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**SHEAR STRENGTH OF BEAMS OF HIGH  
STRENGTH CONCRETE**

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M. P. NIELSEN**

**Serie R**

**No 258**

**1990**

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Tryk:

Afdelingen for Bærende Konstruktioner

Danmarks Tekniske Højskole

Lyngby

ISBN 87-7740-046-1

## Preface

This report is a part of the work carried out by Chen Ganwei during his Ph.D. study at the Department of Structural Engineering, the Technical University of Denmark, Prof. Dr. Techn. M. P. Nielsen acted as supervisor during the study. The work was supported by AEC Consulting Engineers Ltd.

## Resume

Adskillige grupper af forskydningsforsøg med bjælker udført af højstyrkebeton fundet i litteraturen er blevet sammenlignet med teoretiske løsninger. Overensstemmelse mellem forsøg og teori er fundet tilfredsstillende.

## Summary

Several groups of shear tests of beams with high strength concrete, which are found so far in the literature, have been compared with the theoretical solutions of beam shear. The agreement between tests and theory has been found to be satisfactory.

## List of Symbols

a	clear shear span
$A_s$	cross sectional area of horizontal tensile reinforcement
$A_{sw}$	cross sectional area of vertical web reinforcement per unit length
b	web width of beam
C	parameter, $C = \begin{cases} 1 - 2\Phi^* & \Phi^* \leq 1/2 \\ 0 & \Phi^* > 1/2 \end{cases}$
$C_v$	coefficient of variation
D	parameter, $D = \begin{cases} (\mu - 2\Phi^*) / \lambda & \Phi^* \leq \mu/2 \\ 0 & \Phi^* \geq \mu/2 \end{cases}$
$f_c$	mean uniaxial compressive strength of concrete
$f_c^*$	plastic compressive strength of concrete, defined as $f_c^* = \nu f_c$
$f_t$	uniaxial tensile strength
$f_t^*$	plastic tensile strength of concrete, defined as $f_t^* = \rho^* f_c^*$
$f_y$	yield strength of tensile reinforcement
$f_{yw}$	yield strength of web reinforcement
h	total depth of cross section
$h^*$	effective shear depth
$h_e$	effective depth of cross section
k	material constant, $k = (1 + \sin\varphi)/(1 - \sin\varphi)$ ( $\varphi$ angle of friction)
n	number of tests
V	shear force
$V_{cal}$	calculated ultimate shear force
$V_y$	yield load
$V_{test}, V_t$	observed ultimate shear force in test

$\bar{x}$	mean value
$\eta$	ratio, $\eta = \lambda/\mu$
$\lambda$	material constant, $\lambda = 1 - (k - 1)\rho^*$
$\mu$	material constant, $\mu = 1 - (k + 1)\rho^*$
$\nu$	effectiveness factor for the compressive strength of concrete
$\rho^*$	effectiveness factor, $\rho^* = f_t^*/f_c^*$ for the tensile strength of concrete
$\sigma$	standard deviation
$\tau$	shear stress defined as $V/(bh)$ or $V/(bh^*)$
$\varphi$	reinforcement ratio, defined as $A_s/bh$ , angle of friction
$\varphi_v$	vertical reinforcement ratio
$\Phi^*$	effective horizontal reinforcement degree, $\Phi^* = A_s f_y / (b h f_c^*)$
$\Phi_h^*$	effective horizontal reinforcement degree, $\Phi_h^* = A_s f_y / (b h f_c^*)$
$\Phi_v^*$	effective vertical web reinforcement degree, $\Phi_v^* = A_{swv} f_{yw} / (b f_c^*)$
$\Phi_{v0}^*$	critical vertical of web reinforcement degree



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## 1. Introduction

As is well known, concrete ductility decreases appreciably with increasing strength. Therefore it is necessary to check the validity of theoretical shear solutions when applied to high concrete strengths.

## 2. Theoretical solutions

The theoretical solutions will not be derived here. The reader is referred to [2], [3], [6], [7], [8] and [9].

### 2.1. Beams without shear web reinforcement.

#### 2.1.1 Complete solutions

The most complete theory of shear strength is based on a modified theory of plasticity. The empirical formulas still used in many countries will not be evaluated in this report.

The theoretical plastic solutions are modified by replacing the compressive strength of concrete  $f_c$  by  $f_c^* = \nu f_c$  and the tensile strength  $f_t$  by  $f_t^* = \rho^* f_c^*$ .

The complete plastic solutions [3], in which the effect of the tensile strength of concrete has been considered are shown in figure 2.1.

$$\lambda + \mu + D \geq 1$$

$\frac{a}{h}$ \diagdown $\frac{T}{F_c}$ \diagup $\phi^*$	$\phi^* \leq \frac{\mu}{2}$	$\frac{\mu}{2} \leq \phi^* \leq \frac{1}{2}$	$\phi^* \geq \frac{1}{2}$
$\sqrt{\frac{1-D^2}{\eta^2-1}} \leq \frac{a}{h}$	$\frac{1}{2} \sqrt{(\lambda^2 - \mu^2)(1-D^2)}$	$\frac{1}{2} \sqrt{\lambda^2 - \mu^2}$	
$\tan\phi - \frac{D}{\cos\phi} \leq \frac{a}{h} \leq \sqrt{\frac{1-D^2}{\eta^2-1}}$	$\frac{1}{2} [\lambda \sqrt{(\frac{a}{h})^2 + 1 - D^2} - \mu \frac{a}{h}]$	$\frac{1}{2} [\lambda \sqrt{(\frac{a}{h})^2 + 1 - \mu \frac{a}{h}}$	
$\tan\phi - \frac{c}{\cos\phi} \leq \frac{a}{h} \leq \tan\phi - \frac{D}{\cos\phi}$	$\frac{[(\frac{a}{h})^2 + 1](1 - \sin\phi) - 2\phi^*(\frac{a}{h} \cos\phi - \sin\phi)}{2(\frac{a}{h} \sin\phi + \cos\phi)}$		
$\frac{a}{h} \leq \tan\phi - \frac{c}{\cos\phi}$	$\frac{1}{2} [\sqrt{(\frac{a}{h})^2 + 1 - c^2} - \frac{a}{h}]$		$\frac{1}{2} [\sqrt{(\frac{a}{h})^2 + 1 - \frac{a}{h}}$

$$\rho^* = \frac{f_c^*}{f_c}, \quad k = \frac{1 + \sin\phi}{1 - \sin\phi} = 4, \quad \phi = 37^\circ$$

$$\lambda = 1 - \rho^*(k-1) = 1 - 3\rho^*, \quad \eta = \frac{\lambda}{\mu}$$

$$\mu = 1 - \rho^*(k+1) = 1 - 5\rho^*$$

$$\frac{T}{F_c} = \frac{v}{bh f_c^*}, \quad \phi^* = \frac{A_s f_y}{bh f_c^*}$$

$$c = \begin{cases} 1 - 2\phi^* & \text{for } \phi^* \leq \frac{1}{2} \\ 0 & \text{for } \phi^* > \frac{1}{2} \end{cases}, \quad D = \begin{cases} \frac{\mu - 2\phi^*}{\lambda} & \text{for } \phi^* \leq \frac{\mu}{2} \\ 0 & \text{for } \phi^* > \frac{\mu}{2} \end{cases}$$

Figure 2.1 The complete plastic solutions and their boundaries.

The corresponding empirical  $\nu$ -formula with  $\rho^* = 0.03$  has been found as

$$\rho^* = 0.03 \tag{2.1}$$

$$\nu = \frac{0.35(3.5 - \frac{a}{h})(\phi + 2)(1 - 0.2h)}{\sqrt{f_c}} \leq 1.0 \quad \begin{cases} \frac{a}{h} \dagger 2.5 \\ \phi \dagger 2.0 \\ h \dagger 1.25 \end{cases} \tag{2.2}$$

Here,  $f_c$  is in MPa,  $\varphi$  in percent and  $h$  in meter.

The tests of beams without shear reinforcement have been compared with the theoretical formulas.

Examples of the dependence of  $\nu$  on  $f_c$ ,  $a/h$ ,  $\varphi$  and  $h$  in beams with high strength concrete can be seen in figures 2.2, 2.3, 2.4 and 2.5, respectively.

The statistics of the ratios of test to theory and the comparison between test results and theoretical calculations are presented in figure 2.6.

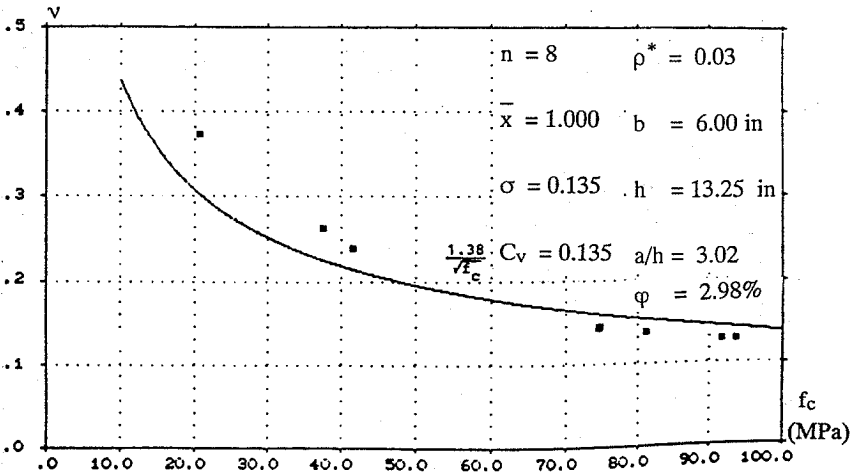


Figure 2.2 The  $\nu$ -dependence on  $f_c$ .

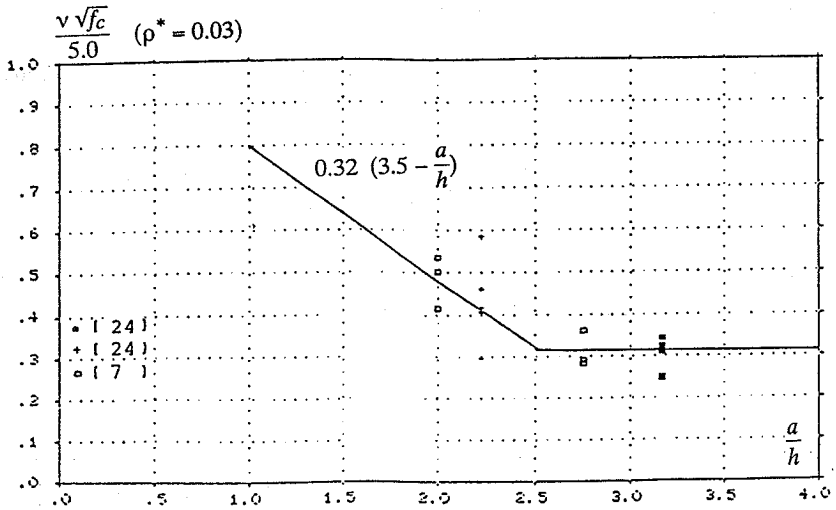


Figure 2.3 The  $\nu$ -dependence on  $a/h$ .

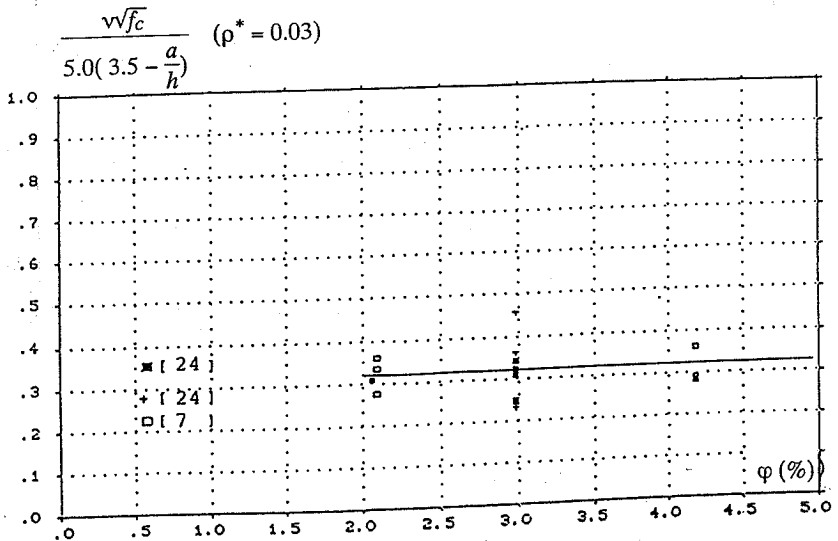


Figure 2.4 The  $\nu$ -dependence on  $\varphi$ .

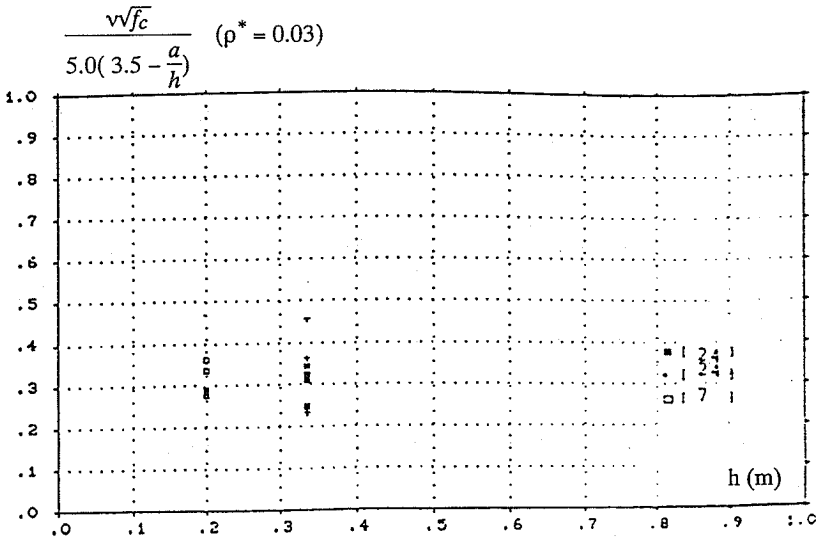


Figure 2.5 The  $\nu$ -dependence on  $h$ .

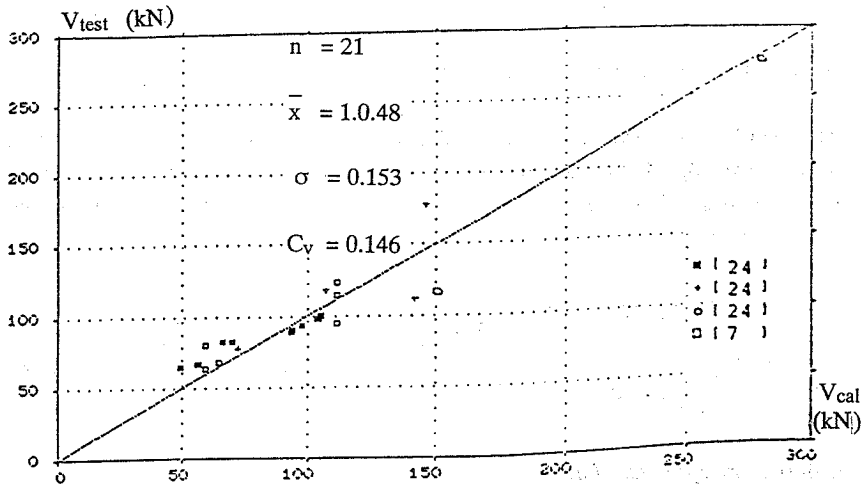


Figure 2.6 Comparison between theory and tests.

### 2.1.2 Simplified solutions

Inserting  $\rho^* = 0$  into the complete plastic shear solutions, i.e. the tensile strength of concrete is neglected, we get the simple shear solutions.

$$\frac{\tau}{f_c} = \begin{cases} \frac{1}{2} \left[ \sqrt{\left(\frac{a}{h}\right)^2 + 4\Phi^*(1-\Phi^*)} - \frac{a}{h} \right] & \text{for } \Phi^* \leq \frac{1}{2} \\ \frac{1}{2} \left[ \sqrt{\left(\frac{a}{h}\right)^2 + 1} - \frac{a}{h} \right] & \text{for } \Phi^* > \frac{1}{2} \end{cases} \quad (2.3)$$

These solutions were given by Nielsen and Bræstrup as exact plastic solutions in [6] and [7].

The corresponding  $\nu$  formula was suggested by Roikjær [9]

$$\nu = \frac{3.5}{\sqrt{f_c}} 0.27 \left(1 + \frac{1}{\sqrt{h}}\right) (0.15 \varphi + 0.58) \left(1.0 + 0.17 \left(\frac{a}{h} - 2.6\right)^2\right) \quad (2.4)$$

Here,  $f_c$  is in MPa,  $\varphi$  in percent and  $h$  in meter

This solution has some disadvantages. The most simple way to eliminate these is to introduce an upper limit of 2.5 in the shear span ratio in the simple solutions, i.e. when the shear span ratio is larger than 2.5 it is put equal to 2.5. The modified simple solutions therefore are

$$\frac{\tau}{f_c} = \begin{cases} \frac{1}{2} \left[ \sqrt{\left(\frac{a}{h}\right)^2 + 4\Phi^*(1-\Phi^*)} - \frac{a}{h} \right] & \text{for } \Phi^* \leq \frac{1}{2} \\ \frac{1}{2} \left[ \sqrt{\left(\frac{a}{h}\right)^2 + 1} - \frac{a}{h} \right] & \text{for } \Phi^* > \frac{1}{2} \end{cases} \quad \left(\frac{a}{h} \leq 2.5\right) \quad (2.5)$$

with the corresponding  $\nu$  formula

$$\nu = \frac{0.60(2-0.4\frac{a}{h}) (\varphi+2) (1-0.25h)}{\sqrt{f_c}} \leq 1.0 \quad \begin{cases} \frac{a}{h} \leq 2.5 \\ \varphi \leq 2.0 \\ h \leq 1.0 \end{cases} \quad (2.6)$$

The comparison between tests and the modified simple solution show that this solution is almost as good as the complete solution taken into account the tensile strength.

## 2.2 Beams with vertical stirrups.

For beams with vertical stirrups subjected to concentrated loads the shear carrying capacity was derived by Nielsen and Bræstrup [2] [8] using the web crushing criterion. The complete solutions are given in figure 2.7.

$\frac{\tau}{f_c} \phi_h^*$ $\phi_v^*$	$\phi_h^* \leq \frac{1}{2}$	$\phi_h^* = \frac{1}{2}$
$\phi_v^* < \phi_{vo}^*$	$\frac{1}{2} \left[ \sqrt{\left[ \frac{a}{h^*} \right]^2 + 4\phi_h^*(1-\phi_h^*) \frac{a}{h^*}} + \phi_v^* \frac{a}{h^*} \right]$	$\frac{1}{2} \left[ \sqrt{\left[ \frac{a}{h^*} \right]^2 + 1} - \frac{a}{h^*} \right] + \phi_v^* \frac{a}{h^*}$
$\phi_{vo}^* \leq \phi_v^* \leq \frac{1}{2}$	$2\sqrt{\phi_h^*(1-\phi_h^*) \phi_v^*(1-\phi_v^*)}$	$\sqrt{\phi_v^*(1-\phi_v^*)}$
$\phi_v^* > \frac{1}{2}$	$\sqrt{\phi_h^*(1-\phi_h^*)}$	$\frac{1}{2}$

(2.7)

$$\phi_{vo}^* = \begin{cases} \frac{\sqrt{\left[ \frac{a}{h^*} \right]^2 + 4\phi_h^*(1-\phi_h^*) \frac{a}{h^*}} - \frac{a}{h^*}}{2\sqrt{\left[ \frac{a}{h^*} \right]^2 + 4\phi_h^*(1-\phi_h^*)}} & \text{valid for } \phi_h^* \leq \frac{1}{2} \\ \frac{\sqrt{\left[ \frac{a}{h^*} \right]^2 + 1} - \frac{a}{h^*}}{2\sqrt{\left[ \frac{a}{h^*} \right]^2 + 1}} & \text{for } \phi_h^* > \frac{1}{2} \end{cases}$$

Figure 2.7.



Here, the effective shear depth  $h^*$  is defined as the distance between the tension and compression stringers. The Danish Code of Practice DS 411 requires the use of the internal moment lever arm "z" calculated at the section of maximum moment as the effective shear depth  $h^*$ .

For T, or I-section beams, we may identify the distance between the center of the compression flange and the centroid of tensile reinforcement as the effective shear depth  $h^*$ .

For conventional slender beams, in which the longitudinal reinforcement is governed by the bending moment calculation, the shear calculation becomes more simple. The solution for the shear carrying capacity is in this case.

$$\frac{\tau}{f_c^*} = \begin{cases} \sqrt{\Phi_v^* (1 - \Phi_v^*)} & \Phi_v^* \leq 0.5 \\ 0.5 & \Phi_v^* > 0.5 \end{cases} \quad (2.8)$$

For such beams,  $\nu$  may be considered as being only depending on the concrete strength. As an average, the straight line

$$\nu = 0.7 - \frac{f_c}{200} \leq 0.5 \quad (f_c \text{ in MPa}) \quad (2.9)$$

can be used.

### 3. Comparison with tests

#### 3.1 Beams without shear reinforcement

Mphonde, A. G. and Frantz, G. C. [5] have tested three series of reinforced concrete beams without shear reinforcement to determine their diagonal cracking strength and ultimate shear capacities. In each series the shear span-depth ratio  $a/d$  was held constant at 1.5, 2.5 or 3.6, while the nominal concrete compressive strength was varied from 21 to 103 MPa. The dimensions are given in figure 3.1.

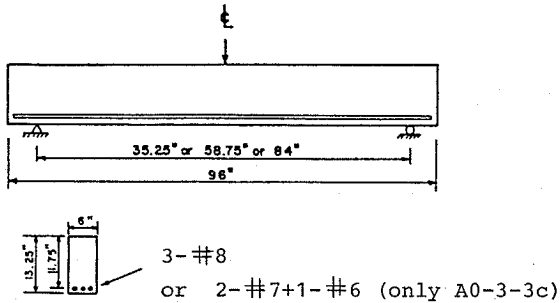


Figure 3.1 Test specimens ( 1 in. = 25.4 mm ).

BEAM MARK	a in	$f_c$ KSI	$A_s$ in <sup>2</sup>	$f_y$ KSI	$V_t$ KIPS	Failure mode
A0--3-3B	42.00	3.011	2.37	60.0	14.50	Diagonal tension
A0--3-3C	42.00	3.935	1.64	60.0	15.00	Diagonal tension
A0--7-3A	42.00	5.463	2.37	60.0	18.50	Diagonal tension
A0--7-3B	42.00	6.037	2.37	60.0	18.60	Diagonal tension
A0-11-3A	42.00	10.867	2.37	60.0	20.20	Diagonal tension
A0-11-3B	42.00	10.825	2.37	60.0	20.10	Diagonal tension
A0-15-3A	42.00	11.797	2.37	60.0	21.00	Diagonal tension
A0-15-3B	42.00	13.587	2.37	60.0	22.50	Diagonal tension
A0-15-3C	42.00	13.319	2.37	60.0	22.00	Diagonal tension
A0--3--2	29.38	2.986	2.37	60.0	17.50	Shear compression
A0--7--2	29.38	6.549	2.37	60.0	26.50	Shear compression
A0-11--2	29.38	11.498	2.37	60.0	25.00	Diagonal tension
A0-15-2A	29.38	12.148	2.37	60.0	40.00	Shear compression
A0-15-2B	29.38	10.065	2.37	60.0	46.20	Shear compression
A0--3--1	17.63	3.346	2.37	60.0	26.10	Shear flexure
A0-15-1A	17.63	11.524	2.37	60.0	62.00	Shear fluxure

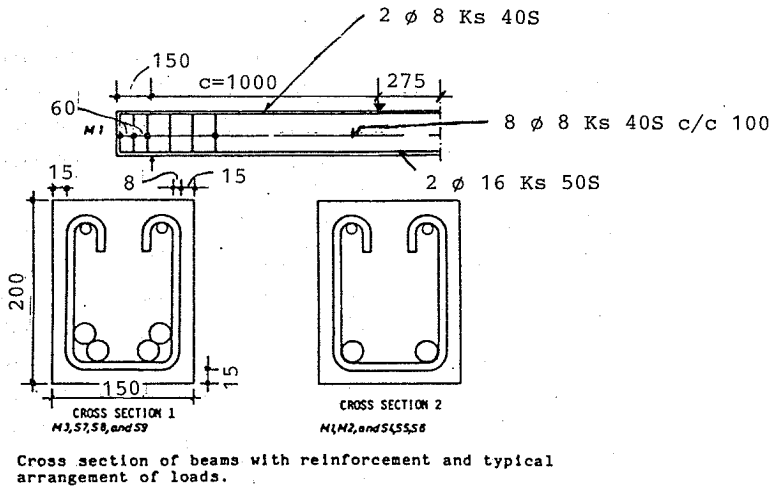
Figure 3.1 Continued

The results of these test series have been utilized in the determination of the effectiveness factor, see section 2.1.

### 3.2 Beams with shear reinforcement

Two groups of shear tests of beams with high strength concrete and vertical stirrups have been found in the literature [1] [4].

Bernhardt, C. J. and Fynboe, C. C. [1] has reported test results for beams in high strength concrete with ordinary aggregates. The tests included beams with cube strength up to 125 MPa. 6 beams without shear reinforcement and 5 beams with shear stirrups was observed to be failing in shear. For beams with shear reinforcement the open stirrups were used. The dimensions of the beams and the arrangements of reinforcement are shown in figure 3.2.



Measurements: mm

Figure 3.2 Cross section of beams with reinforcement and typical arrangement of loads.

BEAM MARK	H <sub>o</sub> cm	a cm	f <sub>c</sub> MPa	A <sub>s</sub> cm <sup>2</sup>	f <sub>y</sub> MPa	V <sub>t</sub> kN	Failure mode
S-----6A	16.7	40	83.2	6.28	510	95	Shear failure
S-----6B	16.7	40	83.2	6.28	510	123	Shear failure
S-----6C	16.7	40	83.2	6.28	510	115	Shear failure
S-----9A	16.0	55	83.2	12.56	510	80	Shear failure
S-----9B	16.0	55	83.2	12.56	510	64	Shear failure
S-----9C	16.0	55	98.4	12.56	510	68	Shear failure

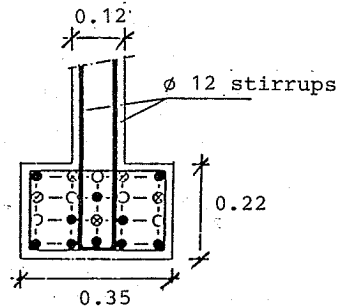
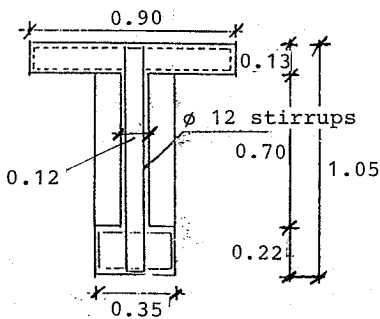
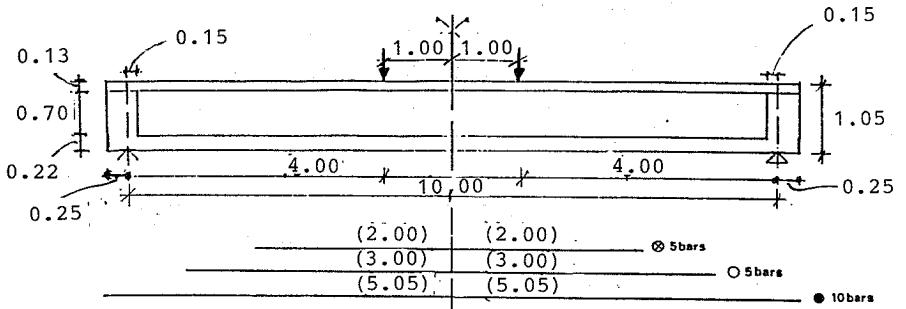
BEAM MARK	H <sub>o</sub> cm	a cm	f <sub>c</sub> MPa	A <sub>s</sub> cm <sup>2</sup>	f <sub>y</sub> MPa	r <sub>v</sub> %	f <sub>yw</sub> MPa	V <sub>t</sub> kN	Failure mode
S--5-A	16.7	40	83.2	6.28	510	0.447	427	110	Shear failure
S--7-A	16.0	55	83.2	12.56	510	0.673	427	140	Shear failure
S--7-B	16.0	55	83.2	12.56	510	0.673	427	150	Shear failure
S--8-A	16.0	55	83.2	12.56	510	0.447	427	125	Shear failure
S--8-B	16.0	55	83.2	12.56	510	0.447	427	135	Shear failure

Figure 3.2 Continued

For the data reported in [1], it has been found that the shear capacity is only 60–70% of that predicted by theory because of the bad arrangement of the open stirrups, see figure 3.2.

By Levi, F. and Marro, P. [4] seven beams, geometrically identical, were tested according to the plan in figure 3.3. In all cases transversal reinforcement was high bend  $\emptyset$  12 mm two legs stirrups with different spacing.

In these tests the shear span  $a = 3.80$  m is valid for all beams. When comparing with the theory, the effective shear depth  $h^*$  is taken as the distance between the centroid of tensile reinforcement and the middle line of the compressive flange.



Measurements : m

Figure 3.3 Test specimen.

BEAM MARK	$f_c$ MPa	$A_s$ cm <sup>2</sup>	$f_y$ MPa	$r_v$ %	$f_{yw}$ MPa	$V_y$ kN	$V_t$ kN	Failure mode
RC30A1	25.0	90.48	500	0.837	480	652	676	Shear failure
RC30A2	25.0	90.48	500	0.837	480	661	688	Shear failure
RC60A1	47.0	106.19	450	0.837	480	870	990	Shear failure
RC60A2	47.0	106.19	450	0.837	480	870	938	Shear failure
RC60B1	50.0	141.37	470	1.256	480	1140	1181	Shear failure
RC60B2	50.0	141.37	470	1.256	480	1160	1239	Shear failure
RC70B1	60.0	141.37	470	1.256	480	1280	1330	Shear failure

Figure 3.3 Continued

The general applicability of the web crushing criterion for beams with high strength of concrete is demonstrated by figure 3.4.

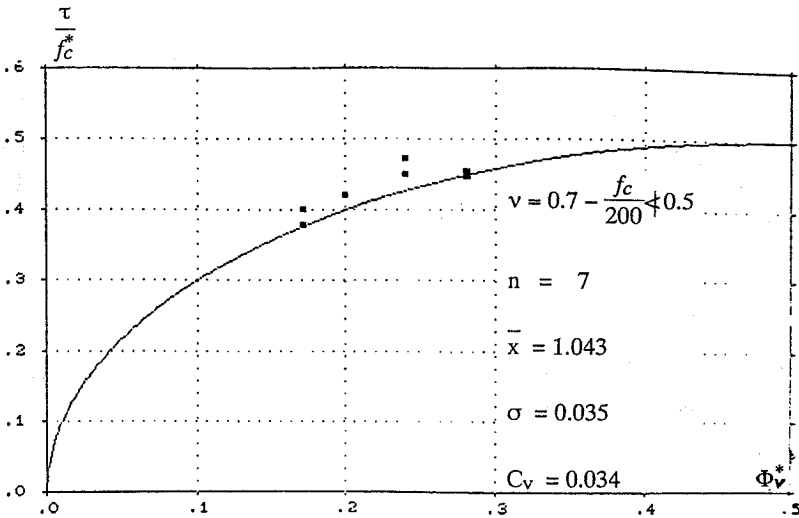


Figure 3.4 The plastic solution of beams with shear reinforcement compared with tests of high strength concrete beams [4].

For this series of large T-beams, the constant  $\nu = 0.55$  is even better than formula (2.9). In this case, for 7 beams failing in shear, the mean value is 1.008, while both the standard deviation and the coefficient of variation are 0.03.

The statistics of the ratios of tests [4] to predicted values by formulae (2.7) and (2.8) and the comparison is depicted in figure 3.5.

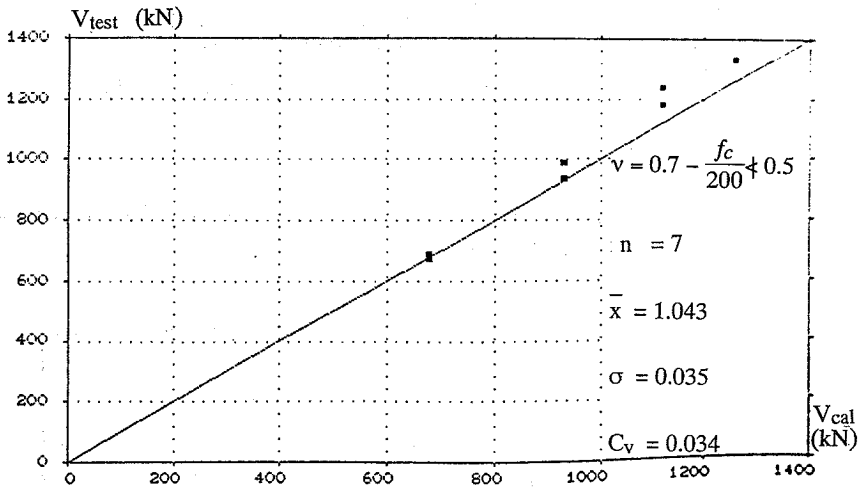


Figure 3.5 Comparison of test results with theoretical calculations of high strength concrete beams with web reinforcement [4].

#### 4. Conclusion

Based on this analysis, it can be concluded that the theoretical solutions based on a modified theory of plasticity, without any difficulties can be extended to high strength concrete.

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PHILOSOPHY 101

1998

1. The first part of the course will deal with the foundations of philosophy, including the history of philosophy and the major figures of the Western tradition. We will begin with the ancient Greeks, and then move on to the medieval and modern periods. The second part of the course will deal with contemporary philosophy, including the philosophy of language, the philosophy of mind, and the philosophy of action. We will also discuss some of the major contemporary philosophers, such as Wittgenstein, Quine, and Rawls. The third part of the course will deal with the philosophy of science, including the philosophy of physics, the philosophy of biology, and the philosophy of psychology. We will also discuss some of the major contemporary philosophers of science, such as Popper, Kuhn, and Lakatos. The fourth part of the course will deal with the philosophy of ethics, including the philosophy of moral theory, the philosophy of moral education, and the philosophy of moral psychology. We will also discuss some of the major contemporary philosophers of ethics, such as Rawls, Macneil, and Rawls. The fifth part of the course will deal with the philosophy of religion, including the philosophy of theism, the philosophy of atheism, and the philosophy of religious experience. We will also discuss some of the major contemporary philosophers of religion, such as Plantinga, Quine, and Rawls. The sixth part of the course will deal with the philosophy of art, including the philosophy of aesthetics, the philosophy of art history, and the philosophy of art criticism. We will also discuss some of the major contemporary philosophers of art, such as Danto, Macneil, and Rawls. The seventh part of the course will deal with the philosophy of law, including the philosophy of legal theory, the philosophy of legal education, and the philosophy of legal psychology. We will also discuss some of the major contemporary philosophers of law, such as Rawls, Macneil, and Rawls. The eighth part of the course will deal with the philosophy of politics, including the philosophy of political theory, the philosophy of political education, and the philosophy of political psychology. We will also discuss some of the major contemporary philosophers of politics, such as Rawls, Macneil, and Rawls. The ninth part of the course will deal with the philosophy of education, including the philosophy of educational theory, the philosophy of educational practice, and the philosophy of educational psychology. We will also discuss some of the major contemporary philosophers of education, such as Rawls, Macneil, and Rawls. The tenth part of the course will deal with the philosophy of social science, including the philosophy of social theory, the philosophy of social practice, and the philosophy of social psychology. We will also discuss some of the major contemporary philosophers of social science, such as Rawls, Macneil, and Rawls. The eleventh part of the course will deal with the philosophy of human nature, including the philosophy of human psychology, the philosophy of human development, and the philosophy of human evolution. We will also discuss some of the major contemporary philosophers of human nature, such as Rawls, Macneil, and Rawls. The twelfth part of the course will deal with the philosophy of the future, including the philosophy of futurology, the philosophy of utopianism, and the philosophy of dystopianism. We will also discuss some of the major contemporary philosophers of the future, such as Rawls, Macneil, and Rawls.

AFDELINGEN FOR BÆRENDE KONSTRUKTIONER  
DANMARKS TEKNISKE HØJSKOLE

Department of Structural Engineering  
Technical University of Denmark, DK-2800 Lyngby

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