An engineering model for structural concrete

Autor(en): **Bruggeling, A.S.G.**

Objekttyp: **Article**

Zeitschrift: **IABSE reports = Rapports AIPC = IVBH Berichte**

Band (Jahr): **62 (1991)**

PDF erstellt am: **12.07.2024**

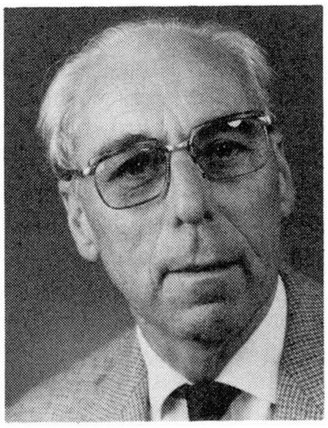
Persistenter Link: https://doi.org/10.5169/seals-47618

An Engineering Model for Structural Concrete

Un modèle d'ingénieur pour une structure en béton

Ein ingenieurmässiges Modell für Konstruktionsbeton

A. S. G. BRUGGELING
Prof. Dr.
Consulting Engineer
Nootdorp, The Netherlands



A. S. G. Bruggeling, born 1923, obtained his degree in Civil Eng. from the Delft Univ. of Technology in 1947. Among other functions, he was Director of a firm producing precast prestressed concrete and headed a firm of consulting engineers. From 1969 to 1986 he was Professor of Concrete Construction at Delft. He received honorary doctorates from the Technological Univ. of Stuttgart and from the Univ. of Leuven.

SUMMARY

The model of structural concrete developed by the author is presented. The main features of this model are: a basic reinforcement of concrete structures and, optionally, an artificial load which is applied by prestressing.

RÉSUMÉ

Un modèle représentatif d'une structure en béton doit être, selon l'auteur, principalement caractérisé par les points suivants: la présence d'une armature minimale dans toute structure en béton, et selon l'application voulue, la présence d'une charge antérieure introduite par précontrainte.

ZUSAMMENFASSUNG

Es wird das Modell «Konstruktionsbeton» vorgestellt, das vom Autor entwickelt wurde. Seine wesentlichen Merkmale sind die Forderung nach einer minimalen schlaffen Bewehrung, und die Aufbringung einer künstlich erzeugten Vorbelastung mittels einer gewählten Vorspannung.

1. GENERAL

In his introductory report Breen presents a state of the art and the reasons for change from the approach with several classes of concrete structures, which is usually applied now, towards a new approach encompassing the entire spectrum of concrete used for structural or load resisting purposes from non-reinforced applications through applications which have a mix of non-prestressed, pretensioned and post-tensioned reinforcement.

In this introductory report an engineering model which is satisfying this new approach will be treated. This model has been developed during the last decade by the author and has already proved to be very useful for practical design.
Several possibilities were tried out in early days but most of them offered too many complications for the designer because the transition from normal reinforced concrete towards prestressed concrete was not "smooth" enough to allow simple comparison between several solutions and adaptation of a design to meet certain requirements. On the other hand with the different models it was not possible to make simple design calculations because problems of cracking of concrete tensile zones, deflection, shear, torsion and time-dependent effects were again made too complex.
A rather simple approach has proved to be the introduction of prestressing as an artificial loading in all these cases in which prestressing could be profitable. The magnitude of this artificial load can vary between nil and high, of course in relationship with other requirements or practical limits. In this respect the concept of "load balancing" as already being introduced by Mehmel in Germany in 1957 and T.Y. Lin in the U.S.A. in 1963 [1] can be mentioned as well as the introduction of three effects of prestressing by the author in his standard work on prestressed concrete published in 1963 [2]. The model of "Structural Concrete", as designated by the author, was presented in 1987 in the magazine Heron [3].

Because it is very important to know what such a name covers the following definition of "Structural Concrete" is given in the Heron paper:

"Structural concrete" refers to any structure built from concrete and in most cases non-prestressed and/or prestressed reinforcement which can - optionally in combination with artificial loading, introduced by prestressing techniques - resist, in a controlled way, all the actions exercised on these structures by loads, imposed deformations and other influences (earthquakes, explosions, etc.). Moreover, these structures must be constructed in a safe and economical way.

In this definition "controlled way" indicates control of deformations, cracking, durability, structural safety, and the like. It is of course of primarily importance that the structures should be constructed in a safe and economic way. This is included in the definition to make clear that "Structural Concrete" is only viable if the design is resulting in projects which can be realized in a safe and especially also economic way.

In this introductory report several aspects will be treated which may clarify the possibilities of the model "Structural Concrete".

2. PRESTRESSING RELATED

2.1 The need of a more general model for concrete structures

A designer needs primarily the possibility of a simple approach of his design. He should not be forced to base his different proposals for the structure on different standards such as related with reinforced concrete, partially and fully prestressed concrete, unbonded tendons, external prestressing, etc. This means that one engineering model covering all the structural possibilities of concrete is very important.

The need for such a model can be explained with the following example.

Limitation, in a given case, of deflections of concrete structures, especially with time, is only possible by changing the construction depth, the shape of the cross-section, the reinforcement ratio (in reinforced concrete structures) or class (i.e. prestressed concrete instead of reinforced concrete). But these changes are often radical and not easy to carry through because specific requirements should be met.
On the other hand the calculation of deflections, especially those due to time-dependent effects, are not simple and also not very reliable. This means that control of deflections often results in rather complicated calculations with the possibility of nearly no knowledge about the effectiveness of their predicted deflections.

A different procedure can be used if a stable deflection of structures - statically determinate or indeterminate ones - is required under certain conditions, for example sustained load. This procedure is to balance this load artificially with prestressing. Of course one must in that case take into account the so-called losses of prestress but they can be estimated between certain relatively close limits. If the sustained load is balanced with prestressing the structure is only subjected to a centrical force and will (nearly) not deflect any more in time but only shorten axially. This solution is applicable without being forced to design a structure in a certain "class" as defined by standards. The structure can be reinforced as well. Also no complicated calculation is needed.

Other examples in which this approach can be used adequately are related to liquid tightness of structures and the control of thermal and cyclic effects.

2.2 Prestressing introduced as an artificial loading

In the author's model of "Structural Concrete" prestressing is introduced as an artificial loading. Two main effects of prestressing - as an artificial loading - should be considered.

Effect I : the axial concentric force which is introduced at the ends of a beam via the anchorages of prestressing tendons or the bond of pretensioned prestressing steel.

Effect II : the upward (or downward) loading which results from the tensile force combined with the curved or draped shape of the tendon profile.

Remark: In the case of a non-concentric prestressing force at the ends of beams, bending moments are also introduced in the structure via these ends. This effect is often very important in precast pretensioned prestressed concrete elements.

Effect I causes shortening of prestressed concrete beams. In many cases this shortening is (partly) restrained by the substructure, such as by friction with support structures and by lateral rigidity of columns connected with the superstructure. With exception of several simply supported (often precast) beams this restraint should be taken into account. It results in a less simple calculation of stress distribution in sections in comparison to normal practice. Due to prestressing only the centroid of the prestressing steel, in a freely supported beam, does not any more coincide with the centre of the compressive force acting in that section. See also 2.3.

An identical effect occurs in statically indeterminate structures. This can be explained with the generally accepted assumption that in every design calculation the compressive force, acting on a given section, has the same magnitude as the tensile force in the tendons. But this assumption is, generally speaking, not true. Nearly always external effects will be present which restrain more or less the axial deformation of a structure. This deformation is, however, inseparably connected with the mean concrete stresses, and their resultant compressive force, in every arbitrary section. The stress distribution in a section depends on the joint effect of the magnitude of the effective compressive force (I) and of the tensile force in the tendons (II) as well.

The effective prestressing force on the concrete section depends also on the actual effective area of the section which should be considered. In the case of a floor structure composed of slabs and rigidly connected beams, the effective flange width of the T-structure is often smaller than the distance between the axis of neighbouring beams. In practice it is generally assumed that in this case most of the actual prestress force is concentrated in the effective flange width and the rib of the T-section or in the column strip of flat slabs. This cross-section is indicated as $A_{c,effective}$. With this prestressing force the stress distribution of the T-section is calculated under dead load and maximum load with the well-known formulas used in calculations of prestressed concrete structures.

The concrete stress in a fibre x due to prestressing only will be calculated from:

$$\sigma_{cx} = P/A_{c,effective} \pm P \cdot e \cdot x/I \pm M \cdot x/I$$

P = actual prestress force in the tendons in a section;

e = distance between centroid of tendons and the centre of gravity of the T-section;

x = distance between the fibre considered and the centre of gravity of the T-section;

I = moment of inertia (second moment of area) of the T-section.

Remark: In a statically indeterminate structure e is the distance between the centre of gravity and the point of application of the compressive force on the section due to prestressing only.

But this calculation is not correct! The compression force P is exerted via the anchorages over the whole slab width at a certain distance from the anchorages. Therefore the actual mean compressive stress is $P/A_{c,actual}$.
$A_{c,actual}$ is the whole cross-section of rib of T-beam (if present) and the slab from centre line to centre line of two adjoining ribs. In many structures $A_{c,actual}$ is (much) larger than $A_{c,effective}$. As a result the actual uniform compressive stress is smaller than the compressive stress $P/A_{c,effective}$. However, in practice it is generally assumed that both stresses are identical, e.g. in U.S.A. Therefore the calculation of σ_{cx} as given before is not correct in these structures. This is again a case in which the effective compressive force differs from the tensile force in the tendons.

2.3 Tensile force in tendons versus effective prestressing force

The magnitude of effect II depends on the tensile force in the tendons.
Losses of prestress in the tendons are caused by:

- the friction losses during prestressing;
- the time-dependent effects (shrinkage, creep, relaxation).

Effect II is an (artificial) load and is carried by a concrete structure in the same way as every external load. The magnitude of this effect is *not* affected by restraints as for effect I mentioned in 2.2 but only affected by losses of prestress. Therefore the effective prestressing force $P_{effective}$ in a given section often differs from the tensile force P in the tendons crossing this section.

This can be clarified as follows:

During the prestressing operation a tensile force developes in a tendon. This tensile force has (generally) a maximum value P_o in the anchorages.
Due to friction losses between the prestressing steel and the sheathing *the tensile force P_y* in a given section y is lower. $P_y < P_o$. Between the anchorages and this section y the tensile force $(P_o - P_y)$ is transferred to the concrete structure by this friction.
If the structure can deform freely the actual compressive force due to prestressing in section y is P_y.

This actual compressive force may, however, be lower because:

1. If $A_{c,actual} > A_{c,effective}$ then:

   $P_{effective} = P_y \cdot A_{c,effective}/A_{c,actual}$

2. If the deformation of the structure is (partly) restrained then the compressive force $P_{effective}$ acting on the (effective) concrete section y is also reduced with the effects of this restraint.

Therefore the resulting *compressive force $P_{effective}$ acting on a section y* due to prestressing of the tendons is often lower than the tensile force P_y in the tendons crossing that section. The point of application of the resultant compressive force $P_{effective}$ in a section of a statically determinate structure due to prestressing only does generally not coincide with the centroid of the tendons.
This phenomenon of non-coincidence of both centroids, in the case of prestressing only, will be explained with the example of such a statically determinate beam. This example is chosen for reasons of simplicity.

- Case 1: No restraint of any axial deformation.
  Section at mid span, eccentricity of centroid of tendons is e.
  Tendons circularly curved - friction losses during prestressing neglected.
  Eccentricity of compressive force (prestressing only) at mid span is e.

- Case 2: Restraint of axial deformation.
  Effect I. Concentric compressive force in section at mid span $P_{effective}$.
  Tensile force in tendons P.
  Effect II. Bending moment in this section due to circular curved tendons (artificial load):

  $M = {}^1/_8\ (P/R).l^2$ with $R = l^2/8e$

  $M = P \cdot e$

  Eccentricity of the effective compressive force, which should be used in the calculation of stresses:

  $e_{effective} = e \cdot P/P_{effective}$

  $e_{effective} > e$ if $P_{effective} < P$

  Due to the difference in the effective prestressing force and the total tensile force in the tendons, the stress distribution in concrete structures is often different from the calculated one and generally less favourable than expected. This is one of the causes of defects in prestressed concrete structures which were, for instance, observed in bridges.

The reduction of the effective prestress cannot be predicted very accurately. The extent of this reduction can sometimes only be ascertained within wide limits. If, however, a structure is designed on the assumption of the most unfavourable values, with respect to the reduction of the effective prestress, the structure may suffer from too high values of prestress if the reality is less unfavourable than assumed. This may result in too large camber and initial compressive stresses which are too high. Therefore the designer should be able to use other methods to limit the sensivity of his structure for these less controllable effects. The structure should behave in a controlled way also in the case of effects which cannot be estimated very precisely. The introduction of prestressing as an *artificial load* in *reinforced concrete structures* offers the possibility of an adequate design. This reinforced concrete structure is, if well-designed, less sensitive to these effects.

2.4 Creep and shrinkage of concrete

The magnitude of time-dependent effects cannot be predicted very precisely in design. One should always consider a large dispersion in these effects. Also due to the execution of concrete structures the dispersion in this effect is large. One should therefore not base a design on very "accurate" calculated losses due to shrinkage, creep and their mutual relationship with relaxation of prestressing steel. A design should, however, not be very sensitive with respect to "losses of prestress". In general, complicated methods of calculations of time-dependent effects should be avoided.
In the same way as stated in 2.3 the design of a concrete structure should be based on the fact that time-dependent effects can only be predicted within very wide limits. Not only the properties of concrete, with respect to creep and shrinkage, cannot be predicted very precisely but also the real behaviour of the concrete structure cannot be determined correctly.

In the first place the calculation of creep and shrinkage are usually treated separately but they are mutually related [4]. In the second place the dimensions of a structure, the shape of the cross-section (e.g. box girder) and the orientation in situ, with respect to solar radiation, wind, rain e.g., are of major importance. In the third place, not the last place, the method of construction, the time of the year and the climatological conditions during execution are very important regarding creep and shrinkage behaviour of the structure, being realized.
It is therefore incongruous that designers present such "precise" calculations of stresses in prestressed sections while exercising so little control and having so little knowledge over the magnitude of the prestressing force at various future times. The design should be made less sensitive to these effects. The model of "Structural Concrete", the *artificially loaded* structure in *reinforced concrete*, allows the design of structures with an adequate behaviour during their lifetime.

3. STRUCTURAL APPROACH VERSUS SECTIONAL APPROACH

The design of a concrete structure should be based on an overall structural approach and not only based on calculation of sections. The introduction of prestressing (if needed) in concrete structures as an artificial loading fits into this approach.

This is resulting in:

- A more realistic approach of losses of prestress and especially on the time-dependent redistribution of stresses over a section.

- The use of a basic reinforcement in nearly every concrete structure. This reinforcement improves the behaviour of the concrete structure, especially in those cases in which cracks cannot be avoided under all conditions of loading and restraints.

If one considers, in the calculations, mainly the stress distribution in sections - the so-called sectional approach - one is confronted with a rather complex problem. In a section there is reinforcement and alternatively also prestressing steel. This section may be subjected to eccentrical normal forces (prestressing) and bending moments (loads). The stress distribution is not easy to calculate, especially not if time-dependent effects are considered. Moreover the results of more sophisticated calculations cannot be controlled easily.

If prestressing is introduced as a load on the structure as such - the so-called structural approach - one is confronted with a reinforced concrete structure (also) subjected to a normal force combined with an artificial load which magnitude is decreasing in time. This approach simplifies the problem. Investigations have shown that a simple approach of prestress losses is generally admitted. If prestress losses are calculated from this approach the calculated bending moment of decompression and the calculated crack width under a given load are between the limits experimentally investigated [5].
In the design one can "play" with artificially introduced loads in reinforced concrete structures and investigate what the most optimal solution is with respect to the control of the structural behaviour, execution and economy. This leads towards a design procedure that can start with a consistent overall structural approach, both in general dimensioning of structural members and in preliminary proportioning of the reinforcement and prestressing. Such a procedure will not be immersed in complicated calculations without a clear view on the structure as such and on its behaviour. To the contrary simple, conventional, analysis of structures is highly efficient and leads to correct reinforcement proportioning. One should keep this simplicity in perspective and one should therefore be careful not to complicate practice by urging more complex models where simple procedures work well.

The author often is using the phrase that we should "demythologise" the design and calculation of our structures. Design is not an aim as such but it is a technological science which enables us to serve practice. If we offer practioners the possibility to simplify the approach of their design we will contribute to a more clear design, a well-controlled execution and a concrete structure which may serve for many years.

In this respect two remarks will be made:

1. With this approach it will be possible to terminate the notation "parasitic" bending moments as some type of mysterious set of moments peculiar to prestressed concrete. The treatment of prestressing as an artificial loading acting on the structure makes it clear that these bending moments are simply the normal bending moments in a statically indeterminate structure due to the prestressing load case. It also makes clear that the stress distribution - e.g. no tensile stresses allowed in every section - should not govern the shape of the tendon profile but rather the consideration that an artificial load of a certain magnitude is required. The "imposed tendon profile" often results in a rather complicated tendon profile. This results in problems and waste of money during the execution as well as often also in loss of durability. The complicated tendon profiles should also be "demythologised"!! The shape of the tendon profile should not be imposed on the designer but the designer should impose this shape on the structure.

2. The introduction of prestressing in a structure is not the right way to tackle the effects of restrained imposed deformations. This restraint is causing a large reduction of concrete stresses. If the axial shortening of a tension member is fully restrained the mean compressive stress σ_{co}, just before restraint, will drop, due to creep effects only, from:

   $$\sigma_{co} \text{ to } \sigma_{ct} = \sigma_{co} \cdot e^{-\phi_t}$$

   ϕ_t is the creep factor.

Already if ϕ_t = 0.5 the initial stress σ_{co} will drop with 39% to 0.61 σ_{co}. Therefore much of the axial prestressing force (I) is transferred to the restraining structures and is no longer effective. If curvatures are restrained identical effects will occur.
These imposed effects can only be controlled effectively with bonded reinforcement and thus acceptance of controlled cracking of the tensile zone. The fact that imposed effects are often of natural origin and show a large dispersion forces one towards this approach because one can use the "softening" of reinforced concrete members, due to the development of its crack pattern, to reduce and control these effects.

4. ASPECTS OF THE ENGINEERING MODEL "STRUCTURAL CONCRETE"

In this overall approach to concrete structures several structural aspects are of major importance. These aspects should not be considered separately for reinforced concrete structures and prestressed concrete structures.

These aspects are:

4.1 The relationship between crack width - crack spacing -deformations and external loads in members

These aspects are treated separately in standards but they are closely connected and belong to *one* approach which cannot be separated in several different parts. In this respect the stiffness of flexural members is very important regarding deflection.

4.2 The bond behaviour of reinforcement and of prestressing tendons (in the case of artificial loading by prestressing) with the surrounding concrete

It should be made clear if, when and why the bond behaviour of tendons should be neglected in the calculation and in the control of crack width.

4.3 The introduction of time-dependent effects in a structure

This introduction should take into account the natural variability in shrinkage and creep of concrete. It is very important to understand when and why time-dependent effects are of importance for the behaviour and on the durability of a structure. For example if a structure is well-designed (read: also reinforced) then cracks in concrete structures resulting from creep and shrinkage can be controlled. Cracking of concrete results also in reduction of stiffness and thus in a less pronounced response of the structure to time-dependent effects.

4.4 The control of the effect of restrained imposed effects

See also 2.4.

4.5 The effects of cyclic loading and/or impact loading

It is not the aim of this report to treat these several aspects in detail. Therefore reference will be made to existing literature, particularly a book [6].
In this book are treated, for example:

- The tension member in structural concrete:

  - Force-elongation relationships.
  - Imposed loading and imposed deformation.
  - Control of crack width.

- The flexural member in structural concrete:

  - Artificial loading.
  - Moment-curvature relationships.
  - Time-dependent effects.
  - Structural approach.

- The design of structural concrete, especially the use of artificial loading by prestressing, is illustrated with several practical examples.

5. THE ROLE OF BONDED REINFORCEMENT

This role is already discussed in this report and can be summarized as follows:

1. To control development of cracks in the process of hardening of concrete.
2. To control crack width especially in the case of (unpredicted and unexpected) restrained imposed deformations.
3. To enable a structure to become less rigid, less stiff, - due to controlled cracking - in the case of imposed effects without loss of durability.
4. To control the stress range in the case of cyclic loading.
5. To allow the structure to respond in a ductile way to impact loading.
6. To develop redistribution of loads in structures at overloading.
7. To strengthen structural parts if necessary.
8. To assure sufficient rotational capacity in the ultimate limit state.

This summary shows how important the role of the non-prestressed (passive) reinforcement is. It should therefore be detailed very carefully. Detailing of the reinforcement is most efficiently carried out by load path models such as "strut and tie models". They can be used in discontinuity zones as well as in zones of gradual change of internal forces.
Special attention should be paid to the nodes between struts and ties. In a sound structure these nodes should be able to connect mutually, with sufficient safety, these ties and struts. Simple models and engineering tools are necessary for the designer to develop a clear, and "transparent", concrete structure model [7 and 8].

6. ARTIFICIAL LOADING

Artificial loading by prestressing can be used to improve the behaviour of the structure with respect to the following aspects:

1. Reduction of the construction depth.
2. Increasing the carrying capacity of structures.
3. Limiting the deflection of the structures due to short-term and long-term loading.
4. Control of cracking of the tensile zone or limiting tensile stresses in this zone in the serviceability limit state.
5. Influencing the behaviour of restrained concrete structures if subjected to imposed curvatures.
6. Improving the shear resistance of structures.
7. Improving the torsional stiffness of structures.
8. Simplification of reinforcement and its detailing.
9. Simplification of the shape of the structures.
10. Assurance of tightness of liquid storage tanks.
11. Simplification of construction procedures and execution.

Prestressing can be introduced internally by tendons, bonded or unbonded, or externally by tendons which of course are generally unbonded. Here all the developments in prestressing technology can be applied.

7. SYNOPSIS

In this introductory report the need towards a more realistic approach of the design of concrete structures and of their detailing is stressed. Prestressed concrete has developed up till now very successfully and with only a few draw-backs. But the lack of a general approach to concrete structures as such acts as a restraint to new applications and also as a restraint to developments leading into the direction of simplification of the construction.
The model "Structural Concrete" which is presented here opens new ways into this direction. The usefulness of such a model cannot be tried out in scientific publications. It should be tried out in practice. This is the reason why the author felt the necessity to present a (more or less) complete model which could be used in real projects [6]. This does not mean that he feels that only his model is the right one. The colloqium should result in a joint venture of several experts developing these aspects in such a way that new standards can be based on this approach and that simple, consistent resources will become available for practical application.

REFERENCES

1. LIN T.Y., Load balancing method for design and analysis of prestressed concrete structures. ACI Journal, Proceedings Vol. 60, no. 6, June 1963.

2. BRUGGELING A.S.G., Theorie en praktijk van het voorgespannen beton (two volumes - in Dutch). Koggeschip, 1963.

3. BRUGGELING A.S.G., Structural concrete: Science into practice. Heron, Vol. 32 (1987), no. 2.
   BRUGGELING A.S.G., A new approach to concrete structures - classification and design. Polska Akademia Nauk, 1989.

4. ROELFSTRA P.E., A numerical approach to investigate the properties of concrete - Numerical concrete. Doctor Thesis no. 788 (1989). Ecole Polytechnique Féderal de Lausanne.

5. BRUGGELING A.S.G., Towards a simple method of analysis for partially prestressed concrete. Research report 5-82-D16, TH-Delft, 1982.

6. BRUGGELING A.S.G., Structural concrete, theory and its application. Balkema Publishers, Rotterdam, 1991.

7. BRUGGELING A.S.G m.m.v. DE BRUIJN W.A., Theorie en praktijk van het gewapend beton (two volumes). Uitgave Stichting PBF - 1986 (in Dutch).

8. BRUGGELING A.S.G., HUYGHE G.F., Prefabrication with concrete. Balkema Publishers, Rotterdam, 1991.