Staalplaat-beton vloeren

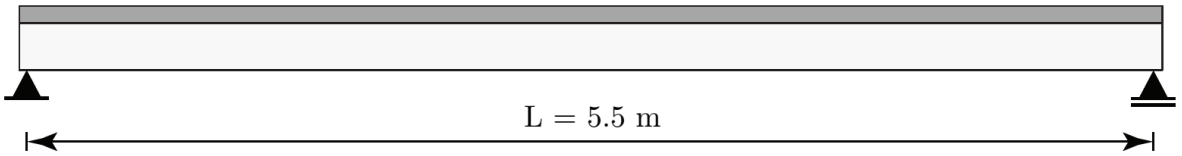
Een theoretisch onderzoek naar een mogelijk ontwerp van een staalplaat-betonvloer met een stempelvrije overspanning van 7.2 meter

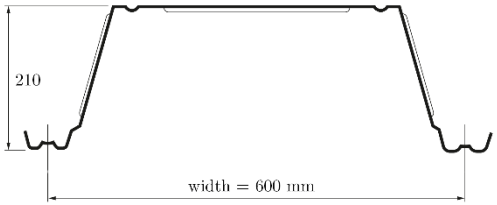
door

J. van Blokland

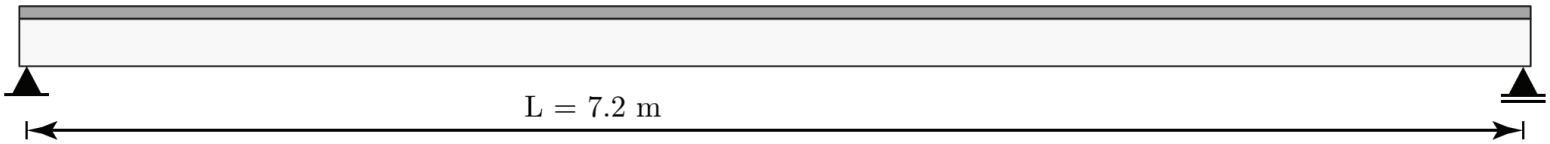
Waarom 7.2 meter?

- huidige hoge staalplaten met een stempelvrije overspanning van 5.5 m

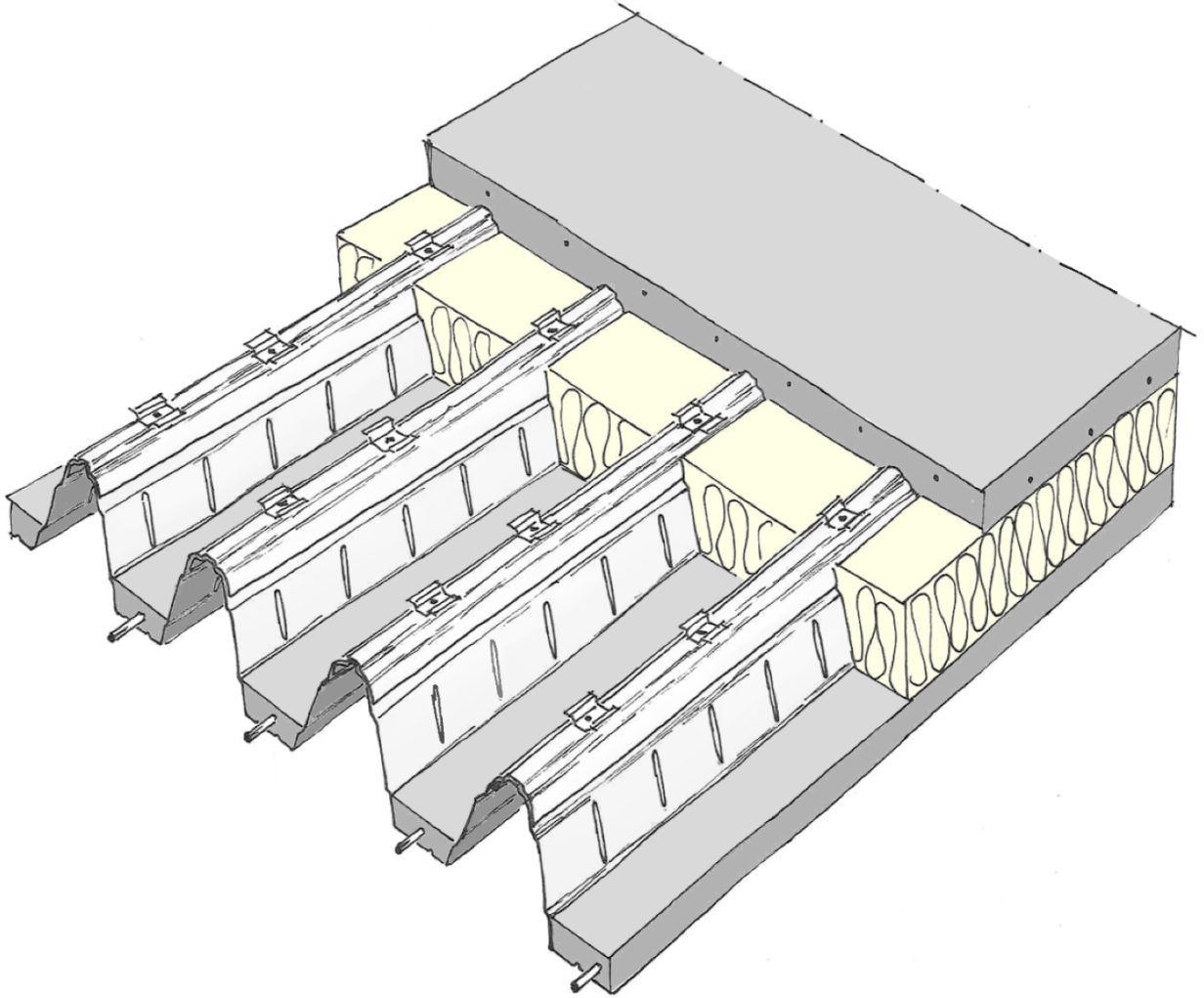




- ontwikkelen van een staalplaat, die een stempelvrije overspanning van 7.2 m mogelijk maakt

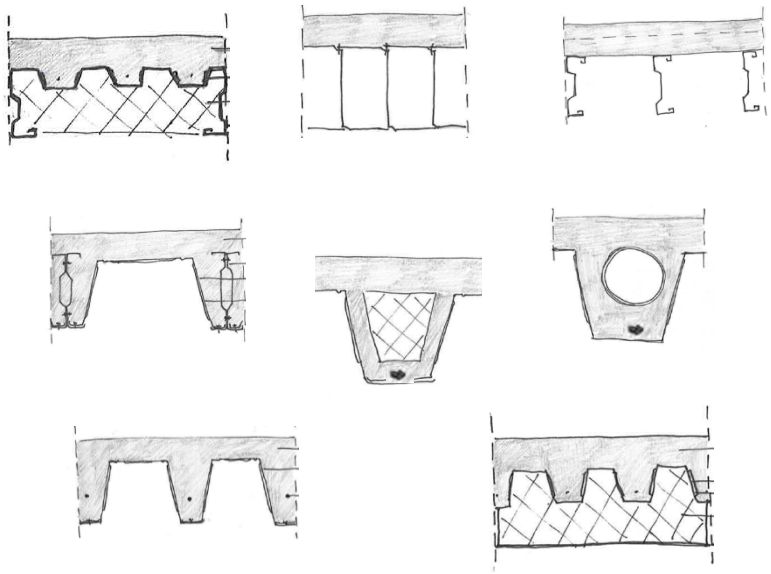


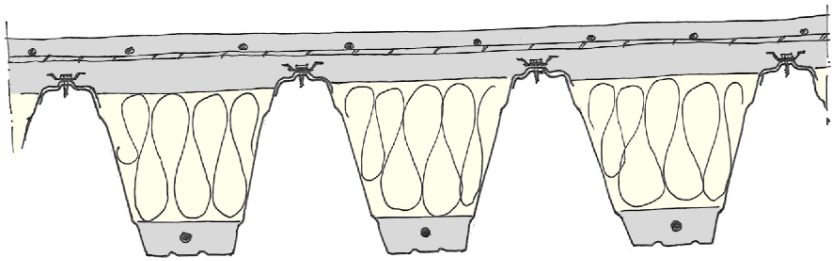
De ‘JorFlor’



Conceptuele studie

- efficiente installatie van de staalplaaten
- laag eigen gewicht van de totale vloer
- brandwerendheid van 90 minuten
- minimaal staal gebruik

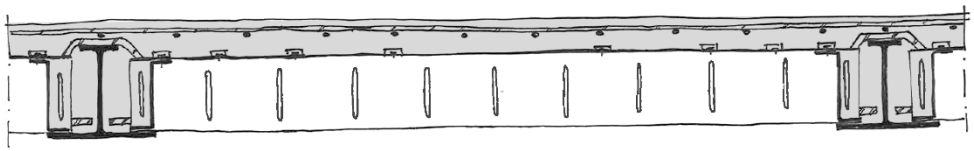


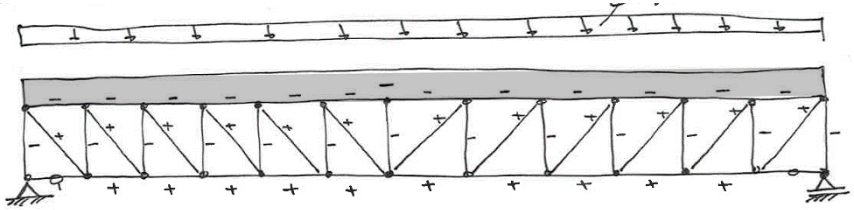


- optimale buigstijfheid met een laag eigen gewicht
- gewichtsreducerende vul-elementen in de ribben

Voorlopige technische verificatie

- tijdens gebruikstoestand

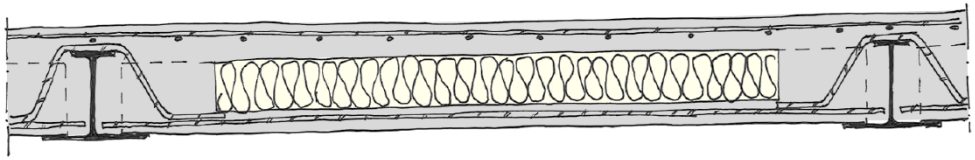


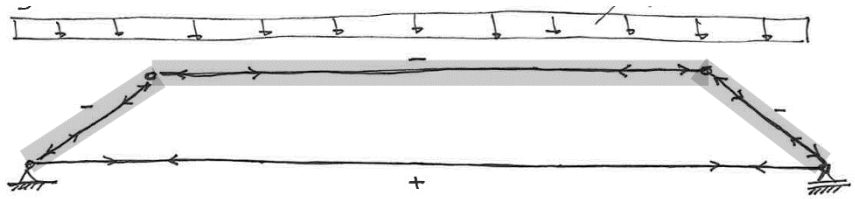


dwarskrachtcapaciteit van het lijf van de staalplaat (1)

afschuifsterkte van de staal-beton verbinding (2)

- tijdens brand

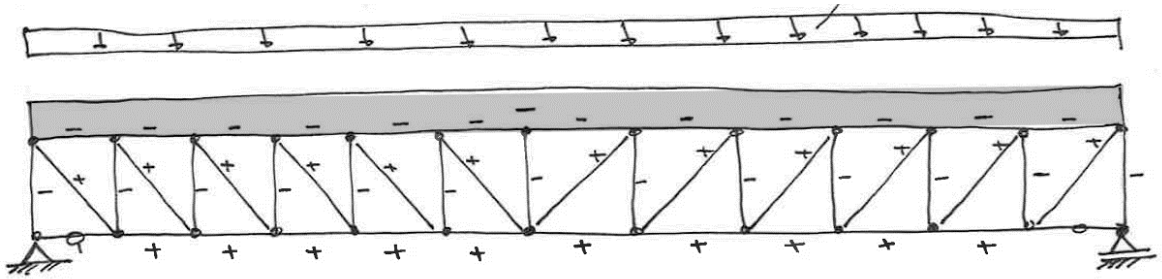




weerstand van de vloer tijdens brand (3)

Dwarskrachtcapaciteit van het lijf van de staalplaat (1)

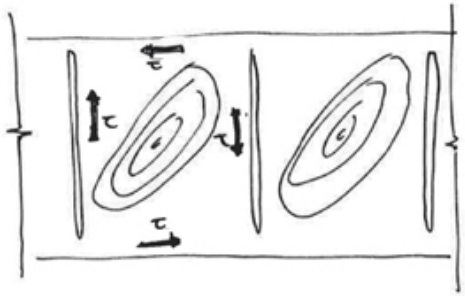
- vakwerk model

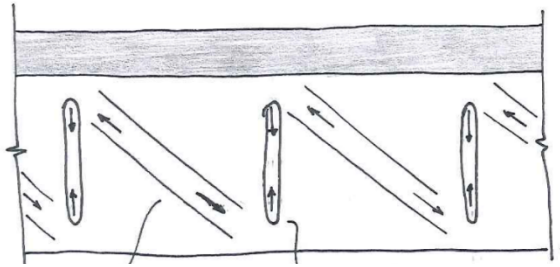


dwarskrachten in het lijf van de plaat

trekstaven en drukstangen

- “de analogie van de dunne plaatligger”





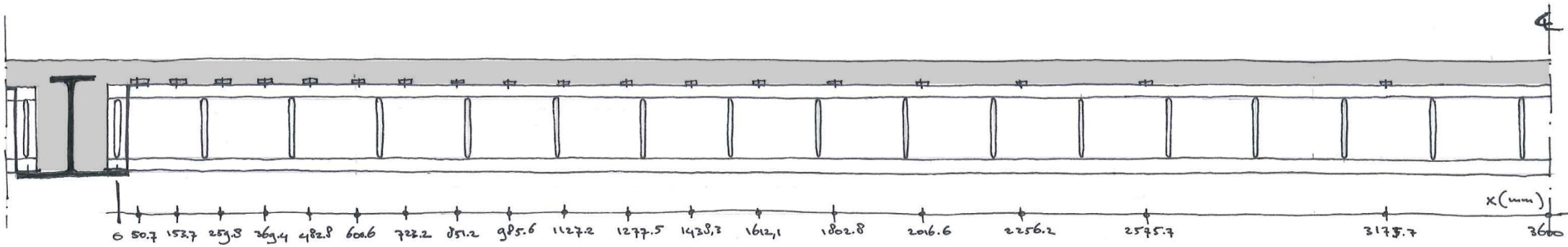
plooien van het lijf van de staalplaat

trekveld = trekstang

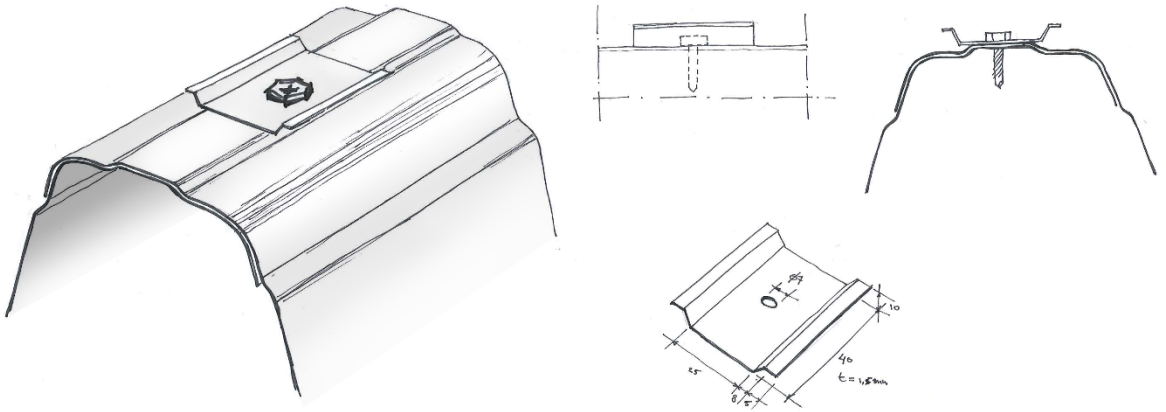
dwarsverstijving = drukstaaf

Staal-beton verbinding (2)

- 18 verbindingselementen per halve overspanning

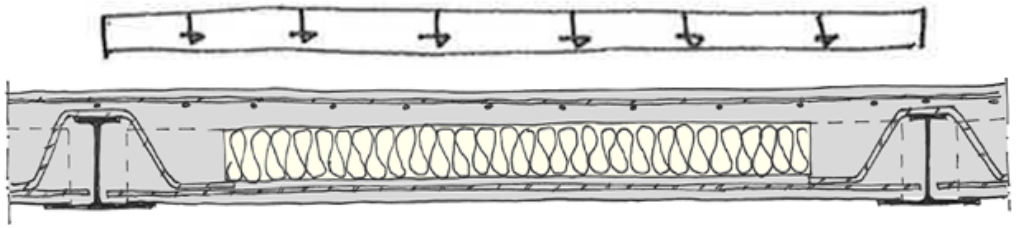


- nieuw type afschuifverbinding



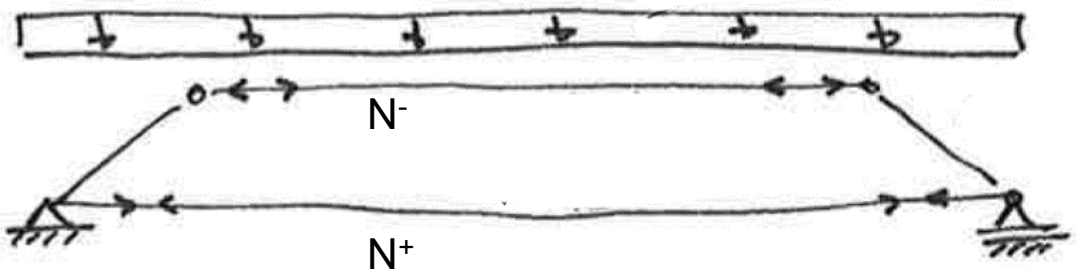
Weerstand tijdens brand

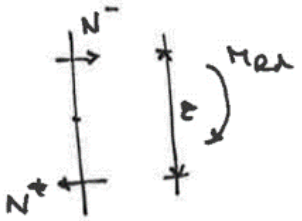
- drukboog en trekstang



60 minuten: rond 16 mm

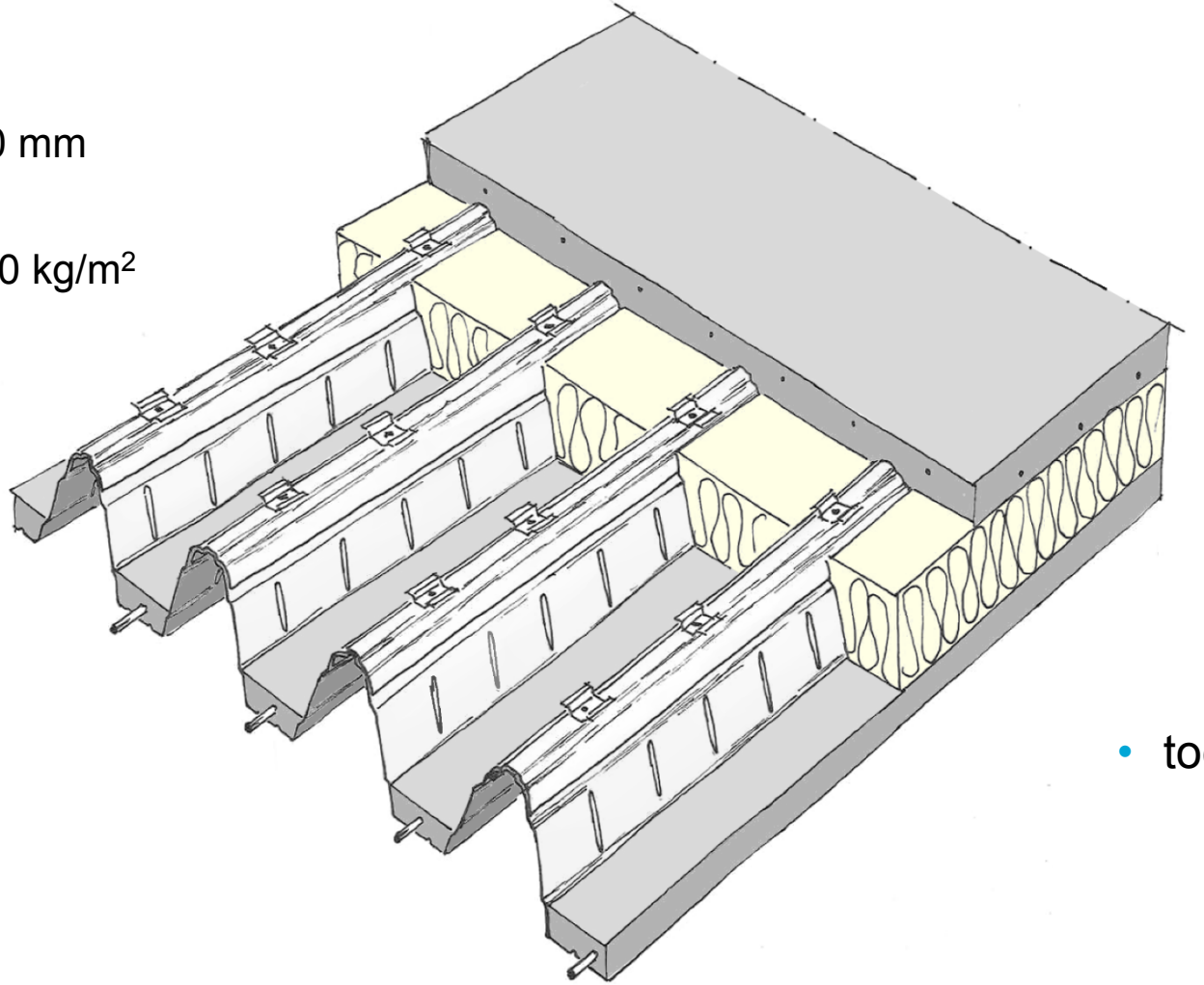
90 minuten: rond 20 mm





The JorFlor

- vloer
  - totale hoogte 280 mm
  - vul-element
  - eigen gewicht 300 kg/m^2
- plaat
  - 7.2 m lang
  - 220 mm hoog
  - 1.20 mm dik
  - 300 mm breed
  - gewicht 50 kg



- toepassing
  - in-situ
  - prefab

Composite Floors

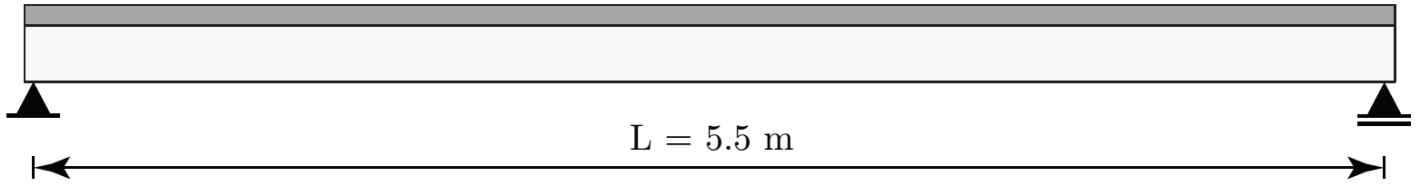
A Theoretical Research into the Design of Steel-Concrete Composite Floors with a Bigger Unpropped Span of 7.2 m

by

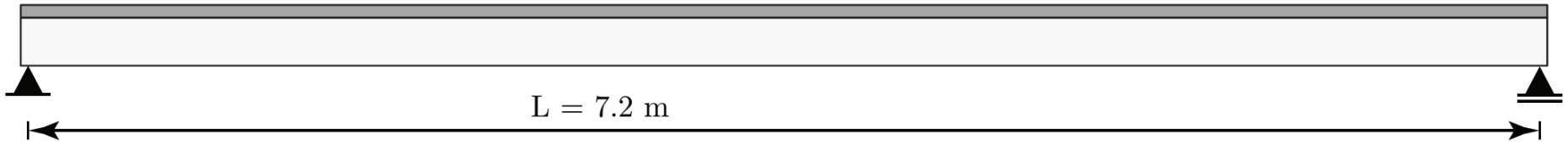
J. van Blokland

Goal of this study

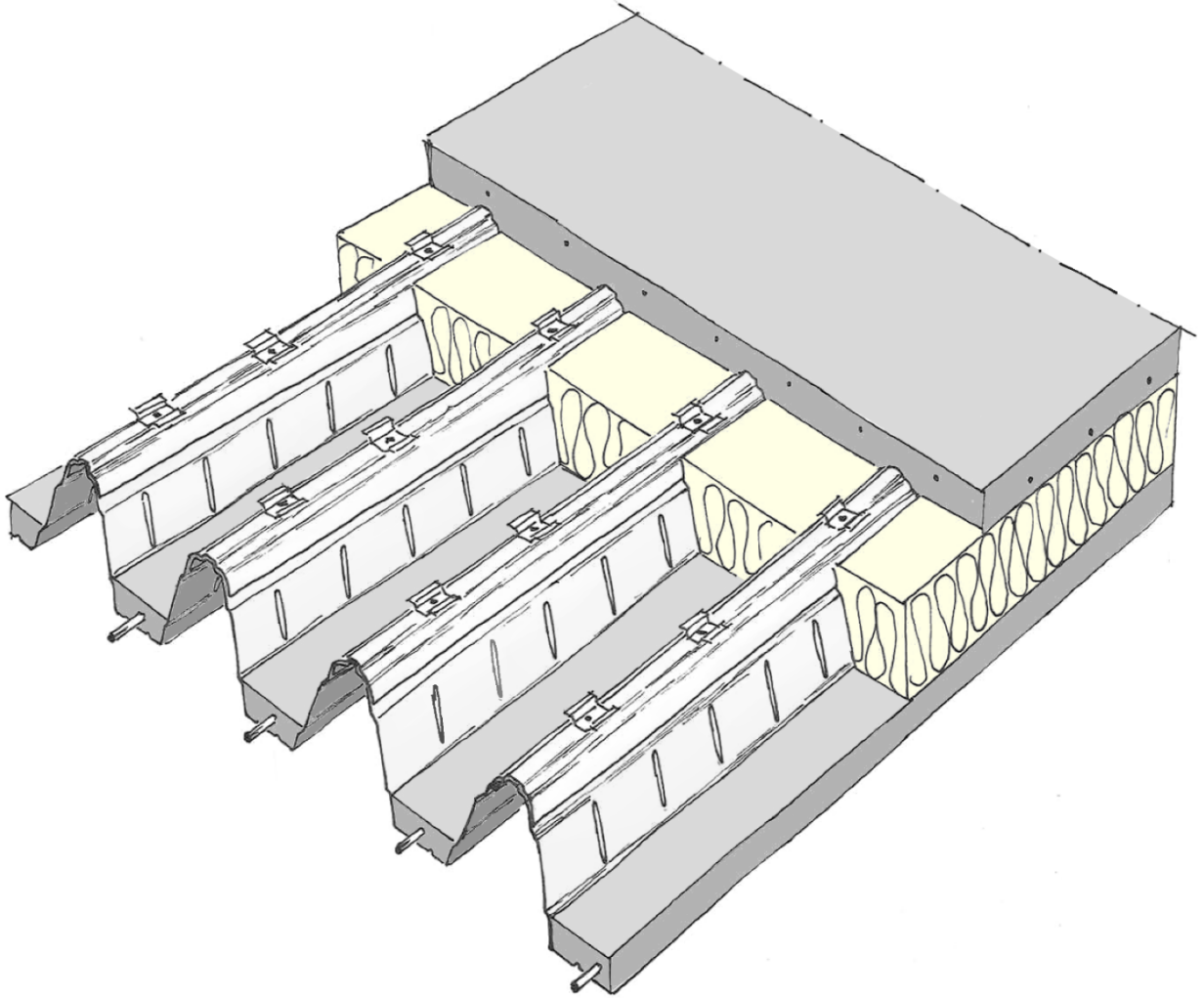
- current deep decks span up to 5.5 m unpropped



- design of a steel-concrete composite floor with a bigger unpropped span of 7.2 m

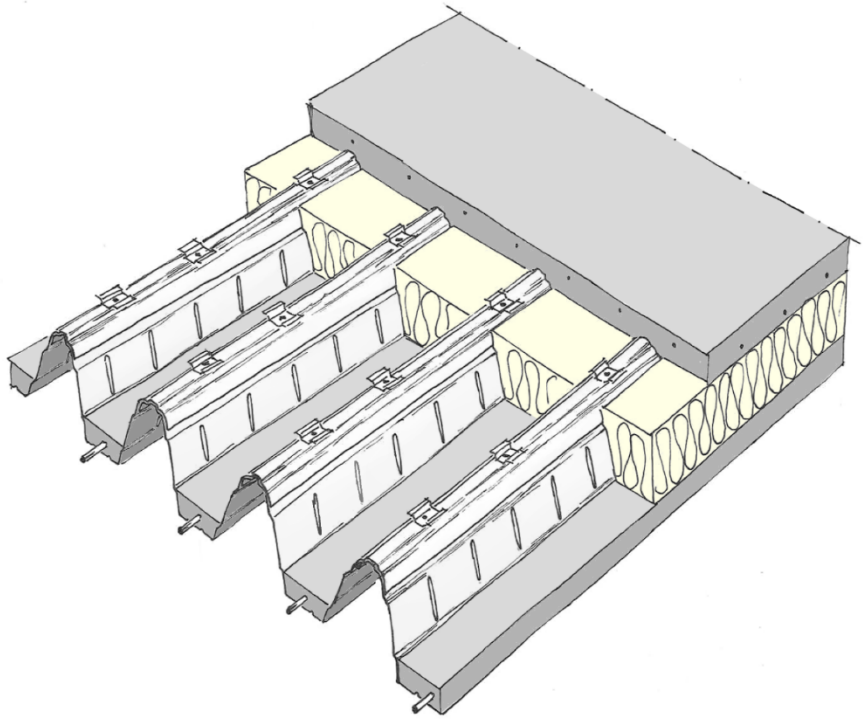


The ‘JorFlor’



Presentation outline

- Part 1: introducing the research
- Part 2: specifying the design
- Part 3: the product
- Part 4: what have we learned?



Part 1

Introducing the Research

An introduction to floor systems

- 3 popular floor systems in the Netherlands

steel floor systems

concrete floor systems

steel-concrete composite floor systems

Steel-concrete composite floors

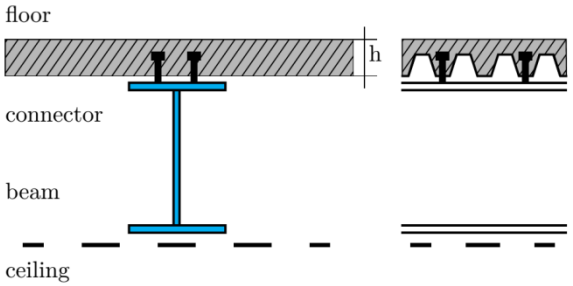
- steel-concrete composite floor

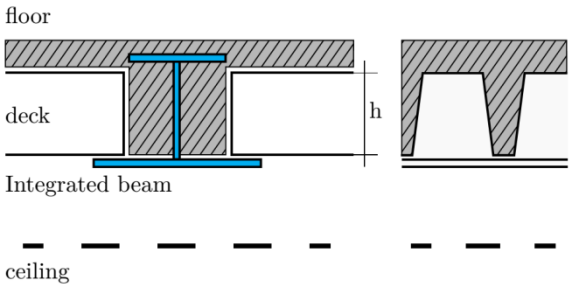
deck (work-floor, shuttering, and reinforcem

reinforcement mesh

in-situ concrete

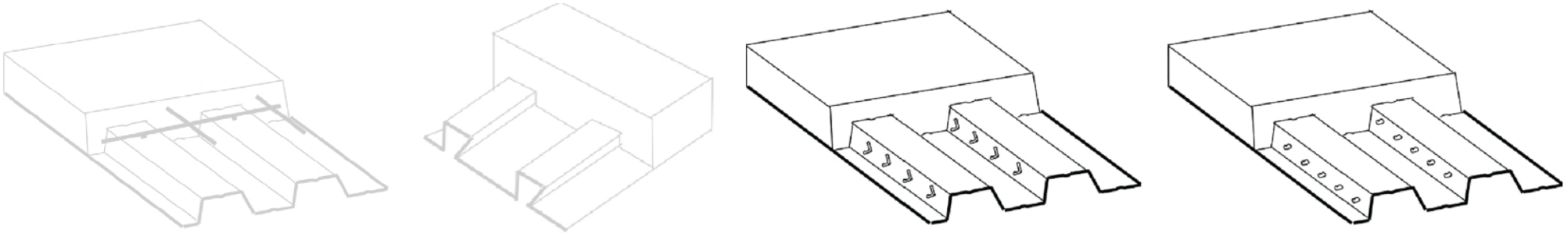
- 2 applications





Composite action

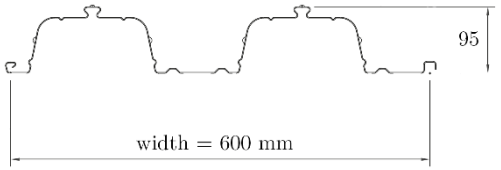
- steel-concrete *'composite'* floor



What is the unpropped span?

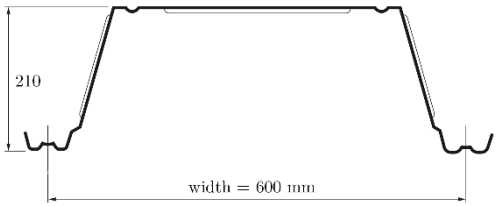
- ‘propped’ construction

- current decking



low profile decks

up to 3.6 m



high profile/deep

up to 5.5 m

Main research question

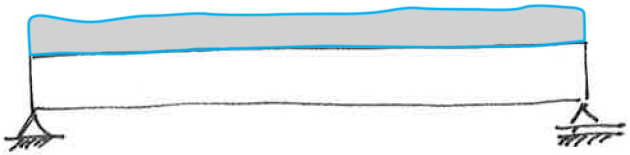
Is it structurally and practically possible to design a steel deck for a steel-concrete composite floor slab that can span 7.2 meter and be constructed without the need of temporary support?

Specification of the design

• manufacturing process	boundary conditions	thickness steel sheet < 1.5 mm
• properties steel-concrete composite floors	maintain current competitive advantages	‘minimum’ construction height <300 m ‘low’ self-weight <300 kg/m^2 ‘good’ fire resistance >90 min
• Dutch building market	improvements/goal	unpropped span of 7.2 m light-weight deck elements <50 kg
• regulations	design rules from the ‘Eurocode’	prevent failure (strength) prevent excessive deformation (stiffn

3 design situations

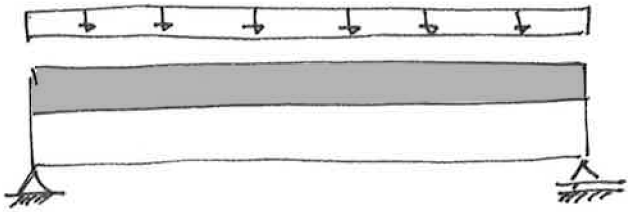
- construction



deck

carries wet concrete

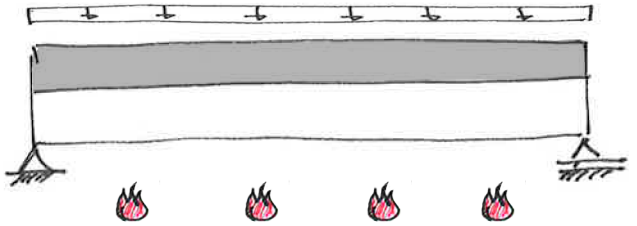
- service life



composite slab

carries self-weight plus live load (4 kN/m^2)

- during fire

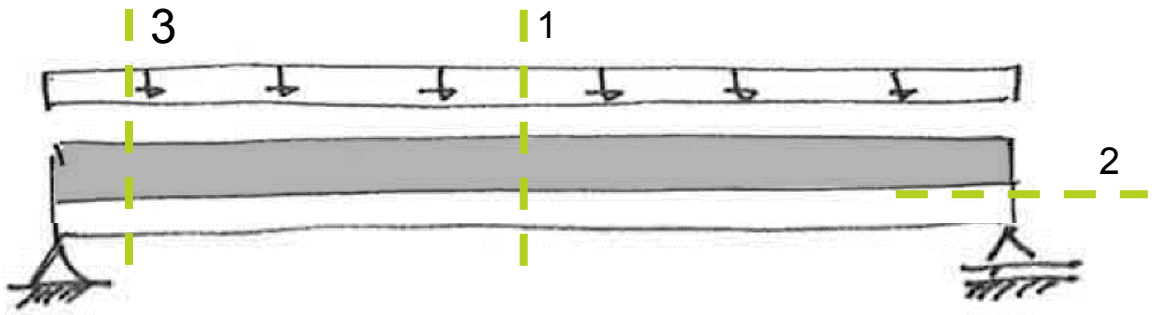


composite slab

carries self-weight plus reduced live load (1.2 kN/m^2)

Design verifications floor

- strength verifications aim to prevent failure



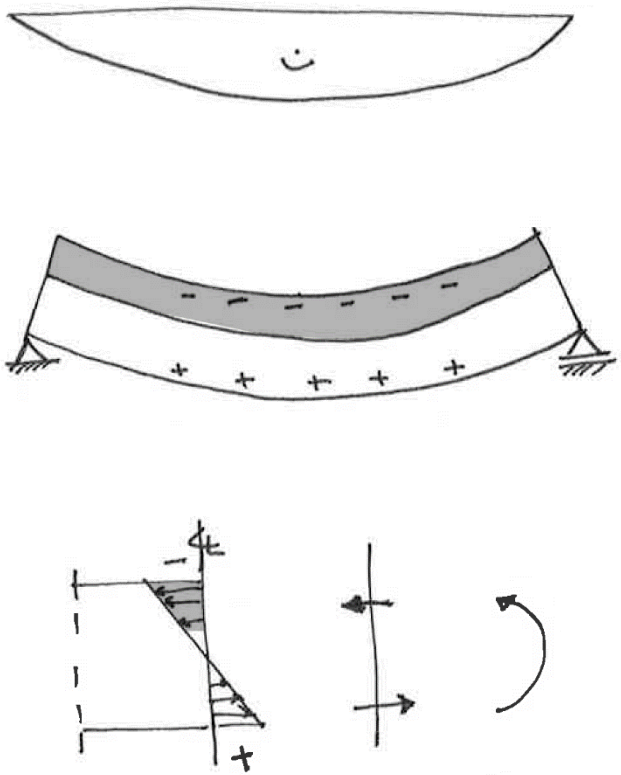
bending (1)

longitudinal shear (2)

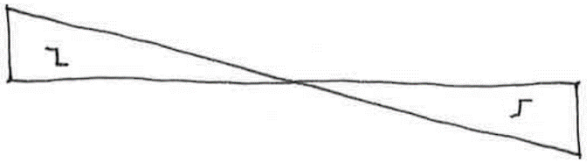
vertical shear (3)

What are bending and shear?

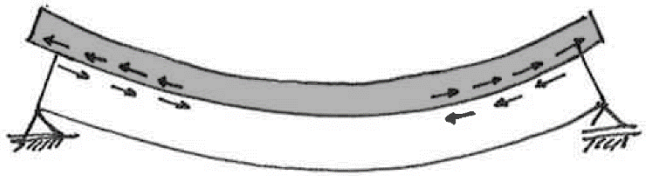
- bending (1)



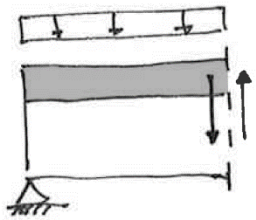
- shear



- longitudinal shear (2)



- vertical shear (3)

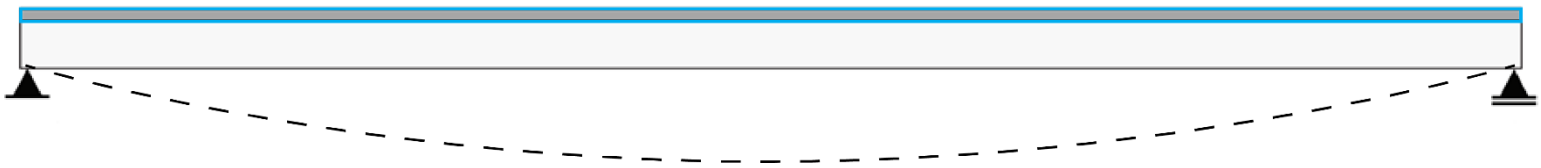


Part 2

Specifying the Design

Is an unpropped span of 7.2 m feasible?

- construction phase



deflection during construction

- current decking

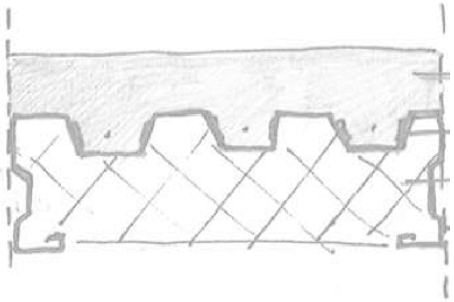
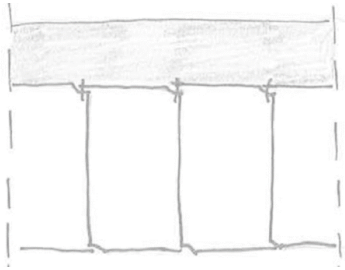
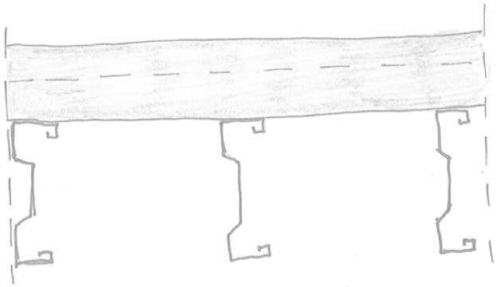
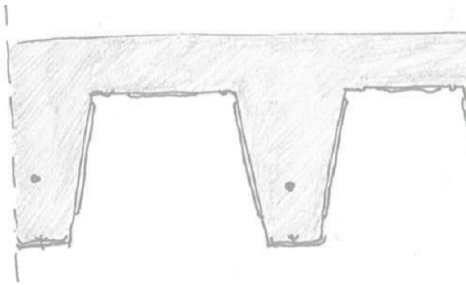
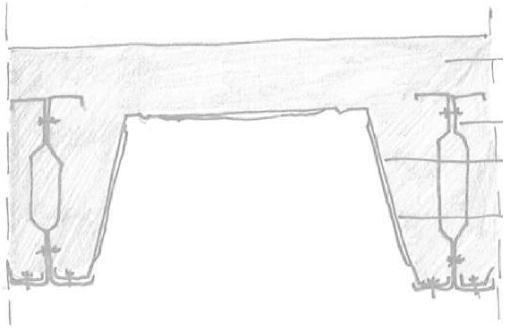
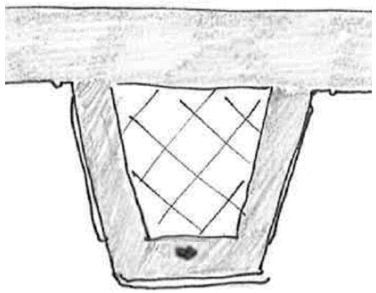
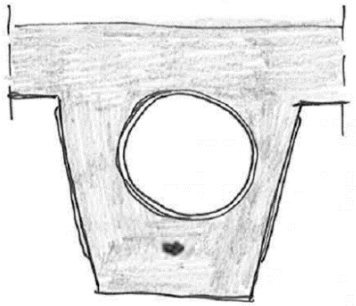
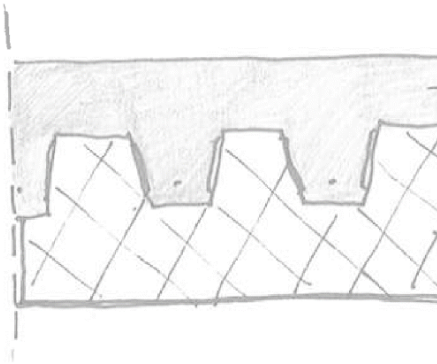
span 7.2 m

sufficient strength

60% more stiffness

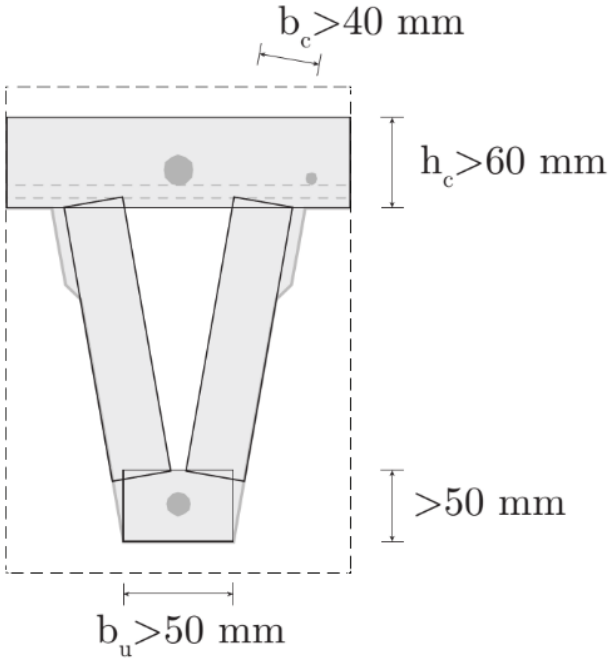
Alternative designs for bigger spans

- more bending stiffness or/and reduced weight

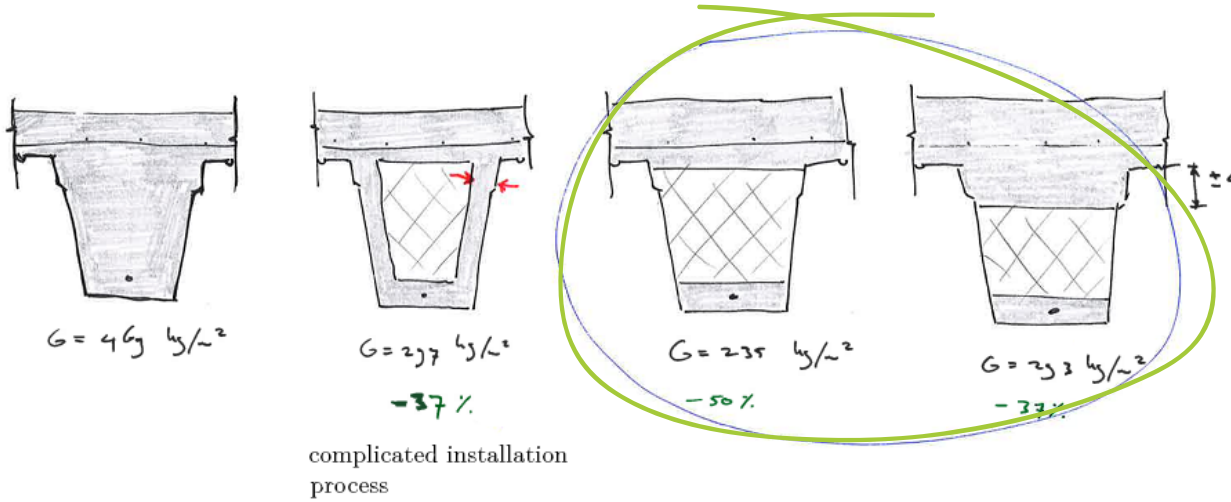









Installation with fill element

- complicated installation



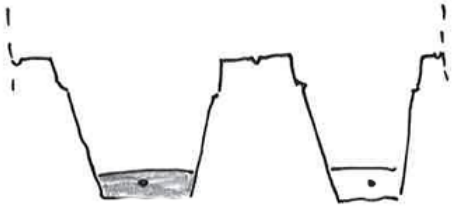
- sufficient weight reduction not possible



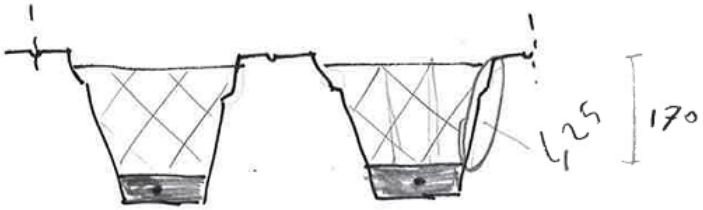
complicated installation process

Double cast with fill element

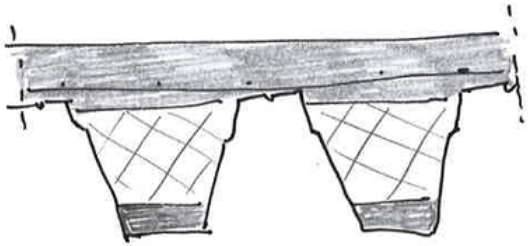
- practical installation process



Instal the decks and position bottom reinforment and cast concrete in the ribs (prefab or in-situ)



Place lightweight elements in the ribs and the top reinforcement

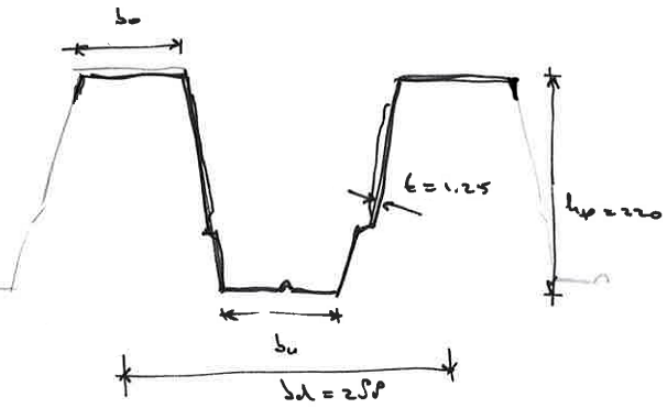


Finisch the floor with a second cast (in-situ)

- prefab or in-situ
- efficient weigth reduction

Starting point for the design of the JorFlor

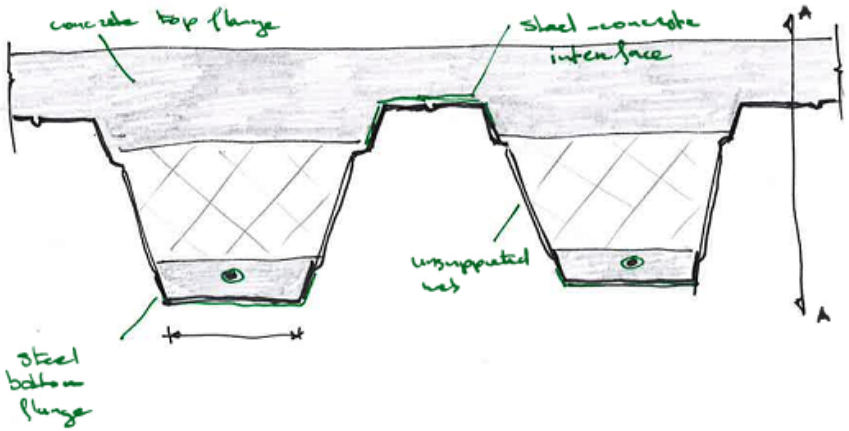
- deck



height deck 220 mm

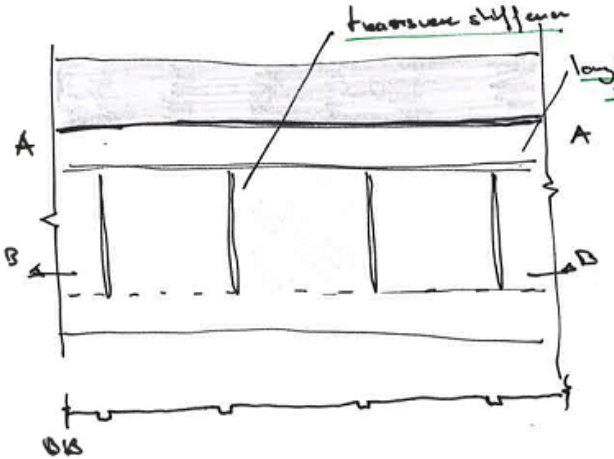
thickness steel 1.20 mm

- composite slab



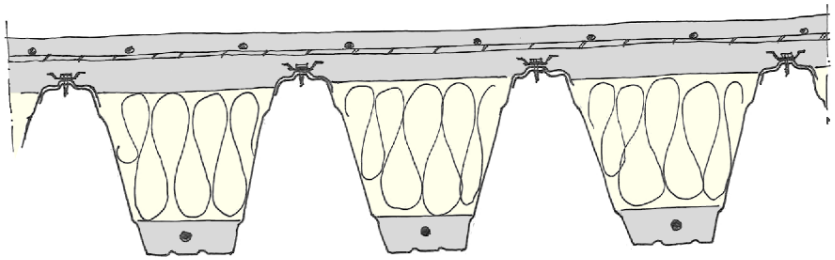
concrete top flange 60 mm

self-weight 300 kg/m^2

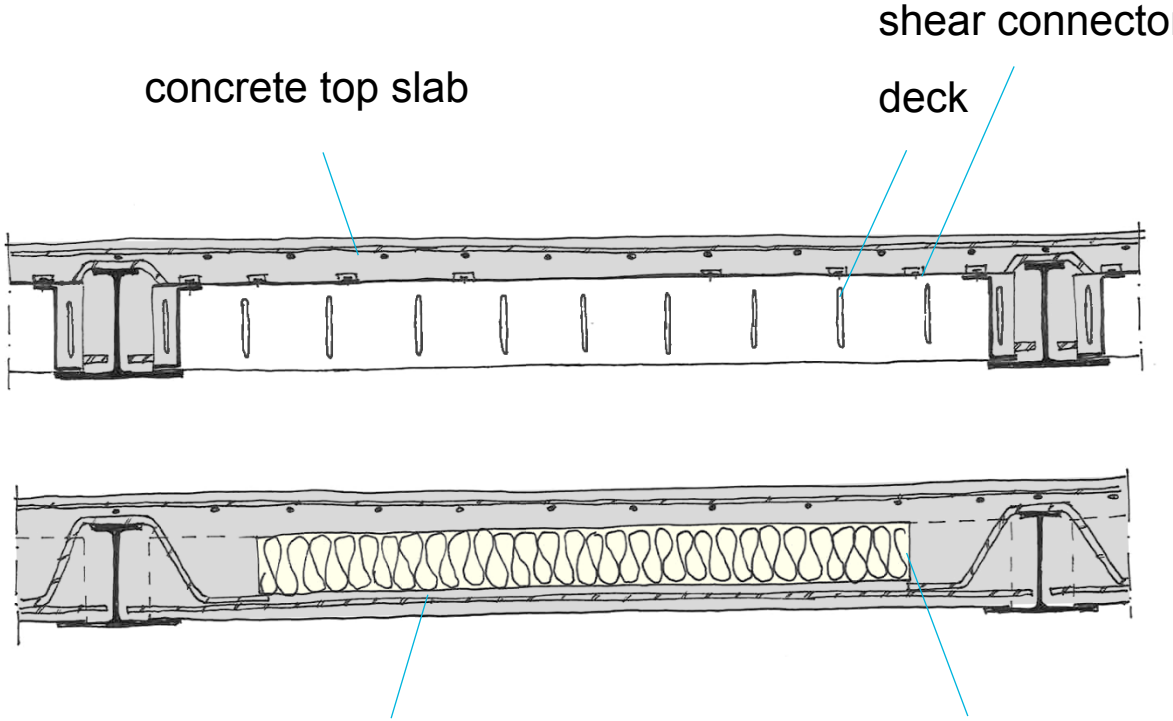


Design challenges of the JorFlor

- no concrete in ribs
  - shear resistance
  - composite action
  - resistance to fire



- structural elements

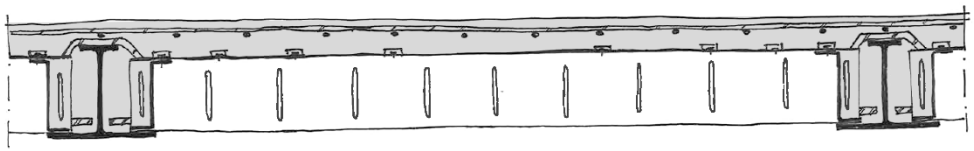


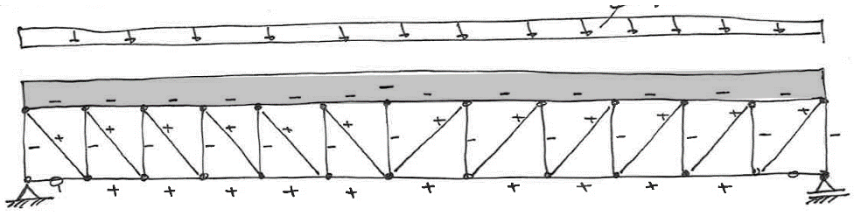
Part 3

The Product

2 situations 2 models

- during service life

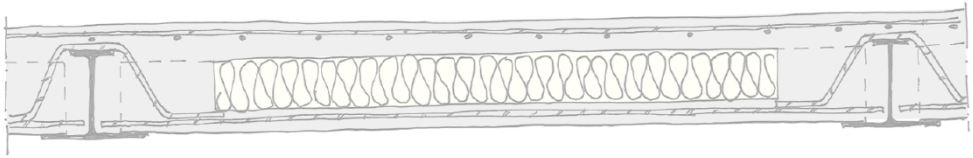


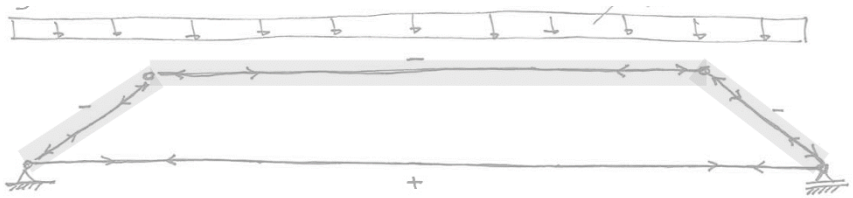


design of the deck to resist shear (1)

design of the shear connection (2)

- during fire

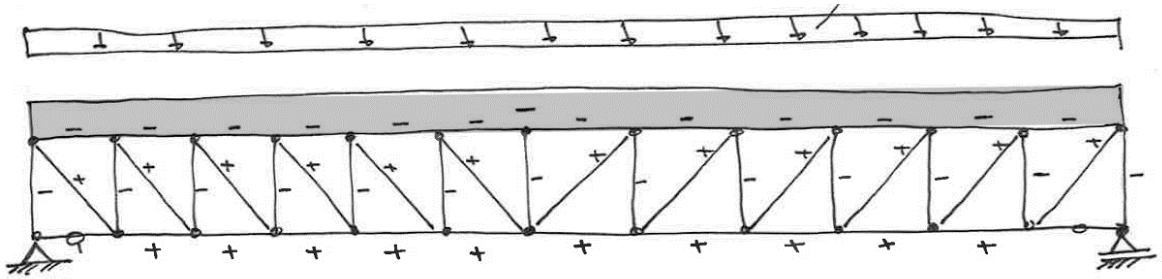




design of the floor to resist fire (3)

Desing of the deck to resist shear (1)

- truss model

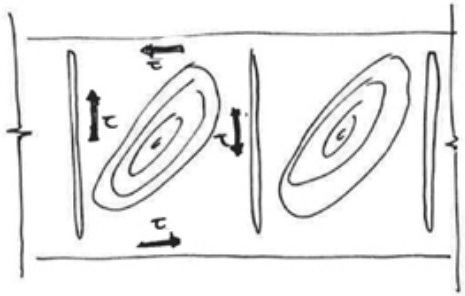


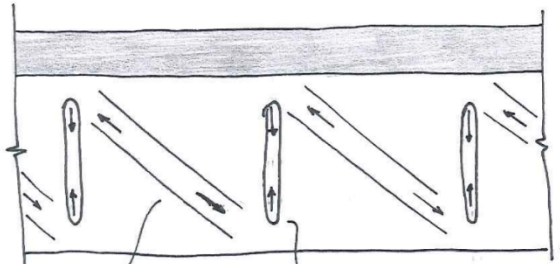
shear in the deck

ties under tension

struts under compression

- tension field method Basler





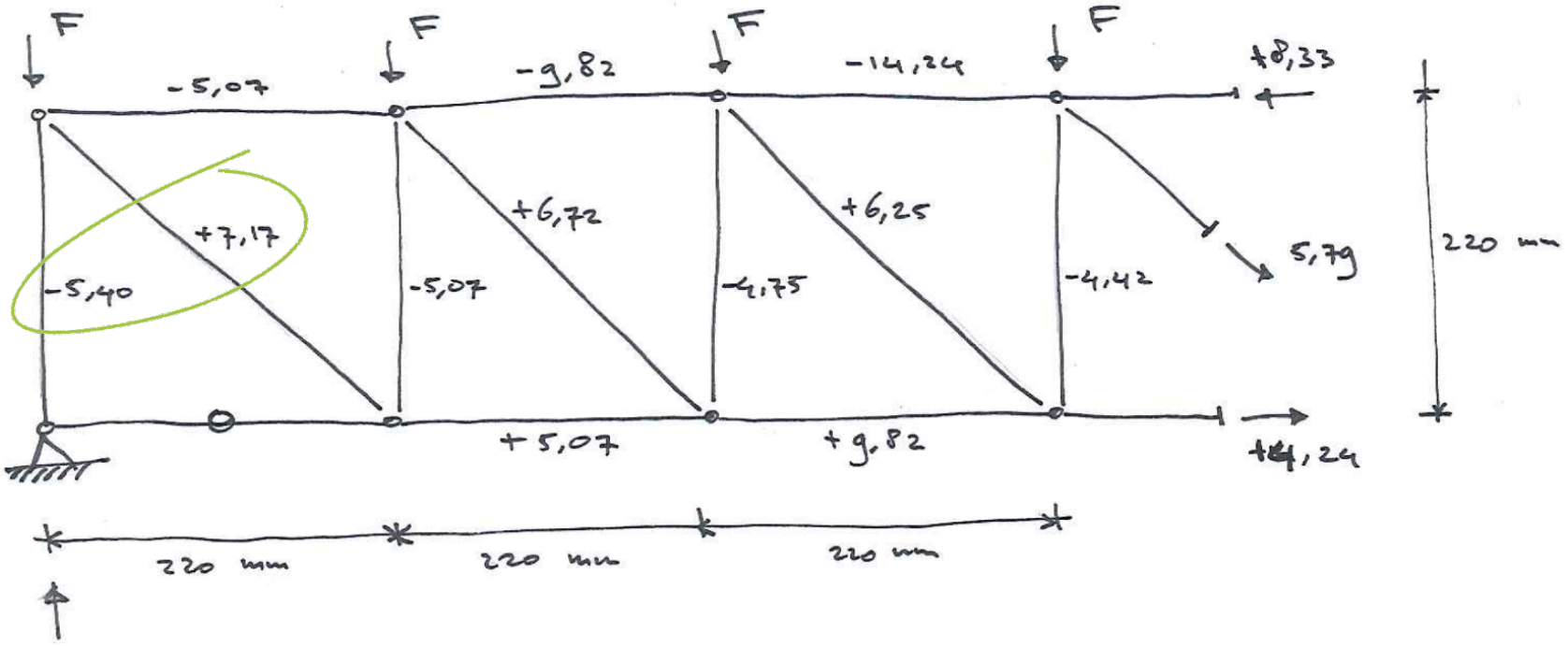
post-buckling behaviour of the web

tension field = ties

transverse stiffener = struts

Shear forces in the web

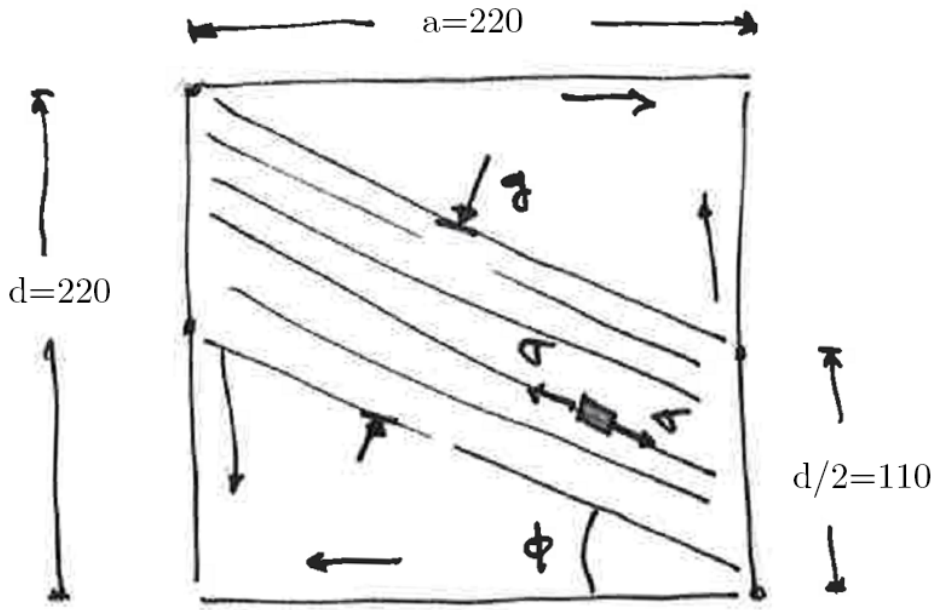
- maximum shear forces

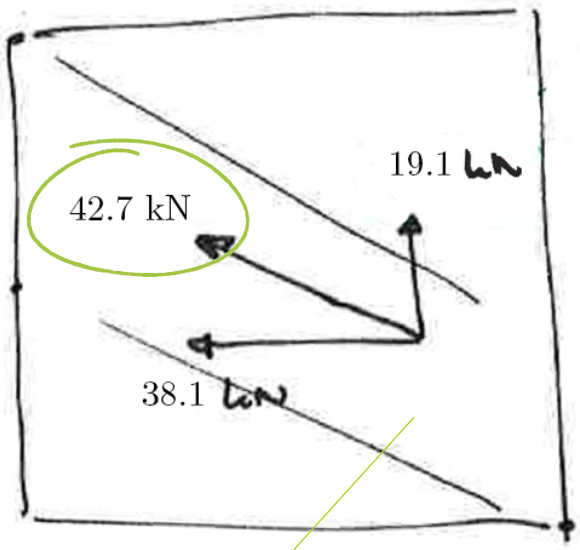


$$V_{Ed} = \frac{q_d \cdot L}{2} = \frac{1,5 \cdot 7,2}{2} = 5,4 \text{ kN}$$

Capacity of the tension field (tie)

- capacity tie = capacity tension field

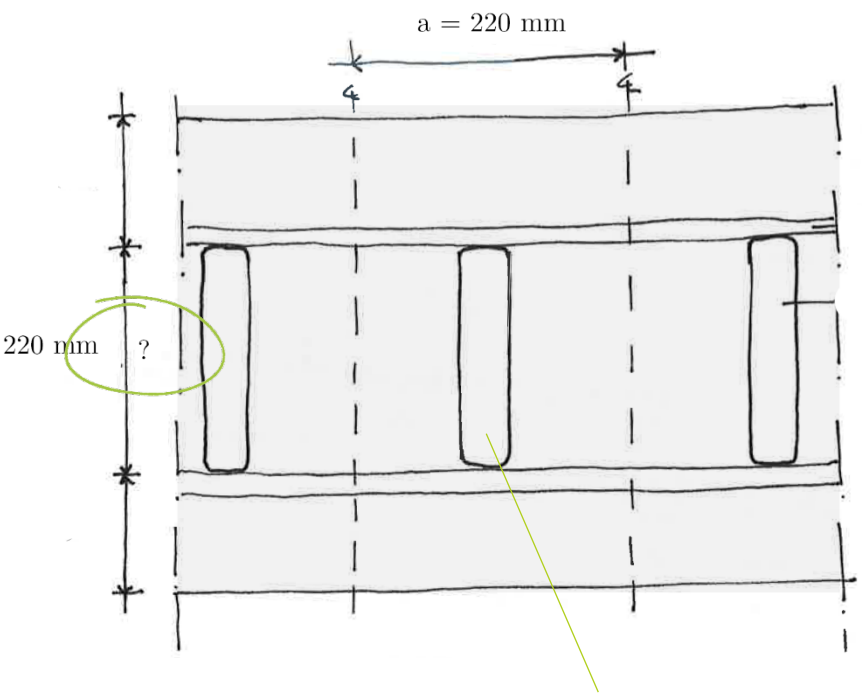


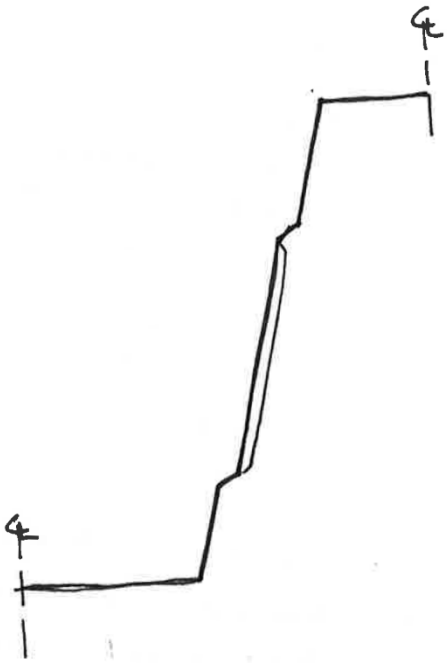


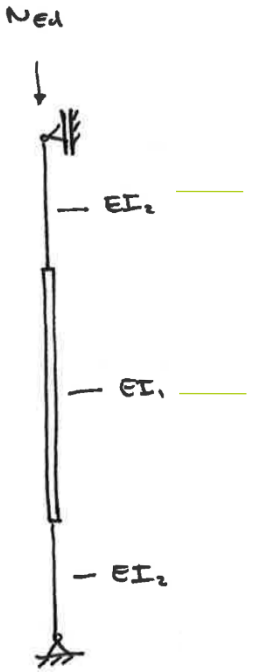
tension field

Capacity transverse stiffener (strut)

- capacity strut = design buckling resistance web







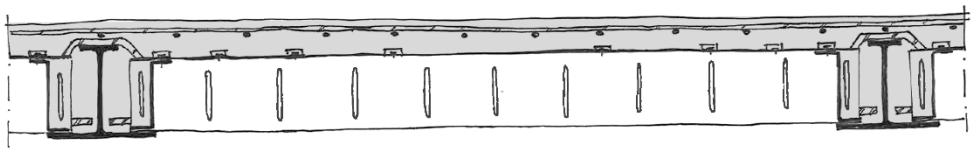
$I_2 = 32.4\ mm^4$

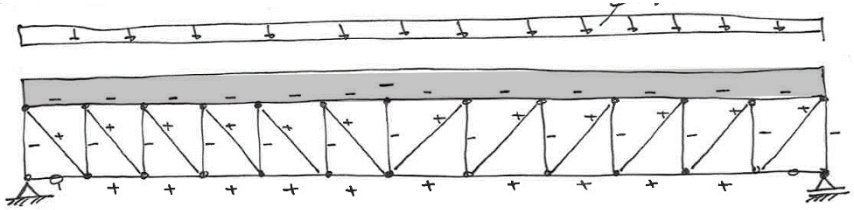
$I_1 = 220.1\ mm^4$

transverse stiffener of 150 mm

2 situations 2 models

- during service life

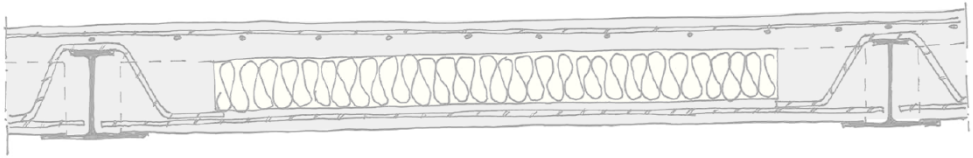


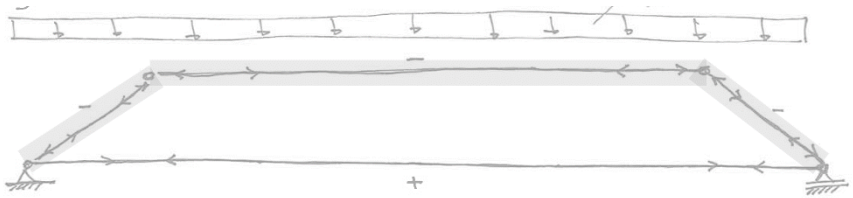


design of the deck to resist shear (1)

design of the shear connection (2)

- during fire





design of the floor to resist fire (3)

Design of the shear connection (2)

- different connectors

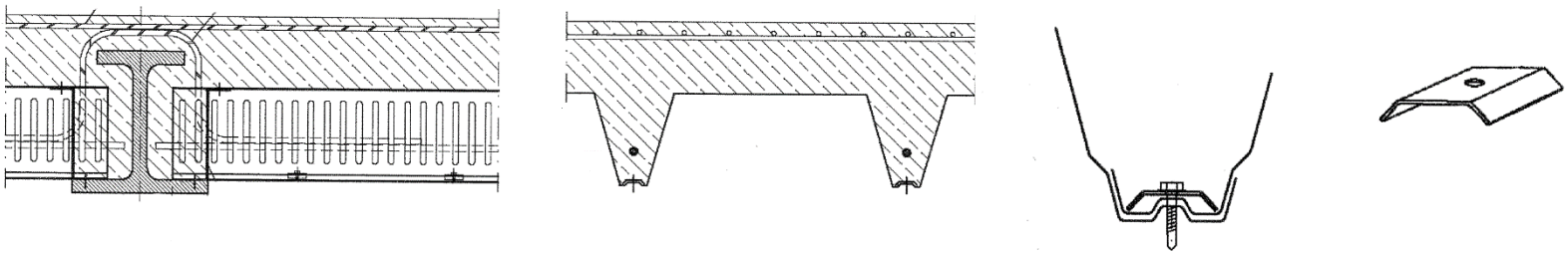
re-entrant profile (a)

embossment (b)

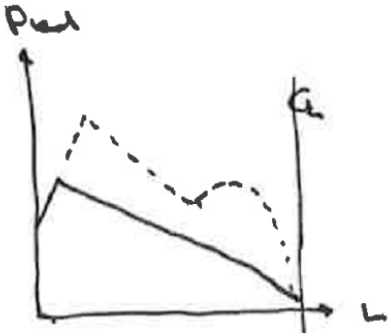
dowel (c)

Assumptions for connectors

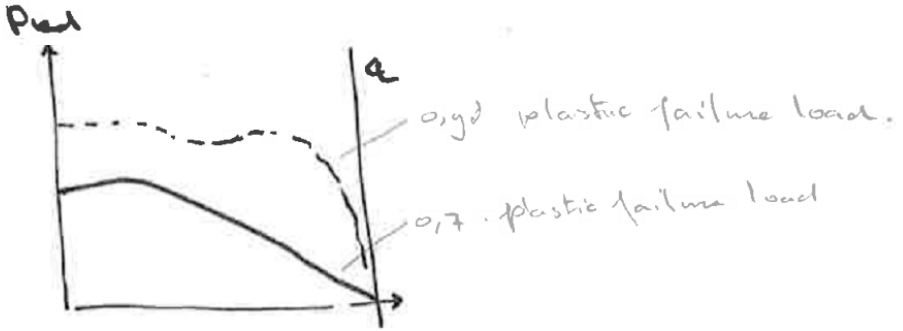
- strength from shear clips ComFlor 210



- rigid behaviour



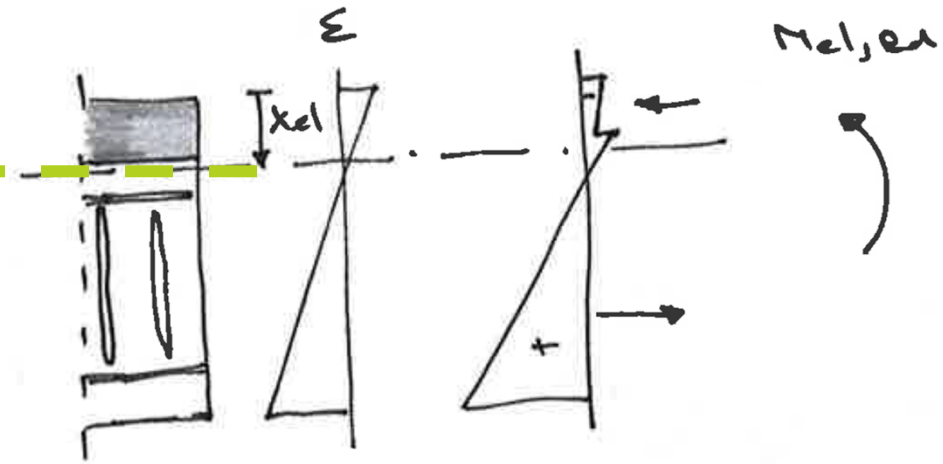
rigid connectors



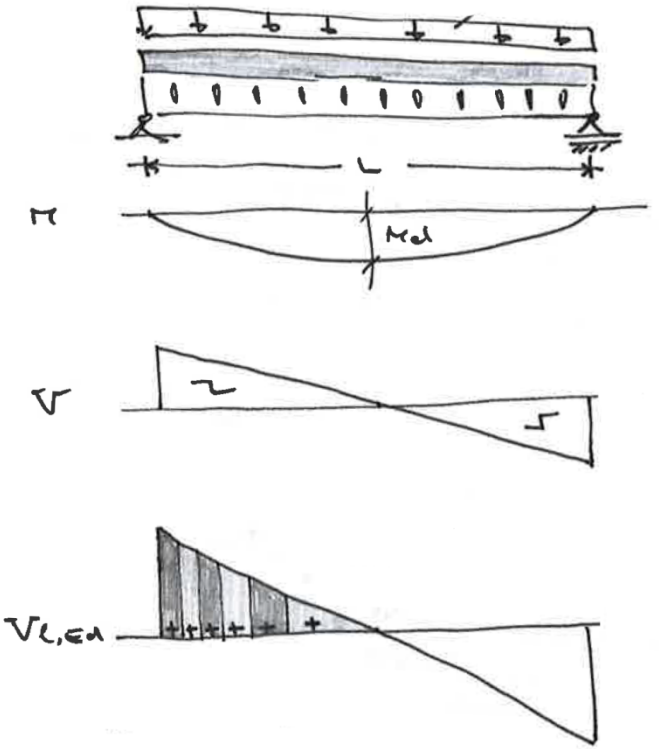
flexible connectors

Longitudinal shear forces

- at the steel-concrete interface



- partial shear connection

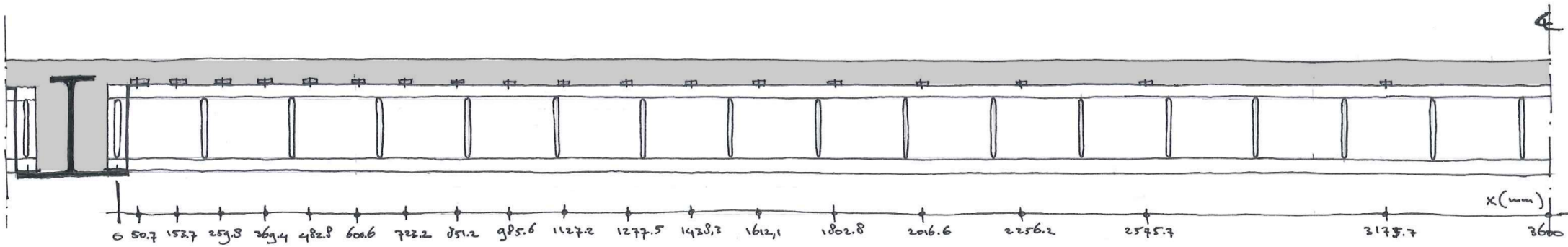


maximum bendi
moment

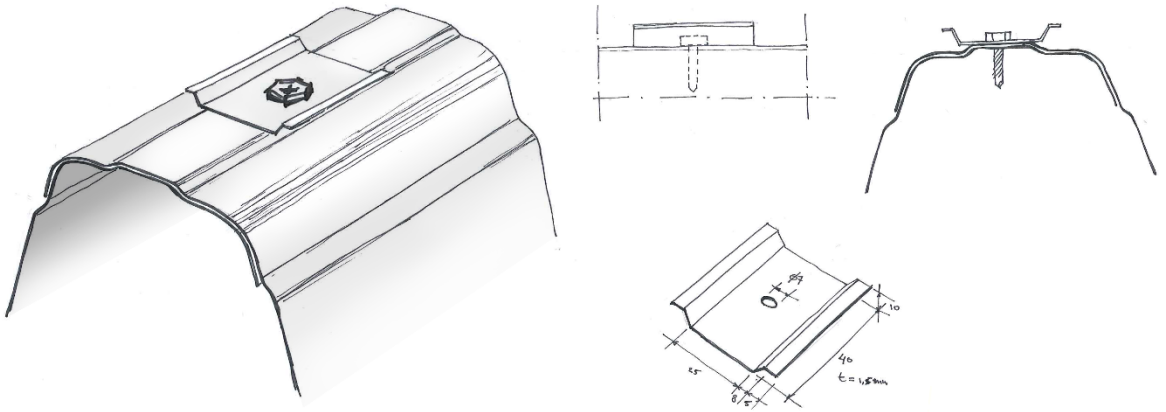
equal surfaces

Shear connectors

- 18 connectors per half-span

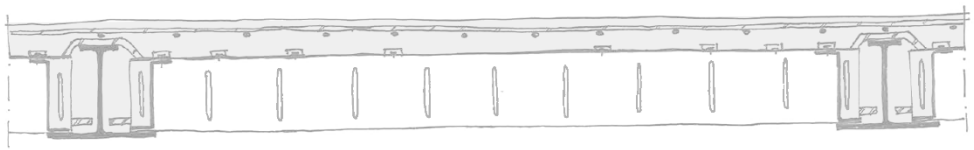


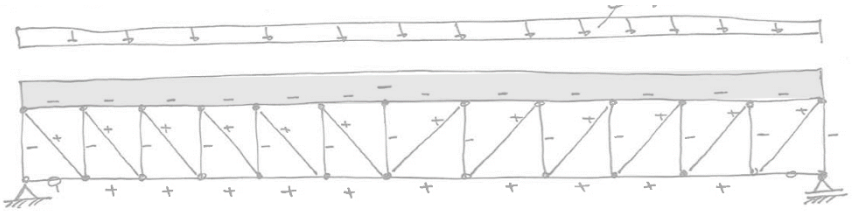
- design improvement for connector



2 situations 2 models

- during service life

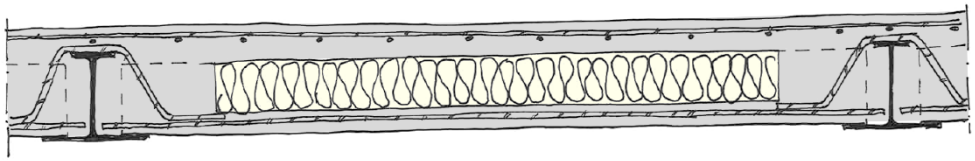


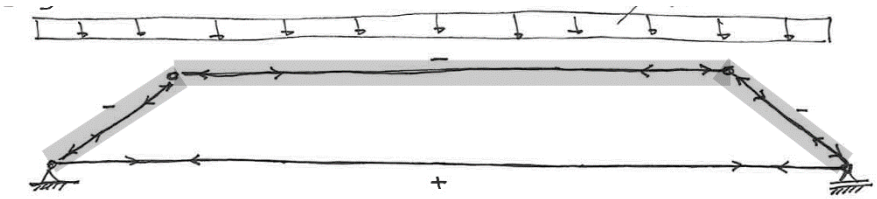


design of the deck to resist shear (1)

design of the shear connection (2)

- during fire

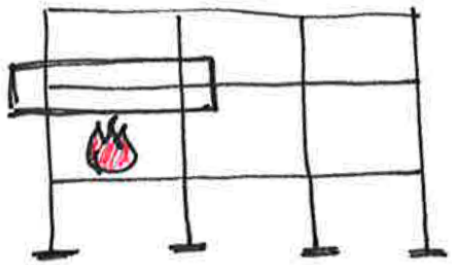




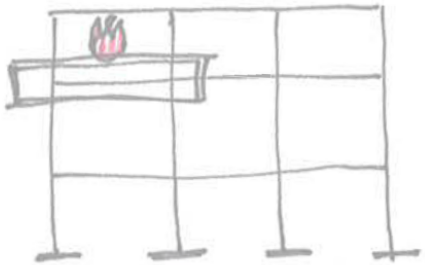
design of the floor to resist fire (3)

Design of the floor slab during fire (3)

- fire load



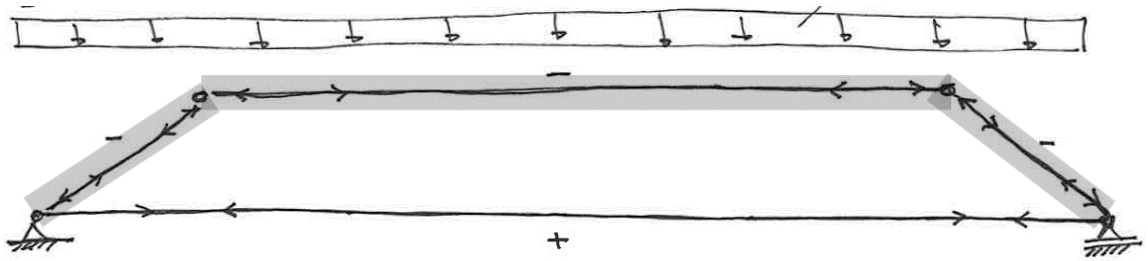
form below



from above

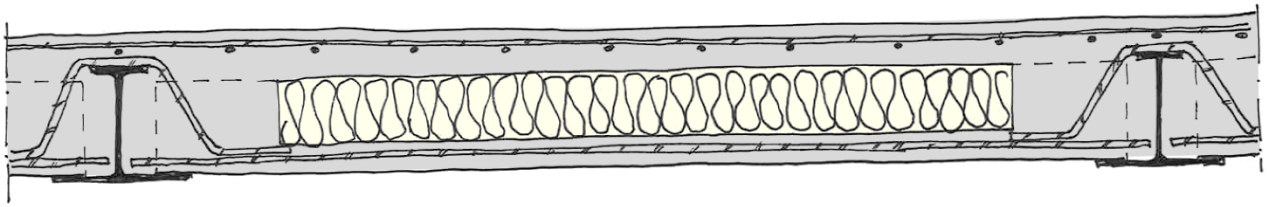
Load path during fire

- compression arch with tensile tie



reduced loads

- design for 60 and 90 minutes resistance

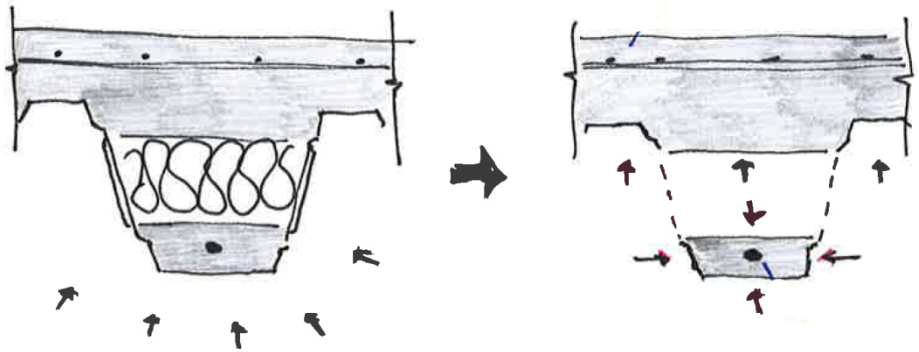


fully cast ribs near support

concrete in bottom ribs

Reduced material properties

- effect of fire on the floor

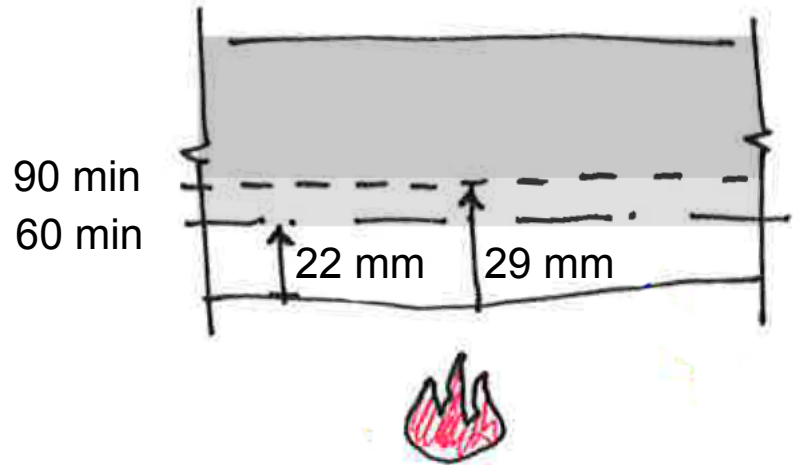


temperature profiles EC2-2

1 side

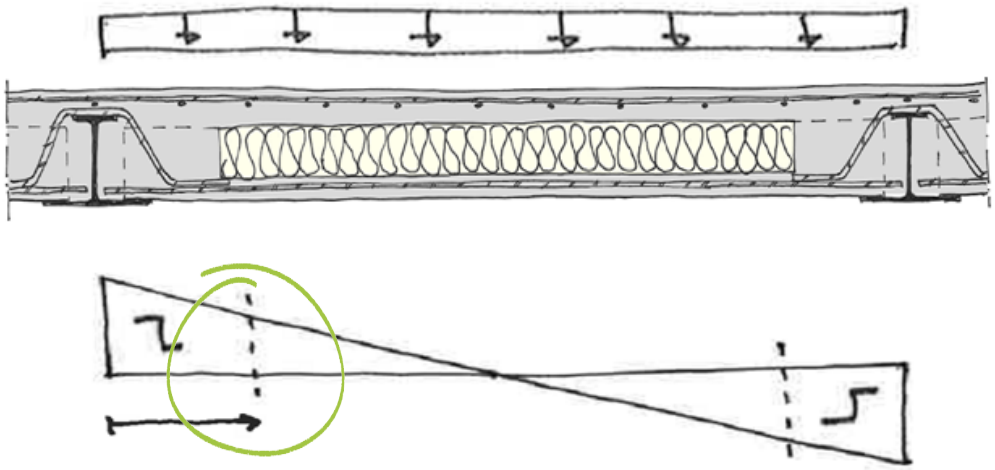
4 sides

- bottom reinforcement
  - after 60 minutes bar is 500˚C
  - after 90 minutes bar is 650˚C
- concrete top slab



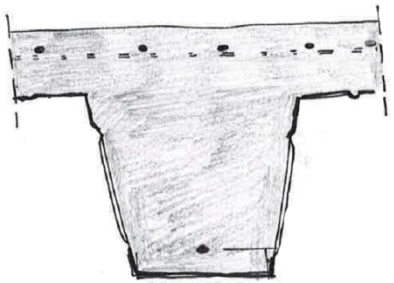
Shear resistance during fire

- shear forces over span

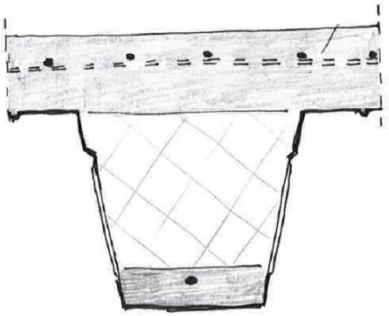


lower shear force

- two cross-section



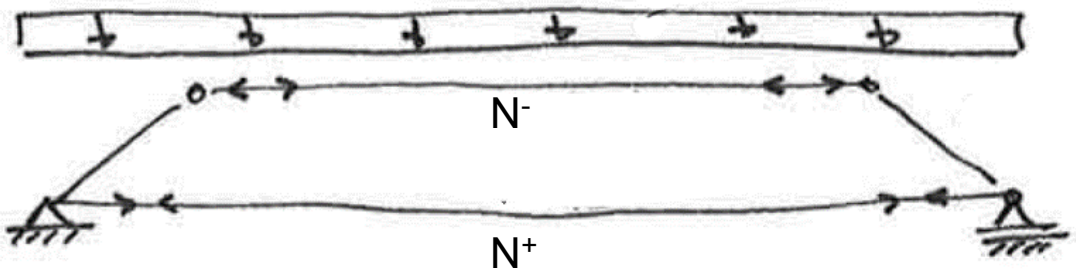
fully cast

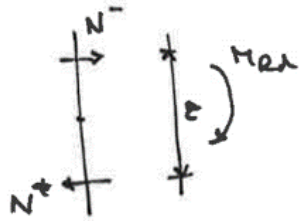


fill element

Bending moment resistance during fire

- bending moment resistance



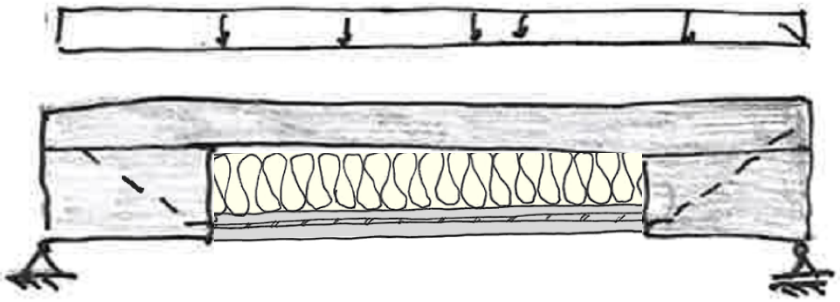


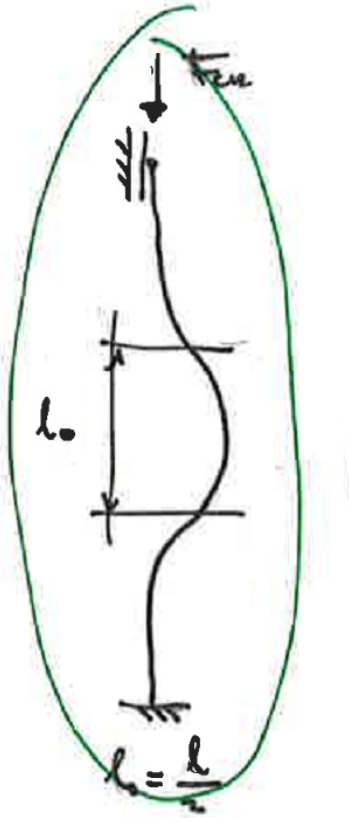
- required bottom reinforcement

	Steel temperature θ(°C)	Strength reduction $\Psi(\theta)$	Required steel area A_s (mm^2)	Chose bar (ømm)	Provided steel area A_s (mm^2)
R 60	500	0.63	137	16	201
R 90	650	0.33	261	20	314

Buckling of the concrete top flange

- concrete top flange unsupported

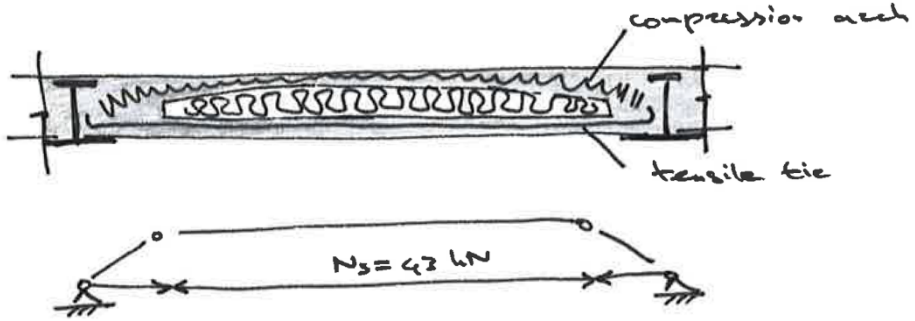




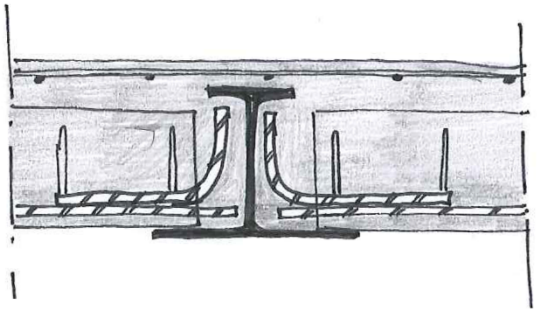
- 2 solutions to prevent buckling
  - design the concrete top flange
  - non-combustible fill element: rock wool

Anchorage of the tension reinforcement

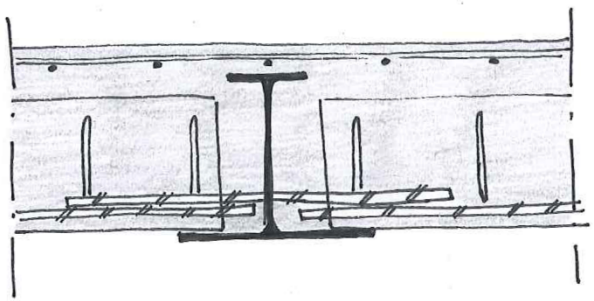
- connect concrete top flange and steel bottom reinforcement



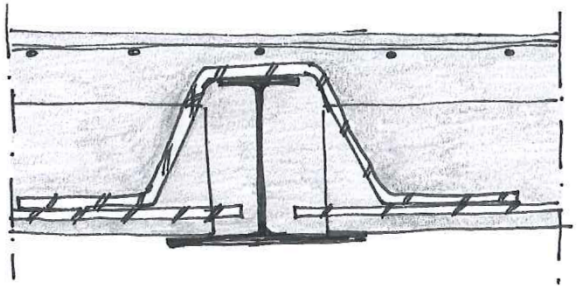
- different types of anchorage



seperate hook



bars through beam



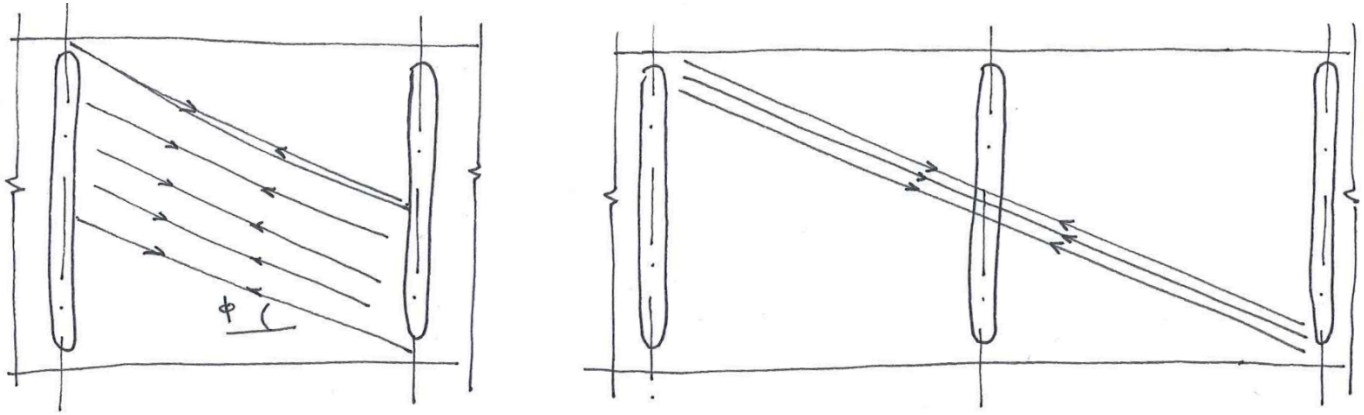
stirrup

Part 4

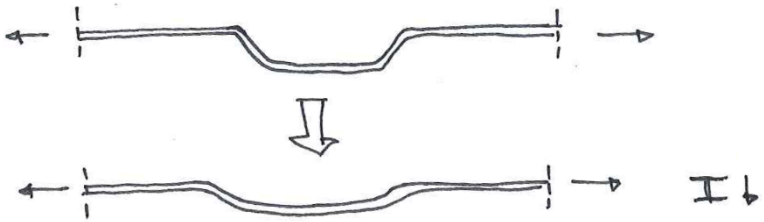
What have we Learned?

Formation of the tension field

- behaviour stiffener influenced



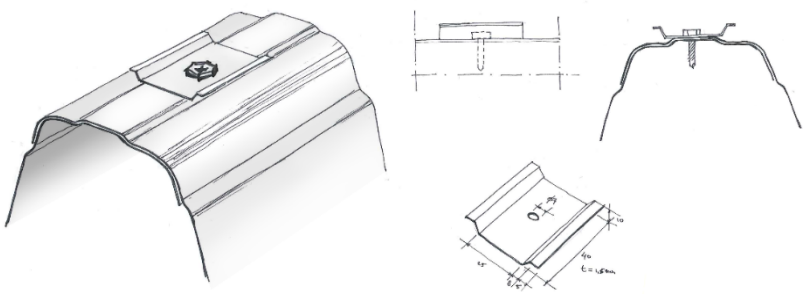
- elongation and weakening stiffener



- FEM model and testing

Shear connector

- design improvement for connector

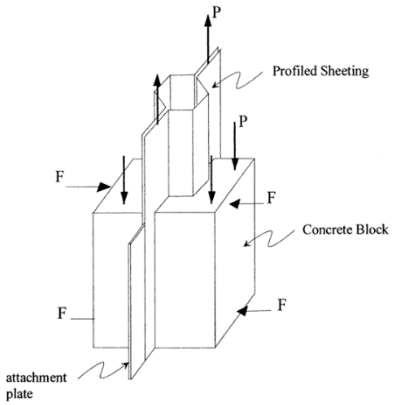


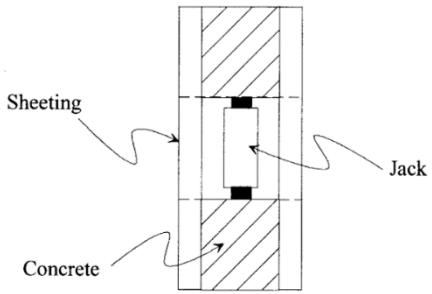
connect panels

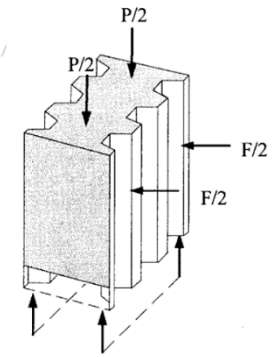
provide composite act

prevent vertical separ

- load-slip behaviour: ‘push tests’







Daniel’s

Porter’s

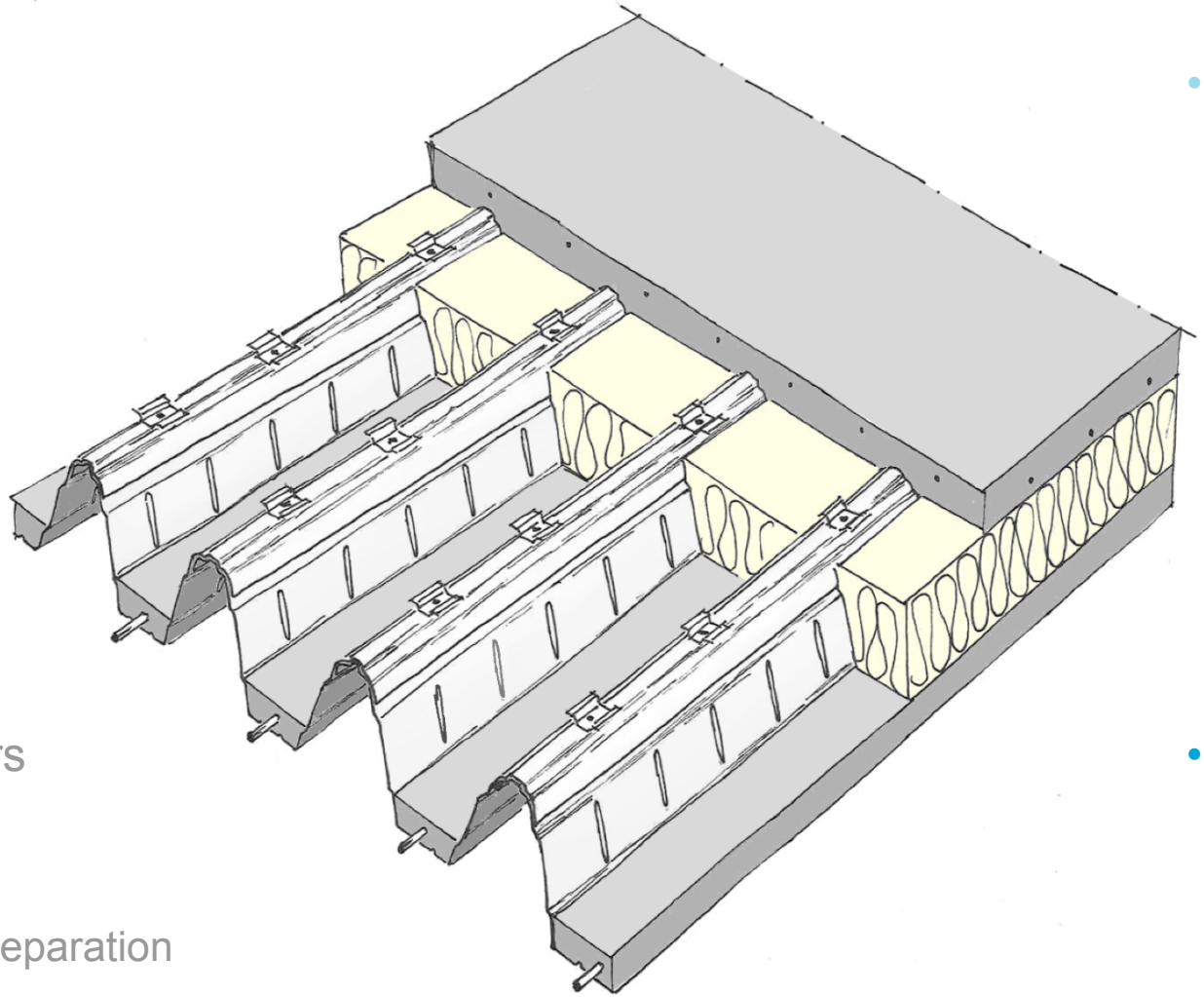
Stark’s

Fire resistance

- fire testing is obligatory
- verify mechanical resistance
- integrity and insulation

The JorFlor

- deck
  - 7.2 m long
  - 220 mm high
  - 1.20 mm thick
  - 300 mm wide
  - weight 50 kg



- floor slab
  - total height 280 mm
  - rock wool fill elemen
  - self-weight 300 kg/m

- improved connectors
  - connect panels
  - composite action
  - prevent vertical separation

- application
  - in-situ
  - prefab

Properties of the Jorflor compared with existing deep decks

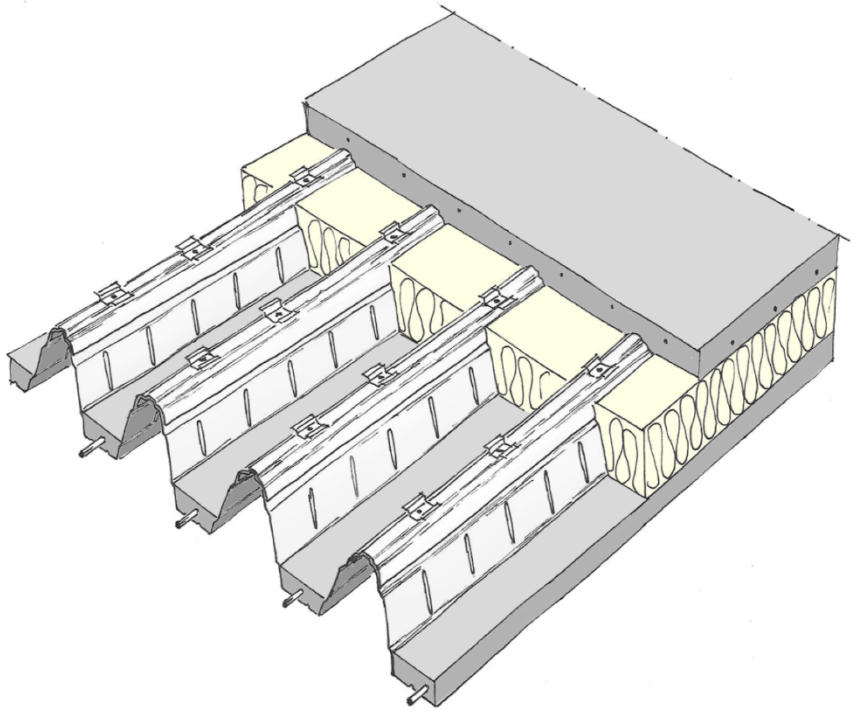
- big unpropped span 7.2 m
- light-weight deck elements 50 kg

- minimal construction height 280 mm
- low self-weight 300 kg/m^2
- good fire resistance 90 min

			Jorflor	CF210	CF225
Deck properties[1)]					
b_d	(mm)	:	300	600	600
h_p	(mm)	:	226	210	225
t	(mm)	:	1.20	1.25	1.25
A_p	(mm^2/m)	:	2970	2017	2278
A_{pe}	(mm^2/m)	:	1759	1426	1717
I_{eff}	(cm^4/m)	:	1896	816	1090
$M_{el,Rd}$	(kNm/m)	:	55.5	23.1	30.8
Floor properties					
h	(mm)	:	280	290	305
L	(m)	:	7.20	5.30	5.45
G[2)]	(kg/m^2)	:	301	303	366
V_c	(l/m^2)	:	107	121	145
G_p	(kN/m^2)	:	0.228	0.157	0.171
G_{deck}	(kg/deck)	:	50	70	79
$G_{ponding}$[3)]	(kg/m^2)	:	41	34	32
t_i	(min)	:	90	90	90

Composite Floors

A Theoretical Research into the Design of Steel-Concrete Composite Floors with a Bigger Unpropped Span of 7.2 m



J. van Blokland

30 September 2015

Graduation committee

Delft University of Technology

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Ir. R. Abspoel

Ir. S. Pasterkamp

Imd Raadgevende Ingenieurs

Ing. R. Stark

Dutch Engineering Raadgevend Ingenieurs B.V.

Ir. H. Prins

Specification of the design

Steel deck	Composite slab
Boundary conditions/assumptions: • maximum thickness steel sheet ≤ 1.5 mm • yield strength steel 350 Mpa • maximum coil width ≤ 1400 mm	• normal weight concrete C20/25
Dimensions: • lightweight deck elements < 50 kg • length deck elements 7.2 m • aim at thickness steel sheet 1.0 up to 1.25 mm • aim at 'minimum amount' of steel A_p/G_p	• aim at 'minimum height' floor slab < 300 mm • aim at 'lightweight' floor slab < 300 kg/m^2
Criteria: • deflection during construction: δ_0< L/180 • deck as: work-floor, shuttering, and reinforcement • construction unpropped • elements are stackable • deck should establish composite behaviour • simple connections: pop nails or self-drilling screws • aim at minimal actions to install floor • prevent LTB steel beam/provide diaphragm action	• total deflection: w_{tot} < L/250 (δ_0 not incl.) • additional deflection: w_{addl} <L/500 • adequate performance of floor vibrations: f_e>3-5 Hz • aim at minimal material use: sustainability • fire resistance ≥ 90 minutes • building services preferably integrated in floor slab • aim at flat bottom slab • monolith floor that provides diaphragm action

Properties of the Jorflor compared with existing deep decks

- Comflor 210
  - t = 1.0 mm
  - L = 4.35 m
  - A_p = 1614 mm²/m
  - G_p = 0.13 kN/m²

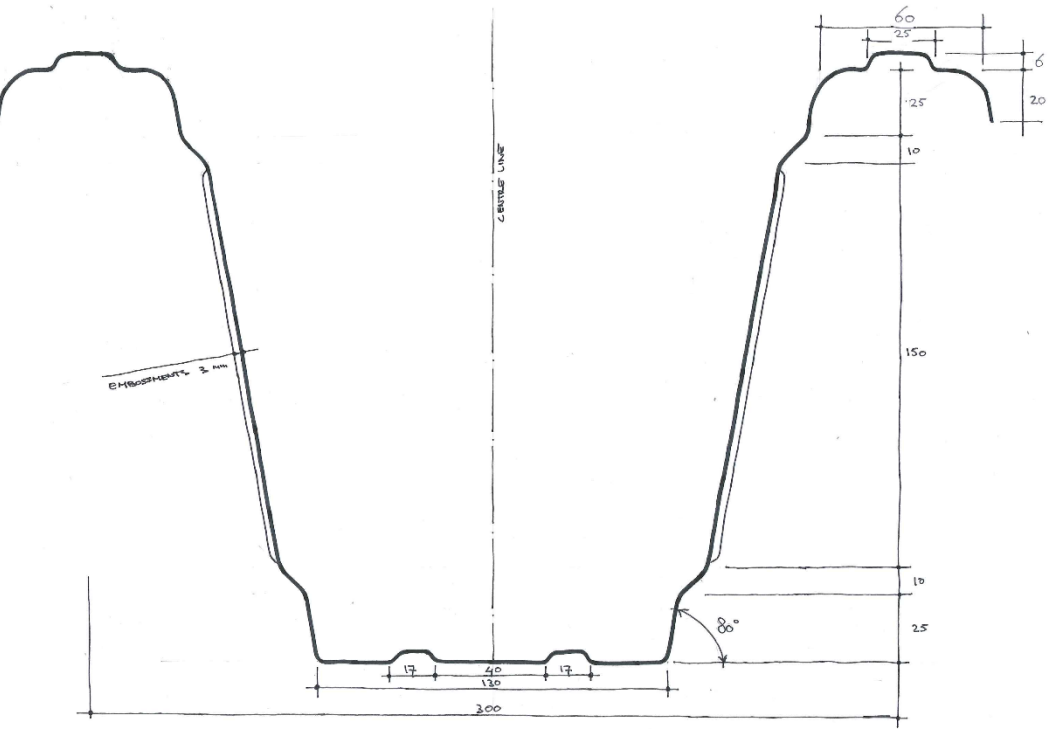
			Jorflor	CF210	CF225
Deck properties[1]					
b_d	(mm)	:	300	600	600
h_p	(mm)	:	226	210	225
t	(mm)	:	1.20	1.25	1.25
A_p	(mm²/m)	:	2970	2017	2278
A_{pe}	(mm²/m)	:	1759	1426	1717
I_{eff}	(cm⁴/m)	:	1896	816	1090
$M_{el,Rd}$	(kNm/m)	:	55.5	23.1	30.8
Floor properties					
h	(mm)	:	280	290	305
L	(m)	:	7.20	5.30	5.45
G[2]	(kg/m²)	:	301	303	366
V_c	(l/m²)	:	107	121	145
G_p	(kN/m²)	:	0.228	0.157	0.171
G_{deck}	(kg/deck)	:	50	70	79
$G_{ponding}$[3]	(kg/m²)	:	41	34	32
t_i	(min)	:	90	90	90

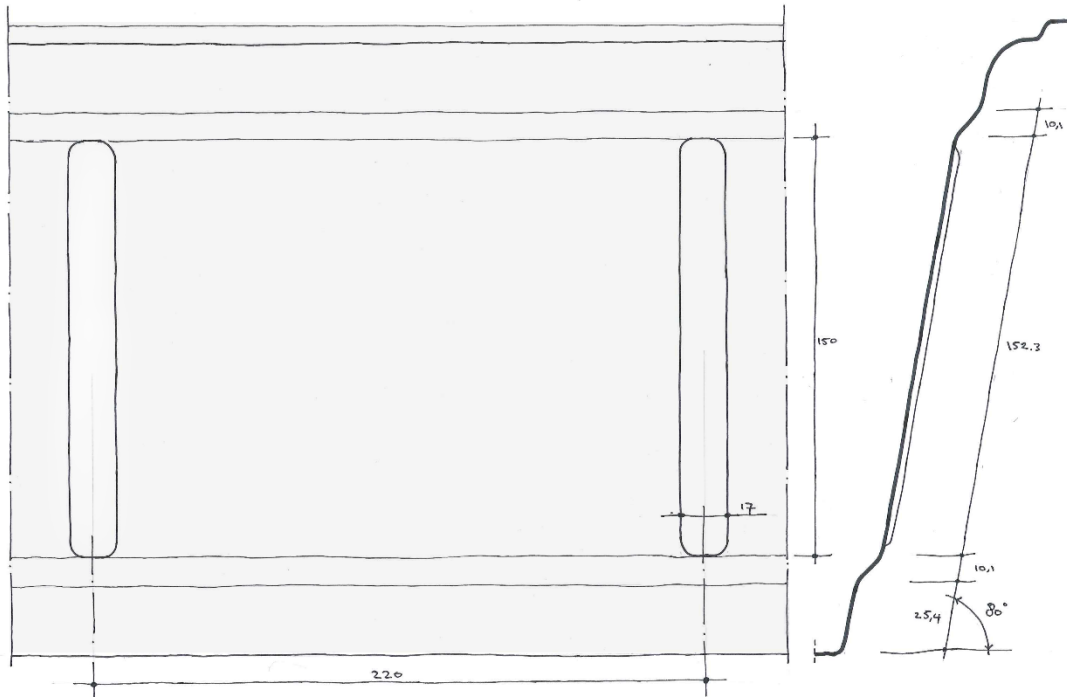
[1] dimensions of deck in next slide

[2] ponding not included in the self-weight

[3] ponding given for the maximum unpropped span

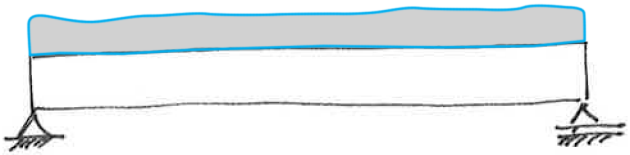
Dimensions of the deck





Loads on the JorFlor

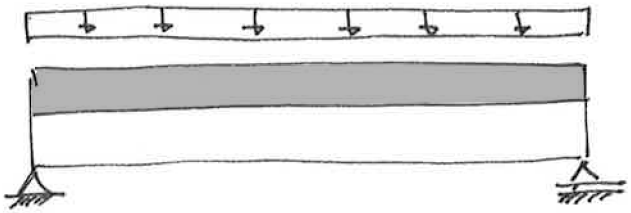
- construction



deck

carries wet concrete

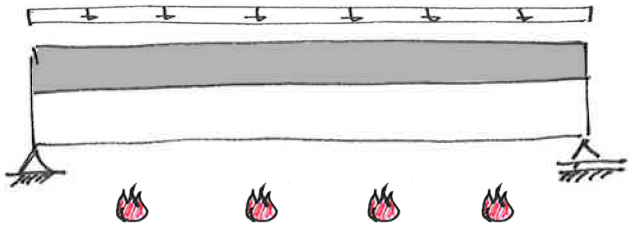
- service life



composite slab

carries self-weight plus live load

- during fire



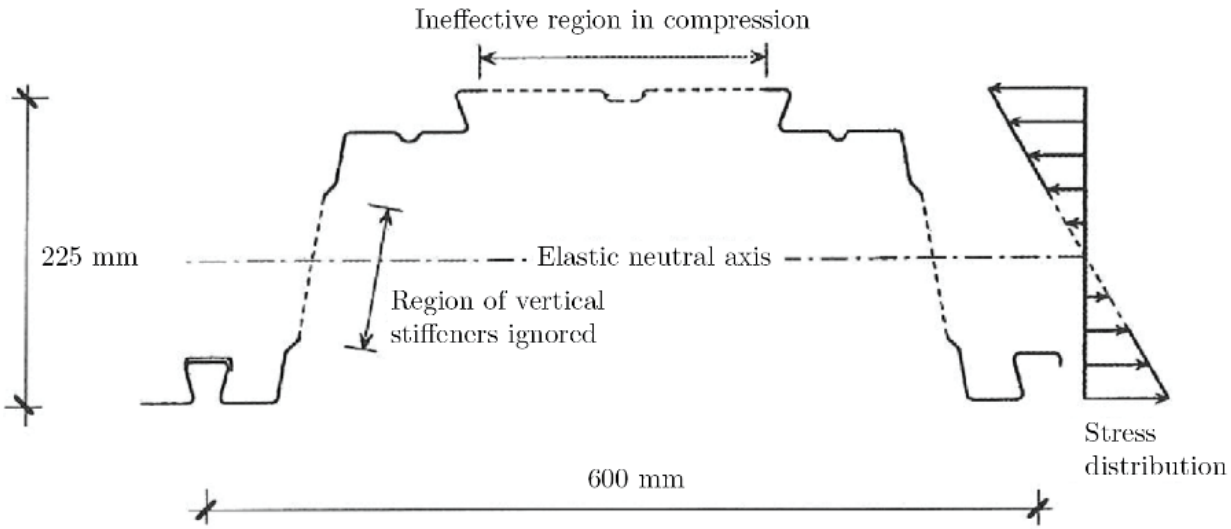
composite slab

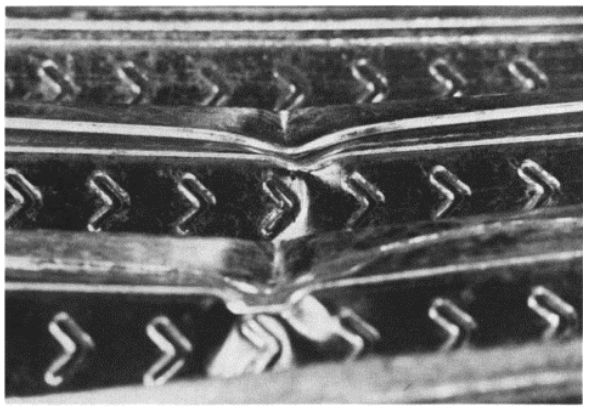
carries self-weight plus reduced live load

	construction	service life	during fire
self-weight	3.0 + 0.4 = 3.4	3.4	3.4
live load	0.75	4.0	1.2
stiffness	3.4	7.4	-
strength	5.2	10.1	4.6

Structural properties

- effective cross-section

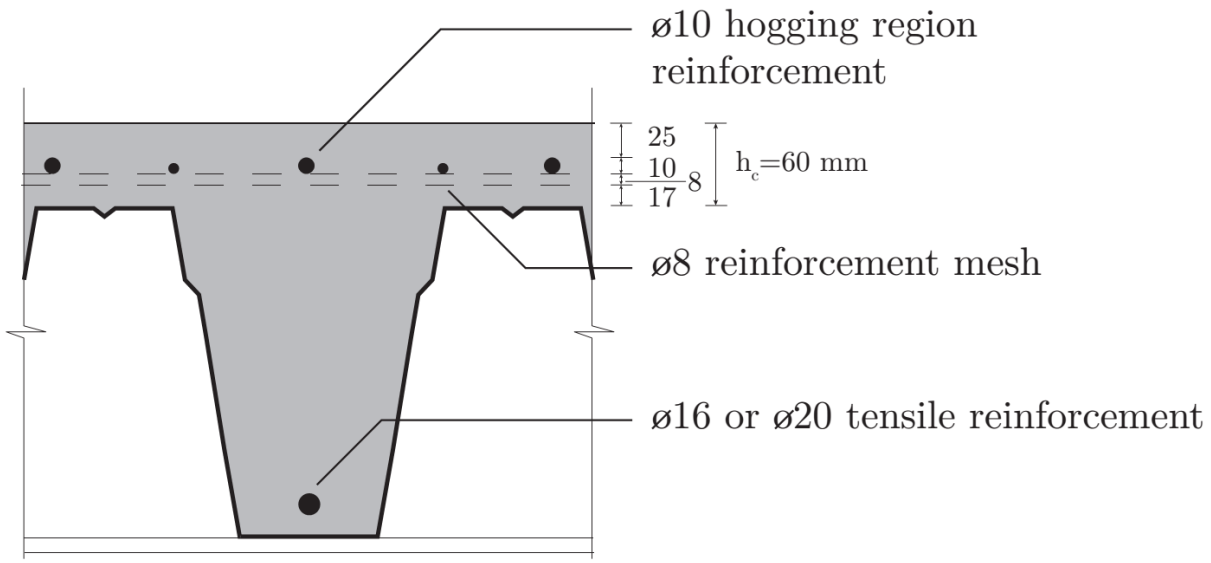




- design thickness steel sheet
  - anti-corrosive zink layer on both sides
  - $t_0 = t - 0.04$ *[mm]*

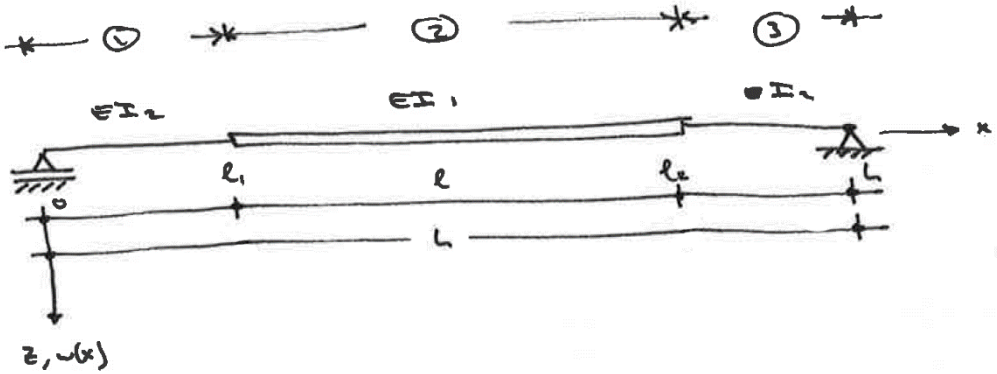
The concrete top flange

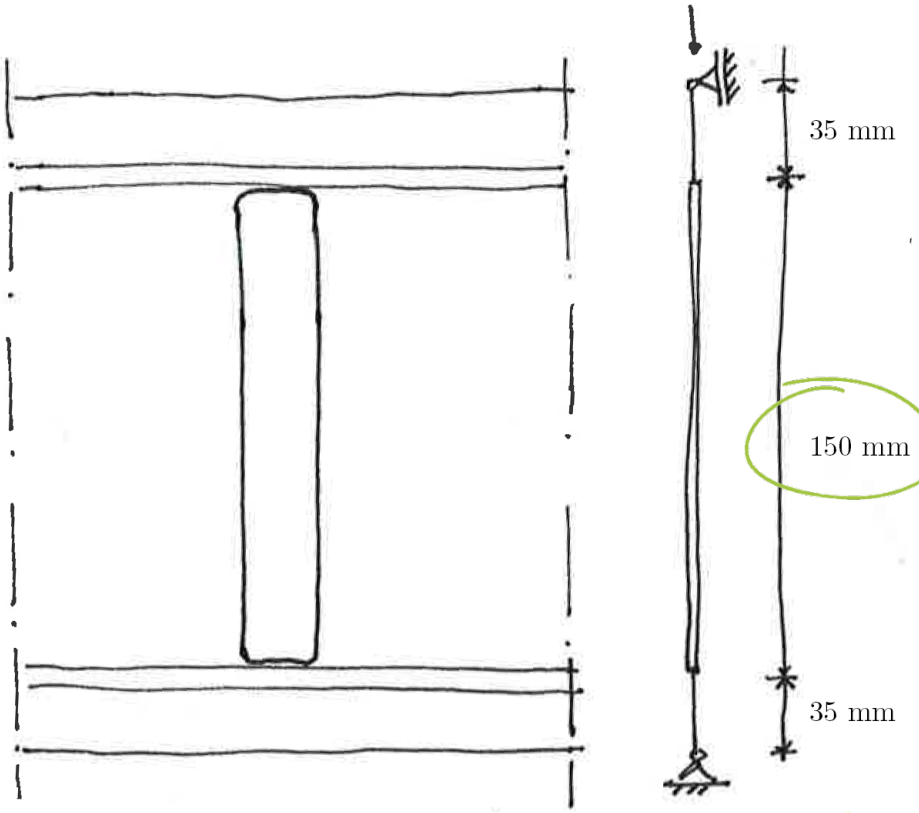
- height top flange 60 mm
- cover 25 mm
- mesh round 8
- fire situation governing
  - 90 minutes fire load
  - only 30 mm slab left



Buckling model

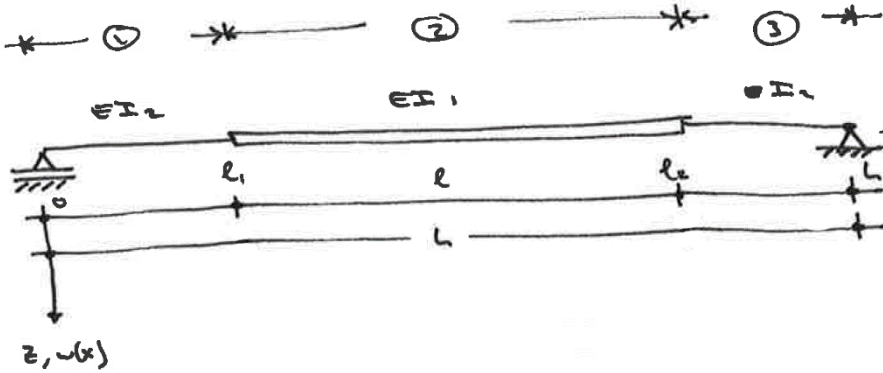
- design buckling resistance
  - Eurler-buckling resistance form model
  - imperfections with rules Eurocode



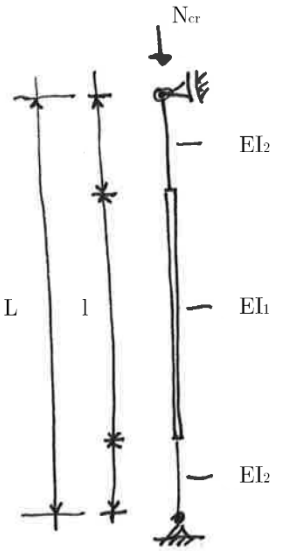


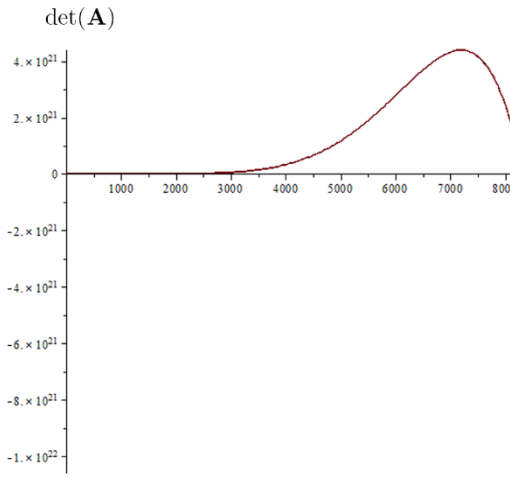
Euler buckling load

- solve 4th order differential equation (DE) in Maple



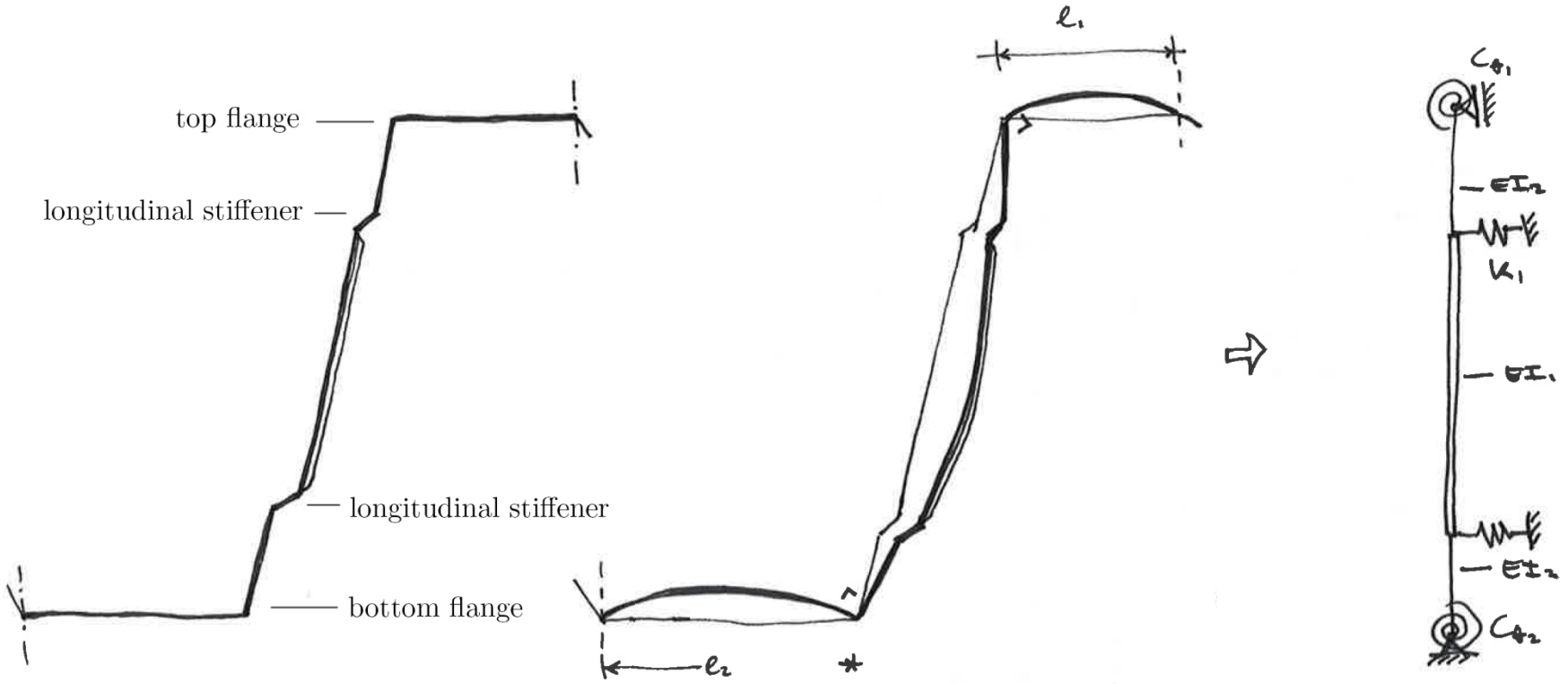
  - 3 DE's
  - 12 homogenous equations: 4 BC's and 8 MC's
  - 12 unknown integration constants: C_1, C_2, .. C_{12}
  - parameters: EI_1, EI_2, and lengths L and l
  - one variable: buckling load F



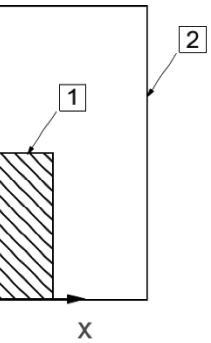


  - 12 equations written in matrix notation
  - **A** $\underline{x}$ = $\underline{0}$
    - **A** is the matrix with all coefficiets (contains F)
    - $\underline{x}$ the vector with the integrations constants
    - $\underline{0}$ the null vector
  - this system of homogenous equations has only a non-trivial solutions if the determinant of **A** is equal to zero: det(**A**)=0
  - det(**A**) = 0 solved in Maple

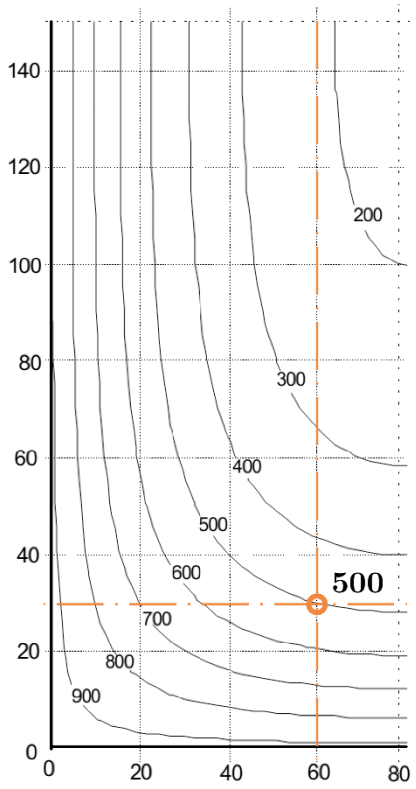
Rotational and translational stiffness



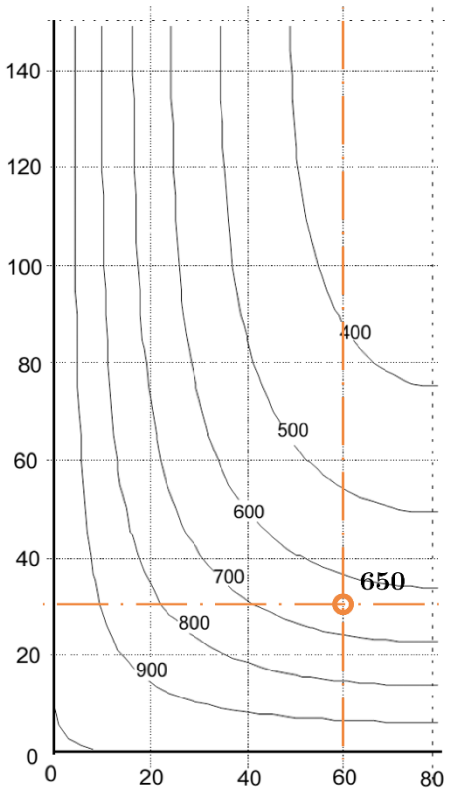
Temperature distributions



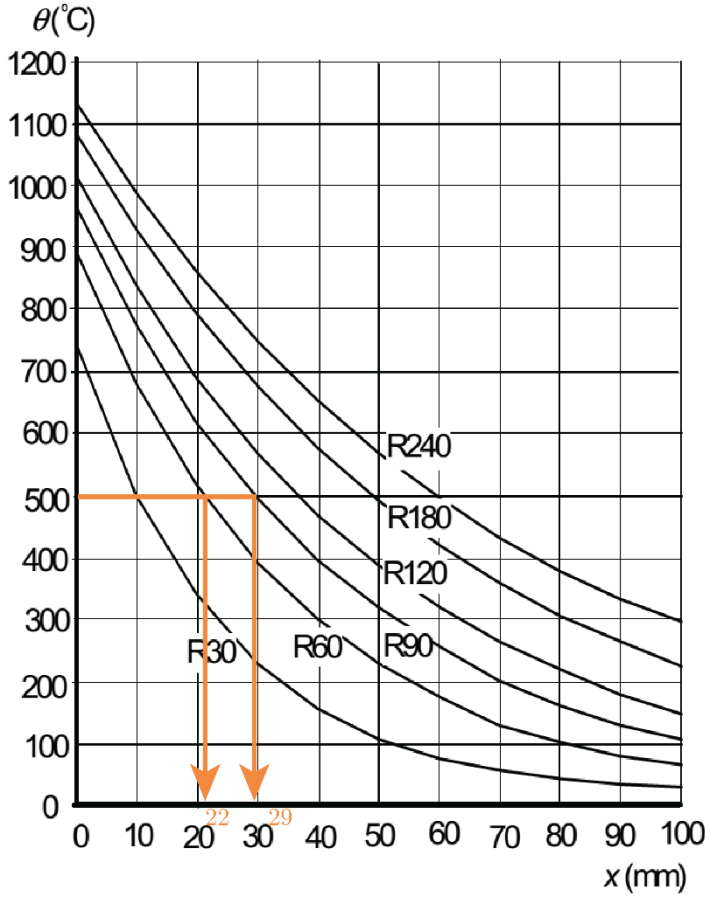
ebied met de temperatuurverdeling
olledige dwarsdoorsnede



R60



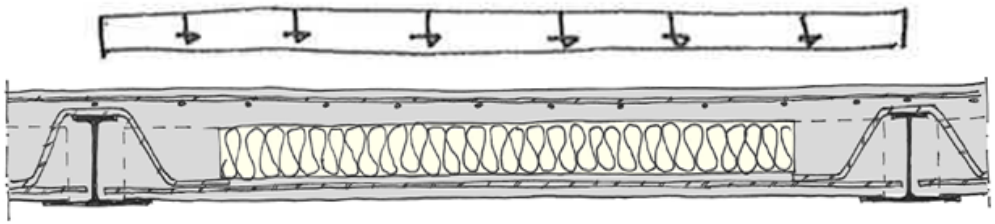
R90



x is de afstand tot het aan brand blootgestelde oppervlak

Bending and shear during fire

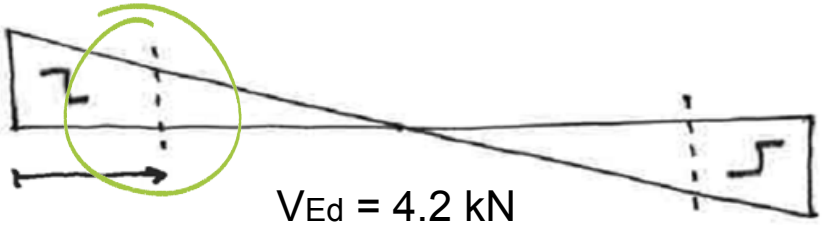
- loads during fire



  - normal force due to bending

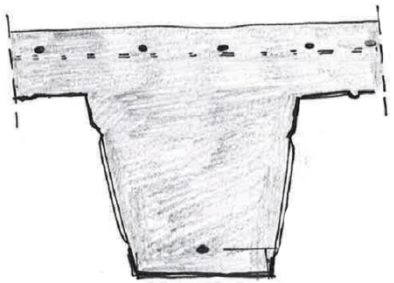
N_{Ed} = -43 kN

  - shear force

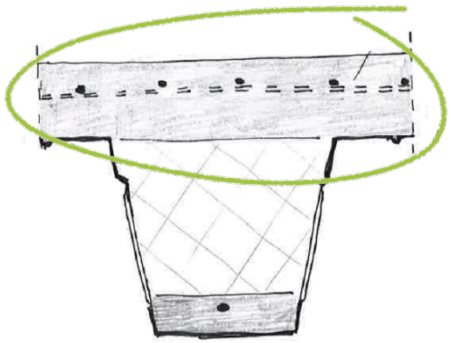


V_{Ed} = 4.2 kN

- resistance during fire



fully cast



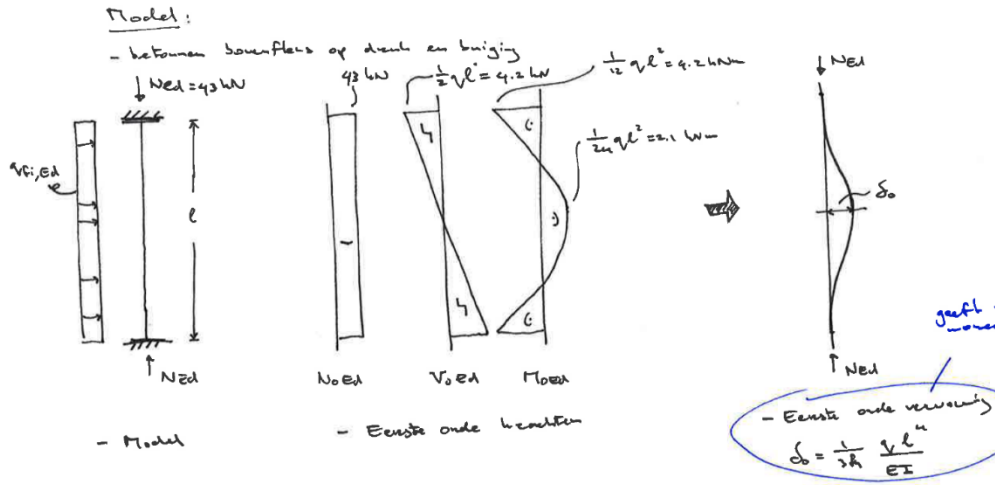
fill element

N_{Rd} = -186 kN

V_{Rd} = 5.1 kN

Design of the concrete top flange to resist buckling

- bending stiffness taken conservative
- 1st order deflection gives 2nd order moment
- 2nd order effect with *n/(n-1)*
- $n = F_{cr}/F$



- first order delfection:
  - $\delta_0 = 1/384 * (q\ L^4)/(EI)$
- final deflection:
  - $\delta_e = \delta_e * n/(n-1)$
- second order moments:
  - at mid-span: $M_2^+ = NEd * \delta e$
  - at support: $M_2^- = (6EI)/(l/2)^2 * \delta e$