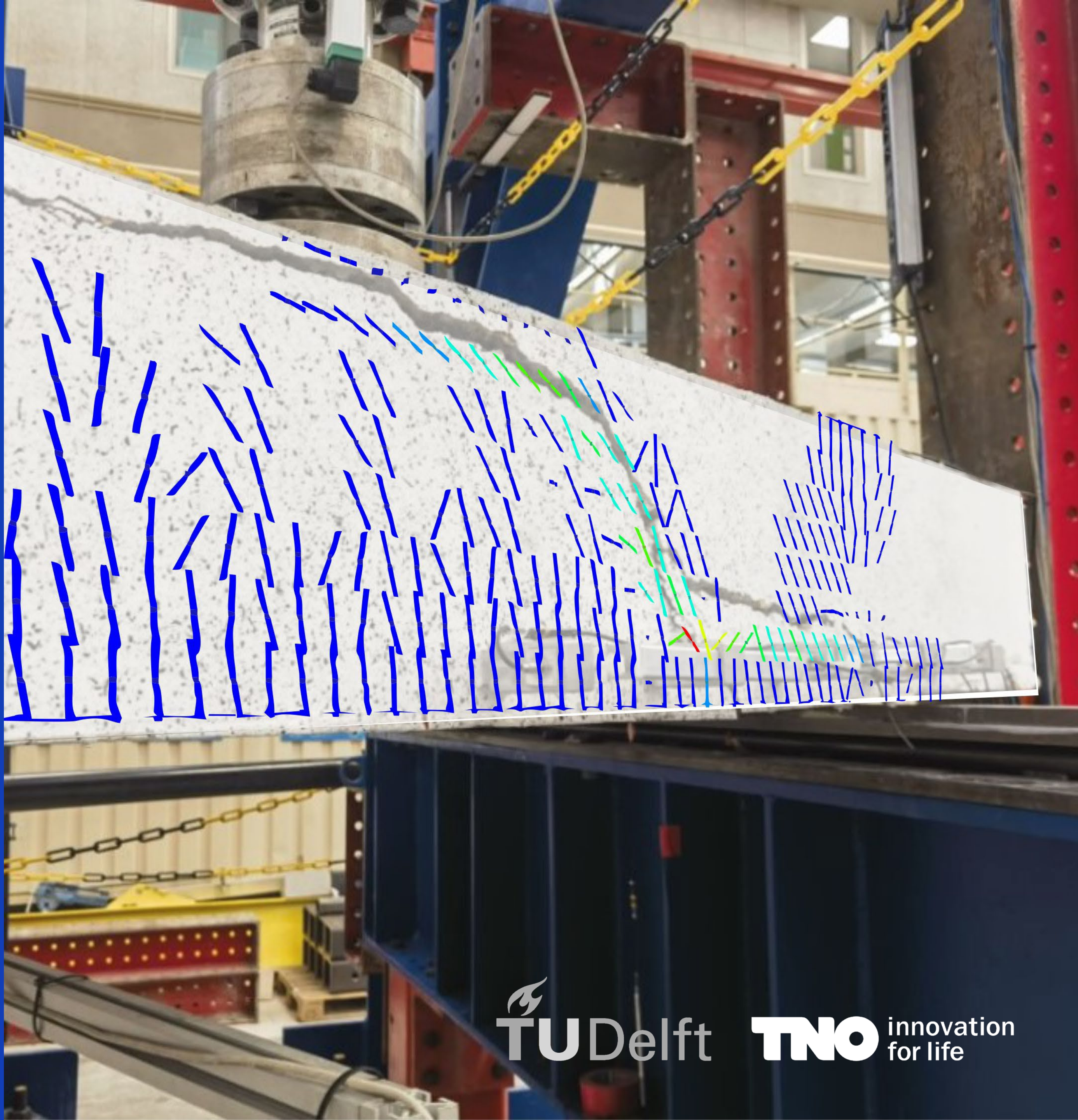
Skew slabs

Experimental tests, code equations and comparison with advanced numerical models

Sanabria Diaz, R.A. (Rafael)



Agenda

1. Problem statement
2. Approaches for shear in members without shear reinforcement
3. Consideration for skews slabs
4. Assessment of skew slabs using **LFEA**
5. Assessment of skew slabs using **NLFEA**
6. Conclusions

My background

2010 –2014 – Civil Engineering, BSc,

(Industrial University of Santander)

2014 –2016 – Structural Designer

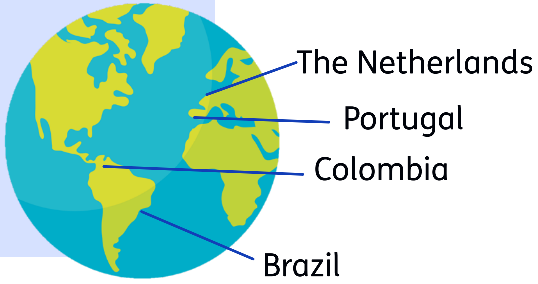
2016 –2023 – MSc and PhD in Concrete Structures (University of Campinas)

2021 –2022 – PhD exchange

(NOVA University)

2023 –2024 – Postdoc (TU Delft)

2024 - Researcher at TNO



Expertise:

Concrete structures,

Structural mechanics,

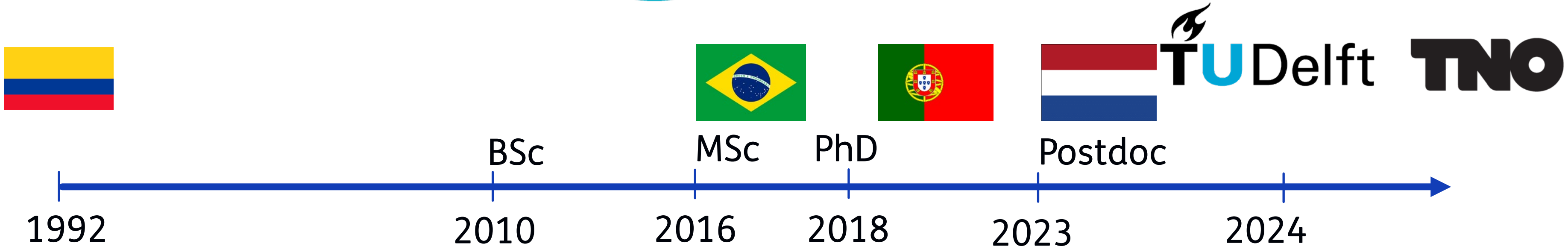
Numerical modelling,

Nonlinear analysis,

Reliability analysis

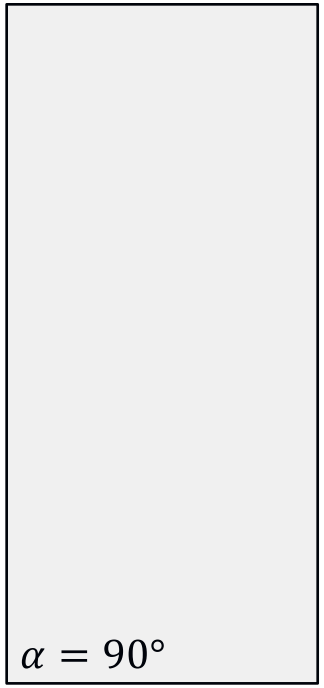
Fracture mechanics,

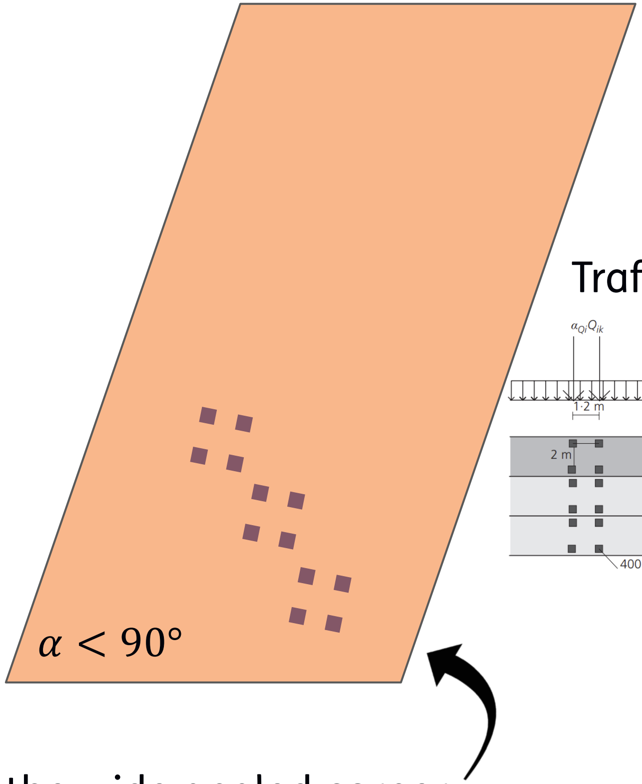
Finite element model



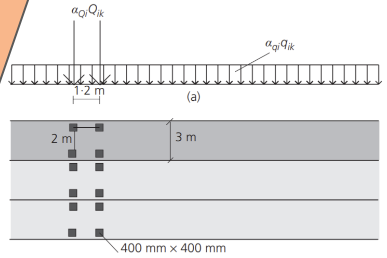
Problem statement

Skewed viaduct bridge KW4 “Frankeneng” in A30 (Ede)





Traffic model



The reaction force at the wide angled corner become more significant as the skew angle decrease [1, 2]

In practice, skew bridges with $75° < \alpha < 90°$ are treated as straight bridges

[1] Hulsebosch C.A. A parametric study on the design of reinforced concrete simply supported skewed slab highway bridges: TU Delft, 2019
[2] Cope R. Flexural shear failure of reinforced concrete slabs bridges: Proceedings of the Institution of Civil Engineers. 1985

Approaches for shear in member without shear reinforcement

- **Current EN 1992-1-1:2004**

$$V_{Rd,c} = \left[C_{Rd,c} \cdot k \cdot (100 \ \cdot \rho_l \cdot f_{ck})^{1/3}\right] \cdot b_w \cdot d$$

$C_{Rd,c}$ equal to $0.18/\gamma_c$ (recommended value)

k size effect factor equal to $1 + \sqrt{200/d} \leq 2$

ρ_l is the longitudinal reinforcement ($\leq 2\%$)

f_{ck} is the characteristic compressive strength of concrete

k_1 is a constant equal to 0.15 (recommended value)

d is the effective depth of the member

Approaches for shear in member without shear reinforcement – cont'd

- **FprEN 1992-1-1:2023**

$$V_{Rd,c} = \frac{0.66}{\gamma_v}\left(100 \cdot \rho_l \cdot f_{ck} \cdot \frac{d_{dg}}{d}\right)^{\frac{1}{3}} b_w \cdot d$$

d_{dg} is a size parameter describing the failure zone roughness, which depends on the concrete type and its aggregate properties, taken as (in [mm]):

$$16\,mm + D_{lower} \leq 40\,mm \;\rightarrow f_{ck} \leq 60\,MPa$$

$$16\,mm + D_{lower}\left(\frac{60}{f_{ck}}\right)^2 \leq 40\,mm \;\rightarrow f_{ck} > 60\,MPa$$

D_{lower} "smallest value of the upper sieve in a aggregate for the coarsest fraction" EN-1260

d is the effective of flexural reinforcement depth, for more refined calculation can be replaced by

$$a_v = \sqrt{\frac{a_{cs}}{4} \cdot d}$$

$$a_{cs} = \left|\frac{M_{Ed}}{V_{Ed}}\right| \geq d$$

Considerations for skew slabs

- **Shear verification for member without shear reinforcement**

$$V_{Rd,c} \geq V_{Ed} \quad \rightarrow \tau_{Rd,c} \geq \tau_{Ed}$$

- **How to determine τ_{Ed} ?**

Using a linear elastic analysis, with $\nu = 0$, G = $G_{elas}/8$ (this approach accounts for the redistribution on the shear field due to cracking) [3].

Clauses in 8.2.1 (FprEN 1992-1-1:2023)

(5) In planar members (such as solid slabs and shells), the design shear force per unit length should calculated as:

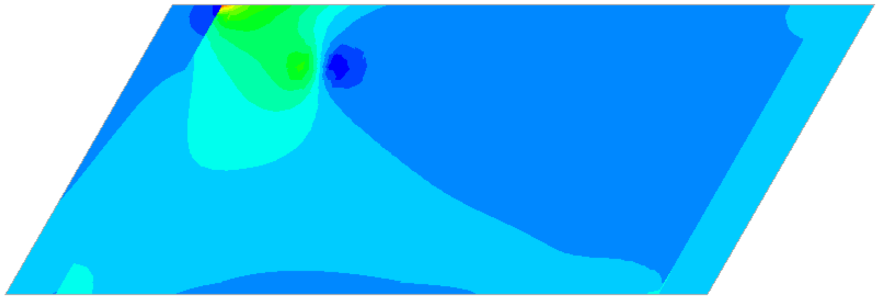
$$v_{Ed} = \sqrt{v_{Ed,x}^2 + v_{Ed,y}^2}$$

(6) When the shear force in planar member is not constant along the control section, it may be averaged over a width not larger than 2d on both sides from the peak of the shear force.

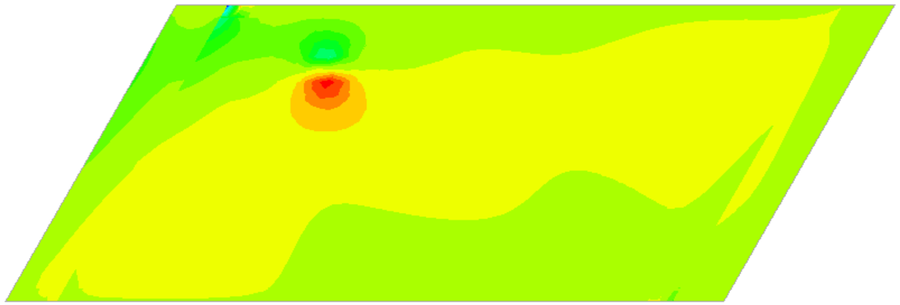
[3] Natario A., Fernandez Ruiz M., Muttoni A. Shear strength of RC slabs under concentrated load near clamped linear support. Engineering Structures. 2014; 76:10-23

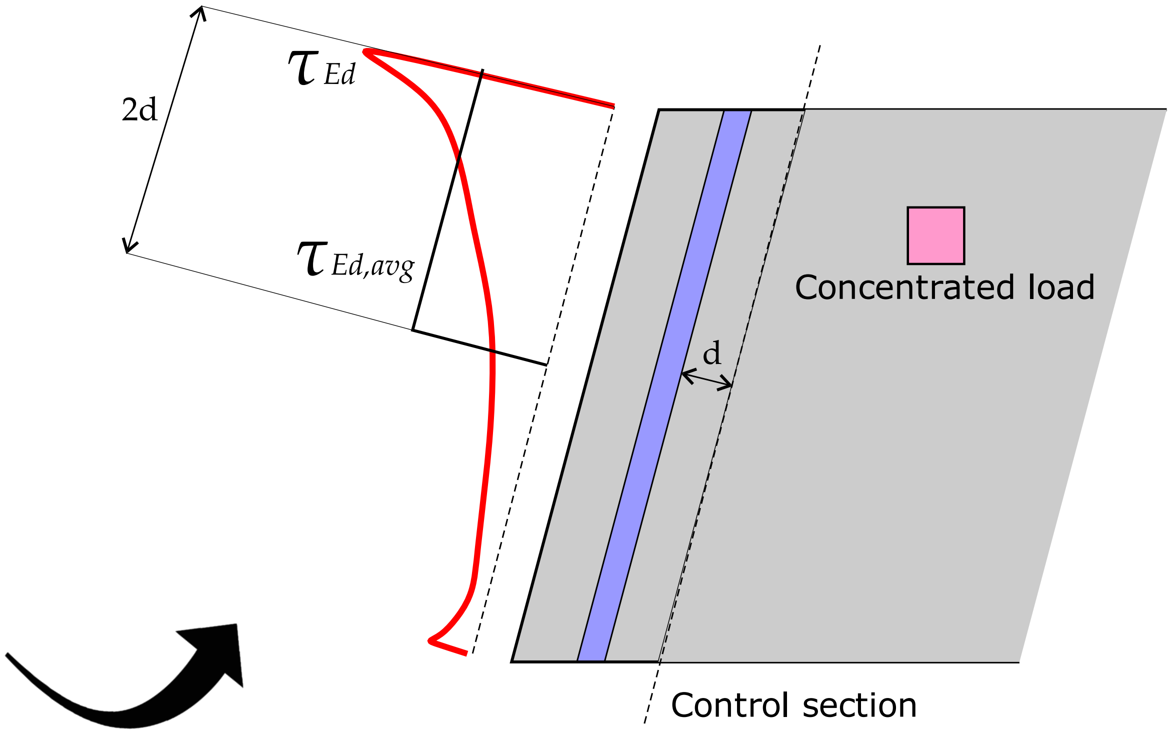
Considerations for skew slabs – cont'd

- **How to determine τ_{Ed}?**



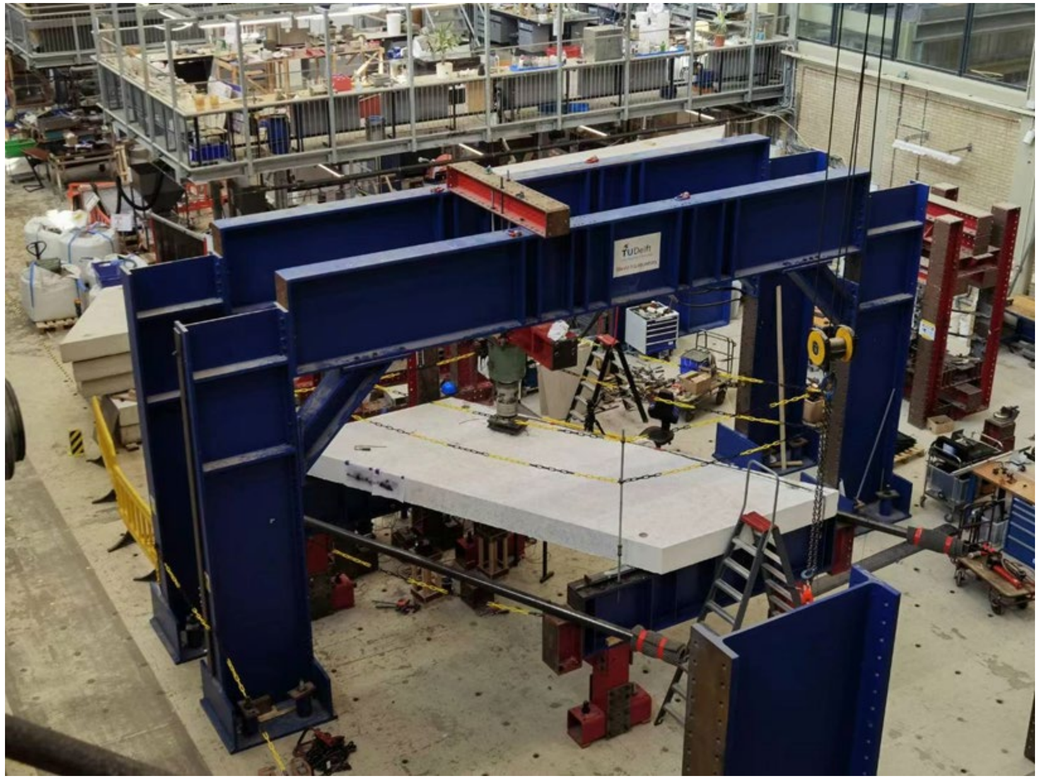
$$v_{Ed} = \sqrt{v_{Ed,x}^2 + v_{Ed,y}^2}$$

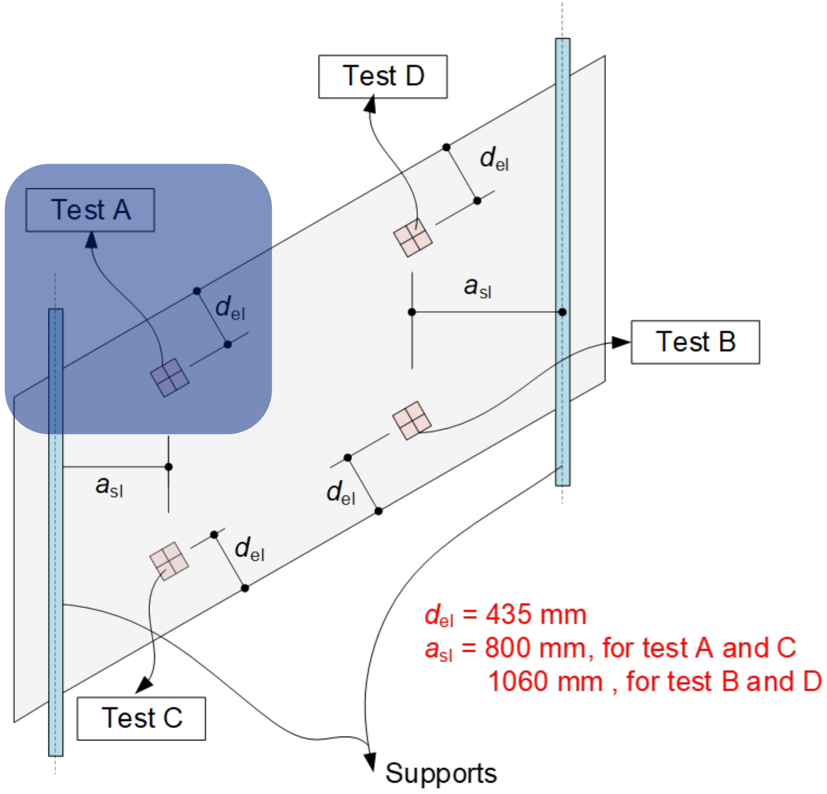




Assessment of skew slabs using LFEA

- Test campaign by J. Lu (2023)

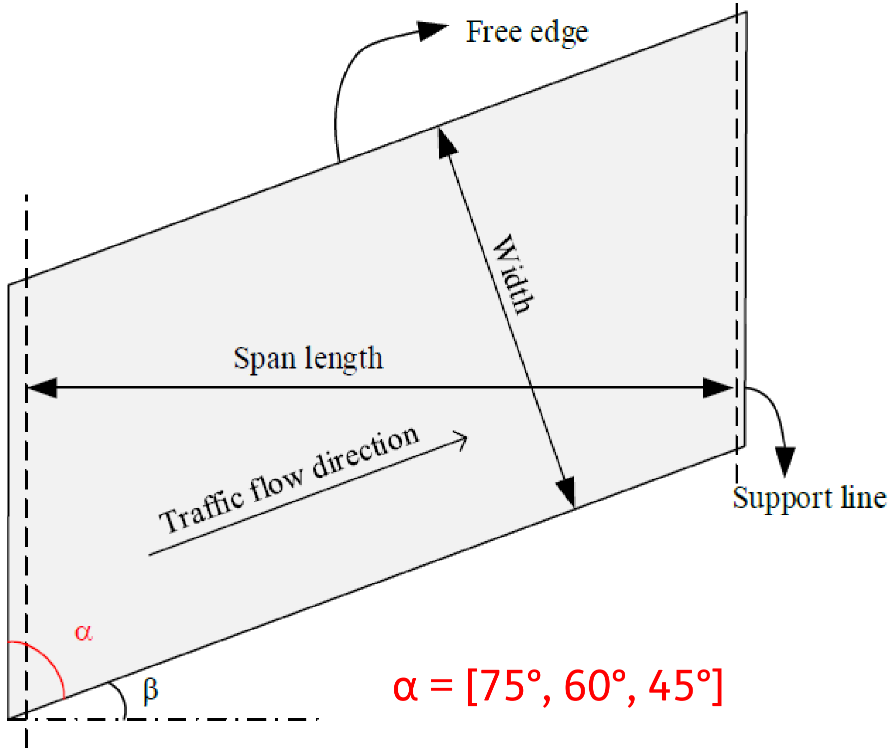




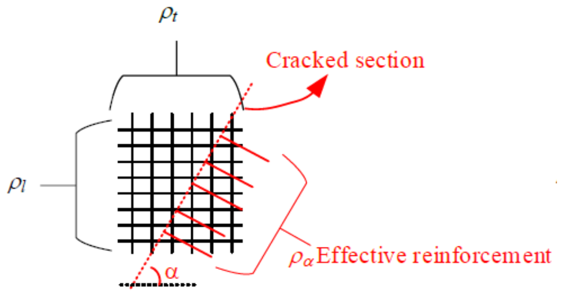
Assessment of skew slabs using LFEA-cont'd

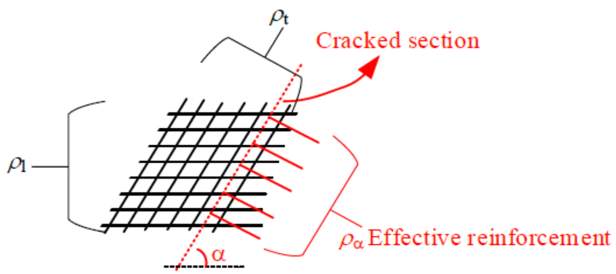
- Test campaign by J. Lu (2023)

Specimen	Span length [m]	Width [m]	Effective d [mm]	fcm [MPa]	ρl [%]	ρt [%]
S75N1	3.6	2	265	70.47	1	0.23
S60N1	3.6	2	265	65.10	1	0.23
S60N2	3.6	2	265	64.70	1	0.23
S60O1	3.6	2	265	69.40	1	0.23
S45N1	3.6	2	265	72.30	1	0.23



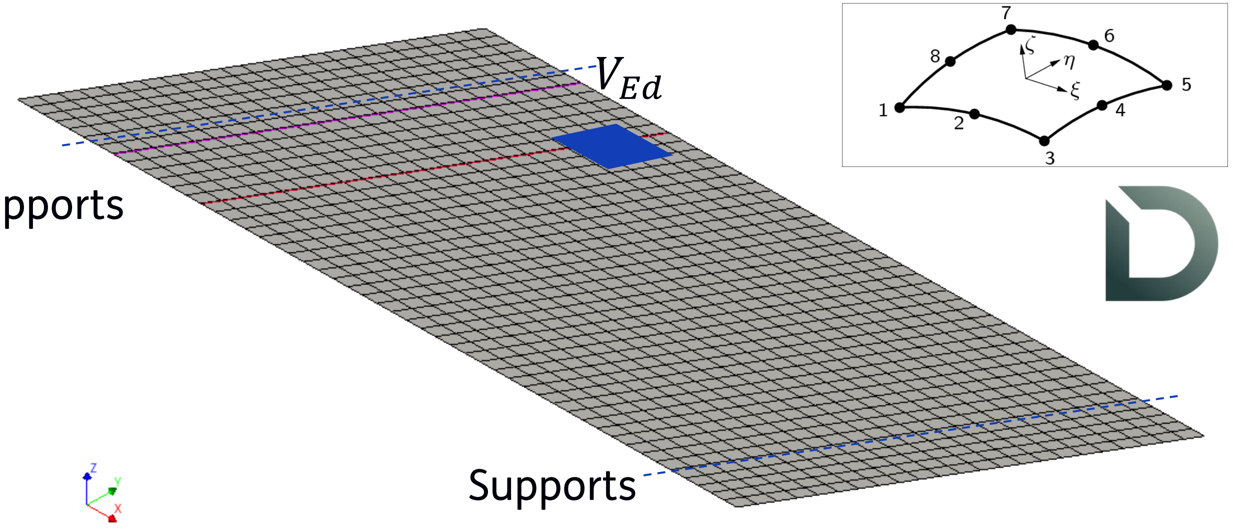
α = [75°, 60°, 45°]





Assessment of skew slabs using LFEA-cont'd

- **Description of numerical models:**



Mesh size: 100 mm
Element type: Quadrilateral, 8 nodes
Integration scheme: 2×2×3

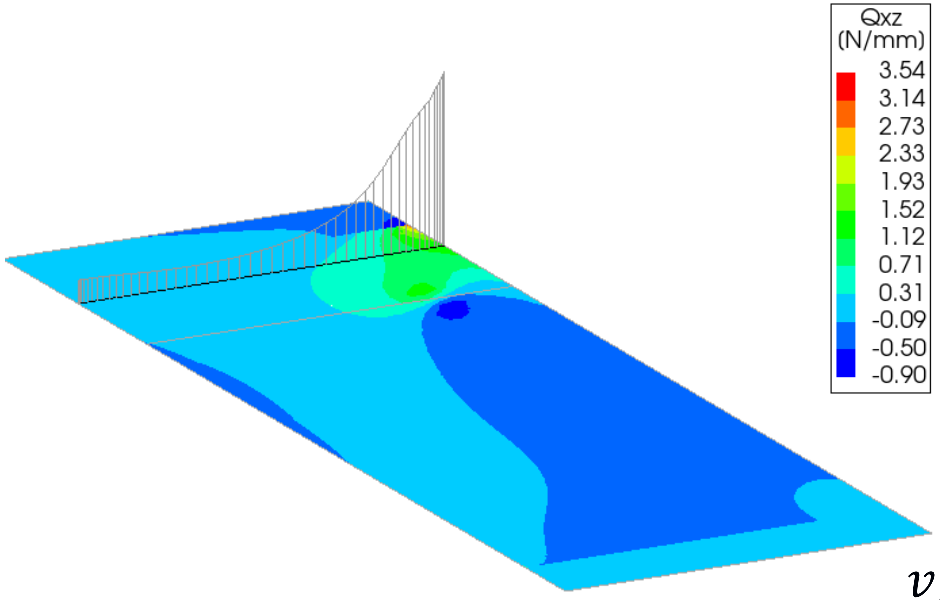
Concrete properties:
E = 30 GPa
$\nu = 0$
$G = G_{elas/8} = 1.5$ GPa

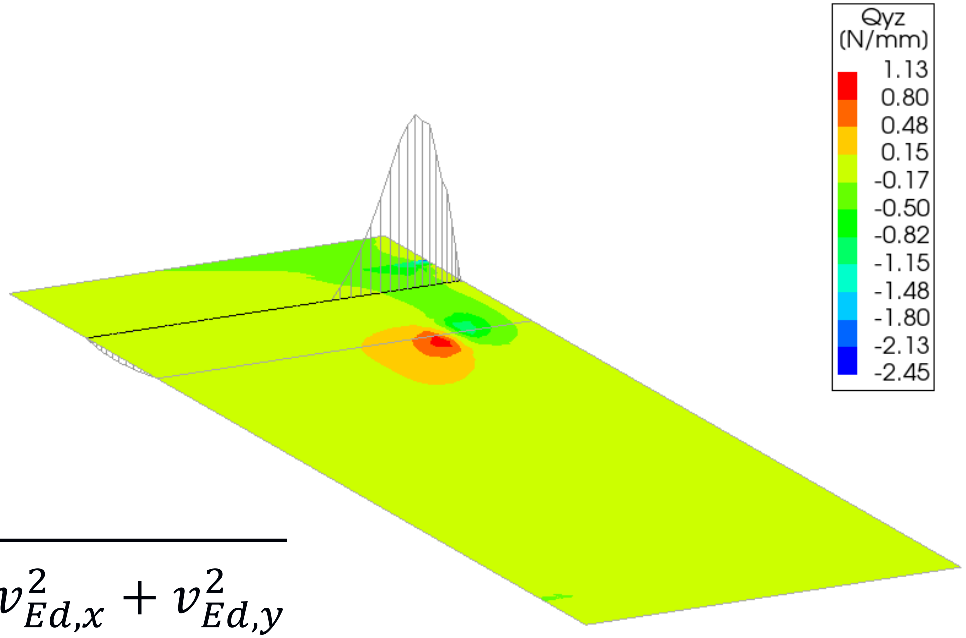
Section control at d from the support

In a design situation, V_{Ed} is known, and the verification is fulfilled by checking the inequality ($\tau_{Ed} \leq \tau_{Rdc,c}$).
To calculate the actual shear resistance ($\tau_{Ed} = \tau_{Rdc,c}$), a unit load can be used (V_{Ed} = 1 kN)

Assessment of skew slabs using LFEA-cont'd

- **Description of numerical models:**

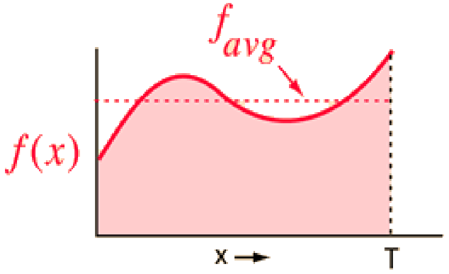




$$v_{Ed} = \sqrt{v_{Ed,x}^2 + v_{Ed,y}^2}$$

(Average within ***2d***, both for FprEC2 and EC2)

$$Avg = \frac{1}{n}\sum_{i=1}^{n} a_i$$

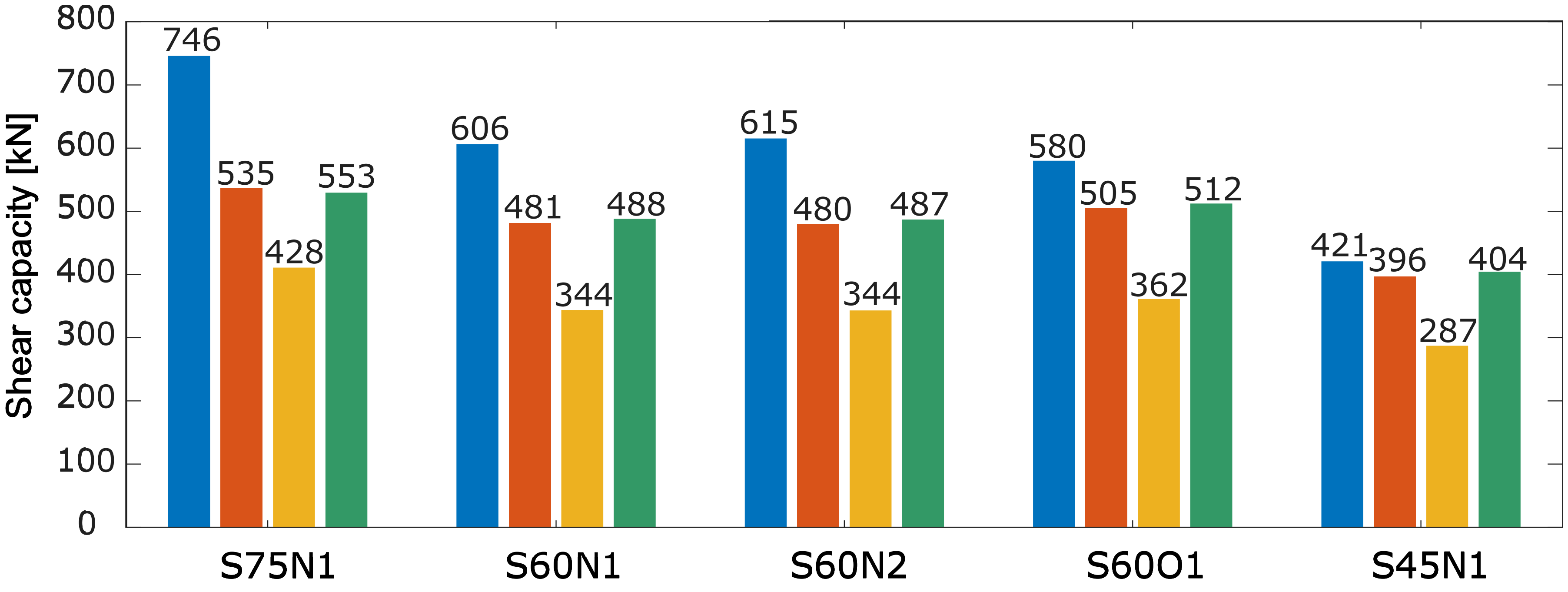


$$\int_0^T f(x)dx = f_{avg}\,T \text{ = area under curve}$$

or $$f_{avg} = \frac{\int_0^T f(x)dx}{T}$$

Assessment of skew slabs using LFEA-cont’d

- **Results comparison:**



Experiments

EN 1992-1-1:2004

FprEN 1992-1-1:2023 (d = d_{nom})

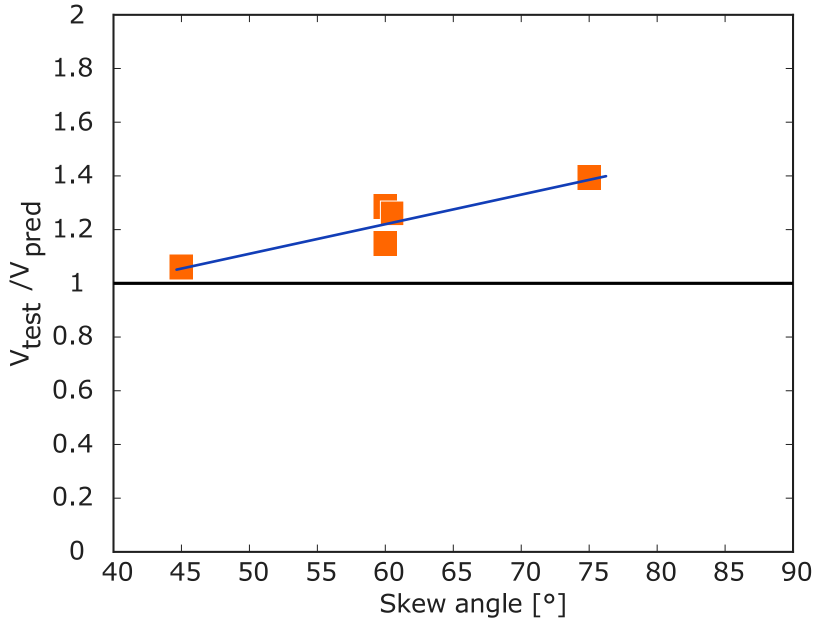
FprEN 1992-1-1:2023 (d = a_v)

One-way shear failure was observed in all the experiments
Shear capacity = Maximum externally applied load
f_{ck} considered f_{cm}
$\gamma_v = 1 \quad C_{Rd,c} = 0.15$

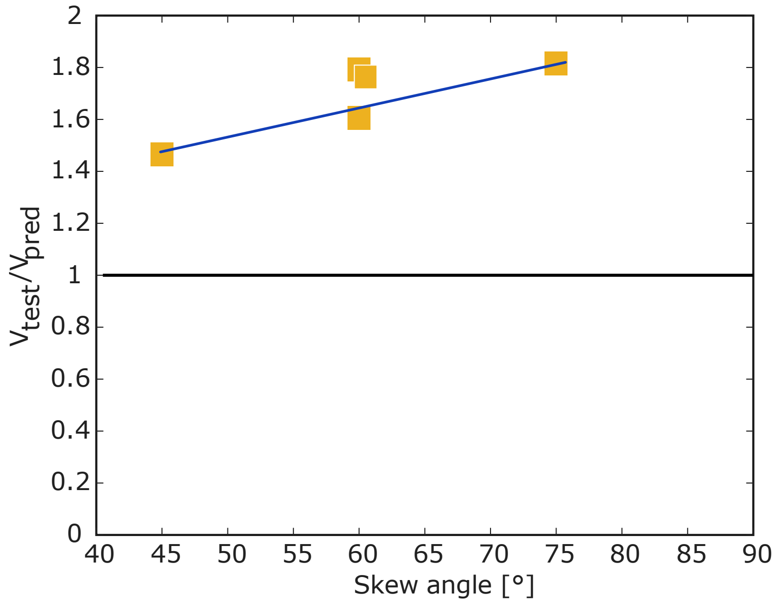
Assessment of skew slabs using LFEA-cont’d

- **Results comparison:**

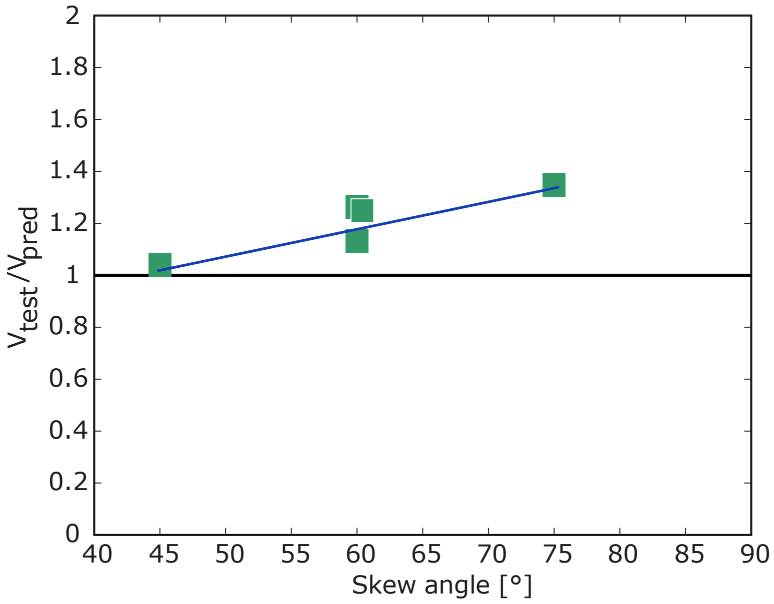
EN 1992-1-1:2004



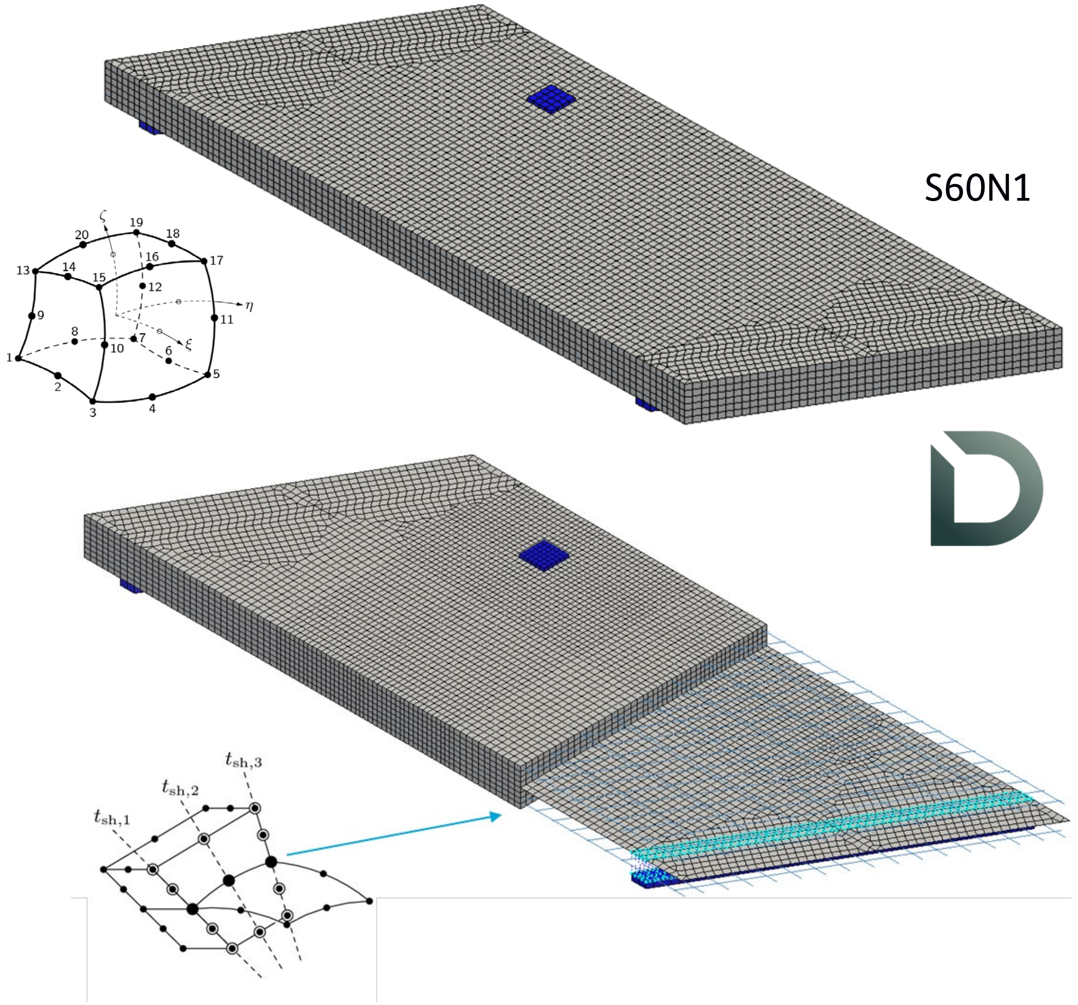
FprEN 1992-1-1:2023 (d = d_{nom})



FprEN 1992-1-1:2023 (d = a_v)



Assessment of skew slabs using NLFEA



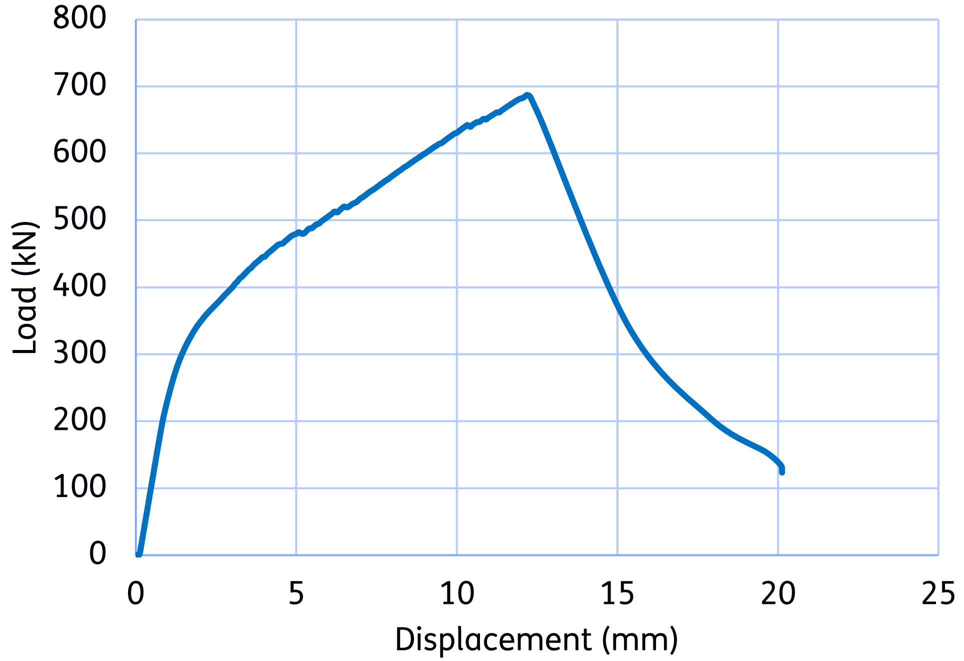
Based on RTD 1016 and previous models:

Constitutive model:
- Concrete: total-strain fixed crack model
- Reinforcing steel: von Mises Plasticity with isotropic hardening (perfect bond)

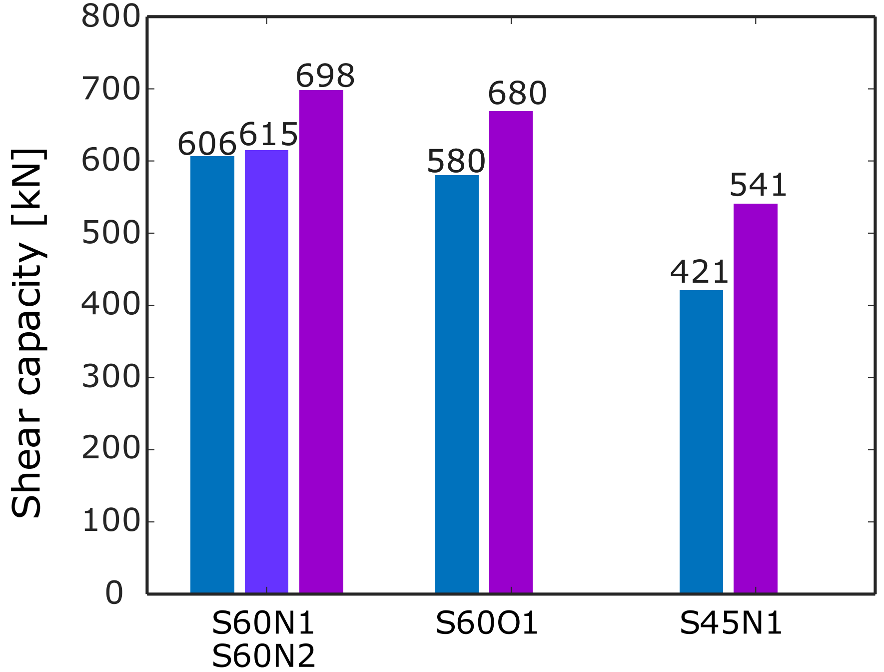
Iterative procedure:
- Newton-Raphson method
- Load-displacement control

Mesh:
- Rebar: embedded reinforcement
- Slab: solid elements and mixed approach
  Mesh size: 38 mm

Assessment of skew slabs using NLFEA



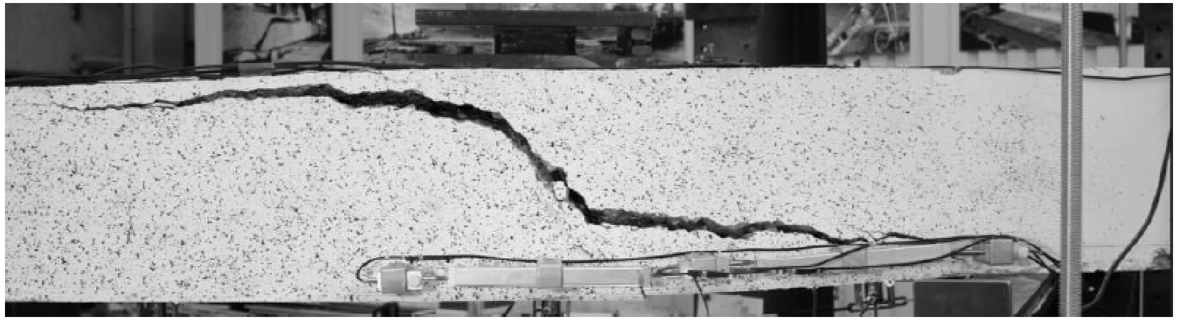
Numerical load-displacement curve for slab S60N1(2)



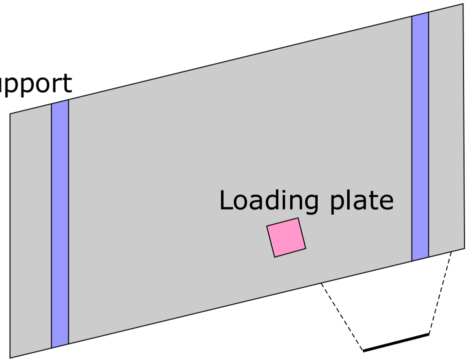
Experiments

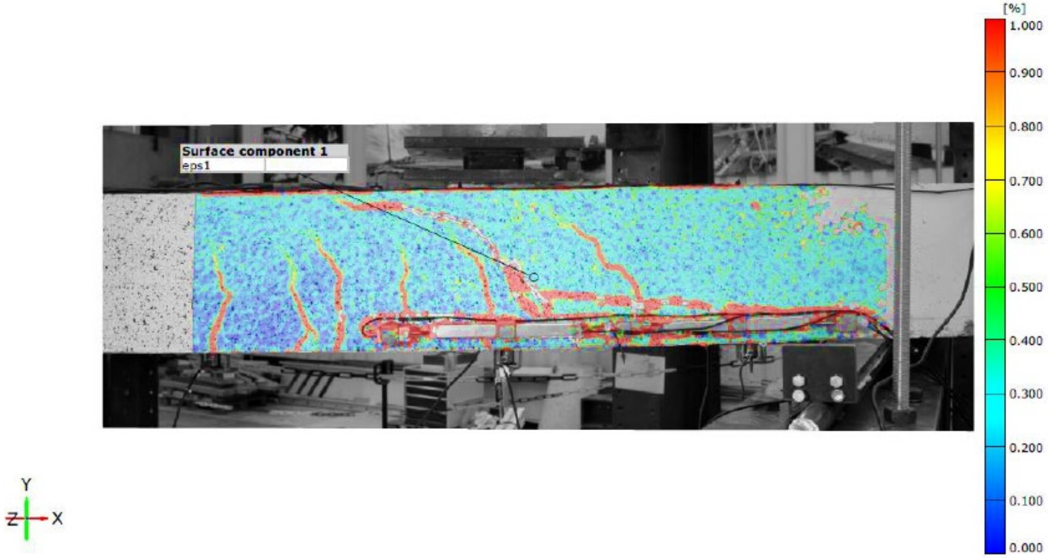
Simulation

Assessment of skew slabs using NLFEA

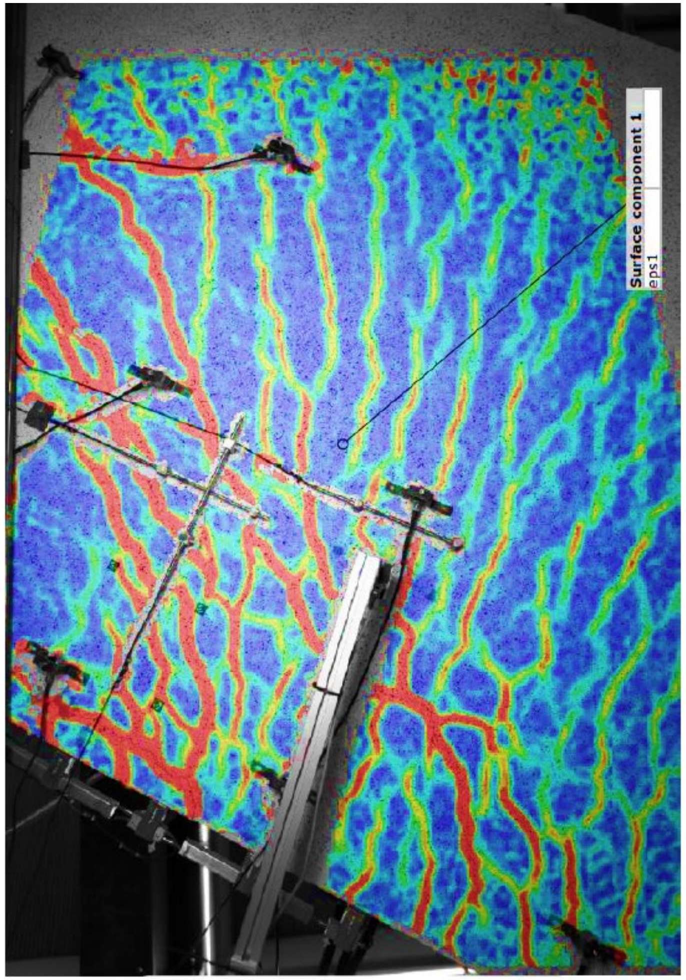


Shear failure S60N2 (Lu et al., 2023)





Assessment of skew slabs using NLFEA



Lu et al. (2024)

In summary…

- EN 1992-1-1:2004 vs FprEN 1992-1-1:2023
  - The approach in the new Eurocode with $d = d_{nom}$ can lead to conservative results (as expected)
  - The approach in the new Eurocode with $d = a_v$ (refined calculation) gives similar results to the current Eurocode when compared to the skew slab specimen considered in this study
  - The tested/predicted ratio decreases when the skew angle is smaller
- LFEA can properly represent the shear stress concentration in skew slabs
- NLFEA provided consistent representation of the crack pattern observed in the experiments