

# DESIGN OF HIGH PERFORMANCE CONCRETE STRUCTURES A SWEDISH HANDBOOK

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## ABSTRACT

Design Recommendations for Structures of High-Performance Concrete are presented regarding: (I) toughness and ductility, (II) bond, and (III) shrinkage, creep, and cracking in young concrete. The recommendations are based upon a joint program funded by six industry companies and three Swedish Research Foundations for seven years 1991/92 - 1997/98 with a total budget of about 6.5 million USD (53 MSEK). The aim of the program was to develop (a) more efficient structures, (b) better production methods, and (c) more durable materials. Some results are highlighted from a Design Handbook based on the structural part of the program.

## INTRODUCTION

A Swedish Research and Development Program on High-Performance Concrete was started in 1991. Six major companies were funding it namely Cementa, Elkem, Euroc Beton, NCC, Skanska, and Strängbetong together with three Research Councils namely the Swedish Council for Building Research (BFR), the Swedish National Board for Industrial and Technical Development (NUTEK) and the Development Fund of the Swedish Construction Industry (SBUF). The annual funding was about 1.1 MUSD (9 MSEK). Research was carried out at the Cement and Concrete Institute (CBI) in Stockholm and at the universities in Göteborg (CTH), Lund (LTH), Luleå (LTU), and Stockholm (KTH).

In this paper some results are presented from a Design Handbook (1998) based on the structural parts of the program, which encompass about one third of it. The other two thirds of the program deal primarily with questions regarding materials and production, Elfgren et al (1995). A Material Handbook (1998) (so far only in Swedish) has also been prepared.

The Design Handbook has a similar outline to the Swedish Handbook of Concrete design, BBK 94 (1994), and recommendations are only given for such concrete qualities (strengths) that go beyond the ones in BBK 94.

The program on structures was started with a literature study, which is summarised in Gabrielsson (1993). Main projects were then started regarding toughness and ductility, bond, and cracking in young concrete.

## MATERIAL PROPERTIES

### Mechanical Properties

A summary of the mechanical properties obtained in the program has been compiled by Nylinder (1998). Based on the results, recommended characteristic values have been proposed in Table 1 for the concrete compressive strength, the concrete tensile strength, the fracture energy, and the modules of elasticity for different concrete strength classes K 80 to K 120. The number in the strength class K corresponds to the demanded compressive strength  $f_K$ . The value  $f_K$  is determined by compression tests on 150-mm cubes according to Swedish Standards.

Table 1 - Characteristic Values of Concrete Material Properties

Concrete class	K80	K90	K100	K110	K120
Compressive strength, MPa	56.5	63.0	70.0	77.0	84.0
Tensile strength, min, MPa	2.7	2.9	3.1	3.3	3.5
Tensile strength, mean, MPa	4.09	4.3	4.6	4.9	5.2
Tensile strength, max, MPa	5.3	5.7	6.1	6.5	6.9
Modulus of Elasticity, GPa	38.5	39.5	40.5	41.5	42.5

The Fracture energy is suggested to be taken as 100, 120, or 150 J/m<sup>2</sup> for concrete with a nominal maximum aggregate size of 8, 16 and 32 mm respectively.

The *fatigue capacity*  $\sigma_{max}/f_{cc}$  has been found to decrease by a factor varying from 1.0 for K 80 to 0.9 for K 130.

### Shrinkage and creep

The *shrinkage strain*,  $\varepsilon_{cs}(t)$ , of a concrete member may be expressed as follows, see the Design Handbook (1998):

$$\varepsilon_{cs}(t) = \varepsilon_{cs0}(t) + \varepsilon_{csd}(t) \quad (1)$$

where  $t$  = time after casting of concrete (days)  
 $\varepsilon_{cs0}(t)$  = shrinkage strain at sealed conditions, which may be denoted autogenous shrinkage  
 $\varepsilon_{csd}(t)$  = additional strain due to drying or wetting caused by humidity exchange with the environment

The limit values for infinite time may be written as

$$\varepsilon_{s0\infty} = (-0.6 + 1.2 \cdot \frac{w}{B}) \cdot 10^{-3} \quad (2)$$

$$\varepsilon_{sd,tot} = (-0.1 - 0.8 \cdot \frac{w}{B}) \cdot 10^{-3} \quad (3)$$

To give an example, a water-binder ratio ( $w/B$ ) of 0.3 we will give an autogenous shrinkage of 0.024 percent and an additional strain due to drying of 0.034 percent.

The *stress-dependent strain (creep)* at time  $t$ ,  $\varepsilon_{c\sigma}(t, t_0)$ , of a concrete member uniaxially loaded with a constant stress  $\sigma_c(t_0)$  at concrete age  $t_0$  may be expressed as follows, see the Design Handbook (1998):

$$\varepsilon_{c\sigma}(t, t_0) = \varepsilon_{ci}(t_0) + \varepsilon_{cc}(t, t_0) = \sigma_c(t_0) \left[ \frac{1}{E_c(t_0)} + \frac{\phi(t, t_0)}{E_{ck}} \right] \quad (4)$$

where  $\varepsilon_{ci}(t_0)$  = initial strain at loading  
 $\varepsilon_{cc}(t, t_0)$  = creep strain at time  $t > t_0$

The *creep coefficient* in (4) may be expressed by

$$\phi(t, t_0) = \phi_0 \beta_{age} \beta_{cd} \quad (5)$$

where  $\phi_0$  = 1.1 = reference creep coefficient typical for HPC  
 $\beta_{age}$  = coefficient considering both age at loading and time span after loading  
 $\beta_{cd}$  = coefficient taking creep at variable humidity into account.

## TOUGHNESS AND DUCTILITY

### General

A basic parameter in fracture mechanics is the *brittleness number*  $B$ . It can be defined in the following way. Let us study a tensile test of a concrete prism. Up to the maximum load (with *stress*  $f_t$  and *deformation*  $\delta E = \varepsilon_t L$ ) the prism basically behaves in an elastic way (*strain*  $\varepsilon_t = f_t / E$ ). After maximum, a narrow fracture zone (FZ) deforms further under falling load. At the same time the material outside the fracture zone is relieved elastically - largely following the first curve back to the origin. The area under the descending curve is defined as the *fracture energy*  $G_F$  which is needed in order to separate the prism into two parts. A characteristic *failure zone deformation*  $\Delta$  can also be defined as  $\Delta = G_F / f_t$ .

Structures can be defined as *brittle* when the elastic deformation  $\delta E$  dominates, whereas the behaviour can be defined as *ductile* when the deformation of the fracture zone  $\Delta$  dominates. The *brittleness number*  $B$  can be defined as



$$B = \delta E / \Delta = \varepsilon_t L / \Delta = f_t^2 L / E G_F \quad (6)$$

The reciprocal value  $1/B$  can be named the *ductility number*. It can be seen that the brittleness/ductility depends on the *length*  $L$ , the *tensile strength*  $f_t$ , the *modulus of elasticity*  $E$ , and the *fracture energy*  $G_F$ . The brittleness number is also proportional to the ratio of elastic to fracture energy:

$$\text{Elastic energy} / \text{Fracture energy} = 0.5 f_t \delta E / G_F = 0.5 f_t^2 L / E G_F \sim B \quad (7)$$

The factor  $E G_F / f_t^2$  is a material parameter which was introduced by Hillerborg (1976) as the *characteristic length*,  $l_{ch}$ . The *brittleness number* was introduced in the form it is given here in the 80-ies by Bache (1995), see Elfgren (1989).

A basic fracture mechanics philosophy is to relate the strength of an object to its brittleness number  $B$  or to the components of  $B$  i. e. the length  $L$ , the tensile strength  $f_t$ , the modulus of elasticity  $E$ , and the fracture energy  $G_F$ .

This way of describing the tensile fracture is now beginning to be introduced in modern design codes. In e. g. the Model Code 1990, CEB-FIP (1993) values are given for the fracture energy  $G_F$  [Nm/m<sup>2</sup>] and a bi-linear stress - crack-opening diagram is proposed for concrete in tension. However, in most traditional codes, e. g. EC-2 (1991), not much can be seen except some empirical formulae for size-effect influences.

### Applications to beams, columns and piles

A series of tests on *rectangular reinforced beams* with various concrete strengths has been carried out by Henrik Gabrielsson (1993). Analysis with the modified compression field theory according to Collins and Mitchell (1990) gave better results than an analysis with a conventional theory. In the Design Handbook (1998) shear and torsion is suggested to be analysed in the same way as in the Canadian Code (1994) based on the modified compression field theory.

Ductility of high-performance *hollow core slabs* and *prestressed concrete cylindrical elements* tested in torsion, bending, and shear has been studied by Henrik Gabrielsson (1996, 1998). The slabs show a certain possibility to redistribution. The cylindrical elements are used as transmission line towers for electric power. It has been proved that also a high strength concrete can give quite a ductile behaviour if the reinforcement is arranged properly. The ductility depends mostly on the amount of transversal reinforcement. Similar results regarding *rotational capacity of beams* have been reached in a project carried out at the Royal Institute of Technology (KTH) by Håkan Fransson (1997). The punching-shear capacity has been studied by Mikael Hallgren (1996).

*Columns in compression* have been tested and analysed by Marianne Grauers (1993) and by Christina Claeson (1995). A fracture-mechanics approach has here been fruitful in the analysis of the results. Design models similar to the ones in CEB-FIP

(1993) are now being proposed in the Design Handbook (1998) . One general and one simplified method are proposed for instability.

*Prestressed concrete piles* have been studied by Gunnar Holmberg (1996) and a design chart for fatigue has been proposed.

*Design examples* are given in the Design Handbook (1998) for prestressed beam elements with cross sections of I-form and as an inverted T. A short railway bridge has also been investigated with concrete of class K 120.

## **BOND**

An interesting bond splitting model has been developed and tested by Keivan Noghabai (1995-99). The model is based on the assumption that the bond stresses around a reinforcement bar give rise to a hydrostatic pressure on the concrete. The pressure is a function of the geometry of the bars and the size of the applied force. Test results have also been analysed with a Finite-Element Method using Inner Softening Bands. Here the localisation of the cracks could be followed. First many small cracks appeared but after a while some of them closed while others grew wider. At failure only a few rather wide cracks remained. The influence of fibres and various amounts of spiral reinforcement was investigated too.

Bond and anchorage of deformed bars have also been studied by Jonas Magnusson (1997). Anchor bolts have been investigated by Ulf Ohlsson et al (1995, 1997). The rules given in the Design Handbook (1998) for bond are based on the concept given in CEB-FIP (1993) but modified according to the recent test results.

## **THERMAL STRESSES AND EARLY AGE CRACKING**

The advent of HPC has rendered the problem of early-age cracking more acute also in slender concrete elements. This is primarily due to the following circumstances:

- (a) High cement content entails increased heat of hydration
- (b) Low water-binder ratios and, in particular, the use of silica fume tend to render the concrete more brittle in tension
- (c) At very low water-binder ratios there is imminent risk of autogenous or chemical shrinkage.

Cracks can be classified in *two categories*, Bernander (1996), Springenschmid (1998):

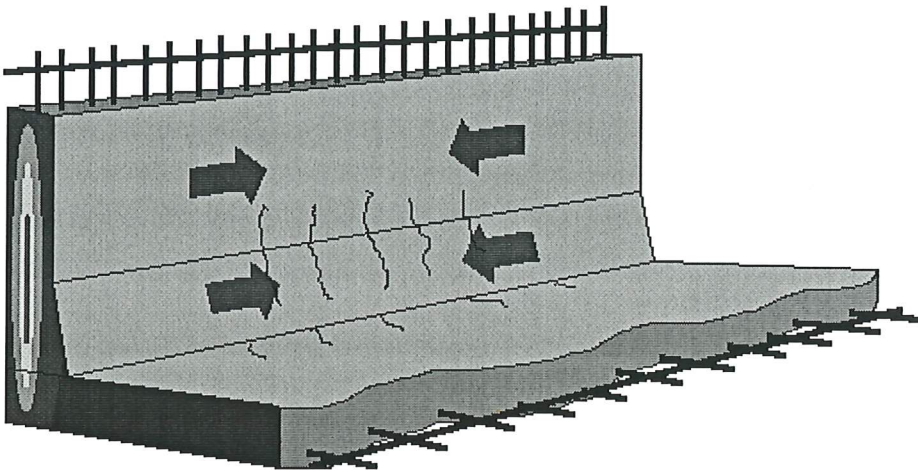
(a) *Early-age cracks in the heating (or expansion) phase*. These cracks appear shortly (one to a few days) after placing and tend to close at the end of the cooling cycle. Very early cracks of this type are usually - but not always - surface cracks. Temperature differentials within a foundation slab or over a closed box-girder section with markedly different wall and slab thickness may e.g. generate through cracks also in the heating phase.



*(b) Cracks occurring in the cooling (or contraction) phase.* These cracks are related to mean negative volume change and generally form 'through' cracks as a result of axial tension or flexure. Depending on dimensions and other prevailing conditions the cracks appear weeks, months and in extreme cases even years after a section has been poured. Cracks forming in the cooling phase tend to remain open permanently.

For HPC elements thermal early age through cracking may be of concern, in particular when water tightness is a crucial requirement. However, the primary crack generation factor in slender elements is often not so much the hydration temperature rise - which is normally relatively small - as the initial difference between the concrete placing temperature and the temperature of older bordering concrete. Another important crack generation factor of HPC is the autogenous shrinkage, which may contribute with an additional negative volume change corresponding to a temperature change of some twenty degrees Celsius.

Restraint depends primarily on the configuration of the restraining structure and the freedom of movement that it permits. An example of spatial distribution of restraint is given in Fig. 1.



*Figure 1. The risks of cracking due to temperature stresses have been studied Stig Bernander, Jan-Erik Jonasson, Mats Emborg et al (1990 - 1999). The picture illustrates cracking in a wall casted on an older slab. From Nilsson et al (1998, 1999).*

Cracking has been studied extensively in young concrete structures. A program has been carried out in order to establish material data and models suitable for computer analysis. In this way tools are being made available with which the hardening technology can be mastered and unwanted cracking can be eliminated by proper procedures. Main results have been presented by Mats Emborg and Stig Bernander (1990, 1994, 1996), Jan-Erik Jonasson (1994), Gustaf Westman (1999), Katarina Ekerfors (1995), Patrik Groth (1996), Hans Hedlund (1996), and Bertil Persson (1998). It is of the utmost importance for an accurate thermal stress analysis, that correct modelling of the mechanical behaviour is performed. It is essential to study

the overall mechanical behaviour and it is not enough to model separate properties as creep, strength development etc. as complicated coupling effects occur in concrete.

## MODIFIED CONCRETE

Recent tests with an *energetically modified cement* have also given interesting results regarding e.g. winter concreting. Silica fume is here activated together with cement in a mechanical-chemical milling process which increases the surface energy of the binder, Vladimir Ronin and Jan-Erik Jonasson (1994, 1997). The activated cement leads to lower binder contents and higher workability.

*Steel fibre reinforcement* is one way to control cracking and to enhance toughness. Tests performed by Patrik Groth (1996) and Keivan Noghabai (1998) indicate a clear tendency towards a plastic behaviour in bending and splitting tests with a fiber volume content of 1 to 2 %. Fibre reinforcement has also been tested as shear reinforcement in concrete beams by Jonas Gustafsson (1997) and Keivan Noghabai (1998). A strong size effect could be seen.

## FIRE

In the design Handbook (1998) fire is treated according to the principle that the concrete cross section is reduced due to the fire action. The 500°C isotherm is used as the limit for the undamaged concrete, Oredsson (1997).

Spalling is proposed to be prevented by the addition of low melting fibres in the concrete mixture. An amount of 2 kg/m<sup>3</sup> is recommended for water-binder ratios ( $w/B$ ) of 0.32 to 0.28 and an amount of 4 kg/m<sup>3</sup> for  $w/B$  of 0.28 to 0.24.

## CONCLUSIONS

High-performance concrete is an efficient material which can be used in many structural applications with good economy. The Swedish R& D program is giving valuable contributions to enable safe and efficient design procedures for structures as beams, columns, transmission poles, piles, and hollow core slabs. An essential prerequisite for modelling of toughness/brittleness of structures is fracture mechanics properties as the fracture energy  $G_F$ , modulus of elasticity  $E_C$ , and tensile strength  $f_t$ .

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The Design Handbook has been edited by a group headed by Lennart Apleberger, NCC. Other members of the editorial group have been Krister Cederwall, CTH, Lennart Elfgren, LTU, and Marianne Grauers, NCC. Contributions to the handbook have also been given by: Yngve Anderberg, Fire Safety Design, Stig Bernander, LTU, Christina Claeson, CTH, Robert Danewid, LTH, Mats Emborg, Betongindustri/LTU, Björn Engström, CTH, Henrik Gabrielsson, LTU, Patrik Groth, LTU, Mikael Hallgren, KTH, Hans Hedlund, LTU, Gunnar Holmberg, Skanska, Håkan Fransson, KTH, Jan-Erik Jonasson, LTU, Sven Kinnunen, KTH, Ulf Kumlin, Abetong, Lars Lindskog, Skanska, Jonas Magnusson, CTH, Keivan Noghabai, LTU, Jens Oredson, Fire Safety Design, Bertil Persson, LTH, Thomas Petersson, Strängbetong, Gunnar Rise, Strängbetong, Rune Sandström, LTU, Stefan Westberg, Abetong, Bo Westerberg, Strängbetong/Tyréns and Gustaf Westman, LTU.

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