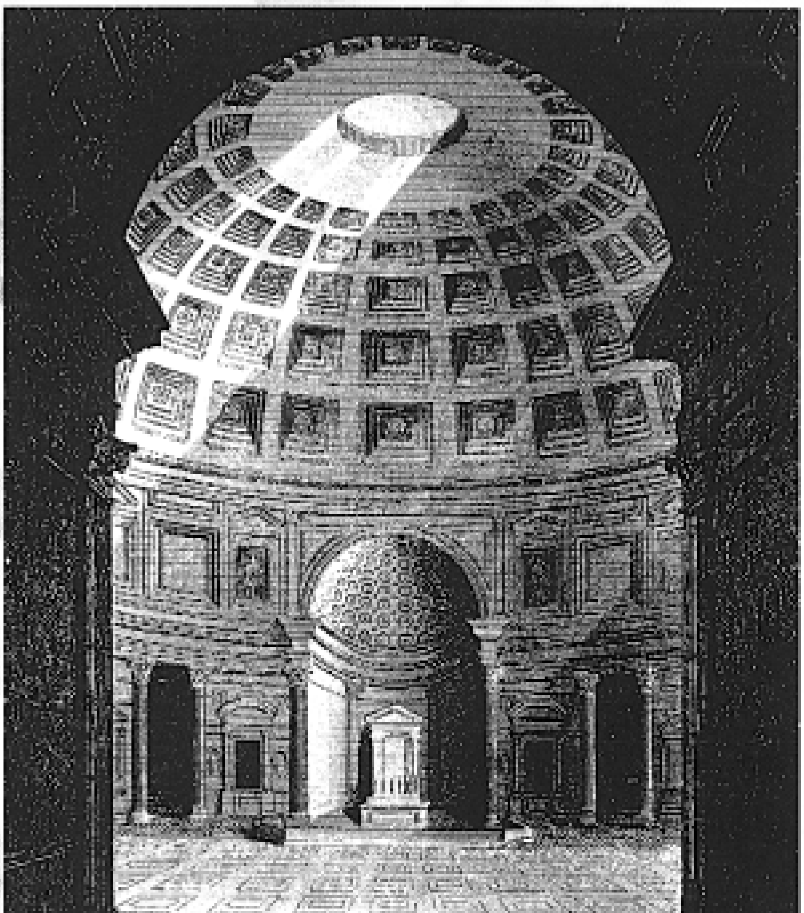
WHY CONCRETE



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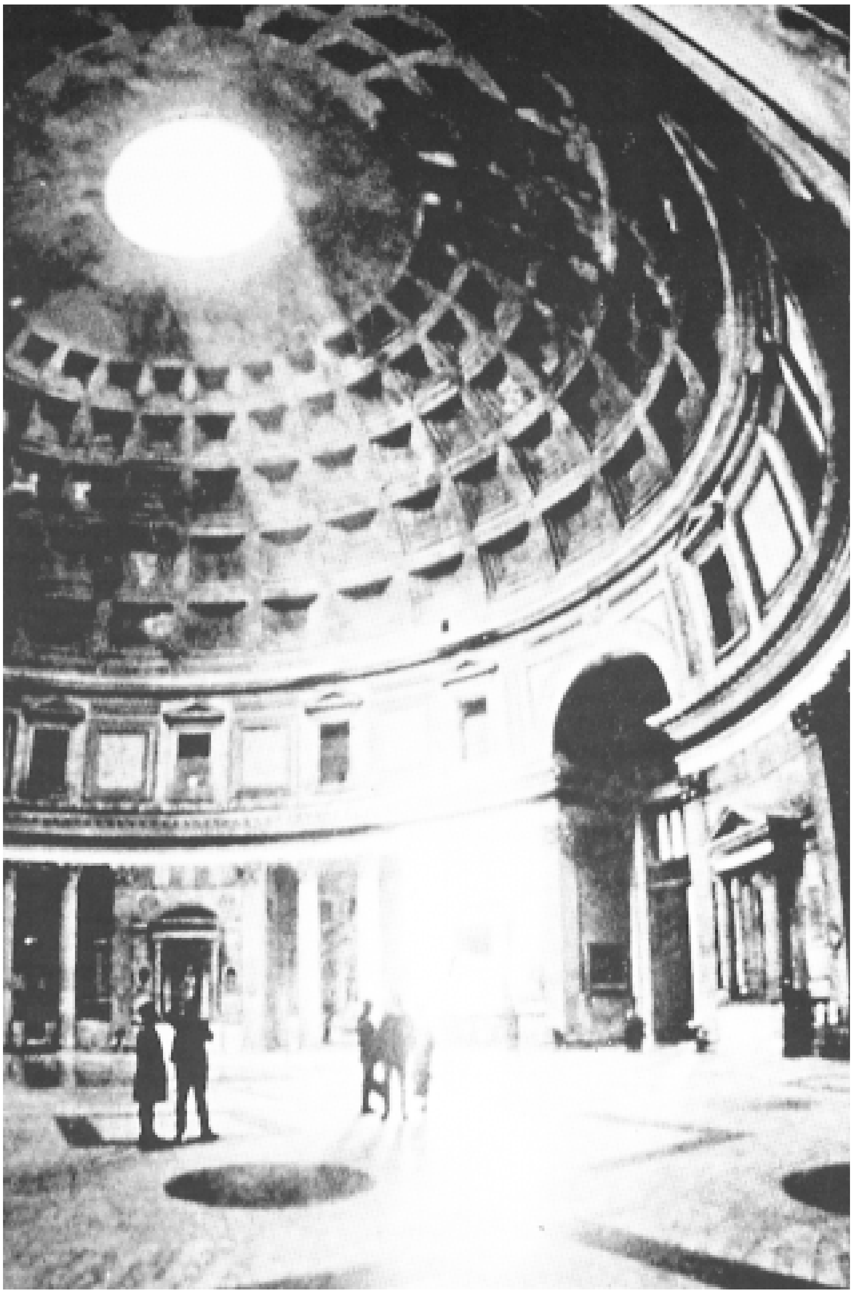

Figure 1 *The Pantheon in Rome built 123 AD; span 43.4 metres*

PREFACE
The lecture here reprinted was given in 1970, but most of the statements are still true today. In 1969 the Building Science Forum of Australia conference committee picked out *economic factors* and *concrete finishes* as the main topics for discussion, and they remain the major problems. Concrete is still the most widely used structural material in Australia, and we have few unresolved problems with the design of concrete structures; the question remains whether any particular building can be erected more cheaply in steel or in concrete.

Our skill in finishing concrete has improved in the intervening years, but it is still difficult to produce a concrete surface that is, after a few years of use, as good as one of natural stone or brick. Today we are less dogmatic about structural honesty which requires concrete to be exposed on the surface, and see more merit in the practice of the 1930's of covering it with a veneer of natural stone.

A PLASTIC MATERIAL?
Although Frank Lloyd Wright is not particularly noted for his use of concrete, he made one of the most penetrating observations on its properties:

"Certain truths regarding the material are clear enough. First, it is a mass material; second, an impressionable one as to surface; third, it is a material which may be made continuous or monolithic within very wide limits; fourth, it is a material which can be chemicalised, coloured or rendered impervious to water; fifth, it is a willing material when fresh, fragile when still young, stubborn when old, lacking always in tensile strength".

He wrote that in 1928 in the *Architectural Record*, at a time when the structural prestige of concrete was rising rapidly but its architectural prestige was still very low. It is worth recalling that the first national Australian concrete code was published only in 1936, and even the first national British code dates only

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from 1934. At that time most cement manufacturers were not really convinced of the aesthetic merits of their product. I remember as a student, ie in the late 1930's, receiving a publicity handout from a northern English cement company which mentioned as the prime architectural merit of concrete that it was so easy to veneer with natural stone that nobody would even suspect the concrete underneath. Yet in the short space of thirty years concrete has become the most important architectural material. Why this rapid change?

I think one reason for the late development is the timing of the discovery of reinforced concrete. It coincided with the Gothic Revival, and although the economics of casting a hundred concrete gargoyles from the same mould seem most attractive, the weathering qualities of concrete gargoyles are very poor because of shrinkage and the stress concentrations caused by the internal corners. The eclecticism of the late19th century was equally unhelpful since concrete, being a new material, tended to be used for the more modern, or should one say more fantastic, projects. Because concrete can be cast into any mould, it was used in particularly complex forms, for which we know it was not suitable, and its poor weathering under those conditions has been one reason for its ill repute in the earlier years of this century.

THE HISTORY OF CONCRETE

Actually it is surprising that reinforced concrete was so late in making its appearance, because plain concrete has a very respectable early history, **Figure 1**. It was used in various parts of the Mediterranean where there were deposits of volcanic ash with natural cementing properties; after visiting the Greek island of Thera, the Santorin of the Crusaders, Le Corbusier remarked on the continuity between the construction of buildings excavated from the Greek Classic period and those of modern times. It was used on a grand scale by Imperial Rome for its baths and for some of its temples; for example, the building which held the record for the longest span from 123 AD until the 19th century the Pantheon in Rome, was of concrete. The recipe for making concrete was well-known. Vitruvius describes the laying of concrete floors, and gives the mix proportions. Several classical writers refer to opus caementitium; Pliny mentions that concrete should only be tempered by the sweat of the mason, which suggests an understanding of the importance of a low water-cement ratio. At any rate, Roman concrete was generally strong and well compacted. I had the opportunity in the early 1950's to test some pieces from the floor of a Roman house in Libya, which had a strength of over 14 MPa; and yet it consisted, according to our chemists, only of lime, brick dust and crushed brick; the concrete made with volcanic ash from Pozzuoli, mentioned by Vitruvius, was, of course, much stronger

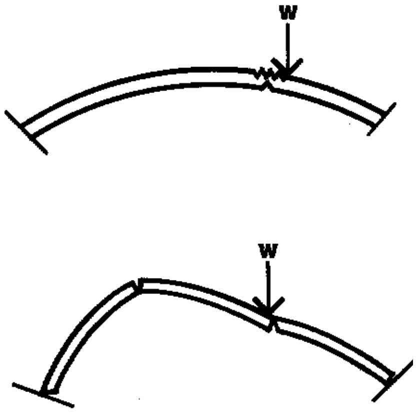


Figure 2 *The failure of a masonry (voissoir) arch*

Why did the use of concrete disappear with the fall of the Roman Empire? From a structural point of view, it is clearly a superior material, **Figure 2**. All traditional masonry structures are basically balancing tricks. When sufficient joints open up, the structure becomes a mechanism and falls down, and the compressive strength of the stone hardly enters into the determination of the strength of the structure Concrete has some tensile strength, and normally performs better than blocks of stone laid in mortar. Even before the days of stone crushers and concrete mixers, it was cheaper to lay concrete than to carve stone. Roman ruins existed not merely in Italy but also in France, Germany and England. The writings of Vitruvius were freely available since the invention of printing, and yet concrete did not reappear until the 19th century

We must be careful to distinguish between two distinct types of Roman concrete; the ordinary opus caementitium, which was made with lime mortar and not waterproof, and that made with pulvis puteolanus, or the waterproof volcanic ash from Pozzuoli near Naples. The more important Roman discovery was the use of concrete as a plastic material which could be poured in place; but the 18th century concentrated on rediscovering the waterproof cement, because it was needed for lighthouses and other structures exposed to the action of water The revival of poured concrete followed only after Portland Cement became freely available.

When Smeaton undertook his investigation on the construction of the third Eddystone Lighthouse in 1756 he knew that waterproof cement was found naturally in the Rhineland and in various parts of the Mediterranean; but the cost of transport was high, and he was curious about the reasons for the waterproof properties of natural cements In the end Smeaton lacked the courage of his own convictions; he discovered quite correctly that waterproof cement is produced by mixing clay with the lime before burning, but he used volcanic ash imported, some accounts say from the Rhineland and some from Italy, in the Eddystone Lighthouse, which was a stone building with waterproof mortar joints. However the first patent for the manufacture of waterproof cement was taken out only five years after the publication of Smeaton's book, and the mass production of artificial waterproof cement, called Portland Cement in almost every language, was well under way by the mid-century

PLAIN CONCRETE

The initial use of waterproof cement was for jointing masonry, and it made possible constructions like Brunel's tunnel under the Thames. This was quickly followed by poured concrete, and many quite magnificent plain concrete arches were built in the Roman manner, **Figure 3**.

However by this time Roman ideas of construction were already obsolete. The Romans had never attempted to reinforce concrete with metal to overcome its weakness in tension, although the use of metal cramps across masonry joints was quite common. Nor had they ever used skeleton frames for tall buildings, although some of the insulae, or

Figure 3 *Plain concrete bridge at Kempten, West Germany, designed and built by Dyckerhoff and Widman in 1904; span 64.6 metres*

tenements, in Ancient Rome are believed to have been as tall as the first skyscraper so called (which was the Montauk Building in Chicago, built in 1882; actually it was only ten storeys high).

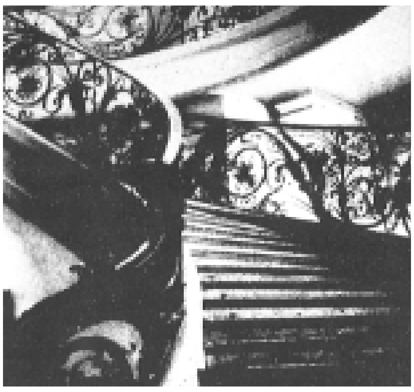
REINFORCED CONCRETE

The use of reinforcement originated in France in the 1850's. There were British patents for its use which go back to 1822, but the concept did not find ready acceptance in England, and as late as 1913 the Committee on Reinforced Concrete, set up by the Institution of Civil Engineers, expressed grave reservations about the use of reinforced concrete. These were by no means without justifcation, because there were serious doubts about the way in which the two materials acted together; and about the design of rigid structures generally. However; ignorance is sometimes fortunate; building authorities in the 19th century would have been even more worried had they known that all concrete surrounding tension reinforcement must be cracked if the steel is to take its full design stress. Today we accept a structural material which is permanently cracked, whose cracks penetrate to the steel, and as everybody knows, steel starts rusting within a few weeks if left exposed to the air. We know it is quite safe; but in 1913 nobody was able to determine the size of the cracks, or explain the manner in which the hydrated cement protected steel from rusting.

The use of reinforced concrete in monolithic form also raised theoretical problems, which were not properly understood in the late-19th century; indeed, purists claim that we stiIl do not understand them properly today. In continuous or rigid construction the bending moments reverse, and the tension reinforcement must sometimes be on the bottom and sometimes on the top. In the case of curved structures, the problem is further complicated by torsion. However; this blissful state of ignorance did not prevent the erection of some quite daring reinforced concrete structures, **Figure 4**. Indeed, as our theoretical knowledge improved in the 20th century we tended to become more cautious.

My reading of reports of 19th century failure suggests that few mistakes were made on the amount of the main reinforcement, although often a great deal more was used than necessary. Evidently empirical rules were quite satisfactory if interpreted generously. Trouble arose mainly because of inadequate cover which led to corrosion, and in some cases to spalling. Excessive hooking also caused trouble. Beams were thought of as spanning between columns. The importance of anchoring plain steel was appreciated quite clearly but hooks tended to be concentrated at column junctions, and the resulting stress concentrations produced a number of failures. Inadequate shear reinforcement was another common cause of trouble. Of course, there were some failures due to plain stupidity and we still get our share of those today

Figure 4 *Curved staircase in the Petit-Palais de Champs Elysees, built by Francois Hennebique in 1898*



THEORY OF REINFORCED CONCRETE

The lack of an adequate theory for the design of building frames was more serious. The steel frame made its appearance in Chicago in 1855; but the great fires in Baltimore in 1904 and in San Francisco in 1906 demonstrated that, without protection by concrete, steel frames were liable to soften and collapse, and the concrete protection, with a fraction of the structural steel used as reinforcement. provided much the same strength as the concrete-encased steel frame. There is, of course ,a limit to the economical height of concrete frames, because the columns, which have to bear the loads transmitted by all the floors above, become too big; but this limit has been rising steadily. Until it can be demonstrated that there are methods of fireproofing without concrete encasement which are really economical, the concrete frame has the edge over the steel frame for medium-sized multi-storey frames.

The use of reinforced concrete in frame structures raised new problems. Steel frames had been designed as cantilevered columns carrying simply supported beams, a method which was well understood in the 19th century, and reasonable in view of the flexible connections between the steel columns and the beams. The much more rigid concrete floor had to be considered as continuous over the columns. One might have argued in favour of designing the entire structure as a rigid frame, but there was no simple method available for doing so in the early years of this century. Alberto Castigliano had, indeed, produced a method for designing rigid frames as far back as 1875, but in the precomputer age it was far too laborious for frames with more than a few degrees of rigidity.

The concept of a rigid concrete floor supported continuously over relatively flexible columns was reasonable so long as columns were small, and floor slabs were stiffened by substantial beams. However; the development of flat-plate construction in the 1940's and 1950's made this approach obsolete, because the stiffnesses of the slab and of the columns were now of comparable magnitude, and one could not design the slab without considering the stiffness of the columns. An analysis based at least on the rigid frame formed by the slab and the columns above and below is the simplest which gives acceptable results.

SPAN

Australia has never been noteworthy for its contributions to reinforced concrete theory Most of our design methods have been borrowed unashamedly either from England or from America; but we have established a couple of records for size. From 1911 to 1912 the Melbourne Public Library was the biggest reinforced concrete dome in the world. One can have reservations about the beauty of this structure while admiring its daring, because it was not merely large for its time, but also the first reinforced concrete structure of any size in Australia. The credit belongs mainly to John Monash, who was the first man to give a formal course on reinforced concrete in Australia, and who was consulted in the early stages. More recently we built the world's longest concrete arch, and it still holds that record by a comfortable margin, **Figure 5**.

People have been interested in bigness since time immemorial. The Seven Wonders of the Ancient World were all wonderful because of their sheer size, not because of their beauty. During the 18th century, architects – as well as young gentlemen on the Grand Tour – would travel great distances in discomfort just to see a particularly big building. The client who asks his architect *"What is the biggest building in the city"*, and then gives instructions to make his a little bigger is not really so different from the clients of previous generations.

What is different now is our ability to meet his demand. From the 2nd until the 19th century the Pantheon held the record, but I doubt if any concrete dome will ever again remain the biggest for so long. The maximum span inside a building, which remained 43.4 metres from Roman time to the mid-19th century, had doubled by 1900, and had risen by a further 50% by 1950. With advances in shell construction it then increased rapidly to 250 metres, and there is no technical reason why it should not go much further. The two largest American domes are relatively isolated, and thus quite acceptable. However the first of the super-domes, the CNIT Exhibition Hall in Paris, quite dwarfs the surrounding buildings which are on the ordinary urban scale of Paris. Until the last century it was generally accepted that an important lady should own and wear a large diamond irrespective of whether it improved her appearance, provided it was bigger than that worn by Mrs Jones. Since it has become technically feasible to make large baubles which are practically indistinguishable from real diamonds, this has come to be looked upon as a vulgarity. We should persuade people that large spans in concrete can no longer be regarded as status symbols, and that they should only be used when they serve a purpose, and not merely because the Joneses have a longer span.

PREFABRICATED CONCRETE

The rigidity of concrete cast monolithically on the site is clearly an asset when we are dealing with large spans or with lateral loads; but it has made the design of reinforced concrete structures more difficult than those of steel. This is at least one of the reasons for the early interest in prefabrication, which was more common in the first decade of this century than in the third. At that time the theory of reinforced concrete was so controversial, that the building up from simple units, each of which could easily be tested, offered particular attractions.

The 1920's were not so favourable for prefabricated concrete, even though this was the period when the concept of prefabrication dominated the thinking of many avant-garde architects and of some government departments. The prefabricated housing programme following the reconstruction of 1919 was, on the whole, a failure. Housing authorities found that it was still cheaper and easier to build by conventional means. People like Le Corbusier and Gropius, on the other hand, thought at that time more in terms of the motor car the ship, and the aeroplane. Prefabrication to them

Figure 5 *Gladesville Bridge, Sydney, span 304.8 metres*

meant metal or plywood. When Le Corbusier mentions mass-produced concrete in Vers une Architecture, he means poured concrete.

By 1919 the theory of reinforced concrete design, although still considered avant garde by some engineers, was quite comprehensive, and it was supported by the extensive experiments carried out by Morsch and Bach in Germany, and by Talbot in America. Mix proportioning and site machinery had greatly improved, and the structural advantages of pouring concrete all in one piece were so obvious that they were hard to resist. The concrete mixer was, of course, a source of dirt on the site, but no more so than the traditional lime pit. The operation required quite a lot of labour but that was still cheap, and after 1929 excessively plentiful.

The position was drastically altered in 1945, when labour had become expensive and in shortly supply, and the need for new buildings in Europe was pressing. In Western Europe the prefabricated concrete housing projects again proved only marginally economical. But Eastern European countries were well satisfied with their production of fully-prefabricated.concrete homes, and they have been using them more and more. On the other hand, the appearance of the completed building leaves much to be desired. The high-rise concrete buildings of the Victorian Housing Commission, although less highly prefabricated and probably not as economical in cost, are better to look at. Indeed, the 30-storey blocks are also a most noteworthy engineering feat, since they are far higher than any built overseas, including Russia.

In spite of the impressive performance of the Victorian Housing Commission, complete prefabrication of concrete buildings is rare in Australia, as it is in America. This is largely due to the success of ready-mixed concrete, which removes one of the dirtiest and most labour-consuming operations from the site to a central mixing plant, and thus constitutes a form of factory production. Precast concrete has, however been used in Australia extensively for facing panels.

SURFACE FINISHES

Surface finish has always been the biggest problem in using concrete. As I have already mentioned, the use of concrete surfaces in neo-Gothic and other eclectic buildings in the late-19th century proved unsatisfactory and it gave concrete a bad name. Concrete is not a good material for intricate detail with internal corners, and this is a fact which is quite separate from the question whether one likes or dislikes neo-Gothic; it is a fact about concrete. It is a good material for strong simple curves, and one can easily cut small holes into it without impairing its strength. It was Auguste Perret's appreciation of these points and his skill in the use of glass which makes him the outstanding, indeed the only architect to use concrete satisfactorily in the early years of this century.

There were, of course, many splendid concrete structures designed by engineers before 1945, but on the whole the cement firm which in 1934 praised the ease with which concrete could be hidden behind a stone veneer was displaying good business sense. During the last war I had lots of time for sightseeing all over England at the army's expense, and I looked at several hundred noteworthy buildings, including most of those erected in concrete during the 1920's and 1930's. They looked rather shabby. Perhaps their owners did not maintain them properly, but I think the architects were more at fault. Moreover few architect-designed buildings of that time made any real use of the plastic qualities of concrete. Mendelsohn's Einstein Tower is often quoted as an example; it was conceived as a concrete structure, but it proved too difficult at the time, and was actually built in brick covered with cement plaster.

Concrete as an architectural material was a rarity before 1945. Today a major building which does not display some concrete is exceptional. The rapid improvement in concrete surface finishes which has taken place in Australia is surprising – an agreeable surprise. When I came back from overseas last year (1969) I formed the impression that the best work here compared favourably with that in England, the United States and Canada, although perhaps not with that of some Continental countries.

We still have not mastered the relation between aggregate size and viewing distance, although J G Wilson published data on this relation fifteen years ago. For example, at close quarters the concrete surfaces of the Australia Square Tower and of Gold Fields House look good. From a distance, which is from where most people see them, the surfaces look dreary and slightly dirty because the individual pieces composing the surfaces are blurred. On the positive side, I was shown during a recent visit to Adelaide an off-white cement, made in South Australia, which gives a finish that is neither dirty-grey nor glaring white, and apparently is not too expensive.

Cost remains, of course, a major factor and I notice that the organising committee for this conference has picked out economic factors, concrete finishes and external cladding as the subjects for tomorrow's discussion. This agrees entirely with my own assessment of the problems which remain to be solved, and I am looking forward to some very informative sessions. Having spent half my working life on structural concrete research, I am not surprised that structure does not figure on the agenda. It demonstrates how far our knowledge of concrete structures has advanced in the last half-century and there is really no greater flattery than to tell a professional group that it is no longer necessary to have a discussion on its work, because the problem is essentially solved.

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