Accuracy of Design of Concrete Structures

Guenter ROMBACH
Professor Dr.-Ing.
Technical University of
Hamburg-Harburg
Denickestr. 17
D-21073 Hamburg
Germany

Prof. Dr.-Ing. Günter Rombach, born 1957, graduated at the University of Karlsruhe as a civil engineer, where he also obtained his doctoral degree. In 1990 he joined the Bilfinger + Berger Company where he worked as a structural engineer. In 1995 he became technical manager for the Second Stage Expressway System in Bangkok. Since 1996 he is Professor of Concrete Structures at the Technical University of Hamburg-Harburg

Summary

The volume of Standards and Codes for design of concrete structures is constantly increasing (e.g. Eurocode 2, DIN 1045-1 draft revision 1998). The prescribed methods for analysis of reinforced or prestressed concrete members are getting more and more sophisticated. Nevertheless due to the great scatter of material properties in practice and the uncertainty of actions the design of concrete structures is of limited accuracy. This has to be considered in Standards. The limitations of accuracy in concrete design are mentioned in this paper.

1. Introduction

Europe and especially Germany has a long tradition with Standards. The first German Code for design of concrete structures was issued in 1925. It was constantly revised during the following years. The new Code DIN 1045-1 [1] which is mainly based on the Eurocode 2 part 1 [2] (referred as EC2 in this paper) will be published in 1999. It includes major changes like e. g. a probabilistic safety concept which requires a more complex definition of actions, limit states theory and some new verifications. It is without doubt that the amount of required analysis will be increased. The purpose of the new code is to improve the safety and durability of concrete structures. However the failures and damages which occurred in the past are mainly caused by bad workmanship or faulty design rather than by simplified Codes.
For the design of concrete structures several assumptions and simplifications are required which limits the accuracy of the design. This can not be overcome by complex models.

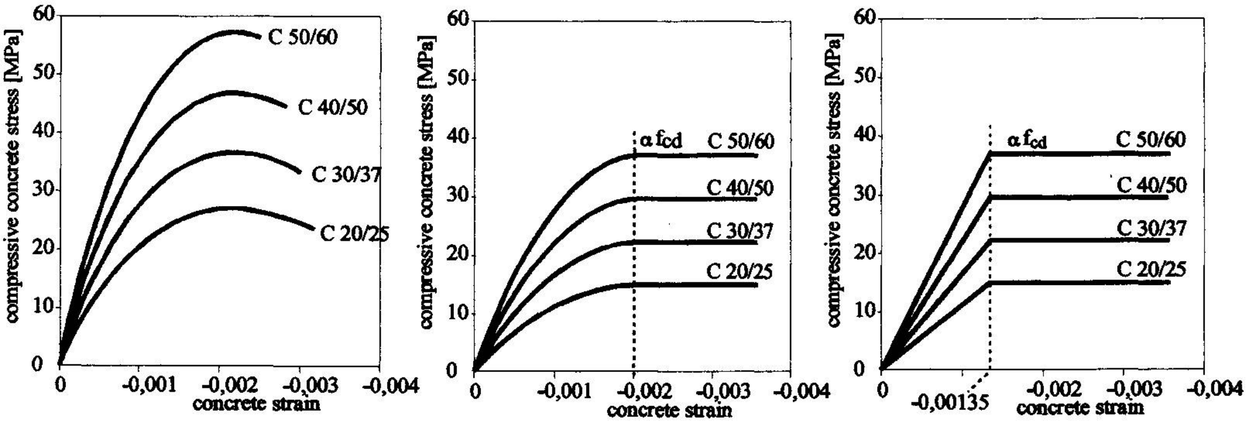
The design of a concrete structure is based on assumptions regarding the material behaviour resp. material properties, actions, structural model and structural analysis. These items are briefly discussed in the following.

2. Material Properties and Material Models

The knowledge of the behaviour of building materials has made a great progress in the last decades. In addition the quality of concrete and steel has been improved. Nevertheless reinforced concrete is a very inhomogeneous material. It's material parameters are highly dependent from several factors like e. g. cement type, water/cement ratio, strength and size of aggregate, admixtures which vary in a certain range. Furthermore the condition during hardening (e.g. temperature, humidity, loading) highly influences the quality and the time dependent behaviour of concrete structures. The workmanship and the environmental conditions are only roughly known when the structure is designed. Therefore all material properties given in Codes can only be a rough approximation of the reality. Furthermore it should be kept in mind that all material properties are obtained by experiments on small specimens (e.g. concrete cylinders). It has to be considered that the behaviour of concrete in experiments may be different from that of real structures.

Stress - strain diagrams of concrete

The section design of a member is mainly based on the stress-strain diagram of concrete. Eurocode 2-1 provides three alternative diagrams, on for structural analysis and 2 for cross-section design.



a) for structural analysis b) and c) for cross-section design

Figure 1 Stress-Strain Diagrams of Concrete according to EC2

All these curves are idealisations of the real behaviour of plain concrete. The reduction factor α which may be assumed to be 0,85 should take into account e. g. long term and size effects. But it should also allow for approximations in the calculations and variations of material properties.

Shrinkage and creep

For normal reinforced structures the influence of shrinkage and creep may be neglected whereas for prestressed constructions it has to be considered in the design. EC2 provides with a detailed method for the calculation of creep coefficients $\varphi(t,t_0)$ and shrinkage strains ε_s. (for details see EC2-1, appendix 1).

Creep coefficient: $\varphi(t,t_0)=\varphi_0\cdot\beta_c(t-t_0)=\varphi_{RH}\cdot\beta(f_{cm})\cdot\beta(t_0)\cdot\beta_c(t-t_0)$ (EC2,eq. A1.1/1.2)

with: $\varphi_{RH}=1+\dfrac{1-RH/100}{0.10\cdot\sqrt[3]{h_0}}$; $\beta(f_{cm})=\dfrac{16.8}{\sqrt{f_{cm}}}=\dfrac{16.8}{\sqrt{f_{ck}+8N/mm^2}}$; $\beta(t_0)=\dfrac{1}{0{,}1+t_o^{0.20}}$; $h_0=\dfrac{2\cdot A_c}{u}$

$$\beta_c(t-t_0)=\left(\frac{t-t_0}{\beta_H+t-t_0}\right)^{0,3};\quad \beta_H=1{,}5\cdot\left[1+(0.012\cdot RH)^{18}\right]\cdot h_0+250\le 1500;\quad t_0=t_{0,T}\cdot\left[9/\left(2+t_{0,T}^{1.2}\right)+1\right]^{\alpha}\ge 0{,}5$$

The complexity of the various equations may deceive the designer with a high accuracy. But there still is a significant difference between experiment and real structures. It should be kept in mind that all input variables are only roughly known during the design stage. Next the time dependent behaviour of concrete structures usually is calculated in a simplified manner, e. g. loss of prestressing force (EC2, eq. 4.10) or redistribution of moments in a continuous beam.

3. Actions

A structure is subjected to permanent, variable and accidental actions like e. g. dead load of the structure, superimposed dead load, wind load, snow load, traffic loads, temperature loads etc. Only the dead load is quite well known during the design stage. All over loads can only be estimated with a rather limited accuracy. This becomes especially true for actions which vary in time and space like e. g. wind loads. A lot of research work has been done in the past on this item leading to more detailed load arrangements. But it should be clear that the designer doesn't need the 'accurate' loads. For the design the worst case and a simple arrangement of forces is required. This may be illustrated by the following example: snow loads. In the past, only a constant load had to be considered in the design of buildings in Germany. The new EC 1 part 7 [4] requires 4 different load cases. This arrangement of loads is more realistic than a constant load. But does it lead to an increase in safety?

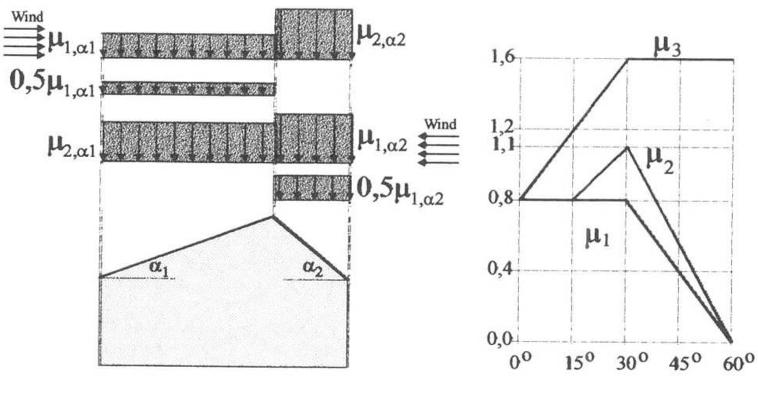


Figure 2 Snow loads according to Eurocode 1 part 7

4. Safety Format - Load Combination

The design of a structure has to be based on the most unfavourable load combination. This can become a tremendous work, if a probabilistic concept with partial safety and various load combination factors is being used like in Eurocode. DIN 1045/78 requires a constant safety factor only.

$S_d \le R_d$ (S$_d$=design value of internal force or moment, R$_d$=design resistance)

ACI: $S_d\left[\gamma_G\cdot G_k+\gamma_Q\cdot\sum Q_{k,i}+\gamma_P\cdot P_k\right]\le R_d\left(f_{ck},f_{yk},f_{pk}\right)/\phi$ with γ_G=1.4 ; γ_Q=1.7

DIN 1045/78: $S_d\left[\gamma\cdot\left(\sum G_k+\sum Q_k\right)+1{,}0\cdot P\right]\le R_d\left(f_{cd},f_{yd},f_{pd}\right)$ with γ=1.75÷2.1

EC2: $S_d\left[\gamma_G\cdot G_k+\gamma_{Q,1}\cdot\sum Q_{k,1}+\sum\gamma_Q\cdot\psi_{0,i}\cdot Q_{k,i}+\gamma_P\cdot P_k\right]\le R_d\left(\frac{f_{ck}}{\gamma_c},\frac{f_{yk}}{\gamma_s},\frac{f_{pk}}{\gamma_p}\right)$

with: γ_G; γ_Q; γ_c; γ_s; γ_p= partial safety factors
$\psi_{0,i}$ = load combination factor

G = permanent actions ; Q = variable actions ; P = prestressing

In theory the characteristic loads, the partial safety factors and the load combination factors are obtained from existing statistical data. In practice however this is rarely the case. The amount of required load combinations is highly increased, if the load combination factors are not constant. According to EC1-1, Tab. 9.3 they vary with the type of building, type and frequency of loading.

The following example, a continuous beam, should illustrate the problem. The structure is subjected to dead load G_k and imposed loads (Q_{k1} - Q_{k6}), whereby the variable actions are treated as independent from each other. The critical load combinations for the ultimate limit state design of the bending moment M 1 are shown in the table. Due to the various load combination factors, the amount of required calculations is highly increased.

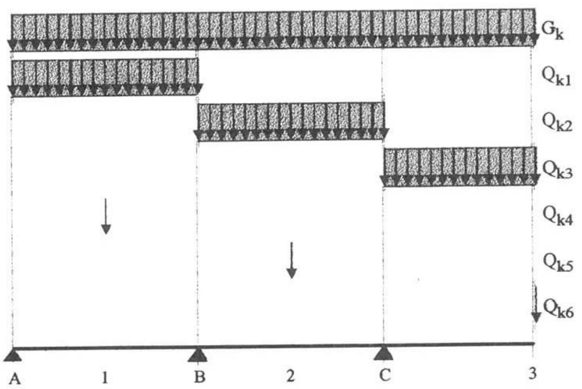


Figure 3 Structure and actions

M1 and support force A	EC2 ULS		SLS γ=1.0	DIN 1045/88 ULS γ=1.75 ψ=1.0
Loadcase	γ	ψ_0	ψ_2	γ
1 : G	1.35	-	1.0	1.75
2 : $Q_{k,1}$	1.50	0.7/1.0	0.3 / 1.0	1.75
3 : $Q_{k,2}$	0.00	-	0.0	0.0
4 : $Q_{k,3}$	1.50	0.7	0.3	1.75
5 : $Q_{k,4}$	1.50	0.7/1.0	0.3 / 1.0	1.75
6 : $Q_{k,5}$	0.00	-	-	0.0
7 : $Q_{k,6}$	1.50	0.7	0.3	1.75

Table 1 Load combination

As can be seen by this example, a „consistent" safety concept can hardly be used in practice even with a computer. This safety format results in a lack of clearness which can become rather dangerous. It is unquestionable that the probabilistic safety concept with partial safety coefficients is more consistent than design with a constant safety factor. Nevertheless simplifications are required.

5. Analysis

For the calculation of forces and moment the engineer has to make a simplified model of the real structure. This includes simplification of the material and the structural behaviour.

The structural analysis can be based on the following idealisations (see e. g. EC2, cl. 2.5.1.1.).

- elastic analysis with or without redistribution
- plastic analysis including strut and tie models
- non-linear analysis

Most analysis is based on a linear behaviour of the structure because all forces and moments can easily be calculated and the superposition of different load cases is possible. Strut and tie models are mostly used for the design of concrete members with non-linear strain distribution like shear walls or regions with concentrated loads. Non-linear analysis is seldom used in practical design e. g. for slender columns and to estimate the deformation of cracked concrete member. It requires the computer and the prior knowledge of all reinforcement. The material parameters which should be used -either mean values or unfavourable values- are still under debate as well as the permissible tensile stresses in unreinforced concrete sections. Non-linear analysis of slabs and shell structures as well as shear should be used for research mainly. Due to their complexity such calculations should be carried out by engineers who have sufficient experience in this field.

6. Design of Sections

The design for ultimate limit state of sections subjected to pure flexure based on the various stress strain curves of concrete is generally accepted. Differences between various Codes still exist in the design for shear and/or torsion.

The design for serviceability limit state includes the computation of stresses and deflections under service load condition and the crack control. Durability and in particular corrosion protection of the reinforcement has become one of the major items in the design. The amount of minimum reinforcement, the concrete cover and the required reinforcement to limit the width of cracks has constantly been increased. The crack width may be obtained from the following relation (EC2, equation 4.80, 4.81 and 4.82):

$$w_k = \beta \cdot s_{rm} \cdot \varepsilon_{sm} = \begin{Bmatrix} 1.3 \\ 1.7 \end{Bmatrix} \cdot \left(50 + 0.25 \cdot k_1 \cdot k_2 \cdot \phi / \rho_r\right) \cdot \frac{\sigma_s}{E_s} \cdot \left(1 - \beta_1 \cdot \beta_2 \cdot \left[\frac{\sigma_{sr}}{\sigma_s}\right]^2\right)$$

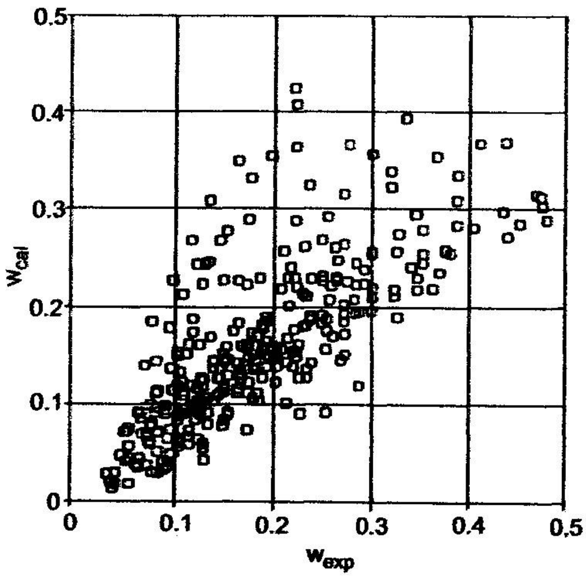


Figure 4 Crack width - calculated versus measured values [5]

Despite the complexity of the equations, the crack width can only be calculated with a rather limited accuracy as shown in figure 4. The designer should be aware of the various reasons for cracking. Good workmanship and detailing is required for crack control rather than sophisticated design models.

7. Example

The limited knowledge in concrete design is demonstrated on a rather simple type of structure, a silo bin. Extensively research had been carried out to estimate the loads due to bulk material. However, there still are a great discrepancies between the different Codes as can be seen from figure 5, where the horizontal wall pressure during discharge for a 27m high silo bin is plotted. A comparative study which was carried out by a FIP Working Group [6] has shown the same results. In addition the study showed that the amount of mild reinforcement differs significantly, more than 100 % in the upper part of the bin, where the minimum reinforcement is the decisive factor.

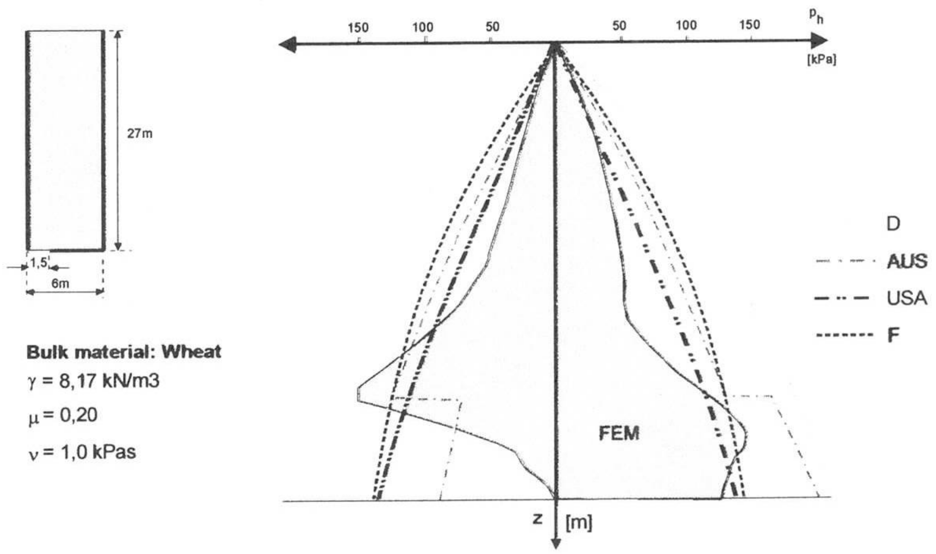


Figure 5 Horizontal wall pressure

After some heavy failures it was recognised that dust explosion may occur in most silos. Taking this accidental action into account loads due to bulk material can be neglected in many cases.

8. Conclusion

In this paper various aspects of concrete design are discussed. It is general accepted that the design of concrete structures can only be of limited accuracy which in practice can't be changed by complex calculations. The increasing complexity offers the risk, that the designer can only rely on figures from computational calculations and loose his feeling for the overall behaviour of the structure. Furthermore, if the regulations become too detailed it may be an obstacle to technical development. The problem is to find a reasonable compromise between state of the art design models ad simplified rules. It should be kept in mind that Codes must be written for practical use and therefore they have to be as simple as possible and not to sophisticated. The design has to be on the „safe side" rather than „precise".

References

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[4] Eurocode 1: Basis of Design of actions on structures, 1995

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[6] FIP Working Group „Silo Design": *Comparative Silo Design*; Report, Karlsruhe, March 1987