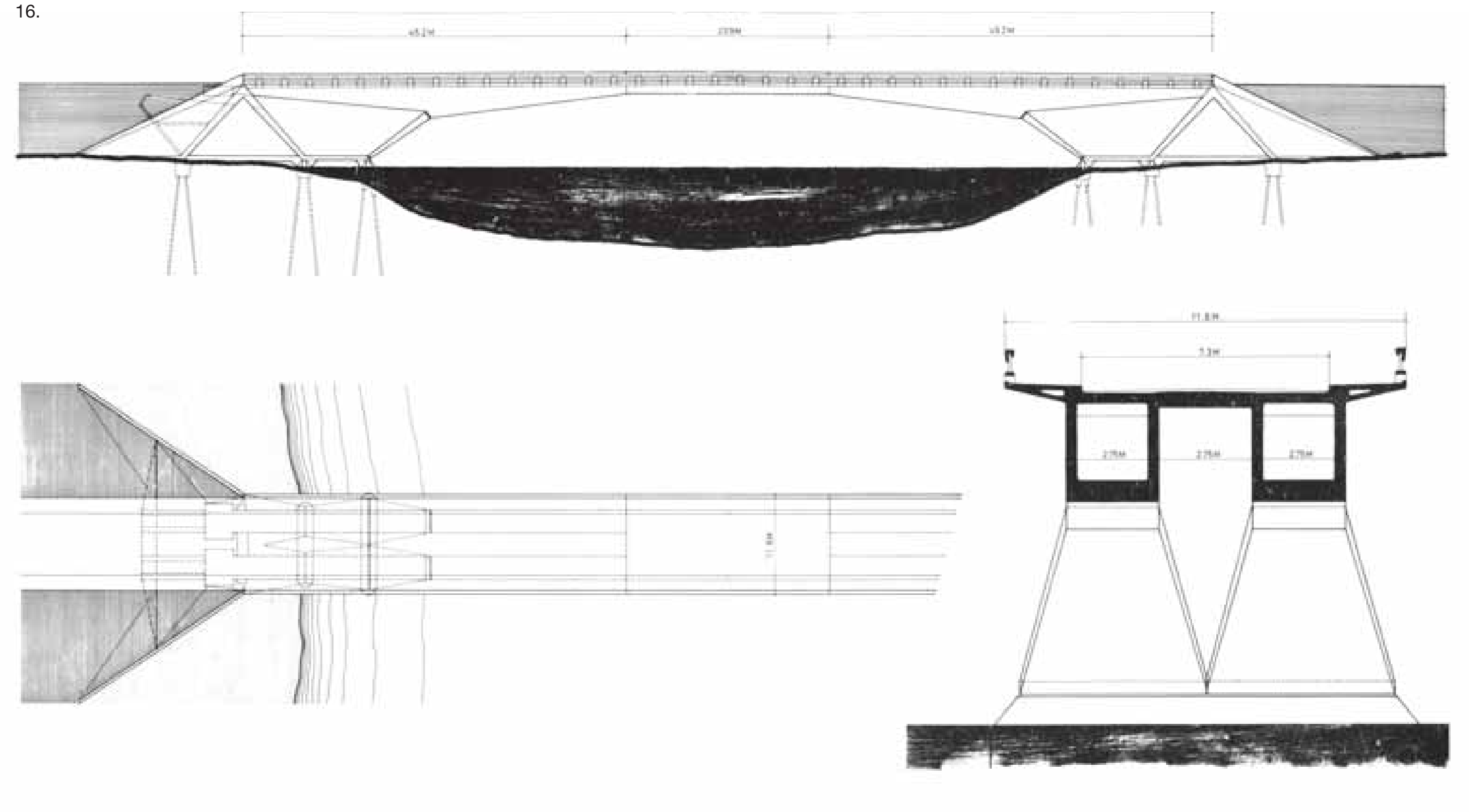
15.

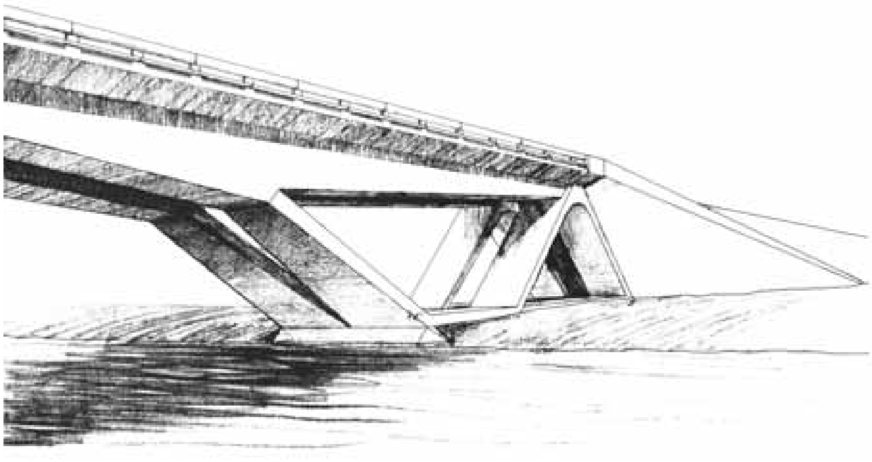
proved difficult because this cannot be compared with an ordinary launching of a ship or a caisson, as the weight of about 600 tons or so of the barge was concentrated on a very small area. Then the spatial requirements of the sliding made it difficult to transfer the shear satisfactorily from the barge to the inclined strut. And then there was a certain ambiguity in the structural system. To begin with, all the tension produced by the action of the inclined strut on the barge was concentrated in the ties, but later, when the "barges" were connected with the ties and each other, most of the tension would be transferred to the upper part of the "barges". This meant that the steel used for the ties would not be fully exploited. For these and other reasons the scheme was changed and went through a number of stages until it emerged as Scheme No 2 (Fig 15).

Here the connection between the inclined strut and the "barge" is direct and simple, and the "barge" itself acts as the tie – and is anchored back to the counterweight at the back by prestressing cables. This means that there is no redundancy of steel, and the statical system is clear. On three rows of piles on each side of the river, a reinforced concrete slab and an A-frame are erected, with a retaining structure at the end which is filled up with boulders and concrete to form a counterweight sufficiently heavy to ensure a reasonable distribution of weight over the pile groups under all conditions of loading. The retaining walls also form a finish to the embankments on both sides but are independent of any settlements of these embankments. How this is achieved will be apparent from Fig 16.

These two structures can absorb the forces transferred to them by the inclined strut and the anchorage of the barge". But this means that the temporary loads induced by the sliding of the "barges", which incidentally have been reduced to two on each side, will have to be taken up by a temporary structure, made of structural steel. When this temporary structure was gone into, it was found that the slots required to accommodate it in the A-frame weakened the latter to such a degree that it could not act as the anchorage for the "barges" without considerable complications of

16.





17.

reinforcement and anchorages for cables, and the design was changed to Scheme 3 (Fig 17) where the apex of the A-frame has been widened and thickened, and a new aesthetic organisation imposed. Fig 18 shows a model of the final scheme.

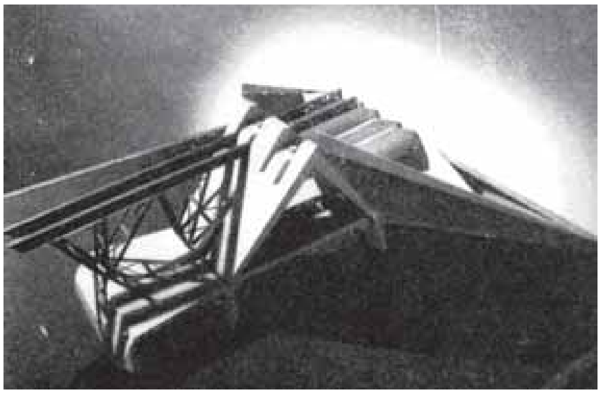
The temporary steel structure used for sliding is shown in Fig 19. In order to save steel, the 3ft high joists used for the sliding are later used in the permanent structure for the suspended centre span. The "barges" are built on formwork supported on this temporary structure, and when completed, and after the formwork and supports have been removed, rest on a 10ft cradle that slides on the joists on ball-bearing tracks. Calculations showed that the friction could by this arrangement easily be reduced to a figure that would allow the barges to slide down the ramp by their own weight. All that would be required in the way of plant was a hand winch with a brake arrangement to control the movement. The inclined strut is also suspended from the temporary steel structure in a slightly lower position (Fig 20), and after the sliding of the barge has been completed, this strut is pivoted into position and Freyssinet flatjacks are then placed between the strut and the "barges". When the "barges" have been anchored and the flatjacks blown up, the weight of the "barge" is taken by the strut and the temporary steel structure is released (Fig 21).

This explanation is, of course, far from complete but will have to suffice here.

The two footpaths at each side of the bridge provide accommodation for services, and are cantilevered out from the main structure. In conformity with the wish to avoid in situ work carried out under difficult conditions, they are composed of precast units of very dense concrete. The detail design allows for adjustment of the cantilevers to obtain a perfect alignment, and provides easy access to the pipes. The precast units are placed by a mobile 2-ton crane from the bridge.

The design of the railings proved to be a very difficult job. Dozens of designs were drawn up, and several of them might have served, but none of them produced in me the feeling of rightness. This was a purely architectural matter, and my architectural training or ability was obviously no match for my critical sense. On one occasion I showed about 20 of these designs to an audience of architects during a lecture, and asked them for their criticisms and advice. The result was disappointing. Although some were able to argue fairly convincingly in favour of one design or another, the favours were more or less evenly distributed over the various designs.

18.



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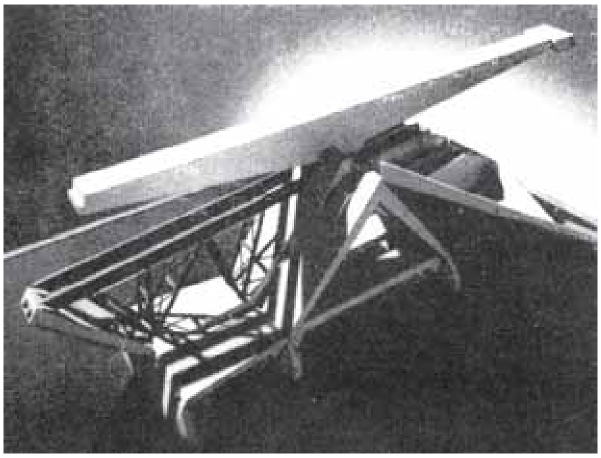

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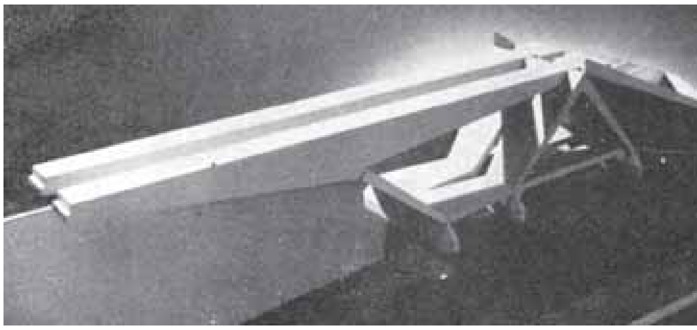

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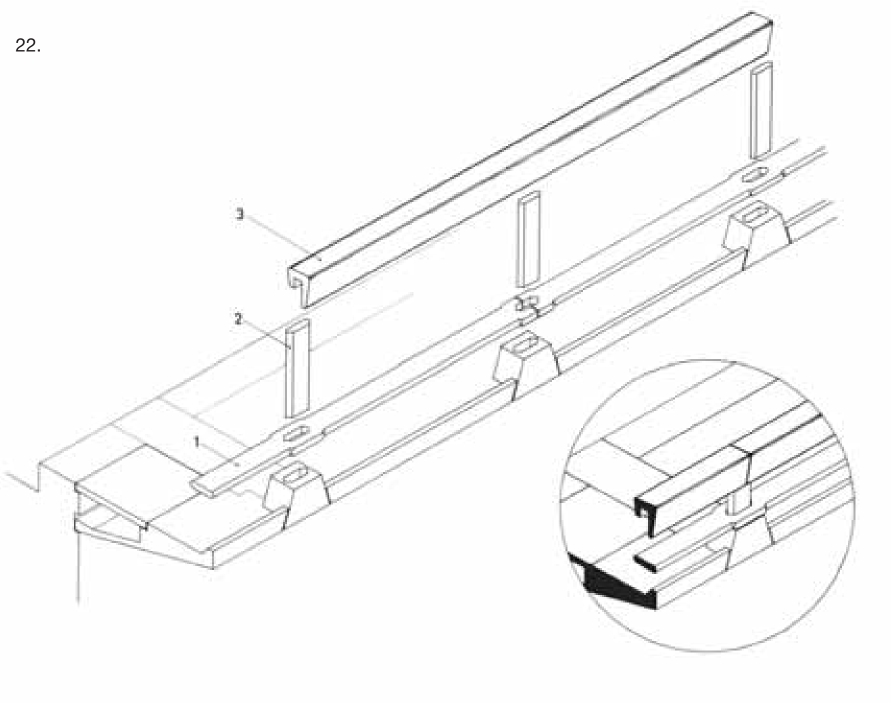
So in the end I went back to basic requirements. I had been considering various combinations of concrete and hardwood – the only two materials which might do the job – but now on the advice of my West African collaborators I ruled out timber and decided to stick to prestressed precast concrete. This meant the units had to be long, preferably able to be produced by the long bench method. Further, I decided against bolts or joints in situ, which would be liable to deteriorate. The units would have to be placed in prepared holes and fitted together so that they stayed put by their own weight – each unit being completely self-contained, and with rounded corners. This led to the design shown on Fig 22 (next page) which can be produced from three forms. The design now at least has a *raison d'être.*

22.



The Black Volta Bridge, Ghana

The next scheme, so far only a sketch design, is also for a bridge in Ghana, but in the northern part of the country where the atmosphere is dry, and where steel and aluminium are possible materials to use. The bridge is to span the Black Volta, which is approximately 505ft wide at this point, but runs in a valley 984ft wide, which is flooded for three months of the year. The profile is as indicated in Fig 23, with a 36ft drop from the outer embankments to the flat valley and further 25ft embankments down to the river, when it is not in flood.

Again, it is desirable to have as few obstructions as possible between the outer embankments, because the river can rise right to the top of these embankments and the current may be very swift. For the same reason it would obviously be cheaper to avoid staging in the river.

The design should be clear from Fig 23. In cross-section the bridge consists of two 12ft high hollow prestressed concrete girders, with steel joists stuck through holes in the girders at 2ft centres to support the roadway and the cantilevered footways. These are timber decking with a covering of asphalt.

There are only four main piers, two on each side, the span between the centre piers, where practically all the loads are concentrated, being 581ft. On these piers A-frames of hollow steel construction support two main cables which run from the outer piers or counterweights at the back over the A-frame and then to the outer end of each concrete girder. These cables in turn support a second set of cables as indicated. Between these two cantilever systems a centre span of aluminium construction is suspended.

The girders are, to begin with, interrupted at the main pier and at the point where the secondary cables support the girders. This makes the system statically determined for the dead load and when the cables have been stressed – by jacks under the main counterweights – and the length of cable adjusted to ensure that the different portions of concrete girders form a straight line. Then the joists

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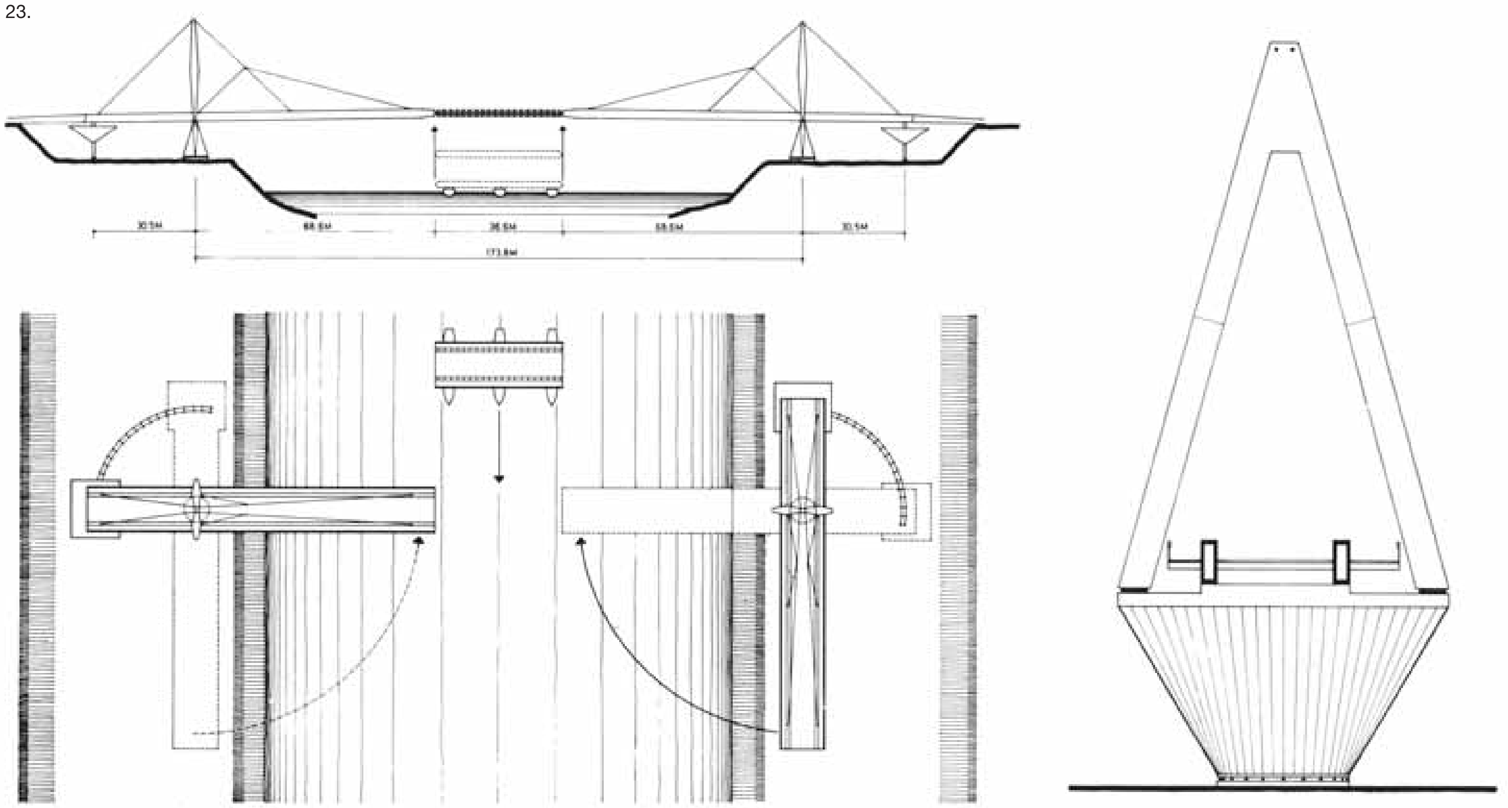

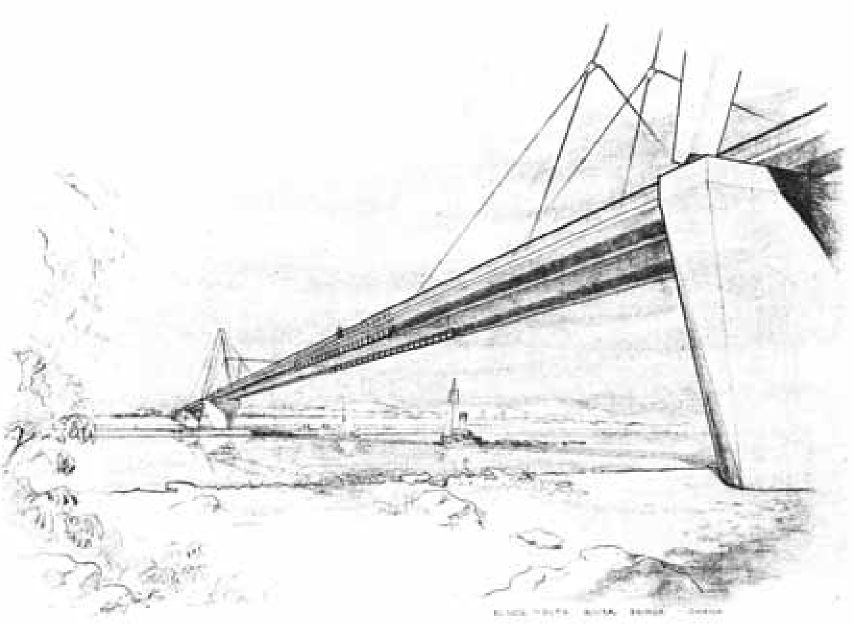

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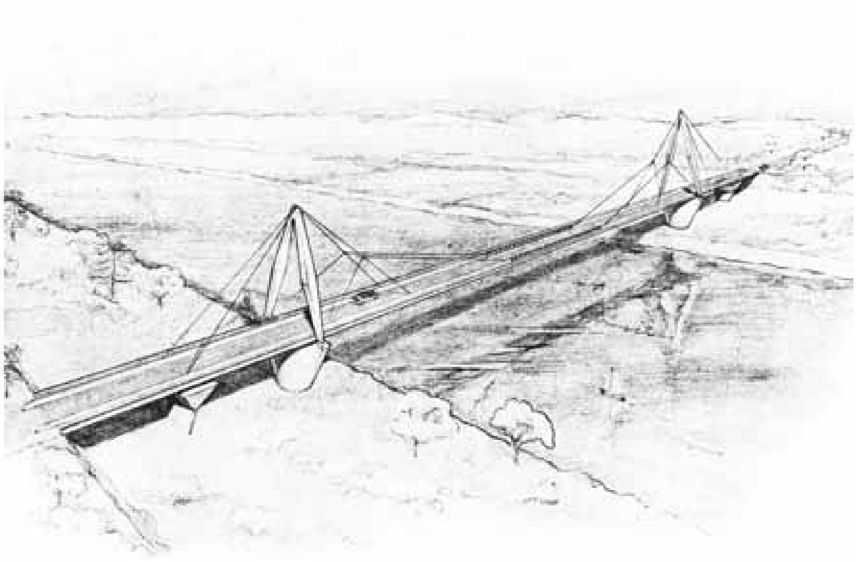

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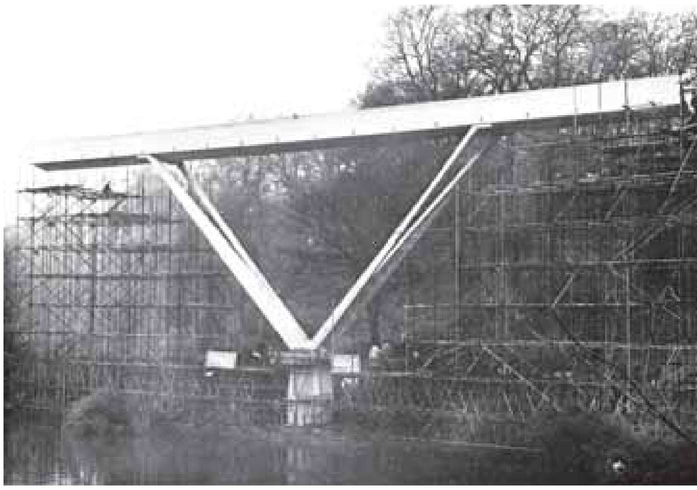
are “frozen” by prestressing and concreting and the girders now take a greater shear in the absorption of the live loads. The system is now statically indeterminate and the calculations somewhat complicated, but the principle is simple enough.

The special feature of this design is, however, that the two cantilevers are constructed on the banks of the river during the dry season in a position parallel with the river, and are then turned round the main piers through a quarter of a circle so that they reach out into the river. As all the load is practically concentrated on the main piers – which are founded on circular caissons 24ft in diameter – the outer piers which act as counterweights can be pushed along a light circular track, thus turning the whole bridge round the centre piers.

Whilst the details have not been worked out yet, it is not anticipated that any major difficulties will be met with in the detail design. Actually the process of turning the bridge on a kind of turntable is a much easier proposition than the sliding of the “barges” in the Ankobra design, because the resultant of all the forces stays in the same position. Figs 24 and 25 show two perspective drawings of the bridge.
This design employs four different structural materials: reinforced concrete, structural steel, aluminium, and timber. This is generally a bad thing, but in this case each material is used for a separate and well-defined part of the bridge, for which its properties are most suited. The guiding principle has been economy of construction, and this has certainly been achieved in this case, if one adheres to the decision that it is undesirable to have supports in the river.



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The principle of constructing the two halves of the bridge on the banks of the river and then turning them out would in this case cut the cost of the bridge considerably as it would make construction independent of the yearly floods. If the four piers were built in one season, and the steel A-frames, formwork and cables were brought to the site, then in the next nine months’ season the prestressed concrete girders and the supporting cables could be constructed, and probably the decks finished as well, because this is only a matter of sticking the joists through the holes in the concrete girders and laying the hardwood roadway.

Conditions here are therefore almost ideal for this method, but there must be many cases where it could be used with advantage, and I am surprised that I have never heard of it being used before. It is at present being used for a footbridge over the river at Durham Cathedral, one of the most beautiful settings in England. Fig 26 shows one half of the bridge nearing completion along the river bank. Although appearance was of major importance in this case, the form was largely influenced by structural and constructional considerations.

Credits

All illustrations ©Arup. The original drawings and photographs were no longer available, and so for this republication of “The design of bridges” the prints in the 1964 *London Newsletter* edition had to be scanned, making some compromise inevitable in image quality.

Diversity and change:

Music, architecture, design, and enabling the future

John Wallace*

1.

Harnessing the strengths and talents of widely diverse people in creative partnership, without loss of individuality, is of vital importance in meeting today's challenges. This article is based on a keynote speech to the 2008 Arup Europe Region Design School.

Dealing with diversity

The theme of this design school is "diversity". As a musician I naturally relate it to a musical form, and the musical form I am going to apply is that of the rhapsody. Over the next three-quarters of an hour or so, I am going to rhapsodise in favour of diversity as a balance to the human tendency to rationalise, to simplify, and to collectivise individuality. I will also illustrate my argument with a diversity of different sounds.

Where do we start with diversity? Back at the beginning. It was during an especially harsh glacial period around 130 000 years ago (perhaps as far back as 195 000 years[1]) that *homo sapiens* evolved in Africa, the earliest specimens so far being found at Omo Kibish in Ethiopia. Our species behaved in quite a different way from its predecessors: the archaeological record begins to show traces of art, ritual, and a new range of technologies, reflecting a more creative mind. A creative mind solves problems, a creative mind embraces a choice of solutions to problems, a creative mind does not think that there is one solution to all problems – and hence diversity has probably been wired into our brains for at least 130 000 years.

The fact that we inhabit a round planet with a molten core whose geology has been evolving for the last 4.5bn years, means that, as *homo sapiens* fanned out from Africa, our species diversified within itself to cope with the many different environments and climates of the world that this geology had helped to produce.

In a former life I was a performing musician and now I have the best job in Scotland - Principal of Scotland's international conservatoire for dance, drama and music. What concerns me is what concerns you:

- the future of our past
- what we take forward into the future with us
- what we leave behind
- what we create anew.

Your field is the built environment – mine is the performing arts environment.

As stock markets crash around our ears…

"…the music plays on."

And when the world's banks falter…

"… on with the Dance! Let joy be unconfined."

When none of it makes any sense…

"… the play's the thing."

Music, dance, and drama are constants of all civilisation. Where they are repressed, people are in trouble. These constants transcend boundaries; they turn work into play for the global population; they underpin the nebulous concept of "reality"; they let us escape to a finer reality; they free our minds to consider diversity; and they turn those creative minds that have been evolving for the past 130 000 years towards solving the problems that proliferating diversity brings to both our tables.

In discussions beforehand with Richard Kent of Arup about this talk, we identified together seven facets of coping with the effects of diversity that I encounter in my job and should share with you:

(1) the point at which excellence intersects with access
(2) how to embrace with other cultures
(3) how to create creative communities
(4) how to cope with the dissonance of creative chaos
(5) how to disseminate culture and ideas
(6) how to be both open and transparent and bold and innovative
(7) how to remain responsive to change.

Here are a few responses to these challenges from my perspective.

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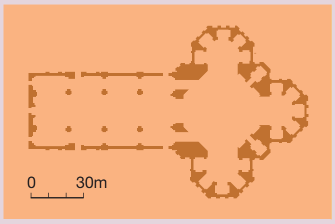
* John Wallace is Principal of the Royal Scottish Academy of Music and Drama (RSAMD) and one of the world's leading trumpet virtuosi.
This article is based on a musically illustrated keynote speech given by him to the Arup Europe Region Design School at the Dunblane Hydro Hotel, Dunblane, Scotland, on 16 October 2008. The theme of the whole Design School (16-18 October) was "diversity".

Design in music

Music grows out of its environment, like architecture and design and engineering. Sometimes music grows out of architecture. One of the earliest examples we know is that of the great early Renaissance composer Guillaume Dufay (?1397-1474), who wrote his motet *Nuper rosarum flores* ("Flowers of Roses") for the completion of the new *Duomo* (cathedral) in Florence (Fig 2), where it was performed in the consecration ceremony on 25 March, 1436. Numbers, and numbers upon numbers – proportions – permeate the structure of both music and architecture. It has been suggested[2] that *Nuper rosarum flores* was constructed by Dufay as a musical equivalent of the plan of the cathedral (Fig 3), which was only crowned by the 42m diameter octagonal dome designed by the architect and engineer Fillipo Brunelleschi (1377-1446) after the remainder of the building had been under construction for more than a century. Though it was subsequently challenged[3], the theory has more recently been reworked and largely reaffirmed[4].


2. The *Duomo*, Florence, Italy.

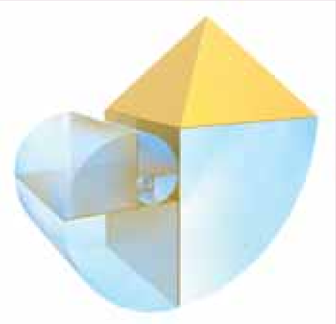


3. The *Duomo* in plan.

Much has been written and speculated about two potent numerical ideas, the golden ratio or section, and the Fibonacci sequence. To explain the former briefly, two quantities are in the golden ratio (Fig 4) if the ratio between the smaller and larger distance or quantity is the same as that between the larger of the two and their sum. It comes out to about 1:1.618 (ie 1 + 1.618 = 2.618; 2.618/1.618 = 1.618). Much architecture from ancient times onwards is said to have been based on golden section proportions – and the same is said of some of the music of Mozart (1756-1791). By contrast, if we move on to the 20th century and Béla Bartók (1881-1945), we come to a direct application of Fibonacci's series (the sequence of numbers that begins with 0 and 1 and in which each subsequent number is the sum of the two preceding, ie 0, 1, 1, 2, 3, 5, 8, 13, etc). This is often represented visually as the Fibonacci spiral. The musicologist Ernö Lendvai analysed in depth[5] the use in Bartók's music of the Fibonacci numbers. Similarly, the Scottish pianist, Roy Howatt, has done stunning work on Debussy to show his use of Fibonacci's series in structuring his musical architecture and, like Bartok, even his chord structures[6].

Debussy wrote one great piece of musical architecture about architecture – his piano work *La Cathédrale Engloutie*. Reverting to the Italian Renaissance, but more than a century and half later and 200km north-east from Dufay's Florence, much of the music of Giovanni Gabrieli (c1555-1612) grew out of the architecture of St Mark's, Venice. The concept of antiphony in large architectural spaces, and of *cori spezzati* – spaced choirs of instruments – led to the symphony (literally in Italian "a sounding together of instruments"), and to the sonata (literally in Italian, "a sounding together of instruments"). (Just like there are 65 words in Icelandic for *financial meltdown*, there are 125 ways of saying *making music* in Italian!) So the great instrumental forms, the symphony and the sonata, find some of their ultimate origins in the architecture of St Mark's. The first examples were Gabrieli's *Symphoniae Sacrae* in 1597 and his posthumous *Canzone e Sonate* of 1615. From them developed, over the following four centuries, an astonishing diversity of abstract musical forms.

4. The golden ratio.



(1) the point at which excellence intersects with access

Diversity makes it more difficult to identify what is good; true excellence and the sacrifices that it entails exclude most of the population; a professional cadre needs a participative population to support its profession; excellence needs access, and vice versa. We at the RSAMD are feeling our way to a balance of excellence with access through our 16 Youthworks centres from Dumfries in the south of Scotland to Orkney in the north, dealing with 1600 students per week. And we are dealing with the challenges raised by the differently abled through the delivery of equal opportunities training to staff and projects within the curriculum to students by the Birds of Paradise Theatre Company, Scotland's "first inclusive touring theatre company working with casts of disabled and non-disabled professional actors"[7].

(2) how to embrace with other cultures

We are dealing with this through the delivery of world music modules by the Scottish Academy of Asian Arts on our Scottish Traditional Music courses, and through assertive recruitment among the ethnic minorities.

3) how to create creative communities…

… out of moody individuals – and most importantly, how to promote a café culture in a cold climate (in one of the top 10 *Lonely Planet* cities in the world)? This led to the formation of democratic creative teams amongst my colleagues out of a former hierarchical structure. (I think you call it empowerment.) I'm still working on the dynamics of the creative relationships and the solo and ensemble behaviours of artistic administrators. The dissolution of the works canteen and replacement by a "creative space" has helped, as has the provision of a decent cup of coffee! Encourage students to self-generate, to think for themselves, to put on their own gigs, to adopt the Danish idea of Fundament – that the first eight weeks of any academic year in a performing arts institution should be a free-form creative beginnings programme.

(4) how to cope with the dissonance of creative chaos (and police the consequent mess)

Always have enough productive work with clear and realistic deadlines for your resident geniuses on your core business (our core business being our students). With this in mind we go out actively recruiting first-rate demanding students nationally and internationally to create a centre of excellence with extremely high international standards in Scotland, for Scotland.

(5) how to disseminate culture and ideas (when surrounded by intellectual apathy and its bedfellows, hubris and greed)

Get them young, temper human hubris with humility, create the context to inspire the cultural movers and shakers of the future to perform well in all the timeless topics humans have had to deal with over the last 130 000 years, and will have to through the stock market crashes of the next 130 000 years, and create respect amongst those young people for the essential human values of freedom and equality.

5. The Royal Scottish Academy of Music and Drama.

(6) how to be open and transparent, and bold and innovative, at the same time

I haven't succeeded in this yet, but I think the secret is to prepare a measured tempo of communication and to have great powers of acceleration and deceleration, all the while taking your people with you. I am Action Man – but actions create reactions and being one step ahead of those reactions means keeping some things to yourself, which isn't really open and transparent. So this is a difficult one for any leader of anything in a modern democracy.

(7) how to remain responsive to change (and a caveat here - when much of it is so superficial)

Surround yourself with people who have superior powers of analysis to your own, and be prepared to change your mind – unless your instinct, formed by 130 000 years of genetic coding, begins to scream at you. Remind yourself of your own personal value system, which should be somewhere up there with that of St Francis of Assisi. When in doubt, do nothing, a difficult concept for Action Man (or Woman), but… doing nothing is a marvellous prelude to action.

Diversity, space, and nomadry

In addition to these magnificent seven facets of dealing with diversity, I also discussed with Richard some of the space challenges I face and for which my training left me totally unprepared. I am the worst thing an architect or designer or engineer can encounter: a performer with no practical nous whatsoever – beyond lip, hand, brain and lung co-ordination – but with limitless needs and panoramic enthusiasms.

The RSAMD now occupies a relatively new building[8], designed by Sir Leslie Martin (Fig 5). Every summer Alan Smith, our Finance Director and I get Gary, our estates guy, who has lived with our building since Day 1 in 1987, to tear the guts out of it, knock it about internally, and bring it back to life, reinvented for each incoming year of students, whose numbers are growing and whose imperatives are morphing. The Academy is now a bionic building with refreshed body parts. Ideally, we need a building the interior of which we can constantly reconfigure to reflect our changing needs.

We will require buildings that have an infinitely greater capacity than at present for flexibility, adaptability, and future-proofing. Our productions in future, all the way to costume and set design and construction, need to embrace the latest filmic, flying, and virtual technologies. Our business is professionals in training now for the future of performance and production.

And human beings now consume a greater diversity of performance product per capita than at any other time in history.

And that diversity is set to grow, because of society and because of the diversity of organisations within that society.

We now think of ourselves as a sedentary society, the members of which live in fixed abodes, but another thing that arose in my conversations with Richard was how much that "sedentary" population actually travels, and just what itchy feet it has. Richard prised out of me the contention that the most successful amongst the present population, including the most successful businesspeople, have returned to a modern form of nomadry. "Nomadry" and "itchy feet" are underlying components of our society; they surfaced rapidly during the course of the 20th century and now continue into the 21st century.

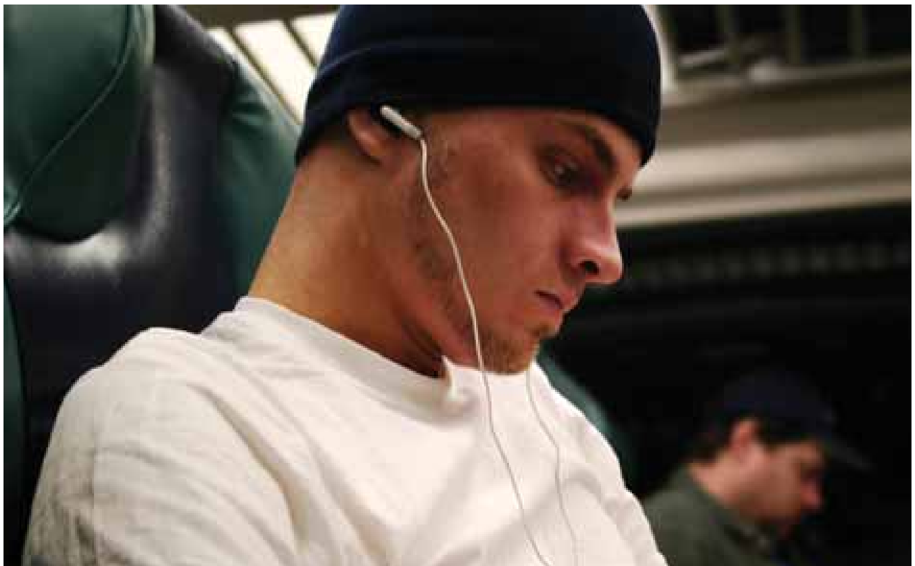
The growth and spread of large urban centres has created a massive class of nomads, called commuters. Similarly, the mass exodus to Spanish beaches every summer has created another class of nomads called tourists, as has the repopulation of the French countryside by the English and Dutch and their *maisons secondaires*. There is thus an annual migration pattern, most visible in the crammed motorways, railways, and airports every Bank Holiday. Add to that the growth of the mobile phone, by which entire populations can be in two places at once while walking, driving, and soon flying. And, we want to consume our culture on the move, as part of granular dispersed constituencies of same and similar interests. The inner nomad in each and every one of us is a restless creature whose instincts it is very hard to pacify.

Nomadry and the trumpet

My specialism is music. And I think I understand nomadry. I used to tour for between six and nine months of the year.

And my instrument is the trumpet. Two early examples are the "cow horn" trumpet and the didge or didjeridoo. The most well-known of the former is the Jewish shofar, still played in synagogues to this day; if the walls of Jericho ever really were blown down, it would have been instruments like these that were responsible. "Didjeridoo" is a descriptive onomatopoeic word dating back only to 1798, but it covers an astonishing variety of wooden trumpets in all shapes and sizes, with hundreds of diverse aboriginal tribal names, and a history of usage that goes back at least 1500 years.

6. One class of nomad, the commuter, finds escape in music.



Trumpeting freedom

The trumpet is the perfect instrument to rhapsodise on freedom because, as our language becomes more restricted and full of hedge funds of caveats, you can pick up a trumpet and tell the truth, the whole truth, and nothing but the truth.

So here are some highlights from the growth of the concept of freedom through the medium of the trumpet. As already noted, since the earliest times it has been a religious and a military instrument – and people have always taken their religion into battle with them. The trumpet became completely identified with battle, death and heroism. The Scots, despite the small size of the country, have been world leaders since William Wallace in the triathlon of battle, death, and heroism. What we call in Glasgow the "Gallus* Trumpet" is the sort of music the Scots played on their heroic trumpets in the time of Mary Queen of Scots.

By the end of the 17th century, Louis XIV was the embodiment of the concept of the Divine Right of Kings. To celebrate one of his military victories, the French composer Marc-Antoine Charpentier (1643-1704) wrote a *Te Deum* which opens with a memorable trumpet tune - French, aristocratic, absolutist, full of haughty heroism, and all belonging to the Sun King by divine right. This was music that grew out of the architecture of Versailles.

7. Detail of the frieze on the *Arc de Triomphe*, Paris.

By 1707, confident Britain, new in its Union of Scotland and England, with its Whig government, saw itself as a land of heroes controlling the high seas.
Its trumpet music is exemplified by the familiar *Trumpet Voluntary* of Jeremiah Clarke (1674-1707), composed for the Haymarket Theatre, just around the corner from Parliament. Then, towards the end of the 18th century, something happened - the French Revolution. The trumpet went from being an aristocratic instrument to a universal instrument, symbolising the freedom of common men and women to be heroes too. *Liberté, égalité, fraternité* – and, yes, *La Marseillaise* started off as a trumpet tune.

Ludwig van Beethoven (1770-1827) is possibly the most interesting composer that ever lived in his evolution of the structures of abstract music. Post-French Revolution, he took up the cause of the universality of humankind, and had his first stab at it in his Fifth Symphony. Then he finessed this idea in his Ninth Symphony, coming up with the "Ode to Joy", a heroic trumpet tune in praise of the universality of humankind.

From that point it was a short step to Guiseppe Verdi (1813-1901), whose triumphal marches became an inspiration in the movement to reunify Italy – Garibaldi's *Risorgimento*. Music and freedom again, another anthem of which in the 20th century was the *Fanfare for the Common Man* by the American composer Aaron Copland (1900-1990).

The fervour of Verdi's melodies and the irresistible tidal surge of his underlying rhythms demonstrate the power of music to generate mass emotion, and that has been a feature of the Bob Geldof phenomena of Live Aid and, more recently, Live 8. Verdi, however, was perhaps the first to utilise the power of music to move a body of people like us to vibrate in unison in a common cause. Although it is passionately and fiercely individual and appeals to us all in diverse ways, it has great powers of bringing people together.

This sort of music works to free and liberate the consciousness to think the unthinkable and to make the future a better place than the present.

8. Live Aid raised £150M for famine relief in Ethiopia. An estimated 400M viewers, across 60 countries, watched the live broadcast.

The three major developments of post-Ice Age man (the Ice Age of 13 000 years ago, not 130 000 years ago) – sedentary agrarian societies, nomad pastoralist fringe-groups, and the development of organized military campaigning – created situations throughout the world that were punctuated by trumpet calls.
The trumpet has always been universal and ubiquitous, and a way of sending coded messages over long distances. It is one of the most diverse of instrument types, and it is the loudest spokesman for diversity I could find.

Historically, for farmer and nomad alike, the animal horn trumpet was an efficient hunting tool, startling prey and driving it towards prepared ground. Between signalling and hunting, the trumpet developed not only a musical idiom, but also a set of transferable skills that allowed the instrument to be pushed towards an altogether more hostile role, accompanying the revolution in weapons technology that brought the bow and arrow, sling, and mace into being.
The large amount of surplus time nomadic people the world over had to spend watching over their flocks gave them the chance to practise – and master – time-consuming skills such as archery and horsemanship. That "spare time gap" between pastoralists and sedentary agrarians would ensure that the nomadic steppe peoples would dominate their farming neighbours for most of known history.

9. The shofar.

So, contrary to popular mythology, nomadry is a more successful way of life than being sedentary – if it were not, why would so many of us indulge in it? It is also economically advantageous to be a nomad. And a Rolling Stone does gather moss; just look at Mick Jagger. Thus mobile homes probably have a future whether on land or sea; the success of piracy off the Horn of Africa and of the Taliban in Afghanistan shows the enduring success of the dark side ofnomadry. However, nomadry also has a brighter side in the future as a possible way of dealing with climate change and the rising of ocean levels.

The extra leisure time of pastoral herding also gave nomadic cultures more opportunity to practise musical instruments, a cultural heritage that can be observed throughout nomadic societies to the present day. (In orchestras, the string section is still known colloquially as "the gypsies".) And, it was almost certainly nomad pastoralists who first developed the chilling insight that, just as trumpets could be used to startle and corral animals and make signals between hunters, so they could be used against humans in battle.

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* **gall(o)us, etc**. adj **1** villainous, rascally **2** wild, unmanageable, bold; impish, mischievous, cheeky. *[From Concise Scots Dictionary, Cambridge University Press, 1985]*.

What about the engineering of these ancient trumpets?

Early man fashioned them from any suitable local elements. Human ingenuity can achieve musical miracles with materials like wood and bark, bamboo, gourds, crustacean shells, and mammal horns. The horns of wild or domesticated animals can be crafted into simple trumpets by hollowing out the core with a heated stick. Conch shells can be dried and bored with a blow-hole. Tree-branches can be hollowed out with fire or termites. Bark can be stretched around a wooden skeleton to form a cone-like trumpet or a massive horn. Even human remains have been hollowed out and lip-blown.

So formerly, before mass production, mass marketing, and global distribution, there was astonishing diversity in something as simple as a tube that you blew through. And, in addition, the many ways a lip-blown instrument can be primitively manufactured means that the trumpet often predates the earliest collective memories of a society: developing into a marker of identity and of cultural pride.

Study of even the earliest references to trumpets reveals the instrument to hold an aura of antiquity, a tool bequeathed to man from an ancient, unrecorded source. The Greeks, for instance, never formed a creation myth for their trumpet – the salpinx - as they had for their plucked string instrument, the lyre, and the woodwind aulos. Other instruments required an explanation for their coming into being: the trumpet had simply “always existed”. It is an example of an early man-made object that acts universally as a cultural transmitter, communicating more than a simple message between living people.

Very similar to some of our greatest buildings.

10. A camel-mounted trumpeter in the parade at the start of the Desert Festival, Rajasthan, a celebration of dance, folk song, and music.

11. Triton blowing a conch shell at the Trevi Fountain, Rome.

Taking the past into the future

But, when we are thinking of the future of our past, and of what we are going to take with us into the future from that past, it is remarkable to dwell on the fact that human beings, from the moment of their emergence as a cultural as well as a biological entity, have in one way or other collected, preserved, and hoarded items that have no other significance than as carriers of messages from the past.

In October 2008 we finally realised that we had entered the 21st century. The present time may prove to be a watershed and nothing may ever be quite the same again. Just as, in music at any rate, the 20th century began on Thursday, 29 May 1913 with the shock of Stravinsky’s *Le Sacre du Printemps* – a landmark, an aural mark, of modernity.

What are you going to do next, after this watershed? How are you going to create and recreate our physical environment? How are you going to do your bit for the billions of people out there?

I do not know your field as well as you do, but I do think there are parallels between architecture and the performance arts. Perhaps it may be helpful to share with you my route forward.

I have here in my brain, body, and trumpet a whole condensation of 130 000 years of human evolution, just as you have in your fields. I know I am just stating the obvious, but between my body and this artefact, this trumpet, which has grown out of our environment through the millennia, there is enough genetic knowledge, experienced through basic instincts, to deal with anything that comes my way, and I can express this knowledge with the aid of this artefact when words are not enough.

My route lies definitely in keeping the gene pool of diversity of choice open, and in countering the pervasive spread of deadening orthodoxy that we meet every day, because of cost pressures, with a profusion of eccentric solutions.

And the fuel of my route is the power of dance, drama, and music to free young minds: the ability of the performing arts to be a powerful educational tool and to expand a society's consciousness and raise a nation's game. And wherever the performing arts perform and flourish, and human beings have the confidence and the self-esteem to perform, modern economies perform and flourish. I believe that the value of performance to the world has to be enormous.

In music, it is firstly the sheer sound that has the effect, initially on the individual and then, like a virus, on the masses. Then it's the melody, harmony, rhythm, phrasing, feeling; all the complex mix of emotions from passionate to dispassionate, that works its magic. And playing an instrument itself – for the player it is like getting the keys to the doors of Paradise.

Conclusion

I said at the outset that I was going to rhapsodise in favour of diversity as a balance to the human tendency to rationalise, to simplify, and to collectivise individuality. The concept of individuality – treating everyone as an individual – requires freedom, and therefore freedom is a prerequisite for diversity. But it seems difficult to blow the trumpet of freedom when all about us there is an increased imperative for the straitjacket of rules and regulation in the financial sector. However, human ingenuity will out, and the freedom of the human spirit will prevail.

And what sort of creative organisation moves a body of diverse people to vibrate in unison whilst preserving the freedom of their own individuality? A partnership like Arup. Looking into the future, this partnership structure is the key to keeping your gene pool of diversity high. People like me, on the outside, admire your form of organisation, and when we look at our own organisations, we realise how much better diversity would flourish within our organisations with your sort of structure.

So to finish, in the most competitive market any of us may have experienced, we have to encourage diversity. On the edge. Exciting. Forbidden. Original. New. Irreverent. In your face. Brooking challenge and seeing it off – diversity.

12. Trumpets often feature in modern band line-ups.

13. The didjeridoo in a very modern "call to action".

After joining the London Symphony Orchestra and then moving to the Philharmonia Orchestra as Principal Trumpet, **John Wallace** enjoyed an international career as a trumpet virtuoso. In 1986 he founded The Wallace Collection, a brass ensemble specialising in modern repertoire challenging to performers and listeners alike. Amongst their many recordings is a disc entitled "The Golden Section" – music of John Tavener, Jim Parker, William Matthias, Michael Nyman, and James MacMillan. John Wallace became Principal of the The Royal Scottish Academy of Music and Drama in 2002 (after which the remaining members of The Wallace Collection renamed their group The Golden Section).

Credits

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Westlink/M1, Northern Ireland

Dom Ainger John Border Chris Caves Paola Dalla Valle Chris Furneaux Tim Gammons
John Griffiths Deepak Jayaram Ray Kendal Ronnie Palmer Alan Phear Andy Ross Guy Stabler

1. Stockman's Lane Junction.

History

Introduction

Constructed on the west side of Belfast, the original Westlink was completed in March 1983 to connect Northern Ireland's M1, M2, and M3 motorways with 3.38km of dual carriageway. By 1998, daily traffic levels had grown from the design 35 000 vehicles to 65 000, putting pressure on key junctions at Grosvenor Road and Broadway. Delays at peak times were creating disruption and frustration for travellers, bringing the link close to breaking point, and it was recognised that the bottlenecks on this key strategic route needed to be addressed. A scheme was developed with the following objectives:

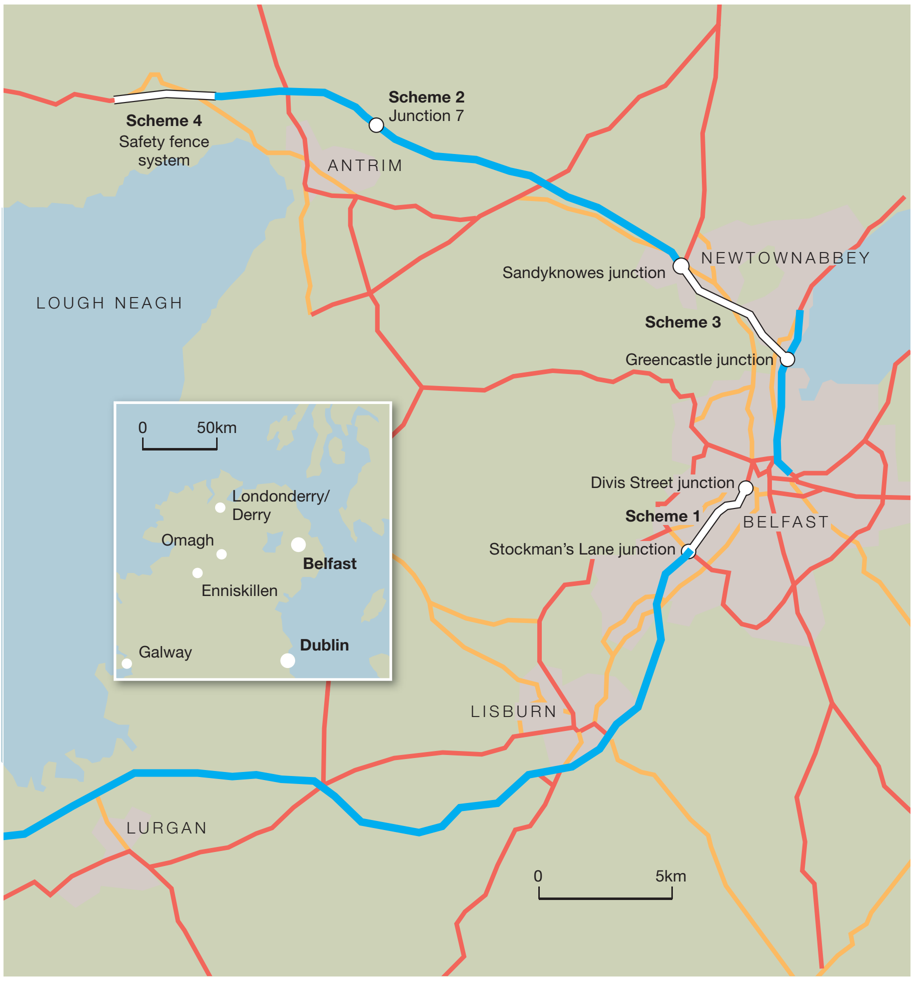
- Accommodate and sustain strategic traffic demand between M1/M2/M3 and Belfast Port.
- Reduce vehicle journey times and operating costs.
- Reduce traffic on parallel routes.
- Improve access to the strategic road network.
- Encourage access into central Belfast by sustainable transport means.
- Enhance the network through the introduction of the latest ITS techniques.
- Protect and enhance the natural and built environment.

The M1/Westlink upgrade is Northern Ireland's top priority road improvement scheme. It was completed and opened six months ahead of programme. Part of the Trans-European Road Network, this major project is vital for shorter and more reliable journeys in and around Belfast. Arup carried out the detailed design for the design/build contractor.

In December 2000 public inquiries were held to consider the environmental statement and designation orders for the M1/Westlink upgrade. Following proposed changes to the design, a further inquiry was held in December 2002, and the vesting orders, which provide the necessary land, became operative in September 2004.
The procurement process ran throughout 2004 and 2005, resulting in final award and start of construction in early 2006.

Purpose

The project forms part of Belfast's current £2bn worth of investment, signalling that the city is getting back on its feet after more than 30 years of difficult times. It was recognised that the road network was of key importance to the Northern Ireland economy's success. This scheme improves the links between the M1, M2, and M3 motorways, enables better access to the south and west of the province and to the Republic of Ireland, and facilitates connections to Belfast city centre, the Port of Belfast, and Belfast City Airport.



2. Key map.

Project outline

The construction element of the entire DBFO (design/build/finance/operate) project comprises four schemes packaged together (Fig 2). The upgrade (Scheme 1) involves major improvements to the M1 and Westlink between the Stockman's Lane junction and the Divis Street junction. These include:

- demolition of existing viaducts and reconstruction of replacement bridges to carry the M1 over Stockman's Lane Junction, along with widening and signalisation of the roundabout and improvements to the slip roads
- widening the M1 Westlink to dual three-lane carriageway
- providing grade separated junctions at Broadway and Grosvenor Road junctions by means of underpass structures
- a separate dedicated busway from Broadway into the Europa bus centre
- a new feature footbridge at Roden Street
- improved facilities for pedestrians and cyclists
- high quality landscaping throughout the corridor.

The DBFO project also involves:

- Scheme 2: construction of new on-slips and junction roundabouts at Antrim Hospital, junction 7 of the M2
- Scheme 3: widening the M2 to three lanes between Sandyknowes and Greencastle junctions
- Scheme 4: upgrading the motorway communications networks and facilities to include state-of-the-art lane control variable message signing, CCTV, emergency telephones, incident detection and transmission networking to the motorway control centre, as well as replacement of safety fence systems to current standards.

Complexity

The upgrade is one of the most challenging projects ever undertaken by the Department for Regional Development Roads Service. The road runs through a very constrained corridor with homes, businesses, and a hospital hugging both sides. As a result of pressure at public inquiry, much of the route was to be below ground level. This presented challenges, as the road runs through some very soft areas of ground with high groundwater, known locally as "sleech", laid down since the last Ice Age.

The Blackstaff river runs the length of the route and other tributaries cross it. Interwoven at the junctions is a tangle of underground and overground utility services ranging from large-diameter gravity and pumped sewers, gas pipelines, and high-voltage overhead power transmission lines. In addition the live road and motorway network runs through the site and needed to be kept moving.

The contractual arrangement

The first roads DBFO of its type in Northern Ireland

The M1/Westlink upgrade has been delivered as part of a public/private partnership. The private sector raised the finance for the improvement schemes, and will be repaid through service payments for maintaining the road network and ensuring its availability throughout the 30-year life of the contract. This DBFO form of contract is based on that used successfully in the UK by the Highways Agency and, as far as Arup is concerned, builds on the firm's previous experience as designer in this form of contract, notably of the M6 Toll[1], completed in 2003.

The Department for Regional Development (DRD) awarded the DBFO contract to Highway Management (City) Ltd (HMG). Roads Service managed the contract for DRD. HMG, the "DBFO company", appointed Highway Management Construction (HMC) as the main contractor under the design/build contract, and in turn HMC appointed Arup as designer (Fig 3). HMC is a consortium of local contractors John Graham (Dromore), and

3. The contracting parties and their roles.

Arup team	Joint veture partners
Promoter **Department of Regional Development Roads Service** DBFO company **Highway Management (City) Ltd** D+B contractor **Highway Management Construction** D+B designer **Arup**	**Graham** **Farrans** **Bilfinger Berger**

Northstone (NI) Ltd (formerly Farrans Ltd), and the major German group Bilfinger Berger. Separately, HMG appointed Highway Management Maintenance (HMM) for the routine maintenance of the DBFO highway network.

Arup's scope of work included design of highways and structures, drainage, geotechnics and traffic signalling, as well as environmental mitigation, motorway communications, and site support.

The DBFO procurement process started in January 2004, with the issue of the works contract notice to the Official Journal of the European Union. A prequalification submission was prepared, with Arup supporting the HMC joint venture; tender documentation was issued in April 2004 to HMC and three other groups, and an intense tender period ensued, with Arup completing preliminary design and risk assessments to allow the tender submission to be made on 15 September 2004.

Following further evaluation, the field was reduced to two bidders who were invited into further negotiation and make a best and final offer (BAFO) on 10 May 2005. Just over a month later, on 21 June, HMC was announced as the provisional preferred bidder. Financial close was achieved on 17 February 2006, though in September 2005 HMC had already asked Arup to commence limited detailed design. Construction started in early 2006, and most sections of the project were completed by early 2009, well ahead of programme.

Arup's approach

The design team

To manage and work on the project design, Arup gathered a substantial team. Its heart was based at the Midlands Campus in Solihull, where the project management and highways, drainage, ground engineering, pavement, and environmental design were carried out. Other Arup offices taking major sections of work included Belfast, Dublin, Cork, and Leeds. Overall, approaching 250 Arup staff worked a total of some 120 000 hours on the project. All those who made a significant contribution to the project are credited at the end of this article.

The firm took the strategic decision that in order to share risk and utilise the complementary skills of partner companies, it would also engage a range of subconsultants to help deliver the design (Fig 5): Benaim, now part of Scott Wilson, carried out the geotechnical and structural design of one of the structures; Serco Integrated Transport undertook the detailed motorway communications design; Siemens did the traffic signal design; Lighting Consultancy and Design Services (LCADS) was the street lighting designer; WA Fairhurst took on the role of road safety auditor; and Halcrow was the Category 3 structure checker.

Project management

Arup was appointed under a fixed fee contract for the detailed design, and so careful management of scope and fee were required. The tender fee had been built up from detailed estimates of the budgets required by individual disciplines to deliver the design. To help comprehend the full scope, and reduce the risk of missing or underestimating design elements needed, the team prepared a design information schedule during the tender.

To manage the budget and monitor spending under all the elements, the tender fee was broken down under more than 150 headings, each of which was assigned its own share of the fee. If and when required and justified, the project manager drew down additional fee from the risk contingency and added it to the individual task budgets. In this way, spend against the original estimates was carefully tracked, and any projected overspend identified early.

The design information release schedule, prepared during tender, was bound into the contact. This identified all deliverable packages and dates by which they would be produced. This document evolved over the project's lifetime and by agreement with the contractor; as and when scheme priorities changed, amendments were made to the delivery programme to suit construction progress.

All contract drawings and documents were submitted electronically on the project extranet, Aconex. Every main participant had access to this, including Roads Service and its agents, HMG (the DBFO company), HMC (contractor), and Arup and all its subconsultants. Workflow procedures were established to allow documents to be submitted for internal review, for Roads Service review, and for construction, all on this system. Aconex allows for common access to documents and clear auditable history of review comments and responses.

4. Timeline to start on site.

	2004	2005	2006
Prequalification	▬ March		
Tender start	● 23 April		
Tender return	● 15 September		
Invitation to BAFO stage	● 6 December		
BAFO return		● 10 May	
Provisional preferred tenderer		● 21 June	
DBFO contract award			3 February ●
Design contract signed			15 February ●
Precommencement activity*		September ▬	
Start on site			30 January ●

*Geotechnical investigation, survey, detailed design.

5. The design team.

Arup team

Midlands Campus
Highways and drainage
Structures
Ground engineering
Pavement
Environmental
Hydraulics
Mechanical/electrical
Planning Supervisor/CDM Co-ordinator

Belfast
Local liaison
Site staff

Cork
Communications co-ordination

Dublin
Structures

Leeds
Utilities design

Newcastle
Geotechnical checking

Additional assistance from **Bristol** and **Cardiff**

Total staff
250

Total man-hours
120 000

Subconsultants

Benaim
Fairhurst
Halcrow
Lighting Consultancy and Design Services
Siemens
Serco

Environmental design

6. The Sedge Warbler: one of the many summer visitors to Bog Meadows Nature Reserve.

Environmental design management ensured that the environmental commitments and requirements were incorporated into the detailed design. Throughout the design life-cycle, the involvement of Arup environmental specialists ensured that the necessary level of design mitigation was at the core of design output.

Arup's ecologists ensured the protection of the local Bog Meadows nature reserve – the largest piece of natural wild land remaining within the urban area of Belfast that lies alongside the M1 – during the works and through the design of an appropriate road drainage system to protect the wetlands present on the site.

Ecological surveys were undertaken to determine the presence of protected species, and these results informed the design and subsequent construction works to ensure minimal impact. Where pernicious or invasive species of weeds were found to be present, eg Japanese knotweed (Fig7), Arup's ecologists advised on the controls needed to avoid spread and subsequent management prior to disposal.

Working closely with the landscape architects, Arup's ecologists identified the key areas of habitat to be protected during the works, on which the landscape planting and seeding proposals could develop. The aim was to provide ecological enhancements that also looked good for the local population.

Arup archaeologists reviewed the design of the archaeological field works, ensuring before submission of the archaeological design that no objection would be raised by the Northern Ireland Environment and Heritage Service. The management approach ensured that no construction could begin until all archaeological work was completed in accordance with the archaeological design.

To integrate the scheme into the surrounding area, good landscape design was important, not only in preservation of key elements, but also enhancement through additional tree planting and ground profiling. Arup landscape architects and highway engineers worked closely to produce the appropriate hard and soft landscape detailing.

This integrated design development once again ensured that appropriate measures were incorporated from the outset. A prime example was the landscape design and asymmetric widening of the M1/Westlink approach to Broadway roundabout to preserve the integrity of the Bog Meadows, a remnant of flood plain pasture and hay meadows (Fig 8).

The prevention of pollution of streams and ditches, planting, seeding and boundary treatments (wall, fences, hedges), ensured that the valuable landscape and ecological elements of the Bog Meadows were retained.

7. Japanese knotweed on Scheme 2 (M2 junction 7).

8. Bog meadows alongside the approach to Broadway roundabout.

The site team

The project construction works were divided into four geographically separate areas (Fig 2), and Scheme 1, the main M1 Westlink site, was subdivided into three separate locations. HMC staffed each site with a mix of personnel from the three parent companies, based in satellite site offices at each work location.

The Arup site team of 5-10 design and inspection staff was based in a core office at Broadway junction on the M1 route. Broadway junction is in a busy urban area and provides access to the Royal Victoria Hospital – Northern Ireland's largest – to Park Shopping Centre, and to extensive commercial and residential areas.

The site team had two distinct roles; firstly to provide design advice and support to HMC in developing the most efficient and economic construction methods, and secondly to monitor and inspect the works to make sure that they were constructed in accordance with the design and construction requirements.

The design support role primarily involved responding to technical queries and processing minor design changes that had to be reviewed and approved by Roads Service's technical advisor. This was particularly important at the start of the Broadway junction work. Here, a major diversion of the culvert that carried the river known locally as Clowney Water was constructed adjacent to the secant piled walls of the underpass and beneath the existing live motorway.

In addition, major 33kV electrical cables and pumped and gravity sewers needed to be diverted and water mains, telephone, and fibre optic service cables relocated, all before the adjacent detailed design was completed. These works were further complicated by extensive and constantly evolving temporary traffic management works at Broadway junction; two motorway lanes in each direction had to be available at all times, as well as access to the hospital and adjacent areas.

During this period, the site team worked closely with the contractors to develop design/construction solutions enabling the works to be built efficiently and in accordance with the contract requirements. The level of monitoring and inspection by the site team had been defined at the outset in the Arup design agreement and incorporated into the contractor's inspection and test plans.

The achievement of monitoring targets was verified by producing examination records, which were incorporated into the integrated quality management system. This permitted interrogation of all documents to facilitate the signing of construction certificates.

Highways pavement

The pavement design and highway levels were developed to utilise the existing pavement wherever possible. Arup's pavement team undertook a review of the existing pavement construction and assessed its strength. This allowed them to produce a pavement design that made best use of the existing pavement, thus minimising the waste generated by the site and the amount of new material required, in line with sustainability objectives.

Detailed investigative surveys of the existing highway pavement determined whether it could be incorporated in the proposed construction, as opposed to full reconstruction. The investigation particularly targeted the hard shoulder, as this would become lane 1 in the proposed widening to three-lane dual carriageway. Additional testing included:

- a ground-penetrating radar (GPR) survey to confirm the thickness of the pavement layers, given the limited amount of as-built information
- a coring survey to calibrate the GPR and provide samples for testing of material properties
- laboratory tests to assess the bituminous material properties, such as void content and percentage of bitumen recovered, and
- dynamic cone penetrometer (DCP) tests to confirm the foundation strength.

The main results of the investigations covered two broadly distinct lengths of the motorway – Stockman's Lane to Broadway roundabout (~1.5km) and Broadway roundabout to Grosvenor (~2km). The results for each were as follows.

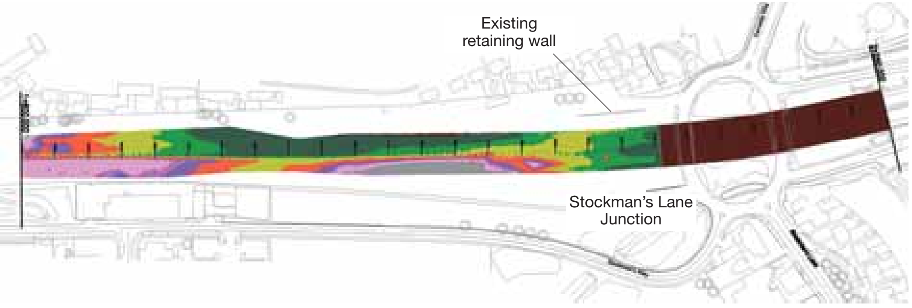
Stockman's Lane to Broadway

The existing construction consisted of a fully flexible pavement. The proposed construction required the existing hard shoulder/bus lane to be reconstructed, as it was thinner than the existing main trafficked lanes 1 and 2. Also the material had a high void content (up to 17%; see Fig 9) and low bitumen penetration, which indicated that the material had oxidised and therefore become more brittle.

9. Example of voided roadbase.

10. Bellevue Bridge with Belfast Lough in the distance.

11. Example of isopachyte plot.



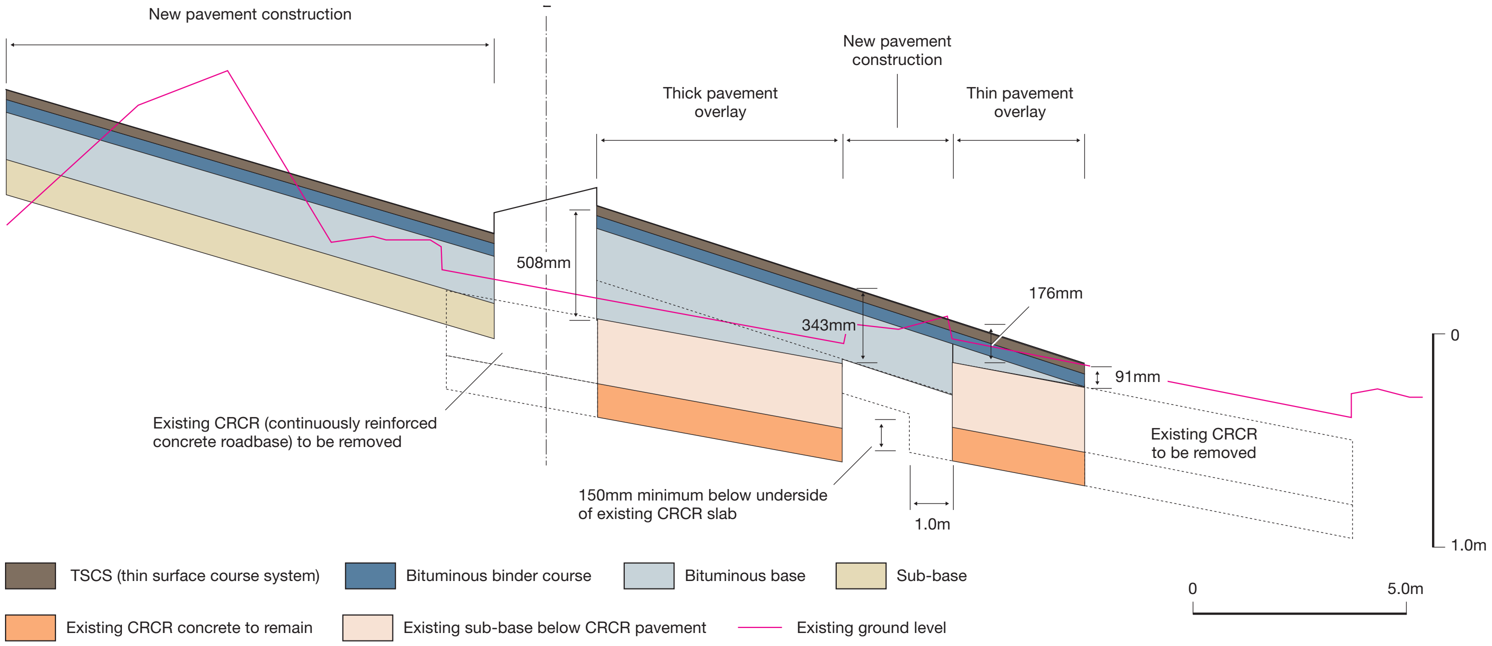
Lanes 1 and 2 were in good condition, and with an overlay could be incorporated into the permanent scheme. The notional overlay thickness needed for a long life pavement, ie designed to withstand more than 80msa (million standard axles), was confirmed through the post-tender investigative data and the previous deflectograph survey (a deflectograph monitors the structural strength of a road by measuring the amount the pavement deflects when subjected to a standard load).

In areas where the existing pavement could be reused, collaboration between the pavement and highways teams ensured that the proposed alignment was as close as possible to the minimum overlay required to strengthen the pavement. The difference between the existing and proposed road surfaces, calculated from the detailed 3-D model (the Isopachyte surface), was used to improve and meet the design criteria (Fig 11). Introducing a vertical concrete step barrier in the central reserve cost-effectively allowed levels on the adjacent carriageways to be independent of each other, further minimising the overlay required. Where the existing pavement was removed, this was recycled and used in the permanent works as capping material, providing considerable savings on the quantities of both the raw materials required and the waste to be disposed.

Broadway to Grosvenor

Here, the existing construction was a concrete pavement overlaid with bituminous material. The concrete was found to be in good condition and could be incorporated into the permanent works, subject to alignment constraints. New bituminous material would replace the existing hot rolled asphalt surfacing.

Between Broadway and Grosvenor the preferred proposed construction method was to replace the existing bituminous construction. However, as the planned highway alignment did not coincide exactly with the existing, the pavement team prepared a detailed design statement for construction through this part of the scheme, maximising the amount of existing pavement incorporated in the permanent works. In preparing the construction methodology, several design issues had to be considered including optimisation of overlay thickness, location of concrete slab joints in relation to wheel track zones, maximising retention of the existing pavement, and maintaining the continuity of the sub-base drainage. A typical cross-section for the main carriageway is shown in Fig 12.



12. Typical cross-section between Broadway and Grosvenor.

13. Scheme 3 under construction.

Ground engineering

Belfast, like many cities, was built where it was due to the needs of trade, and as with many port cities, this resulted in it being constructed on poor ground. The underlying soft and compressible alluvial silt locally known as “sleech” influenced Belfast’s development. Sleech was mentioned in the BBC’s popular television programme *Coast*, which included a quote from the late 18th century that Belfast was “a poor place to build a city, but a great place to site one”[2]. The city’s historic buildings of the 19th and early 20th century were mostly constructed on timber piles taking the foundation loads down through the sleech to the underlying till and bedrock.

The M1-Westlink Scheme 1 ground engineering works were concentrated on the three main junctions: Stockman’s Lane roundabout at the south end; Broadway junction in the middle of the route; and Grosvenor Road junction at the city end.

Much of the alignment is constructed over sleech, the thickness of which exceeds 8m at Broadway junction and Grosvenor Road junction. These alluvial deposits are underlain by stiff glacial clays and dense sands which in turn rest on sandstone bedrock, and dolomitic intrusions are encountered around Roden Street. Depth to bedrock varies between 12m at Stockman’s Lane and 25m at the city end of the site. Groundwater is found at 1-2m below original ground level and flows across the alignment from the higher ground at the west towards the city centre.

Three stages of ground investigation were undertaken: a pre-tender phase, a second during the tender process, and a third following contract award. The last of these was specified by Arup and focused on obtaining:

(1) a better understanding of groundwater flows at Broadway junction, where the deep underpass could potentially act as a subsurface dam

(2) the variation in thickness and the engineering properties of the sleech for embankment design at Grosvenor Road junction and Roden Street, and

(3) the depth to, and quality of, bedrock at the principal structures, so as to inform the pile design.

A pump test was designed for Broadway junction. A local ground investigation contractor executed the work and Arup hydrogeologists in Leeds prepared a hydrogeological report.

14. Broadway underpass northern approach.

Additional penetration tests using piezocones were undertaken, which included dissipation testing in both the sleech and the underlying glacial clays to establish their consolidation properties.

A combination of cable percussion and rotary drilling techniques was used to establish the depth to bedrock and obtain samples for laboratory testing.

Hard/firm secant wall construction was selected for the underpasses. This limits cantilever wall movements and provides watertightness, as well as using the contractor's expertise in this method.

At Broadway junction, the findings of the hydrogeological report were used to design out the potential for groundwater damming, while considering the environmentally sensitive Bog Meadows immediately adjacent. At Grosvenor Road junction, excavation depth within the underpass was reduced by the addition of approach embankments to the overbridge.

The potential for embankment settlement at Grosvenor Road junction and at Roden Street was overcome by constructing the core of the embankments with the proprietary expanded clay lightweight fill *Maxit*. Its gravel-sized ceramic granules are manufactured by heating and firing natural marine clay, and it weighs about 80% less than conventional embankment fill material. Once confined beneath the road sub-base it provides a stiff foundation to the road pavement. This construction was found to be cheaper and quicker than the conventional piled embankment solution. The M1-Westlink project was one of the largest applications of expanded clay lightweight fill on a trunk road project in the UK to date. The fill was brought in by ship to Belfast harbour.

Utilities

Utility diversions were concentrated at the major grade-separated junctions at Broadway and Grosvenor Road, where existing utilities had to be abandoned to enable construction of the underpasses. Arup did the detailed design for diverting four gravity sewers ranging in diameter from 225mm-1.5m, one 900mm diameter sewage rising main, and two small diameter water mains, total length 2.2km. Various pipe materials and jointing systems were used, to which Arup applied the pipeline engineering expertise developed through its work for water industry clients in the UK, and on water main and sewer diversions from other highway schemes such as the A1(M) upgrades in Yorkshire.

Routefinding for diversions was challenging, constrained by the narrow limits of deviation and the need to maintain connections from branch sewers. Also, the corridors available alongside the new highway were congested with other utilities. These challenges were overcome through a partnering approach, whereby the contractor would use his site presence and local knowledge to verify proposed routes, passing sketches and concept designs to Arup to develop the detailed designs and produce construction drawings.

In the case of the sewage rising main, Arup adopted a flexible approach to material selection. The team commissioned a specialist sub-consultant to carry out a surge analysis of the proposed rising main, so as to quantify the maximum and minimum (sub-atmospheric) operating pressures. A thin-walled polyethylene (PE) pipe could thus be specified, minimising cost without compromising performance. Consultation with the pipe manufacturer and thorough research of water industry practice was

15. Parapet railings at Grosvenor Road junction.

16. Temporary propping at Broadway underpass.

17. Broadway underpass northern portal.

required to convince the adopting authority, Water Service, that the PE pipe would not collapse under the negative pressures that might be experienced in the rising main in the event of pump failure.

At this large diameter (900mm), bends and other fittings for the PE rising main were long lead items, so to meet the contractor's procurement and construction programme, steel fabrications were specified. Since PE pipe under pressure will expand circumferentially but contract longitudinally, careful detailing of fused and bolted joints was required to resist the end-load forces at the transition between PE pipes and steel bends and tees.

Some sections of open trench installation lay in the sleech. Here, the team developed a bespoke pipe bedding detail, with the trench reinforced with geogrids to mitigate against differential settlement in the poor ground conditions.

The contractor took the lead on installation method, including pipejacking/auger boring under the existing M1 motorway to install a 1.2m diameter gravity sewer and 900mm diameter rising main across the Broadway junction.

All the designs had to be to adoptable standards, and submitted to Water Service for review and approval. Arup supported the contractor in providing responses to technical queries.

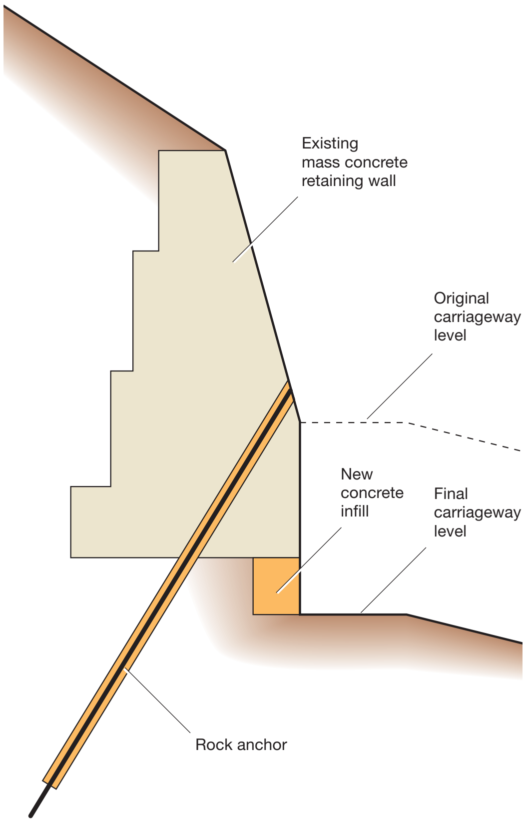
Structures

Broadway junction and underpass

This 500m cutting and 140m long tunnel under the final junction roundabout was designed by Benaim, acting as sub-consultant to Arup. The reinforced concrete secant piles forming the retaining walls of the cutting required a complex system of temporary propping and depropping to ensure deflections and forces in the walls were minimised (Fig 16). Temporary dewatering was provided during construction as the cutting penetrated sand/gravel layers. Permanent propping to the walls is through a reinforced concrete slab beneath the carriageway; this was designed to double as a road base under wheel loads to minimise costs.

Grosvenor junction and underpass

This 320m long cutting utilised 1.2m diameter reinforced concrete secant piles similar to those in Broadway. A 35m span overbridge carries Grosvenor Road over the new motorway. Its deck is designed to be structurally integral with the secant piles and it has curved precast concrete cladding panels forming the deck edges to satisfy particular planning conditions. Side road traffic was temporarily routed over a bailey bridge while the cutting works progressed beneath.



18. Strengthening of existing retaining wall.

Upgrading existing structures

Carriageway geometry on six existing bridges had to be altered to improve road alignment, and new safer vehicle restraint systems installed, which potentially necessitated replacement of the existing decks. This expensive proposition was avoided through the selection of parapet systems that impose lower forces on decks, such that only minimal modification or strengthening was required to the deck cantilevers.

Existing retaining walls (on Scheme 3) adjacent to the existing carriageway (while in cuttings) were potentially destabilised by the carriageway having to be lowered by as much as 1m. Ground anchors were proposed, installed through the walls into the ground beneath to provide the walls with additional sliding and overturning resistance, thus avoiding having to replace the walls (Fig 18).

Roden Street footbridge and 3-D modelling

The existing footbridge at Roden Street had to be demolished as it was in the way of the new construction, and the client wanted its replacement, a 37m span, to be a landmark structure reconnecting the communities on either side of the highway. Access compliant with the UK's Disability Discrimination Act (DDA) was required at both ends, which necessitated long ramps within a highly constrained site.

A deceptively simple Vierendeel truss solution was developed, based on the original concept prepared by Roads Service's engineer, Scott Wilson. This gave an open structure with clean lines in elevation but a curved form in section to add interest to the crossing. The main span form was carried through into the western approach switch-back ramps, which wrap around simple concrete columns. The eastern approach is stretched into an elliptical spiral concrete structure, which continues onto a landscaped earth embankment of the same form.

Three-dimensional CAD modelling enabled a solution to be developed quickly within the difficult constraints and geometry involved. As services were unearthed on site, these were incorporated into the model so that the relationships between them and the structure's foundations were clear to designers and constructors alike. Any resulting changes needed to the foundations became easier to derive and justify.

Links were also developed between the CAD and analysis models to improve co-ordination and response times between design, drafting and the site, to changes in the scheme.

The work on this footbridge was one of many Arup projects that presage a future[3, 4] where work will increasingly be designed in 3-D, with any increase in design costs outweighed by the following benefits:

- ability to visualise finished scheme as design develops
- availability of rendered images for planning purposes
- incorporation of existing constraints and services (enabling clash detection)
- potential for 4-D construction planning by the contractor
- direct link between design and steel fabrication without fabrication drawings (where fabricators are set up for this).

The ultimate aim is to avoid the use of paper drawings altogether, whilst recognising that this also requires appropriate processes to be developed within design, contractor, and client organisations.

19. 3-D CAD images of the exterior and interior Roden Street footbridge.

20. Exterior of the completed Roden Street footbridge.

21. Walking through Roden Street footbridge.

22. ITS in operation, noth of Stockman's Lane junction.

Intelligent transport systems

Intelligent transport systems (ITS) help transport operators to improve safety, optimise the available infrastructure or road space, improve transport choice, deliver value management, and manage planned and unplanned events. As for travellers, ITS makes their journeys more efficient through reducing congestion, providing travel information, and improving journey time reliability. Arup's responsibility included the planning, management, stakeholder liaison, and integration of the communications and technology measures into its overall design packages and programme.

As a strategic access route to Belfast's M2 and M3 motorways, connecting the city centre, port, and airport, the M1 Westlink has long suffered from major congestion and at peak times exceeded design capacity. In support of the benefits being delivered by widening the carriageway and improved access, the network has been further enhanced by the introduction of the latest ITS techniques and measures. These have been designed to make greater use of the available road space, at the same time improving safety for road users, and reducing congestion and its associated impact on the environment through vehicle emissions and fossil fuel use.

For Westlink, these benefits have been achieved by integrating several ITS measures to provide network operators with the tools to implement traffic strategies through automatic, semi-automatic or manual processes. The main operator tools that have been provided include:

- incident detection through vehicle detection and surveillance systems
- incident management by lane control signals and both strategic and tactical message signs
- traffic strategy deployment using variable speed limits.

Ancillary systems to support safe operation of road users and the road network include emergency roadside telephones, pumping station telemetry, and traffic signals.

The ITS systems require a permanent supporting communications network. This comprises fibre optic and copper cable interfaced at each end of the project to existing networks, and also connected to the client's information and control centre to provide real-time traffic information and colour images of conditions on the network. Certain functionality, such as the CCTV surveillance and control systems, need robust and reliable data transmission, and to afford such protection, the fibre optic communications backbone has network resilience through redundancy and automatic re-routing facilities.

23. Grosvenor underpass at night.

24. Improved access benefits the 7000 staff at the nearby Royal Victoria Hospital.

The facts and figures

- approximately 300 people employed by the contractor during construction
- 375 000 tonnes of material excavated (equivalent to the weight of two-thirds of the population of Ireland, north and south)
- 32 500m^3 of concrete used: enough to fill 13 Olympic-size swimming pools
- 1600 concrete piles 1.2m in diameter, average18m long, retaining the underpasses
- over 25km of concrete piles: the largest piling contract in all of Ireland
- over 100 000 tonnes of surface materials
- seven-span, 137m long temporary bridge crossing the M1/Westlink at Grosvenor.

Planning future traffic capacity and the benefits realisation of investments requires accurate traffic information for forecasting. A comprehensive system of traffic classification and vehicle counting was designed and installed to locally store and later transmit conditioned data to a central facility.

One significant complexity in the project was the application of lane and speed control to a unique section of road network of changing characteristics throughout its length, including changes to the number of lanes, discontinuity of hard shoulder, and sections without hard shoulder.

Most the project was undertaken on existing carriageways that had to remain open with minimal disruption to road users. This restriction required extensive planning and implementation of temporary communications networks to maintain the integrity of the existing safety systems.

Social benefits

The existing M1/A12 provided the main route into Belfast from the southwest, but severed the residential and commercial areas in the southwest of the city. There were limited opportunities to cross the existing route, with minimal pedestrian and cyclist facilities. The new scheme maintains and where possible improves these.

The remodelled junctions at Stockman's, Broadway, and Grosvenor include signalised pedestrian crossings and improved cycle facilities, improving the connectivity across the existing route.

The centrepiece of the scheme involves the 140m underpass that takes the M1/A12 beneath the Broadway junction, therefore providing a new public area which strengthens the links by removing all through traffic from the junction. The landscaping design and routes through the junction are aimed at making journeys more appealing to pedestrians and cyclists, and act as a catalyst for improvement in the wider area. The scheme also gives greatly improved access to the nearby Royal Victoria Hospital between Grosvenor and Broadway junctions, which employs around 7000 staff.

The increase in traffic volumes and associated congestion previously experienced on the M1/A12 prompted traffic to divert onto other parallel routes, including the Falls, Lisburn, and Malone Roads. The widening is intended to reduce congestion, improve amenity of the other routes for pedestrians, and help reduce community severance.

During the works, several initiatives were put in place to encourage road users to switch to public transport. This led to less impact than expected during construction and assisted in maintaining good public opinion of the scheme.

Economic benefits

The M1 motorway and A12 Westlink form part of the Eastern Seaboard Key Transport Corridor which provides high capacity road and rail links between Belfast and Dublin and onward towards Larne, Warrenpoint, and Rosslare. The link also forms part of European route E-01 and is thus of strategic importance to Northern Ireland and the wider Europe. As Northern Ireland's capital, Belfast depends on road transport to move most of the goods to and from its port.

In recent years this route has been characterised by its significant congestion resulting from at-grade junctions and lack of lane capacity. This not only disrupted though traffic but impacted on traffic entering and exiting the city centre. The completed project addresses each of these issues, offering free-flowing access around the A12 Westlink and better access to the city centre. With the completion of the York Street interchange in the centre of Belfast, which is planned to follow, the scheme will ultimately provide a complete free flowing link between the M1, M2 and M3 corridors. The junction strategy adopted on the scheme will also help to improve journey times and journey time reliability, and will deliver economic benefits associated with this reduction in congestion.

The scheme includes bus lane facilities which utilise the hard shoulder of the M1 during peak periods to ensure that the economic benefits of fast and efficient public transport are realised. This also includes a dedicated bus-only link from Broadway roundabout to Belfast central bus and rail stations.

Progress

Work started on Scheme 1 in early 2006, with the construction of the culverts to allow the diversion of the watercourses at Broadway and the construction of a temporary bridge at Grosvenor to keep Grosvenor Road open during the works. The first major milestone was reached in October 2007 when the new Grosvenor Road bridge was opened to the public, with the remainder of the junction being completed in March 2008. The second major milestone was the opening of the new Broadway underpass in July 2008. The remainder of Scheme 1 was completed in early 2009.

Work started in April 2007 to widen the M2 motorway and replace three existing overbridges including Hightown bridge. This was completed and opened in September 2008.

The other works associated with Schemes 2 and 4 have been undertaken in parallel with the major works on the M1/A12 and M2. Work on new M2 slip roads at the Antrim Hospital junction started in late 2006 and was completed mid-2007. The other safety barrier and motorway communications works which form Scheme 4 are due to be completed in early 2009 alongside Schemes 1 and 3. Overall, the entire project was completed six months ahead of the original construction programme.

Credits

Client: Highway Management Construction Ltd **Lead designer (highways, structures, drainage, ground engineering, traffic signalling, environmental mitigation, motorway communications, and site supervision):** Arup - Mark Adams, Dom Ainger, Clive Aubrey, Maria Batko, Jaswant Birdi, Kim Blackmore, John Border, Grainne Breen, Adam Bryce, Alex Bryson, Neil Cameron, Savina Carluccio, Desiree Carolus, Stephen Carter, Chris Caves, Harry Clements, Mark Cowan, Lewis Cowley, Nathan Crabtree, Paul Cruise, Wilma Cruz, Paola Dalla Valle, Mark Darlow, Andy Davidson, Lee Davison, Simon Dean, Barry Dooley, Ana Duarte, David Edwards, Nick Ferro, Rob Franklin, Russell Fraser, Marek Fuks, Chris Furneaux, Lee Gill, Anna Gracey, Naomi Green, Geoff Griffiths, John Griffiths, Stuart Haden, Mick Hall, John Hammon, Simon Harris, Russell Harrison, Steve Henry, Oliver Hofmann, Andrew Huckson. Gareth Hughes, David Hurton, Catherine James, Deepak Jayaram, Daniel Jirasko, Irfanullah Kahn, Matt Knight, Linus Kuncewicz, Michael Larvin, Charlotte Lawson, Andrew Lloyd, Chris Madigan, Tony Marshall, Karen Mayo, David McShane, Silole Menezes, Juliet Mian, Nette Mijares, Maria Mingallon-Villajos, Clayton Mitchell, Gavin Newlands,Oliver Nicholas, Joanna Nobbs, Nick O'Riordan, Diji Oludipo, Mazen Omran, Miklos Orova, Simon Owen, Keith Padbury, Michael Page, Ronnie Palmer, Hemal Patel, Michael Penfold, Alan Phear, David Pinto, Daniel Potts, Richard Price, Tom Price, Mario Querol, Andrew Ridley, Andy Ross, Adriana Santos, Diane Sadleir, Justice Sechele, Malcolm Sim, Mark Skinner, Guy Stabler, David Stevens, Thomas Stock, Paul Summers, Suresh Tank, Hermione Thompson, Steven Thompson, Cliff Topham-Steele, Andrew Turner, Michael Tyrrell, Jan Valenta, Martin Vanicek, Stuart Walker, Wen Xiao Wang, Mark Waterhouse, Pete Weston, David Whittles, Craig Wiggins, Eric Wilde, Pete Wilkie, Heather Wilson, Lukasz Wojnarski, David Wolliston, Roger Wong, Ying Zhou **Subconsultants to Arup – Broadway junction and underpass design:** Benaim **Communications design:** Serco Integrated Transport **Traffic signal design:** Siemens **Street lighting design:** Lighting Consultancy and Design Services **Road safety auditor:** WA Fairhurst **Category 3 structure checker:** Halcrow **Main contractor:** Highway Management Construction (JV of John Graham (Dromore)/ Northstone (NI) Ltd/Bilfinger Berger **Illustrations:** 1, 11, 13-15, 17, 22-24 Andrew Hazard; 2-5, 12, 18 Nigel Whale; 6 Anna Kravchuk/Dreamstime; 7, 9, 10, 16, 19 Arup; 8 Department for Regional Development Roads Service; 20, 21 ©Stephen Leckie, Scott Wilson.

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Ronnie Palmer is an Associate of Arup in the Midlands Campus. He led the environmental mitigation team on M1/Westlink.

Alan Phear is an Associate Director of Arup in the Midlands Campus. He led the ground engineering design on M1/Westlink.

Andy Ross is an engineer in Arup's Glasgow office. He was a member of the ground engineering design team on M1/Westlink.

Guy Stabler is a senior engineer in the Midlands Campus. He co-ordinated the structural engineering design on M1/Westlink.

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(2) SOMERVILLE, C. Coast: the journey continues. BBC Books, 2006.

(3) BAILEY, P *et al*. The Virtual Building. *The Arup Journal*, *43*(2), pp15-25, 2/2008.

(4) SIMONDETTI, A. Designer's Toolkit 2020: A vision for the design practice. *The Arup Journal*, *43*(2), pp15-25, 2/2008.

Celebrating 20 years of Arup Japan


1

Century Tower, Tokyo

1987-1991
Client: Century Tower
Architect: Foster and Partners

London-based structural engineering design to scheme stage of 21-storey office building with eccentric K-braced structure for seismic resistance.


2

Kansai International Airport, Osaka

1988-1994
Client: Kansai International Airport Corporation
Architect: Renzo Piano Building Workshop Japan in joint venture with ADP, JAC, and Nikken Sekkei

London-based SMEP and fire engineering design of a 1.6km long, 291 000m² terminal building on an artificial island.

The Arup Journal, 30(1), pp14-22, 1/1995.


3

Museum of Fruit, Yamanashi

1992-1995
Client: Yamanashi Prefecture
Architect: Itsuko Hasegawa Atelier

Full structural engineering design and site supervision for museum comprising three glazed steel shell structures up to 20m high and 50m wide, with a conservatory for growing plants.


4

Osaka Maritime Museum

1993-2000
Client: Osaka Port and Harbour Authority
Architect: Paul Andreu Architects with Tohata Architects & Engineers

Structural and mechanical engineering design of 70m diameter steel lattice dome, positioned offshore in Osaka Bay, and of associated onshore structures.

The Arup Journal, 36(1), pp21-27, 1/2001.


8

Maison Hermès, Tokyo

1998-2001
Client: Hermès Japon
Architect: Renzo Piano Building Workshop

SMEP scheme design and site supervision of a very slender 11-storey building, whose innovatory "stepping column" seismic-resistant design was inspired by traditional Japanese wooden pagodas (see also pp42-44).


9

National Theatre Okinawa, Okinawa

1998-2003
Client: Okinawa General Bureau Development Construction
Architect: Shin Takamatsu Architect & Associates

Structural engineering design and site supervision for new 14 000m² national dance theatre in reinforced concrete, including two halls and educational facilities.


10

Central Japan International Airport, Aichi

1999-2005
Client: Central Japan International Airport
Architect: Nikken Sekkei in joint venture with Azusa, HOK, and Arup

Structural and façade engineering design, design review, and site supervision for airport terminal handling 17M passengers annually.

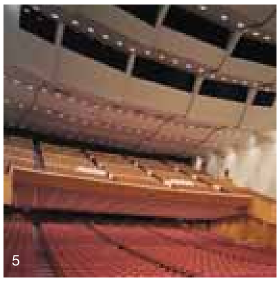
The Arup Journal, 40(3), pp50-56, 3/2005.


11

NTT DoCoMo tower, Osaka

2000-2004
Client: NTT Docomo Inc
Architect: NTT Facilities

Structural and seismic engineering design of a 1650 tonne, 145.4m tall cable-guyed steel telecommunications tower on top of a 12-storey building (see also pp45-48).



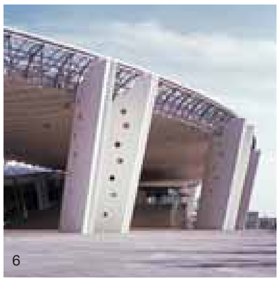
5

Osaka International Convention Centre

1994-2000
Client: Osaka Prefecture
Architect: Kisho Kurokawa Architect & Associates in joint venture with Epstein and Arup

Full structural design of 13-storey, 104m tall, 67 000m^2 conference centre, including review of seismic engineering design following the 1995 Hanshin-Awaji earthquake.

The Arup Journal, 36(1), pp15-20, 1/2001.



6

Fukushima Convention Centre

1995-1998
Client: Fukushima Prefecture
Architect: Atsushi Kitagawara Architects

Structural engineering design and fire, lighting, and acoustics consultancy for four-storey, 23 000m^2 steel-framed convention centre and exhibition hall.

7

Toyota Stadium, Toyota City, Aichi

1997-2001
Client: Toyota City
Architect: Kisho Kurokawa Architect and Associates

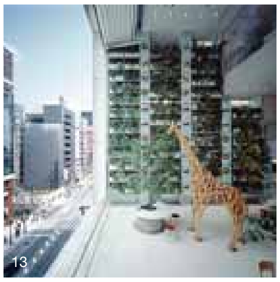
Seismic, structural, and geotechnical engineering design of a 45 000-seat arena beneath a retractable, cable-suspended, roof (see also pp38-41).

12

Sony City, Tokyo

2003-2006
Client: Sony Life Insurance Co Ltd
Architect: Plantec Architects

Structural, seismic, and façade engineering design for 22-storey near-cubic office building with base isolation seismic protection (see also pp49-51).



13

Nicolas G Hayek Center, Tokyo

2005-2007
Client: Swatch Group Japan
Architect: Shigeru Ban Architects

Structural engineering design and site supervision for a 14-storey, 5480m^2 building housing boutiques for seven luxury lines of the Swatch Group. Seismic protection is by the self-mass damper (SMD) system (see also p52-54).

14

Namics Techno-core facility, Niigata

2006-2008
Client: Namics Corporation
Architect: Riken Yamamoto & Field Shop

Structural design and site supervision of an 8800m^2, two-storey office building and research facility, with a cast steel pivot column base to realise a "mushroom" structural system.

Design in an earthquake zone

Shigeru Hikone Mitsuhiro Kanada
Ryota Kidokoro Masato Minami
Ikuhide Shibata

Introduction

In 1989, 20 years ago, Arup registered as a design office in Tokyo. At the time Mike Shears, then a member of the firm's main board and more recently chair of its trustees, described the initial objective as a "small but brilliant" team stationed in Japan and closely linked with Arup globally.

Arup Japan has endeavoured to meet this goal and to exceed it. Its engineers have won many awards and accolades. It fosters creativity and innovation through close ties with the design and research community. It deploys cutting-edge seismic technology and design techniques, and recruits graduates from the principal engineering schools. All this has been widely acknowledged by the local architectural community. Japan's leading architects elect to work with Arup Japan on projects in Japan and elsewhere.

The initial group of structural engineers was joined in time by MEP, project management, fire, façade, and lighting specialists, and the practice is now working hard to grow its 3-D CAD skills and sustainable consulting offering to Japanese companies working domestically and outside Japan.

In the pages that follow, this special anniversary *Arup Journal* feature presents some of the key projects in the history of Arup Japan that have a particular emphasis on seismic design innovation.

Mind-Body Column, Osaka

"I want to create a slender 15m high steel sculpture with velvet-like skin."

Introduction

Antony Gormley is an English sculptor known for creating steel sculptures using his own body as a motif, and most famous for the massive *Angel of the North*[1]. By contrast, this 2000 project was to be slender, resembling an obelisk, and using 20 steel castings stacked one on top of another (Figs 15, 16). The site was a public plaza in Osaka, amidst four office towers. The interaction began with some light-hearted questions from Arup as structural engineer to probe the meaning of the work: "Why are you using your own body as a motif?"; "Why must the sculpture be made of steel?"; "Why do you want to connect two forms back-to-back?"; "Why do you want to stack the forms one on top of another?"; "Why can there be no welding involved?"; "Why is a velvet-like skin necessary?"

Seismic design in Japan – a short history

1914 Prof Riki Sano's thesis on seismic-resisting structures proposes an applied lateral load – a certain percentage of the building mass applied at each floor level.

1923 Tokyo is hit by the Great Kanto Earthquake, which devastates the city and kills over 100 000 people.

1924 The Japanese "Code of practice for buildings in an urban area" is revised and a lateral load of 10% of the weight of the building is introduced for seismic design, in effect creating the world`s first seismic code. This is based on observation of the lateral load on 30% of the mass in the downtown area in Tokyo, and on the allowable stress considered as 10% of the static force.

1947 This code is revised when building materials standards are introduced. Structural design now has to consider two cases – long-term and short-term load combinations – and the intensity of the lateral load is revised to 20% of the mass.

1963 31m total building height limit removed following the Great Kanto Earthquake.

1965 The Building Centre for Japan (BCJ) is established especially for technically challenging and innovative structures that don't comply with existing codes. The committee members are academics and expert engineers who report on technical acceptance to the Ministry of Construction. This procedure aids designers who desire unrestricted use of new materials/technology.

1968 The Tokachioki earthquake causes many column shear failures in reinforced concrete buildings.

1970-71 The building code responds by specifying reinforcing tie bar details for reinforced concrete columns.

1970 Japan's first really high-rise building (30-storey Kasumigaseki Building) completed.

1980 A new seismic code is introduced. The dynamic aspects of design are considered in detail, but some criticise the new code as too prescriptive. There are two criteria for design, one for possible occurrence once or twice during the building's lifetime, and the other for a possible severe event estimated from the historic data at the site.

1980 New structural systems using isolation and seismic energy control (damping technology) develop rapidly.

1993 The Japan Society of Seismic Isolation is established to centralise the research, education, further promotion, design, construction, and maintenance of seismic isolation devices.

1995 South Hyogo Prefecture Earthquake (aka "Kobe earthquake") hits Kansai, and some buildings designed under the new code sustain unpredicted damage. The seismically isolated buildings perform well, but one residential high-rise designed in the late 1970s has an unexpected brittle fracture of a main column built up from thick steel plates (the steel and the welds had insufficient toughness to take the required plastic elongation).

2000 To reduce waiting times, peer reviews from approved private practices become obtainable. Each city has an approval body, architecture division, that checks calculations, drawings, etc. The BCJ continues to provide approval for exceptional buildings.

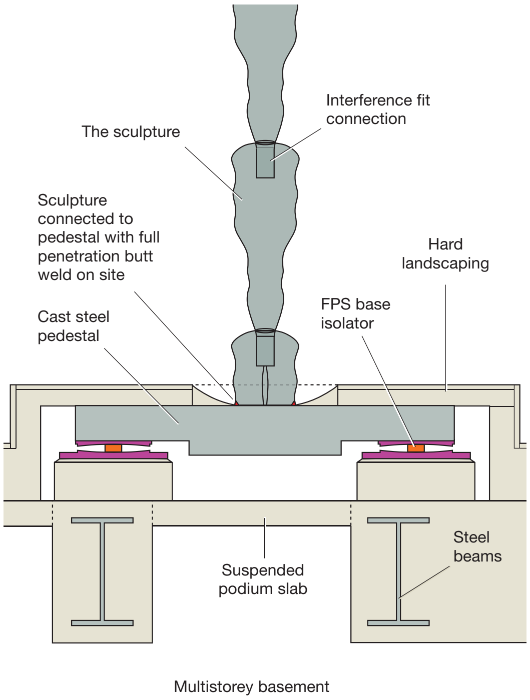
2007 A new structural review process is introduced with a requirement for structural and services engineers' qualifications.

The following projects are all performance-based designs approved by the BCJ, which became more common after the South Hyogo Prefecture Earthquake. Structural engineers are now responsible for communicating directly with clients so as to set clear seismic design targets and agree them before the design.

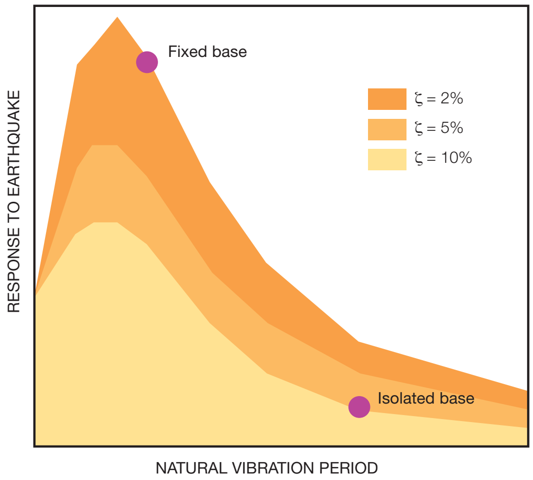
15. Completed *Mind-Body Column*.

16. Front and side elevation.

17. Wooden model.



18. Cast steel pedestal supported by four FPS base isolators.



19. Generic graph of response spectrum showing beneficial period shift and reduction in response if the structure is base isolated.

FPS base isolation system

The wood form that Arup received from Gormley was moulded exactly in his form (Fig 17). The ankle-width is 170mm, and the distance between the axes of each pair of opposing ankles is 265mm.

The overall height of 15.4m has a 1:90 aspect ratio – an extremely slender proportion – and the whole sculpture is also very heavy, at around 15 tonnes. It was clearly going to be difficult to make it as earthquake-resistant as it needed to be in such a seismically active country.

To solve this problem, four FPS (friction pendulum system) isolators were installed at its base under the pedestal. Each comprises a concave surface, an articulated bearing, and a cover plate. In an earthquake the bearing slides on the concave surface, allowing the structure to move relative to the base. FPS isolators – similar to lead-rubber or high damping rubber bearings – cause the vibration period of structures to change. Although dependent upon the scale of the supported structure, FPS offers some advantages over rubber-based bearings; it is not affected by temperature or aging, it is durable, and has a high vertical stiffness (Fig 19).

The FPS system reduced the response acceleration by approximately two-thirds, so that the sculpture would not be damaged or collapse even in the largest earthquake. Also, to prevent uplift and to stop the isolators being moved by wind, the pedestal was given a weight of some 25 tons (Fig 18).

This performance-based design by Arup needed, and was granted, special approval by Japan's Ministry of Construction.

20. Cast steel piece before machine processing.

21. Interior of vertical connection before insertion.

22. Portion of connection to be inserted.

23. Commencing shrinkage fit (fitting time two seconds).

Velvet-like skin

In Japan, with its harsh natural environment, base isolation and seismic control technology are well developed, and wind and earthquake resistance did not represent the greatest challenge. The biggest question was how to bring out the material's natural look, with a subtle artisan flavour.

Normally, cast pieces are produced by pouring molten steel into a sand mold. Imprints from this leave blemishes on the outer surface, so imprint resistor is brushed onto the mold surface beforehand. However, this in turn leaves unsightly brush marks that reduce surface quality. In addition, water blow holes, deformations due to heat treating, and weld flashes where separate molds are joined, are unavoidable. These marks could have been eliminated by grinding and using adhesive metal, but that would have spoilt the velvet skin quality.

How could a cast piece that needed no repair be created? Through simulation and trial-and-error, the team investigated all possible production processes, moving thereby from the realm of structural engineering into that of sculpture. Rusting of the surface was an important quality sought by the sculptor, so in the end ordinary structural steel was used and treated in accordance with his specification (Fig 20).

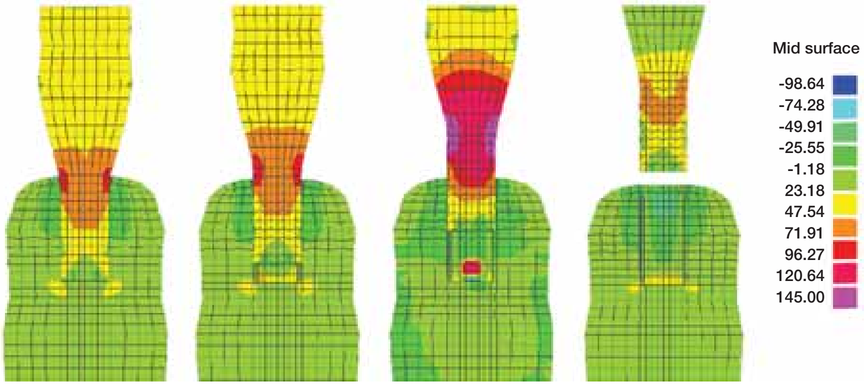
Interference fitting

The stacked figures needed robust connections, and for this the team chose interference fitting, a method commonly used to produce marine cylinders and camshafts. The upper torso sections were warmed by an electric heater for four hours to 240ºC, thus widening the neck holes. The lower ankle sections were immersed for 30 minutes in -270ºC liquid nitrogen, cooling them to -100ºC with resulting shrinkage. Each shrunken ankle could then be fit into a widened neck and then brought back to room temperature, resulting in a secure connection (Figs 21-23).

Normal interference fittings are applied to circular sections, not elliptical as here, so predicting prestress at the joint was difficult. The team used the analysis software *LS-DYNA 3D* to simulate and study the relationship between fitting area size and the shrinking pressure or tensile strength. Two models were made, with a contact surface between them having a specified friction coefficient and a prestress to model the contact pressure. The analysis results, later verified by a physical pull-out test, enabled the final joint size to be determined. The "female" element was 93 x 150mm, and the "male" only 1/600 larger, 93.15 x 150.25mm (Figs 24, 25).

Each cast "body" includes several different shapes, so an extraordinarily high degree of precision was required throughout, entailing many judgements and resolutions in every process from the mechanical production to the shrink fittings – a particular challenge each time (Fig 26).

24. Still images from the *LS-DYNA* tensile pull-out model show the connection between two castings being pulled apart. The results of the *LS-DYNA* analysis were later verified by physical testing.



25. Shrink-fitted test piece for tensile strength testing.

26. Cast steel elements connected.

27. Completed *Mind-Body Column.*

Mind-Body Column

The completed sculpture and its base are founded on a suspended podium slab over a multi-storey basement. The sculpture was craned into position as a unit and field-welded to the base.

Work on the project began in March 2000, and it was completed in June . The artwork was named *Mind-Body Column*, a continuous human body moulded from steel, symbolizing the earth itself, standing slender yet sturdy in a valley between high-rise buildings. Orange rust runs down the velvet-like skin, a permanent but continually changing patina (Fig 27, 28).

Reference

(1) BROWN, M, *et al. The Angel of the North, The Arup Journal, 33*(2), pp15-17, 2/1998.

Credits

Client: Rail City West Development, Osaka **Sculptor:** Anthony Gormley **Structural engineer:** Arup – Shigeru Hikone, Mitsuhiro Kanada, Ikuhide Shibata.

28.

29. East side of exterior.

Toyota Stadium, Toyota City, Aichi

Introduction

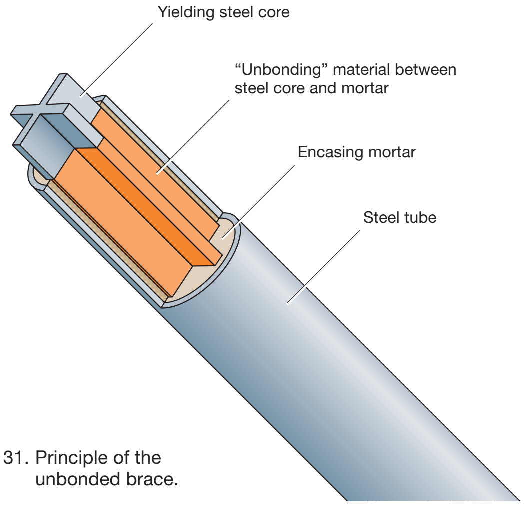
Toyota Stadium was built to commemorate the 50th anniversary of Toyota City as a municipality. It was designed by Kisho Kurokawa Architect & Associates for Toyota City, and is one of several projects intended to revitalise central Japan. Completed in 2001, this 45 000-seater arena hosts world-class soccer, rugby, American football, and other types of event. Arup's scope of work for it embraced seismic, structural, and geotechnical engineering design.

Form and system

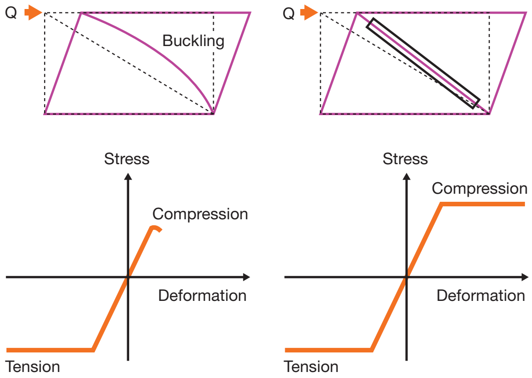
The stadium's form and structural system were intended both to create optimal conditions for spectators and players, and to allow for the growth of natural turf. The stands are four independent structures (north, south, east, and west), those on the east (Fig 29) and west sides being taller to accommodate the maximum number of people and provide prime views. By contrast, the north and south stands are low to allow in the wind and sunlight needed for the pitch.

The 40 000m² roof is suspended from four large masts – placed between the stands so as not to obstruct sightlines – and an intricate network of cables, creating a dynamic, open atmosphere (Fig 30a). Two keel trusses extending along the roof interface support the large retractable roof

30. Interior view showing movable screen and retractable roof in (a) open and (b) closed positions.



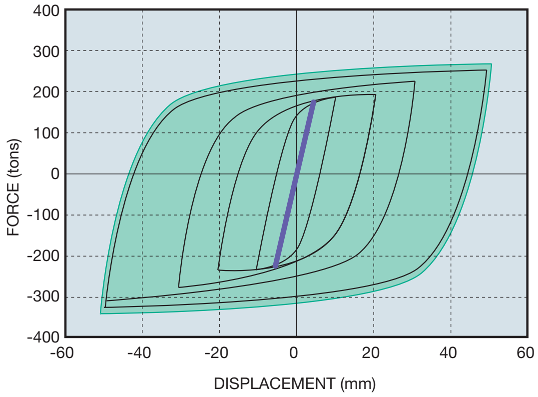
31. Principle of the unbonded brace.



(a) Conventional brace.

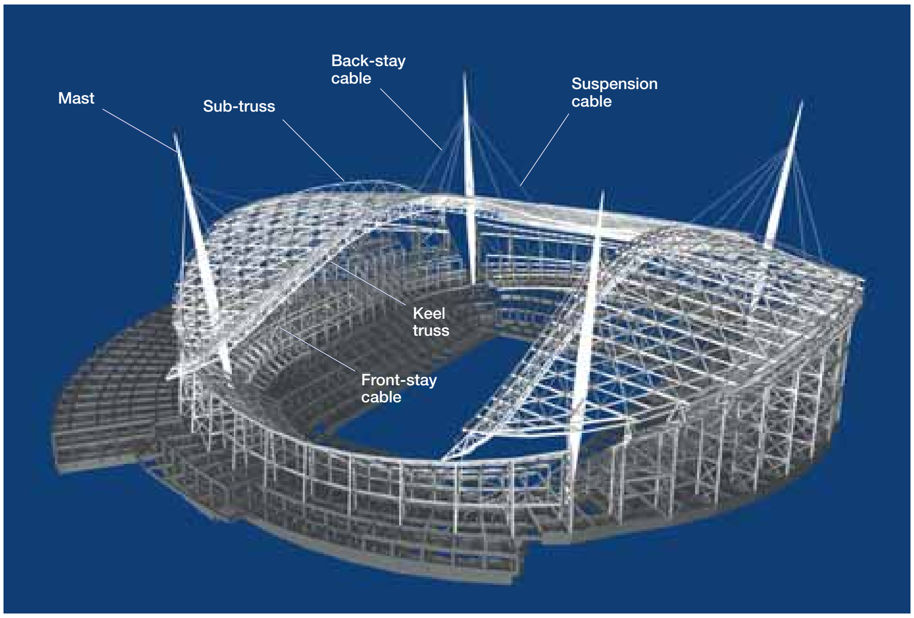
(b) Unbonded brace.

32. Conventional vs unbonded braces.



33. Unbonded brace hysteresis curve.

34. Unbonded brace connection detail.



35. Key features of the structure.

and a movable LED screen. The air-inflated membrane mechanism that forms the retractable roof spans between the keel trusses; its inclusion in the design allows flexible control of outside exposure to the stadium interior (Fig 30b).

Stand structure and unbonded brace

The stand structure as a whole divides into upper and lower parts at the plaza level – it is the upper stands that exist as the four independent structures with masts in between. The design team utilised a steel frame structure to allow greater planning flexibility, whilst to meet the challenging design targets, a "damage-tolerant" seismic design approach was adopted. Specifically, this entailed placing within the structure sacrificial elements that yield and absorb seismic energy, protecting the rest of the building from damage.

The team selected a type of steel hysteretic damper, the "unbonded brace" developed by Nippon Steel Corp, for the sacrificial elements. These act as energy-absorbing dampers by taking advantage of the elastic-plastic hysteretic curve experienced under large cyclic axial loading. They comprise a core material in the form of flat or cross-shaped steel braces, covered with debonding chemicals that can stretch and shrink freely under seismic loads. Lateral buckling of the steel braces is constrained by the mortar-encased steel tube. The steel used for the core braces has a minimum yield point of 235N/mm^2; in addition, an upper boundary of 295N/mm^2 was specified to ensure that variation in material property was minimised and the damping performance stabilised (Figs 31-34).

Cable-suspended roof

The cable-stayed roof system comprise the four 90m tall masts, the two 250m long, 6.25m deep keel trusses, and approximately 60 parallel wire strand cables. Perhaps the stadium's most notable characteristics are the use of the four inclined masts and the 3-D stay cable arrangements. The system is balanced by the in-plane stay cables from the keel truss, and the back-stay cables that span from the top of the stand structures and the end of the keel truss. In turn, the ends of the keel trusses are anchored down to the bottom of the stand structure by the front stay cables (Fig 35). The entire system was stabilised by prestressing the cables to prevent any loss of tension under wind and seismic loading. The cables are the parallel wire strand type, the individual wires being 7mm zinc-galvanised with a yield stress of 1600Mpa.

36. The stadium from the air.

Masts

The masts are cigar-shaped, 3.5m in diameter at the middle and tapering down to 1.5m at both ends. Each was constructed by bending plates up to 70mm thick and welding the ends together. Different grades of steel were used for the north and south masts, reflecting the different dead loads in the masts when the retractable roof is parked in the open position. The axial forces induced by the cable reactions and self-weight are 60 000kN for the north side masts and 40 000kN for the south side masts. To avoid undesirable moment build-up at the bases, each mast rests on a pivot bearing connection. The masts maintain their designed 7.5° tilt by the balance of the interdependent cable forces alone.

The pivot bearings are of cast steel. The contact area of each base is a convex sphere, matching the concave contact area at the bottom of the mast, the interface forming a ball and socket joint. The masts do not experience uplift forces under any load combination. Compression and shear forces of the masts are transferred via the bearing contact surfaces.

Cables

Ten cables converge to a single working point at the top of each mast (Fig 37), where the connection is a tubular steel casting with several nosepieces, weighing some 40 tons (Fig 38). The cables vary in diameter from 140mm to 200mm, depending on tensile forces. The forces in the cables range from 5000-7000kN under long-term load, while the maximum short-term tensile force of 11 000kN is induced by seismic loading. To achieve a smooth force transfer from the cable to the mast – and in view of cost considerations – double cables were bound together by two-way sockets prior to attaching them to the mast.

For ease of access, prestress was applied to the cables at the keel truss side rather than the mast side. The prestressing end detail is a tubular cast connection accommodating a centre-hole type oil jack, and the prestressing was applied by pulling the end of the cable with the oil jack and then inserting semi-circular spacers between the cable end socket and the ribbed flange of the cast connection piece.

37. Mast and cables.

38. Nosepiece.

39. Retracted roof above the north stand.

40. Standard parking position of the movable screen above the north stand.

Retractable roof with air-inflated membrane structure

The retractable roof, which takes about an hour to open, comprises a foldable truss plus air-inflated membrane mats. To aid growth of the grass pitch, the roof's stationary position is above the northern stand (Fig 39). Each triangular truss (90m span with 6m depth) has an independent rack-and-pinion driving system. As the adjacent trusses move apart, the connecting folded trusses open up and the air-inflated membrane unit (13.5m x 73m) follows by adjusting its form.

The motor of the driving system employs an inverter to control its speed and an electromagnetic brake as a fail-safe device.

The team selected PVC-polyester, a suitably flexible material, for the membrane, as the surface would not be exposed to ultraviolet light when parked at the standard position. The double skin fabric is inflated using a compressor located within the roof trusses. A spring with a 600mm stroke connects the triangular truss to the moving mechanism so as to absorb the relative movement between the retractable and fixed roof during its operation and under seismic load. The spring extends the fundamental period of the retractable roof to four seconds.

Movable screen

An LED screen is hung from a bowstring truss attached to the bottom chord of the keel trusses on either side. So as to cater to various event requirements, the entire truss can slide across and hold a stationary position at the centre of the field (Fig 40). The standard parking position of the screen is above the north stand. In addition, the LED screen can be lowered and rotated using a set of motors and cables.

Credits

Client: Toyota City **Architect:** Kisho Kurokawa Architect & Associates **Seismic, structural, and geotechnical engineer:** Arup - Andrew Allsop, Chris Carroll, Conrad Izatt, Mitsuhiro Kanada, Ziggy Lubkowski, Andrew Mole, Arata Oguri, Ikuhide Shibata.

Award

2002 Japan Structural Consultants Association Structural Design Award.

Maison Hermès, Tokyo: Building on the past – the "stepping column" system

Introduction

Located in Ginza, a Tokyo district renowned as one of the most exclusive shopping areas in the world, Maison Hermès is the corporate headquarters and flagship retail store of the fashion house, Hermès Japon. Arup was engaged from the outset in 1998 as structural engineer, with the additional roles of building services engineer for the scheme design only, and site supervisor.

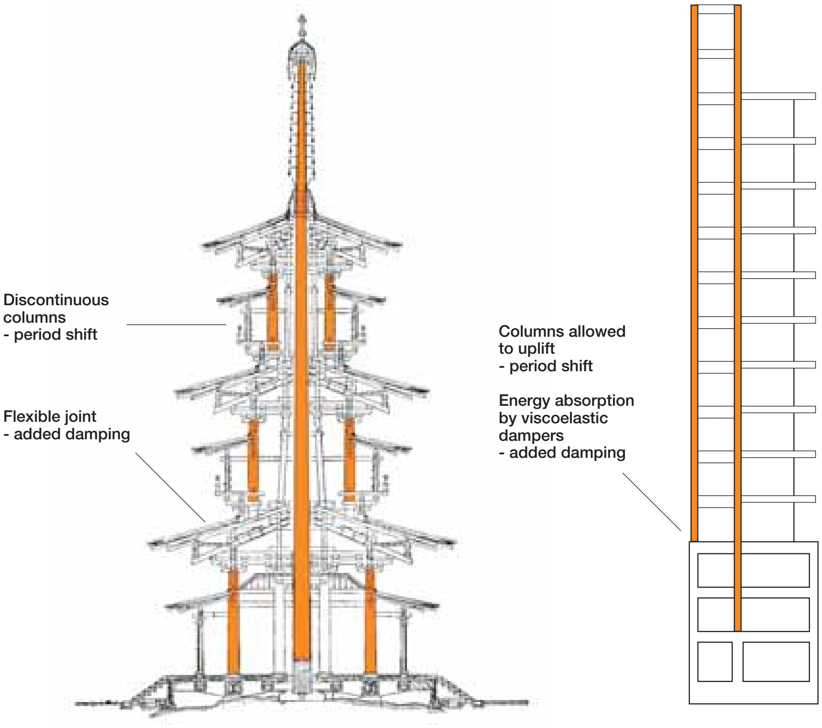
Inspired by traditional Japanese lanterns, architect Renzo Piano's design intent was realised through a translucent glass block façade that drastically changes the building's expression from day to night (Figs 41, 42). Similarly inspired by a hint from the country's past, Arup designed a radical structural scheme based on the engineering ingenuity of historic Japanese wooden pagodas, aimed at counteracting the large seismic forces that could be induced into such a slender, elegant building. The team was drawn both from the Tokyo office and the Advanced Technology group in London.

41. Maison Hermès in daylight.

42. Maison Hermès at night.

The challenge, and a solution from the past

A common issue for slender buildings is the high tensile forces in their columns from the overturning moment induced by large seismic events. This often leads to heavy foundations as counterweights or tension-resisting piles. The building deformation characteristic also makes it difficult to utilise seismic damper systems, as slender buildings tend to deform in overall flexural bending rather than inter-storey shear drift, whilst damper devices (much like the shock absorbers in automobiles) rely on the latter as the stroke. The challenge for the Arup team was to develop an effective seismic control system leading to an efficient structure, while ensuring the proportional elegance of the architectural design intent.



43. Sesmic-resistant technologies from the fifth and 21st centuries: the Japanese pagoda and Maison Hermès.

Intriguingly, despite onerous earthquake conditions in Japan, it is reported that out of the 500 or so wooden pagodas, only two have collapsed as the result of an earthquake in the last 1400 years. What makes it possible for these slender pagodas to survive earthquakes? The answer is that the joints in the structure are kept loose to avoid the extreme build-up of forces that can lead to catastrophic failure. For example, the columns at the lowest storey are not bound to the ground, enabling them to lift up when the earthquake-induced tension force exceeds the gravity loads. A vital hint from the intuitive engineering from the past, this "stepping column" proved the system of choice for this structure (Fig 43).

Application

Maison Hermès is a 12-storey steel-framed building approximately 50m in height, which resulted in an aspect ratio for the main frame of more than 10:1. Vertical support is provided by three sets of columns spaced at 3.6m along the short side facing the street. The rear line of columns is allowed to step up vertically, reducing the building's stiffness and thus the impact from an earthquake. In summary, when experiencing large seismic forces, the structure is designed to flex and pivot around the centre row of columns, applying compression force to the front row and in turn slightly lifting up the rear.

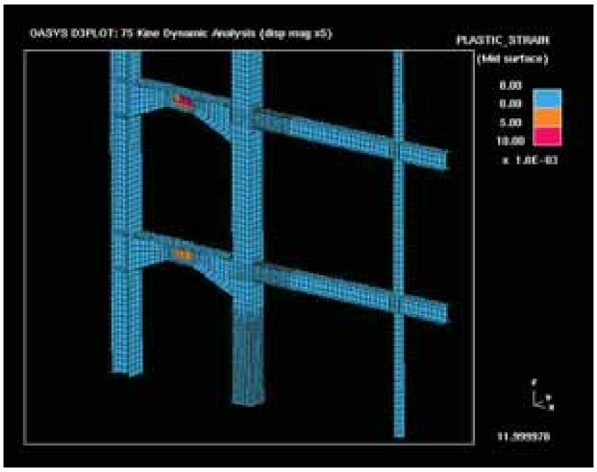
To control the impact load and achieve balance in the drift performance of the system, damping is incorporated in the form of a multi-layered sandwich of steel and viscoelastic material – a device that Arup specially designed for this scheme (Fig 44). As the columns lift up, the viscoelastic dampers are stretched (sheared) and so absorb some of the system's energy and reduce the building drift.

Impact analysis

As the stepping column system is a half-cycle damper without a steady state, unique and innovative even by Japan's seismic engineering standards, the team conducted rigorous analyses to verify the behaviour. Naturally, the issue of impact of the stepping column as it hits the ground necessitated in-depth studies.

44. Rendering of stepping column detail (a) and stepping column being craned into place (b).

45. *LS-DYNA* impact analysis model.



46. Stepping column and surrounding frame.

47. The elegant interior.

The Arup team realised that analysis methods and software developed to simulate car crash tests could be applied to verify the impact performance. Whilst the time step of 0.01 seconds for the non-linear time history analysis was sufficiently small to capture the overall behaviour of the structure, to quantify the effect of the impact-induced “stress wave” the time step and element size needed to be much smaller. This being the case, *LS-DYNA*, an explicit code commonly used to perform vehicular crash worthiness analysis with a time step of 0.000001 sec (a millionth of a second!), was used for this work.

Through these analyses, the team found that while a heavier mass has larger momentum leading to a higher overall maximum force, the stress wave is independent of the mass. As a result, the complex force paths through various elements in the stepping column were plotted in detail – demonstrating that the impact-induced force occurred with a offset in time and was a mere 10% of the maximum force that the columns experience.

Theory to reality

The immense challenges of developing this seismic control system were successfully overcome as a result of Arup’s seamless global collaboration efforts, expertise gained by the firm’s work in state-of-the-art analysis techniques, the involvement of Japanese experts in viscoelastic damper applications… and a key inspiration from the country’s past. The impressive workmanship of Japanese steel craftsmen also played a vital role in realising the intricate detailing of the special connection joints.

Throughout, the drive for appropriate innovation and excellence contributed to delivering this internationally designed, modern, yet elegantly “Japanese” piece of architecture. Begun on site in December 1999 and completed in May 2001, the building has successfully withstood the numerous small and moderately-scaled seismic events that have occurred in Tokyo since.

48. Entrance to the store.

Credits

Client: Hermès Japon **Architect:** Renzo Piano Building Workshop **Structural and building services engineer (scheme design only) and site supervisor:** Arup – Mitsuhiro Kanada, Bob Lang, Masato Minami, Andrew Mole, Yoshiyuki Mori, Paul Sloman **General contractors:** Takenaka Corporation **Interior design:** Rena Dumas Architecture Intérieure **Viscoelastic damping material:** Sumitomo 3M.

Awards

2002 Gengo Matsui Award for Structural Design

2003 Building Contractors Award.

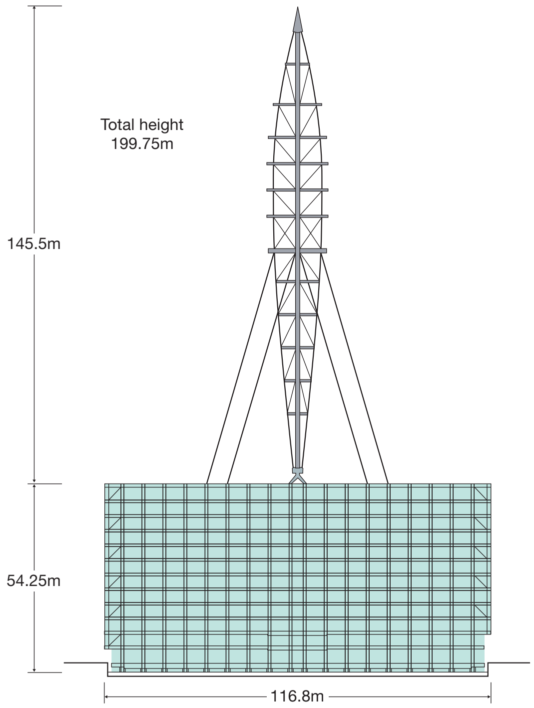
NTT DoCoMo tower, Osaka

Introduction

NTT DoCoMo, a subsidiary of Japan's telephone operator NTT (NipponTelegraph and Telephone), is the country's main mobile phone operator. The DoCoMo tower, for which Arup undertook the structural and seismic engineering design, is a unique cable-guyed telecommunications tower completed in December 2004 on the roof of a large seismically-isolated telecommunications building (Figs 49-51).

Arup Japan led the structural design team in collaboration with the Advanced Technology Group in London and the Detroit, USA, office. ATG London carried out non-linear time history analysis to verify the analysis done in Tokyo, while Detroit undertook 3-D finite element stress analyses of the cast pieces. The site was on reclaimed land, so the structural and foundation design was strongly influenced by the soil conditions. The design criteria for the building required that the structure should remain elastic even for the greatest anticipated earthquake, and to satisfy these criteria, a seismic isolation system and damping devices were installed in the middle storeys. The tower itself has to remain elastic under wind loading, which was estimated from wind tunnel test results to be extremely high, due to the proximity of several tall buildings. Damping devices were installed to satisfy the design criteria for the tower.

49. Elevation of the NTT DoCoMo tower and building.



50. Aerial view of the NTT DoCoMo building and tower, showing the location overlooking Osaka Bay.

51. The tower and building at night.

Structural overview of the building

The telecommunications facility is a 12-storey building 54.25m high, 116.8m wide (X-direction), and 43.2m deep (Y-direction). Constructed on a 6.4m grid, its total floor area is 60 993.42m².

The seismic isolation system was essential to guarantee sufficient safety and to maintain building functions in the event of a disaster like a major earthquake. It comprises 46 lead rubber bearings, 42 rubber bearings, and four cross-linear bearings – 92 isolators in all. The lead rubber bearings and rubber bearings are 1000-1500mm in diameter and 280mm in total thickness of the rubber portion.

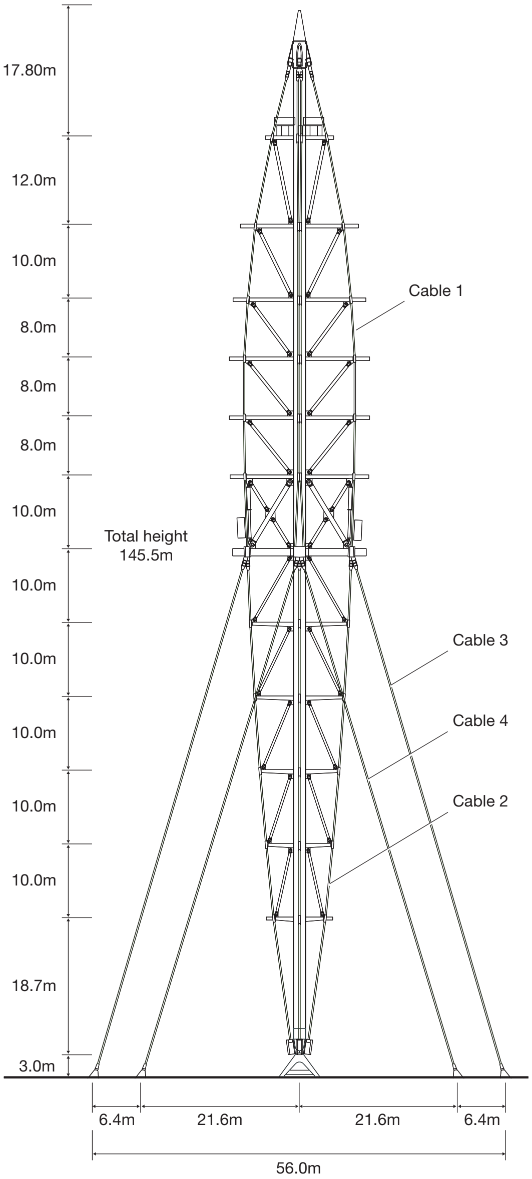
The braced and rigid frame uses concrete-filled columns and steel beams, and viscous walls are employed for the damping devices, of which 24 and 22 are arranged in the X- and Y-directions respectively between the third and eighth storeys.

Structural overview of the tower

Simply explained, the structure is a pinned column held upright by four pairs of stay cables, a straightforward and appropriate scheme for this particular location.

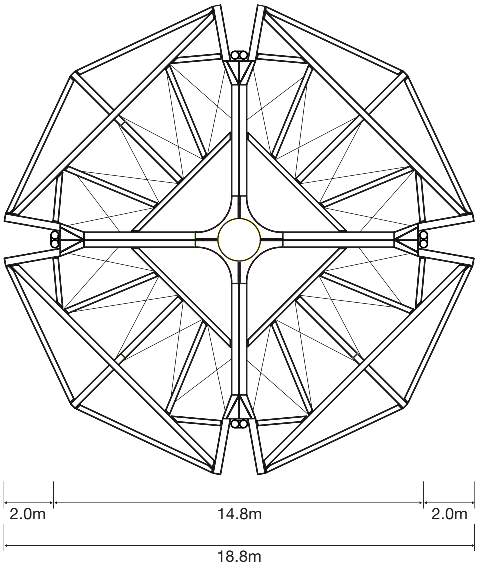
Weighing approximately 1650 tonnes, the steel tower rises to a height of 145.5m above the building. The spinal mast element is a 1.7m diameter hollow tube with a wall thickness that varies between 50-80mm. The cables are the parallel wire strand (PWS) type, 200mm in diameter, and made up of 499 galvanized steel wires wrapped in a polyethylene coating. The remaining frame elements comprise built-up boxes, pipes, and H-sections. Steel cast pieces form the cable connections (Figs 52-54).

52. Close-up of the tower.



53. Elevation.

54. Typical platform.

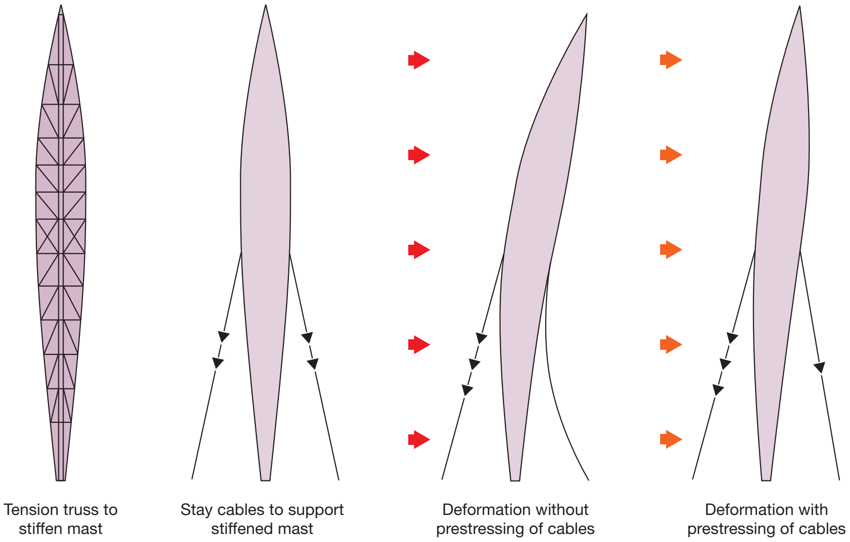


Tension truss

To stiffen the steel central mast, four sets of prestressed steel cables and outriggers extend the entire height of the tower. In profile each set forms a bowstring truss, a system that works in a similar manner to the rigging mechanism of a yacht's mast. During construction, the cables were slid over the saddle pieces of each outrigger, then prestressed at the ends located at the centre and base of the tower. In each set the upper pair of cables (cable 1, Fig 53) was prestressed to 5500kN (11 000kN per pair), and the lower set of cables (cable 2, Fig 53) applied with 5000kN of prestress.

Stay cables

The stay cables are arranged in pairs extending in four directions, rather than the minimum of three, so as to match the building's symmetry. The cable layout in plan stabilises the tower's potential to twist, as well as giving a margin of safety in the unlikely event that one cable is severed. Stay cables 3 and 4 (Fig 53) are prestressed to 6000kN and 7500kN respectively. With a combination of prestress from the stays and tension truss cables, the mast element experiences approximately 85 000kN of axial force. The overall behaviour of the structure is shown in Fig 55.



55. Structural behaviour.

57. Rotational damping tubes.

56. Tuned mass dampers.

Dampers

Damping devices were installed in the tower to reduce deformation under seismic and wind loading. On the top platform two 7.5 tonne tuned mass dampers were set, consisting of layered rubber pads and steel plates with a mass at the top, tuned to reduce the response (Fig 56).

In addition, four pairs of rotational damping tubes were installed in parallel with the cable truss near the centre platforms to dampen the tower's bending movement (Fig 57). It is important to note that the effects of the dampers were not considered in the structural design of the members, but to introduce an improved structural performance under service loads.

58. Five-way cable connection.

Cast steel elements

Once the structural behaviour was understood, the next main challenge for the design team was to develop the connection details, these being probably the most critical elements of the structure. It was apparent early in the design that standard connection details were not an option for design forces of this magnitude.

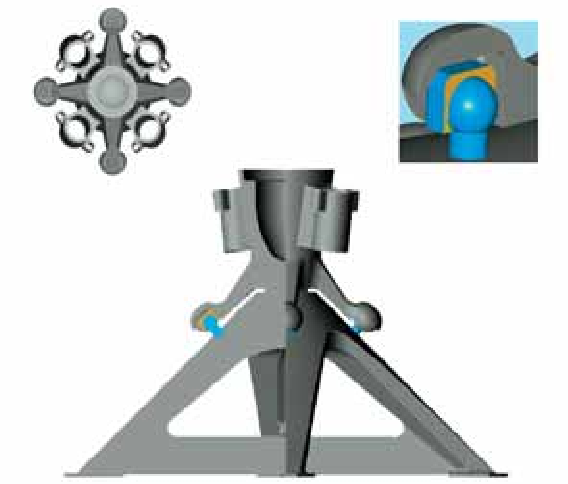
Cable joints: The end joints of the cables fell into two types, the difference being whether the side in question required a hydraulic jack to be installed. For both types, the forces are transmitted via contact bearing surfaces (Fig 58).

Saddle clamps: The clamp pieces, which are attached to the ends of each outrigger, were left loose during the installation and prestressing of the cables to allow slippage. When the desired tension force was applied, the clamps were tightened to grip the cable, completing the tension truss. Such connections are commonly used in cable-stayed bridges (Fig 59).

Base pivot joint: To allow rotational deformation in all directions at the base of the mast, a pivoted joint was introduced. It is divided into two halves, the bottom piece consisting of a convex bearing surface with four legs extending to the building, and the top piece with a concave surface that is attached to the central mast. Since the joint does not experience uplift forces, the axial and shear forces are transmitted through the bearing pressure between the two pieces. In addition, it has a special stopper mechanism to suppress the mast's torsional movement (Figs 60, 61).

59. Saddle clamps.

60. Pivot bearing in situ.



61. Pivot bearing detail.

Credits

Client: NTT Docomo Inc **Architect:** NTT Facilities
Structural and seismic engineer: Arup – Richard Brookes, Xiaonian Duan, Mitsuhiro Kanada, Tim Keer, Ryota Kidokoro, Andrew Mole, Ikuhide Shibata.

Awards

2005 Japanese Society of Steel Construction Outstanding Achievement Award

2005 Illuminating Engineering Society of North America International Illumination Design Section Award.

Sony City, Tokyo:
A diagrid combined with base isolation

Introduction

This high-profiled office building, on an 18 165m^2 site at Shinagawa in the heart of Tokyo, is a massive 20-storey near-cube, 100m x 70m on plan and 99.4m in height. The middle and upper storeys are office space with typical storey-to-storey heights of 4.55m, while the lower floors contain a large conference hall, meeting rooms, cafés, and restaurants. Two basement floors accommodate a car park and machine rooms. Designed by Plantec Architects with Arup as structural, seismic, and façade engineer, this building was completed in 2006.

Base isolation

The adoption of a base isolation system as the chosen method of seismic protection was driven by two key factors: the architect's desire for a light transparent façade with an expressed diagrid, and the client's requirement for a high degree of seismic safety.

In a base isolation system the structure is decoupled from horizontal movements of the ground by the use of a layer of bearings that are vertically very stiff but horizontally very flexible. In the case of Sony City these are multilayered laminates of elastomeric steel and rubber, made by vulcanisation bonding of the rubber sheets to thin steel plates (Fig 63). These bearings greatly reduce the structure's fundamental frequency so that deformation occurs entirely in the isolation layer. This reduction detunes the building from the high frequencies that contain large amounts of energy from ground shaking. In consequence it doesn't absorb earthquake energy but rather dodges it. Damping to the system is provided by the high damping elastomeric rubber in the isolators combined with viscous dampers.

62. External view.

63. Close-up of rubber bearings.

Structural outline

Plantec Architects wanted to express the perimeter diagrid structure and to use a double skin façade. The benefits of a diagrid structure are well known, in particular its high degree of horizontal structural stiffness, while a double skin façade provides noise and thermal insulation and allows natural daylighting and airflow ventilation. However, the presence of the delicate and expensive diamond-shaped double skin façade module between the braces of the diagrid meant that storey drifts needed to be tightly controlled.

This requirement imposed by the façade seems like a good match with the naturally high stiffness of the diagrid. However, in earthquake-prone regions, the high stiffness of diagrids for buildings shaped like Sony City attracts very large seismic forces, resulting in a heavy and uneconomical structure.

An additional factor was that, as a high-profiled office building, it needed to protect not only human lives and tangible property but also important electronic data.

Taking advantage of the stiff nature of the structural scheme (resulting from the architectural design intent) and at the same time meeting the challenging seismic performance requirements, Arup's proposed solution was to base isolate the building. There is a cost premium for using base

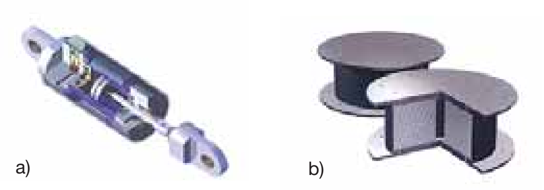
Table 1. Design criteria in earthquake of 500-year return period.

Superstructure	All structural members in elastic state Storey drift angle within 1/500
Isolating layer	Deformation of isolators less than 250% No tension in isolators Strokes of viscous dampers less than 550mm
Substructure	All structural members in elastic state

isolation; typically it adds about 5% to the cost of the structure, even when the reduction in structural material is factored in. The additional cost lies mainly in additional excavation and extra floor structure. Services and elevators passing through the isolation layer have to be carefully detailed to permit lateral movements of up to 500mm. But the benefits for this project were great. It enabled the the diagrid design intent to be achieved and furthermore provided exceptionally high seismic performance.

The isolating layer is between the first and second basement floors and comprises 200 rubber bearings, of which 184 are high-damping bearings, and 40 viscous dampers (Fig 64). The bearings were subject to full-scale tests, in pairs, the first time this has been done. Each of the columns of the inner frame, which are subject to large axial forces, is supported by four rubber bearings. The viscous dampers are located in the perimeter so that they work effectively against both translational and twisting motion.

In order to transfer the lateral force from the superstructure smoothly, its steel columns were embedded in the isolating layer and steel elements were cast into the ground floor beams. Within the superstructure there are concrete filled tubes (CFT) for the internal columns (Fig 65), while the substructure is a reinforced concrete construction with shear walls.

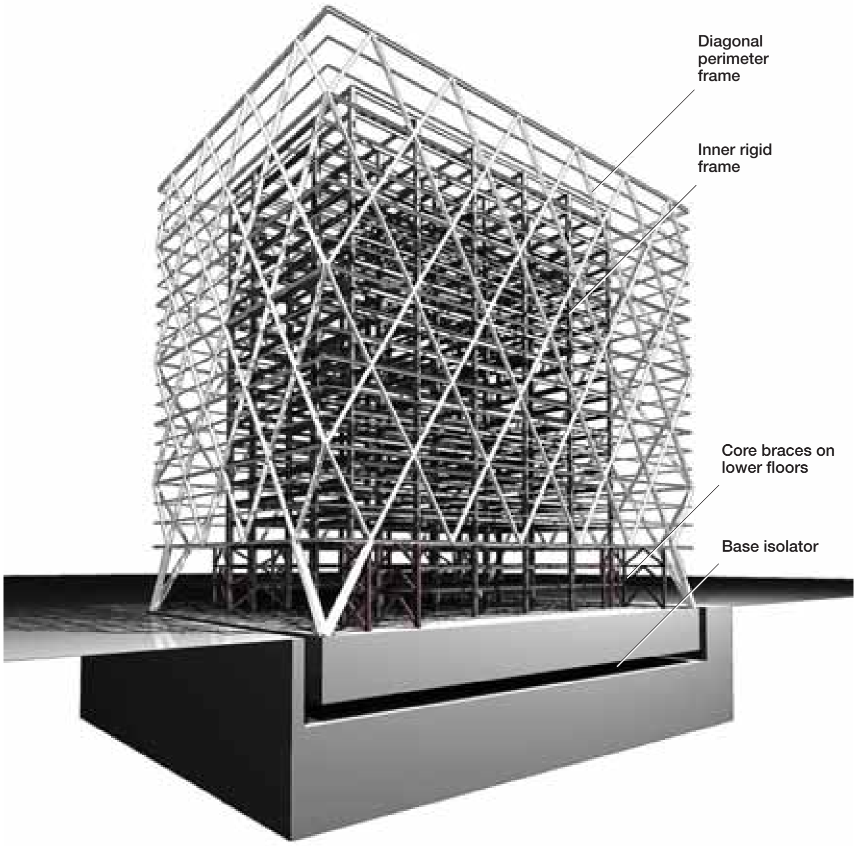

a)
b)

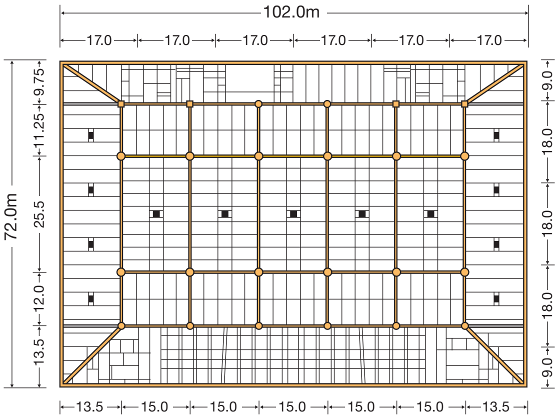
64. Viscous damper (a) and (b) rubber bearing.

65. CFT internal columns.

66. Aerial view.

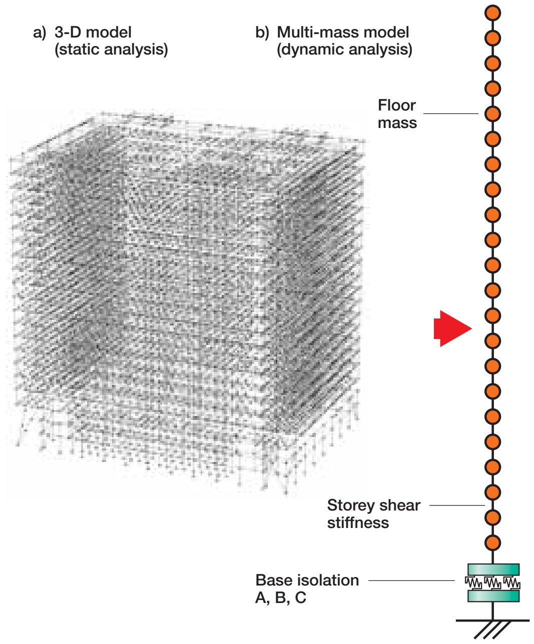
67. Structural system.



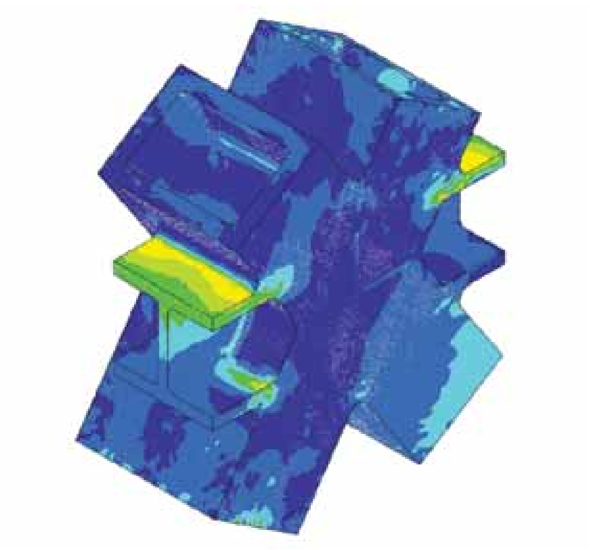


68. Structural plan of typical floor.

69. Analysis models.



70. Finite element analyses of the cast steel nodes were carried out to check that the local stresses were within allowable limits. Resultant forces obtained from the GSA analysis of the whole structure were used for the analysis.



The superstructure comprises the perimeter diagrid frame, an inner moment frame, and braced cores in the lowest three storeys (Fig 67). The diagrid members are 500mm x 700mm rectangular hollow sections except in the lowest three storeys, where 1200mm square hollow sections are used. The connections are formed every three storeys by welding high-strength cast steel connections to diagrid members so that the full strength of each member can be utilised. As site welding is less reliable than shop welding, particularly for cast steel, 800mm long brackets were shop-welded to the cast steel connections which in turn were welded to the diagrid members on site.

The typical floor bay is 15m by 25.5m for a flexible office layout and is supported by grillage beams (Fig 68). The internal frame typically consists of CFT columns of 1300mm to 1800mm diameter, 1000mm deep primary beams and 600mm deep secondary beams. The natural frequency of the floor bays is relatively low (approximately 3Hz) so tuned mass dampers were installed to reduce floor vibration.

Seismic analysis

A multi-degree-of-freedom model, based on the result of the 3-D static analysis model and the nominal properties of the rubber bearings and viscous dampers, was created to carry out non-linear time history analyses. Also, a suite of seven seismic time history inputs, each with varying characteristics, was utilised to assess and validate the performance of the structure and damping system (Figs 69, 70).

Time-history analyses were conducted for three different models: soft, middle stiff, and stiff isolation. The above-mentioned seven waves were applied to each of these three models in two orthogonal axes, which resulted in 42 analysis cases in total.

Conclusion

Arup's structural solution for Sony City utilised base isolation technology, thereby meeting the client's request for exceptionally high resilience in strong earthquakes and at the same time supporting the architect's design intent. Sony City is Arup's only completed base-isolated building, although there are others in the design stage.

71. Sony City in the Shinagawa district skyline.

Credits

Client: Sony Life Insurance Co Ltd **Architect:** Plantec Architects Structural, seismic, and façade engineer: Arup – Keiko Katsumoto, Ryota Kidokoro, Masato Minami, Jin Sasaki, Ikuhide Shibata, Eiko Suzuki, Hitoshi Yonamine.

Award

Japan Society of Seismic Isolation (JSSI) Annual Seismic Isolation Award 2008.

Nicolas G Hayek Center, Tokyo

Introduction

Designed by architect Shigeru Ban with Arup as structural engineer and site supervisor, the Nicolas G Hayek Center – the Swatch Group's new flagship building in the Ginza district of Tokyo – is filled with innovations, ranging from elevating showrooms, to multi-storey retractable glass exterior walls, to moving floors for reducing the seismic forces induced into the building. Utilising a combination of base isolation and mass damper technology, this "self-mass damper" (SMD) system is a seismic control concept inspired by the pendulum movement of an antique clock.

Overview of structure

As well as the innovative seismic passive control system, key structural features of this building include multiple atria throughout and a sculptural undulating roof. The structural system derives from the Arup team's endeavour to resolve the unique spatial layout and satisfy the client's demand for a highly seismic-resistant structure.

The building is founded on a stiff soil layer 14m below grade, using a raft foundation system, and as there was an existing basement structure, Arup proposed to use its walls as temporary shoring (thus dealing with the limited workspace typical of the densely populated Ginza district).

Numerous openings were required at ground level to accommodate nine elevators, two stairwells, and a car lift – leaving very little floor plate area to transfer the lateral forces into the surrounding basement walls. Ground-level slabs were reinforced with steel plates 6-12mm thick to ensure proper transfer of forces.

From ground level, a three-storey retail atrium extends through the building's longitudinal direction – effectively carving away the much-needed moment frames at the base of the structure. To reinforce the lateral stability of these bottom few levels, three sets of core framing were introduced. The general superstructure comprises a rigid steel moment frame every 2.4m longitudinally, and the SMD systems to counter the building's seismic response were located at floors 9, 10, 12, and 13.

Contrasting with the overall box shape, the architect envisaged a light, free-form roof floating above the structure. Its geometry was determined by a series of form-finding techniques available in Arup's *GSA* software. In accordance with the architect's image of a "woven" object, the structural scheme comprises a pair of stacked steel plates extending in three directions.

Self-mass damper (SMD) system

Background

Much discussion at schematic design stage showed clearly that the client wished to target a challenging seismic performance grade outside recommended performance-based design practice. Specifically, the additional requirements were:
(1) main structural elements to remain elastic under level 2 (500-year return period) earthquake, and (2) collapse to be prevented under level 3 (1000-year return).
To achieve such targets with economical feasibility, the Arup team determined that damping would be essential, and embarked on a thorough exploration of systems that would best fit the structure without compromising the architectural intent.

Initially a pendulum-type mass damper system was proposed, but while an interesting concept, it was not clear that it would be appropriate and effective here. With Japan's plethora of damping devices in mind, the design team began investigating the effectiveness and pros/cons of other systems. To achieve stringent performance targets, base isolation would be the usual choice, but as Ginza real estate prices are amongst the highest in the world, allocating a 1m wide strip of clearance around the perimeter to absorb the base isolation movement was deemed inappropriate. The team looked at installing available damping devices within the allowable three core frames, but this would have been inadequate due to the bending

72. Swatch Group's flagship building.

73. Three-storey atrium at ground level, with multiple glass showroom elevators.

74. Fifth floor atrium with retracted glass exterior wall.

deformation shape of the slender core frames. Though a mass damper would depend on the mobilised mass quantity and tuning of the system, preliminary studies indicated that such a system could be extremely effective for this slender building.

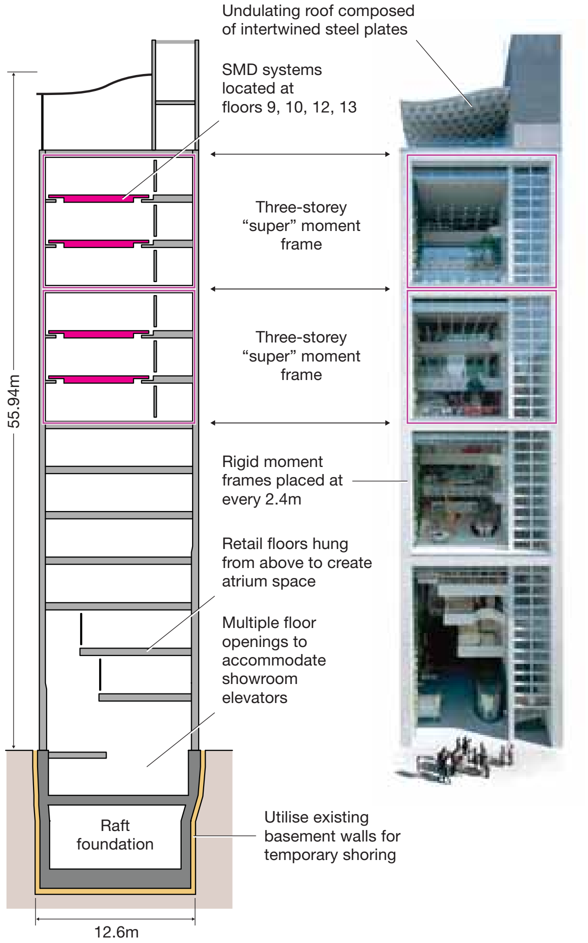
Evolution of the mass damper scheme

Unlike mass damping to control low-energy wind responses, to deal with large seismic forces by this method requires a great deal of mass to be effective. Characteristically, practical effectiveness begins at around 5% mobilisation of the building mass. As the mobilised mass increases, the system can be more appropriately categorised as a mid-level isolation system, and finally when the mobilised mass is 100% of the building mass, it becomes a base-isolated structure.

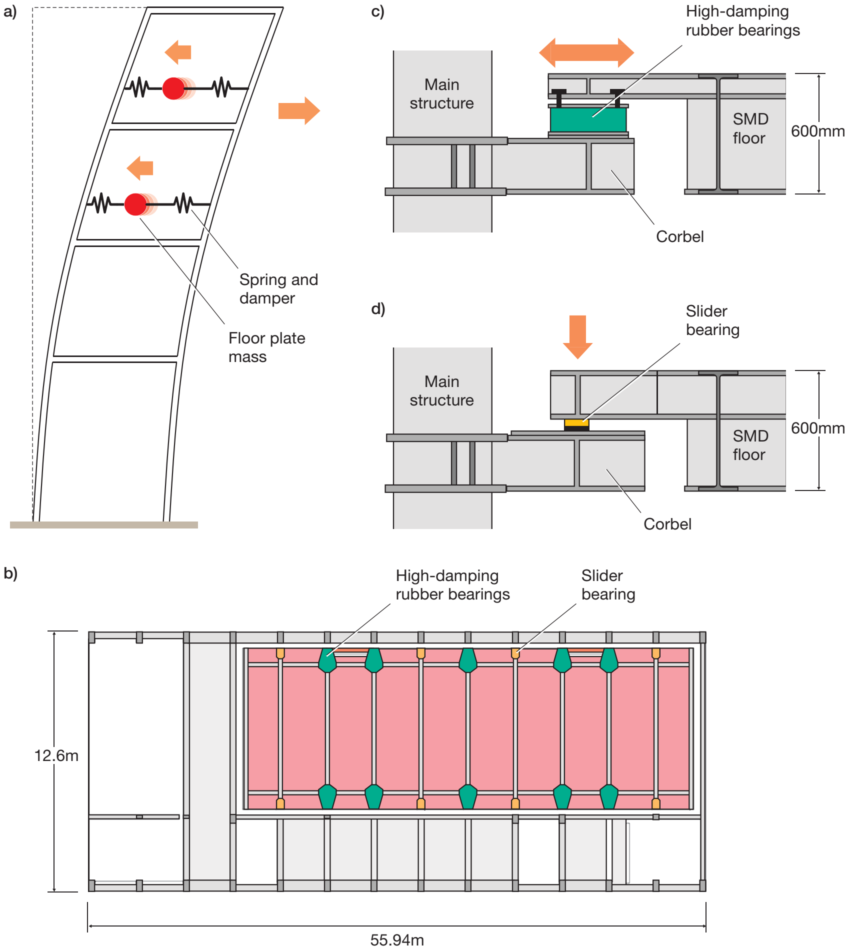
Typically, mass dampers are integrated into buildings by augmenting unutilised mass into the structure, but if, say, 10% of the total building mass is added at the top for seismic control, it is detrimental in terms of overall impact on the building. This is why mass dampers are not used to control seismic response. The design team therefore looked at how to mobilise existing, necessary mass as a mass damper.

The front elevation (Fig 72) clearly shows the building's groups of three-storey atria (sky gardens). With the upper sky garden blocks and the resulting three-level "super-frame" impression in mind (Fig 75), the first proposal was to hang two of the floors, released from the building to create a "swinging pendulum" utilising the floor plate's self-mass. However, due to issues such as the hanger elements intruding into the office space and vertical displacements of the floors due to the rocking movement, alternatives were explored.

75. Key structural features, including three-storey "super-frames".



76. The "self-mass damper" system: (a) concept (b) floor-plan; (c) section showing rubber bearing and (d) slider bearing.



77. Free-form roof structure.

Instead of being hung, the floor plates could be supported vertically by corbels extending from the main structure within the beam depth. These floor plates would be isolated laterally, but still connected to the main structure by special spring and damper devices. Although not a pendulum, this system utilises structural self-weight to form a damper with significant mass. The next step was to find a suitable bearing device to realise this system.

Development of the device (Fig 76)

Available configurations of base isolator bearings were found to be too large and stiff, and so with the realisation that nothing suitable already existed, the team consulted a leading manufacturer.

High-damping rubbers in typical base isolator bearings exhibit bi-linear behaviour – initially very stiff but subsequently softer beyond a certain applied shear force. In addition, this bi-linear stiffness can be adjusted by varying the height and area of the high-damping rubber material. Typically, to prevent crushing under the building's weight, multiple steel plates are sandwiched between the rubber layers, which also makes the bearing extremely stiff laterally. Following several discussions, the solution of creating a device that includes only layers of high-damping rubber and sized according to the required bi-linear property was reached – a newly-developed device using familiar materials. Since these rubber dampers cannot resist vertical loads due to the exclusion of steel plates, the team decided that the floors should be supported by slider bearings with extremely low friction coefficient. This combination of high-damping rubber and slider bearings was then placed in plan to balance the required vertical support and lateral stiffness. Thus the final scheme for this mass damper system was envisioned and the design moved forward.

The self-mass damper system

The floor plates on levels 9, 10, 12, and 13 were chosen to be isolated from the main structure and utilised as the mass damper, and the new system was named "self-mass damper" to highlight the use of existing mass. Its key characteristics include:

- Each SMD floor plate is approximately 100 tons, with the combined mass of the four floors equivalent to 10% of the superstructure mass.
- Each combination of bearings for each level is tuned to provide maximum damping to the overall structure while maintaining an acceptable level of lateral deformation. The SMD floor is allowed to move in all directions and is thus uniformly effective.
- Each rubber damper unit was tested (Fig 78) to confirm characteristics, followed by a full-scale push-release test on site. Measurement devices were installed to verify movement following a seismic event.
- Non-linear 3-D time history analyses using a suite of seven seismic inputs were conducted to simulate the SMD system and building behaviour during large seismic events. Although a stick model analysis approach is commonly used in Japan to simulate building and damping behaviour, this unprecedented system required full 3-D model analysis.
- Although the SMD system's effectiveness fluctuates depending on the seismic time history input, it was established that seismic response of the structure decreased in all cases. The system is most effective against earthquakes that resonate with the building's dynamic properties, resulting in a maximum base shear reduction of 37%.

Conclusion

The Nicolas G Hayek Center was commissioned in February 2005 following the architect's competition win the previous November. It went on site in December 2005, and was completed in April 2007. The daring architectural concept, combined with the Swatch Group Japan's wish for a structure with high seismic resistance, resulted in the implementation of a new type of mass damper passive control system. The SMD system was found to successfully reduce the seismic design load by over 30%, leading to a robust yet efficient structure and increasing the building's potential lifespan.

78. Rubber damper testing.

Credits

Client: Swatch Group Japan **Architect:** Shigeru Ban Architects **Structural engineer and site supervisor:** Arup – Shigeru Hikone, Ryota Kidokoro, Jin Sasaki **General contractor:** Suruga Corporation and Kajima Corporation **Rubber damper manufacturer:** Toyo Rubber.

Awards

2008 JSCA Structural Design Award

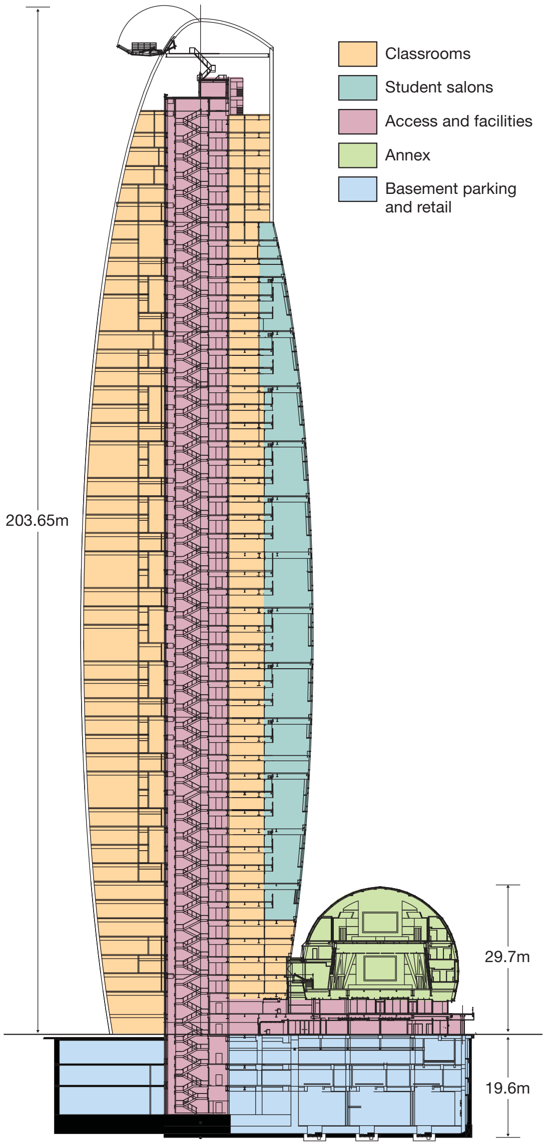
2009 Architectural Institute of Japan Architectural Design Award.

MODE GAKUEN
Cocoon Tower

Introduction

Mode Gakuen is a vocational school for students in the fields of fashion and interior and graphic design, with bases in Tokyo, Osaka, Nagoya, and Paris. In 2004 Mode Gakuen instituted an architectural competition for its new Tokyo location, and this was won by Tange Associates. Located in Nishi-Shinjuku in the heart of Tokyo, this 203.65m-high, 50-storey skyscraper was commissioned in February 2005 and completed in October 2008. It is the second-tallest educational building in the world and the 17th-tallest building in Tokyo.

79. Architectural section.

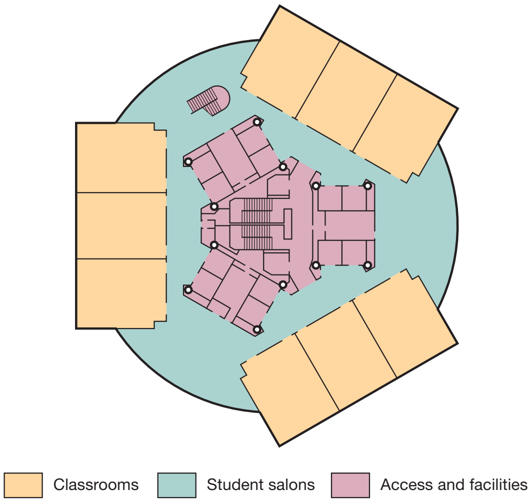


80. External view.

The tower's curved outline and distinctive cocoon shape (Figs 79, 80) are intended by the architect to symbolise a nurturing of the students that it accommodates, and form a boldly different presence amid a dense cluster of conventionally box-like skyscrapers. The building actually contains three educational bodies catering for around 10 000 students. As well as the Tokyo Mode Gakuen fashion school, it also accommodates HAL Tokyo and Shuto Iko, which are respectively information technology and medical schools.

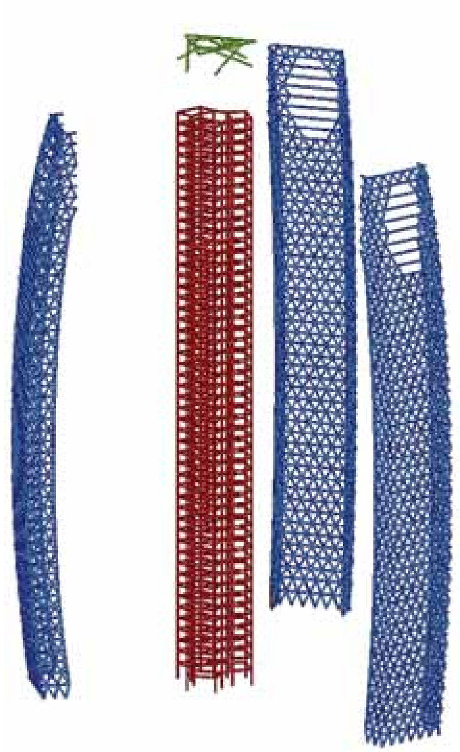
The typical tower floor plan is circular with the three rectangular classroom plans imposed on top (Fig 81). Each classroom is 24m wide. The depths of the classrooms vary as the perimeter surface draws an elliptical curve vertically. Spaces between the classrooms are used as small atria where students can refresh themselves between classes.

Next to the tower on the same site is a 30m high elliptical annex, containing two large lecture theatres and some retail outlets, including a bookshop. Both the high-rise building and annex share the same four-storey basement structure which is used for car parking and retail space.



81. Typical floor plan.

82. Structural system.



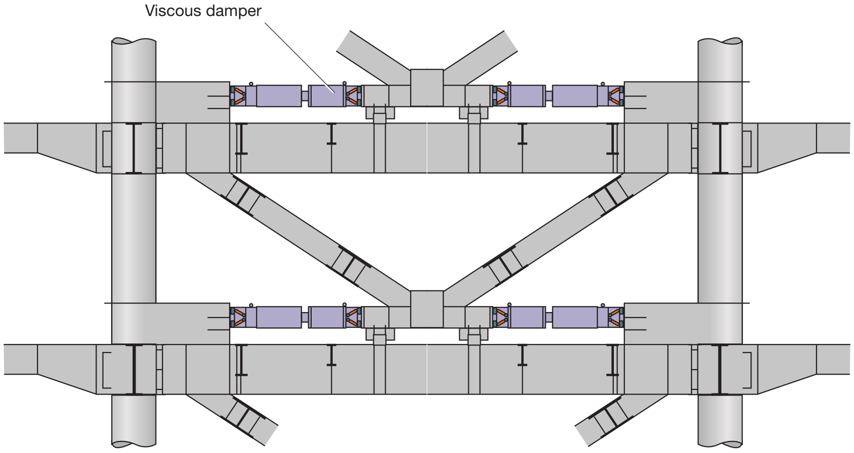
The main structure comprises three elliptical diagrid frames and an inner core frame (Fig 82). Because the three diagrid frames are connected rigidly with each other at the base and the top only, the building has relatively large shear deformations in the middle storeys due to the bending of each diagrid frame. The structure can be viewed as a portal frame with large rotations in the middle and smaller rotations at the top and bottom. The inter-storey displacement of the perimeter frame is largely through bending, while that of the inner core is by shear. Viscous dampers are utilised to exploit the shear deformation of the inner core and to dissipate the associated seismic energy. On each floor from the 15th to the 39th, the inner core has six viscous dampers, which reduce the seismic force that needs to be resisted by the structure.

Structural outline

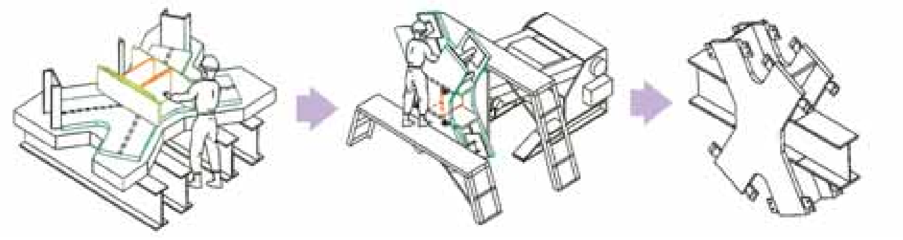
Both superstructures are of steel with concrete-filled tubular columns in the inner core. The basement is a composite construction of steel and reinforced concrete with concrete shear walls, while the foundations combine a 3.8m thick raft slab and cast in situ concrete piles. The pile positions could not coincide with the column positions due to the complexity of the column arrangement, so the raft above the piles was used to transfer the vertical forces from the columns to the piles.

83. Internal view of classroom showing diagrid frames.

84. South entrance to tower (left) and annex (right).



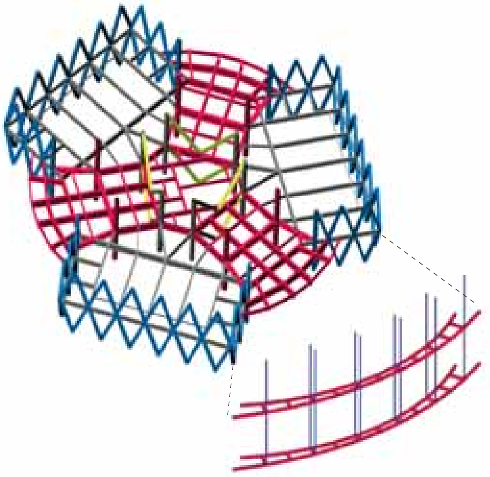
87. Typical floor section showing location of viscous dampers on vierendeel beam.



88. Fabricating the intersection node.

85. Three-storey atrium.

86. Typical floor structure showing location of vierendeel beams.



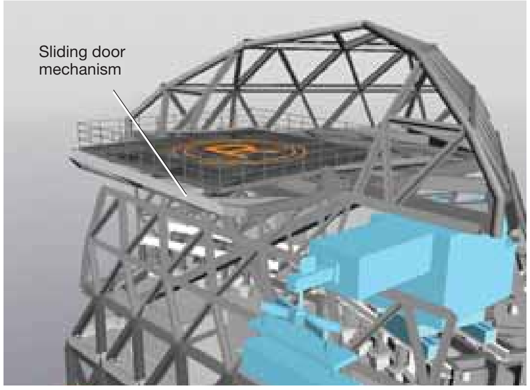
The diagrid frames at the perimeter are 24m wide with intersections every 4m on each floor level, curving in a vertical ellipse and giving to the structure a wide stance so that it can efficiently transfer lateral force and overturning moment from earthquake or wind to the basement. Storey heights are such that the distance on the elliptical line is uniformly 3.7m, allowing the diagrid members to intersect at the same angle on each floor. This shows the external patterns smoothly, and significantly simplified the fabrication of steel and exterior cladding units. Diagrid members are mainly I-sections 400mm wide and 400mm deep – relatively small for such a slender, high-rise building and helping to maximise the internal space.

The floor beams of classrooms support the floor loads and connect the diagrid frames and the inner core horizontally, preventing out-of-plane buckling of the diagrid frames. Most of the classrooms are architecturally designed to expose floor beams and service ducts in the ceiling (Fig 83) while other areas are finished by ceiling panels. Parallel floor beams are rigidly connected to the intersection of the diagrid frames and cranked at the beam above the partition between classroom and corridor towards the columns of the inner core. The floor beams are rigidly connected at both ends. As a result, the exposed beams in the classrooms look well-ordered. Furthermore the diagrid frames are robustly stiffened against out-of-plane buckling.

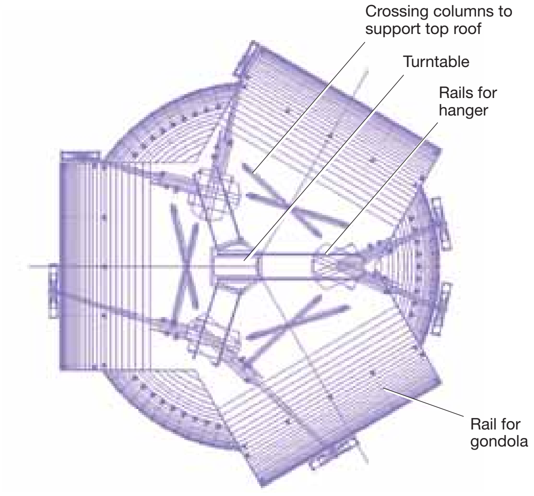
At intermediate levels there are three-storey atriums for the students to refresh themselves. Their external glazing is three storeys high and the maximum width is nearly 20m. Double-arched vierendeel truss beams at each floor level carry the weight of glazing panels and resist wind pressure. The vierendeel beams are hung from the beams above so that no structural member obstructs the view on any storey (Figs 85-86).

Connection design is one of the challenges of a diagrid structure, because many members (seven in this case) from various angles are concentrated at one point. There were numerous meetings between the engineers and fabricators to find a solution that was reasonable to fabricate and structurally robust. In the adopted solution the intersection node is fabricated from several rolled plates (Fig 88) and butt-welded with the diagrid and floor members on site.

89. Panoramic views from the top floor.



90. Hovering space and gondola hanger.



91. Movement trails of gondola hanger arm.

Roof facilities

The priority given to the architectural profile means that, unlike most high-rise buildings, it does not have a flat surface on top. However, an exterior cleaning system and provision of a hovering space for helicopters are essential for a high-rise building in Japan, so to provide such a hovering space of 10m square, a retractable roof was designed (Fig 90). Half of the floor is attached to the retractable roof. At the request of Tokyo Fire Department the roof can be opened within eight minutes by a pair of hydraulic jacks to form the hovering space.

The maximum wind speed that allows hovering is 15m/sec. Although the shape of the retractable roof suggests the possibility of aerodynamic unstable vibration during opening, it has been confirmed that this should not occur even in a 30m/sec wind speed, as per the Japanese loading standard.

A gondola hanger for exterior cleaning is installed below the hovering space and moves around on rails arranged in a Y-shape with a turntable at the centre. The hanger is able to deliver the gondola to all external surfaces of the building by extending and revolving the arm at each end of the Y-shaped rails (Fig 91).

To enable the hanger to revolve the arm, the floor for hovering and the top roof are supported only by three pairs of crossing columns. The perimeter steelwork on the same level as the hanger's arm consists of sliding doors.

The annex

As already noted, the annex next to the tower contains shops and large lecture theatres (Figs 79, 92). Its roof structure is a reinforced concrete shell varying between 150mm and 200mm thick, and spanning 30m x 45m. A special permanent formwork spaceframe system called *Trusswall* was used to support the shell, eliminating the need for conventional formwork.

92. Lecture theatre in the annex.

Conclusion

Many high-rise buildings have been built in highly seismic countries like Japan in recent decades, but most of them are box-shaped with vertical columns. The very different shape of this building, as proposed by the architect, was strongly favoured by the client, and so those involved in its structural design and construction made every effort to achieve the shape. The completion, therefore of this uniquely shaped skyscraper may be regarded as a significant achievement in Japan's history of high-rise buildings.

Credits

Client: Mode Gakuen Architect: Tange Associates Structural engineer and site supervisor: Arup – Junichiro Ito, Masato Minami, Kazuyuki Ohara, Ikuhide Shibata, Yusuke Shirai, Justin Stolze Damper manufacturer: KYB, Hitachi General contractor: Shimizu Corporation.

Award

The Emporis Skyscraper Award 2008.

Shigeru Hikone is a Principal of Arup and the leader of Arup Japan in Tokyo. He was Project Director for the *Mind-Body Column*, Toyota Stadium, DoCoMo tower, Sony City, Nicolas G Hayek Center, and MODE GAKUEN Cocoon Tower.

Mitsuhiro Kanada is an Associate Director of Arup, based in London. He was the senior structural engineer for the *Mind-Body Column* and Maison Hermès.

Ryota Kidokoro is an Associate of Arup in the Tokyo office. He was a structural engineer on the DoCoMo tower and Project Manager for the Nicolas G Hayek Center.

Masato Minami is a senior engineer with Arup in the Tokyo office. He was deputy project manager for MODE GAKUEN Cocoon Tower and a structural engineer for Sony City.

Ikuhide Shibata is a Senior Associate of Arup and structural engineering leader in the Tokyo office. He was Project Manager for *Mind-Body Column*, Toyota Stadium, DoCoMo tower, Sony City, and MODE GAKUEN Cocoon Tower.

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About Arup

Arup is a global organisation of designers, engineers, planners, and business consultants, founded in 1946 by Sir Ove Arup (1895-1988). It has a constantly evolving skills base, and works with local and international clients around the world.

Arup is owned by Trusts established for the benefit of its staff and for charitable purposes, with no external shareholders. This ownership structure, together with the core values set down by Sir Ove Arup, are fundamental to the way the firm is organised and operates.

Independence enables Arup to:

- shape its own direction and take a long-term view, unhampered by short-term pressures from external shareholders
- distribute its profits through reinvestment in learning, research and development, to staff through a global profit-sharing scheme, and by donation to charitable organisations.

Arup's core values drive a strong culture of sharing and collaboration.

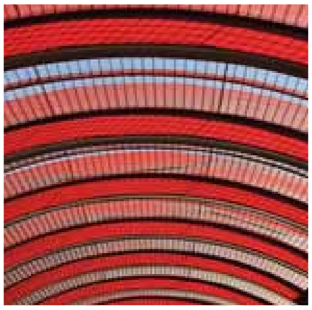
All this results in:

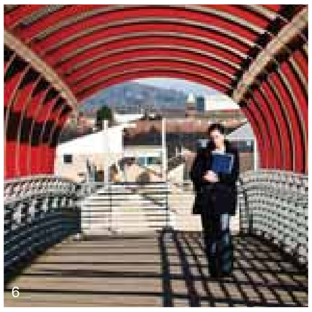
- a dynamic working environment that inspires creativity and innovation
- a commitment to the environment and the communities where we work that defines our approach to work, to clients and collaborators, and to our own members
- robust professional and personal networks that are reinforced by positive policies on equality, fairness, staff mobility, and knowledge sharing
- the ability to grow organically by attracting and retaining the best and brightest individuals from around the world – and from a broad range of cultures – who share those core values and beliefs in social usefulness, sustainable development, and excellence in the quality of our work.

With this combination of global reach and a collaborative approach that is values-driven, Arup is uniquely positioned to fulfil its aim to shape a better world.

93.

ARUP





Illustrations: 1. Pivot bearing for NTT DoCoMo tower, Osaka: Shinwa; 2. Retractable roof at Toyota Stadium, Toyota City, Aichi: Toyota City; 3. Maison Hermès, Tokyo: Michel Denance; 4. Sony City: Koji Kobayashi/SPIRA; 5. *Mind-Body Column*, Osaka: Arup; 6. Roden Street footbridge, Westlink/M1, Belfast: Andrew Hazard Photography & Design; 7. Sir Ove Arup on Kingsgate footbridge, Durham, England, during construction, 1963: Arup; 8. MODE GAKUEN Cocoon Tower: SS Tokyo; 9. The trumpet: one of the most ancient of musical instruments and a symbol of freedom and diversity: iStockphoto/Karla Caspari; 10. Free-form roof structure for the Nicolas G Hayek Center, Tokyo: Hiroyuki Hirai.

Front cover: MODE GAKUEN Cocoon Tower: SS Tokyo.

Inside front cover: Water-colour by Roger Rigby of Sir Ove Arup on Kingsgate footbridge, originally painted for the Ove Arup 90th birthday edition of *The Arup Journal*, spring 1985.

Special thanks to **Dara McDonnell**, **Keiko Katsumoto**, and **Ryota Kidokoro** for co-ordinating the Arup Japan 20th anniversary feature.

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