Contest of two deep reinforced RC slab strips

Yuguang Yang, Cor van der Veen
and Ane de Boer

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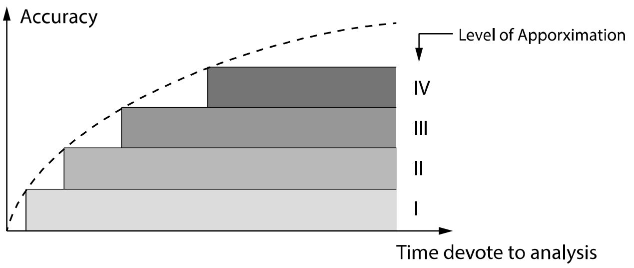
Background

- Level of Approximation approach in *fib* Model Code 2010



- Shear behaviour of RC members without shear reinforcement is a challenging research topic due to the complex failure mechanism

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Dia 2

adb2 Approximation instead of

ane de boer; 18-5-2019

Shear capacity of members without shear reinforcement – MC2010

- General expression: $V_{Rd,c} = k_v \frac{\sqrt{f_{ck}}}{\gamma_c} z b_w$
- LoA I: $k_v = \frac{180}{1000 + 1.25z}$
- LoA II: $k_v = \frac{0.4}{1 + 1500\varepsilon_x} \frac{1300}{1000 + k_{dg} z}$
- Can nonlinear FEM become LoA III or LoA IV ?

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FEM guidelines

- First issue 2012 RC & PRC girders;
- Issue: 2015 RC & PRC girders + RC slabs
- Last issue 2017; Issue 2019 is in review!
- Related workshops:
  - 2007: Initiative Shear Force workshop
  - 2014: Contest T-girder, Parma
  - **2019: Contest two simple reinforced beams**

Table 2-2: Statistical properties of the modelling uncertainty per failure mode

Failure mode	Mean	CoV
Bending	0.97	0.04
Flexural shear in beams	1.01	0.08
Shear in slabs	1.39	0.10
All	1.15	0.19

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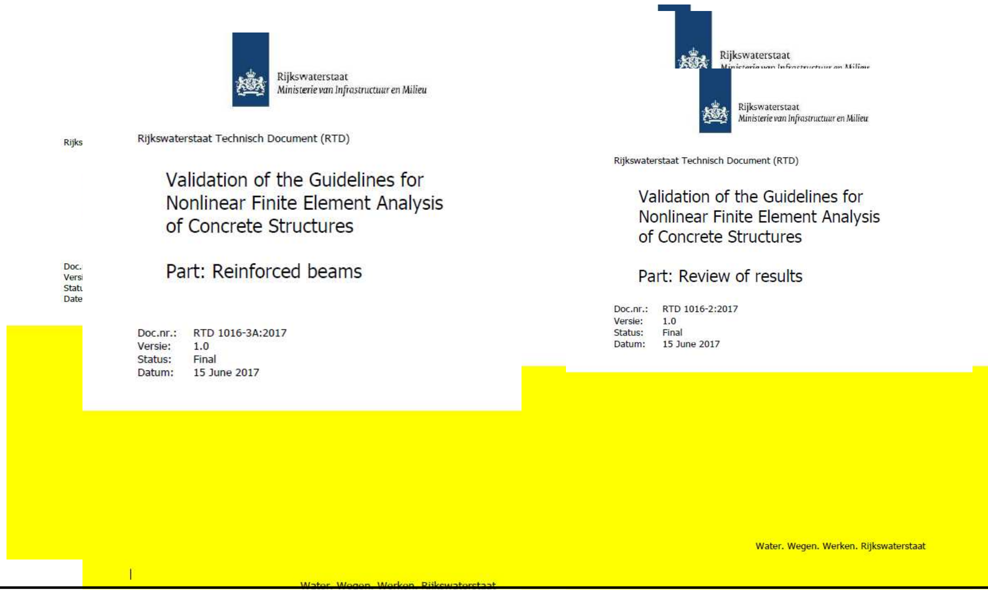
FEM Guideline Reports


Rijkswaterstaat
Ministerie van Infrastructuur en Milieu

Rijkswaterstaat Technisch Document (RTD)

Validation of the Guidelines for
Nonlinear Finite Element Analysis
of Concrete Structures

Part: Reinforced beams

Doc.nr.: RTD 1016-3A:2017
Versie: 1.0
Status: Final
Datum: 15 June 2017

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Rijkswaterstaat Technisch Document (RTD)

Validation of the Guidelines for
Nonlinear Finite Element Analysis
of Concrete Structures

Part: Review of results

Doc.nr.: RTD 1016-2:2017
Versie: 1.0
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Water. Wegen. Werken. Rijkswaterstaat

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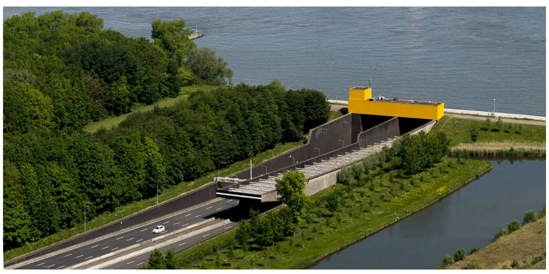
Shear tests on concrete slab strips

- Reinforced concrete slab is a widely applied structure type
- No shear reinforcement, low longitudinal reinforcement ratio, large effective depth, plain bars



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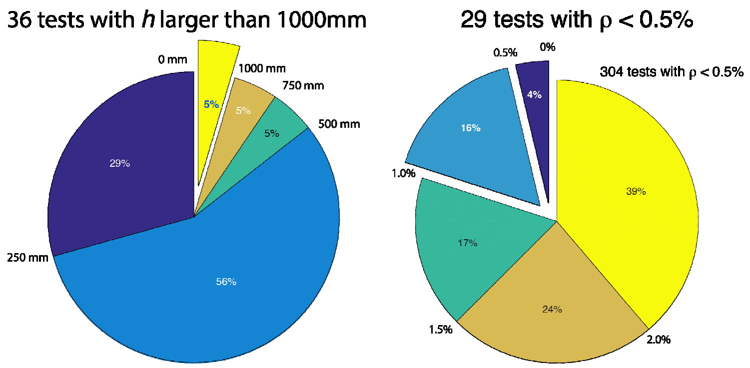
Experimental research program

- Shear behaviour of RC slab strips with **REALISTIC** design parameters for infrastructure

ACI-DAfStb shear database
784 tests (filtered data)
24 tests with h > 1000 mm
and ρ < 1%

Few tests of plain bar reinforced members



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Experimental program

- At TU Delft a large research program on shear behaviour of concrete slab strips was carried out since 2016
- In total **153** tests with **96** tests of shear failure
- 7 test series with main variables including
  - Concrete strength: f_{cm} = 20 MPa and f_{cm} = 65 MPa
  - Specimen depth: h = 300, 500, 800 and **1200** mm
  - Rebar type: Plain bars with f_{ym} = 284 MPa and normal ribbed bars with f_{ym} = 550 MPa
  - Reinforcement ratio
  - Loading positions: *a/d*

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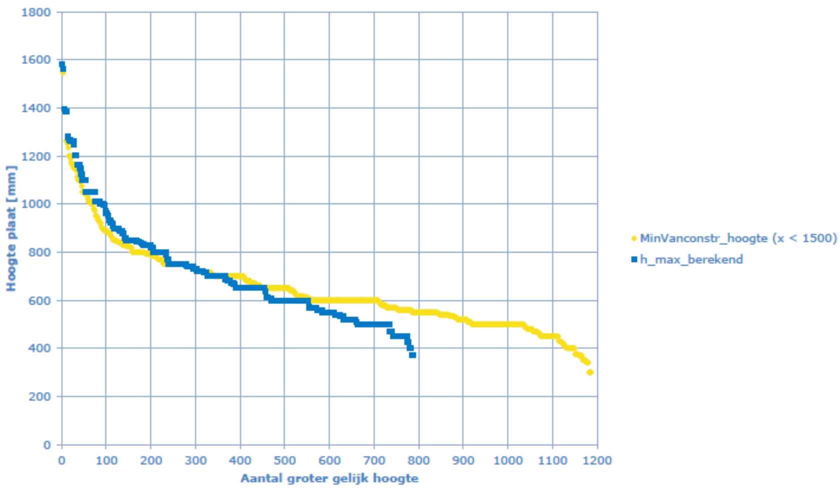
Thickness range of Dutch slab bridges



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Output of the research

- Effect of rebar type to shear capacity

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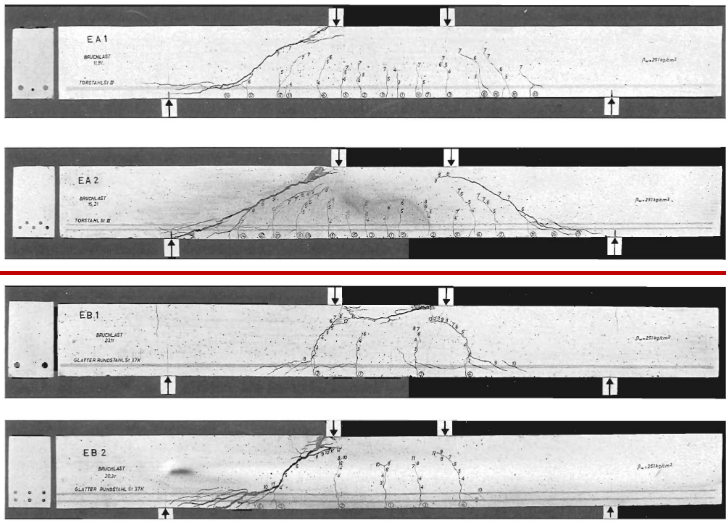
Ribbed bars



P = 116.6 kN

P = 149.0 kN

Plain bars

P = 226.4 kN

P = 198.0 kN

Leonhardt & Walther, 1962

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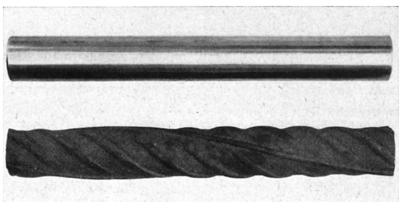
Output of the research

- Effect of rebar type to shear capacity



Leonhardt & Walther

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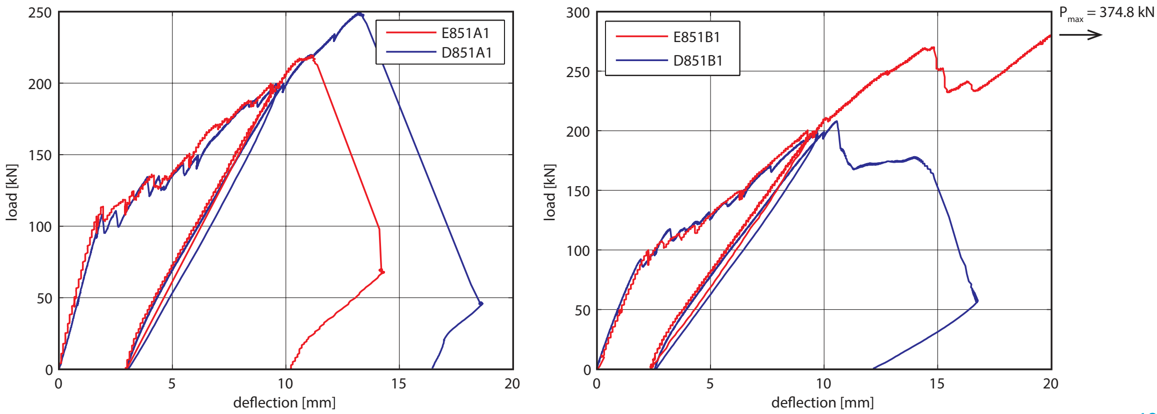
Output of the research

- Effect of rebar type to shear capacity



Output of the research

- Effect of rebar type to shear capacity
- Understanding the transition between failure modes

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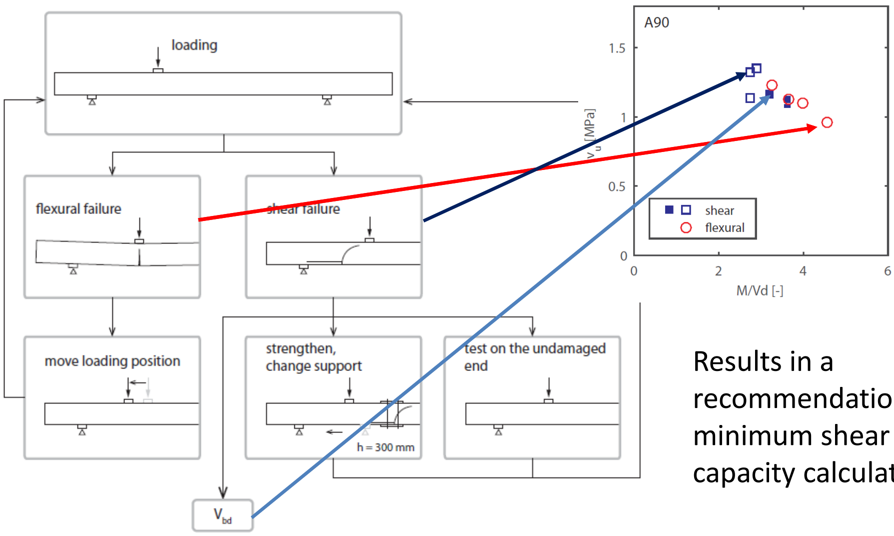
Output of the research



Results in a recommendation on minimum shear capacity calculation

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Output of the research

- Effect of rebar type to shear capacity
- Understanding the transition between failure modes
- Re-explore the size effect

$$V_{Rd,c} = \left[C_{Rd,c} k (100 \rho_l f_{ck})^{1/3} + k_1 \sigma_{cp} \right] b_w d$$

$$v_{\min} = 0.035 k^{3/2} f_{ck}^{1/2} \quad \text{with} \quad k = 1 + \sqrt{\frac{200}{d}} \leq 2.0$$

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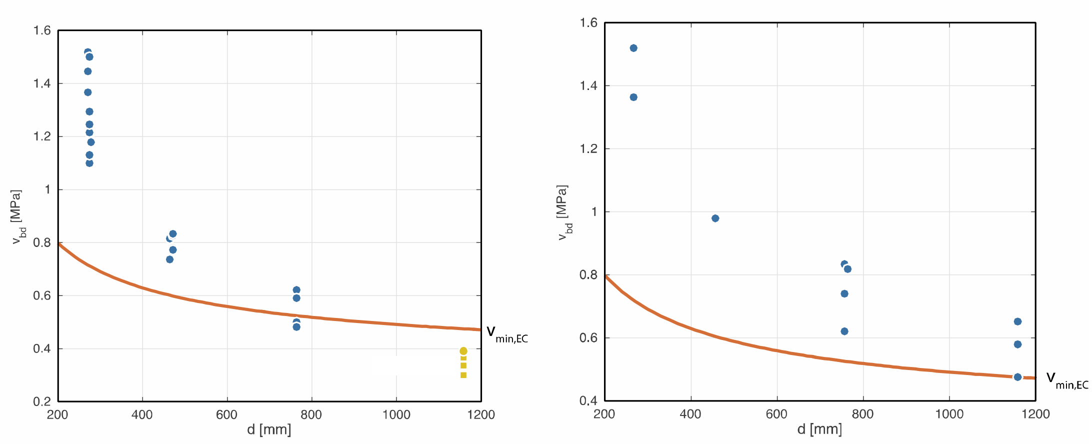
Size effect of Eurocode v_{min}



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Output of the research

- Effect of rebar type to shear capacity
- Understanding the transition between failure modes
- Re-explore the size effect
- Better understanding of shear failure mechanism

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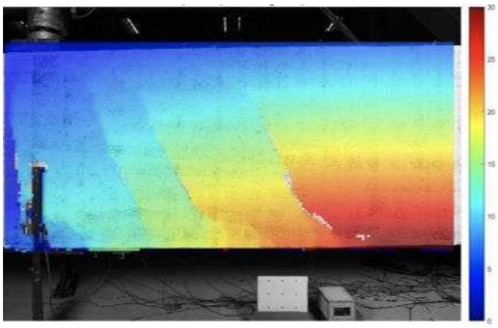
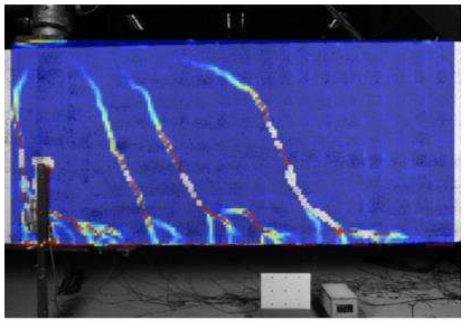
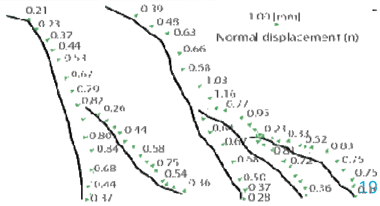
shear failure mechanism – DIC







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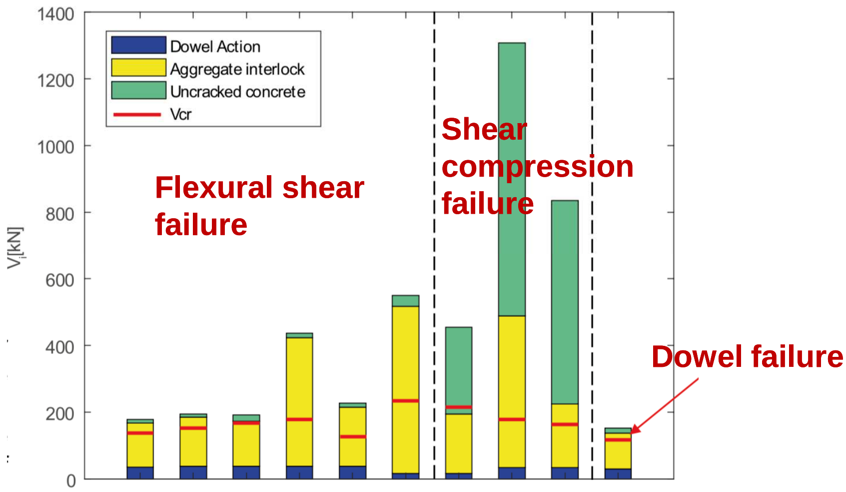
Contribution of different shear carrying mechisms



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Selection of tests

- Shear tests that have not been reported in literature
- Deep beam, with little reinforcement ratio 0.35 % + reference test with reasonable reinforcement ratio 1.18%
- Only 4 similar tests available in literature:

Shioya, T.; Iguro, M.; Nojiri, Y.; Akiayma, H.; Okada, T. (1989): Shear Strength of Large Reinforced Concrete Beams.

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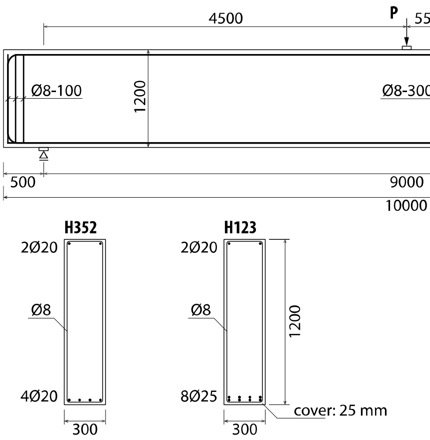
Configurations of the tests

- Reinforcement design



H352 configurations was tested twice

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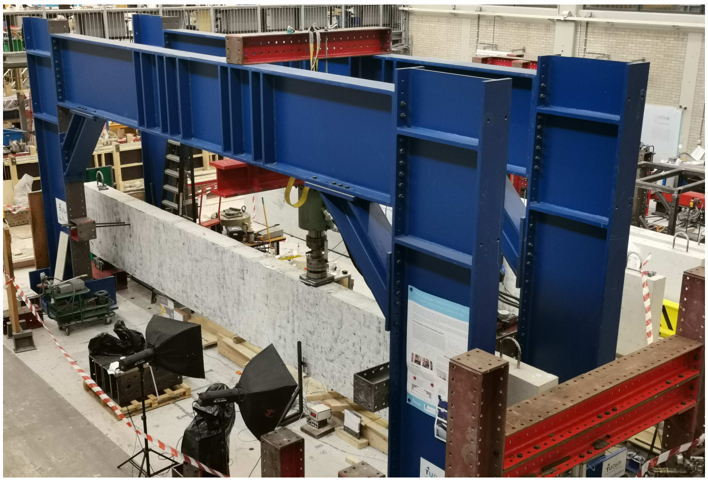
Dia 21

adb3 include the two figures of the aci special edition; I will send you both figures
ane de boer; 18-5-2019

Dia 22

adb4 reinforcement two layers are simply welded to each other
ane de boer; 18-5-2019

Configurations of the tests



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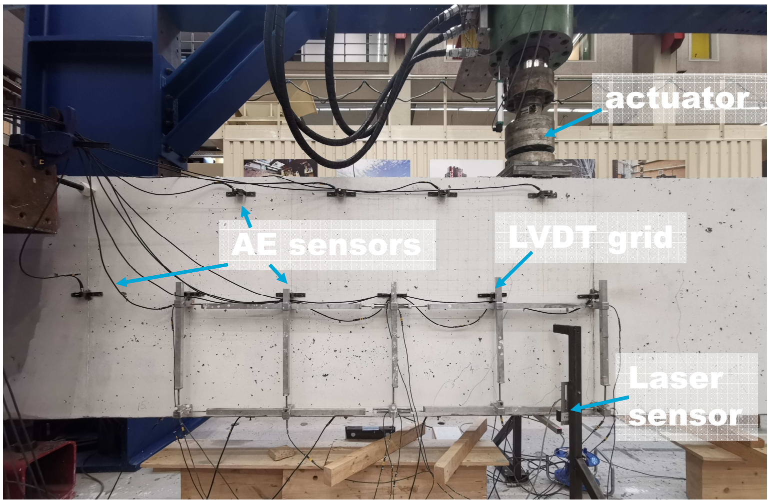
Configurations of the tests



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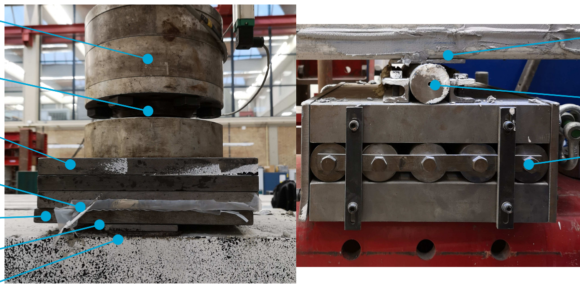
Configurations of the tests

- Actuator
- Ball hinge
- Steel plates
- Teflon layer with grease
- Steel plate
- 100 mm Steel plate
- felt



- 100 mm Steel plate
- Steel roller
- Rolling package

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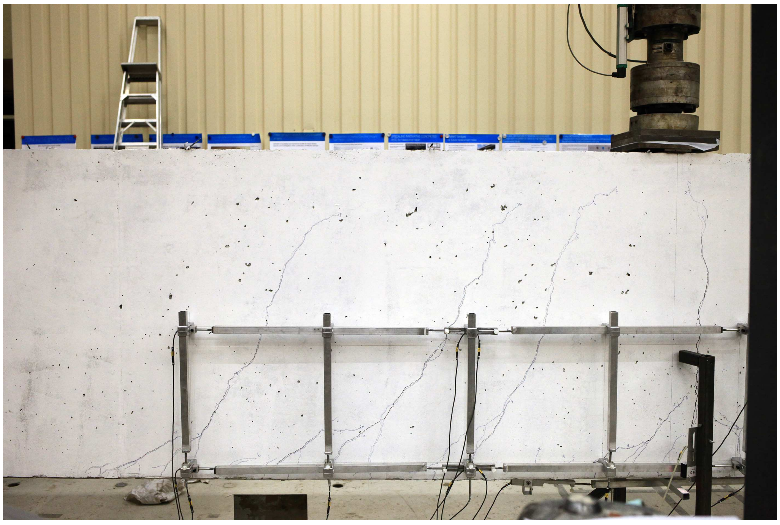
Results

H352 (H321)

- Key parameters $f_{cube,m} = 86.9\ \mathrm{MPa}$ $\boxed{\rho = 0.36\%}$ $a = 4500\ \mathrm{mm}$ $d = 1160\ \mathrm{mm}$
- Two tests with the same configurations
- H351 and H352

H351 before failure



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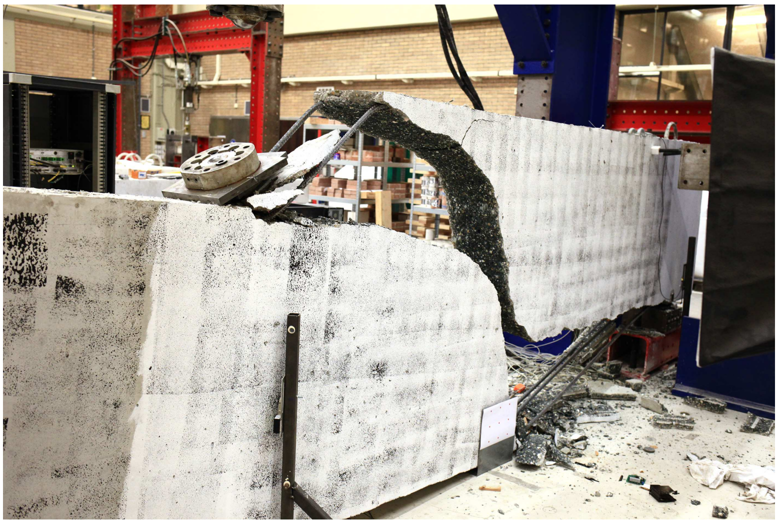
H351 after failure



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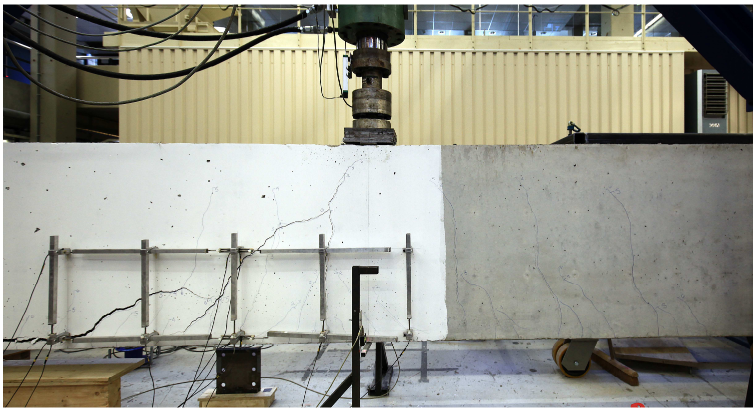
H352

- Key parameters $f_{cube,m} = 86.9$ MPa $\boxed{\rho = 0.36\%}$ $d = 1160$ mm $a = 4500$ mm



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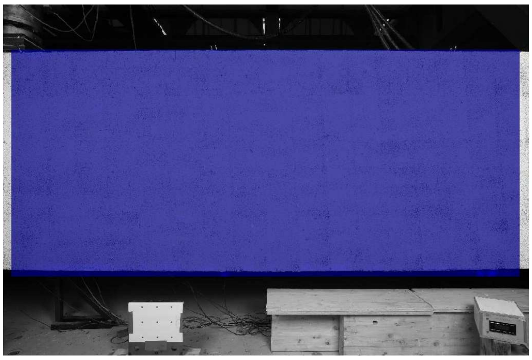
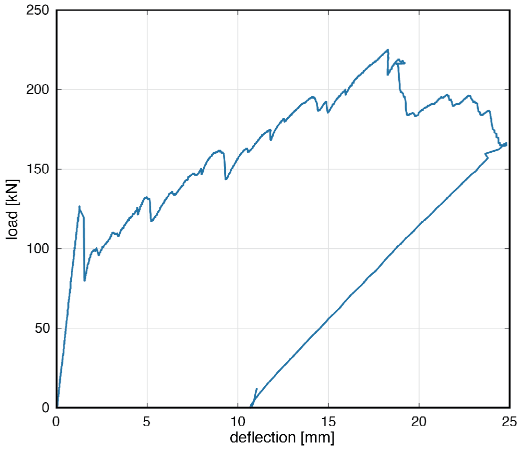
H352 P = 0 kN





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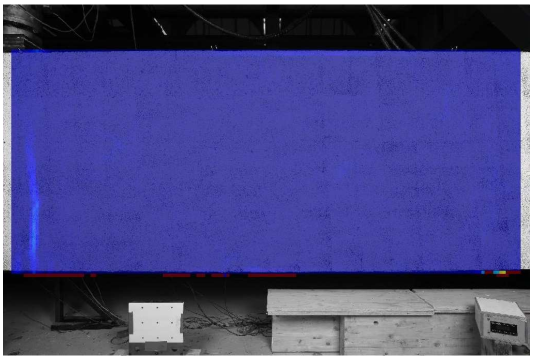
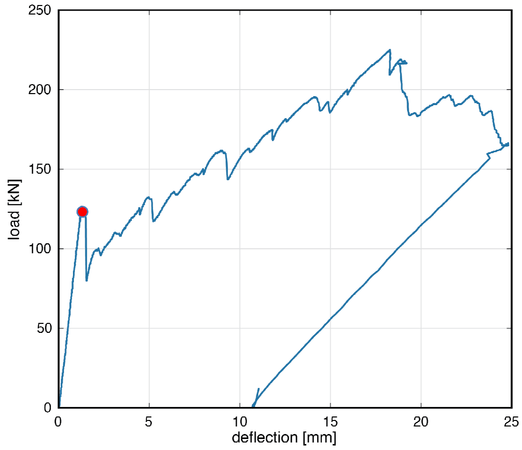
H352 P = 125 kN





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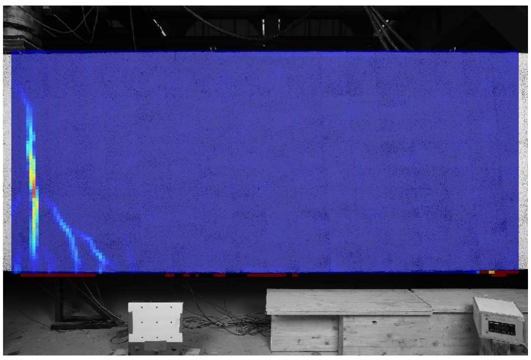
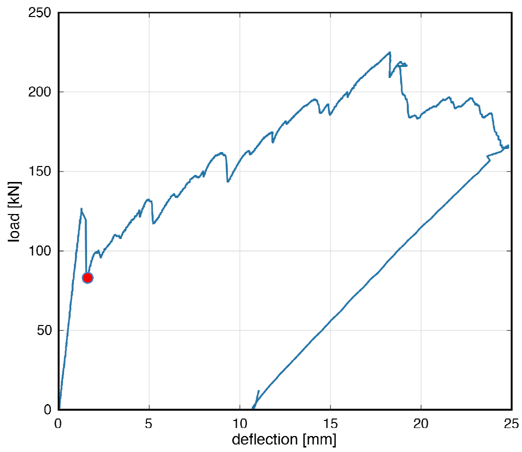
H352 P = 85 kN





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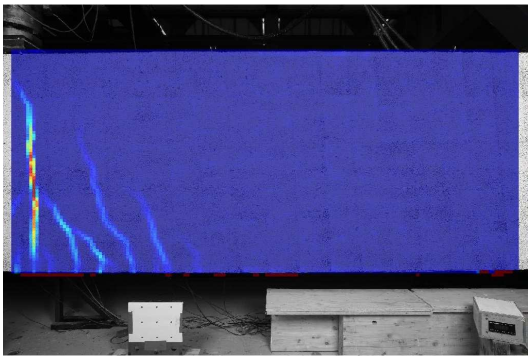
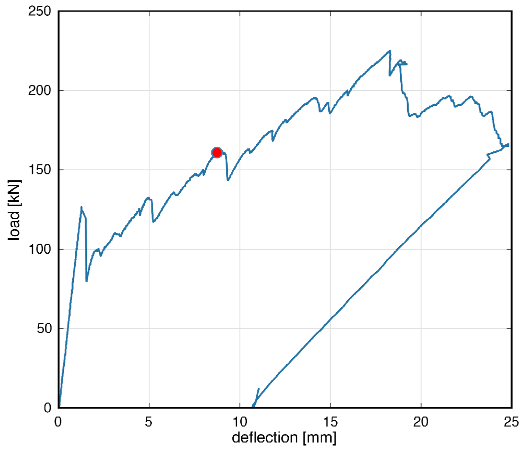
34

H352 P = 150 kN





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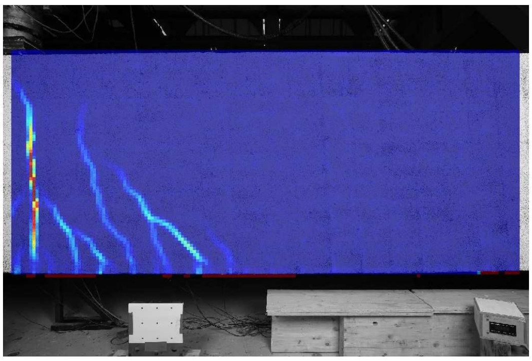
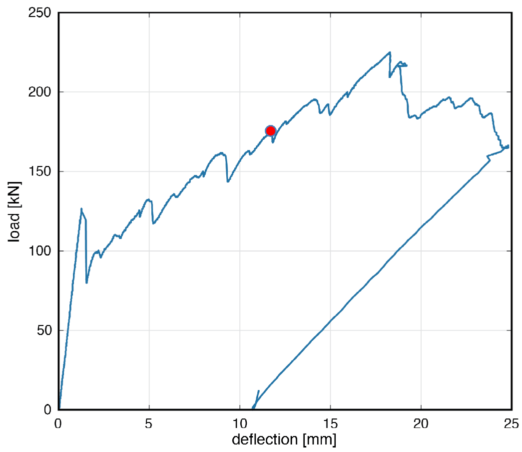
H352 P = 175 kN





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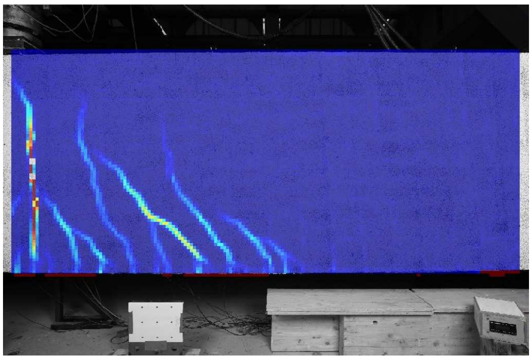
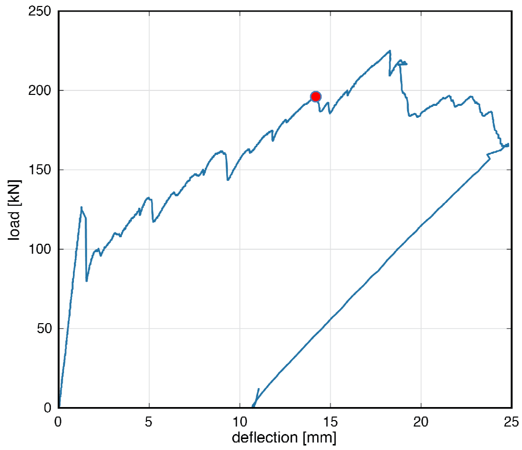
H352 P = 190 kN





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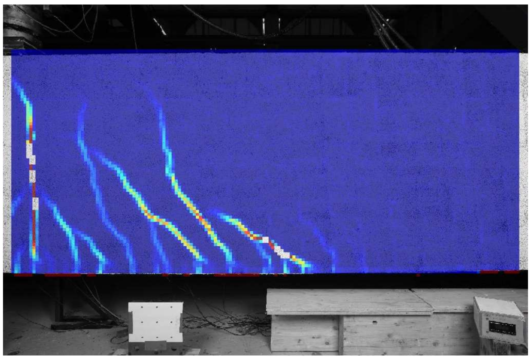
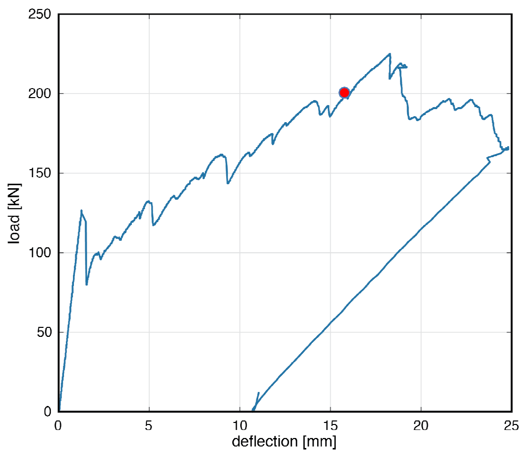
37

H352 P = 200 kN





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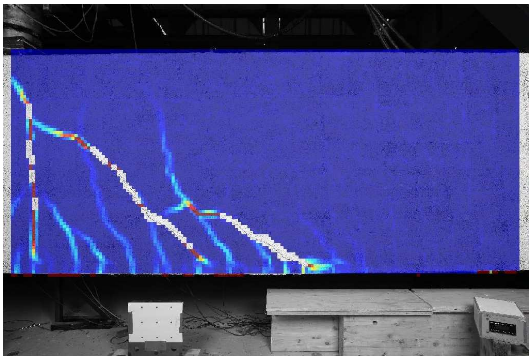
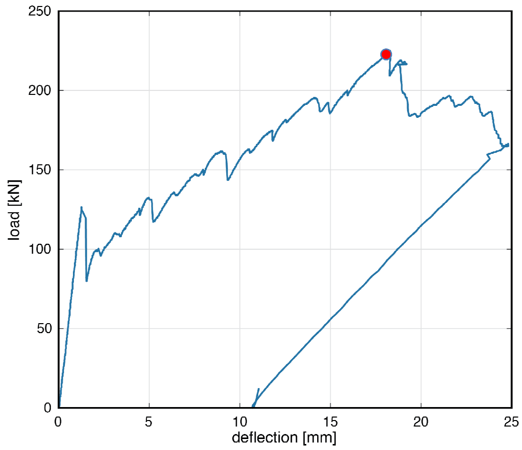
H352 P = 218 kN





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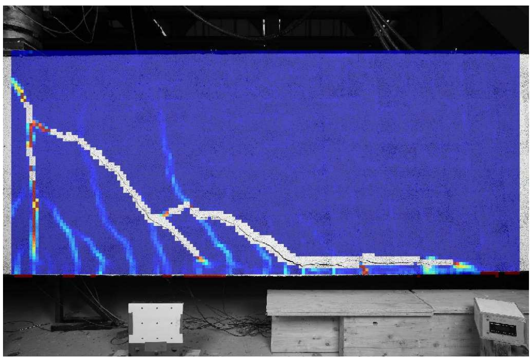
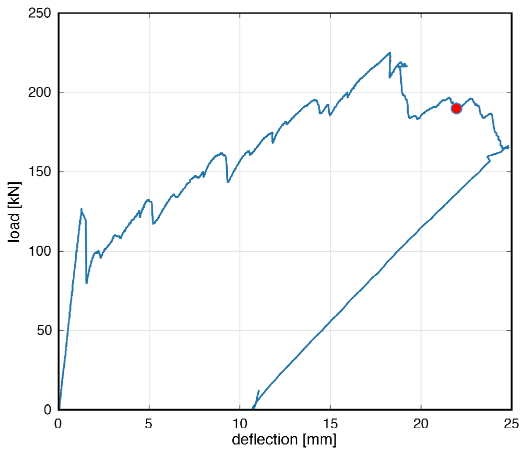
H352 P = 185 kN





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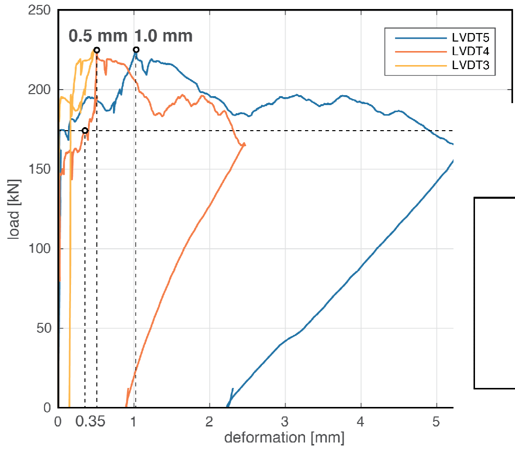
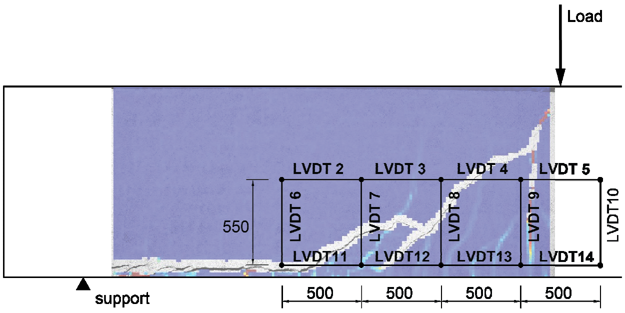
H352 crack opening





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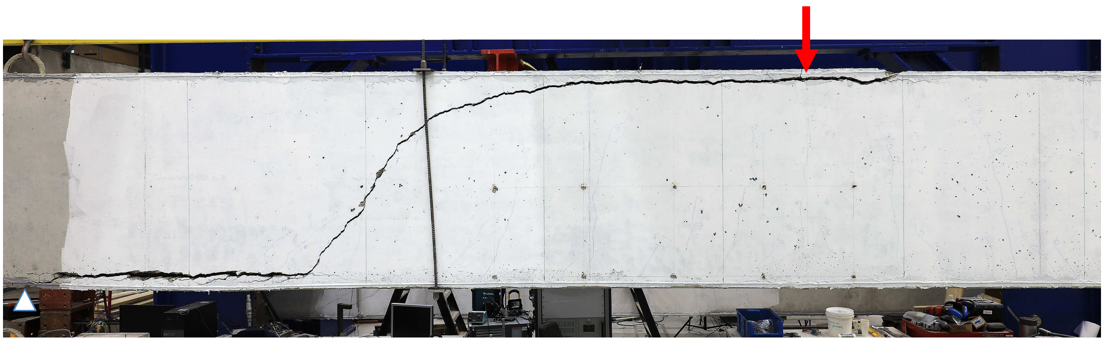
H123

- Key parameters $f_{cube,m} = 86.9\text{ MPa}$ $\boxed{\rho = 1.12\%}$ $a = 4500\text{ mm}$ $d = 1150\text{ mm}$



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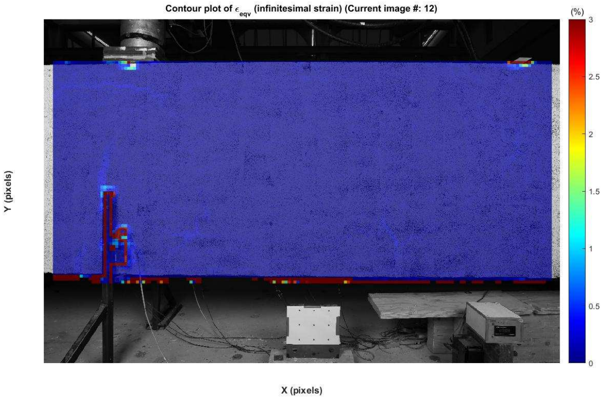
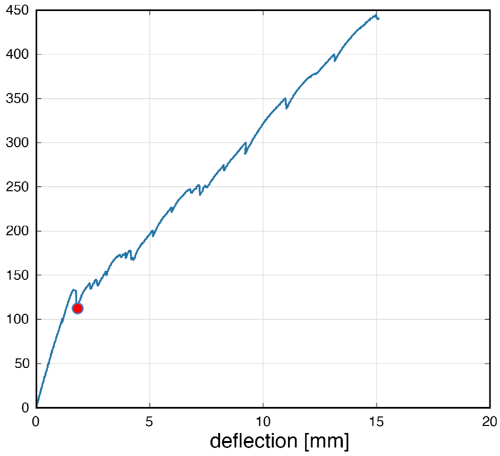
H123 P = 114 kN





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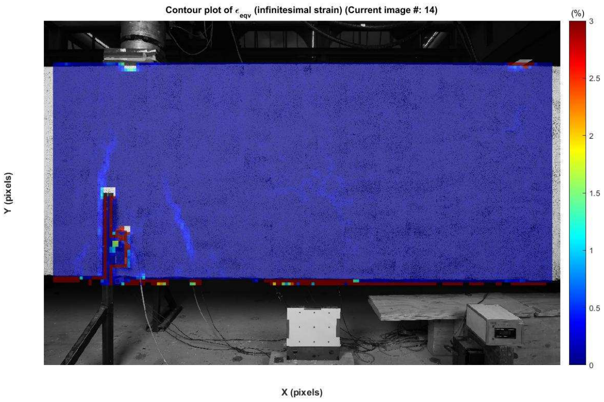
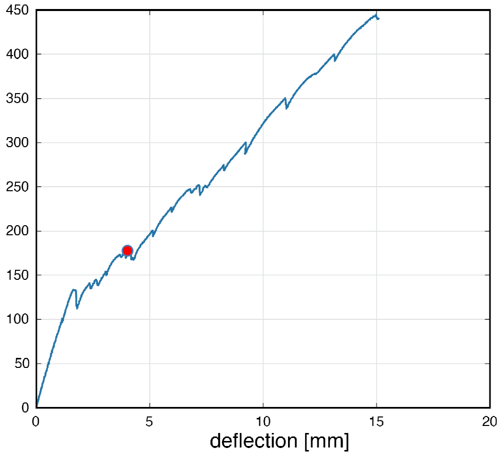
H123 P = 187 kN





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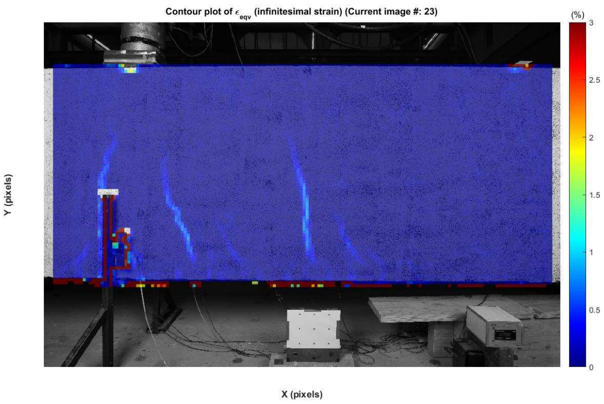
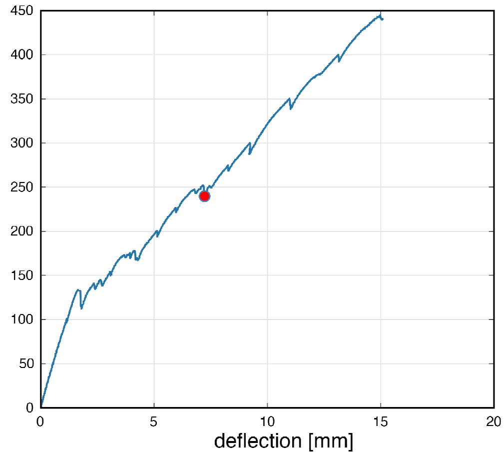
H123 P = 247 kN





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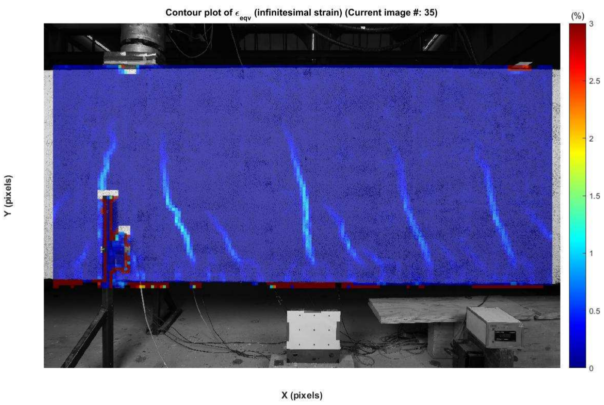
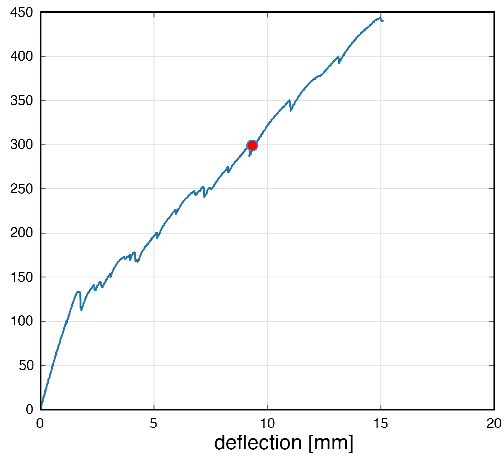
H123 P = 300 kN





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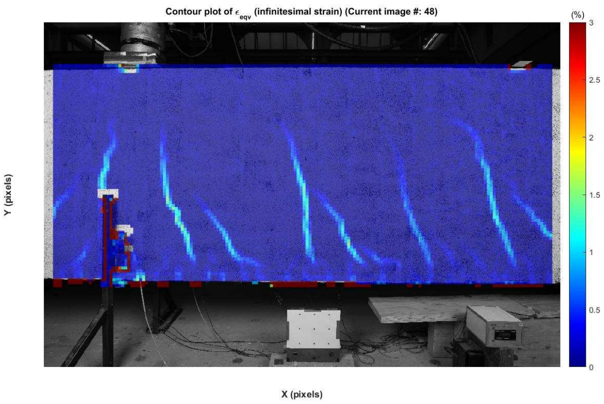
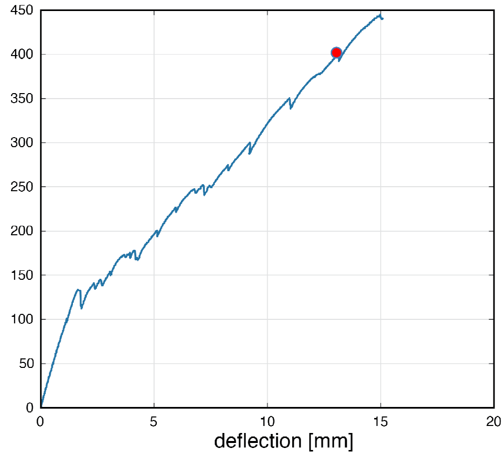
H123 P = 400 kN





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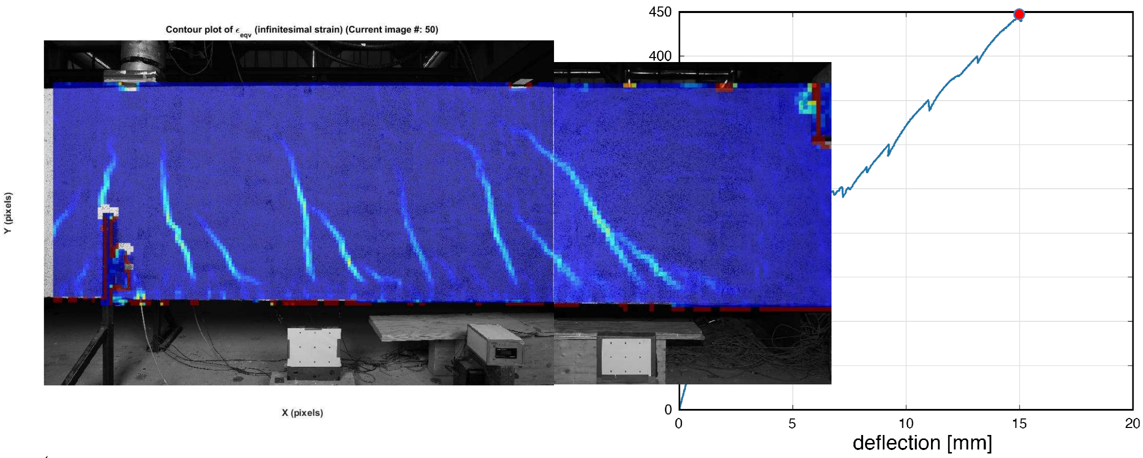
H123 P = 440 kN



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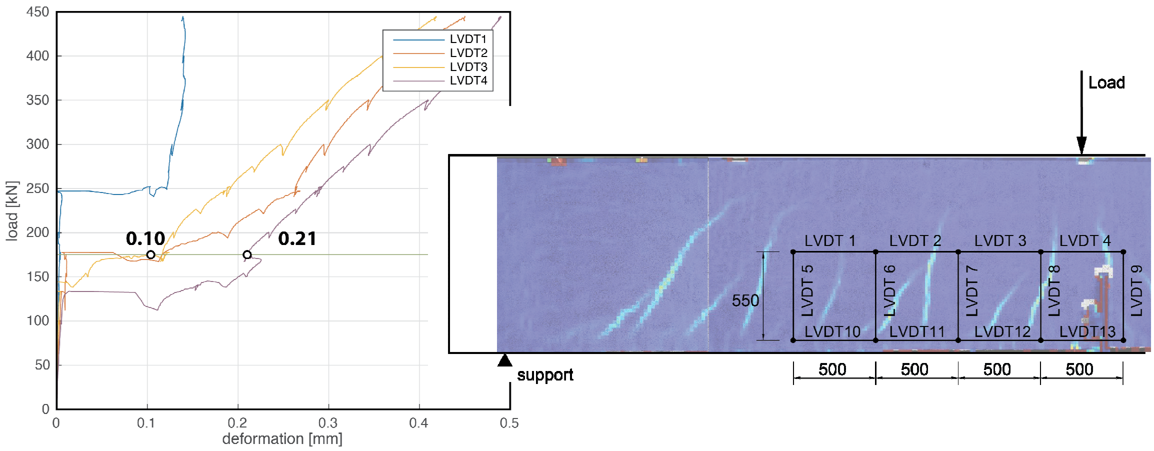
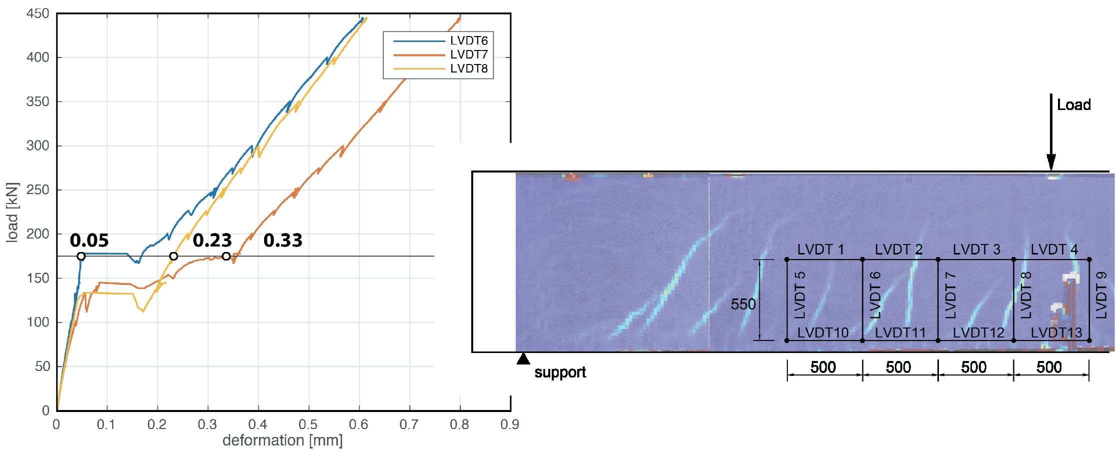
H123 crack opening



H123 crack opening



Results

- 8 teams participated the Lustrum contest with 10 contributions
- 4 FEM packages were used: Diana, Atena, Abaqus and AEM

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Results – H352 (H351)

- Two repeated tests H351 and H352
- Peak load: 197 kN and 225 kN -> 211 kN (mean)
- $\mathrm{MEAN}(P_{fem} / P_u) = 298.9\%$ $\mathrm{STD}(P_{fem} / P_u) = 104.6\%$
- On average **significant** overestimation
- **Two** predictions within 20% of confidence margin
- Eurocode **significantly overestimates** the capacity

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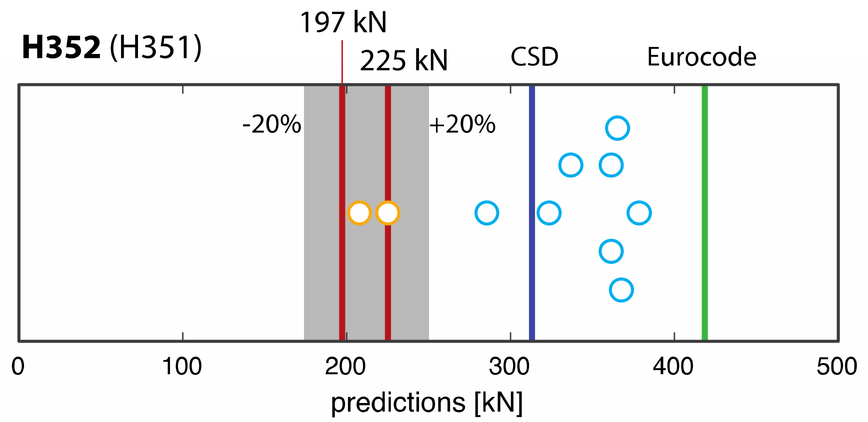
Results – H352 (H351)



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Results – H123

- Peak load: 445 kN
- $\mathrm{MEAN}(P_{fem} / P_u) = 72.2\% \quad \mathrm{STD}(P_{fem} / P_u) = 13.9\%$
- Overestimation, but less extreme
- **Two** predictions below the test results
- **Two** predictions within 20% of confidence margin
- Eurocode still clearly **overestimates** the capacity

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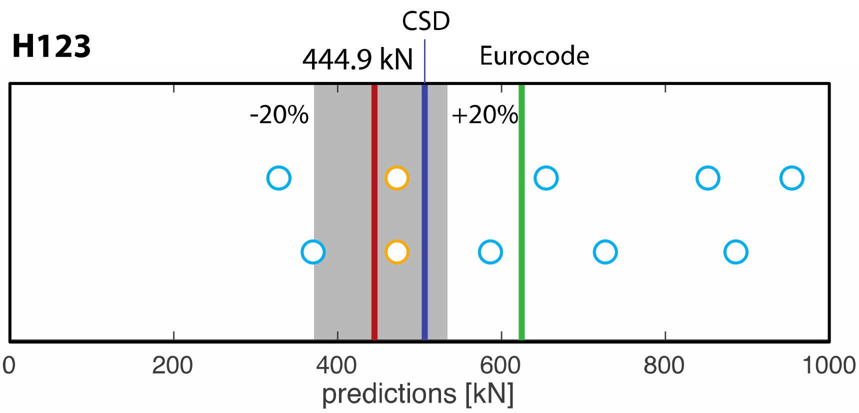
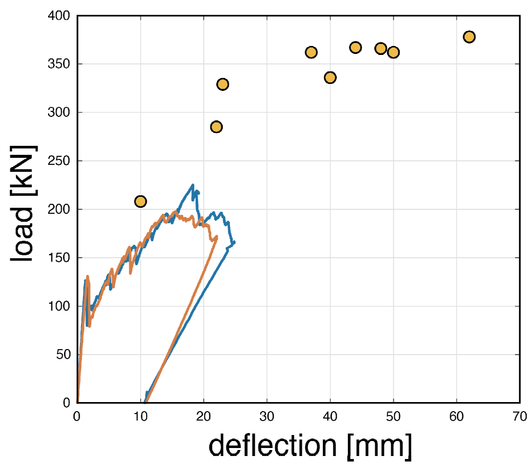
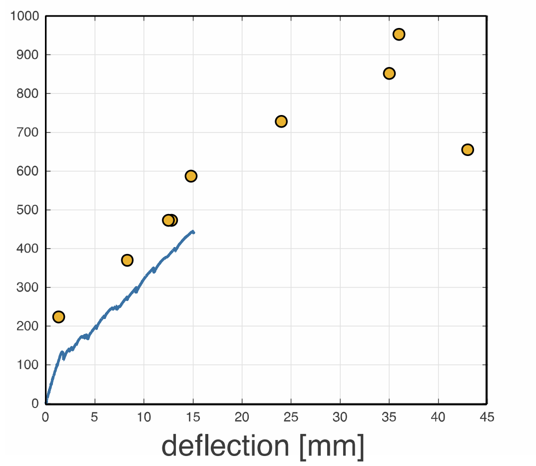
Results – H123



Other aspects: deformation





Thus, the winner is …

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Evaluation criteria

I. Peak load prediction of both tests

II. Correct failure mode

III. Crack width at 175 kN

IV. Crack width and pattern just before failure

- Higher items have higher priorities

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