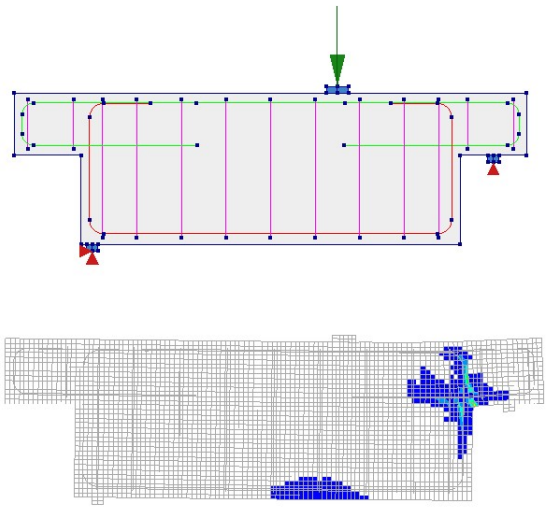
NLFEA of concrete bridges and viaducts with dapped ends (tanden en nokken)

M.Pari, R.Tai & G.Dieteren | TNO

07 February 2024



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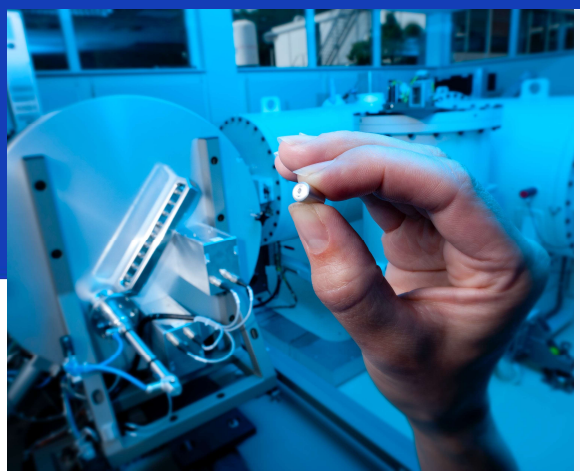
Agenda



1. Background of research
2. Benchmark experiments
3. NLFEA
4. Conclusions & Outlook

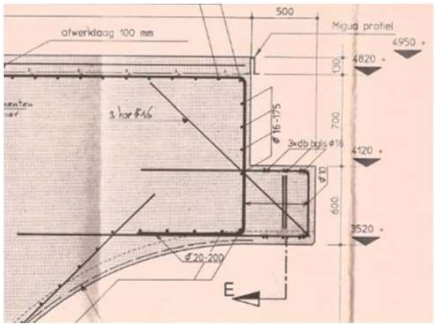
2

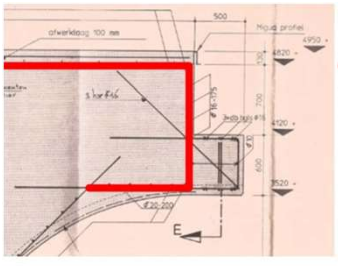
Background of research

3

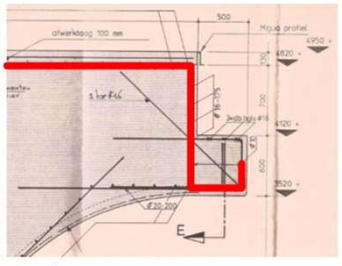
Background of research

- Vulnerable concrete bridges and viaducts in the Netherlands with "incorrectly" detailed main bent-reinforcement in the dapped-end.
- The detail is difficult to inspect, but corrosion is highly probable due to the accumulation of de-icing salts





Fout



Goed

Pictures: S. Pasterkamp, "Schade Nelson Mandelabrug: Onderzoeken naar scheurvorming aanleiding tot sluiten van brug over A12 bij Zoetermeer", Cement Online, 22 december 2022

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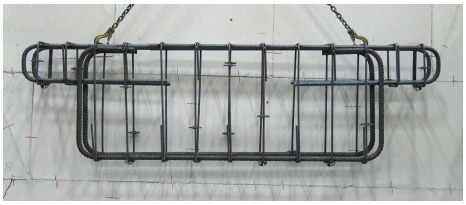
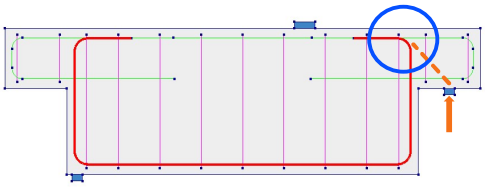
Background of research

- Questions arise over the force-flow along the compressive strut
  - Cracking at the re-entrant corner can lead to a limited height of the compressed zone
  - Risk of premature shearing of the compression strut along the main bent-reinforcement before significant forces develop

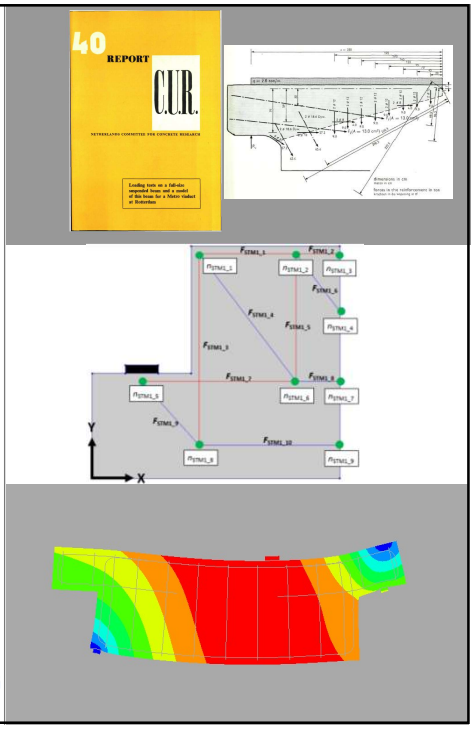


- To this end, this problem is studied under the Vervangen en Renovatie (V&R) research program (**TNO** & **Rijkswaterstaat** collaboration) .
  - Main goal: develop a uniform reassessment method for these structures (for now without considering corrosion, later with corrosion effects).



State-of-the-art assessment methods

- "Snedemethode" based on CUR rapport 40[I]
- Strut-Tie models based on the new generation Eurocode[II]
- Nonlinear Finite Element Analyses (NLFEA)



[I] CUR Civieltechnisch Centrum Uitvoering Research en Regelgeving (1969), "*CUR report 40 Loading tests on a full-size suspended beam and a model of this beam for a metro viaduct at Rotterdam*"

[II] CEN European Committee for Standardization (2021). "*prEN 1992-1-1:2021-09*."

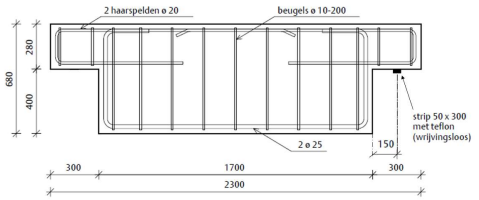
Research Methodology

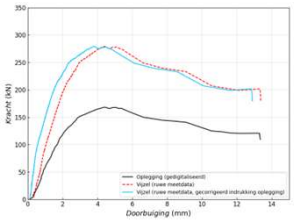
- Goal: Develop NLFEM modelling approach for reassessment of concrete structures with dapped-ends.
- Steps:
  - Identify representative experimental benchmarks where the "nokken" have incorrect detailing (sparse in literature)
    - Kleinman Case (2007) – TU Eindhoven
    - Steinle Case (1975) – Otto Graaf Institute, Stuttgart
  - Develop NLFEM modelling approach by validation against Kleinman's case
  - Re-validate the modelling strategy derived from Kleinman's case using Steinle's case
  - Derive conclusions and directions for future work

Benchmark experiments

Kleinman (2007) – TU Eindhoven

- Experiment “2A” of the test series from Kleinman (2007)
- Representative of the incorrect detailing of the main-bent reinforcement
- Well-documented brittle shear failure
  - Force-displacement response
  - Failure mechanism

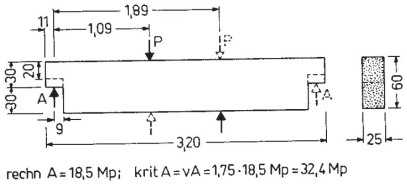




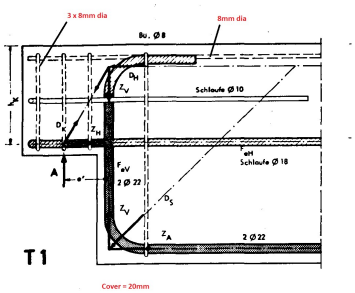
Kleinman, C. S. (2007). Nokken met die tanden!(2): proevenserie legt fout in voorschriften bloot. Cement, 59(2), 78-80.

Steinle (1975) – Otto-Graaf institute, Stuttgart

- T1 beam with a similar layout – representative of the incorrect detailing of the main-bent reinforcement
- Sliding of the structure along the main-bent reinforcement (shear failure)
  - Only load vs crack width (at corner) at load-steps
  - Failure mechanism described only in words.
- Uncertainty in material properties: Rebar not tested, concrete cube tests.
- Slight differences in reinforcement layout: No stirrups in main-span, extra hairpin



rechn A = 18,5 Mp; krit A = vA = 1,75 · 18,5 Mp = 32,4 Mp



Steinle, A., and Rostasy, F.S. (1975). The structural behaviour of party cut-away ends of beams (In German), Betonwerk + Fertigteil-techniek, 6.

NLFEA – Modelling aspects

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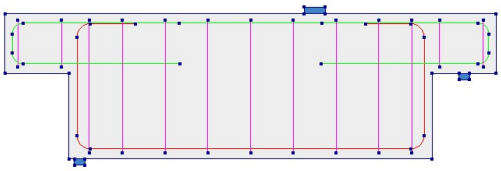
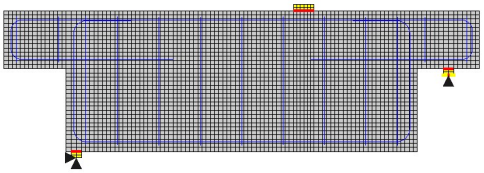
Initial modelling approach

- DIANA 10.7
- Geometry: Based on experiments
- Mesh:
  - Elements (20mm size)
  - Plane stress – Concrete & Support plates
  - Embedded reinforcement (perfect bond, with reduced tip stiffness based on average anchorage length) – Reinforcing steel
  - Zero-thickness Line Interface – b/w support and concrete
- Constitutive models (properties from Exp, RTD 1016, *fib* MC 2010)
  - Total strain Rotating Crack Model – Concrete
  - Linear Elastic – Steel Support plates
  - Von Mises Plasticity with Isotropic Hardening - Reinforcing steel
  - No-Tension & Low-friction interfaces - b/w support/loading plate and concrete





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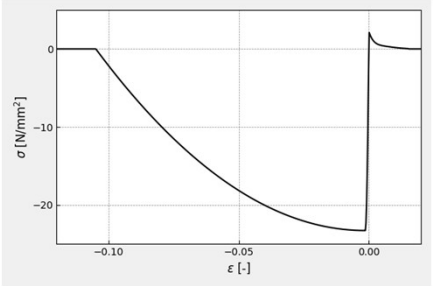

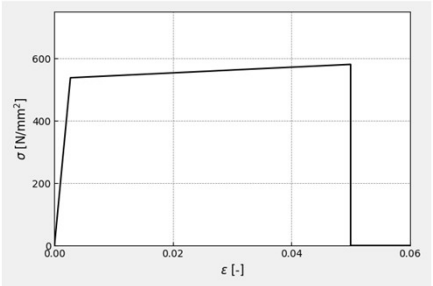

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NLFEA – Results

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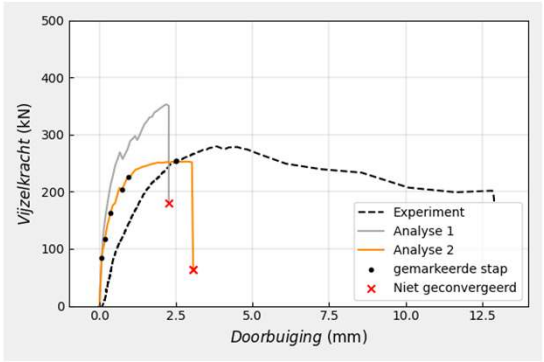
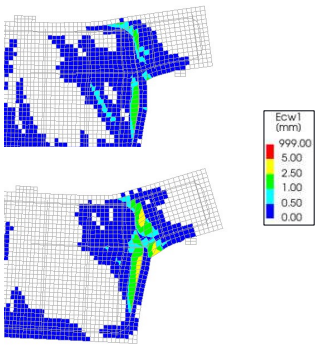
Kleinman results

- Reference: Initial modelling approach
- Variation: Perfect bond conditions with design anchorage length (reduced tip stiffness)



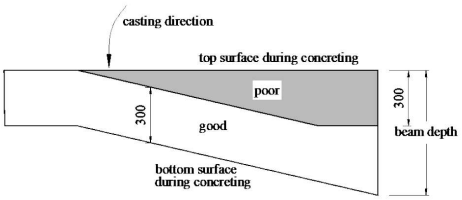


Crack plots at peak load

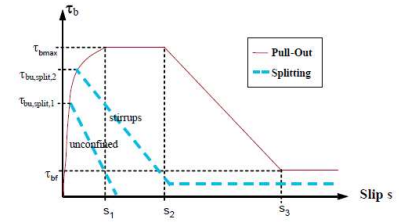
Conclusion: Incorrect failure mechanism

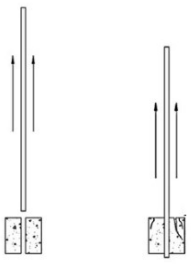
Bond-slip modelling

- Bond-Slip Relations – *fib* Model Code 2010
- To start: Use of global bond-slip relations
- Table of the *fib* ModelCode is for a very specific case!



Definition of good and poor bond conditions



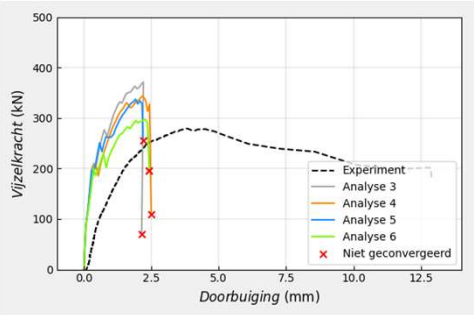


	1	2	3	4	5	6
	Pull-Out (PO)		Splitting (SP)			
	$\varepsilon_s < \varepsilon_{s,y}$		$\varepsilon_s < \varepsilon_{s,y}$			
	Good bond cond.	All other bond cond.	Good bond cond.		All other bond cond.	
			unconfined	stirrups	unconfined	stirrups
τ_{bmax}	$2.5\sqrt{f_{cm}}$	$1.25\sqrt{f_{cm}}$	$7.0\left(\frac{f_{cm}}{25}\right)^{0.25}$	$8.0\left(\frac{f_{cm}}{25}\right)^{0.25}$	$5.0\left(\frac{f_{cm}}{25}\right)^{0.25}$	$5.5\left(\frac{f_{cm}}{25}\right)^{0.25}$
s_1	1.0 mm	1.8 mm	$s(\tau_{bmax})$	$s(\tau_{bmax})$	$s(\tau_{bmax})$	$s(\tau_{bmax})$
s_2	2.0 mm	3.6 mm	s_1	s_1	s_1	s_1
s_3	c_{clear} [1]	c_{clear} [1]	$1.2s_1$	$0.5c_{clear}$ [1]	$1.2s_1$	$0.5c_{clear}$ [1]
α	0.4	0.4	0.4	0.4	0.4	0.4
τ_{bf}	$0.40\,\tau_{bmax}$	$0.40\,\tau_{bmax}$	0	$0.4\,\tau_{bmax}$	0	$0.4\,\tau_{bmax}$

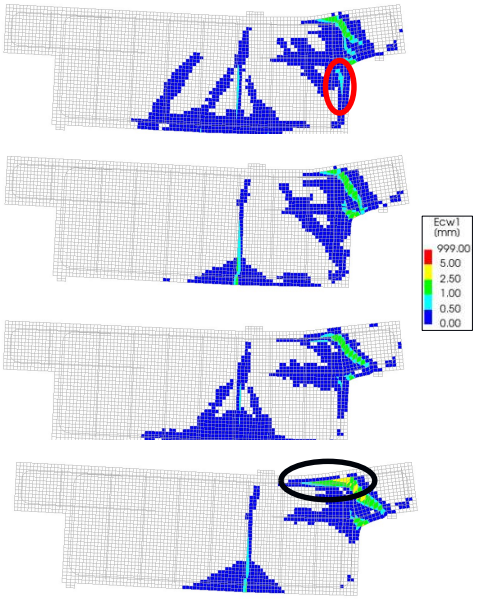
1) c_{clear} is the clear distance between ribs

Kleinman results

- 4 Variations: Global Pull-Out & Splitting failures (*fib* MC 2010) for all reinforcements **except stirrups and including stirrups**



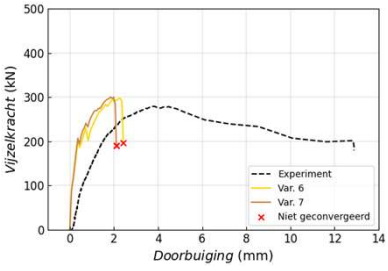
Conclusion: Bond-slip relations are required for a better prediction

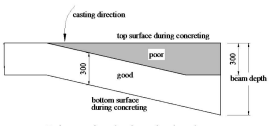


Crack plots at peak load

Kleinman results

Variation : Location-based unique bond-slip relations (*fib* MC 2010) as against a global bond-slip relation





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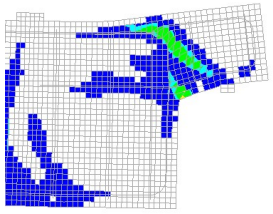
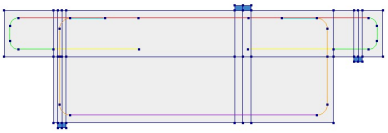
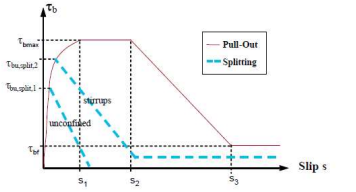


Crack plot at peak load





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s_3	c_{clear} [1)]	c_{clear} [1)]	$1.2s_1$	$0.5c_{clear}$ [1)]	$1.2s_1$	$0.5c_{clear}$ [1)]
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τ_{bf}	$0.40\,\tau_{bmax}$	$0.40\,\tau_{bmax}$	0	$0.4\,\tau_{bmax}$	0	$0.4\,\tau_{bmax}$

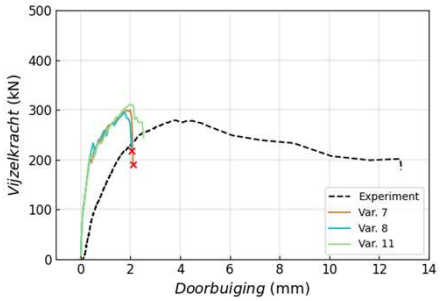
1) c_{clear} is the clear distance between ribs

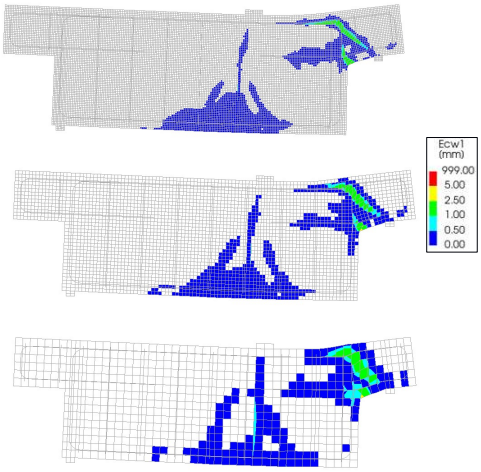
Conclusion: Local Bond-slip relations similar to global splitting-type bond-slip variation; but has better physiological motivation !

Kleinman results

- Mesh sensitivity:

  10mm, 20mm (reference with location based bond-slip)
  and 40mm (maximum element size RTD1016 recommendation)





Crack plots at peak load

Take away: Similar crack patterns but peak force varies slightly.
Good to investigate with RTD 1016's max. element size and later the sensitivity.

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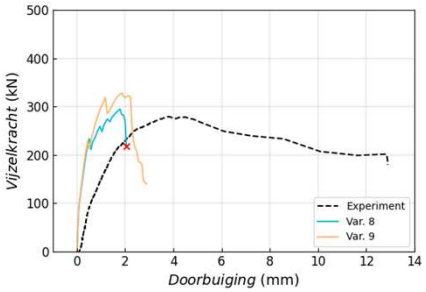
Kleinman results

- Bond-slip reinforcement: Truss (#8) or Beam (#9) formulation ?



Take away:– Choice between Truss/beam formulation of bond-slip to be given attention ! Sensitive to normal stiffness of the interface – produces locking effect (crossing bars and additional rotational DOF).

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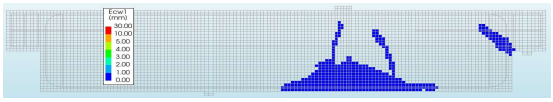
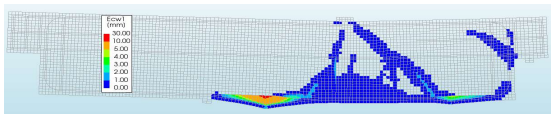
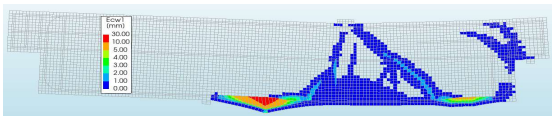
Steinle results

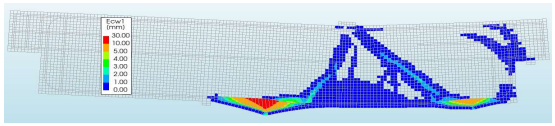


Modelling strategy: Modelling approach with local bond-slip relations (as observed in Kleinman's case) !!

- Crack propagation with increasing load
  - Start: Flexural cracks in main-span & cracking along re-entrant corner
  - Delamination of concrete around reinforcement
  - Flexural-shear cracks in the main-span







Conclusion: Incorrect Failure mechanism !

Steinle - Variations

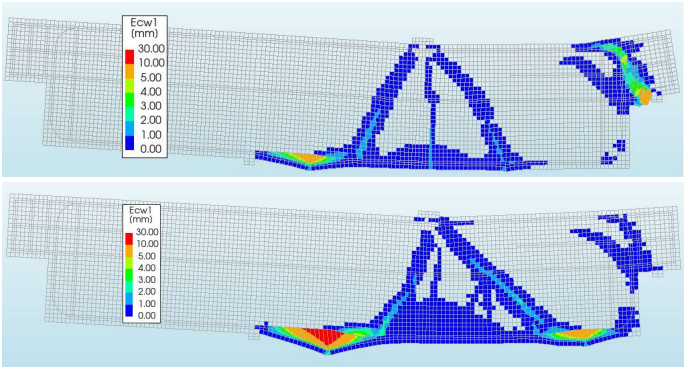
- To account for lack of proper documentation on supports
  - Different sized support plates
  - Different material model for support-concrete interface – Linear, No Tension and Coulomb-Friction
- Increase Yield Strength (Based on other tests : value of the actual mean yield strength can be 1,15 – 1,3 times the required value of the codes)
- Additional transverse pressure in the dapped-end and/or anchorage stiffness

All variations yield the same delamination cracks

Except a new alternative one which departs from the concluded modelling approach from Kleinman!

Steinle - Variations

- Global Pull-out bond slip (poor conditions 22mm dia): Shear failure of the dapped end. Left top figure
- Misleading ? – Loss of Anchorage ? Right figure
- Anchorage stiffness – Incorrect failure mechanism as before. Left bottom figure



Conclusions and Outlook

Conclusions

- Modelling strategy derived from Kleinman's benckmark:
  - Total-strain based rotating cracking model for concrete & Vonmises plasticity for Steel reinforcements.
  - Bond-slip reinforcements (truss)
  - MC 2010 provisions for location-based bond-slip relations

- Same strategy leads to different failure mechanism in Steinle's benchmark NLFEA
  - Possibly competing failure mechanisms (flexural-delamination cracks and shear failure along dapped end)
  - Force-Controlled experiment being simulated in displacement control (jump over mechanisms ?)
  - Steinle's case has no stirrups in the span – Maybe Fixed crack model (as suggested by recent studies ?)
  - Uncertainty in rebar material property and direct load transfer via diagonal strut (different gedrongenheid)

- Both studies reiterate the need for a robust modelling strategy towards NLFEA of incorrectly detailed dapped end beams
  - Need for more representative, well documented, benchmarks – Experiments?

Outlook

Within the V&R program to address reassessment of concrete structures with dapped-end beams:

- ➢ Preparations for representative experiments.
- ➢ Case study research based on an actual bridge, including a comparison of 2D and 3D NLFEA.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TNO innovation for life
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