The Assessment of Crushing Behaviour in Over-Reinforced Concrete Elements

A comparison between linear and nonlinear modelling

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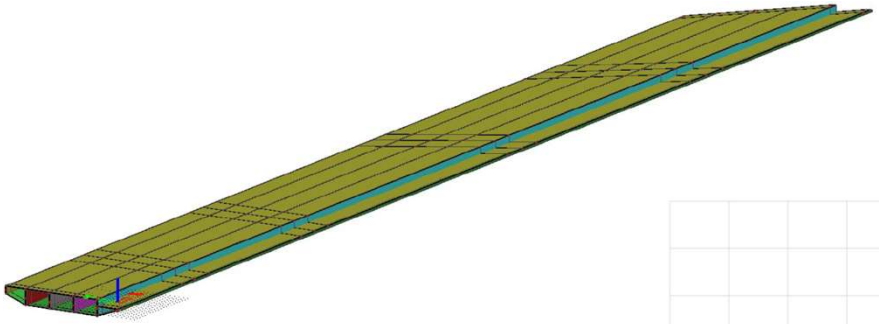
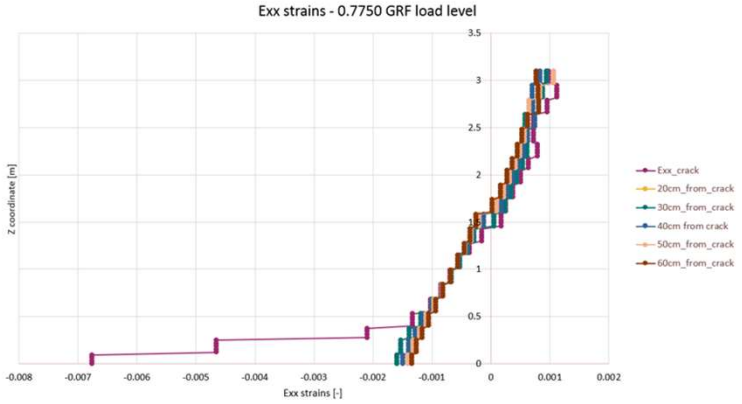
Outline of presentation

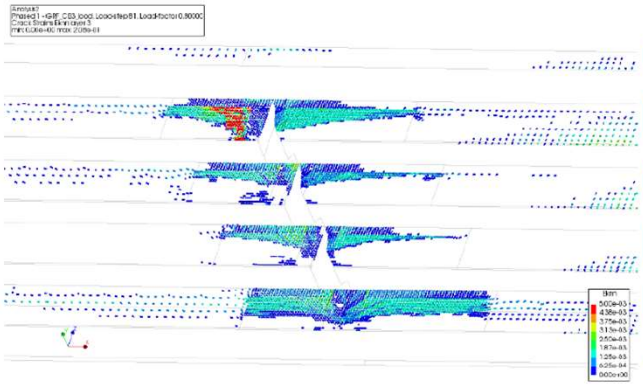
- Introduction
- Methodology
- Models
- Results
- Conclusion and recommendations

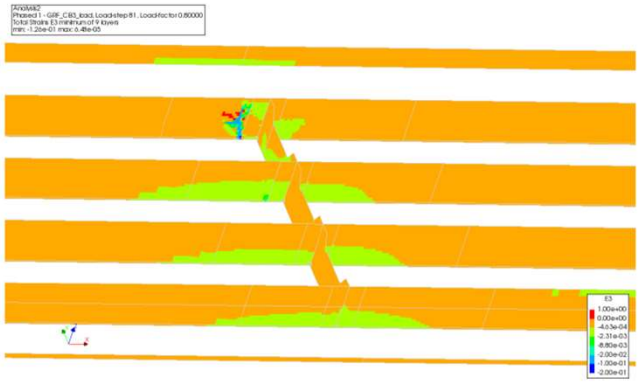
Introduction

- Rozenoord bridge
- Bending moment capacity
- Euler-Bernoulli beam theory





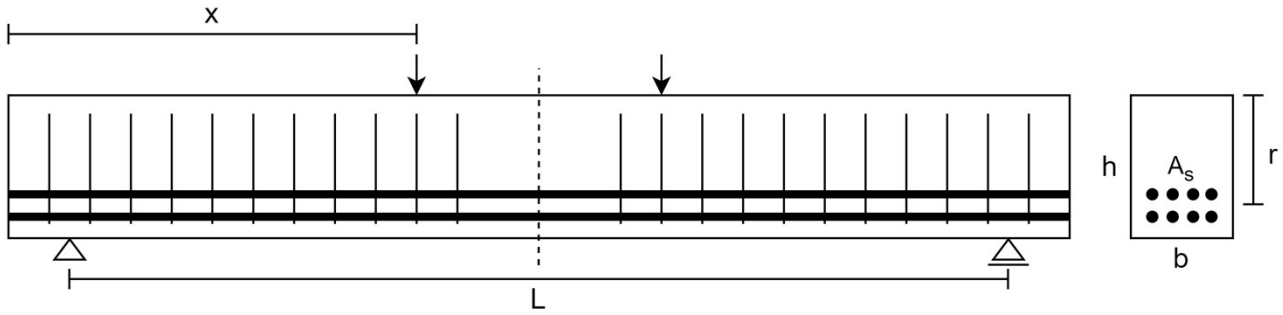




“How does the linear Eurocode cross-sectional check compare to the numerical nonlinear check performed in the GRF safety format in over-reinforced concrete beams?”

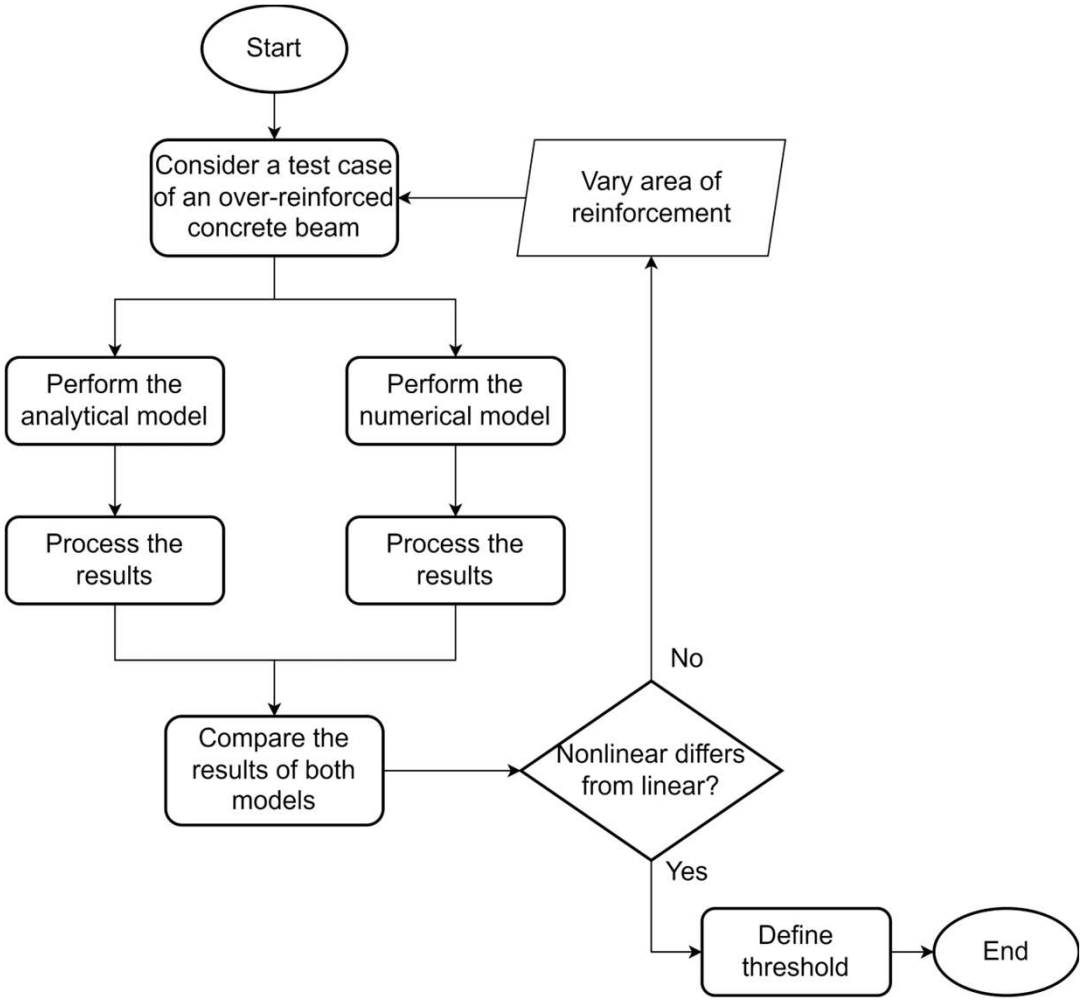
Scope of study

- Bending moment capacity
- Simple test cases
- Reinforcement ratios
- Bonded reinforcement



Methodology

- Flowchart
- Analytical model by Python
- Numerical model by DIANA FEA



Safety format

- Partial Safety Factors (PSF)
- Global Resistance Factor (GRF)

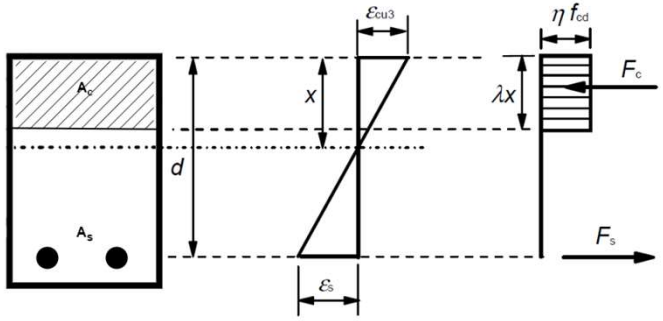
	Steel governing		Concrete governing	
	Steel	Concrete	Steel	Concrete
Mean strength factor	1.1	0.85	1.52	1.17
Partial safety factor (γ_s, γ_c)	1.15	1.5	1.15	1.5
Global resistance factor (γ_0)	1.27	1.27	1.75	1.75

$$\frac{f_{cm}}{f_{ck}} = \frac{56}{48} = 1.17$$

$$\gamma_0 = 1.17 * 1.5 = 1.75 \quad \Rightarrow \quad \frac{\gamma_0}{1.15} = \frac{1.75}{1.15} = 1.52$$

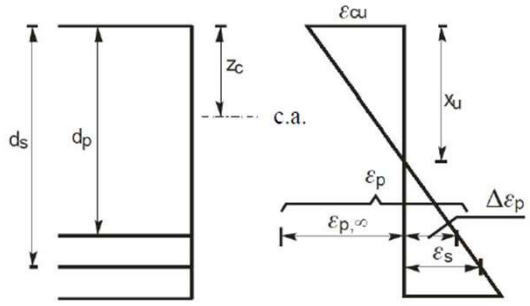
Analytical model

- Constructed using Python
- Max. strain is 3.5‰
- Horizontal equilibrium
- Rotational capacity
- Strain with linear theory



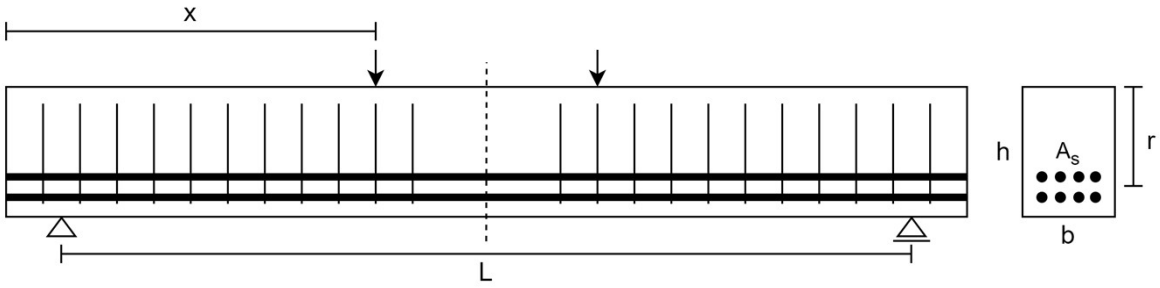
$$\frac{x_u}{d_{eff}} = \frac{\varepsilon_{cu} * 10^6}{\varepsilon_{cu} * 10^6 + 7f}$$

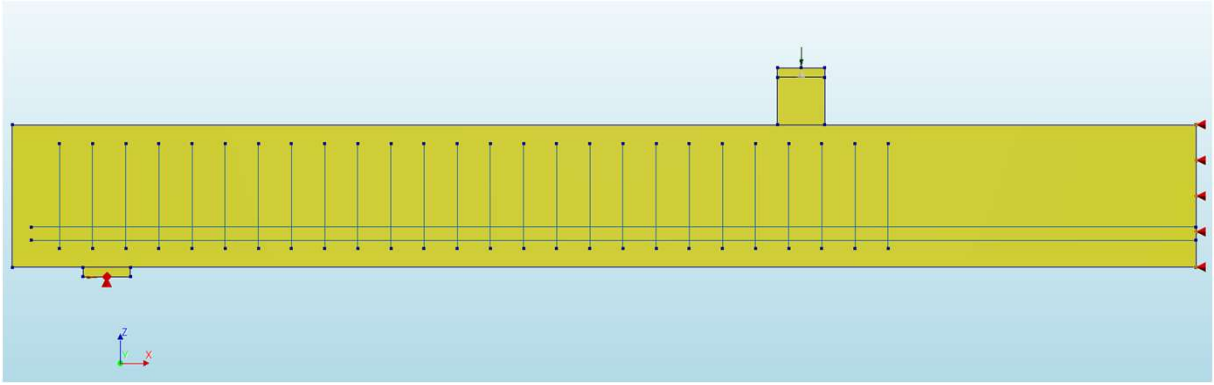
$$f = \frac{(\frac{f_{pk}}{\gamma_s} - \sigma_{pm\infty})A_p + f_{yd}A_s}{A_p + A_s}$$



Numerical model

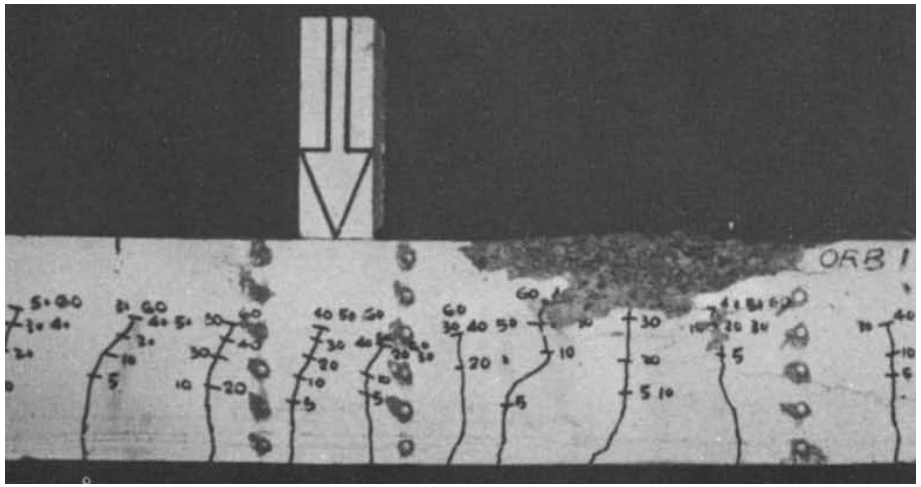
- Constructed using DIANA FEA
- Symmetry
- Curved shell elements
- Displacement controlled analysis
- Benchmark

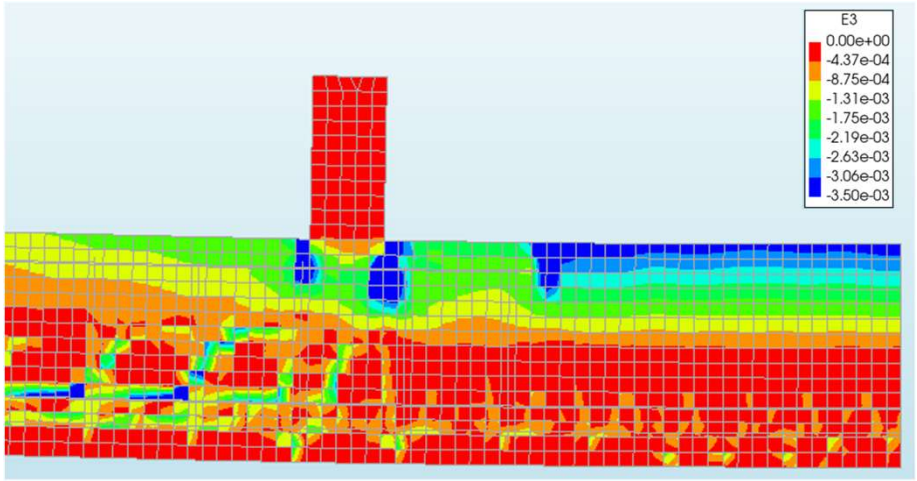




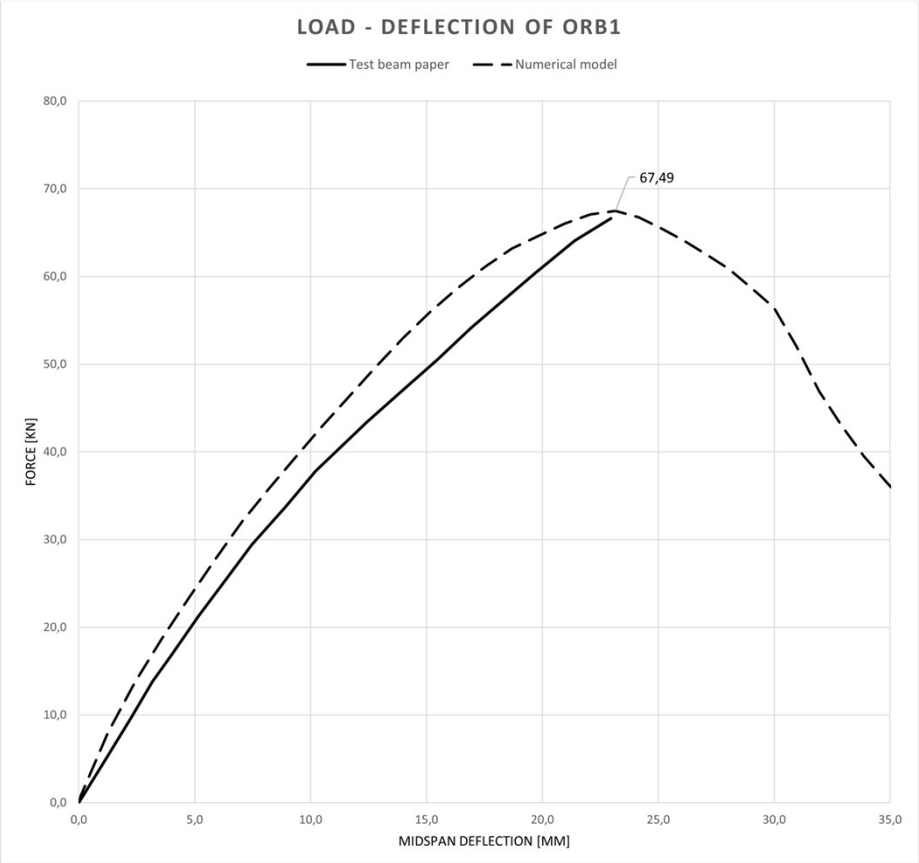
Benchmark

- Four-point bending test (Jones et al., 1982)
- Tensile and compressive fracture energy

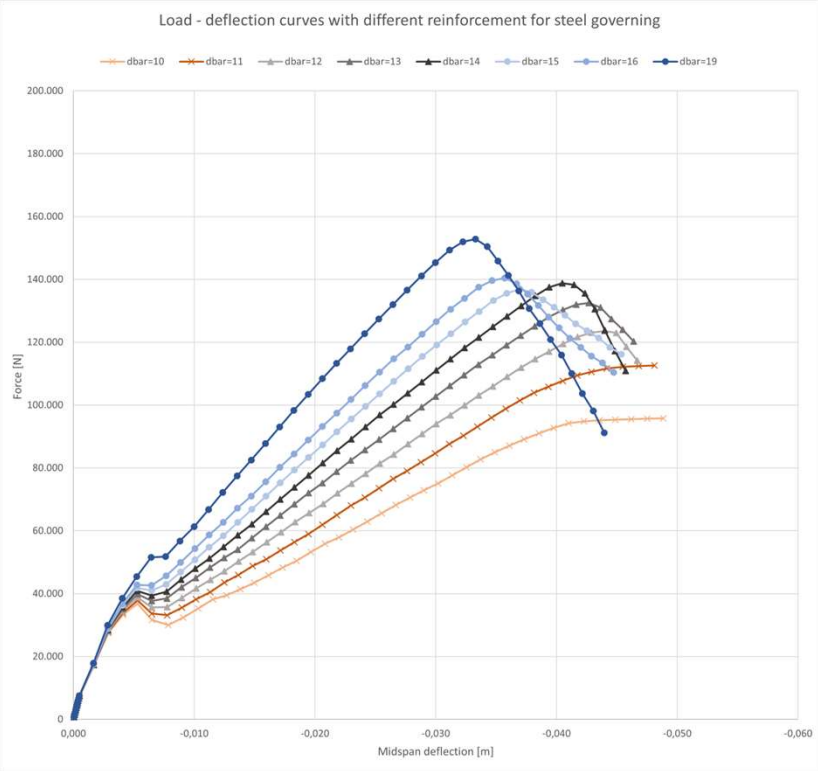


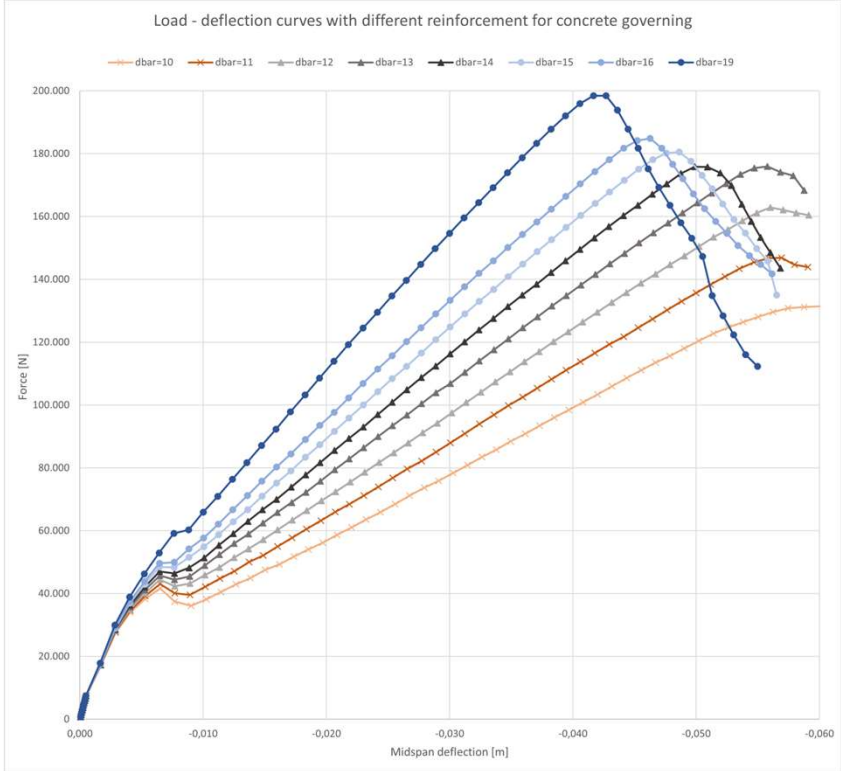


Benchmark



Results


Load - deflection curves with different reinforcement for steel governing
dbar=10
dbar=11
dbar=12
dbar=13
dbar=14
dbar=15
dbar=16
dbar=19
200.000
180.000
160.000
140.000
120.000
100.000
80.000
60.000
40.000
20.000
0
Force [N]
0,000
-0,010
-0,020
-0,030
-0,040
-0,050
-0,060
Midspan deflection [m]


Load - deflection curves with different reinforcement for concrete governing
dbar=10
dbar=11
dbar=12
dbar=13
dbar=14
dbar=15
dbar=16
dbar=19
200.000
180.000
160.000
140.000
120.000
100.000
80.000
60.000
40.000
20.000
0
Force [N]
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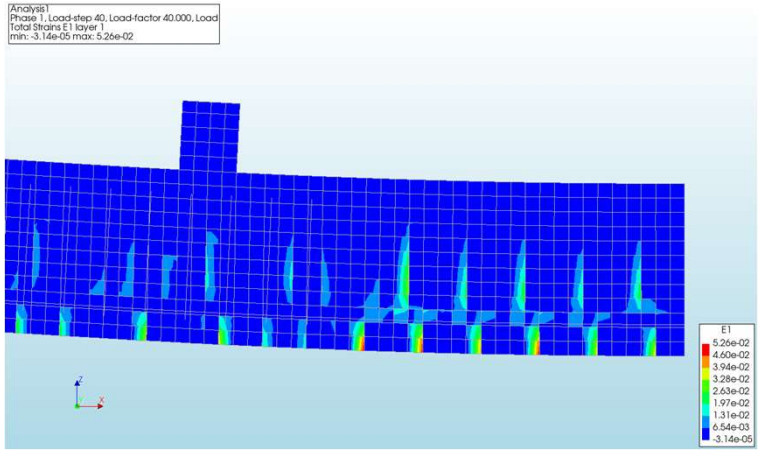
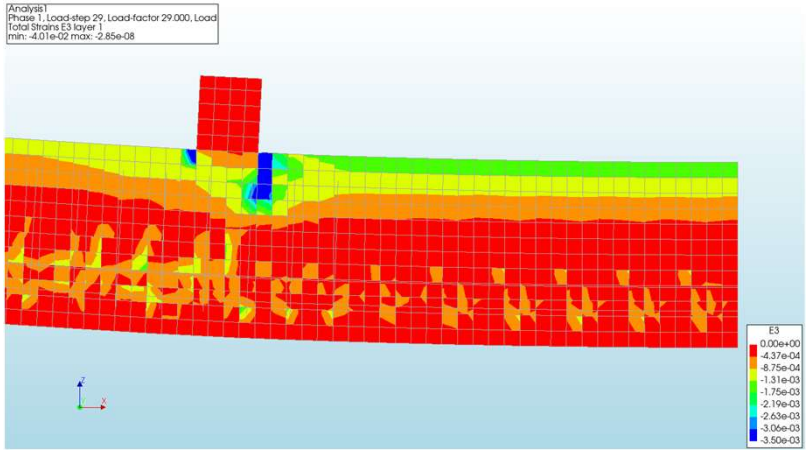
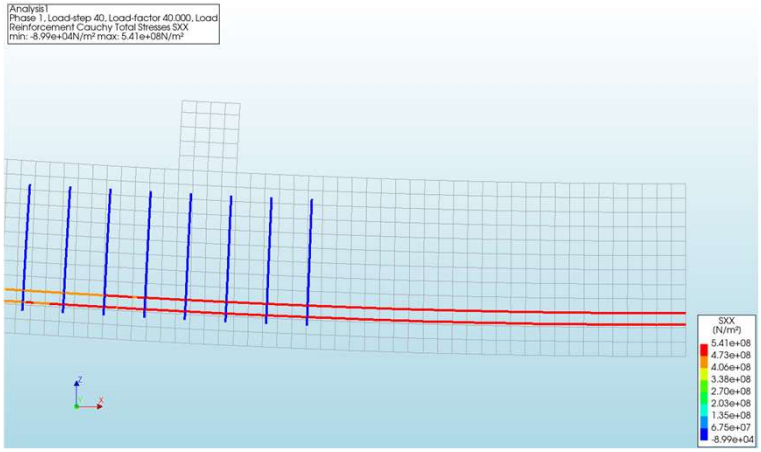
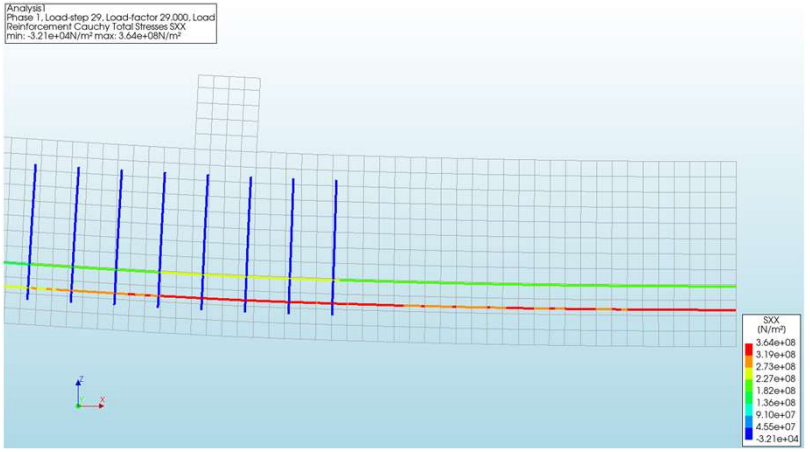
Midspan deflection [m]

Results

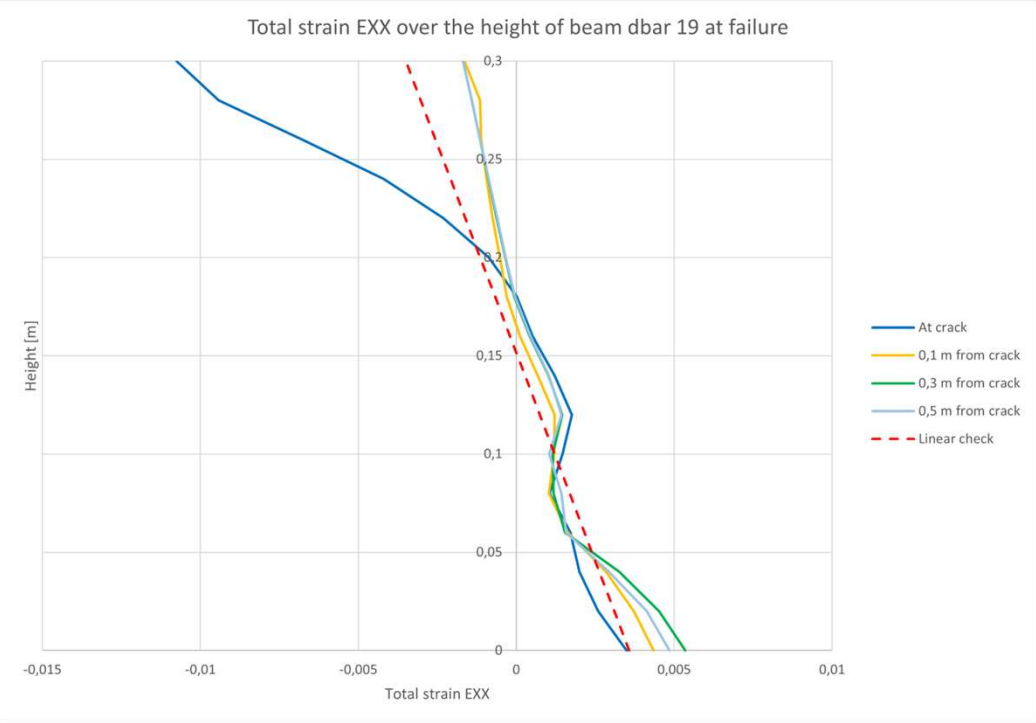

Analysis1
Phase 1, Load-step 40, Load-factor 40.000, Load
Total Strains E1 layer 1
min: -3.14e-05 max: 5.26e-02
E1
5.26e-02
4.60e-02
3.94e-02
3.28e-02
2.63e-02
1.97e-02
1.31e-02
6.54e-03
-3.14e-05

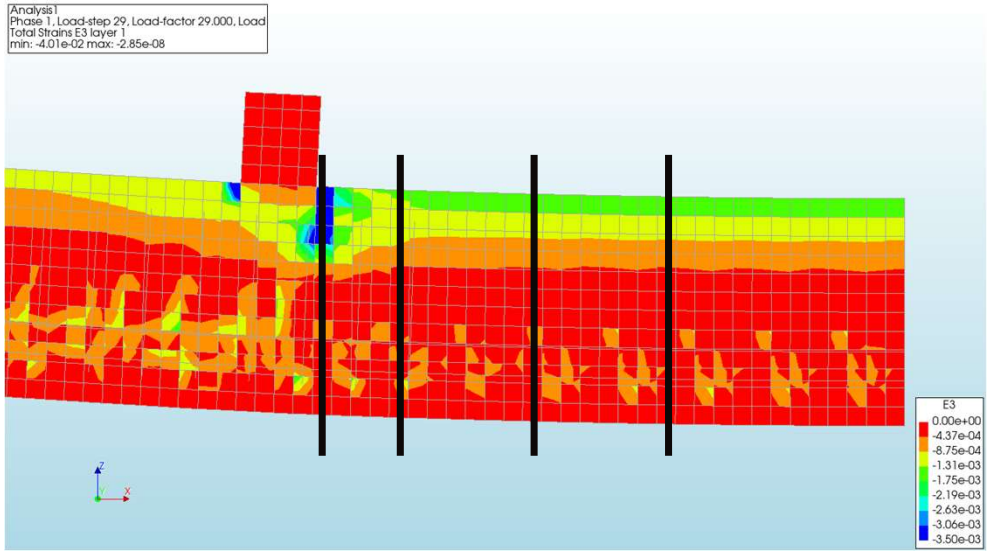

Analysis1
Phase 1, Load-step 29, Load-factor 29.000, Load
Total Strains E3 layer 1
min: -4.01e-02 max: -2.85e-08
E3
0.00e+00
-4.37e-04
-8.75e-04
-1.31e-03
-1.75e-03
-2.19e-03
-2.63e-03
-3.06e-03
-3.50e-03


Analysis1
Phase 1, Load-step 40, Load-factor 40.000, Load
Reinforcement Cauchy Total Stresses SXX
min: -8.99e+04N/m² max: 5.41e+08N/m²
SXX
(N/m²)
5.41e+08
4.73e+08
4.06e+08
3.38e+08
2.70e+08
2.03e+08
1.35e+08
6.75e+07
-8.99e+04


Analysis1
Phase 1, Load-step 29, Load-factor 29.000, Load
Reinforcement Cauchy Total Stresses SXX
min: -3.21e+04N/m² max: 3.64e+08N/m²
SXX
(N/m²)
3.64e+08
3.19e+08
2.73e+08
2.27e+08
1.82e+08
1.36e+08
9.10e+07
4.55e+07
-3.21e+04

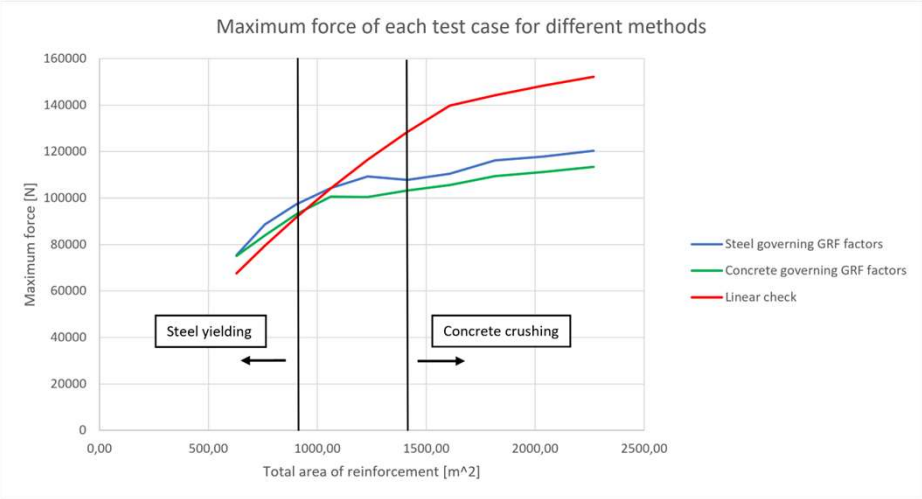
Results


Total strain EXX over the height of beam dbar 19 at failure
Height [m]
0,3
0,25
0,2
0,15
0,1
0,05
0
-0,015
-0,01
-0,005
0
0,005
0,01
Total strain EXX
At crack
0,1 m from crack
0,3 m from crack
0,5 m from crack
Linear check


Analysis 1
Phase 1, Load-step 29, Load-factor 29.000, Load
Total Strains E3 layer 1
min: -4.01e-02 max: -2.85e-08
E3
0.00e+00
-4.37e-04
-8.75e-04
-1.31e-03
-1.75e-03
-2.19e-03
-2.63e-03
-3.06e-03
-3.50e-03

Results

		Linear		Nonlinear steel			Nonlinear concrete		
dbar	A_s / A_c	F [kN]	Failure	F [kN]	UC	Failure	F [kN]	UC	Failure
10	0.010	67.51	Steel	75.41	1.12	Steel	75.12	1.11	Steel
11	0.013	79.48	Steel	88.65	1.12	Steel	83.91	1.06	Steel
12	0.015	91.77	Steel	97.31	1.06	Edge	93.07	1.01	Edge
13	0.018	104.18	Steel	104.33	1.00	Edge	100.52	0.96	Edge
14	0.021	116.48	Steel	109.30	0.94	Edge	100.49	0.86	Concrete
15	0.024	128.45	Steel	107.78	0.84	Concrete	103.17	0.80	Concrete
16	0.027	139.82	Steel	110.52	0.79	Concrete	105.62	0.76	Concrete
17	0.030	144.22	Steel	116.14	0.81	Concrete	109.38	0.76	Concrete
18	0.034	148.28	Concrete	117.82	0.79	Concrete	111.23	0.75	Concrete
19	0.038	152.22	Concrete	120.30	0.79	Concrete	113.41	0.75	Concrete



Conclusion and recommendations

- Linear check not conservative
- GRF method affect outcome

Important factors of future research:

- Different material properties
- Dimensions
- Shape of cross-section
- Convergence criterion

Sensitivity study