Vattenfall AB

SHEAR FORCE CAPACITY OF EXISTING CONCRETE SLABS

Study of shear force capacity and design philosophy of reinforced concrete slabs over the years

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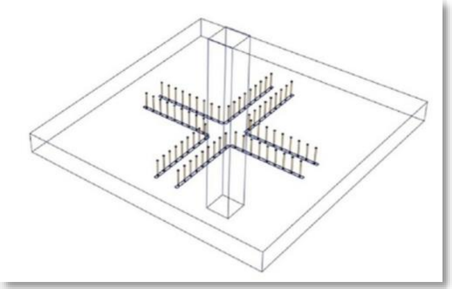
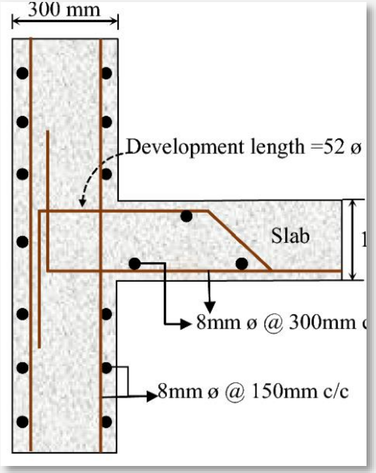
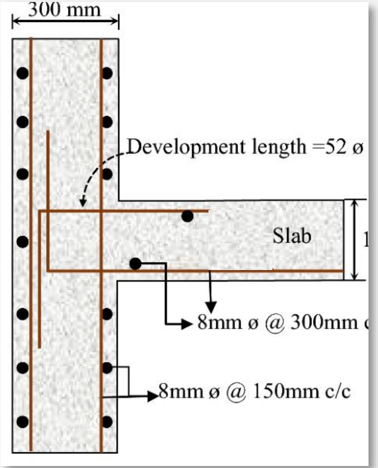
Why this study is important?

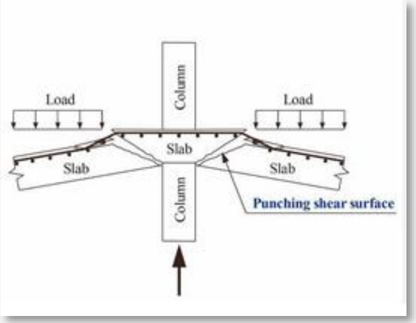
- As Swedish nuclear power plants are facing longer operating times, the risk of damage to the concrete slabs supporting the facilities increases.







Old Buildings



Old Buildings

Why this study is important?

- Is shear failure sudden & brittle? High risk in existing buildings.
- Lack of shear reinforcement in old slabs? Potential weaknesses.

Need to assess if older buildings still meet current safety requirements

- Older norms may have overestimated strength?
- Changes in Swedish Design Standards Over Time? Older Swedish norms vs. modern EC2

Safety margins

Background

These regulations have taken on different forms, including binding rules, general advice, instructions, and recommendations

Building codes in Sweden from 1947 until today (Boverket, Byggregler – en historisk översikt, 2022)

Standard		Published - valid to
BABS	Byggnadsstyrelsens anvisningar till byggnadsstadgan *Byggnadsstyrelsen's instructions for the Building Code*	1947 - 1950 1950 - 1960 1960 - 1968
SBN	Svensk Bygg Norm *Swedish Building Code*	1968 – 1976 1976 – 1982 1982 – 1987
PBL	Plan- och bygglagen *The Planning and Building Act*	1987 - 2011 2011 –1989
NR	Boverkets nybyggnadsregler *Boverket's Rules for New Construction*	BFS 1988:18 NR 1. 1989-1993
BBR [a)]	Boverkets byggregler *Boverket's Building Rules*	BFS 1993:57 BBR 1. 1994 - 2011 BFS 2011:6 BBR 18. 2011 - 2015
BKR	Boverkets konstruktionsregler *Boverket's Designing Rules*	BFS 1993:58 BKR 1 1994 -2010
EKS [a)]	Europeiska konstruktionsstandarderna, Eurokoder, EK *European Standards, Eurocodes, EC*	BFS 2008:8 EKS 1. 2008 - 2011 BFS 2011:10 EKS 8. 2011 - 2013

[a)]Valid

At the beginning of 2011, the European Standard Eurocode became mandatory for the design of supporting structures in Sweden, replacing the previous Swedish handbook BBK 04 (Boverkets Handbok om Betongkonstruktioner, 2004)

Introduction

Purpose:

The project proposal aims to **increase** knowledge about **shear force capacity** in reinforced concrete slabs

(Because existing concrete slabs in nuclear facilities are normally designed without special shear reinforcement except (in some building) for at columns where punching shear force may occur)

The proposal was relevant due to the potential extension of the operational life of Swedish nuclear power plants and changes in plant design.

Goals:

- The goal of the study is to **identify shear force capacity** in existing reinforced concrete slabs when using current standards (Eurocode 2). How do these older slabs compare to modern standards? Do they still provide sufficient shear capacity, or do they pose a potential risk?

Objectives

1. Comparison of design codes

List of standards that referred to shear force capacity for reinforced concrete slab without shear reinforcement and punching shear.

Publications	Shear force capacity	Punching shear
Eurocode 2	Section 6.2	Section 6.4
BKR_BBK04	Section 3.7, there is a limit to tensile strength (f_{ct}) of 2.7 MPa	Section 3.12
BKR_BBk79	Section 3.7.2 Same as in BBK04 without any limit regarding f_{ct}	Section 6.5.4
SBN 80	B7:1968 page 23	B7 8:27
SBN 75	B7:1968 page 23	B7 8:27
SBN67	SOU 1957:25 Recommended to see B7:1968 page 23	B7 8:27

- **Eurocode 2**

$$V_{Rd,c} = \left(\frac{0.18\,k}{\gamma_c}\ \sqrt[3]{100\,\rho\, f_{ck}}\right) b_w d$$

- **BBK 04 Method 1**

$$V_{Rd,c\_BBK04} = (0.3\ \xi(1{+}50\rho)\ f_{ct})\ b_w\ d$$

BBK 04 Method 2

$$V_{Rd,c\_BBK04} = \left(\frac{0.18\,k}{1.5\,\gamma_n}\ \sqrt[3]{100\,\rho\, f_{cck}}\right) b_w d$$

- **B7**

$$V_{Rd,c\_B7} = \tau_{bo} b_w d$$

Objectives

2. Search for other descriptions of the problem

Searching for other studies that address the issue, perhaps related to other industries.

1. Shear Strengthening of Existing Concrete Slabs, 2018

- **Loads**

Table 2.1 Comparison between values for distributed imposed loads [kN/m²] in Eurocode, BKR and SBN. Values from SBN are presented with "normal occurrence".

Specific Use	Eurocode	BKR		SBN	
		Free*	Fixed*	Free*	Fixed*
Areas for domestic and residential activities	1.5 – 2.0	1.5	0.5	1.5	0.5
Office areas	2.0 – 3.0	1.5	1.0	1.5	1.0

*Generally, a fixed action will affect the structure at the same place in the same way, whereas a free action could be moved or altered. Most actions will, however, consist of two parts, one fixed and one free.

Table 2.2 Examples of partial factors for load combination in ultimate limit state according to Eurocode and BKR.

Type of load	Eurocode	BKR
Permanent load	1.35	1.0
Variable load	1.5	1.3

Table 2.3 Different safety classes and their corresponding partial factors.

Category	Eurocode	BKR
Safety class 1	0.83	1.0
Safety class 2	0.91	1.1
Safety class 3	1.0	1.2

Table 2.4 Combined partial factors for load combinations and safety classes for Eurocode and BKR.

Category	Eurocode	BKR	Eurocode	BKR
	Permanent	Permanent	Variable	Variable
Safety class 1	1.12	1.0	1.25	1.3
Safety class 2	1.22	1.1	1.36	1.43
Safety class 3	1.35	1.2	1.5	1.56

- Loads are treated with the partial factor safety method both in Eurocode and BKR, but not in SBN.
- The partial factors that are utilized by Eurocode and BKR for the load combinations and safety classes differ.

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Objectives

Search for other descriptions of the problem

- **Shear design**

The resistance according to Eurocode 2 is below that of BBK and SBN, around 30% lower. A reason for this lies in the fact that Eurocode does not add the concrete and shear reinforcement contributions together.

Table 2.6 Determined capacities for the illustrated example.

Design code	Shear capacity [kN]
Eurocode 2	184
BBK	263
SBN	265

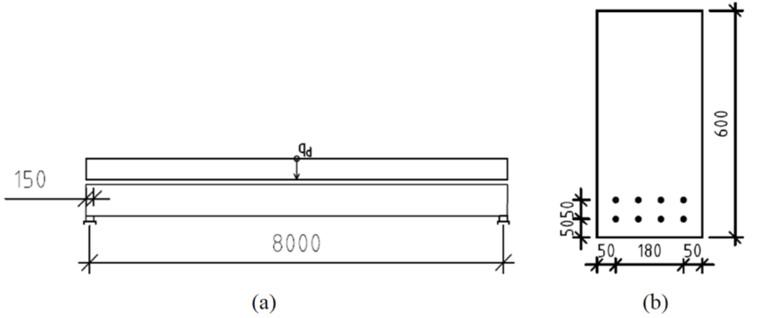

Figure 2.19 Views of the studied beam: (a) Elevation view; (b) Cross-sectional view.

The shear reinforcement consisted of 8 mm diameter steel bars with an even spacing of 140 mm. The capacity was then determined according to both BBK04 and SBN80 for the same input values as for the Eurocode

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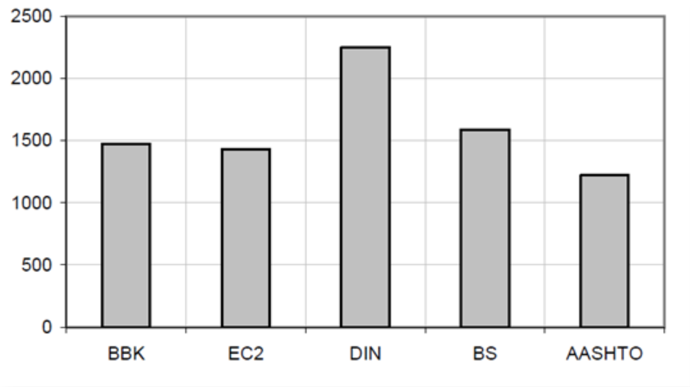
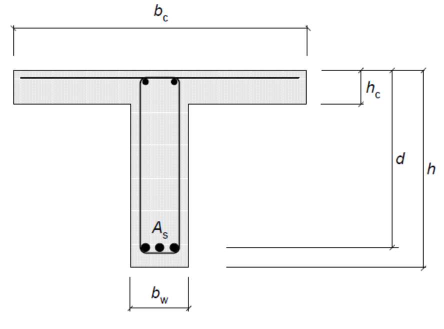
Objectives

Search for other descriptions of the problem

2. Tvärkraftsdimensionering. Jämförelser mellan olika normer, 2002

- svensk: BBK 94 + BRO 94
- europeisk: Eurocode 2 (prEN 1992-1-1, July 2002) Design of concrete structures
- tysk: DIN 1045-1 (juli 2001) Tragwerke aus Beton, Stahlbetong und Spannbeton
- brittisk: BS 5400-4:1990 Code of practise for design of concrete bridges
- amerikansk: AASHTO LRFD Bridge Design Specifications 1998





Objectives

Search for other descriptions of the problem

3. Genomstansning av betongplattor, en jämförelse av några europeiska normer, 1993

Av de sju normer/metoder som här studeras bygger fem på modellen med kontrollyta. De är

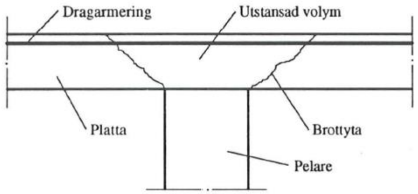
- den nu gällande svenska bestämmelserna för betongkonstruktioner BBK 79
- dansk norm DS 411
- engelsk norm BS 8110
- tysk norm DIN 1045
- CEB-FIP Model Code 1990, vilket är en norm som utarbetats av Europeiska Betong-Kommittén och Internationella Spännbetong Federationen.

De övriga två

- den innan BBK 79 gällande svenska normen B7
- den noggrannare metoden som finns i Betonghandboken

Normer	Egentyngd	Nyttig last
BBK 79 och Betonghandbok	1,0	1,3
DS 411	1,0	1,3
BS 8110	1,4	1,6
CEB Model Code	1,35	1,5

Tabell 5.1 Föreskrivna värden på γ_f förutsatt att endast egentyngd och nyttig last verkar på plattan och att båda verkar ogynnsamt.



Figur 2.1 Genomstansningsbrott hos betongplatta upplagd på pelare.

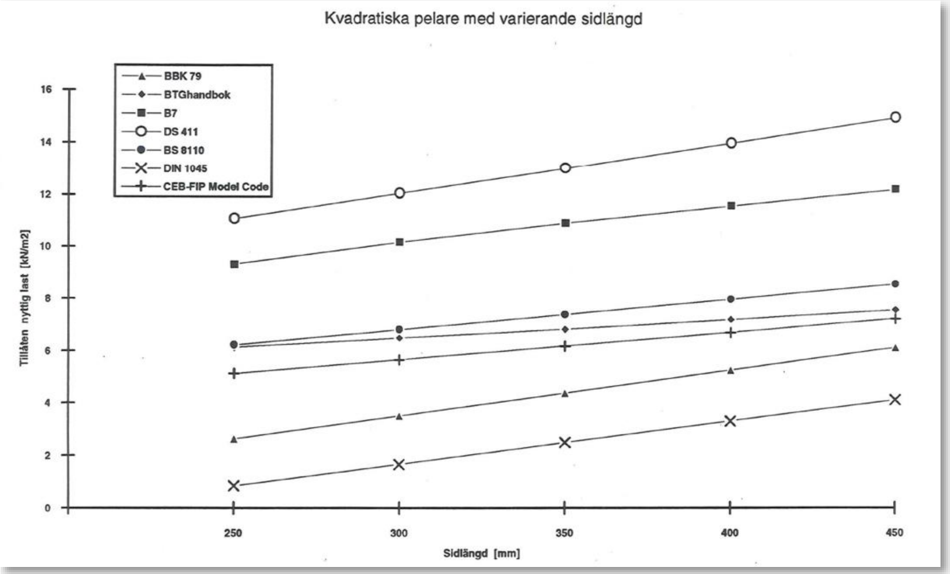
Normer	Oarmerad betong	Armerad betong	Armeringsstål
BBK 79 och Betonghandbok	1,5	1,5	1,1
DS 411	2,5	1,8	1,4
BS 8110	1,5	1,25 *	1,15
CEB Model Code	1,5	1,5	1,15

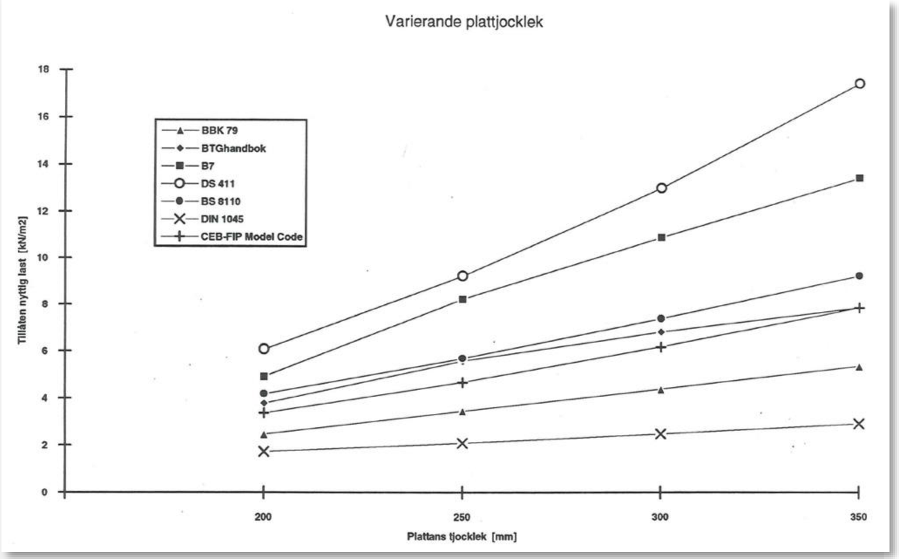
* avser skjuvhållfasthet utan skjuvarmering

Tabell 5.2 Föreskrivna värden på γ_m.

Objectives

Search for other descriptions of the problem





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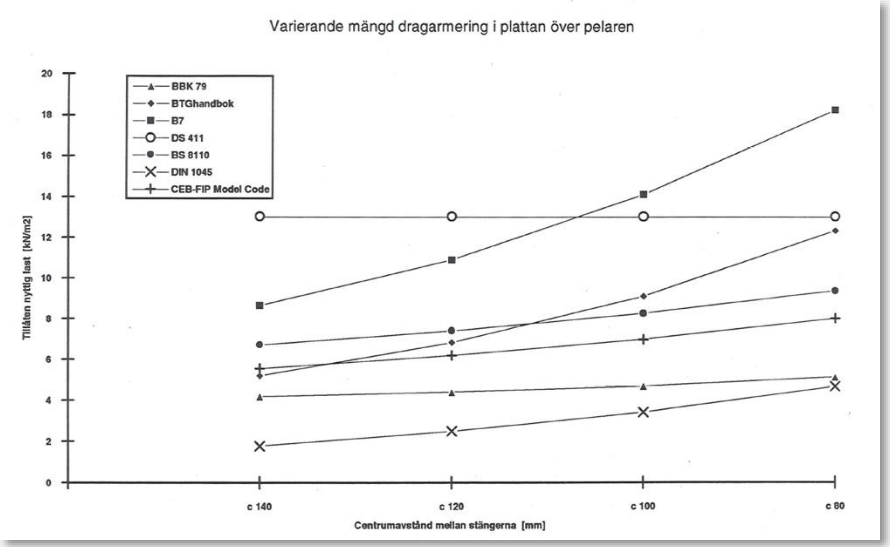
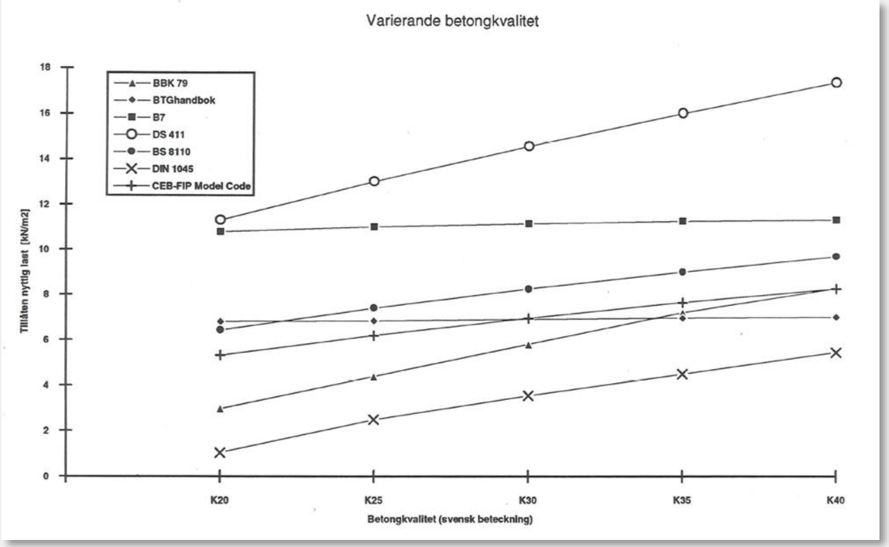
Objectives

Search for other descriptions of the problem





Identification of critical parameters

- **Concrete strength**

Classification in Swedish codes	f_{cck_B7}# (MPa)	f_{ctk_B7} (MPa)	τ_{bo}¤ (MPa)	Concrete class+ (BBK04, 2004)	f_{cck_BBK04} (MPa)	f_{ctk_BBK04} (MPa)	Concrete class (SS-EN1992-1-1:2005, 2004)	$f_{ctk,0.05}$ (MPa)
K8*	5.50	0.75	-	-	-	-	-	-
K12*	8.50	0.90	-	-	-	-	-	-
K16 / K160	11.50	1.05	0.294	C12/15	11.50	1.05	C12/15	1.10
K20 / K200	14.50	1.20	0.343	C16/20	15.50	1.25	C16/20	1.30
K25 / K250	18.00	1.40	0.392	C20/25	19.00	1.45	C20/25	1.50
K30	21.50	1.60	0.422	-	-	-	-	-
K35 / K350	25.00	1.80	0.461	C25/30	24.40	1.70	C25/30	1.80
K40 / K400	28.50	1.95	0.491	C28/35	27.00	1.80	-	-
-	-	-	-	C30/37	29.00	1.9	-	-
K45 / K450	32.00	2.10	0.520	C32/40	30.50	2.00	C30/37	2.00
K50 / K500	35.50	2.25	0.550	C35/45	33.50	2.10	C35/45	2.20
K55 / K550	39.00	2.40	0.569	C40/50	38.00	2.40	C40/50	2.50
K60 / K600	42.50	2.50	0.590	C45/55	43.00	2.55	C45/55	2.70
K70	49.50	2.50	-	C50/60	47.50	2.75	C50/60	2.90
-	-	-	-	C54/65	51.50	2.80	C55/67	3.00
-	-	-	-	C55/67	52.00	2.85	-	-
-	-	-	-	C58/70	55.00	2.90	-	-
K80	56.60	2.50	-	C60/75	57.00	2.95	C60/75	3.10

* For lightweight concrete (BBK79, 1988), p.23.

The characteristic (5%) cylinder strength (150 mm x 300 mm) , 20 ± 2 ^{0}C temperature, and water-cure conditions, according to CEP-FIP Model Code for Concrete Structures (BBK79, 1988), p.23

+ Different characteristic compressive strength are used for lightweight concrete, Table 7.221b (BBK04, 2004), p.33

¤ Concrete shear stresses, Table 2:261 (1 MPa equals 0.0981 kp/cm^2) in (B7, 1968), p. 23.

Objectives

Identification of critical parameters

- **Slab thickness**

Eurocode 2

$$V_{Rd,c} = \left(C_{Rd,c}\, k \sqrt[3]{100\,\rho\, f_{ck}} + k_1\, \sigma_{cp}\right) b_w d$$

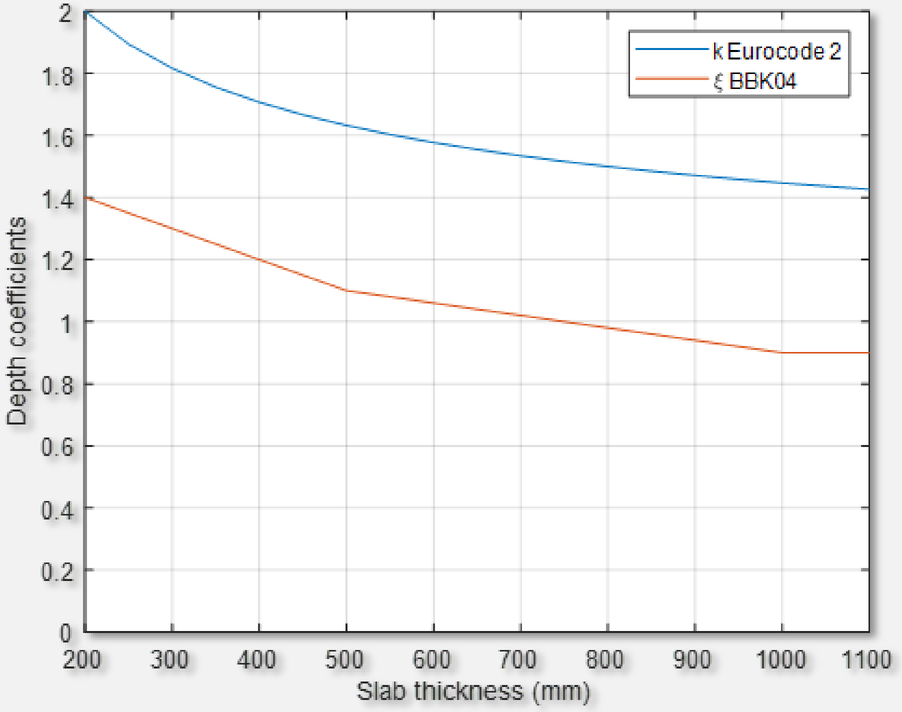
$$k = 1 + \sqrt{\frac{200}{d}} \leq 2.0 \quad (d \text{ in mm})$$

Boverket BBK-04

$$V_{c\_BBK04} = b_w\, d\, f_v$$

f_v is concrete shear strength.
$f_v = 0.3\,\xi(1+50\rho)\,f_{ct}$

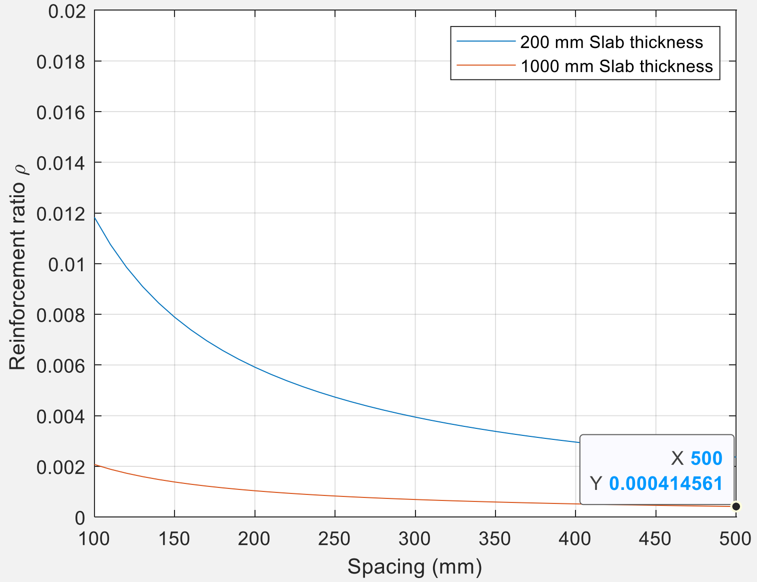
$$\xi = \begin{cases} 1.4 & \text{for} \quad d \leq 0.2 \text{ m} \\ 1.6 - d & \text{for} \quad 0.2 \text{ m} < d \leq 0.5 \text{ m} \\ 1.3 - 0.4d & \text{for} \quad 0.5 \text{ m} < d \leq 1.0 \text{ m} \\ 0.9 & \text{for} \quad 1.0 \text{ m} < d \end{cases}$$



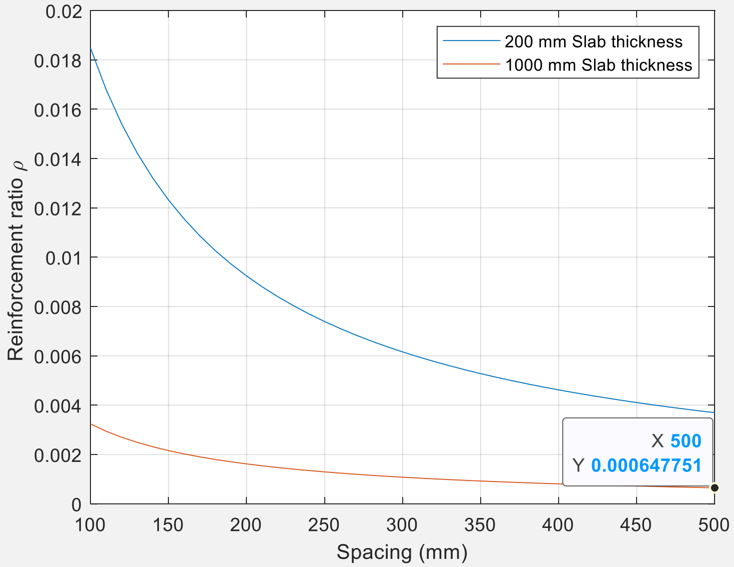
Objectives

Identification of critical parameters

- **Reinforcement content**



Steel reinforcement diameter, 16 mm, min rho 0.00041



Steel reinforcement diameter, 20 mm

Results

Comparative calculations

- Shear force capacity

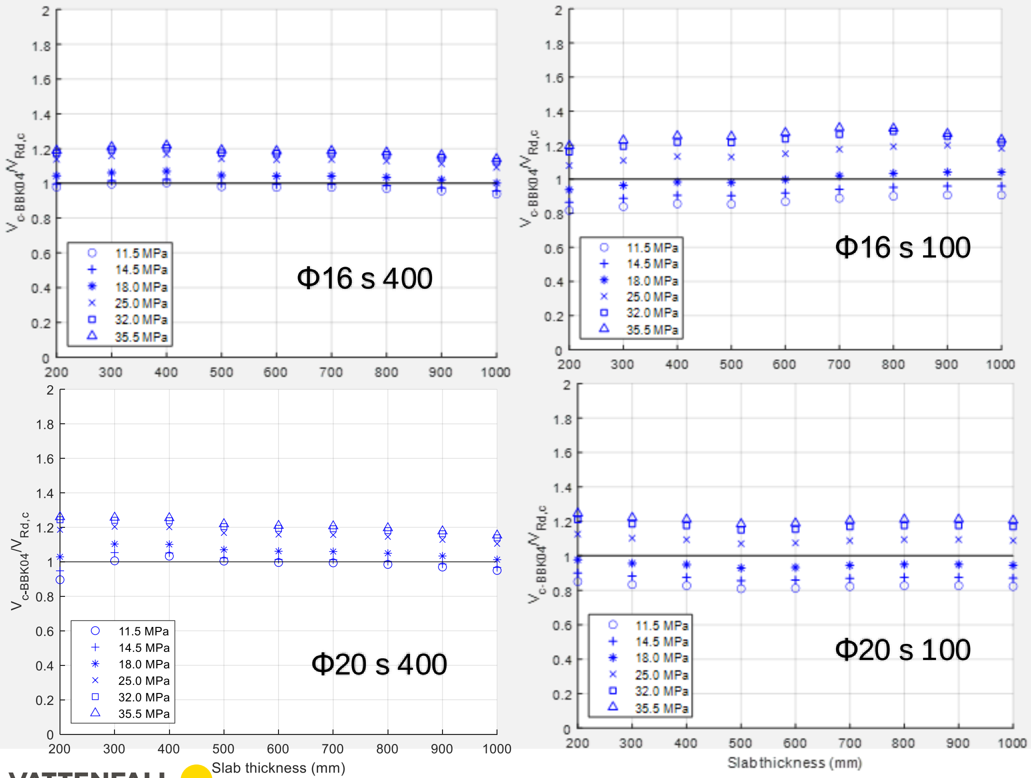
- Eurocode 2

$$V_{Rd,c} = \left(\frac{0.18\,k}{\gamma_c}\;\sqrt[3]{100\,\rho\,f_{ck}}\right) b_w d$$

-BBK 04 Method 1

$$V_{c\_BBK04} = (0.3\,\xi(1+50\rho)\,f_{ct})\,b_w\,d$$

Safety class 1



Results

Comparative calculations

- Shear force capacity

Safety class 3

Eurocode 2

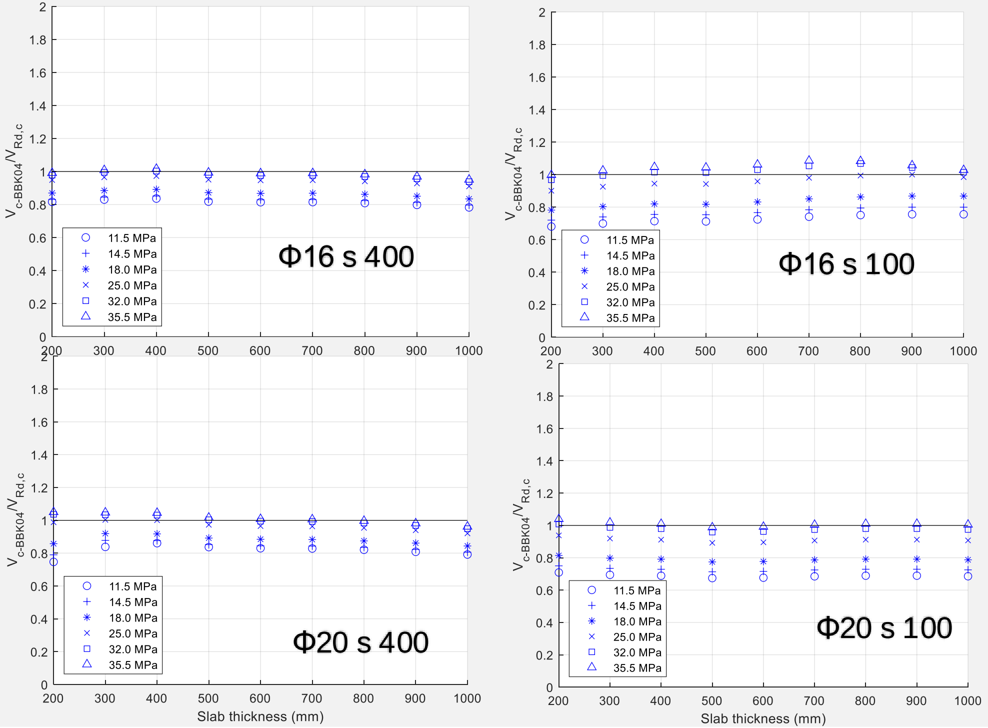
$$V_{Rd,c} = \left(C_{Rd,c}\, k \sqrt[3]{100\, \rho\, f_{ck}} + k_1\, \sigma_{cp}\right) b_w d$$

Boverket BBK-04

$$V_{c\_BBK04} = b_w\, d\, f_v$$

f_v is concrete shear strength.

$$f_v = 0.3\, \xi (1+50\rho)\, f_{ct}$$



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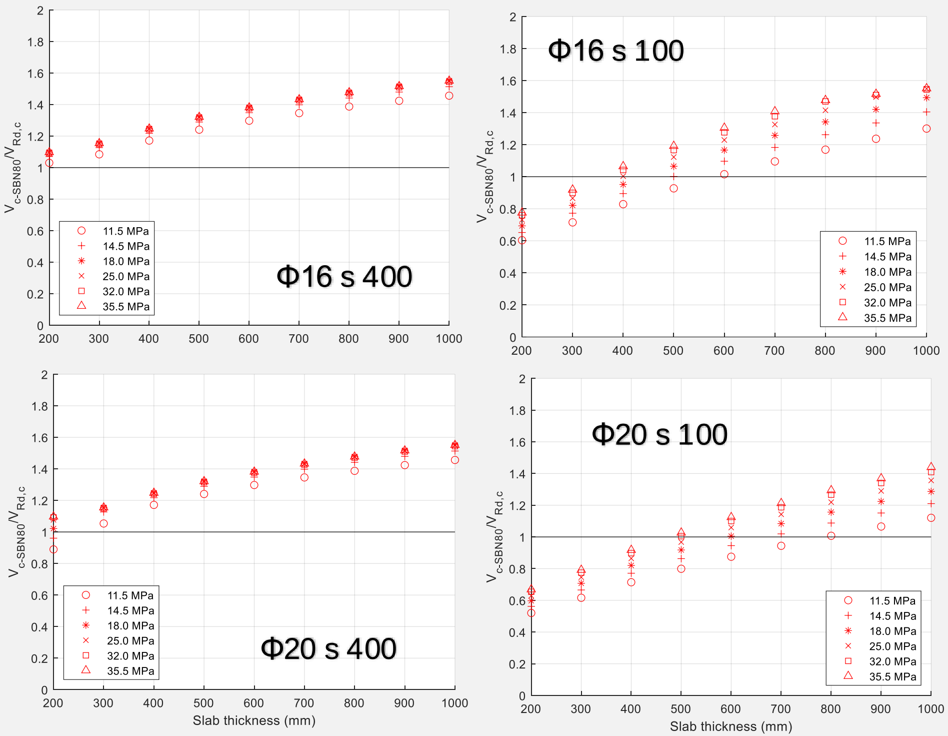
Results

Comparative calculations

- Shear force capacity



- Eurocode 2

$$V_{Rd,c} = \left(\frac{0.18\,k}{\gamma_c}\sqrt[3]{100\,\rho\,f_{ck}}\right) b_w d$$

B7

$$V_{Rd,c\_B7} = \tau_{bo} b_w d$$

Table 3 Characteristic strength for different codes in Sweden and Eurocode 2

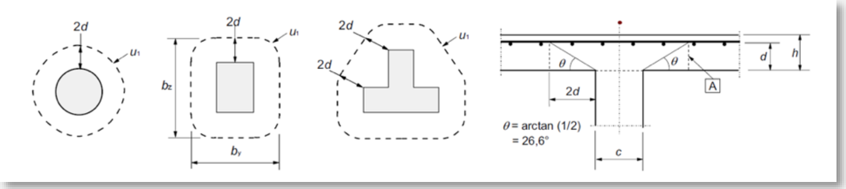
Classification in Swedish codes	f_{cck_B5}# (MPa)	f_{ctk_B5} (MPa)	τ_{bo}¤ (MPa)	Concrete class+ (BBK04, 2004)	f_{cck_BBK04} (MPa)	f_{ctk_BBK04} (MPa)	Concrete class (SS-EN1992-1-1:2005, 2004)	$f_{ctk,0.05}$ (MPa)
K8*	5.50	0.75					-	-
K12*	8.50	0.90						-
K16 / K160	11.50	1.05	0.294	C12/15	11.50	1.05	C12/15	1.10
K20 / K200	14.50	1.20	0.343	C16/20	15.50	1.25	C16/20	1.30
K25 / K250	18.00	1.40	0.392	C20/25	19.00	1.45	C20/25	1.50
K30	21.50	1.60	0.422					
K35 / K350	25.00	1.80	0.461	C25/30	24.40	1.70	C25/30	1.80
K40 / K400	28.50	1.95	0.491	C28/35	27.00	1.80		
				C30/37	29.00	1.9		
K45 / K450	32.00	2.10	0.520	C32/40	30.50	2.00	C30/37	2.00
K50 / K500	35.50	2.25	0.550	C35/45	33.50	2.10	C35/45	2.20
K55 / K550	39.00	2.40	0.569	C40/50	38.00	2.40	C40/50	2.50
K60 / K600	42.50	2.50	0.590	C45/55	43.00	2.55	C45/55	2.70

Results

Comparative calculations

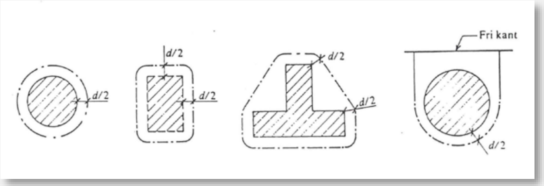
PUNCHING SHEAR CAPACITY

Eurocode 2



$$V_{Ed,c} = v_{Ed,c} \,.\, u_1 . d_{eff}$$

Boverket BBK-79

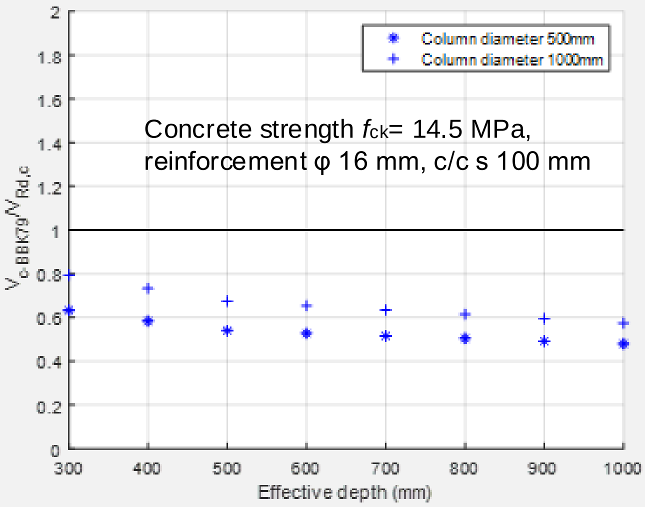


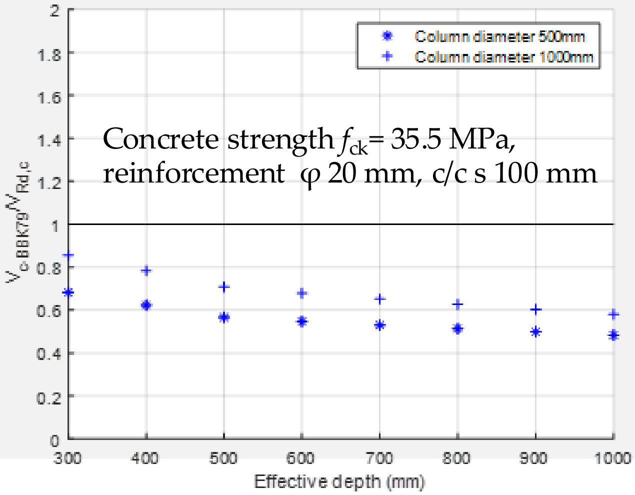
$$f_{v1} = 0.45\,\xi(1+50\rho_2)\,f_{ct}$$

where

$$\xi = \begin{cases} 1.4 & \text{for } d \le 0.2\text{ m} \\ 1.6 - d & \text{for } 0.2\text{ m} < d \le 0.5\text{ m} \\ 1.3 - 0.4d & \text{for } 0.5\text{ m} < d \le 1.0\text{ m} \\ 0.9 & \text{for } 1.0\text{ m} < d \end{cases}$$

$$V_u = \mu \,.\, f_{v1} \,.\, u . d_{eff}$$



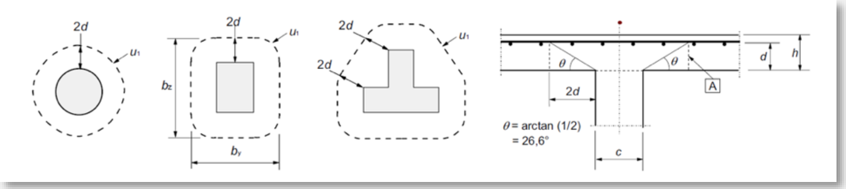


Results

Comparative calculations

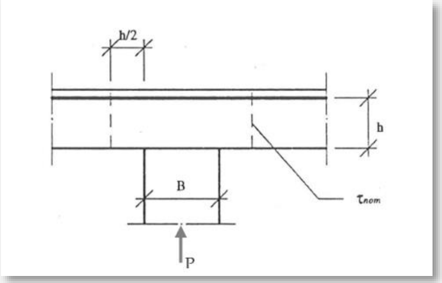
- PUNCHING SHEAR CAPACITY

Eurocode 2



$$V_{Ed,c} = v_{Ed,c} \,.\, u_1 . d_{eff}$$

B7

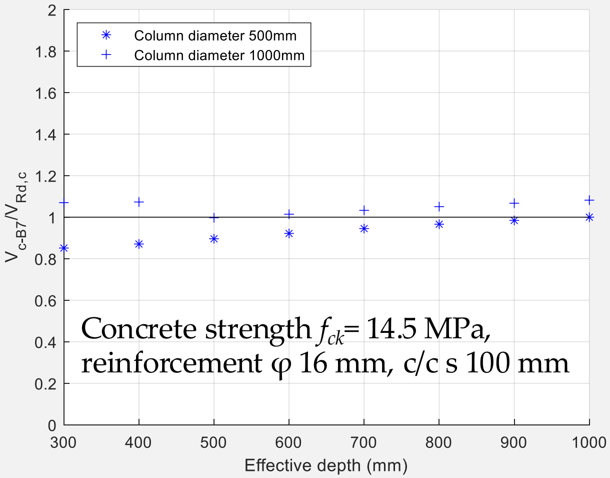


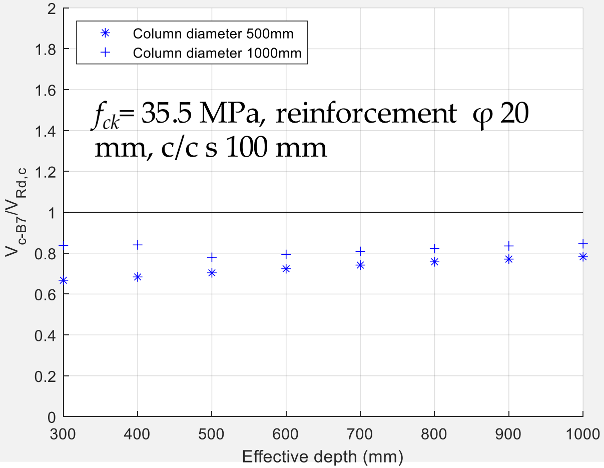
$$\tau_1 = \tau_0 \frac{15}{10 + \frac{c}{2h}}$$

där c är stödarmeringens utsträckning över pelare
τ_0 beror på betongkvaliteten enligt tabell 4.1

Betong	K200	K250	K300	K350	K400
τ_0 [kp/cm^2]	10,5	11,5	12,5	13,0	13,5

Tabell 4.1



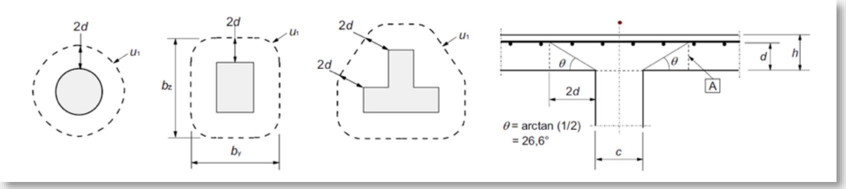


Results

Comparative calculations

- PUNCHING SHEAR CAPACITY

Eurocode 2



$$V_{Ed,c} = v_{Ed,c} \,.\, u_1 . d_{eff}$$

Concrete Handbook

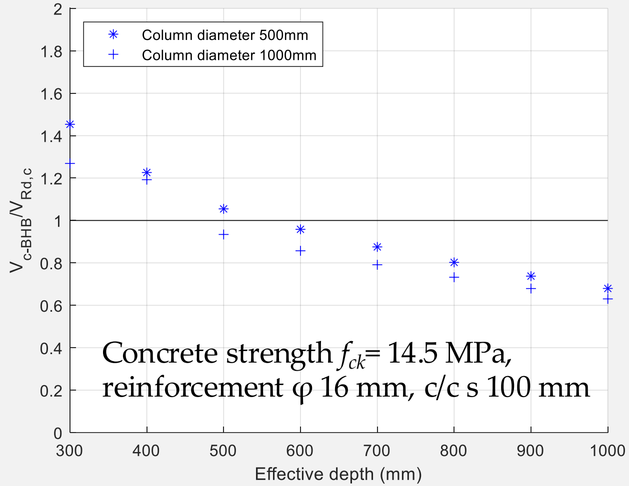
$$\tau_{v,nom} = \frac{F}{\pi d(B+d)} \leq f_{v1} \qquad (22)$$

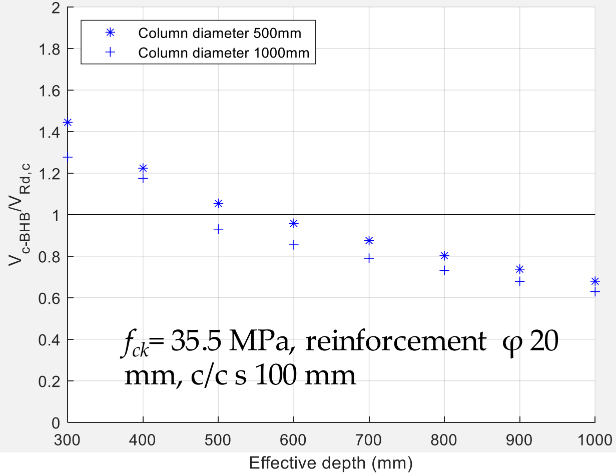
f_{v1} shear strength without shear reinforcement.

$$f_{v1} = 0.9 \cdot 0.6 \cdot \xi \cdot \alpha \cdot f_{v1,id} \qquad (23)$$

ξ is a coefficient that takes into account the influence of the plate thickness.

α is a coefficient that depends on the ratios B/d, c/d and f_{st}, f_{cc}.





Conclusions

Comparison Criteria	BBK04 / BBK79	B7	BHB
Shear Force Capacity	Overestimates (up to 25%) for low reinforcement; aligns with EC2 for high reinforcement.	Overestimates (up to 25% for slabs of 200–400 mm thickness)	
- Effect of Strength	Overestimate with an increase in the compressive strength of concrete higher than 15 MPa.	Base shear strength approach does not adjust for compressive strength	
- Safety Factor	Using safety factor ($\gamma n = 1.2$) leading to lower predictions (10–15% lower than EC2 for safety class 3)	No explicit safety classes adjustments	
- Slab Thickness	Predictions depend on reinforcement levels more than slab thickness. However, a slight variation ranging between 5 – 10 % can be observed for moderate reinforcement ratios.	Overestimates capacity for moderate slab thicknesses (200–400 mm) up to 25% higher than EC2.	
Punching Shear	Underestimates by ~35-40% due to a shorter control perimeter (d/2 from the column face)	Closer to EC2 for thicker slabs but overestimates for thinner slabs	Matches EC2 for most slabs but underestimates for deep slabs (>500 mm)
- Reinforcement Impact	Conservative estimates, lacks reinforcement adaptability	Uses experimental factors but still overestimates	Overestimation reduces as depth increases
General Observations	Not fully align with EC2 for shear force. Good margins for punching shear.	Lacks reinforcement adaptability and overestimates in moderate slab thicknesses for both shear and punching	Generally, matches EC2 for deep slabs in punching shear

Thank you!

Any questions?