C

Concrete and reinforced-concrete structures

Constructions en béton et béton armé

Massivbau

II

Current problems of concrete and reinforced concrete; prestressed concrete

Problèmes actuels du béton et du béton armé; béton précontraint

Aktuelle Probleme des Betons und des Eisenbetons; vorgespannter Beton

General report — Rapport général — Generalbericht

F. G. THOMAS, Ph.D., B.SC., M.I.C.E.
Building Research Station, Watford, England

INTRODUCTION

Structural engineers are increasingly tending to consider the ultimate strength of the structures they design, rather than the stress conditions at working loads. This tendency has not yet been fully reflected in by-laws and codes of practice, partly because of lack of agreement amongst research workers of the method of assessing ultimate strengths and partly because of a reluctance on the part of many designers to adopt a new philosophy of design. In this philosophy it is necessary to consider the resistances of a structure to the effects of a number of possible eventualities and to relate these resistances to the likelihood of the eventualities occurring, so that the risk of excessive distortion or cracking, or of collapse, is not unduly high.

It is clearly necessary, before this philosophy can be codified for reinforced concrete—and codification of the design basis is in most countries an essential preliminary before a new method is acceptable to the building authorities—that advocates of the new procedure should determine:

(i) the criteria for failure of simple elements, of continuous systems and, if possible, of the complete composite construction;
(ii) the criteria for cracking and other features affecting the durability of the structure;
and (iii) the factors influencing the resistance of structures to incidental eventualities, such as fire, impact and dynamic loading.

It is to be hoped that the papers presented under theme CII, together with the discussions at the Congress, will help to give the information required in each of these groups.

Design on the basis of ultimate strength

It is perhaps unfortunate that the emphasis of research has been so much towards the study of the ultimate strength of simply-supported beams, and so little towards the determination of the strength of continuous systems. Further studies of the behaviour of beams are certainly necessary for conditions which are becoming more common, such as impact and dynamic load, but for which few data are at present available. Research is required also on the ultimate strengths of prestressed-concrete beams to establish to what extent the initial stress conditions affect the behaviour of the beams at incipient failure. But the strength of an ordinary reinforced-concrete beam can be assessed with sufficient accuracy for practical purposes from any one of half a dozen theories which have been put forward in the last twenty-five years, so long as the ultimate strength is dependent on either the tensile strength of the reinforcement or the compressive strength of the concrete. The 1952 Congress would mark a great advance if the representatives from many countries could agree that one of the theories should be adopted as a universal basis for assessing the strength of reinforced-concrete beams.

On the grounds of simplicity and of sufficient accuracy, Whitney's method, using a rectangular stress block for the compression in the concrete above the neutral axis, might well be accepted, with perhaps some small modification to the values of the stresses suggested by Whitney, after consideration and discussion on the paper by E. Torroja and A. Paez under theme CII 1 and that by P. W. Abeles under theme CII 2. It is very desirable that a method should be agreed upon so that it could be introduced in building regulations as a basis for "load-factor" design. The usual method of designing beams in current use is based on limiting permissible stresses at working loads, using an arbitrary modular ratio; with this method, progress in the use of high-quality steel is being hindered, because a reduction in percentage of steel leads to a rise in the position of the neutral axis and a corresponding increase in the compressive stress in the concrete, leading sometimes to the necessity for deeper sections.

In the design of reinforced-concrete columns the anomalous position arises that axially-loaded colums are designed from considerations of the ultimate strength of the column whereas eccentrically-loaded columns are proportioned so as to conform with specified stress limitations under working loads, again introducing the modular ratio into the computations. The value of high-strength steel for the compressive reinforcement of columns is not recognised in the British codes of practice, and experimental evidence on this matter is desirable in the interests of steel economy.

It is becoming increasingly clear that the limitations to progress in the design of reinforced-concrete members on an ultimate-load basis arise from insufficient knowledge of the strain-capacity of concrete. The term "strain-capacity" was used many years ago in referring to the extensibility of concrete; but the strain-capacity in compression is a much more important property which merits greater study than has been given to it so far. Since fundamental investigation of the stress–strain characteristics of concrete at incipient failure involves many difficulties, it is probable that new practical design rules will initially be evolved from tests on columns and beams with high-strength reinforcement. However, fundamental studies such as those described in the paper by Torroja and Paez need to be continued. This paper illustrates well the difficulties and complications of analysis based on the rheological properties of the concrete and steel. These complications would have been increased if consideration had been given to the strains in the concrete after the maximum strength had been passed, but the deformations at this stage are often of importance in deciding the ultimate strength of a beam and may also affect the strength of columns reinforced with high-strength steel.

When the primary failure of reinforced concrete is due to weakness in shear or bond, the assessment of the ultimate load-carrying capacity of the structural system is usually very inexact. In recent years increased attention to these properties has been given by research workers but much remains to be done. The paper by H. J. Cowan and S. Armstrong under theme CII1 is a particularly welcome inclusion in the Congress programme because of the very scanty information on the subject of torsional strength of concrete. It is interesting to find that the bending of a beam increases its resistance to torsion. The concluding remarks of the paper indicate a simple method of dealing with the problem of combined bending and torsion in design, although it is perhaps not altogether desirable to have a "considerable reserve in strength which can be used to reduce the factor of safety." The considerable reserve would appear to be in terms of resistance to torsional failure only, and in order to reduce the general load factor against failure of a beam, whether due primarily to bending or torsion, it is presumably necessary to introduce less shear reinforcement to resist twisting, taking into account the helpful effect of bending. The work of Cowan and Armstrong indicates that a more rational design approach need not be very complicated.

The paper by H. Nylander on the non-uniform shrinkage of concrete under theme CII1 deals with the development of secondary stresses and bending moments which occur in structures for normal working load conditions. Considerations of this paper reminds one that although the emphasis in design may in future move towards ultimate strength or "limit design," it will still be necessary to pay some attention to the behaviour of the structure for its normal conditions in practice. Assuming that the structure has been designed to have a suitable margin of safety against collapse, the *stress* conditions at any time during the life of the structures have little importance in themselves, except in so far as they affect the durability or efficiency of the structure. This matter is dealt with later in this report, but it may be noted here that the more the engineer changes to "limit design," the more necessary it becomes to be able to assess the cracking and distortions that occur at working loads. For this purpose the studies reported by Nylander will be of value. It is particularly satisfying to observe that not only does he point out an effect which was not commonly known to be of importance, but he has also devised a practical method of avoiding the complications arising from non-uniform shrinkage of the concrete.

The continuity of structural systems

In many structures, particularly multi-storey buildings, the ultimate strength is greatly enhanced by the effects of continuity and by the interaction between the several parts of the construction. There is also often a reserve of strength due to the ability of the structure to deform plastically at highly stressed parts, with a consequent redistribution of stress and moments, tending successively to develop the full strength of more and more parts of the structure.

The value of continuity has been well understood by reinforced-concrete designers in the past, but the effects of moment redistribution have not been fully allowed for, partly because of insufficient knowledge of the phenomenon and partly because of the preoccupation of the designer with working-load conditions rather than ultimate strength. For prestressed concrete, the initial development was largely with simple beams, since, as G. Magnel says in his paper under theme CII 2, it was necessary to get thoroughly acquainted with the new technique by applying it first to the easiest case. But for maximum economy, continuity must be introduced and its effects properly assessed, and in prestressed concrete there are several practical and theoretical difficulties. These are discussed briefly by Magnel in a realistic manner and it is clear that the difficulties are not insuperable and that some of the advantages of continuity can be attained already; indeed, continuous structures of prestressed concrete have been successfully built. Much more information is required, however, on the behaviour of such structures at incipient failure, as it appears possible that moment redistribution may not be as important as in ordinary reinforced-concrete structures.

A matter which is receiving attention in England is the structural interaction between parts of a building which are not at present assumed in design to behave as a composite system. For example, if a panel wall is built on a reinforced-concrete beam it would commonly be assumed that the dead weight of the panel acts as a uniformly distributed load on the beam. In fact, the panel may largely support itself as a deep beam and further, if resistance to horizontal shear is developed at the junction between the panel and the reinforced-concrete beam the resistance of this beam to other loading may be considerably increased, the panel and beam acting together as one composite structural system. From the research so far completed it is evident that the cladding of a building often strengthens and stiffens the structural framework rather than imposing loading upon it.

Another type of interaction of some value is that between a floor slab and its supporting beams. It is usual to design the slab on the basis of the bending moments deduced from the elastic theory assuming rigid edge-supports. In practice the deflection of the beams leads to a transfer of bending moment from the beam to the slab; and since the load factor for the slab is greater than for the beam, this transfer is of advantage. Further studies of the composite system of slab and beams, as distinct from experiments on beams and slabs separately, will help to give a more accurate guide to the real load factors in practice, and so allow an advance towards more economical design.

Durability and cracking

One of the reasons commonly advanced for limiting permissible stresses in the tensile reinforcement of beams is the need to avoid wide cracks which would lead to corrosion of the steel. It is probable that higher stresses do, in general, lead to greater widths of cracks; and that the risk of corrosion is increased somewhat with wider cracks. Nevertheless, it is by no means certain that the tensile steel-stress is a *primary* factor affecting the durability of reinforced concrete.

Studies of cracking, including that by L. P. Brice in theme CII 1, show clearly that the surface characteristics of a reinforcing bar may be of much greater importance than the stress in the bar in determining the widths of the individual cracks. The stress almost directly controls the *total* cracking, i.e. the sum of the widths of all cracks in a beam, but if the bond is so good that the cracking is well distributed the stress can be high before serious corrosion will occur.

It is probable that corrosion in practice has resulted more from the porosity of poor quality concrete than from cracks. Indeed, many cracks have been *caused* by corrosion, and in seeking for means of improving the durability of reinforced concrete it would be well to consider first the materials used rather than the stresses permitted. It is interesting to note that in the latest British code of practice for reinforced concrete (C.P. 114) the specified cover of concrete over the reinforcing bars has been increased, particularly for external work, beyond the values which have previously been acceptable.

It is commonly supposed that the introduction of prestressed concrete will automatically improve the durability of concrete structures, but this supposition may not be realised unless the new technique is accompanied by a marked improvement in the quality of the concrete.

Fire resistance

There is very little information on the fire resistance of reinforced concrete and fundamental research on this matter is urgently required. The use of prestressing has introduced new problems, and development in the use of prestressed concrete for some structures may be hindered by the lack of knowledge on its resistance to fire. It seems possible that the liability of the concrete to spall in a fire may be increased by the precompression in the concrete, and that the high-tensile steel wires exposed to the fire as a result of spalling will suffer a more serious loss in strength than would occur with the mild-steel bars commonly used in ordinary reinforced concrete. On the other hand, it is not difficult to arrange in design that the cover of concrete over the prestressing elements is greater than is economically possible in reinforced concrete.

One difficulty with prestressed concrete that has been damaged, whether by fire or otherwise, is that an assessment must be made of the extent to which the prestress has been lost. It may sometimes be possible to reimpose the prestressing forces, but often repair (as distinct from reconstruction) would be impracticable for prestressed concrete members when similar or greater damage in ordinary reinforced concrete could be repaired without difficulty so that the strength and stiffness is fully re-established.

Resistance to dynamic loading

With the modern tendency to increase permissible stresses and at the same time to reduce the design superimposed loadings, the possibility of secondary failure due to dynamic loading is becoming more important. More fatigue tests on structural members are necessary, particularly those including high-strength steel as reinforcement or as prestressing elements. The effect of high fluctuating stresses on the bond between steel and concrete, and the fatigue limit for high-strength concrete, are other matters requiring study if maximum economy in design is to be achieved. From the limited evidence available, it seems that the fatigue strength of prestressed concrete compares favourably with that of ordinary reinforced concrete. As would be expected, the ratio of the repeated load to cause cracking in a fatigue test on a prestressed concrete beam is a very high proportion of the load that would cause cracking to occur in a static test. The endurance limit for complete fatigue failure also appears to be a higher proportion of the static strength for prestressed members. However, as higher-strength steel is used the fatigue properties tend to deteriorate, and the use of deformed bars to improve bond may also impair the fatigue strength.

For impact loading, also, tests have shown that the use of cold-worked steel as reinforcement for concrete, in place of ordinary mild steel, is a disadvantage, owing to the reduction in ductility that accompanies work-hardening.

Indeed, it is evident that the use of "high-quality" steel and concrete involves the necessity for considering to what extent these materials are improved, if at all, in regard to secondary effects. For example, a higher compressive strength for the concrete may not mean a higher strain-capacity in compression, nor a corresponding increase in shear, bond or fatigue strength.

Constructional methods

In recent years there has been a tendency to modify traditional methods of construction by increased prefabrication of structural elements and the development of mechanical plant on construction sites. This tendency, which can be justified on both technical and economic grounds, is likely to be continued. The mechanical plant need not always be elaborate or expensive, even for very large projects such as the construction of the Marignane hangar described by N. Esquillan in his paper under theme CII 1; but commonly special equipment is necessary for lifting large prefabricated units, such as floor or wall slabs, into position. For reinforced-concrete work, systems of prefabricated reinforcement have been developed whereby the reinforcements for beams and columns are manufactured as complete units in a factory and later erected to form a rigid self-supporting framework which is then encased in concrete. In other systems structural elements are precast and in assembly special arrangements are adopted for obtaining continuity between the various elements; some of these arrangements are discussed in Esquillan's paper.

The prestressed-concrete bridge described in the paper by H. Lossier and M. Bonnet (theme CII 2) has a number of interesting features. The cables used were of steel wire-rope and the type of anchorage was such that the tension in the cable could be adjusted both during construction and also later to allow for shrinkage and creep. The difficulties arising from friction in cables at positions where they change direction were avoided by using hinged concrete segments. Many gauges were installed for determining the deformations of the concrete and the steel during construction and subsequently.

Summary

The trend of modern design methods towards consideration of a load factor against failure introduces many complications. It is necessary not only to obtain the agreement of engineers on the method of estimation of the ultimate strengths of structural elements and of continuous systems, but also to assess the resistance of structures to incidental eventualities that may arise during their normal life.

It is probable that a sufficiently accurate assessment of the ultimate strength of a reinforced-concrete beam can be obtained from any one of several methods that have

been advanced, and the reporter suggests that emphasis in the development of design methods should now be moved towards a consideration of the ultimate strength of continuous systems.

With increasing encroachment into the margin of safety, it is becoming more necessary to check the ability of a structure to bear secondary stresses due to shear or bond, and to ensure that higher stresses under working-load conditions do not lead to fatigue failure.

Even if the primary basis of design is a load factor against collapse, it is still essential to calculate the deformations for normal loadings to ensure that distortions and cracking are within reasonable limits. Although cracking may affect the durability of reinforced concrete, it is unlikely that it is the major factor to be considered, and it is desirable that further study should be made of the causes of deterioration.

The increasing use of so-called "high-quality" materials is also bringing its own problems, since it appears that the marked improvement in quality applies only to some properties of the materials whilst other properties may not be much better, if at all, than those possessed by materials of "ordinary quality."

In the construction of reinforced-concrete structures, the tendency to introduce greater prefabrication is noted. This tendency is likely to be continued, particularly as this method of construction is very suitable for prestressed-concrete work also.

Résumé

La tendance des méthodes modernes de calcul des ouvrages à faire intervenir un facteur de charge par rapport à la rupture donne lieu à de nombreuses complications. Il est nécessaire non seulement de réaliser l'accord des ingénieurs sur la méthode d'estimation des charges de rupture des éléments d'ouvrages et des systèmes continus, mais aussi d'évaluer la résistance des ouvrages aux différentes éventualités qui peuvent se manifester au cours de leur existence.

Il est probable que l'on puisse arriver à une estimation suffisamment précise de la charge de rupture d'une poutre en béton armé à l'aide de l'une des méthodes qui ont été proposées et l'auteur suggère qu'en matière de nouvelles méthodes de calcul, l'intérêt s'oriente vers la prise en compte de la charge de rupture des systèmes continus.

Devant l'empiètement croissant sur la marge de sécurité, il devient de plus en plus nécessaire de vérifier l'aptitude d'un ouvrage donné à supporter les contraintes secondaires qui résultent du cisaillement ou de l'assemblage et de s'assurer que les charges plus élevées qui interviennent dans les conditions de service ne conduisent pas à la rupture par fatigue.

Dans le cas même où le calcul d'un ouvrage est initialement basé sur un facteur de charge par rapport à la rupture, il est encore essentiel de calculer les déformations correspondant aux charges normales, afin de s'assurer que les distorsions et fissurations restent dans des limites raisonnables. Bien que la fissuration puisse affecter la durée du béton armé, il est peu probable que ce soit le facteur principal à considérer et il serait opportun de poursuivre l'étude des causes de détérioration des ouvrages.

L'emploi croissant de matériaux dits "à hautes caractéristiques" fait également intervenir des problémes particuliers; il semble en effet que l'amélioration notable de la qualité ne s'applique qu'à quelques caractéristiques des matériaux, car certaines autres caractéristiques peuvent n'être que peu supérieures, si même elles le sont, à celles des matériaux de qualité "ordinaire."

On note, dans la construction des ouvrages en béton armé, la tendance à adopter

de plus en plus largement la préfabrication. Il est probable que cette tendance se maintiendra, tout particulièrement pour cette raison qu'elle est également très favourable à la réalisation de la précontrainte.

Zusammenfassung

Die Tendenz moderner Berechnungsmethoden, einen Lastfaktor in Bezug auf den Bruch anzuwenden, bringt viele Schwierigkeiten mit sich. Nicht nur ist es notwendig, von allen Ingenieuren anerkannte Methoden zur Bestimmung der Tragfähigkeit von Konstruktionsteilen und durchlaufenden Systemen aufzustellen, sondern man muss auch die Widerstandsfähigkeit der Bauten gegen Zufälligkeiten abschätzen können, welche während ihrer natürlichen Lebensdauer eintreffen.

Wahrscheinlich kann durch irgend eine der bisher entwickelten Methoden eine genügend genaue Bestimmung der Bruchgrenze eines Eisenbetonbalkens erhalten werden und der Autor schlägt vor, dass das Hauptgewicht in der Entwicklung der Berechnungsmethoden nun darauf gelegt werden soll, die Tragfähigkeit von durchlaufenden Systemen zu bestimmen.

Mit der ständigen Verringerung des Sicherheitsspielraumes wird es immer notwendiger, die Bauwerke auf zusätzliche Spannungen aus Schub oder Querbeanspruchung zu prüfen und dafür zu sorgen, dass höhere Spannungen unter der Gebrauchslast nicht zu Ermüdungsbrüchen führen.

Selbst wenn das Grundlegende an der Berechnung ein Lastfaktor gegen Bruch ist, so erscheint es trotzdem wichtig, die Verformungen für normale Belastung zu berechnen und zu beachten, dass Verzerrungen und Risse in vernünftigen Grenzen bleiben. Auch wenn Risse die Dauerhaftigkeit des Betons herabsetzen können, ist dies kaum der zu beachtende Hauptfaktor un es wäre zu wünschen, dass weitere Untersuchungen über die Ursachen des Zerfalls gemacht würden.

Die zunehmende Anwendung von hochwertigen Baustoffen bringt ebenfalls seine eigenen Probleme, indem es scheint, dass sich die angegebenen Qualitätsverbesserungen nur auf einzelne Eigenschaften des Baustoffes beziehen, während andere wenig oder gar nicht besser sind als beim gewöhnlichen Baustoff.

In der Konstruktion von Eisenbetonbauten zeigt sich die Tendenz, immer mehr die Vorfabrikation einzuführen. Diese Tendenz wird wahrscheinlichweiter verfolgt werden, hauptsächlich weil diese Methode auch für vorgespannten Beton sehr geeignet ist.