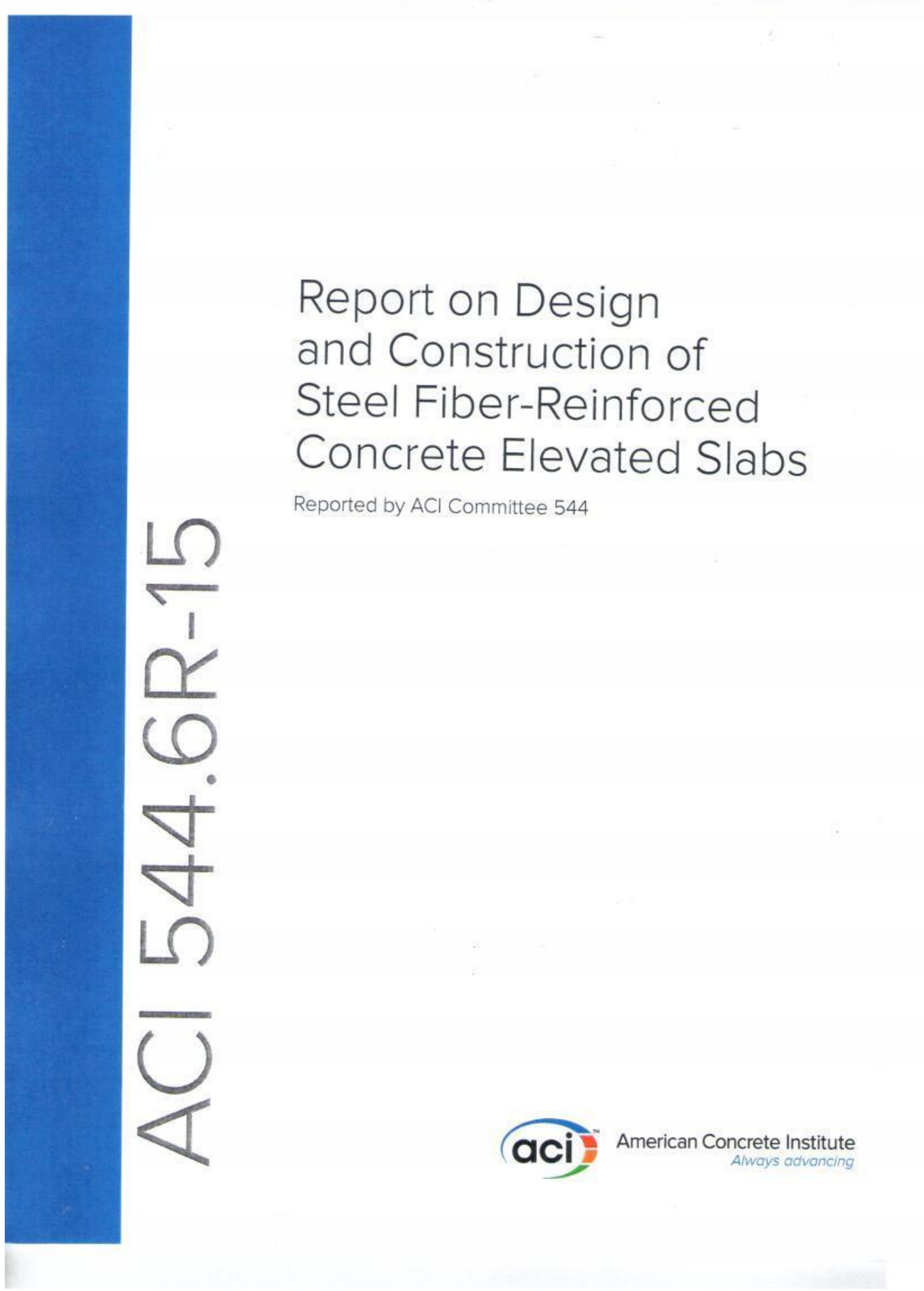

ACI 544.6R-15

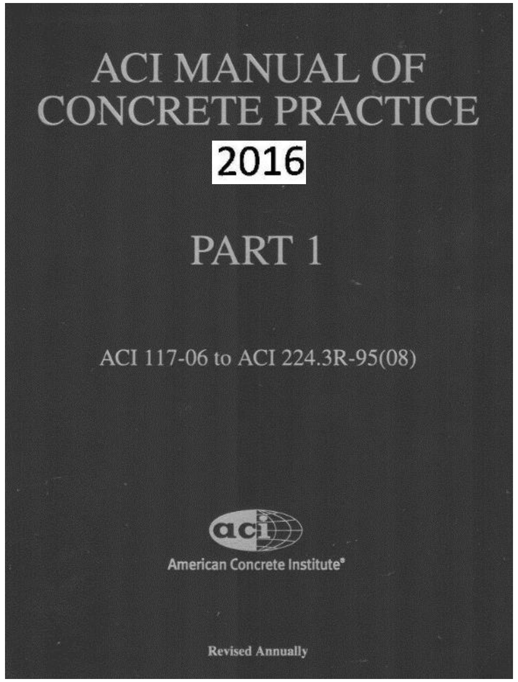
Report on Design and Construction of Steel Fiber-Reinforced Concrete Elevated Slabs

Reported by ACI Committee 544

aci American Concrete Institute
Always advancing

A new « American Concrete Institute » report released as from november 2015

The report is part of the
« ACI Manual of Concrete Practice » Ed, 2016 and further


ACI MANUAL OF
CONCRETE PRACTICE
2016

PART 1

ACI 117-06 to ACI 224.3R-95(08)

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Revised Annually

How to use ACI 544 6R15 ?

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Introduction

In the last 23 years over 15 million m² of SFRC piled slabs have been completed and , 100 buildings have been completed with SFRC suspended elevated flat slabs:

Piled slabs called **G-SRFS** (G: ground)

Applications – Suspended slab on piles

TAB-STRUCTURAL suspended floor system:

Elavated supended slabs called **E-SFRS** (E: elevated)

A number of full scale tests from 1994 to 2014:

Ternat (1994),Townsville (2000), Bissen (2004), Nieuw Vennep (2005), Tallinn (2007), Klaipeda (2011), Eindhoven (2011), Göteborg (2014),

JCU
JAMES COOK UNIVERSITY

FULL-SCALE TESTING OF A FIBRE-REINFORCED SUSPENDED CONCRETE SLAB

LUKE ST. GEORGE
CIVIL ENGINEERING

INTRODUCTION

The full scale test was performed by constructing a 9.6 m x 9.6 m concrete slab suspended on 16 columns. The slab consisted of nine 3.1 m x 3.1 m bays and was 160 mm thick. The slab was reinforced with Twincone steel fibres at a dosage of 50 kg per cubic metre of concrete.

OBJECTIVES

- Apply loads to the centre bay and a corner bay to determine their maximum load carrying capacities.
- Measure deflections at six points on each bay at each loading increment.
- Observe crack patterns on the top and bottom of each bay.
- Develop a Finite Element Model (F.E.M) of a conventionally reinforced slab comparing its strength and cost with a steel fibre reinforced concrete (SFRC) slab.

Contact: Luke St. George / Dr. John Ginger and Dr. W. Karunasena

METHODOLOGY

The Twincone fibres were added directly into the hopper of the concrete trucks, and mixed into the concrete. The first attempt at pouring the slab was unsuccessful as the firbes balled within the mix. This problem was rectified in the second attempt with the use of a fibre blower and a revised mix design.

A rigid I-section was used in order to apply the loads to the slab bays. The beam was inserted into two frames that were bolted to the slab with draw-bolts that extended from the columns. A hydraulic jack applied was placed between the I-section and the slab in order to apply the loads.

Deflections were measured using six VRT instruments

SLAB RESULTS

- Max load capacity of centre bay = 400 kN
- Max load capacity of corner bay = 300 kN
- Max deflection of centre bay = 29.64 mm
- Max deflection of corner bay = 31.16 mm
- The crack patterns for the top and bottom faces of the centre bay are given below

BOTTOM FACE
TOP FACE

F.E.M RESULTS

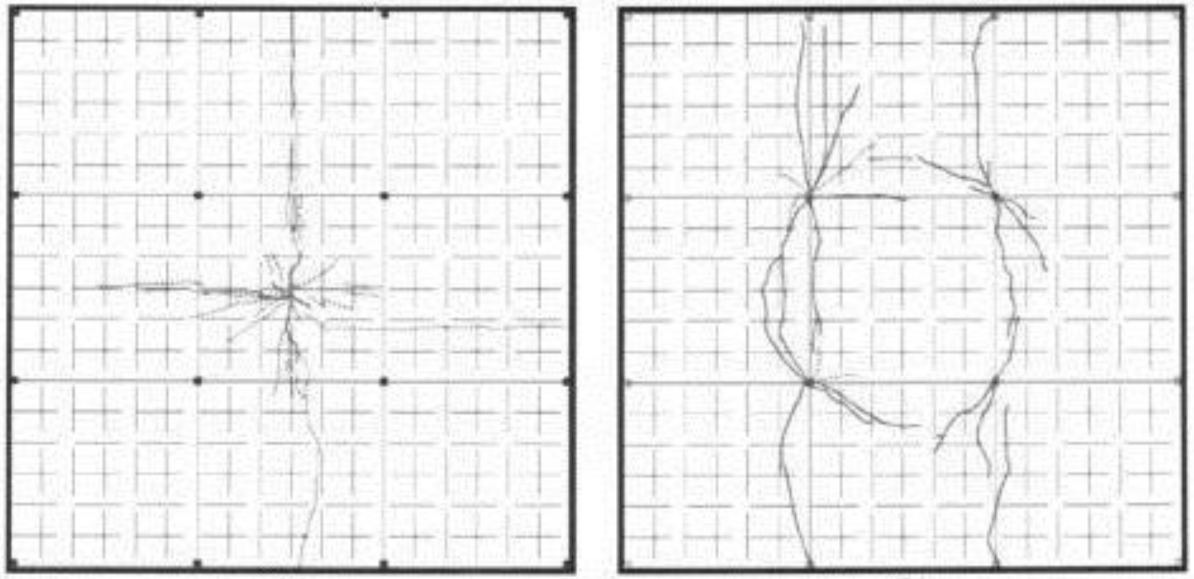
- A conventionally reinforced slab would require approx. three times the amount of steel as the SFRC slab to hold identical loads.
- A conventionally reinforced slab would cost approx. twice as much as a SFRC slab.

CONCLUSIONS

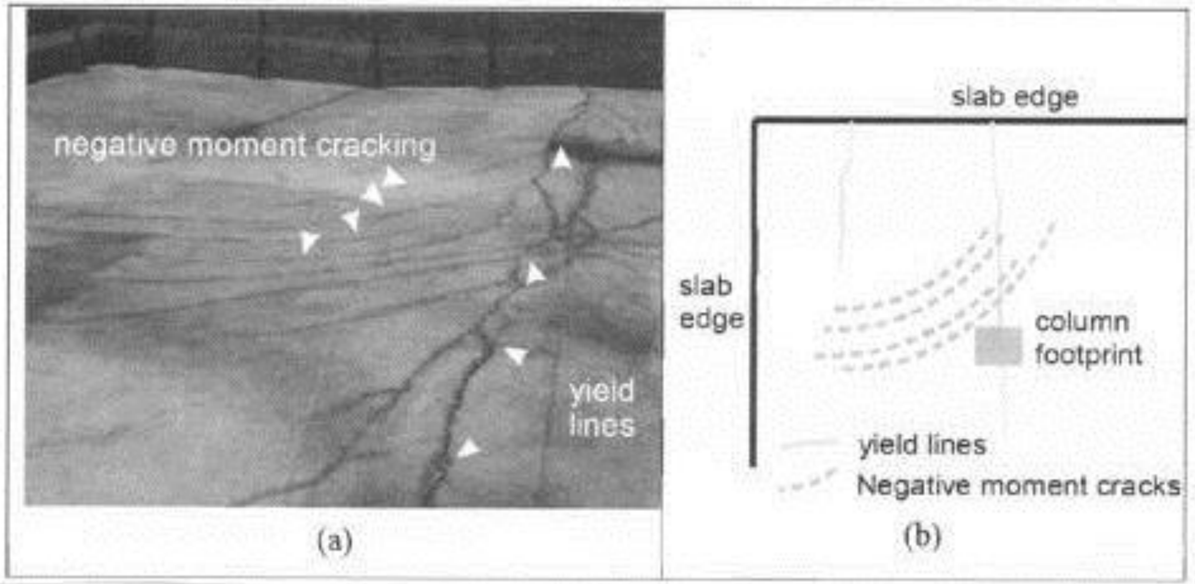
Steel fibre reinforced concrete offers a safe and economical alternative to conventionally reinforced concrete.

Full scale elevated SFRC slab cracking and yield lines:

Centre Point Loading
3 x 6 m x 6 m - 200mm
P (cracking) = 120kN
P (ultimate) = 500kN


(a) (b)

At the free corner span:
P(ultimate) = 300kN
Residual loading at 260mm deflection: 150kN



(a) (b)

Example: Tallinn full scale test (2007)

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Centre Point loading of 600kN

First crack at 120kN

UDL = 5kN/m²

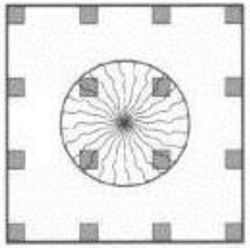
2mm deflection

Cracking pattern : 0,3mm/250kN

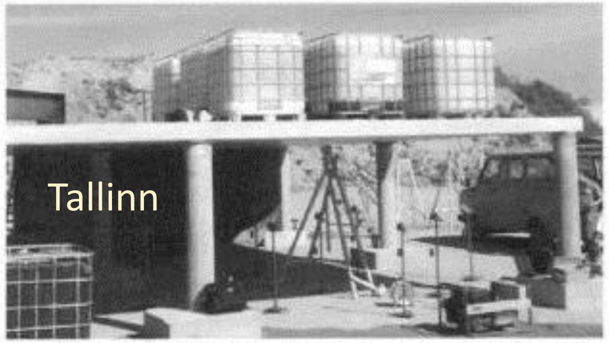
600kN: 3mm crack opening.

Bottom cracks only.

3 x 6 m x 6m spans
18m x 18m
200mm
70kg/m³ HE+1/60
steelfibres



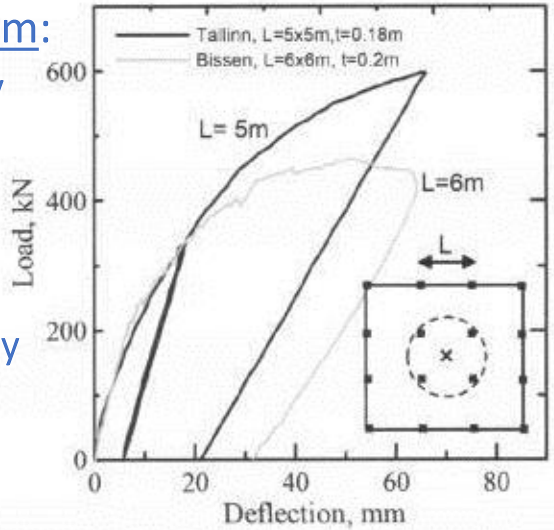
2 full scale tests up to rupture



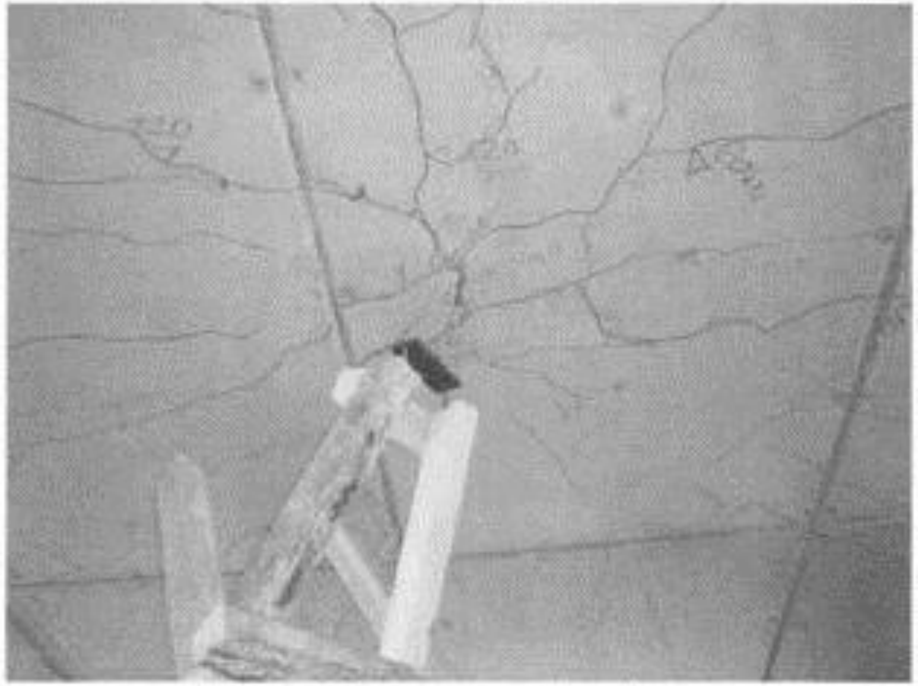
Center point loading diagram:

Ultimate loading intensity
450 - 650kN

first crack loading intensity
120 - 150 kN



Typical cracking of 0,3mm opening at 250kN loading intensity



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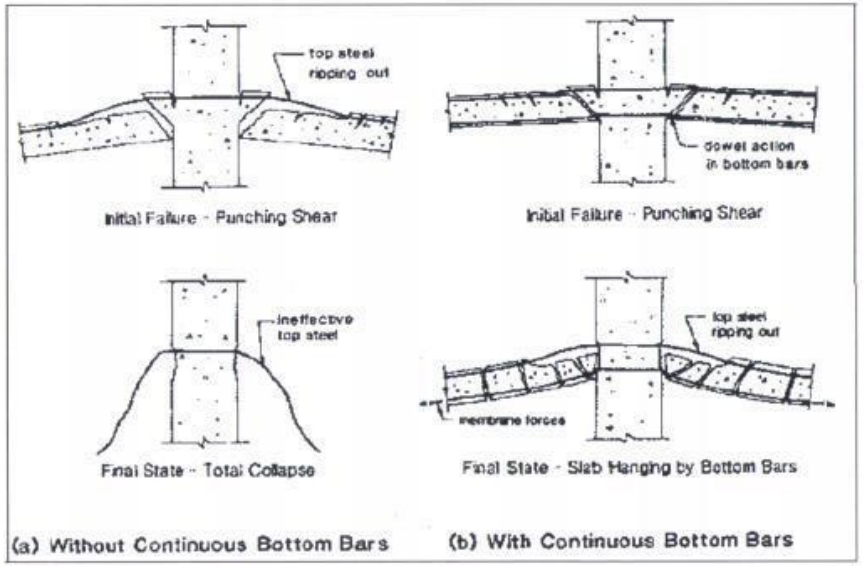
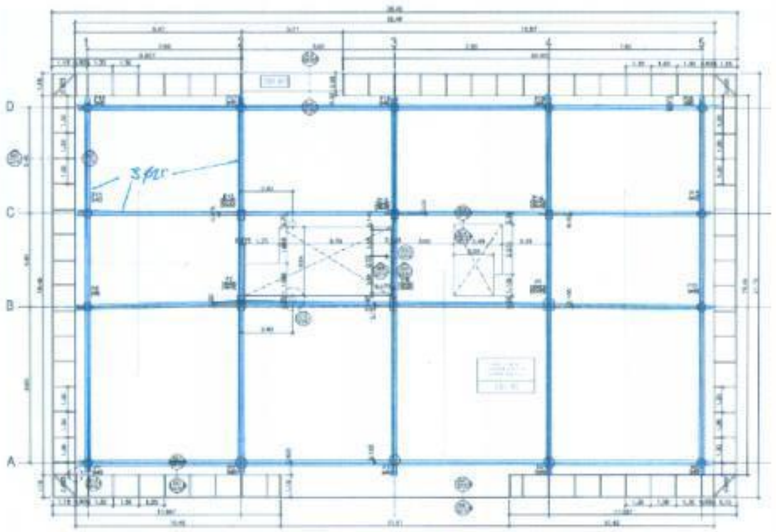
Minimum Structural Integrity Reinforcing also called Anti-Progressive Collapse Rebars



(a) Without Continuous Bottom Bars (b) With Continuous Bottom Bars



ARMADURA "APC": 3ø25, CARA INFERIOR, EN LÍNEAS DE PILARES

APC rebars in blue
(LKS project-Spain)

APC/SIR bottom rebars running from column to column

ACI 544 6R15 : mandatory Anti-Progressive-Collapse rebars in the bottom from column to column
APC rebars prevent progressive collapse if one or more column fail

A practical case of a 180mm slab of column grid of 5m x 5m subjected to 4kN/m² Live Load; columns of 250mm diametre

$t := 180\text{mm}$

slab thickness

$f_{ck} := 30$

cylinder strength(characteristic) (N/mm²)

$f_{ckc} := 37$

(cube strength)

$f_{ctm} := 0.3\cdot\left(f_{ck}\right)^{\frac{2}{3}} = 2.896$ x U (= 1N/mm²)

tensile strength of plain concrete

$\omega := \dfrac{f_{ck}}{f_{ctm}} = 10.357$

ratio

$f_{r3k} := 6.00$ N/mm²

65 kg/m³ HE+1/60
EN 14651

$\sigma_{cr} := f_{ctm}$

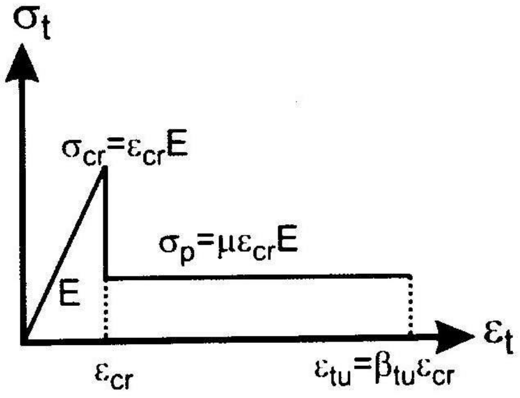
$\mu := \dfrac{f_{r3k}}{3.104\cdot f_{ctm}} = 0.667$

Mobasher relation (from theory)

$u := 1\dfrac{N}{mm^2}$

$m_{Rdaci} := \dfrac{3\cdot\omega\cdot\mu}{\omega+\mu}\cdot f_{ctm}\cdot\dfrac{t^2\cdot u}{6} = 29.419\cdot kN\cdot\dfrac{m}{m}$

(Eq.6.4.1b and H.8)
Resiting moment of the section



From ACI 544-8R16

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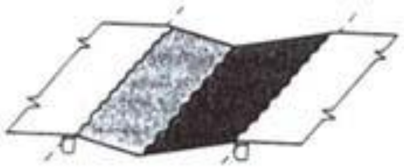
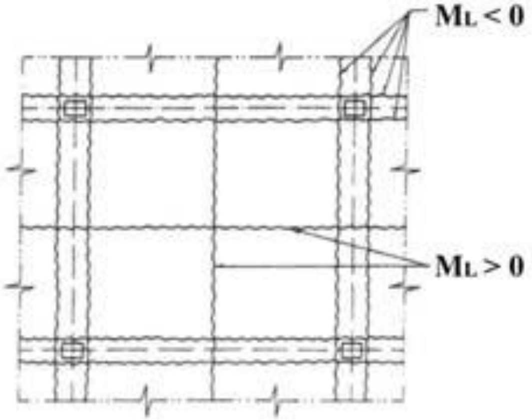
Determination of the design moments

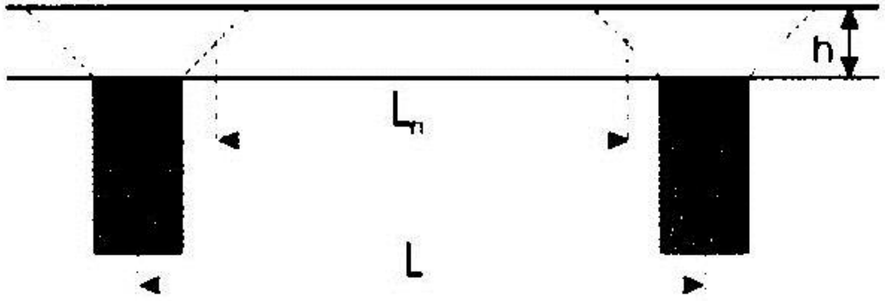
Interior panel: $M_{di} = q \times L^2_{rxi} / 16$

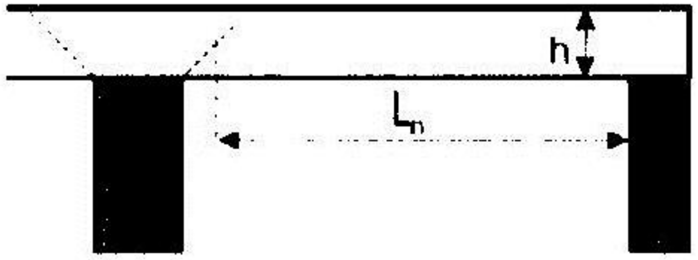
Edge panel: $M_{de} = q \times L^2_{rxe} / 12$

Corner panel: $M_{dc} = q \times L^2_{rxc} / 8$









ACI 5446R15 uses a NET SPAN so that
L_N = Gross Span – Thickness – Diametre

$\gamma_c := 24 \frac{kN}{m^3}$ Concrete volumic mass

$q := 4 \frac{kN}{m^2}$ UDL Live Load

$W_G := \gamma_c \cdot t = 4.32 \cdot \frac{kN}{m^2}$ slab unit weight

$D := 250mm$ column diametre

$L_x := 5m$

$L_y := 5m$ spans (Gross spans)

$\lambda_{DL} := 1.2 \qquad \lambda_{LL} := 1.6$ load factors ACI 318

$$\lambda_Q := \frac{(\lambda_{DL} \cdot W_G + \lambda_{LL} \cdot q)}{W_G + q} = 1.392$$

average load factor

$(\lambda_{DL} \cdot W_G + \lambda_{LL} \cdot q) = 11.584 \frac{kN}{m^2}$ factored loading

$L_{rx} := L_x - D - t = 4.57 m$ Net spans

$L_{ry} := L_y - D - t = 4.57 m$

$\Phi_P := 1.00$ reduction factor of resisting moment

$$M_{Px} := \left[\frac{(\lambda_{DL} \cdot W_G + \lambda_{LL} \cdot q) \cdot (L_{rx})^2}{12} \right] = 20.161 \frac{1}{m} \cdot kN \cdot m$$

design moment
Edge span (corner)
(eq.7.5.3c and 6.3.1.1m)

$$\frac{M_{Px}}{\Phi_P \cdot m_{Rdaci}} = 0.685$$

< 1, OK

M(SLS) = 20,16/1,392 = 14,48kNm/m

Σσ (SLS) = 6 x 14480/ (180 x 180) = 2,68N/mm²

The slab is not cracked under the SLS loading,

One single diagram where all tested specimen are shown togeteher:
-standard prismatic specimens
-statically indeterminated round slabs
-4 Full scale slabs: Ternat,Townsville,Bissen and Talinn

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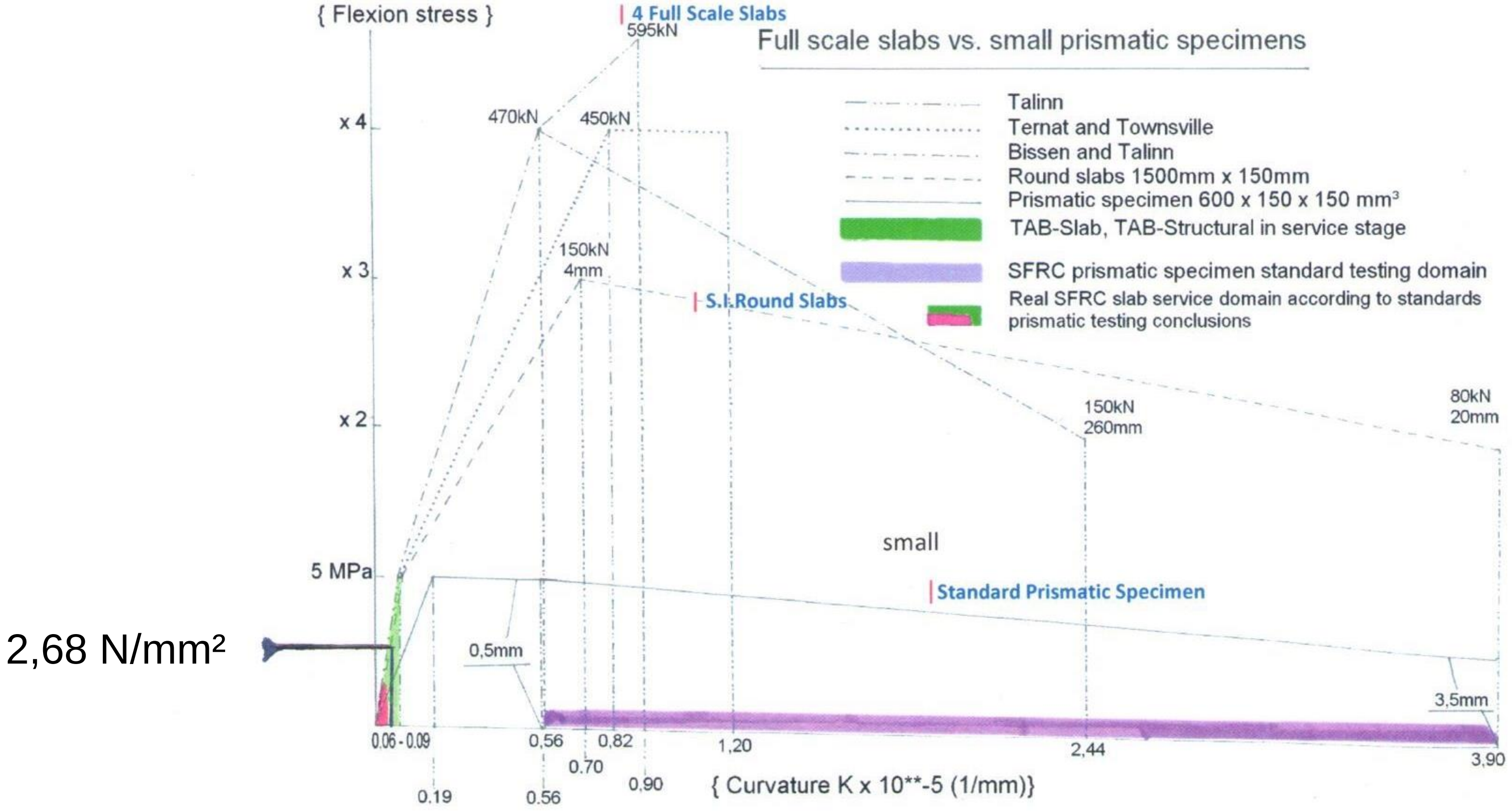
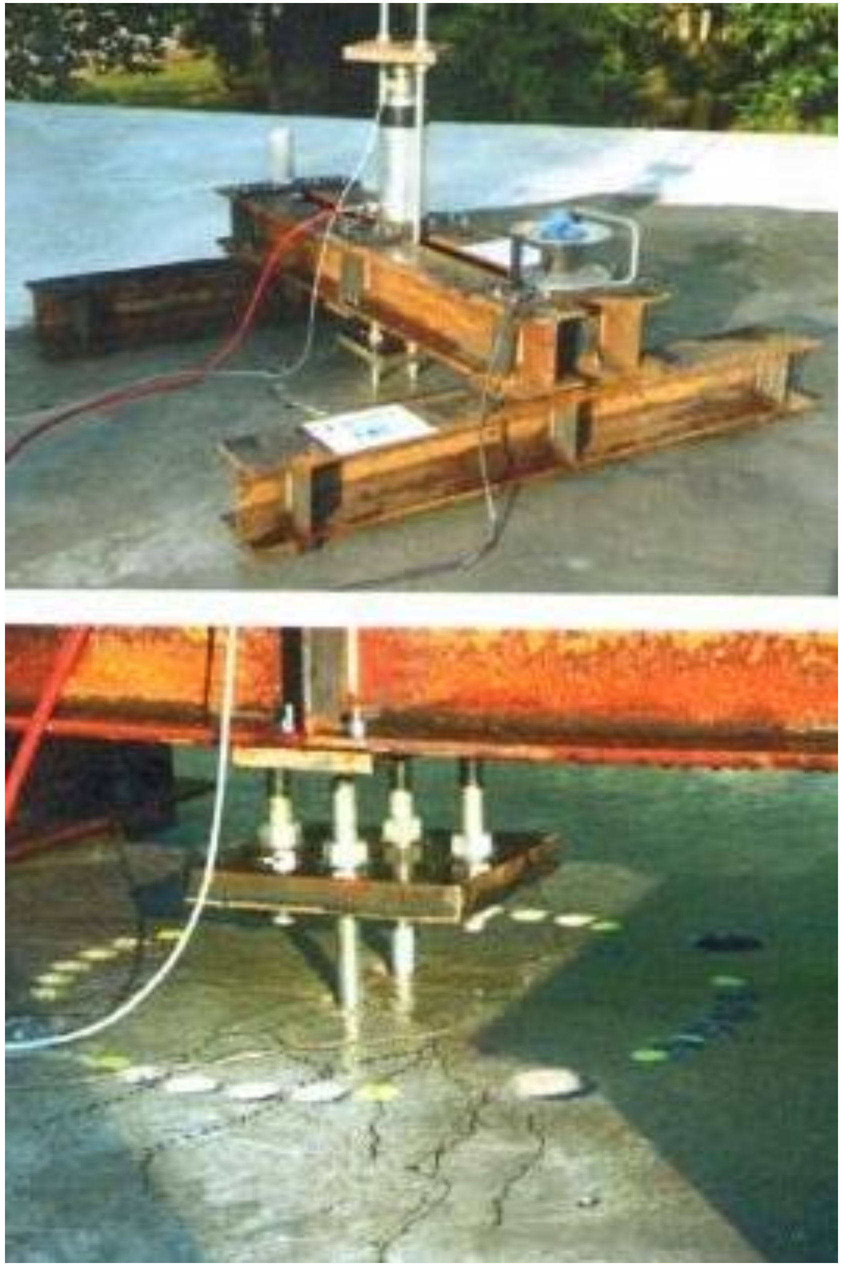
$M/EI = 1/R = K$ and $K = 1/R = 4\,d/L^2$; I : moment of Inertia; K: curvature; d: deflexion; L = span

K(beam at fr3)/K(slab SLS) = 3,90/0,06 = 65 !!





Punching-out resistance around a column support or a point loading

Examples: -**200mm slab** with 70kg/m³ HE+1/60 steelfibres has a 2000 kN Punching- Out resistance (center point loading) and 1100kN at the edge,
-**160mm slab** with 35 kg/m³ HE+1/60 has a 700kN Punching-Out resistance

When the span to depth ratio of the slab is smaller than 30, the mode of rupture of SFRC slabs is the flexion and punching-out is never critical

The photos: the slab is weakened by 60% of section suppression along the critical shear perimetre to be able to see a punching-out rupture,

ACI 544 6R15 : calculation of the shear/punching-out effect

punching shear verification:

$$V := 2\cdot\pi\cdot\left(\frac{3\cdot t + D}{2}\right)\cdot t\cdot 0.66\cdot\mu\cdot\sigma_{cr}\cdot u = 569.932\cdot kN$$

Shear resistance at critical perimetre (eq.7.6a)

$$R := \left(\lambda_{DL}\cdot W_G + \lambda_{LL}\cdot q\right)\cdot L_x\cdot L_y = 289.6\cdot kN$$

total factored reaction of a column (5m x 5m grid, 180mm, 4kN/m² .Live Loading

$$\frac{R}{V} = 0.508$$

<1, OK

D = column diametre ; t = slab thickness; $\mu = f_{r3k} / (3{,}104 \times f_{ctm})$; $\sigma_{cr} = f\ ctm$

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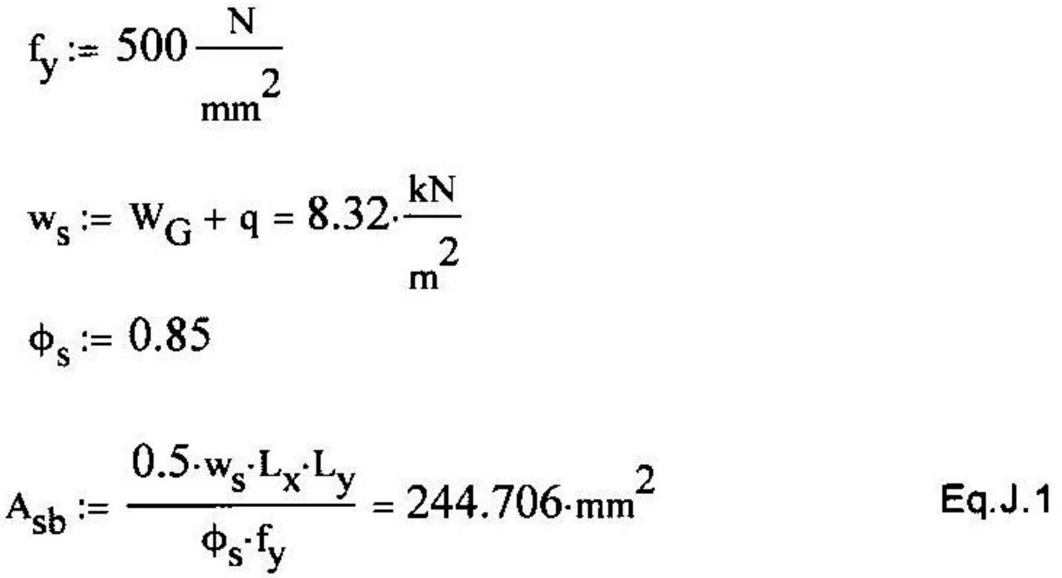
ACI 544 6R15 : Anti - Progressive Collapse Reinforcing is mandatory

The ACI 544 6R15 APC provision is the same as in the Canadian Standard CSA 92 13,3 applicable to all kinds of suspended elevated concrete slabs

Anti-Progressive Collapse Reinforcing

5 m x 5 m column grid; 180mm thickness; 4kN/m² Live Loading; 70kg/m³ HE+1/60 steel fibres



$$f_y := 500 \frac{N}{mm^2}$$

$$w_s := W_G + q = 8.32 \cdot \frac{kN}{m^2}$$

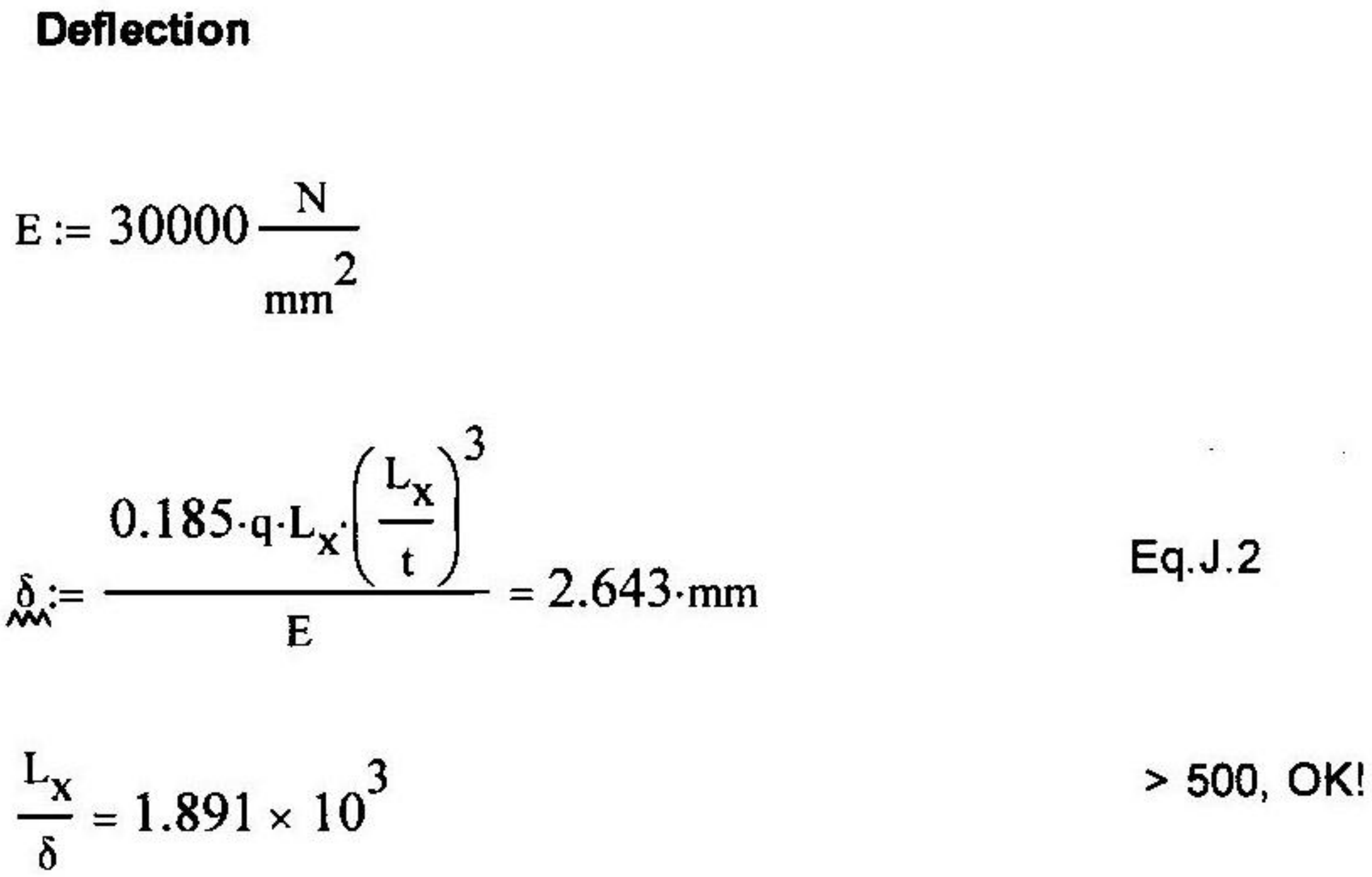
$$\phi_s := 0.85$$

$$A_{sb} := \frac{0.5 \cdot w_s \cdot L_x \cdot L_y}{\phi_s \cdot f_y} = 244.706 \cdot mm^2 \qquad \text{Eq.J.1}$$

Install 3 rebars of 12mm dia (339 mm²> 245 mm²) in the bottom going from column to column (passing over the footprint of the column) and along the perimetre of the slab.

ACI544 6R15: rapid calculation of the deflection,

5 m x 5 m column grid; 180mm thickness; 4kN/m² Live Loading; 70kg/m³ HE+1/60 steel fibres



Deflection

$$E := 30000\,\frac{N}{mm^2}$$

$$\delta := \frac{0.185 \cdot q \cdot L_x \cdot \left(\frac{L_x}{t}\right)^3}{E} = 2.643 \cdot mm$$

Eq.J.2

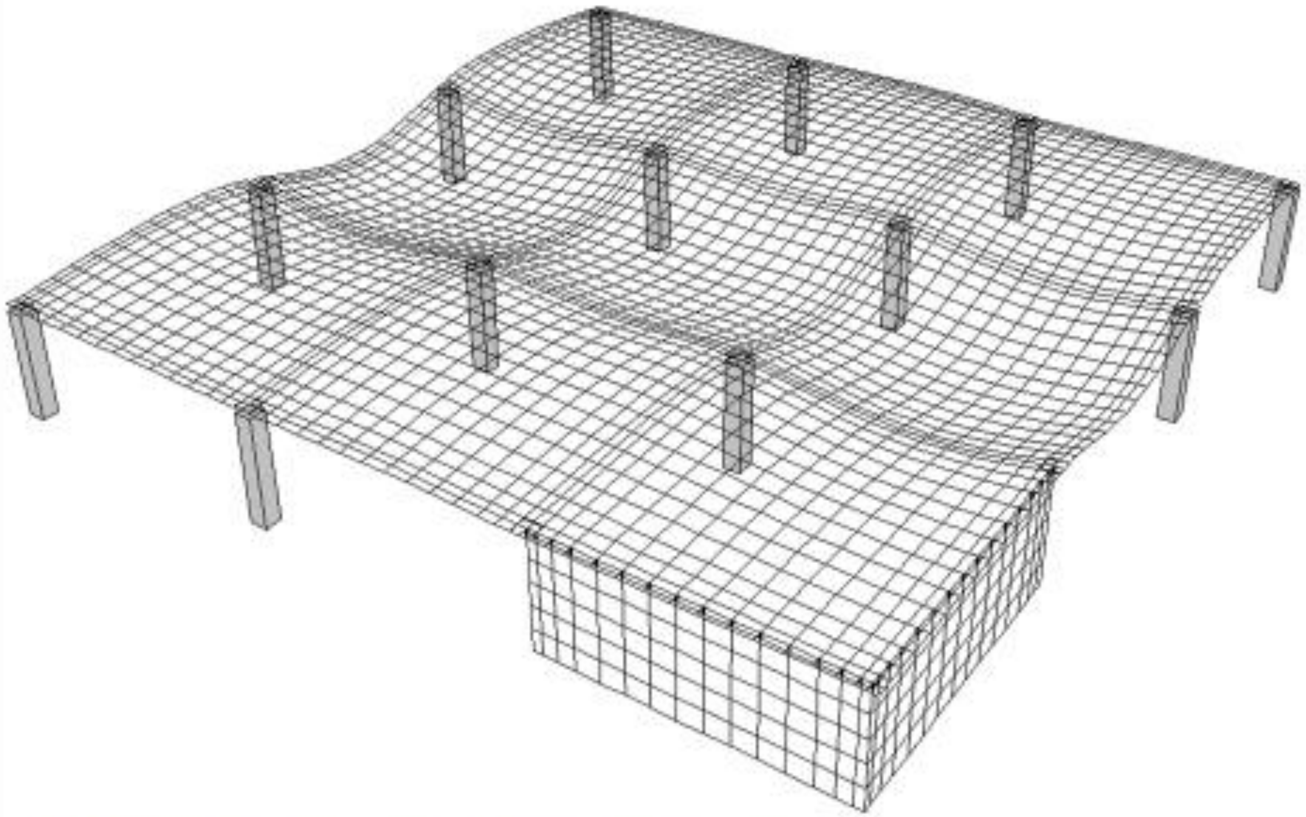
$$\frac{L_x}{\delta} = 1.891 \times 10^3$$

> 500, OK!

Checking of the SLS deflection of the slab:

ACI 544 6R15 compares well to F.E.M methods :

$\delta = 1{,}71\text{mm} \times 4/3 = 2{,}28\text{mm} < 2{,}643\text{mm}$



Deformed shape under U2 / central row 3kN/m2 (max deflection of 1.71mm)

Experimental deflection at 3 days of loading application:

$\delta = 2\text{mm} \times 4/5 = 1{,}6\text{mm}$

Various examples of the applications in free suspended elevated slabs, piled slabs and raft foundations

Example 1: LKS Building, Bilbao, Spain
engineering office building
32.45m x 19.45m , 4 levels plus roof ; 8m x 7.80m grid of columns

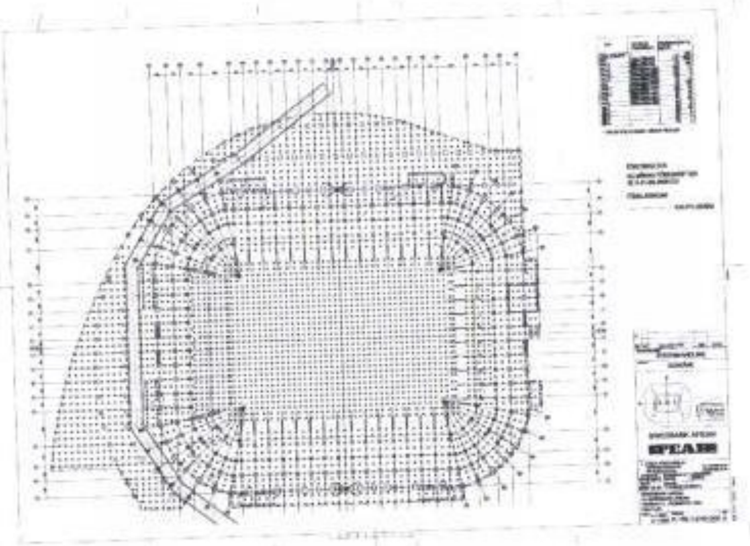
Elevated suspended slabs TAB-Slab™:

Office project LKS Bilbao, Spain: 4000m^2 slabs for **LKS structural engineers** new headquarters

-5 storeys building of 800m^2 each
(4000m^2 in total)
-d = 280 mm span : 8m; up to 6kN/m^2 live load
-100kg/m^3 of TABIX1.3/50
-Structural Integrity Reinforcing: 3 dia 20mm in the bottom from column to column

Rocca-al-Mare tower, Tallinn/Estonia

Example of a slab on pile in Sweden: The Swedbank Arena (Stockholm) -Swerock-Peab).



Grass area: 3m x 3m pile grid, 600kN P.L.,300mm slab 45kg/m³ HE+1/60
Technical rooms: up to 5m x 5m pile grid and 15kN/m² + P.L. and
Thicknesses of 250mm to 300mm with up to 50kg/m³ HE+1/60

General raft foundation
for office and housing structures

Also designed following ACI 544 6R15

400 mm thick 50 kg/m^3 HE+ 1/50
Ground water pressure of 3 m
GF +4

350 mm 45 k g/m^3 HE+ 1/50 social housing
GF +3

Residence Maritime - Brussels
Raft between secant piles
400-700mm thickness
5m underground water pressure
50kg/m^3 HE+1/60

300 mm with 500 mm thickening under the columns
45 kg/m^3 HE+ 1/60 ; GF + 5 ; 2000m