Shear in Reinforced Concrete Slabs

under Concentrated Loads close to Supports

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Overview

- Introduction

- Overview of experiments
- Beams vs. slabs

- Modified Bond Model
- Code extension proposal

- Application to practice

- Conclusions

Motivation (1)

Bridges from 60s and 70s

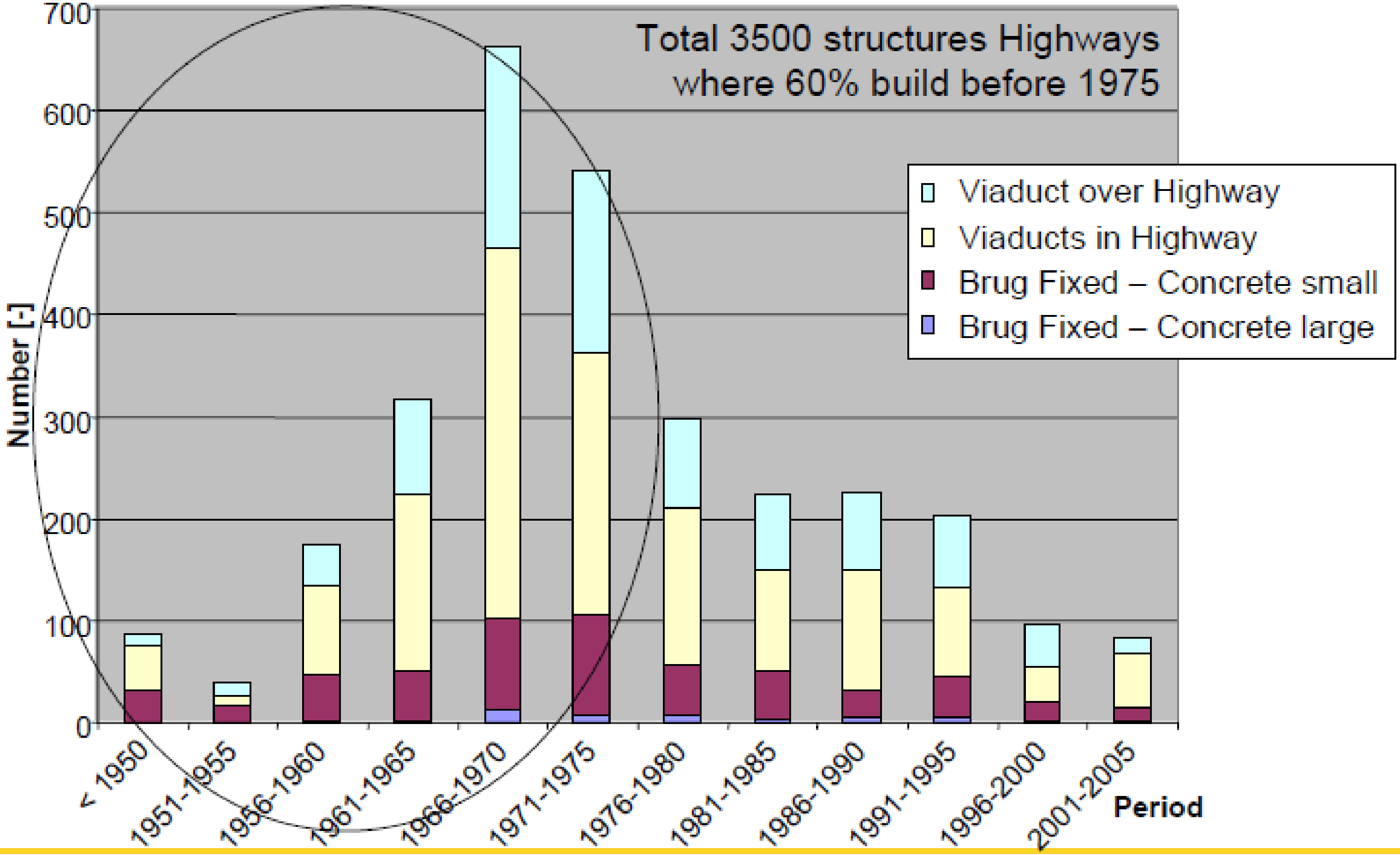
The Hague in 1959

Increased live loads

heavy and long truck
(600 kN > perm. max = 50ton)

End of service life + larger loads

Motivation (2)



Motivation (3)

- First checks since mid-2000s
  - 3715 structures to be studied
  - 600 slab bridges shear-critical
- But: checks according to design rules
- => Residual capacity???
- Hidden reserves of the bearing capacity

Highways in the Netherlands

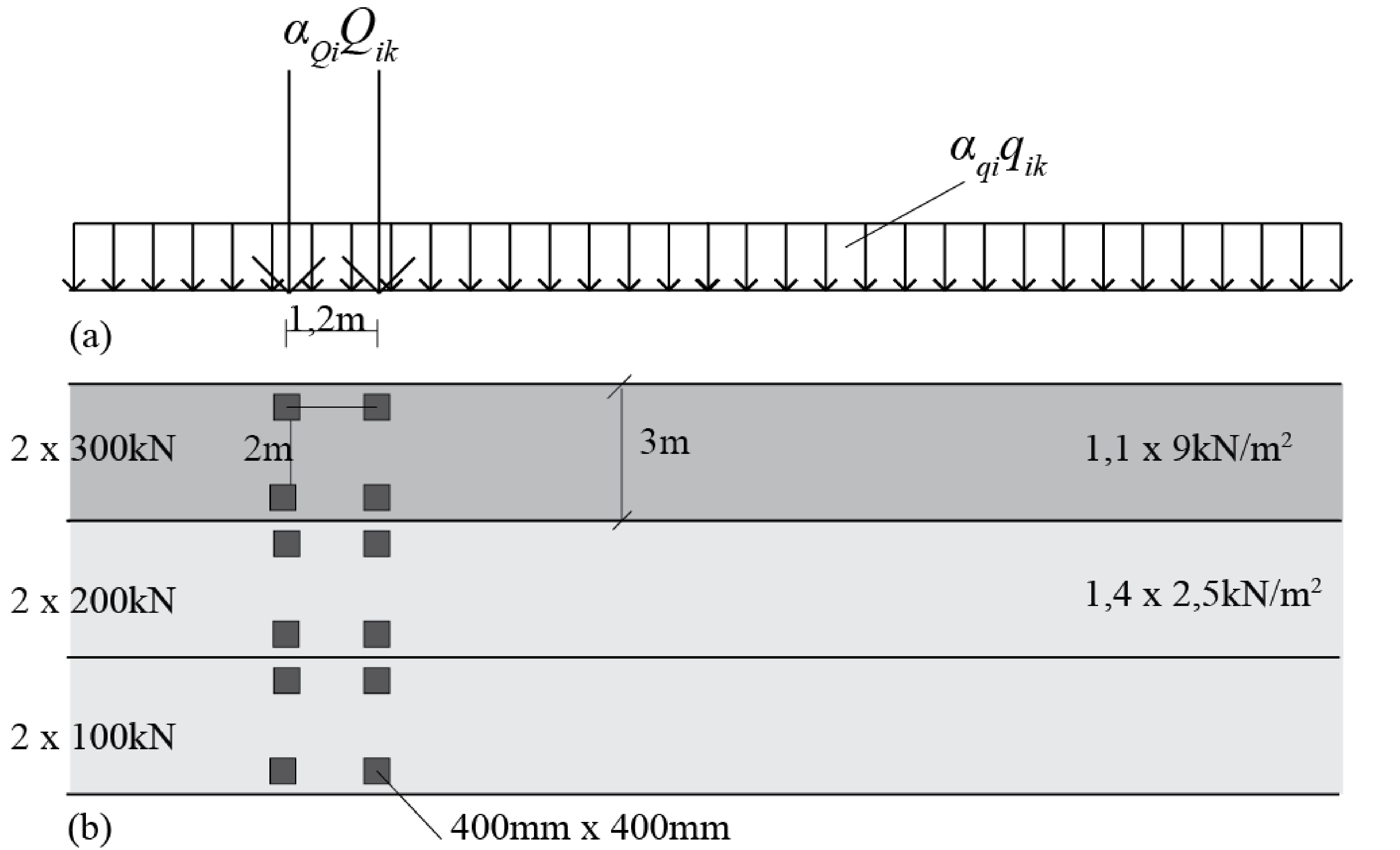
Project description (1)

- Capacity of existing bridges
  - TU Delft
    - Concrete Structures
    - Structural Mechanics
  - TNO
  - RWS

- Concrete Structures
  - Long-term tensile strength
  - Beam shear – sustained loads
  - Continuous girders – shear
  - Prestressed slabs – punching
  - **Slab bridges - shear/punching**

Concrete bridges

Live Loads in NEN-EN 1991-2:2003

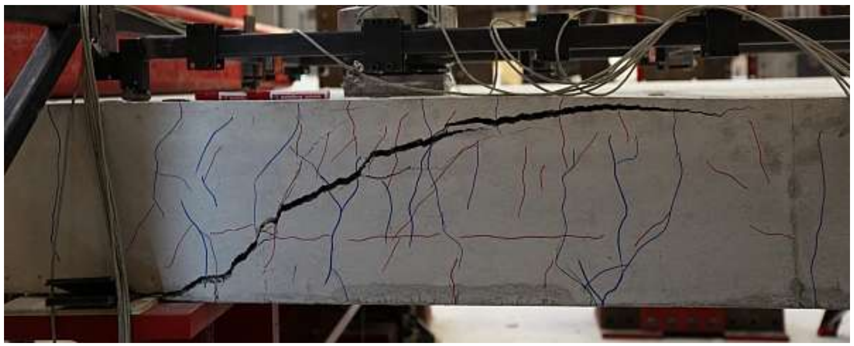


Shear Failure (1)

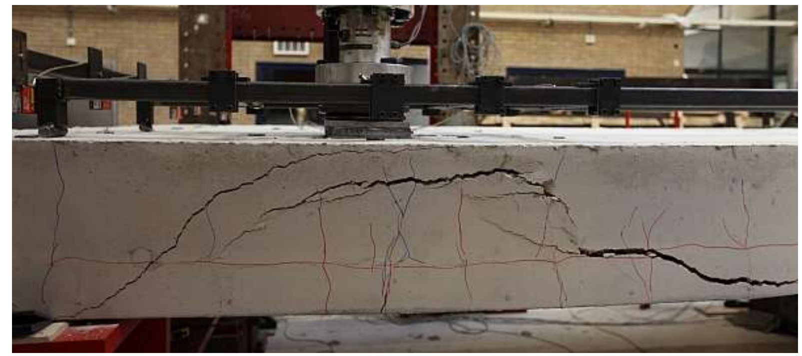
Shear failure of the de la Concorde bridge, Laval

Shear failures of bridges: rare but brittle failures

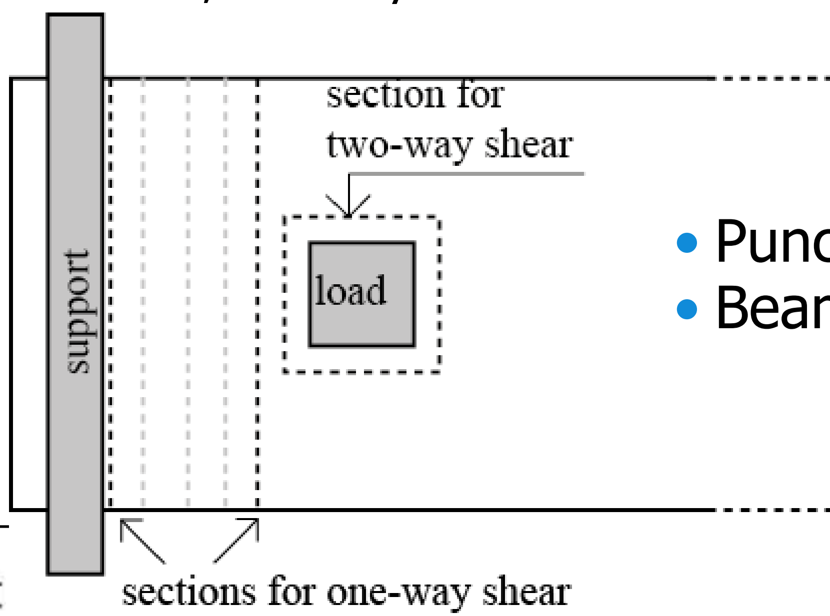
Shear Failure (2)
Beam shear vs. Punching shear



Beam shear, one-way shear



Punching shear, two-way shear

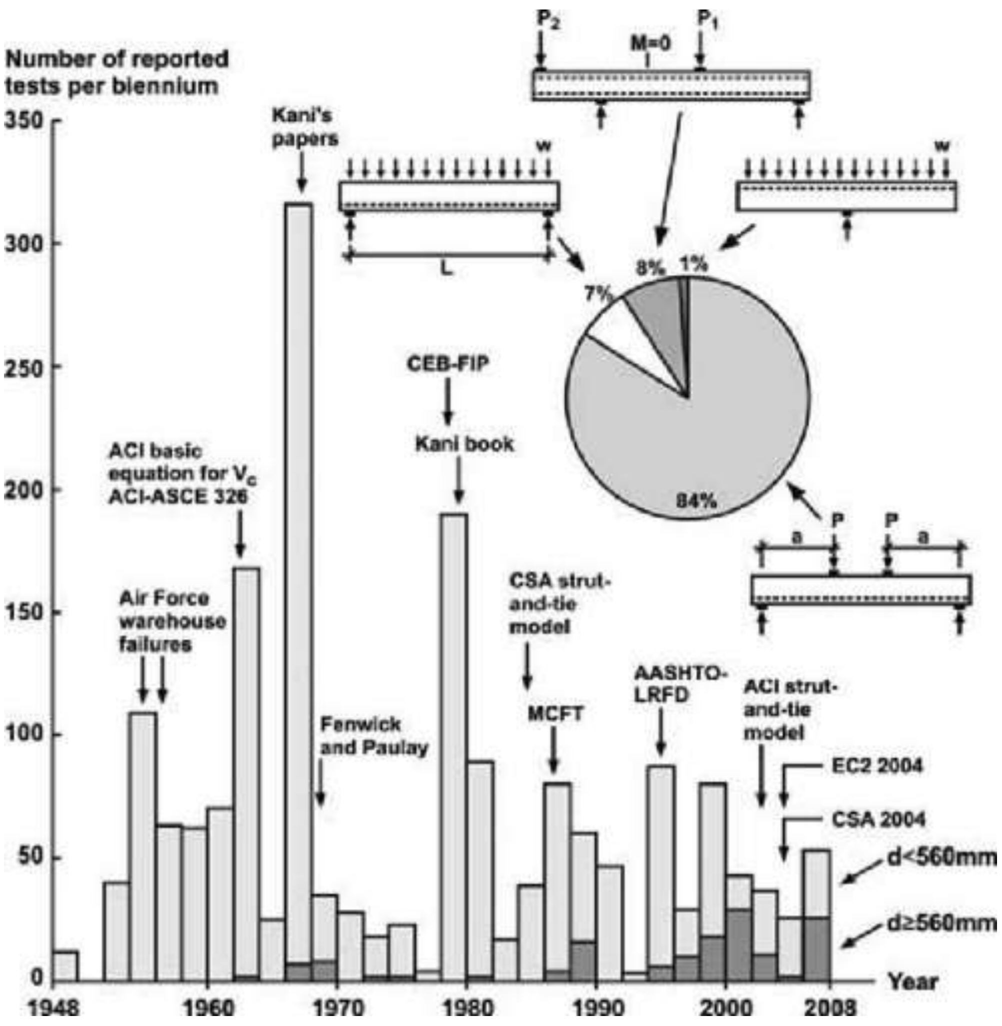


- Punching shear over perimeter
- Beam shear over (effective) width

Shear Failure (3)
Beam shear

- Since 1899 (Ritter)
- 1955: collapse of warehouse

- Most experiments:
  - Beams
  - Heavily reinforced
  - Small size
  - Slender (a/d ≥ 2,5)
- Basis for design codes



amount of shear experiments done

Shear Failure (3)
Beam shear

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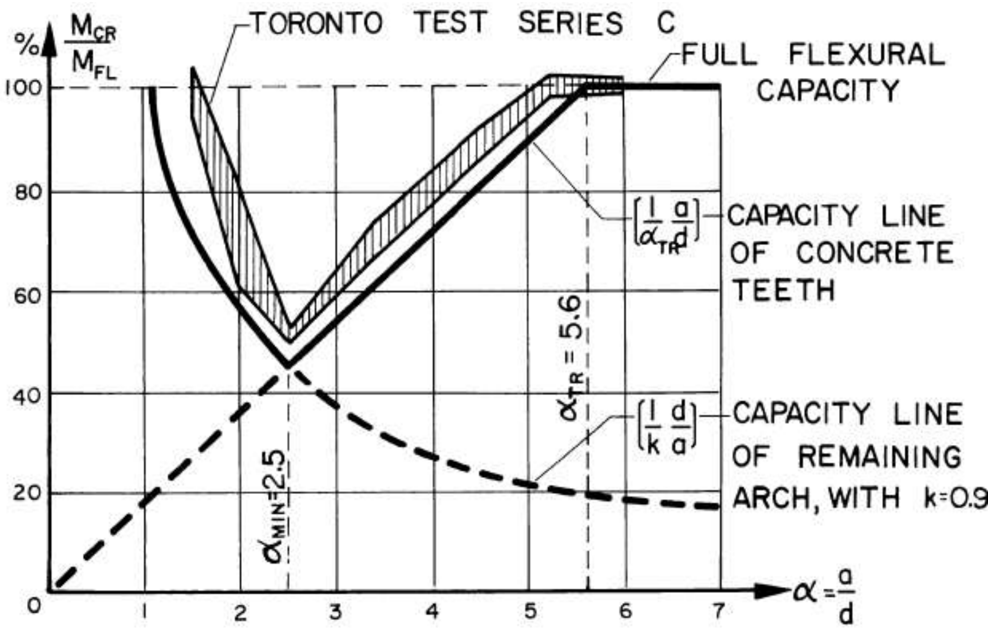
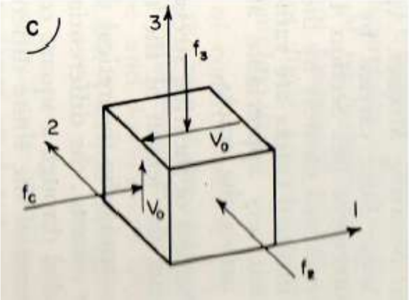


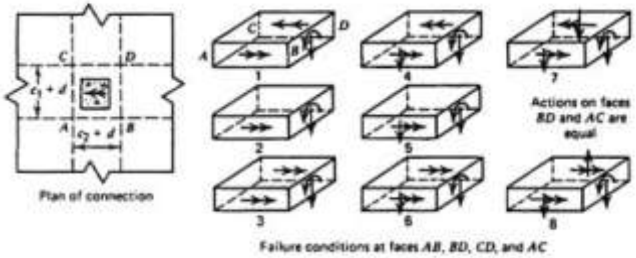
Influence of shear span

Shear Failure (4)
Punching shear

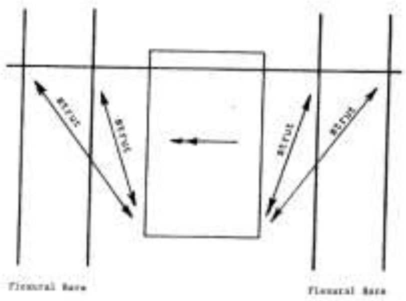
Categories of methods for punching shear



Shear stress



Beam analogy



Strut and tie

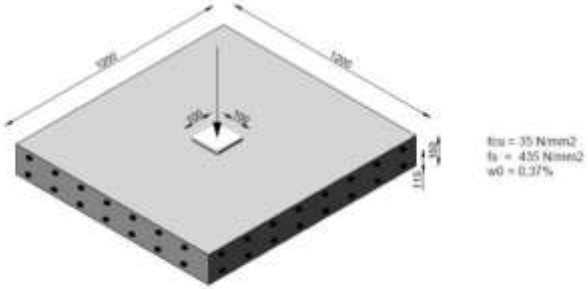


Plate theory / FEM

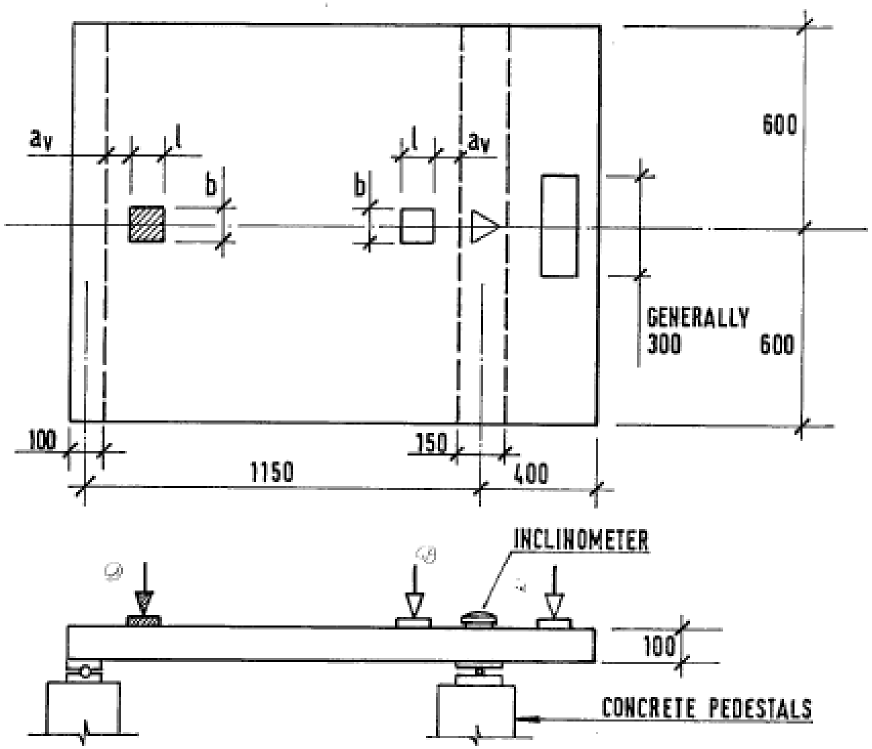
The nature of shear failure is still not fully understood!

Slabs under concentrated loads (1)

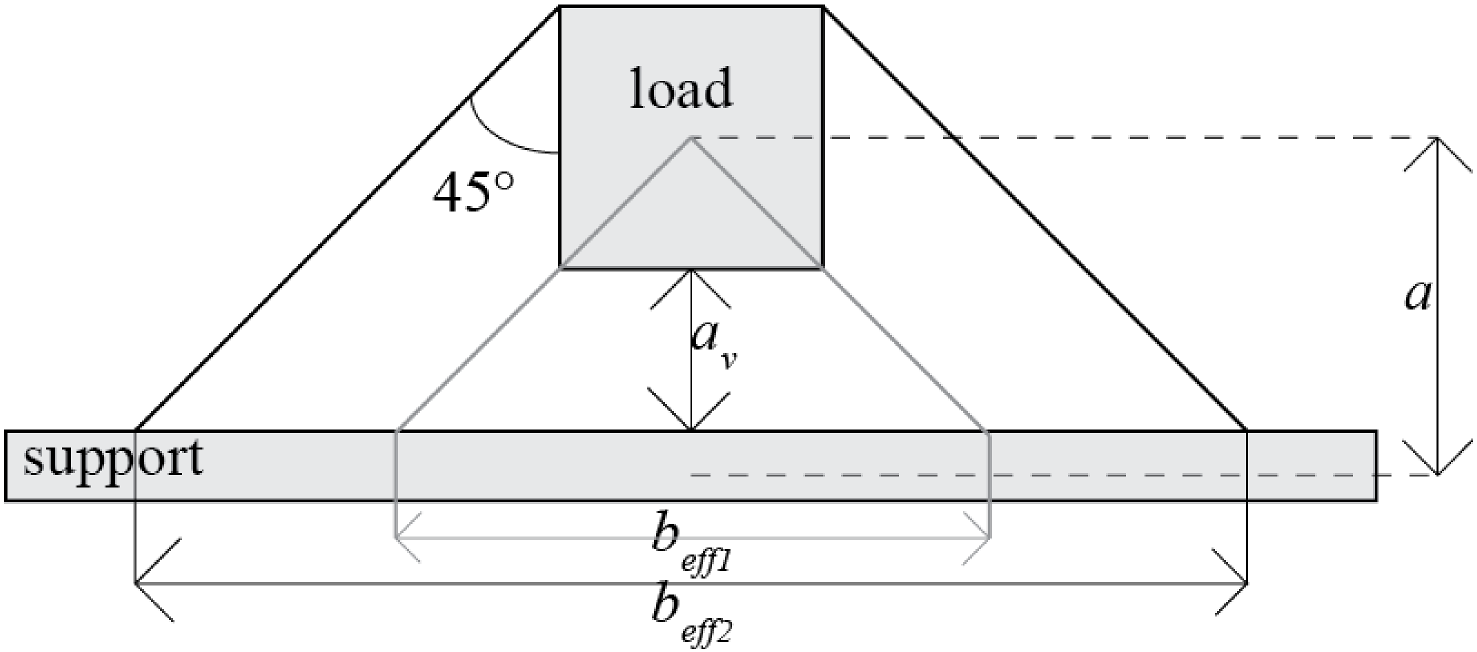
- Transverse load redistribution

- Additional dimension in slabs
- Expected higher capacity than beams

- First experiments: Regan (1982)

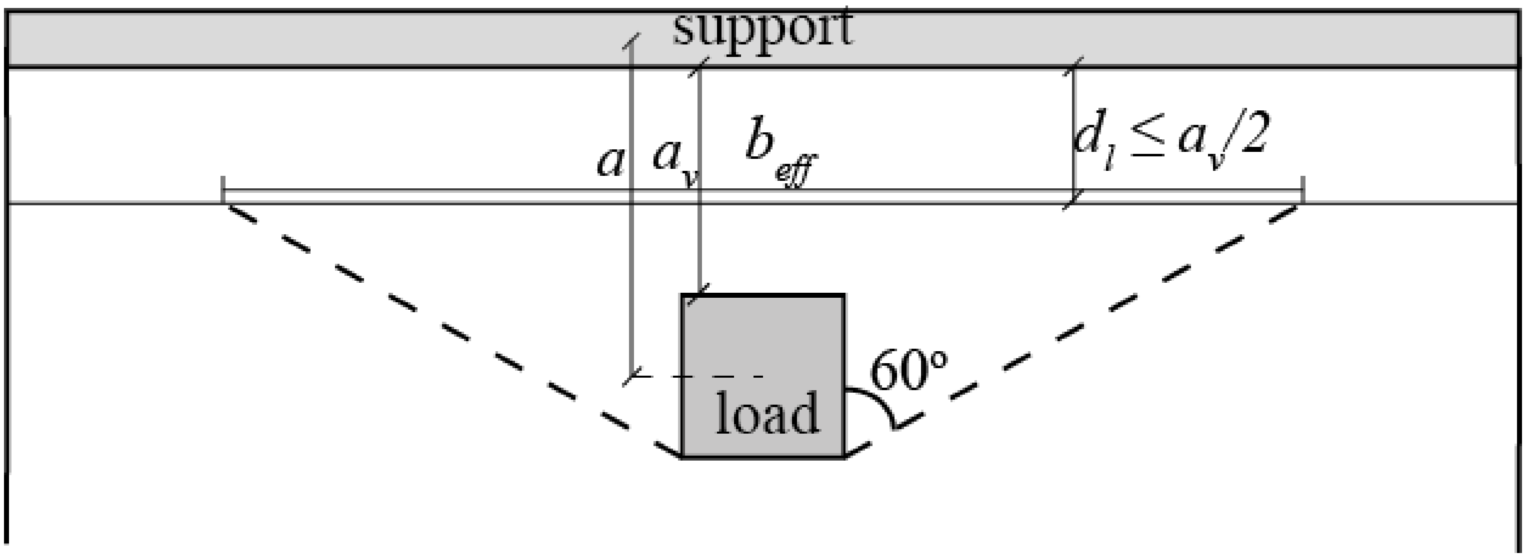


Slabs under concentrated loads (2)



- Shear stress over effective width
- Fixed width, eg. 1 m
- Load spreading method

Slabs under concentrated loads (2)

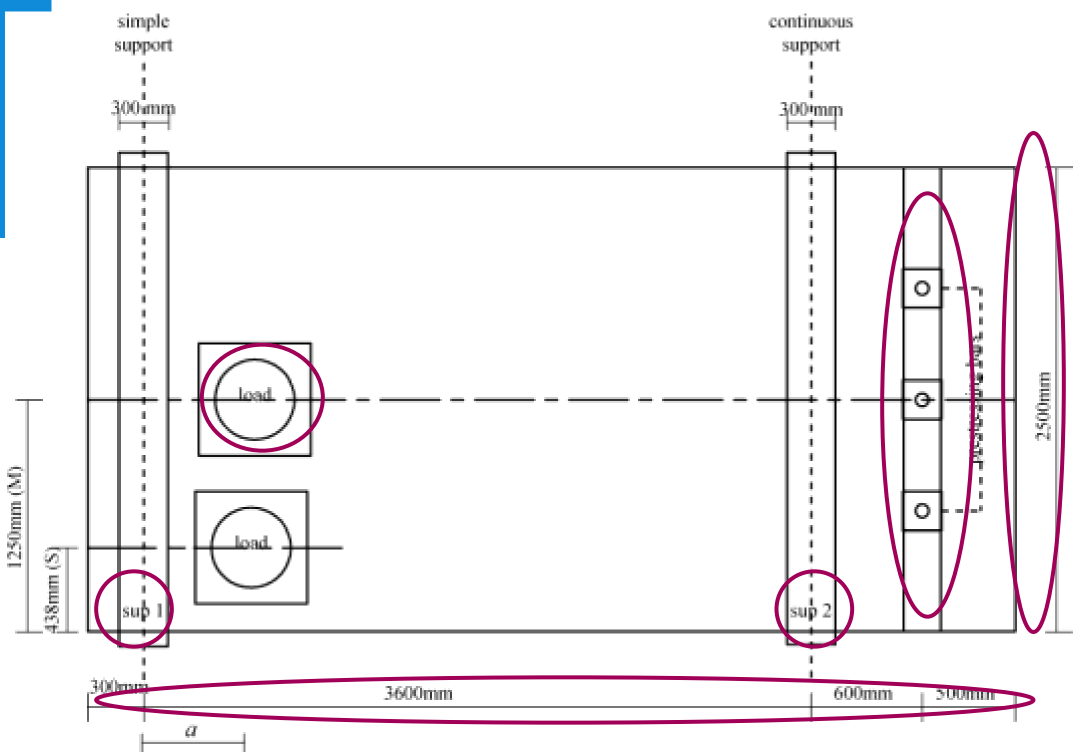


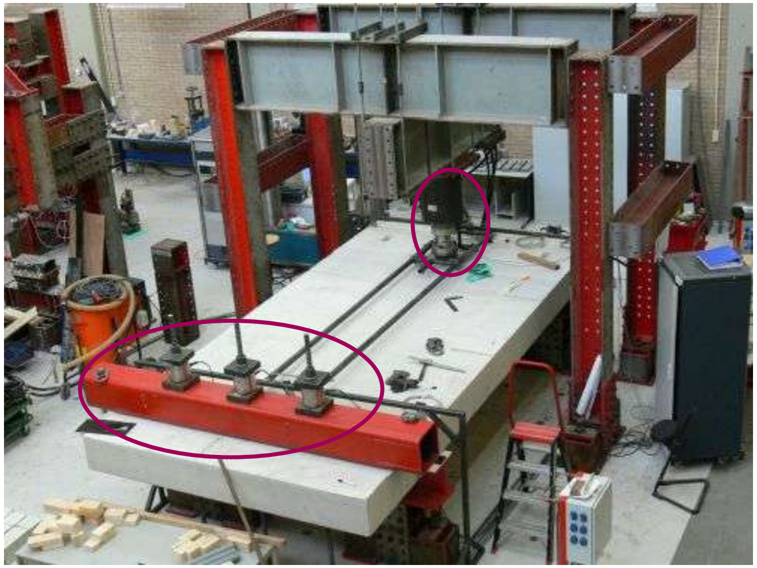
- Shear stress over effective width
- Fixed width, eg. 1 m
- Load spreading method

Goals

- *Assess shear capacity of slabs under concentrated loads*
- *Determine effective width in shear*

Experiments (1)





Size: 5m x 2,5m (variable) x 0,3m = scale 1:2

Continuous support, Line supports

Concentrated load: vary a/d and position along width

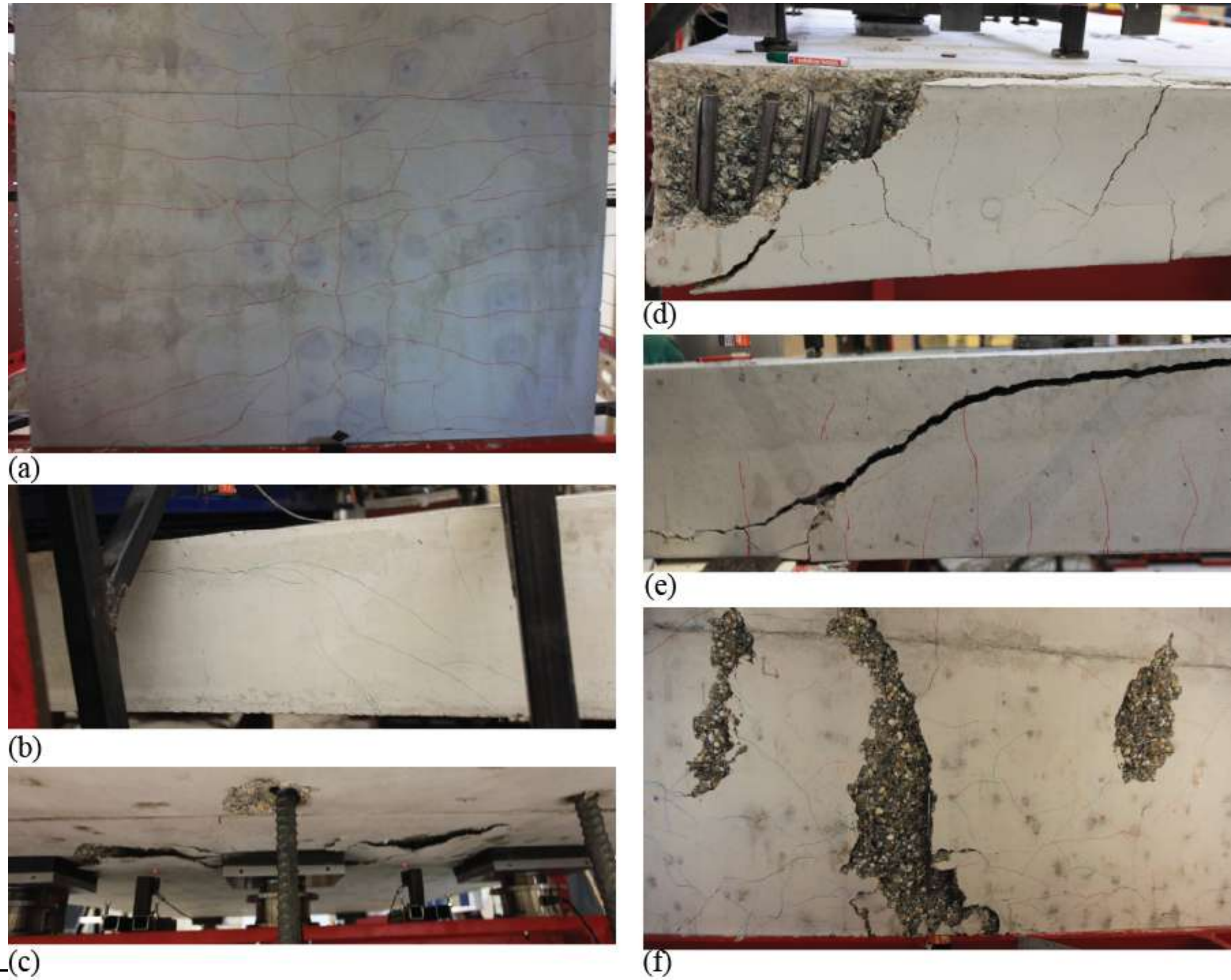
Experiments (2)

- 2nd series experimental work:
  - Slabs under combined loading
  - Line load
    - Preloading
    - 50% of strength from slab strips
  - Concentrated load until failure
- Conclusions from 1st series valid when combining loads?

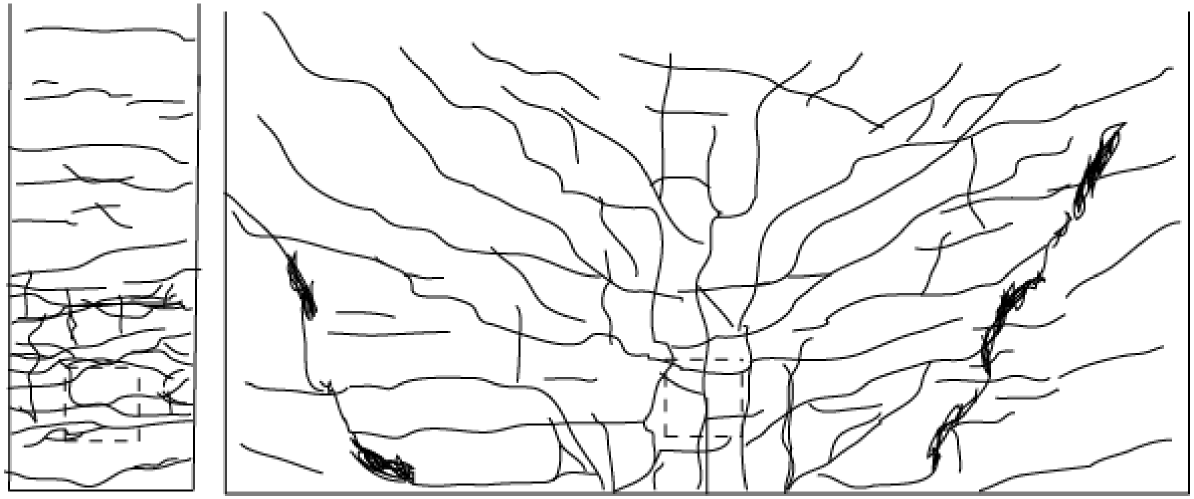
- 26 experiments, 8 slabs

- Overall: 156 experiments, 38 slabs

Experiments (3)

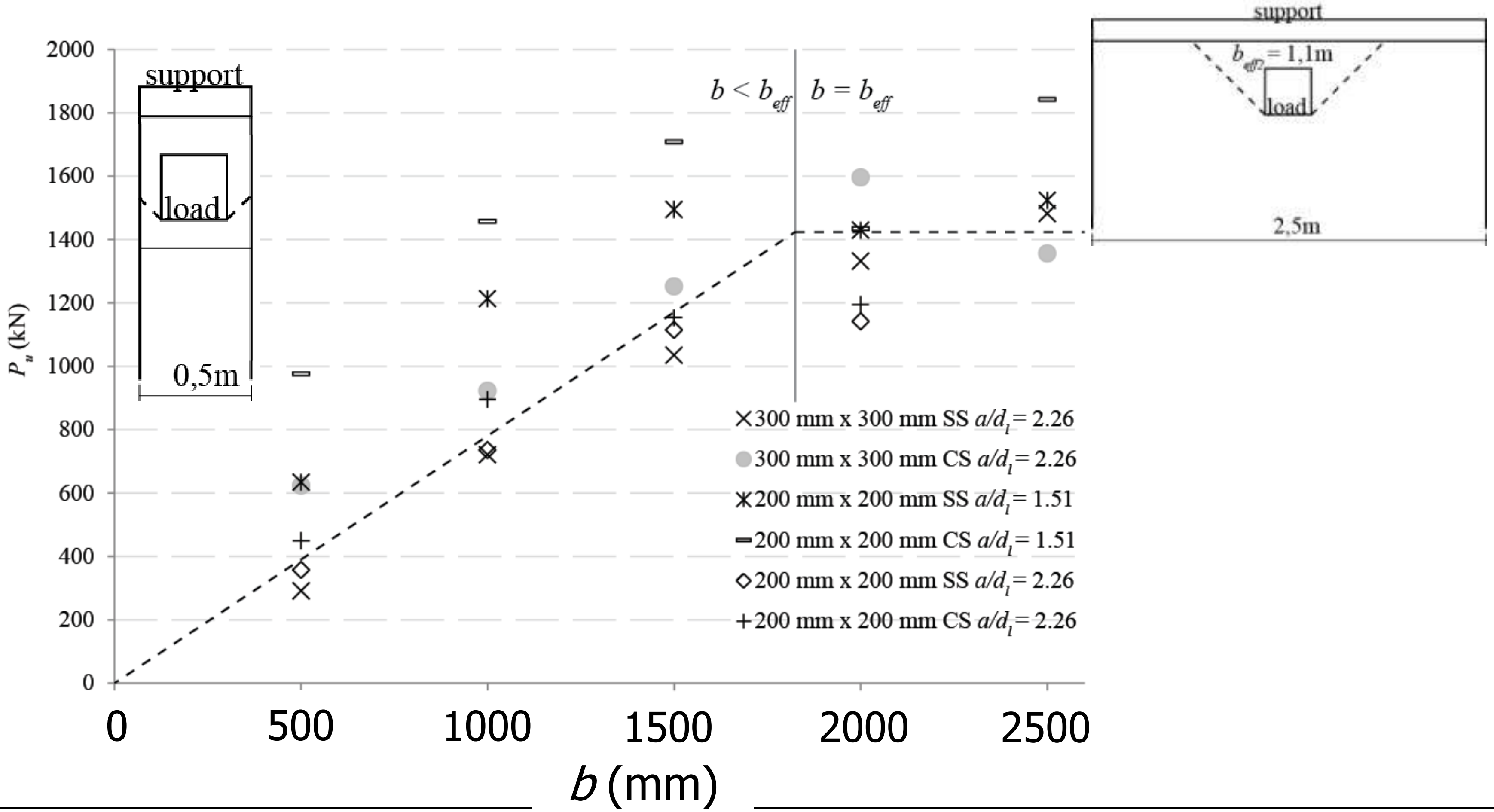


Slabs vs. beams (1)


(a) (b)

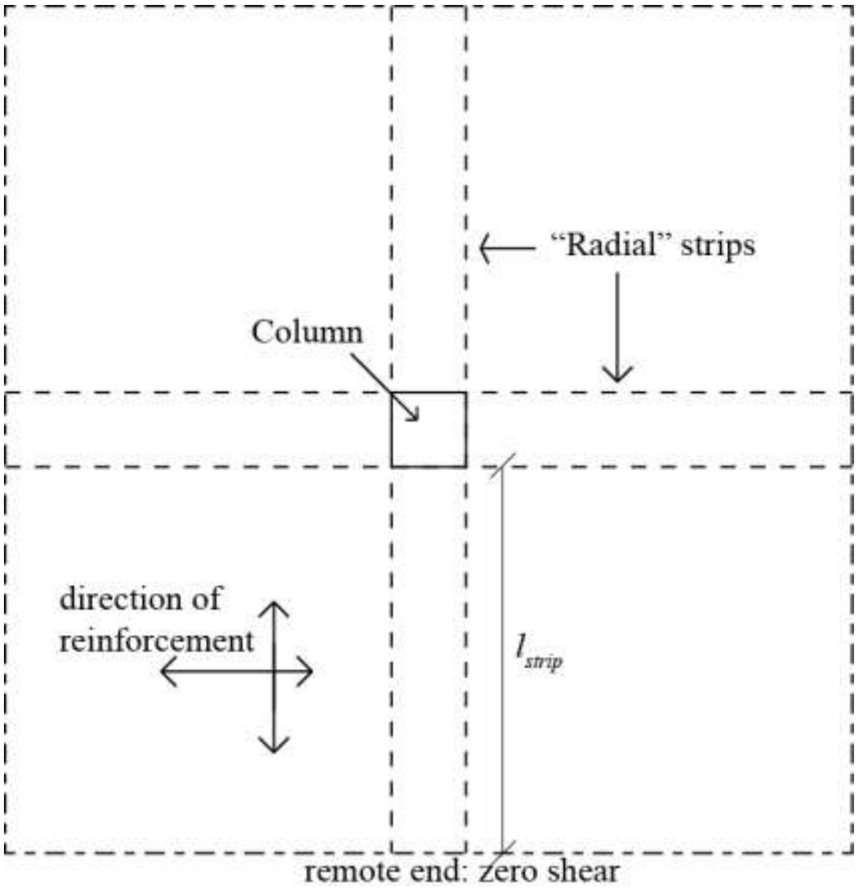
- Transverse load redistribution
- Geometry governing in slabs
- Location of load
  - result of different load-carrying paths
- Mid support vs end support
  - influence of transverse moment
- Wheel size
  - more 3D action

Slabs vs. beams (2)

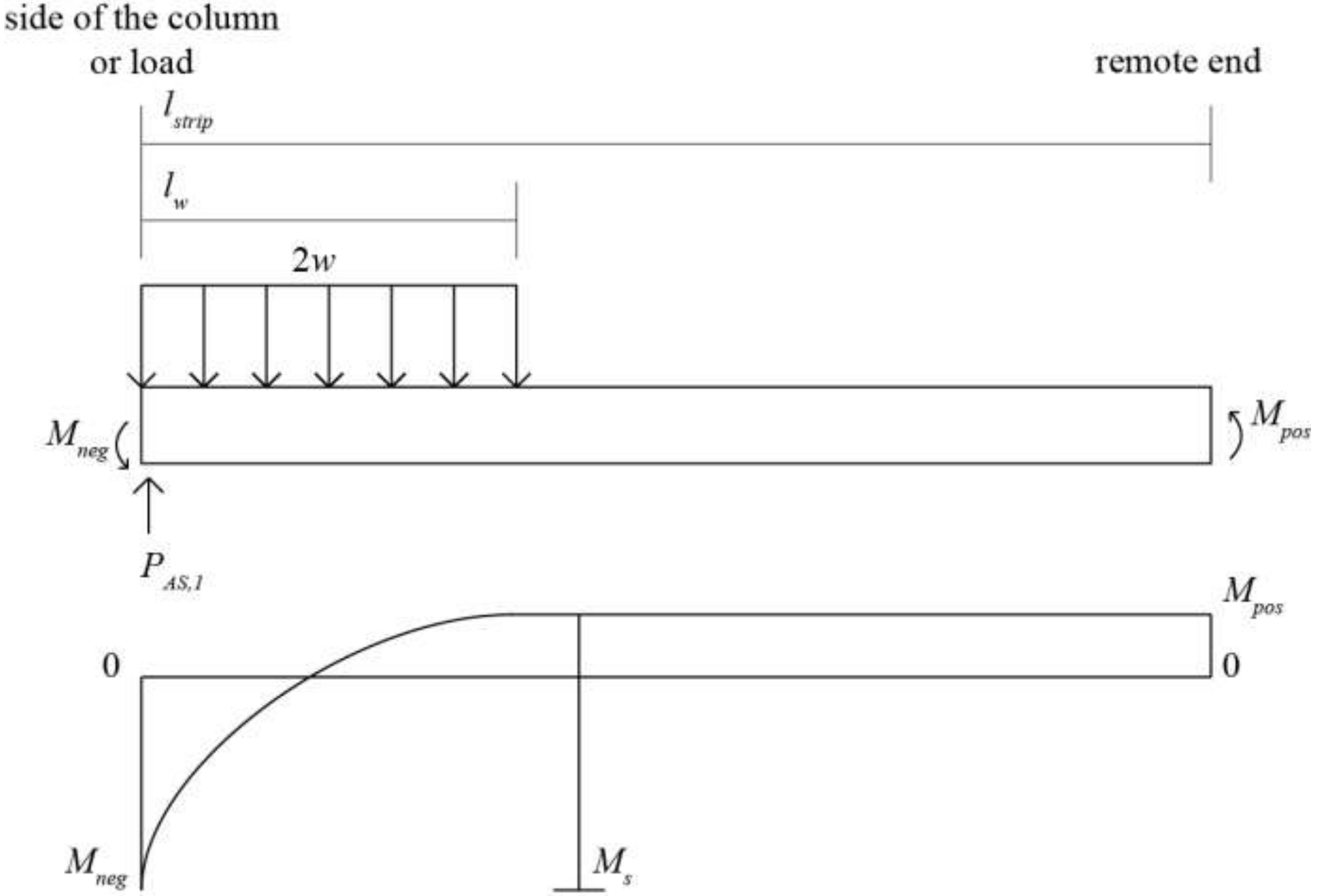


Modified Bond Model (1)

- Based on Bond Model (Alexander and Simmonds, 1990)
- For slabs with concentrated load in middle



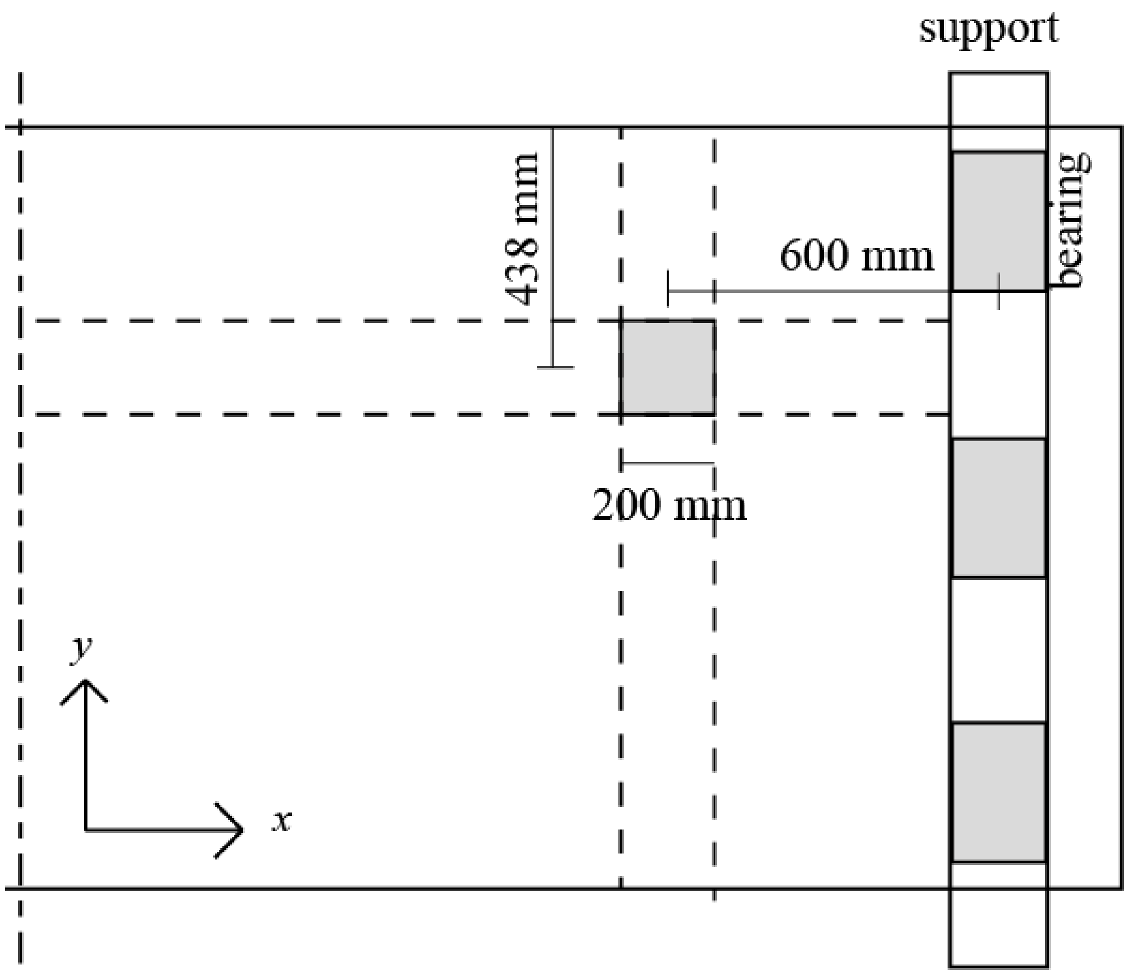
Modified Bond Model (2)



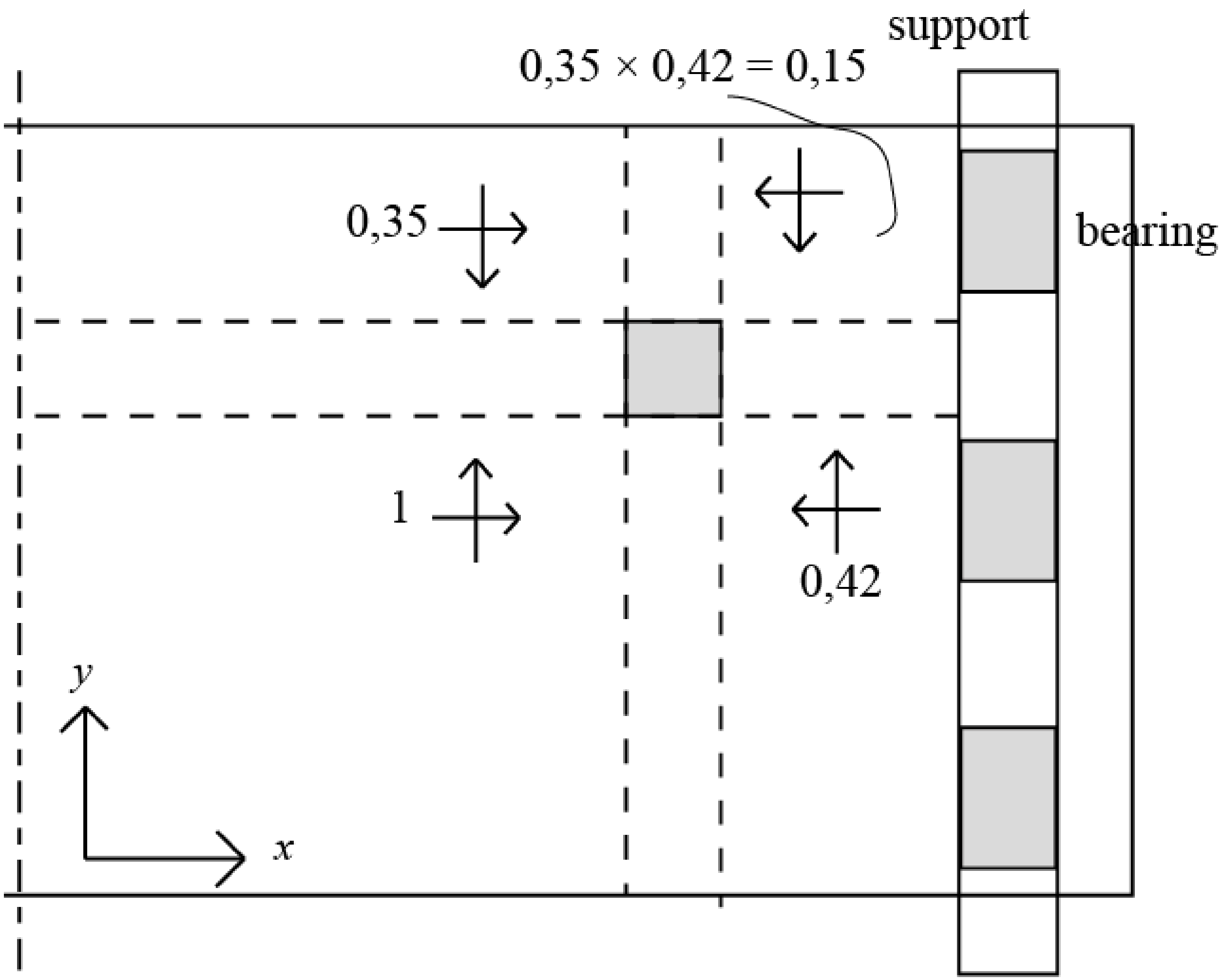
Modified Bond Model (3)

- Adapted for slabs with concentrated load close to support
- Geometry is governing as in experiments
- Determine factor that reduces capacity of “radial” strip
- Maximum load: based on sum capacity of 4 strips

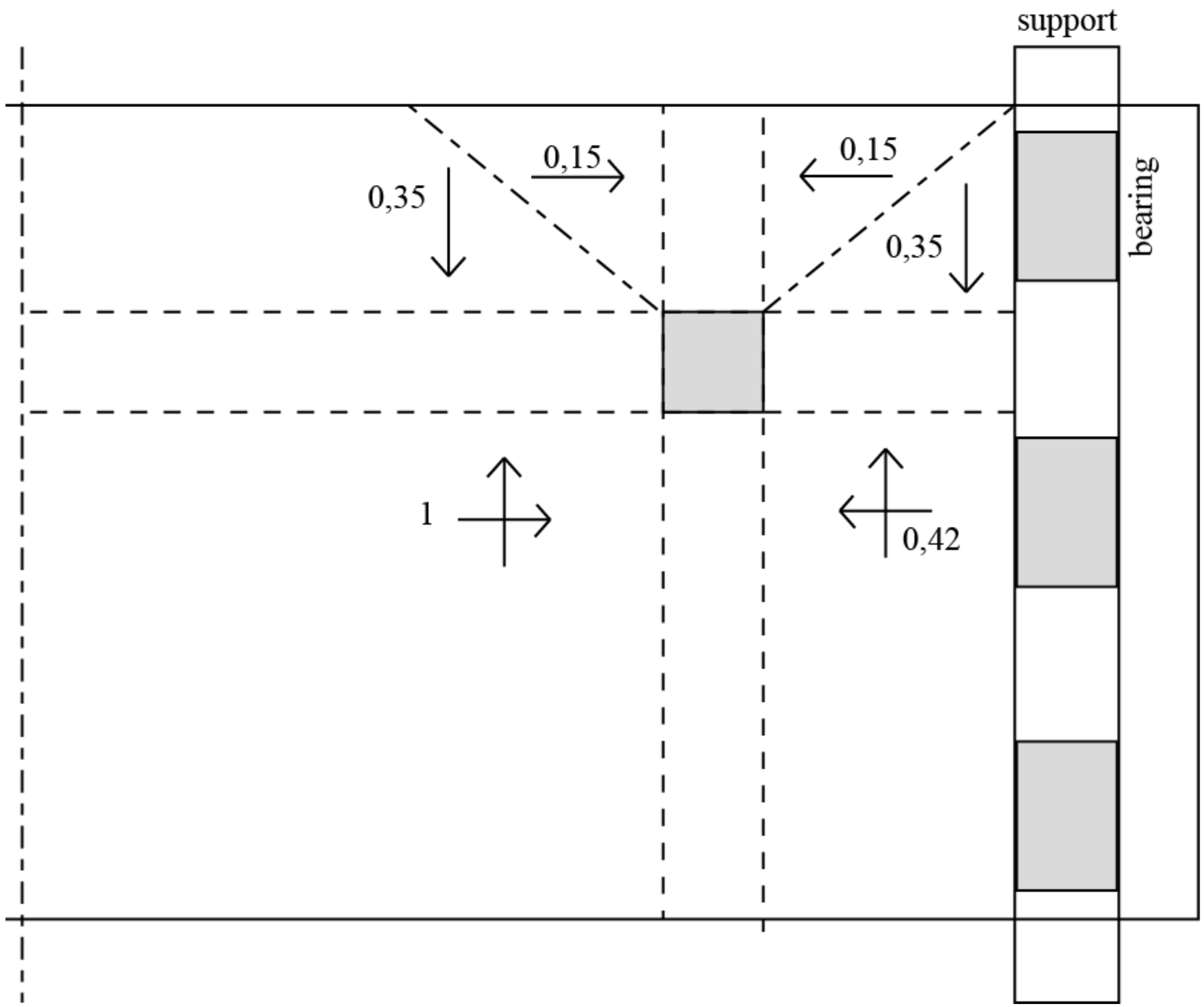
Modified Bond Model (4)



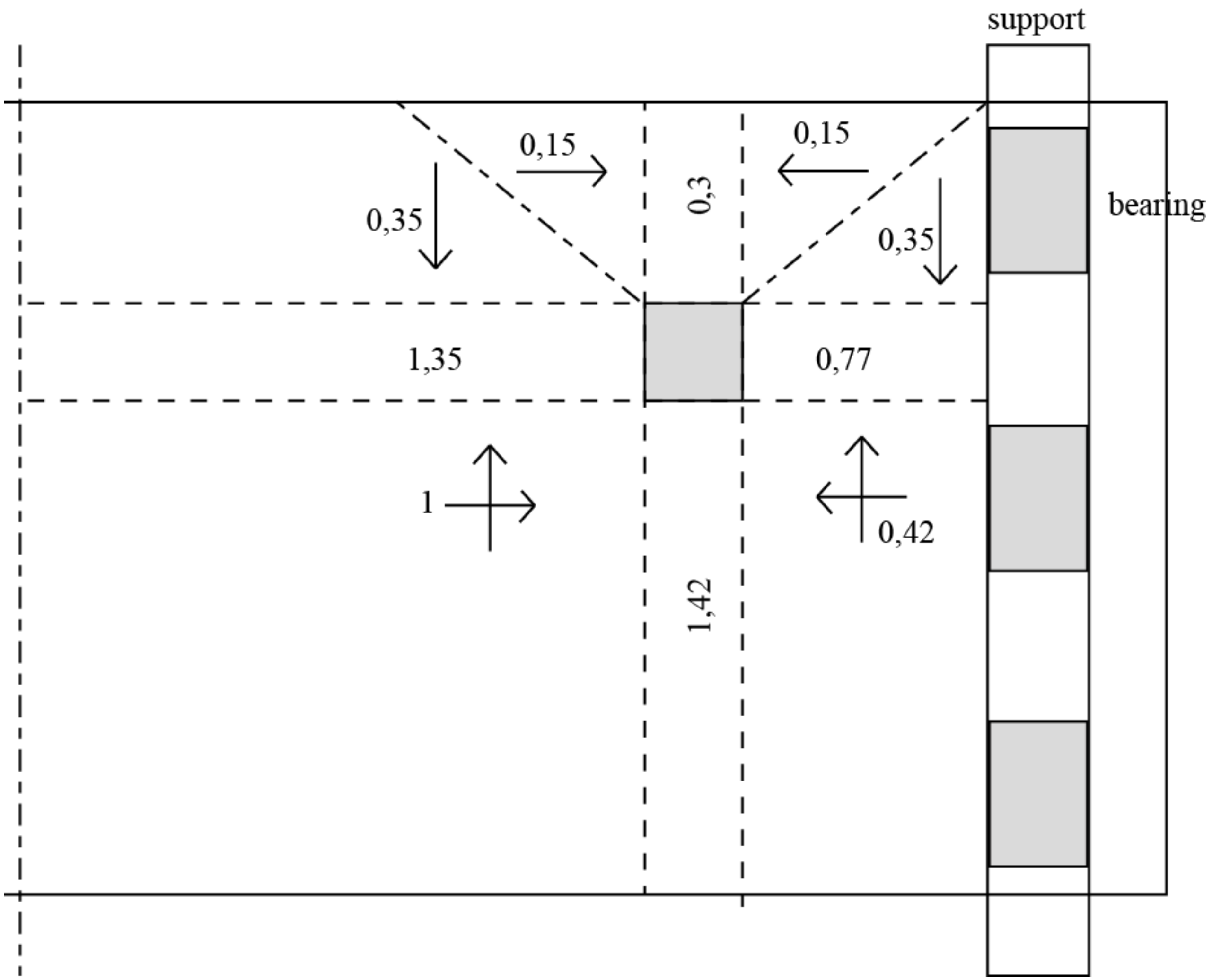
Modified Bond Model (5)



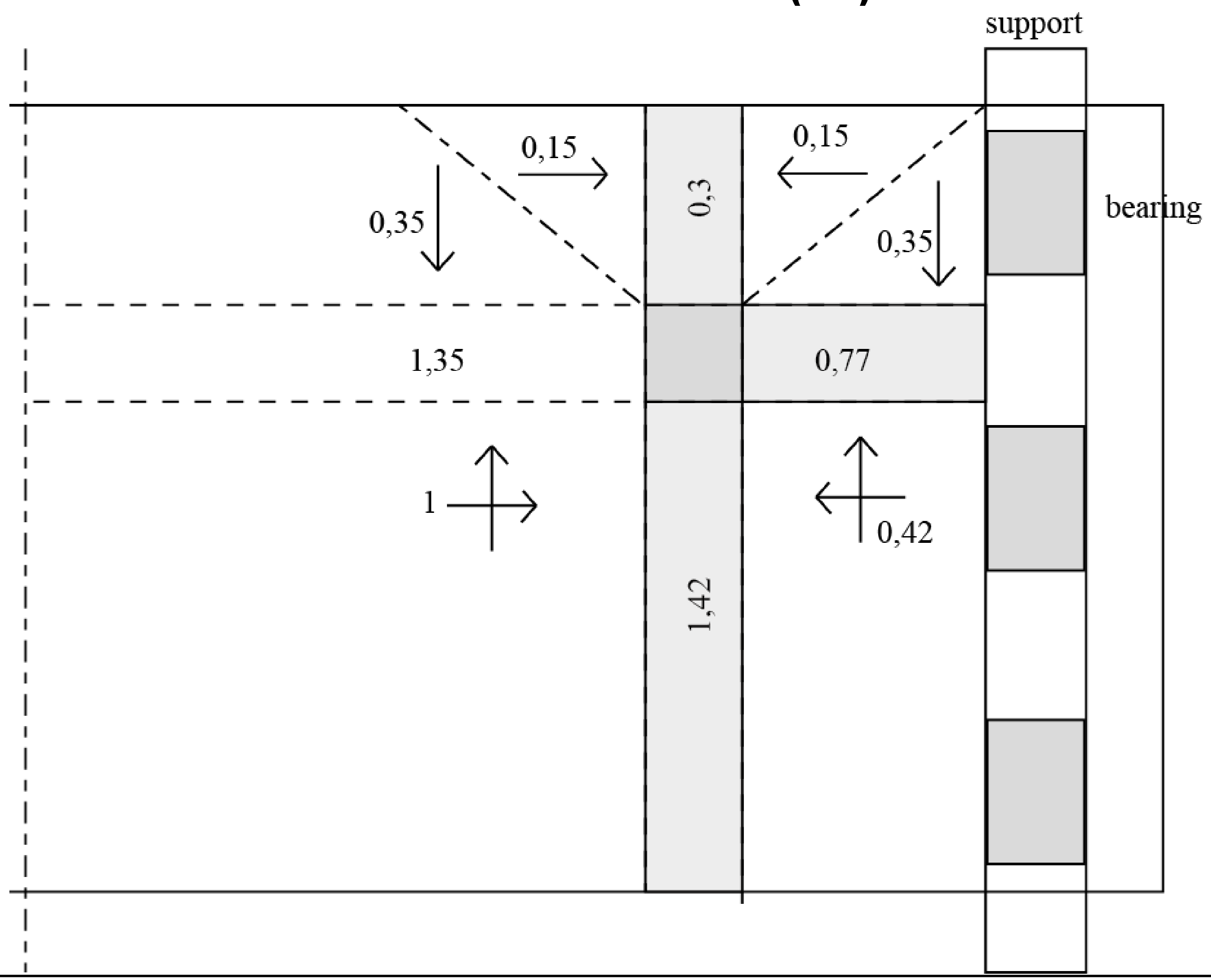
Modified Bond Model (6)



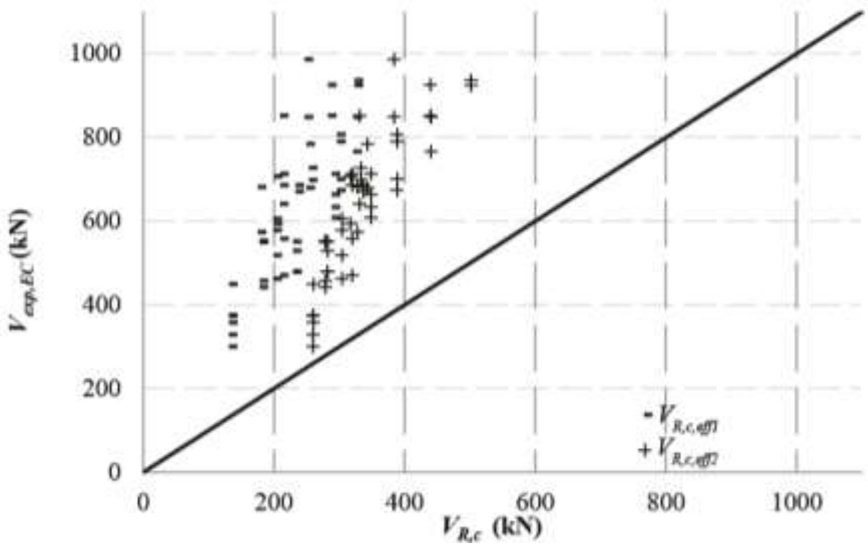
Modified Bond Model (7)



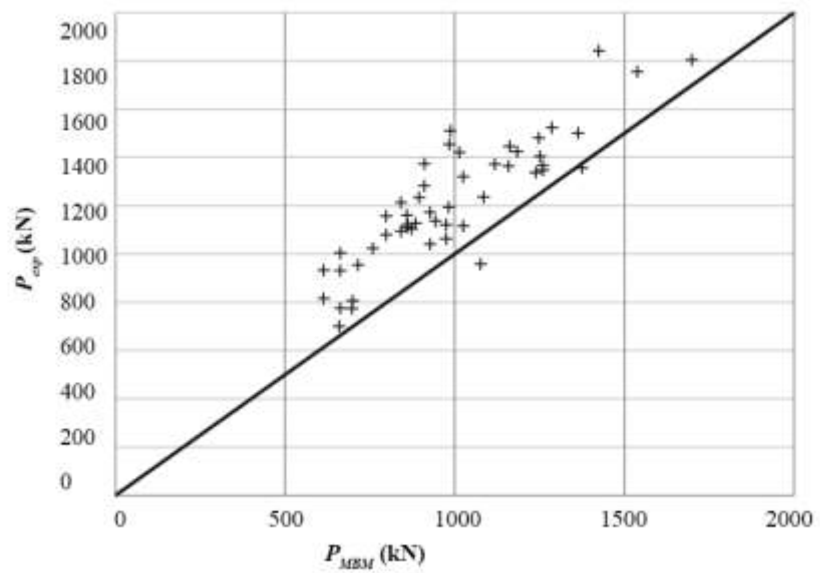
Modified Bond Model (8)



Modified Bond Model (9)



Experiments vs Eurocode shear



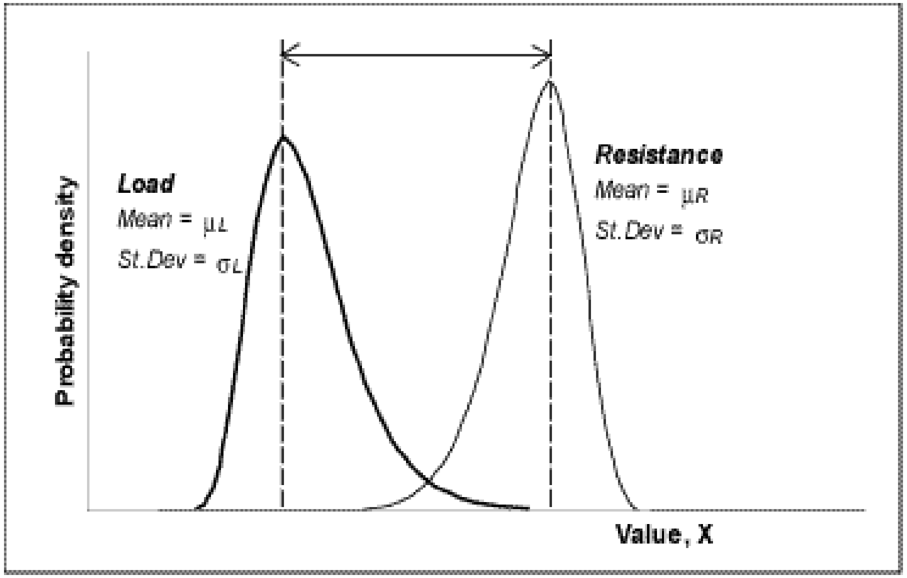
Experiments vs Modified Bond Model

Code extension proposal
Limit State function

$$P_f = P \quad R < R_d$$

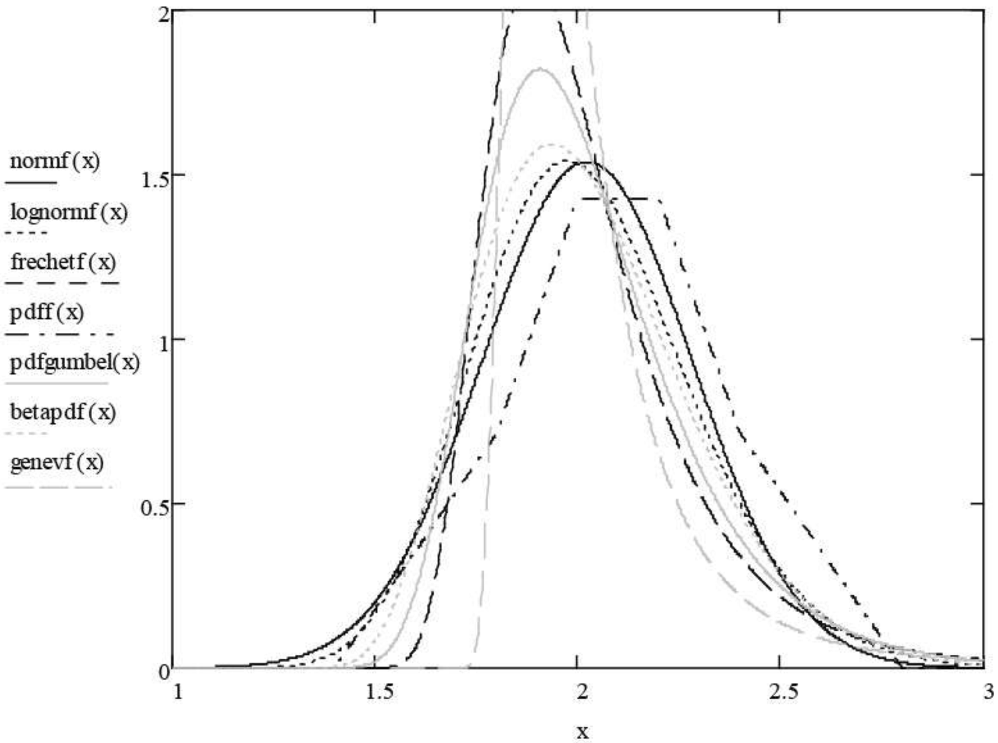
Experiment vs. Design value

- Experiment
  - mean values
  - Test/Predicted ratio
- Design value
  - characteristic values

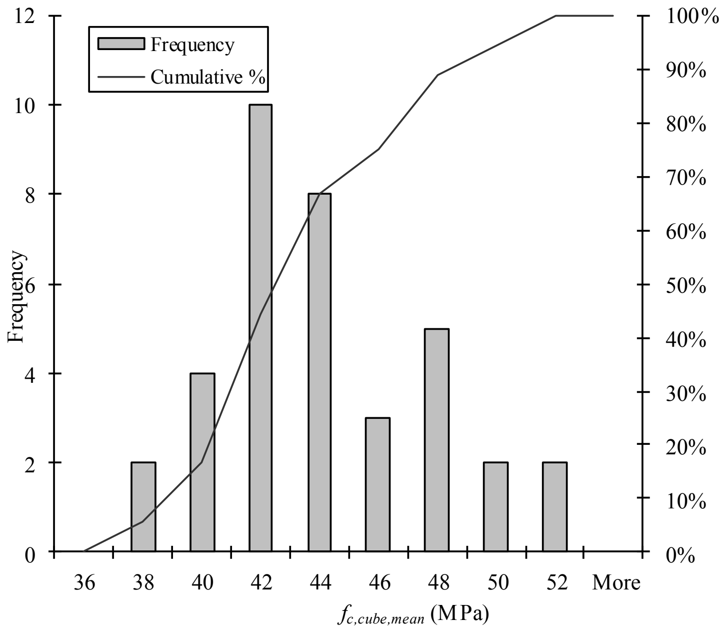


Reliability analysis based on load and resistance

Code extension proposal
Random variables



Test/Predicted

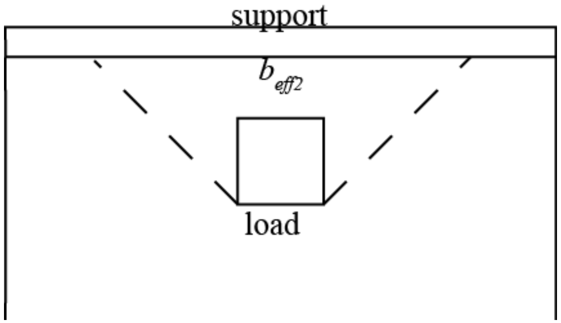


concrete compressive strength

Code extension proposal
Slabs subjected to Wheel Loads

$$V_{Rd,c,prop} = C_{Rd,c} k \left(100 \rho_l f_{ck}\right)^{1/3} b_{eff,red} d_l \left(1.9 - \frac{f_{ck}}{225}\right)$$

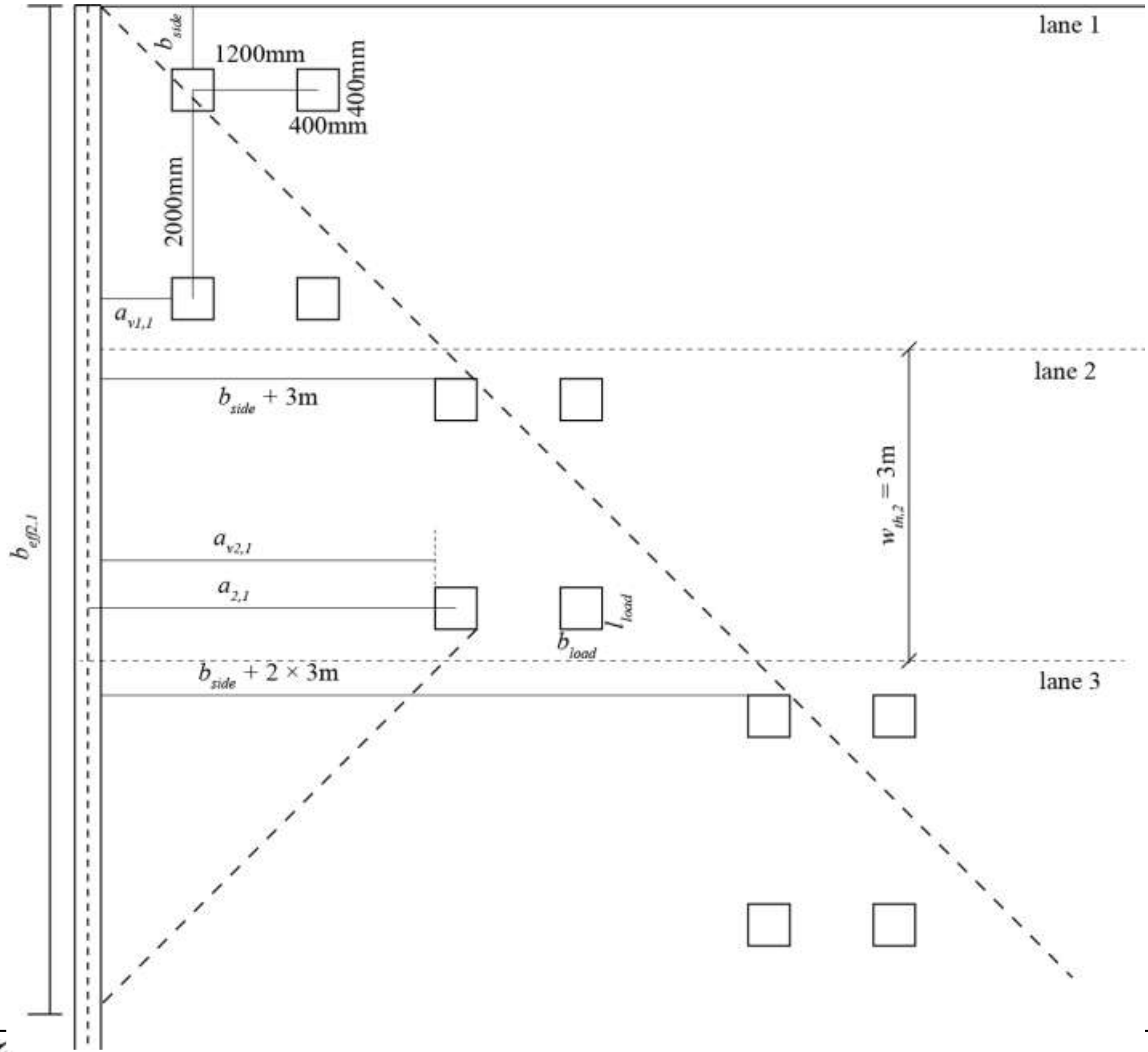
$$b_{eff,red} = \left(0.52 \frac{l_{sup}}{b} + 0.48\right) b_{eff}$$



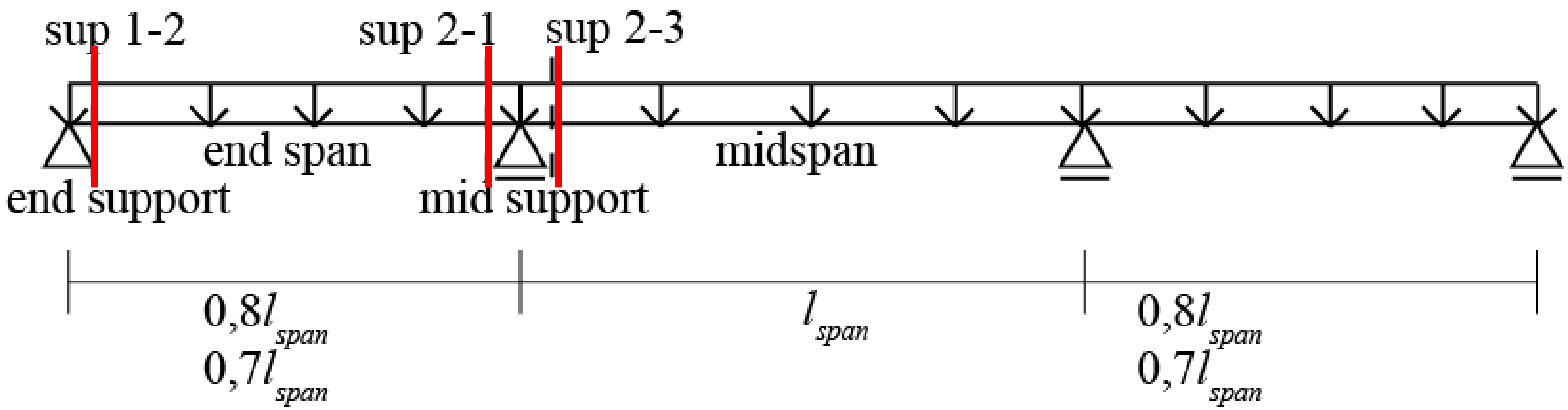
- Enhancement factor depends on f_{ck}
  - Experiments: f_{ck} not as in shear formula
- Effect of reduced support width
- Proposal for $a_v \leq 2.5d_l$

Application to practice (1)

- Evaluating existing solid slab bridges:
  - NEN-EN 1992-1-1:2005
  - 25% reduction of contribution concentrated load close to support
  - $\beta = a_v/2d$
  - Combined: $\beta_{new} = a_v/2{,}5d$
  - Effective width: French method and minimum 4d


lane 1
b_side
1200mm
400mm
400mm
2000mm
a_v1,1
lane 2
b_side + 3m
w_th,2 = 3m
b_eff2,1
a_v2,1
a_2,1
l_load
b_load
b_side + 2 × 3m
lane 3

Application to practice (3)



- Checks at indicated sections
- 9 existing Dutch solid slab bridges

Application to practice (4)

- Shear **stresses**: influence of recommendations
  - QS-EC2: wheel loads at a_v = 2,5d_l
  - QS-VBC: wheel loads at a_v = d_l
  - QS-EC2 18% reduction in loads

- Shear **capacity**:
  - QS-EC2: $v_{Rd,c} \sim \rho, d$
  - low reinforcement + deep section = small shear capacity
  - QS-VBC: $\tau_1 \sim f_{ck}$ only

- QS-EC2 improved selection ability

Sustainability

Economics

- Repair cost
- Demolition cost
- Recycling cost
- New construction

Environment

- Impact of repair
- Impact of replacement
- CO_2 emissions
- Materials
- Transport

Social

- Visual impact
- Traffic delays
- Employment

Impact on Sustainability

Example replacement of 3-span slab bridge (deck only)

- Economic cost: 500k – 640k €
- Environmental cost: 136 ton CO_2
  - Blast furnace cement: 74 ton CO_2
  - Portland slag cement: 122 ton CO_2
- Social cost: case-dependent
  - can be 9 times economic cost
- Scope: 600 slab bridges

Summary & Conclusions

- Slabs under concentrated loads behave differently in shear than beams
- Beneficial effect of transverse load redistribution

- Modified Bond Model improvement as compared to Eurocode
- Code extension proposal for transverse load redistribution

- Application to practice: reduction in loads

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