Background

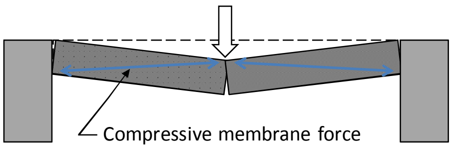
- Research into Reserve Capacity of Dutch Concrete Bridges
  - Shear capacity of beams and slabs without shear reinforcement (Yang, Lantsoght)
  - Long-term loading effect on shear capacity (Sarkhosh)
  - Use of NLFEA for load capacity evaluation
  - Compressive membrane action in prestressed concrete deck slabs (Amir)

Evaluation of load capacity with NLFEA

- Workshop at start → large scatter in results of tests with shear failure
- Benchmark studies of experiments in literature (ATENA and DIANA)
- Guidelines for Nonlinear Finite Element Analysis of Concrete Structures. Scope: Girder Members (RTD 1016:2012)
- International Contest: does Guidelines result in reduction of scatter?

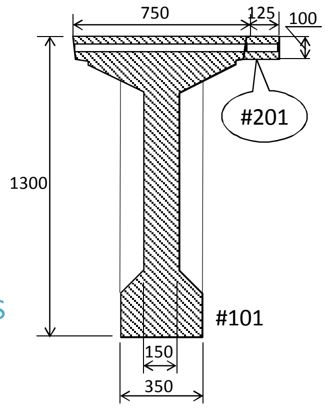
International Contest (1)

- Tests compressive membrane action
  - Scale 1:2 of existing bridge structure
  - 4 prefabricated beams with cast in situ prestressed deck slabs
  - After punching tests, deck slabs removed
  - 3-point-bending tests on beams



International Contest (2)

- Girders
  - Dimensions
    - Length 12 m, depth 1,3 m
    - #101 symmetric, #201 asymmetric
    - Empty ducts in upper flange
  - Materials
    - Concrete cube strength
      - At prestress release 54 MPa
      - At testing 90 MPa
    - Ribbed bars nominal B500
    - Prestressing strand nominal Y1860S
  - Prestress
    - Cable force before release given
    - Effective prestress to be estimated

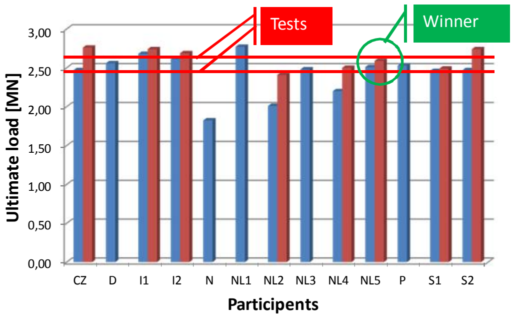


International Contest (3)

- Questions
  - Maximum (and minimum) load at failure
  - Failure mechanism
  - Crack pattern at 75% and at 100% of failure load
  - Crack width at 75% of failure load
  - Load-displacement diagram
- Guidelines should be followed
  - Modeling: Materials, FE's, Prestressing, Existing cracks, Loads, Boundary conditions
  - Analysis, Limit State Verification, Reporting

International Contest (4)

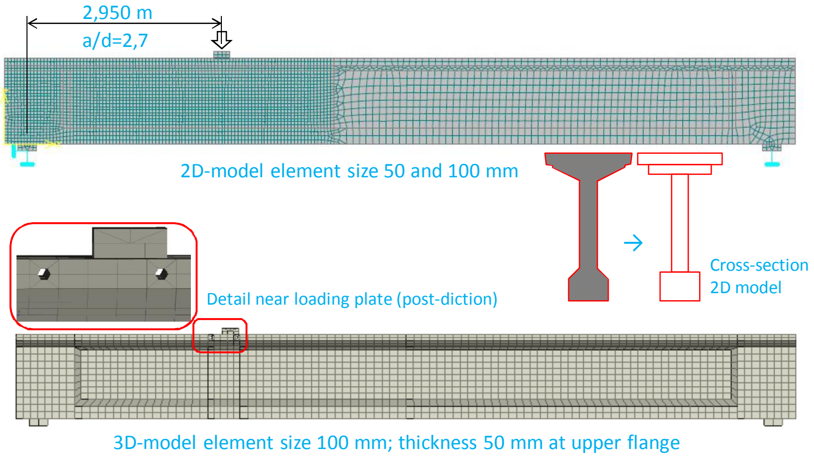
- 13 participants from 7 countries in EU
- Universities and consulting firms
- Various programs, mostly NLFE codes
- Results:



Modeling (1)

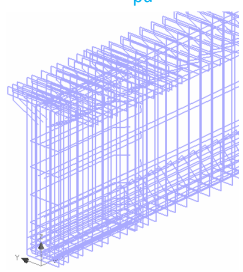
- 2D or 3D?
  - Symmetric girder mainly plain stress and if local effects near loading point negligible → 2D
  - Asymmetric girder → transverse bending and empty ducts near loading plate → 3D
  - After consultation with Cervenka
    - Den Uijl → 2D
    - Cervenka → 3D

Modeling (2)



Modeling (3)

- Material properties (average values)
  - Cube strength 90 MPa → f_c= 76,5 MPa
  - Compressive strength reduction in cracked region to 80% (→ 61,2 MPa)
  - Ribbed bars f_{sy}= 549 MPa f_{su}= 607 MPa ε_{su}= 0,05
  - Strand f_{py}= 1705 MPa f_{pu}= 1994 MPa ε_{pu}= 0,05
- Stirrups
  - In web 2Ø10-120 mm
  - In beam end 6Ø10-100 mm
- Prestress
  - 24 strands Ø15,7 mm
  - After 20% losses 1142 MPa
  - Built up in 4 steps over 600 mm
- Finite Element Grid
  - 50 mm in critical zone, 100 mm outside critical zone

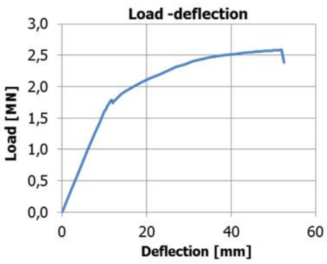


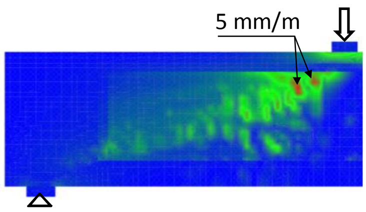
Modeling (4)

- Loading plate and supports
  - Steel LE
- Interface between loading plate and girder
  - Cohesion and tensile strength = 0 MPa
  - Friction coefficient = 0,1
- Bond
  - Ribbed bar (1<slip<3 mm) 21 MPa
  - Strand
    - Along transmission length 6,5 MPa
    - Outside transmission length 3,0 MPa

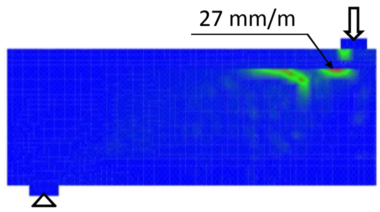
Ultimate load

- Ultimate load
  - $P_{u,max}$ = 2,59 MN
  - $P_{u,min}$ = 2,51 MN
- Failure mode
  - Shear compression



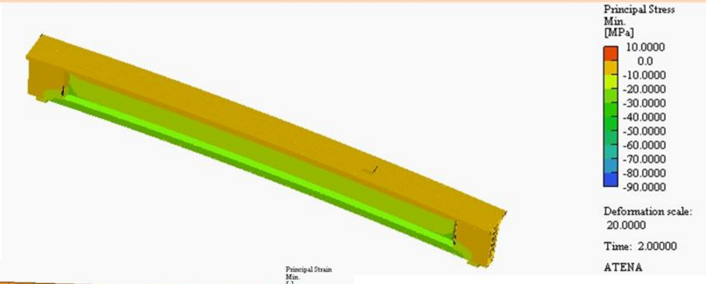


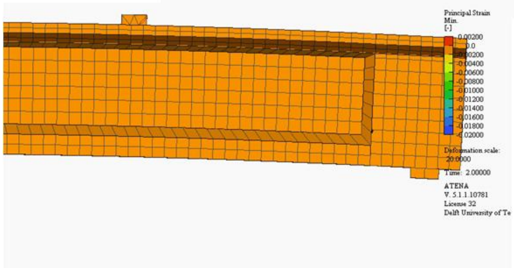
Min principal strain at ultimate load



Min principal strain just after ultimate load

Crack development

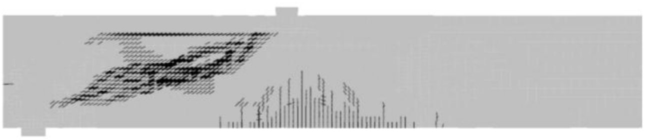




3D-simulation

- Eccentric cross-section
- Cracks > 0,01 mm
- Only 1st cracks
- Displacements × 20
- Min. principal stress/strain

Crack width



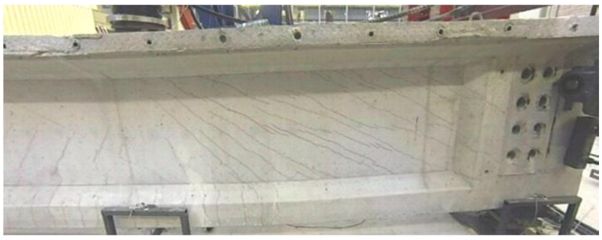
Cracks > 0,1 mm at 75% of ultimate load

At 75% of ultimate load	In web [mm]	At bottom side [mm]
Crack width in simulation	0,35 – 0,55	0,25 – 0,35
Crack width in test	0,05 – 0,15	0,20
Crack spacing in simulation	100	200
Crack spacing in tests	99/64	128/141

Various considerations

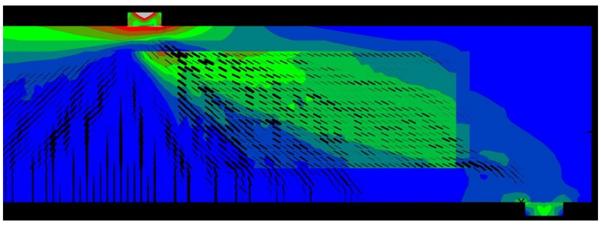
- Choices
  - Mid-beam versus edge beam: same load, transverse bending
  - Upper flange not critical → no empty ducts included
  - Non-uniform loading by loading device not considered
- Effect of:
  - Concrete strength 10% lower → P_u 3% lower
  - Prestress level 10% lower → P_u not lower
  - Yield stress steel Nominal instead of average → P_u 1,5% lower
  - Element size 50 mm → 100 mm → P_u 1,7% lower
- Ultimate load:
  - Minimum estimated as 3% lower based on effect of variations

Flexural or Shear Failure? (1)

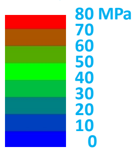


Girder #101
a/d = 2,7
Last step to failure

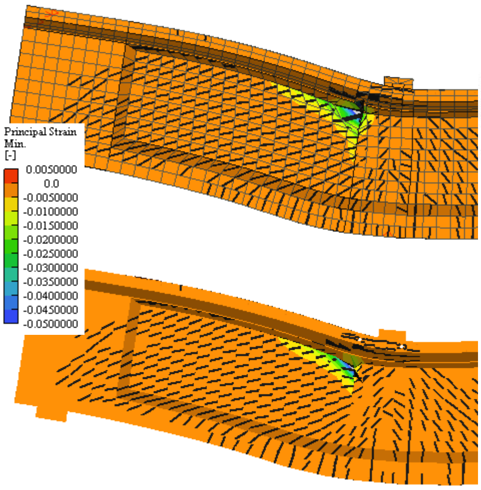
f_{cm} = 76,5 MPa
$0{,}8 \cdot f_{cm}$ = 61,2 MPa

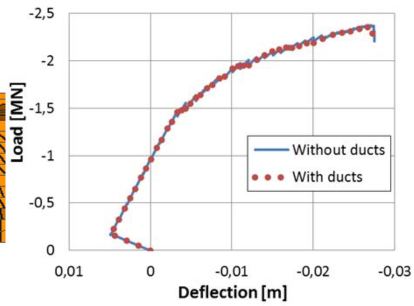


Cracks > 0,01 mm
Min. principal stress



Flexural or shear failure? (2)





- 3D without and with empty ducts
  - Displacement ×25
  - Same load-deflection
  - Both shear compression failure
  - More cracks in upper flange with empty ducts

Flexural or shear failure? (3)

3D-simulation #201
- Eccentric cross-section
- Displacements × 25
- Top view at P_u

Test #201
- Mixed failure at small flange side

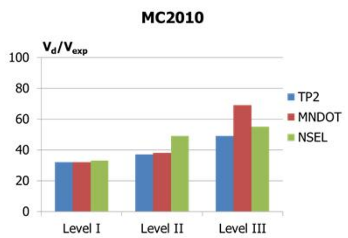
Test #301
- Test after Contest
- Reduced a/d (2,7→2,0)
- Empty ducts filled up
- Shear compression failure

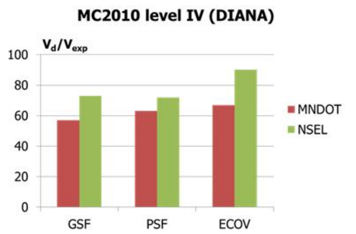
NLFEA Guidelines (1)

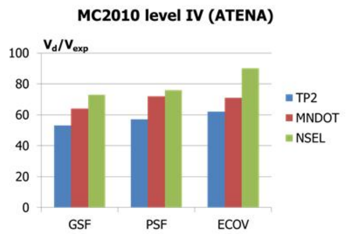
- General
  - Guidelines meant for assessment of structures, not for estimating real strength
  - Real SLS much lower than 75% of real strength
- Materials
  - Here average instead of characteristic values
  - In ATENA concrete properties connected to cube strength
  - Material models in ATENA comply with Guidelines
- Analysis
  - Calculation methods in ATENA comply with Guidelines
  - Convergence criteria in ATENA comply with Guidelines

NLFEA Guidelines (2)

- *fib* Model Code 2010
  - Levels of Approximation
    - Level I-III Analytical
    - Level IV NLFEA
  - Level IV safe and high capacity
    - (Structural Concrete 2013,V14,#3)







Concluding Remarks

- NLFEA is an important tool for structural analysis
- Validation of models is important
- Guidelines may contribute to reduction of scatter
- An International Contest provides an inspiring platform to show the state-of-the -art

Acknowledgement