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Theme 1

Structural Concrete

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Why Structural Concrete?

Pourquoi un colloque sur les structures en béton?

Warum konstruktiver Beton?

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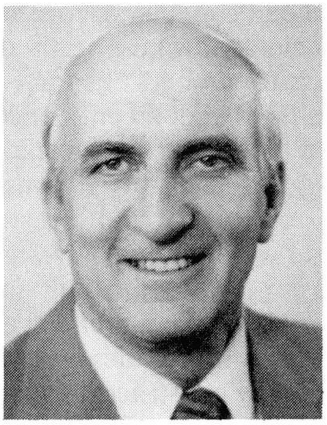

John E. Breen has received a number of awards from ACI, ASCE, PCI and FIP for his reinforced prestressed concrete research contributions. He is immediate past Chairman of the Building Code Committee and is currently chairman of IABSE Working Commission III – Concrete Structures.

SUMMARY

This introductory report outlines the purposes of the Colloquium, defines several important terms and concepts, and suggests a general framework for developing future professional practices, codes and standards, and educational approaches to structural concrete. It calls on all colloquium participants to be objective, prepared, and predisposed to participate in meaningful discussions and dialogues with their professional colleagues from around the world who are expected to be present in Stuttgart, in April 1991.

RÉSUMÉ

Ce rapport d'introduction esquisse les buts du Colloque, définit plusieurs termes et concepts importants, suggère un cadre général pour le développement de procédures futures, normes et codes professionnels et finalement, expose und approche nouvelle dans l'enseignement du béton armé et précontraint. Un appel est lancé aux participants afin qu'ils soient objectifs, préparés et désireux de participer à d'enrichissants dialogues et discussions avec leurs collègues du monde entier, présents à Stuttgart en avril 1991.

ZUSAMMENFASSUNG

In diesem einführenden Bericht werden die Absichten und Ziele des Kolloquiums besprochen, einige wichtige Fachausdrücke und Konzepte definiert, und generelle Rahmenbedingungen für die Entwicklung zukünftiger Normen und Industriestandards sowie neuer Lehrmethoden für den konstruktiven Betonbau vorgeschlagen. Alle Kolloquiumsteilnehmer werden aufgerufen, objektiv und vorbereitet zu sein und die Bereitschaft zu fruchtbaren Diskussionen und Dialogen mit den Fachkollegen aus aller Welt, die im April 1991 in Stuttgart erwartet werden, mitzubringen.

1. INTRODUCTION

1.1 Background

The foundations of reinforced concrete theory and design began to be systematically constructed approximately 100 years ago. The basic concepts and fundamental design of prestressed concrete are more than 50 years old. In the ensuing decades a vigorous industry has developed which is serving mankind well in providing concrete structures for shelter, for commerce, for industry, for transportation and for many untold facets of daily life. Around the globe myriad studies have been conducted, conclusions drawn, papers published, design codes established, technical societies formed, textbooks written, students educated, design professionals developed, and great numbers of concrete structures successfully designed and built. All of these occurrences have added confidence to an impressive array of knowledge and experience with reinforced and prestressed concrete structures. Reasonable observers well may wonder why at this point in history it is useful and necessary to re-examine the fundamental approaches to reinforced and prestressed concrete design. Structural engineering has become a world-wide industry. Designers from one nation or continent are frequently found designing a project to be built in another nation or continent. The communications technology explosion has created global interaction in many fields and certainly in structural engineering. For decades several organizations have worked diligently at efforts to harmonize design and construction practices for concrete structures. While some of these efforts have been successful on a regional basis, often they have resulted in further polarization and formulation of yet another set of divergent committee reports, codes or standards. It is precisely the plethora of information, theories, organizations, codes and standards, trade and professional organizations, empirical and semi-rational approaches to bits and pieces of the industry, and the general absence of an overall unifying approach that led to discussions within IABSE Working Commission III - Concrete Structures - about possible actions that could be taken to encourage unification of structural concrete approaches. These concerns ultimately led to the organization of this colloquium.

1.2 Purpose and Objectives

The basic objective of this colloquium is to bring together a broad spectrum of leaders from the design, construction, research, academic and regulatory communities to intensively re-examine the broad fields of reinforced and prestressed concrete theory, design and construction with the overall objective of developing unified, consistent analysis and design approaches which will apply to the entire range of structural concrete. In this undertaking a full range of topics must be treated and consistent recommendations developed so as to:

Re-orient education and professional practice from its present divisive state. We must move from the accepted status quo in which separate university courses, textbooks, and standards of practice often exist for reinforced concrete structures and for prestressed concrete structures into a unified program where students and practitioners think of a single continuum of structural concrete.

Redirect the engineer's primary focus to careful consideration of overall structural behavior emphasizing the efficient flow of forces throughout the structure. We must dispel the present wide preoccupation with complex analysis procedures and often highly empirical and often incomplete sectional mechanics approaches which tend to both distract the designers from fundamental behavior and impart a false sense of accuracy to beginning designers.

Introduce useful, transparent models. We must formulate models which can enhance the designers visualization of structural action. They must provide meaningful insight that will lead to improved detailing which will efficiently account for all important load effects, load paths, and restraints.

Eliminate unnecessary and sometimes counter-productive conflicts in Codes and Standards. We must call for unification of national or regional regulations for non-prestressed and prestressed concrete into single documents with a consistent overall design approach.

Develop an overall framework of analysis, design and detailing which will make it easier to mix structural concrete systems with other structural materials (mixed or composite construction).

The author realizes that such objectives may seem extremely idealistic and unattainable to some and even unnecessary to others who are from geographical areas where a high level of harmonization has been attained. However, it is my firm conviction that if a broad group of leaders convenes in Stuttgart for this Colloquium and if every participant arrives with a desire to honestly and effectively share their experience and their wisdom without being inhibited by past organizational, national, or regional biases, we will see considerable and even surprising progress towards meeting these objectives. The final attainment of these objectives can be greatly advanced if each participant will review their proposed contributions to ensure that such broad goals are emphasized.

2. DEFINITIONS

2.1 Proposed Definitions

In order to help all participants clearly communicate their ideas regarding the subject of this Colloquium, the following terms are initially defined herein (although the definitions may be altered at the Colloquium):

Structural Concrete: The term for the entire spectrum of concrete used for structural or load resisting purposes from non-reinforced applications (as sometimes found in foundations or pedestals) through applications which have a mix of non-prestressed, pretensioned, and/or post-tensioned reinforcement.

Active Reinforcement: The term for any reinforcement which is mechanically, electrically, or chemically stressed by constructor controlled methods during the construction process. Only that portion of the active reinforcement capacity which is developed by these construction operations is considered active reinforcement.

Passive Reinforcement: The term for any reinforcement which is not actively stressed by constructor controlled methods in the construction process. This includes the developable capacity of active reinforcement elements in excess of that actively stressed during the construction process.

Prestressing Loads: The constructor controlled loads applied in the construction process by stressing wires, strands or bars. These prestressing loads should be considered as applied loads on the structure. These loads can have axial load effects, bending load effects due to the eccentricity of the point of application, and shear and bending load effects due to the curvature or draped profile of the tendons. The magnitude of the load effects may vary over time due to time dependent losses and may vary along the tendon due to friction and wobble effects.

2.2 Superfluous Terminology

With the adoption of an overall inclusive term such as structural concrete, several traditional but confusing or contradictory terms should be phased out of the structural engineering vocabulary. These include terms such as:

Fully prestressed concrete: This term, which originated from the E. Freyssinet concept of a new material in a pristine, uncracked state, is basically a misnomer since structural elements which are completely in compression at the service load state are often fully cracked at the ultimate load state. In addition, such members often contain substantial amounts of passive (non-stressed reinforcement) for shear and torsion resistance as well as control of bursting and spalling tension in the anchorage regions.

Partially prestressed concrete: This term is one of considerable confusion meaning to some that only a portion of the reinforcement is prestressed while meaning to others that the level of prestressing forces is such that flexural tensile stress may be present at service load conditions.

Reinforced concrete: This term is a traditional term to delineate plain concrete (no reinforcing included) from concrete which has reinforcing elements to carry tensile forces when concrete cracks or to stiffen the compression zones. In practice it is often used to distinguish concrete members with no prestressed reinforcement from concrete members with prestressed reinforcement. Even here there is a potential for confusion since prestressed concrete members are often reinforced with non-prestressed reinforcement to resist shear, diagonal tension, torsion, or anchorage zone tensile stresses.

Secondary (or Parasitic) Moments: This term is often used to describe bending moments set up in continuous prestressed concrete members due to boundary conditions which restrain deformations due to the constructor applied prestressing forces. When the prestressing force is considered as an applied loading on the structure, a conventional structural analysis which considers the boundary restraints will provide the correct magnitude and location of such moments. If such an analysis considers the changes in stiffness at various advanced loading states, a greatly improved understanding of the roles and effects of such moments at the ultimate limit state is given.

2.3 Useful Technical Terminology

The following generally recognized technical terms will continue to be useful to describe construction processes or conditions but do not require separate codes, standards, or design processes (due to their familiarity, they are not defined here):

pretensioning
post-tensioning
internal tendons
external tendons
bonded reinforcement
unbonded reinforcement
precast concrete
cast-in-situ concrete

3. CURRENT INCONSISTENCIES

3.1 General

Many of the inconsistencies mentioned in this section reflect the author's North American experiences, but discussions and experiences in other countries indicate that many are more universal problems.

3.2 Education

In spite of the rapidly growing use of prestressed concrete construction (in the United States prestressed concrete bridge construction volume is now a multiple of 3 over reinforced concrete bridge construction), most American universities do not teach analysis or design of prestressed concrete structures in the required basic reinforced concrete courses. In fact, a majority of US universities either have no prestressed concrete course or restrict access to prestressed concrete courses to graduate students. Major textbooks are either predominantly "reinforced concrete" (non-prestressed concrete) or exclusively "prestressed concrete." In spite of the great commonality in design and behavior of non-prestressed and prestressed concrete, most young engineers-in-education are given the image that there are fundamental and complex differences between "reinforced concrete" and "prestressed concrete."

3.3 Codes and Standards

In many countries there are separate and often conflicting standards for the design and construction of prestressed concrete structures and non-prestressed concrete structures. Some examples include:

- There is often different notation used for the same properties in national standards -- Example: the yield point strength of reinforcement:

  USA Buildings - ACI 318 non-prestressed - f_y
  USA Bridges - AASHTO non-prestressed - f_y
  USA Buildings - ACI 318 prestressed - f_{py}
  USA Bridges - AASHTO prestressed - f^*_y

- Fundamentally different formulations are used to express the same fundamental principle depending on whether it is for "reinforced" or for "prestressed" concrete. An excellent example is the ACI Building Code limitation on maximum reinforcement percentage. The desire is to ensure ductility in flexural behavior at the ultimate limit state. This is done by a definition of "balanced strain" conditions and a limitation that $\rho_{max} = 3/4\ \rho_{bal}$ for non-prestressed construction. In spite of the fact that a basically similar provision is desired for prestressed concrete flexural members, it is expressed by a complex series of equations devoid of physical interpretation or recognition. A consistent approach defining limiting strain or curvature conditions could be used which would apply to all cases and make usage simpler as well as more logical.

- Many countries have completely different codes for reinforced and for prestressed concrete. This can lead to substantial confusion. For example, take the case of a multistory building built with non-prestressed columns and post-tensioned floor slabs. Assume that lateral stability must be provided by frame action without shear walls or other bracing. Which code should be used for the design and checking of overall stability? Obviously the code for prestressed concrete envisions prestressed flat slabs but does not necessarily consider the importance of their stiffening the non-prestressed columns. Obviously the code for reinforced concrete considers stability of the columns but does not necessarily consider the possible different restraint from a prestressed slab as compared to a non-prestressed slab. Often the existing codes can have contradictory requirements or even worse, can ignore important details such as column-slab connections.

- In Germany a variety of codes for prestressed concrete are in use. Depending on the level of allowable extreme fiber tensile stresses, DIN 4227/1 applies to fully prestressed and partially prestressed concrete, while DIN 4227/2 addresses prestressed concrete with lower levels of prestressing force ("Teilweise Vorspannung"). Part 3 of DIN 4227 applies to segmental construction and Part 2 addresses prestressed concrete with unbonded tendons. It is interesting to compare the shear design provisions of DIN 1045 (non-prestressed concrete) and DIN 4227/1 (fully and partially prestressed concrete) for the case of non-prestressed girder subjected to shear and axial compression and a prestressed girder with shear, respectively. Although the two cases are physically identical, the design provisions are quite different. For non-prestressed concrete girders, shear design is based on a truss model with 45 degree struts. Flatter strut angles are considered indirectly by designing for a reduced shear force ("Verminderte Schubbewehrung") (DIN 1045, Section 17.5). If the axial compression force is applied by a prestressing tendon rather than externally, a truss model different from the model for non-prestressed concrete is used. In prestressed concrete girders the strut angles are smaller than 45 degrees and depend on the state of stress in the girder (DIN 4227/1, Section 12.4). Concrete stresses due to shear forces and torsion are also handled differently for prestressed and non-prestressed concrete. For non-prestressed concrete girders an interaction equation for shear stresses due to shear forces and shear stresses due to torsion has to be satisfied, while for prestressed concrete compressive stresses are determined from truss models for shear and torsion in some cases, and by simple addition of shear stresses in other cases.

- Many codes and standards are "blindly" adopting excellent, research-proven formulations without considering their practicality in the design and construction process. Recent complex, so called "exact" proposals for items such as shear and torsion strength, prestress losses, flat slab design, and deflection calculations are examples. Codes must always facilitate and harmonize with practice. They should protect the public in a reasonable manner without "hog-tieing" the designer.

  Designers are often confused by the intent of Codes and Standards which tend to reflect a great deal of empirical development and a very narrow range of direct applications. Designers interested in the introduction of new and progressive concepts are often blocked by the narrowness of current codes and standards. It has been difficult to use modern analytical techniques such as finite element analyses under many current codes since the standards were framed in terms of linear frame analysis procedures such as moment distribution or matrix methods. On the one hand this prohibits some skilled designers from using applicable advanced concepts for complex structures while on the other hand the absence of common sense guidelines allows unscrupulous designers wide latitude to proceed with risky designs.

3.4 Professional Practice

In many countries, the current framework of codes and standards has resulted in patterns of professional practice where the designer pays major attention to local section behavior based on empirical, sometimes illogical approaches at the expense of attention to overall design concepts and force paths. The designer is *de facto* encouraged to consider the structure on a member by member and section by section basis. Dimensioning and selection of reinforcement seldom consider overall behavior and member interaction. Committees in technical societies are organized in narrow fields (shear and torsion; bond; columns) and tend to produce ponderous reports which further emphasize local behavior and mask overall action. In many nations, designers have little feel for overall detailing. Codes have had to be amended to tell designers to remember to design the joints between members and to tie all pieces of the structure together. Such warnings would be unnecessary if professional practice emphasized primary attention to overall structural behavior and performance. Member and section behavior should be an important, but second level consideration. Dimensioning and detailing should be based on transparent models which provide logical and efficient force paths to ensure proper behavior and performance of the overall structure under all loading conditions.

3.5 Technical and Professional Societies

The fragmentation of the overall industry has caused considerable overlap and duplication in committee activities as well as often conflicting recommendations for code and standard changes. In the USA there is an American Concrete Institute, a Prestressed Concrete Institute and a Post-Tensioned Concrete Institute, besides numerous concrete construction associations. While these groups may have valid purposes as trade associations, the duplication and conflicts in technical activities is unnecessarily counter-productive. Similar redundancy exists at the international level between groups like ACI and CEB on the one hand and FIP on the other hand. The role of IABSE is even less clear. A restructuring of the roles and relations of such organizations could flow from a more modern view point of structural concrete as a continuum.

3.6 Research and Development

Modern trends in research and development in structural concrete lead to considerable fragmentation and unnecessary waste. Researchers seem more and more interested in exploration of isolated variables with specimens that in many cases are unrepresentative of any practical range of variables. Analysis procedures have far out stripped detailing procedures. Attention has been riveted on the strength limit state in spite of mounting serviceability and durability problems. The R&D community in academia tends to substantially lag the innovative developments of brilliant designers. A more holistic view of structural concrete would put emphasis on studying overall behavior rather than isolated actions. The power of modern computer graphics should enhance such holistic views. This is a major challenge for the R&D community.

3.7 Lessons from Actual Structures

Numerous structures have experienced substantial distress and actual failure due to poor detailing induced by the lack of overall consideration of the flow of forces and the restraints active in the structure. A few examples would include:

- a large parking structure where extremely heavy moment resisting frames with stiff columns were utilized to resist hurricane force design winds. Lack of consideration of the large in plane membrane forces caused by the restraint of the stiff columns to differential temperature and shrinkage shortenings in the slabs resulted in over thirty-thousand meters of slab cracks with a width greater than 0.8mm. The slabs were detailed with extra temperature reinforcement which was discontinuous across each span. The designers met arbitrary, empirical code provisions concerning the minimum area of temperature and shrinkage reinforcement but by not providing sufficient reinforcement in a continuous pattern they did not provide proper direct tension resistance. In fairness to the designers, one must say that the code intent was not clearly expressed because the fundamental behavior desired was never clearly stated.

- a medium size office building for a major engineering company collapsed immediately prior to occupancy when a 3-phase air conditioner motor was connected incorrectly. The motor shook badly when the power was activated and the entire two story prestressed concrete building totally collapsed. Subsequent investigations indicated that the prestressed tilt-up wall panels and cast-in-situ post-tensioned beams were proportioned correctly in terms of section-by-section analysis but no thought or actual attention was given to tieing the various members together. The post-tensioned beams had no supports under their ends and were simply resting against the tilt-up wall panels, largely cantilevering full span while balanced upon a middle wall. When friction forces between wall panel and beam were broken, the structure collapsed. Minimal attention to force paths would have prevented the collapse.

- a curved, post-tensioned bridge girder exploded during stressing when the tendons ripped laterally out of the concrete. No tie back reinforcement was present to equilibrate the out of plane forces when the tendon was stressed. Simple strut-and-tie models would have warned of this problem.

The number of examples of similar failures due to poor detailing is legion. All point towards the absence of a good rationale for detailing and a preoccupation with local section strength while neglecting the overall structural and environmental actions.

4. THE PROMISE OF A STRUCTURAL CONCRETE APPROACH

4.1 Methodology

The basic objective of what is being termed the "Structural Concrete Approach" is to eliminate distracting and artificial barriers which tend to compartmentalize the designer's thinking. Present approaches tend to emphasize sectional load effects and local resistances rather than more global attention to overall load paths and resisting elements. The "Structural Concrete Approach" puts emphasis on the structural designer carefully envisioning load paths and deformation restraints in the preliminary design stages, choosing logical structural systems to efficiently channel the loads smoothly to the foundations and to minimize restraint forces, and only then to go on to member proportioning and reinforcement detailing. It puts emphasis on the use of highly transparent models such as strut-and-tie models (STM) for the formulation of efficient and adequate reinforcement details. The STM requires full development of the tie capacity between nodes and hence implies proper anchorage or development of the reinforcement. In some cases the STM recognizes that concrete tensile stresses play major roles and the designer can decide if and when it is proper to rely on such tensile capacity.

4.2 Rigor Required

Loadings and material properties are rarely known to a level of accuracy of two significant figures at the design stage. Load and resistance factors are judged highly acceptable if expressed in two significant figures. The basic safety index of a structure cannot be more accurate than this level of input regardless of the level of sophistication of the analysis procedures. The emphasis on rigor required in the application of a consistent structural concrete theory should be to simply maintain a level of accuracy sufficient to preserve the basic accuracy of known loads and material properties and to guard against gross errors. High precision in calculating nodal stresses, strut widths, anchorage lengths, reinforcement areas, or similar quantities is neither possible nor necessary. Rather than devoting large amounts of resources to sophisticated analyses which are in actuality based on wild guesses at actual stiffnesses and on crudely estimated loads, the designer should give priority to making sure that all load cases, all restraint cases, all equilibrium checks, and all possible instabilities are considered. In addition, approximate estimates of construction forces and environmental effects such as creep, relaxation, shrinkage, differential temperature, and differential settlement should be checked for every case to determine if such effects could be significant and warrant further attention in design. Attention to durability considerations such as cover, proper material properties, and quality assurance should receive substantially increased emphasis.

4.3 Tools Available

The primary analysis requirements for developing a consistent design approach to structural concrete are the availability of highly transparent design-oriented analysis tools like STM along with development of design aids and interactive graphic programs that can assist inexperienced designers (including skilled experienced designers working with a new and very different application) in tracing force paths in structures. Complex structures may require 3-D models which can be well displayed by modern graphic packages if some effort is made to develop interactive STM packages. Where experience or intuition is insufficient for visualizing the load paths and consequent STM for a structure, an elastic Finite Element Analysis (FEA) can provide a good beginning in constructing an appropriate STM. As non-linear analysis packages develop, it is possible non-linear FEA may be useful for formulation of such STM. However, since the compatibility induced elastic stresses can result in severe local cracking, some local crack control reinforcement is almost inevitable. The linear FEA does point out the likelihood of such cracking and is useful in detailing for service level load crack control.

4.4 Performance Requirements and Limit State Approaches

One of the largest areas for synthesis of knowledge and adaptation of basic detailing procedures is the incorporation of service load level performance requirements in the basically equilibrium oriented ultimate load limit state approaches such as STM. It is an adage in the USA that "the phone rings often about a crack here and a sag there, it rarely if ever rings about something falling down." Hardy Cross said **"Strength is Essential... but otherwise Unimportant."** If the proposed approach to a consistent design for structural concrete is to be successful, it must incorporate and improve on performance in areas such as deflection control, crack control, durability, and fatigue resistance. If engineers broadly accept the full spectrum of structural concrete, it will almost certainly lead to increased use of active reinforcement with its positive contributions to deflection control and crack control. Detailing must carefully consider corrosion protection and fatigue resistance since the smaller, high strength wires often used in prestressing tendons are more susceptible to corrosion and pose more fatigue danger if stress reversals are present. However, the higher quality concrete usually utilized can lead to improved durability as long as detailing **and** construction practices are carefully and generously done.

5. CHALLENGES

5.1 General

There are several types of challenges which must be taken up by those participating in the colloquium. First and foremost is that of **objectivity**. The intent of the organizing committee is not to start a stampede but to have a rational, in-depth examination of the promise, the potential, and the pitfalls of a unified approach to structural concrete. Everyone must be willing to minimize their biases and prejudices -- pro and con. The second challenge is that of **participation**, both as speakers and as listeners, and most of all as facilitators, persons who push and pull for progress. The third challenge is that of **preparation**. It is expected that each registrant will read the prepared papers, reflect on their own experience and circumstances, and come to the colloquium ready to look forward and to participate in dialogues, rather than to be educated, amused or confused. Authors must carefully examine their proposed contributions and ensure that they address general themes rather than highly detailed technicalities.

5.2 Technical

There are a number of technical issues requiring further exploration and development in order to develop a fully consistent approach to structural concrete design. These include:

- Methods and criteria for selection of highly appropriate structural systems for various types of loadings, geometries, and restraints;
- Educational aids and design aids that focus on and emphasize overall structural action rather than traditional (and often empirical) sectional mechanics;
- Criteria for selecting portions of a structure where more transparent models like STM are required and for recognizing applications where quicker or simpler conventional analysis procedures and sectional mechanics approaches are adequate;
- Criteria for judging when certain load, restraint or material effects are significant as well as for incorporating serviceability considerations into plasticity based design approaches;
- Criteria for balancing accuracy vs. simplicity in analysis, proportioning, and detailing procedures.

5.3 Political

There are a number of issues which cut across organizational, commercial and national lines. These include:

- How can a unified design concept based on a broad spectrum such as proposed for structural concrete be developed and propagated on an international basis to match the growing international practice of structural engineering?

- How can existing textbook authors, trade and professional associations, design offices with established (expensive) computer programs, narrow focus researchers, regulatory authorities, and the myriad of others who form the structural concrete industry be enlisted in a movement to support and broaden a consistent approach to structural concrete in place of present, fragmented, less satisfactory approaches?

6. CONCLUSION

When IABSE Working Commission III, Concrete Structures, began the discussions which have culminated in the organizations of this Colloquium, there was a general feeling that some positive steps were required to develop a more consistent and unified approach to structural concrete design on a world-wide basis. It was also felt by many that some type of a unified Code of Practice should be developed by IABSE as a "model" for other organizations. Vigorous criticism by others pointed out that IABSE did not traditionally engage in code development and it could serve best as a catalyst for technical discussion and exchange of information.

This colloquium presents a unique opportunity for advancing both points of view. Clearly, the colloquium presents the opportunity for thoughtful reassessment of the present "State-of-the Art" and discussion of new directions. Further, it presents a unique opportunity for a broad based international group to develop a general consensus on the desirability of future directions. A positive outcome from the Colloquium can only be ensured if each author, each speaker, each questioner, each discusser, every participant makes an effort to reexamine the broad questions outlined in the Preliminary Invitation and tailors his presentation to address these topics.

At the closing session of the Colloquium, the general level of consensus on various questions and approaches will be examined. It is hoped that the results of this examination will allow development of a strong statement that can spur other national and international groups to reexamine their current approaches and develop a more consistent approach to the continuous spectrum that is structural concrete. Each and every participant can have a role in shaping this consensus by careful attention to the views of others and clear exposition of their own views. As we prepare for the new century and millennium, we owe it to those who have gone before us to make a concerted attempt to unify, simplify, and most importantly, de-mystify structural concrete.

An Engineering Model for Structural Concrete

Un modèle d'ingénieur pour une structure en béton

Ein ingenieurmässiges Modell für Konstruktionsbeton

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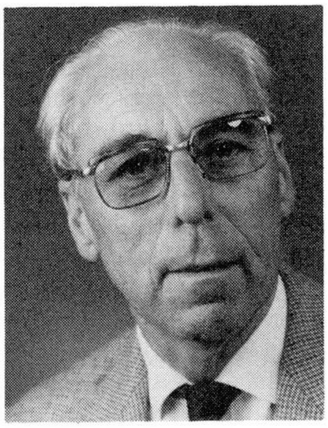

A. S. G. Bruggeling, born 1923, obtained his degree in Civil Eng. from the Delft Univ. of Technology in 1947. Among other functions, he was Director of a firm producing precast prestressed concrete and headed a firm of consulting engineers. From 1969 to 1986 he was Professor of Concrete Construction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

   σ_{co} 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 Fédéral 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.