Amsterdamsebrug

Fully nonlinear reassessment analysis – lessons learned

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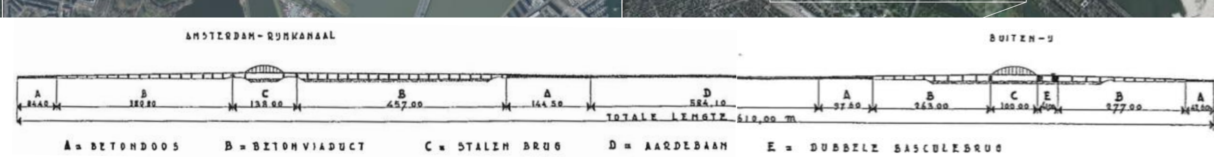

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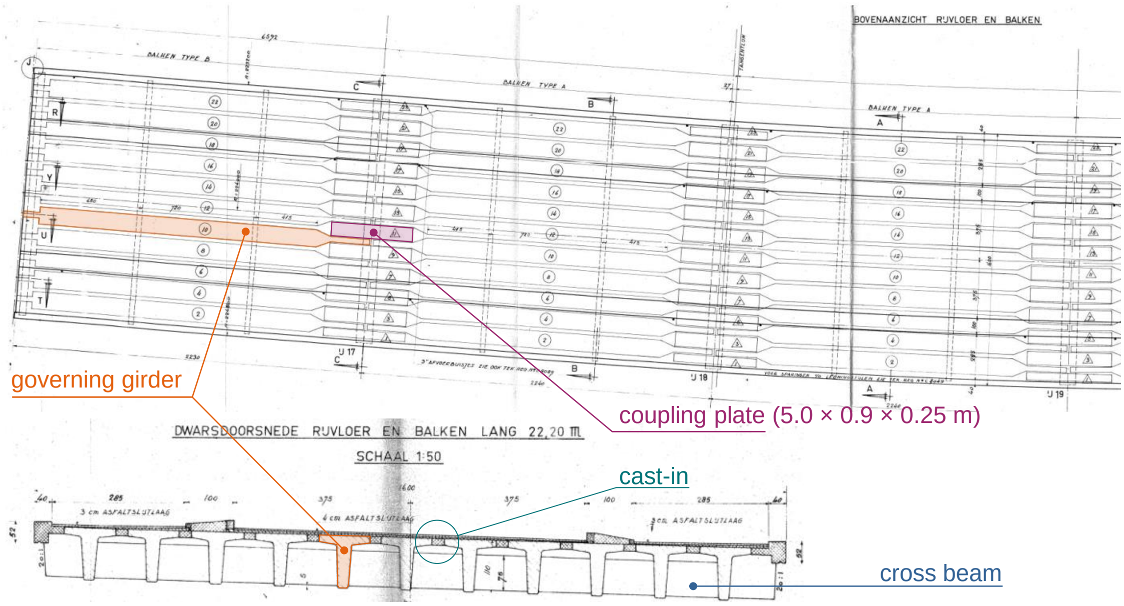

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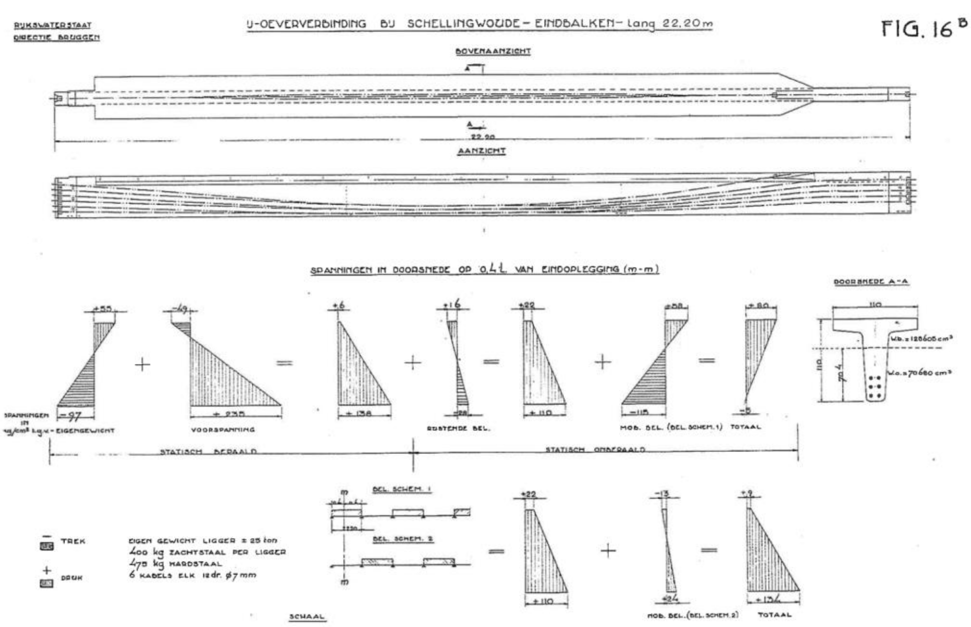

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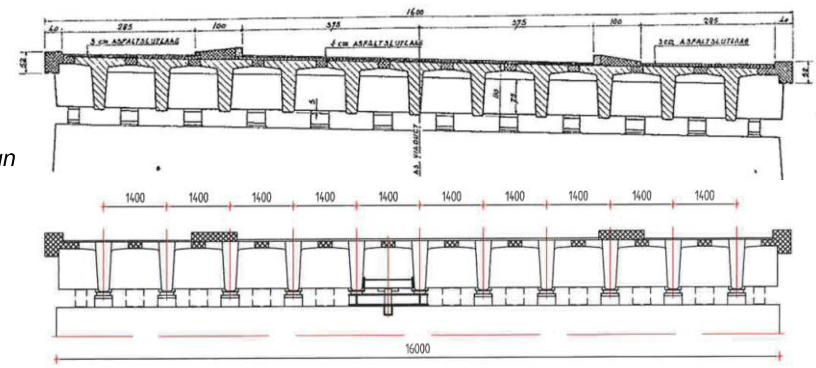
Renovation (2014)

Exchange of bearings

- Original bridge: steel bearings (fixed and sliding) under cross beams in-between girders
- Renovation: elastomeric bearings under girders

original design



renovation

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approach

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problem statement

Quick scan: UC shear 1.85

Governing girder: 5th girder in end span, close to intermediate support

Failure mechanism: shear tension

Perform NL Analysis to explore the margins for governing load position

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modelling approach

Combination of solid elements and shells:

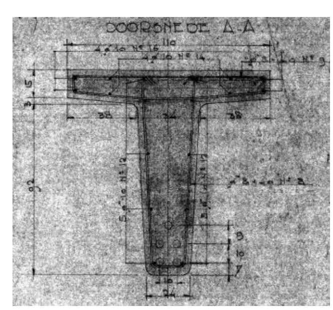
- 3D: governing girder and associated parts of deck, cross beam and coupling plate
- 2.5D: all other parts

Accurate modelling of prestress tendons

- Enables good prediction of working prestress including creep and shrinkage
- Enables accurate contribution of inclined prestress to shear capacity

Reinforcement as grids

- Economic modelling
- Sensitivity analysis: account for eventual poor detailing of shear reinforcement



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analysis set up

Staged analysis with creep and shrinkage under service loads…

- Construction stages: isolated isostatic girders → continuous multi span bridge, exchange of supports
- Creep and shrinkage analysis

… followed by

- Incrementing loads up to failure

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model description

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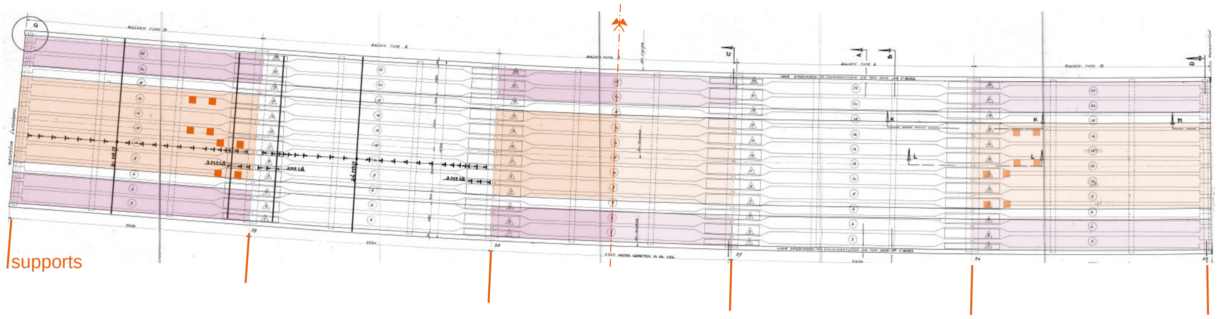
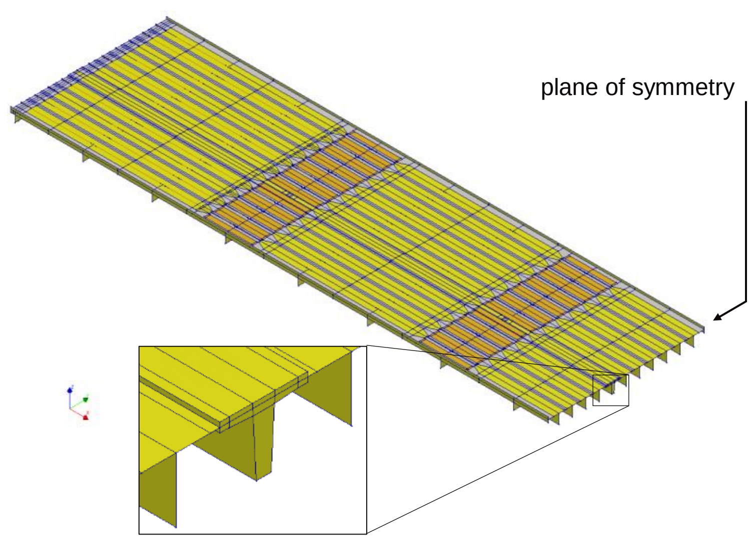
Reduce model to essential scheme



ignore horizontal curvature
assume symmetry + checkerboard loading
requirements: model at least 3 spans and assume fully clamped support at model end
preliminary analysis: clamped edge (symmetry plane) at 2.5 better solution

Geometry



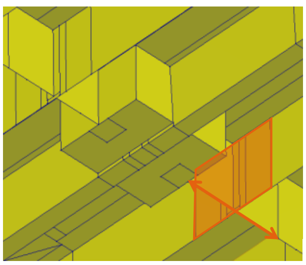
Connection girder – primary cross beam

challenge: matching the stiffness of shell girders and solid girders

different behavior

- solid girders ‘run into’ cross beams: less curvature within cross beam
- shell girders run up to centerline of cross beam: more flexibility

solution: increase shell girder width within cross beam



zone ‘within’ cross beam: width = c.t.c. girders = 1.4 m

prestress

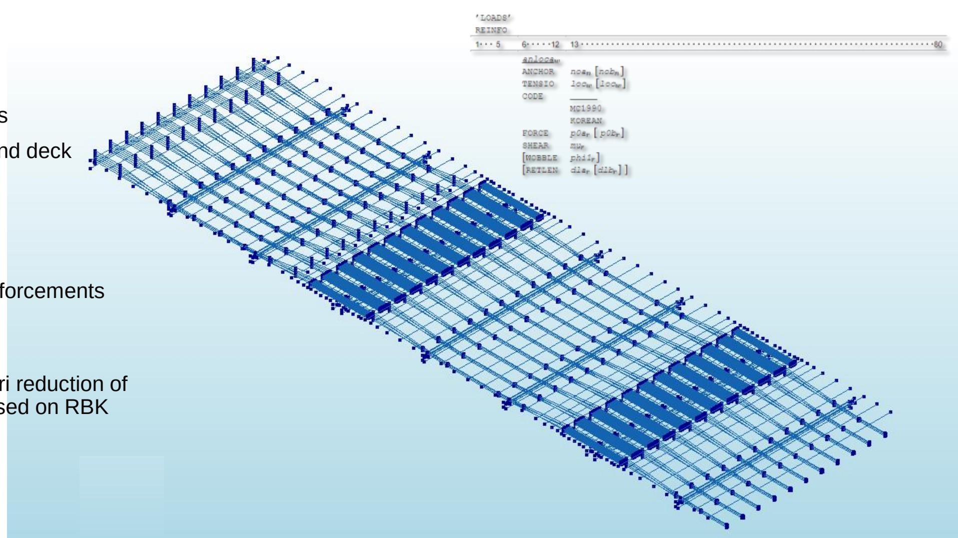
strands in girders

wires in coupling plates

bars in cross beams and deck

prestress application:

- post-tensioned reinforcements
- wedge set per prestress type
- relaxation as a-priori reduction of initial prestress, based on RBK



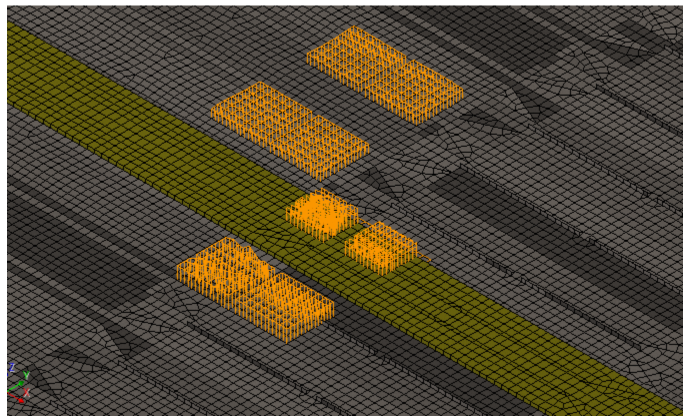
finite element mesh

average element size: 0.15 m

7 elements in girder height

element size limit according to softening: 0.22 m

FE mesh, solid elements in yellow, truck wheel loads indicated



connecting shells to solids

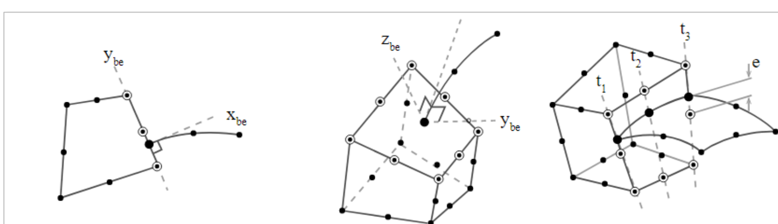
DOF's don't match

- shells: ux, uy, uz, φx, φy
- solids: ux, uy, uz

Coupling with automatic tyings

Strong feature, but handle with care

- prevents warping of the section
- impossible to connect T-shaped sections



(a) beam to plane stress or infinite shell to plane strain or shell of revolution to solid ring

(b) beam to solid

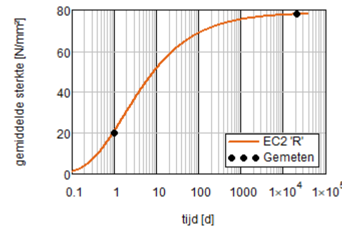
(c) shell to solid

material behavior

Concrete
- Total Strain Rotating Crack model
- Tension: exponential softening
- Compression: parabolic softening with reduction due to lateral tension
- Creep: Kelvin chain based on Model Code 2010 creep function for initial strength
- Shrinkage: strain development based on Model Code 2010

Steel (prestressing and reinforcement)
- Von Mises plasticity with stress drop at rupture
- Horizontal yield branch for reinforcement
- Inclined yield branch for prestressing

All material properties based on GRF safety format



strength development

safety format: Global Resistance Factor (GRF)

Basic idea
- Calculate ‘mean’ failure load based on ‘mean’ values for material properties
- Divide ‘mean’ failure load by global resistance factor to find design failure load

For reinforced/prestressed concrete: account for difference in material uncertainty
- global resistance factor based on steel uncertainty: 1.2 (γ_s) × 1.15 (model uncertainty for shear) = 1.38
- reduce concrete strength a-priori in order to avoid underestimation of uncertainty: GRF-mean $f_{cm.GRF}$ = 0.85 f_{ck}

Practical application
- Increment loads up to at least design load × global resistance factor

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large models, scattered damage and result reliability

convergence established based on norms for internal energy, displacements or out-of-balance forces **for the entire model**

scattered damage spoils the convergence norm, especially for energy
- e.g. large zones with bending cracks and a tiny zone with critical shear crack
- variation in internal energy in shear zone is not significant because of not so interesting ‘bending noise’

approaches
- use multiple convergence criteria
- be careful with results from non-converged steps, especially when convergence is not re-established
- always evaluate reliability based on mechanisms or violation of material laws

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analyses performed

linear static analysis
- model verification
- comparison with quick scan

creep and shrinkage analysis
- verification of assumed prestress relaxation
- effects of permanent loads and time

incrementing variable loads up to failure
- determine failure load
- determine failure mechanism

sensitivity analysis

results and interpretation

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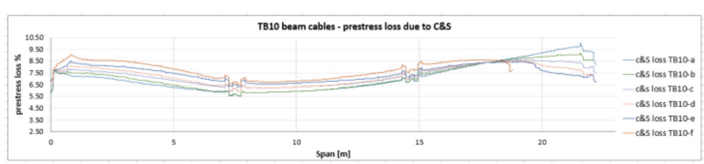
creep and shrinkage

losses differ per component (7.0-12.5%)

losses not uniform per component

component	average C&S loss [%]
girder 5	7.5
coupling plates	7.0
end cross beam	12.5
primary cross beam	12.5
secondary cross beam	10.5

average prestress loss due to C&S per component



prestress loss due to C&S per cable along length

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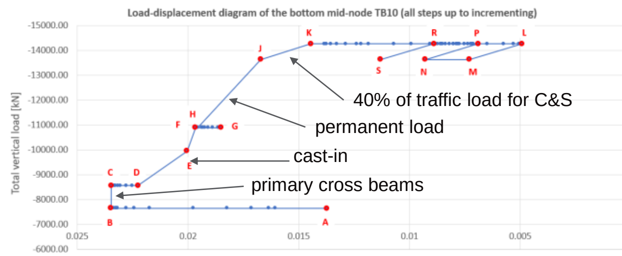
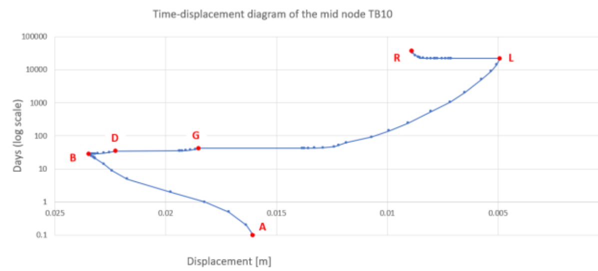
creep and shrinkage

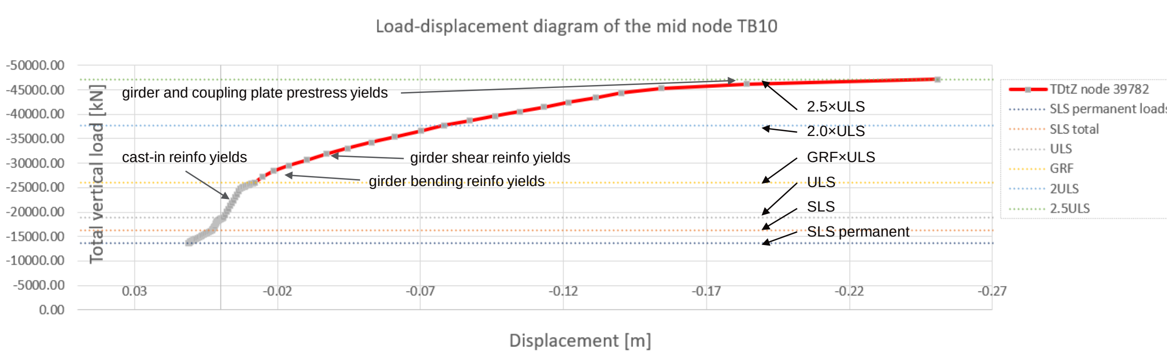
load-displacement (top) or time-displacement (bottom)?

creep and shrinkage with 40% of variable load (EC2)?





incrementing variable load: lotal load versus mid span deflection



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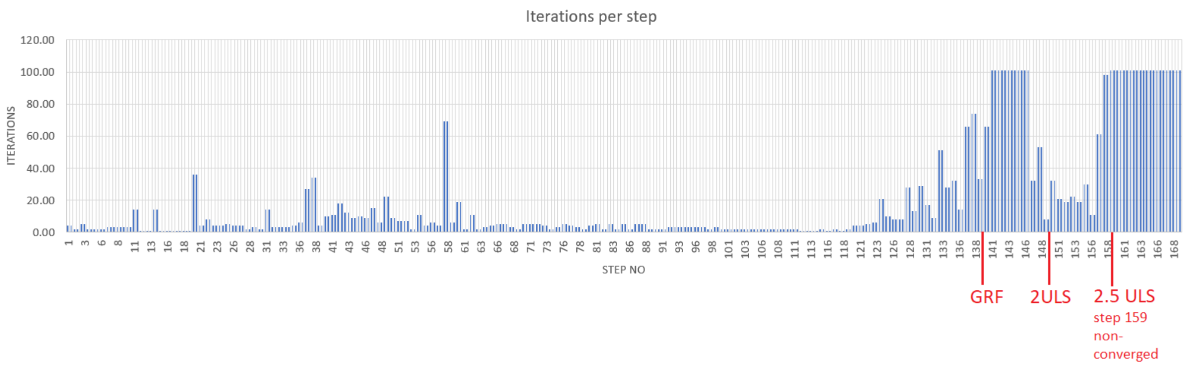
convergence behavior



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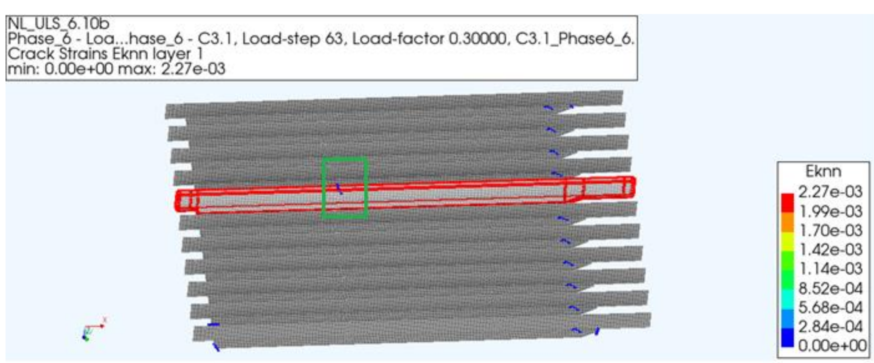
development cracking in girders

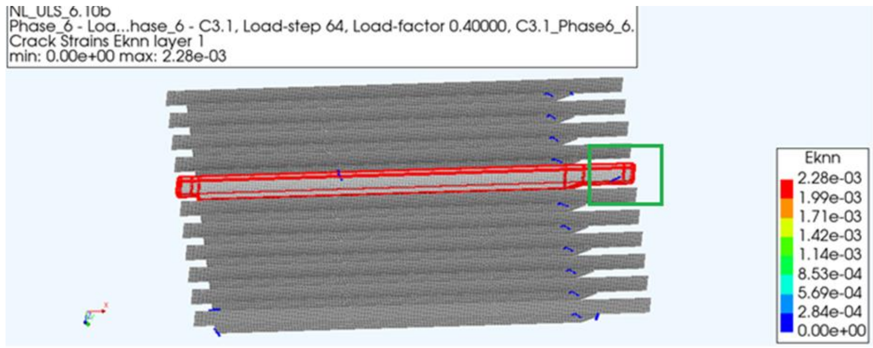
‘bending’ crack at intermediate cross beam location, shortly after ULS



girders 1st span, seen from below!

development cracking in girders: birth of shear crack

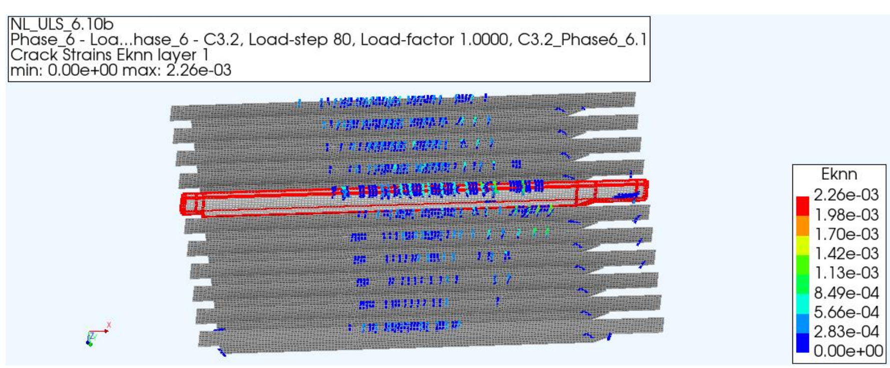
first shear crack in governing girder, shortly after first ‘bending’ crack



girders 1st span, seen from below!

development cracking in girders

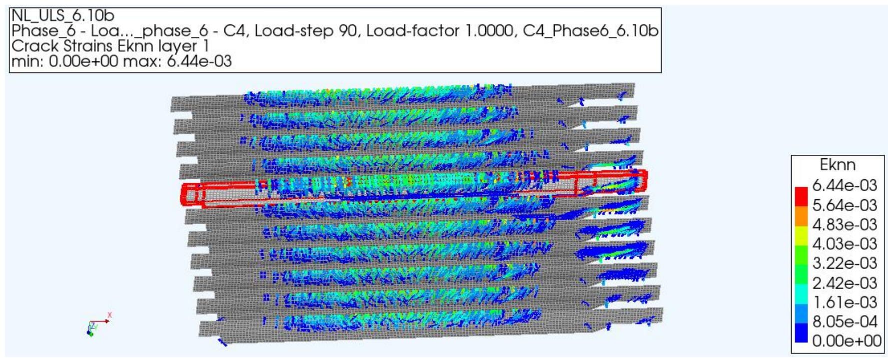
crack pattern at GRF×ULS load level



girders 1st span, seen from below!

development cracking in girders

crack pattern at 2.0×ULS load level: shear crack develops



girders 1st span, seen from below!

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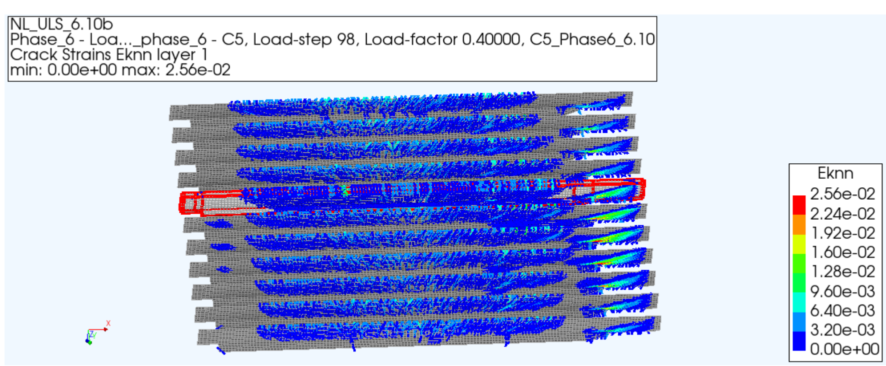
development cracking in girders

crack pattern at 2.4×ULS load level: shear crack dominates crack strain plot



girders 1st span, seen from below!

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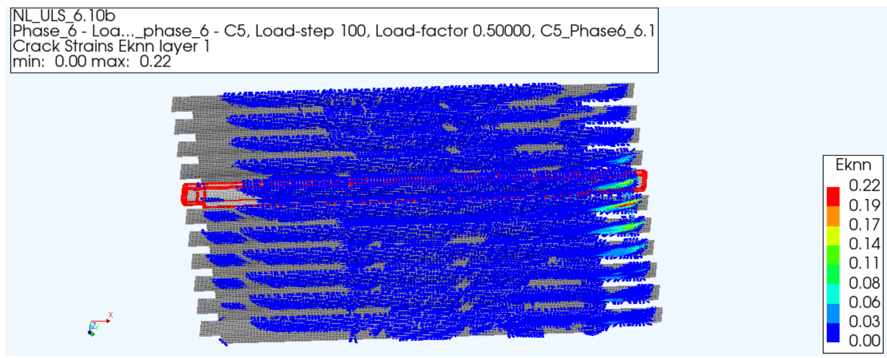
development cracking in girders

crack pattern at 2.5×ULS load level: crack strains ‘infinite’



girders 1st span, seen from below!

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crack development governing girder

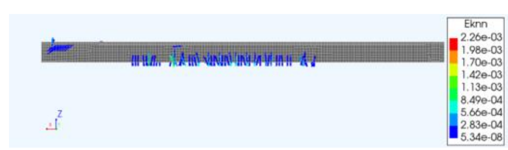
shear crack starts before bending cracks

bending cracks develop faster than shear crack up to 2.0 ULS

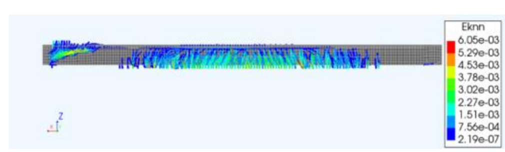
failure mechanism: shear

trigger: yielding of girder prestress

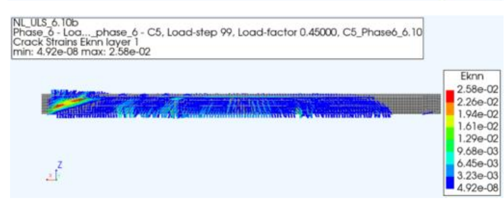
GRF×ULS



2.0×ULS



2.45×ULS



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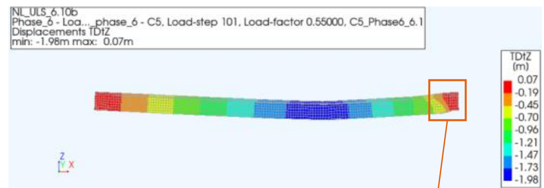
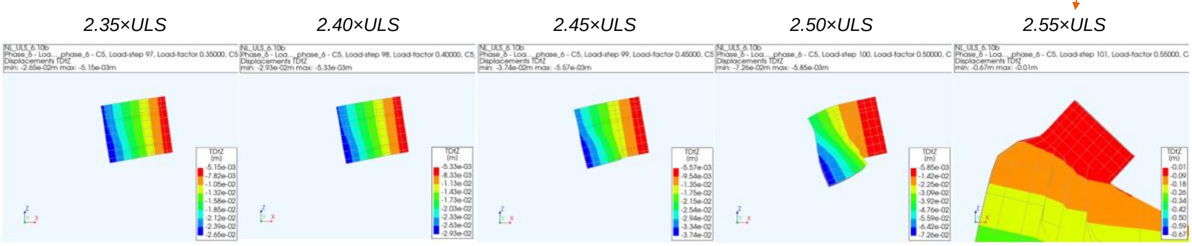
deformations shear zone

shear mechanism starts to develop at 2.45×ULS





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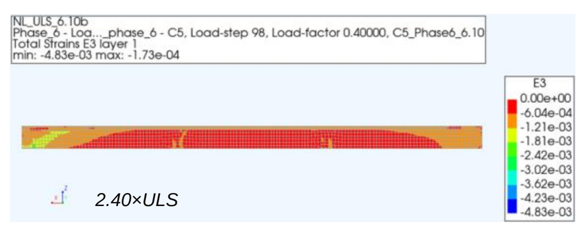
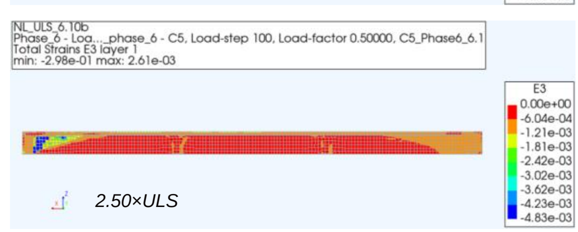
more to say about the mechanism

anatomy of a mechanism

- shear crack develops → shear reinfo and prestress take over
- shear reinfo yiels → prestress takes load increments
- prestress yields → strut takes over but no capacity left
- strut crushes → failure

is this still what we call shear tension failure? (guess: 'no')





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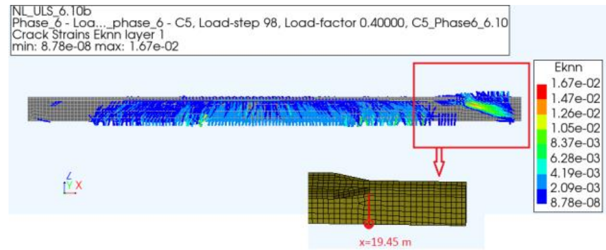
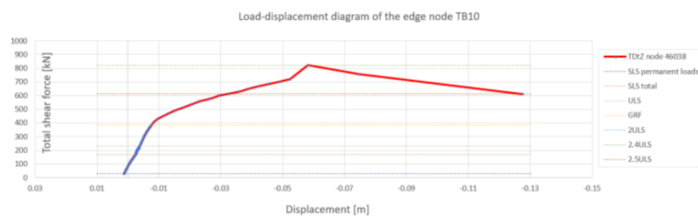
and even more to say

shear force vs shear displacement

shear force drops when shear displacement increases: neighbouring girders take over

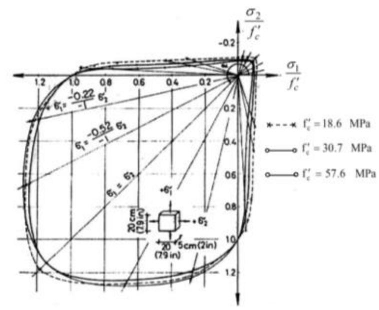




sensitivity analysis

what to vary?

1. simple creep and shrinkage analysis: apply the calculated losses a-priory
2. as 1, but with +50% losses
3. less prestress (-10%)
4. reduced tensile strength in shear zone
5. reduced tensile strength overall (-20%)
6. support settlement (2nd support, 10 mm)
7. precrack with bending focused traffic preload
8. combination of 3 and 5
9. more waiting time before activation of cast-ins (1 year)
10. reduced effectivity shear reinforcement (-75%)



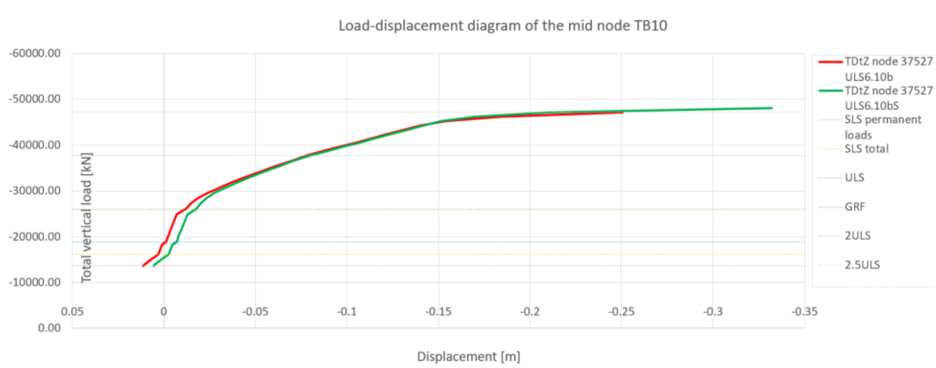
simple creep and shear: does it matter?

not really

displacement at start

same failure load

comparable deformation



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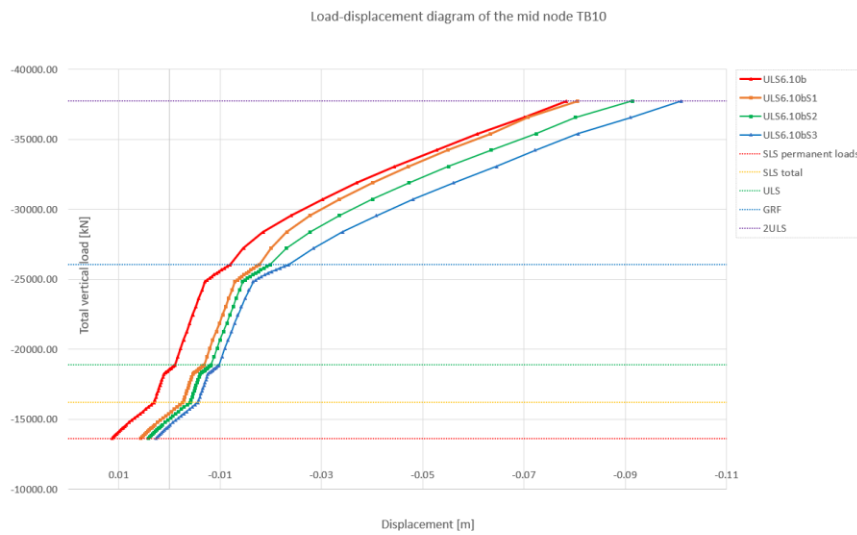
variants 1-3

different start situation depending on creep/shrinkage and prestress

curves more or less parallell



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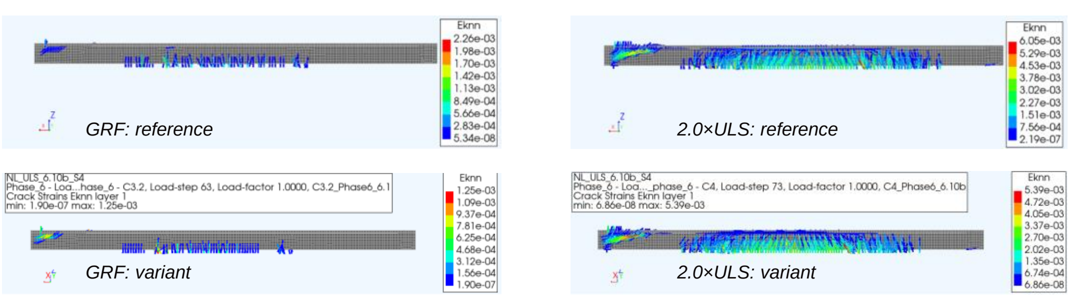
variant 4: reduced tensile strength in shear zone

shear crack developes faster, but same behavior at 2.0×ULS



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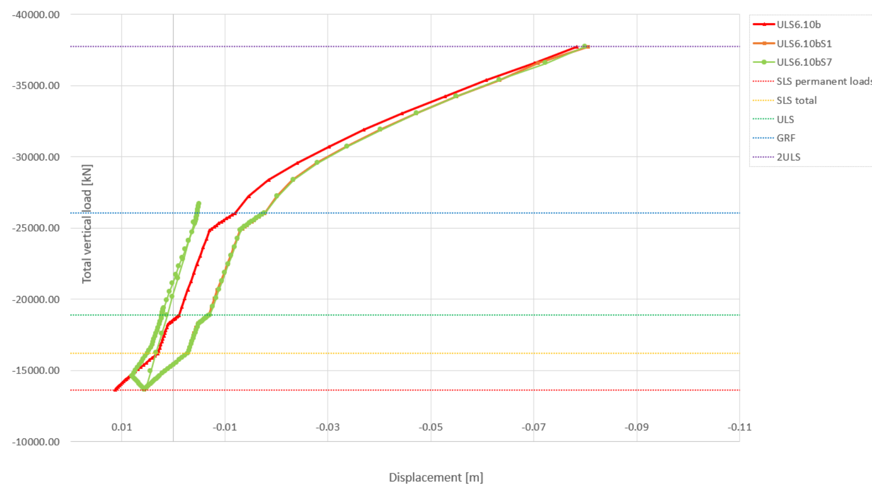
variant 7: precracked with bending focused traffic preload

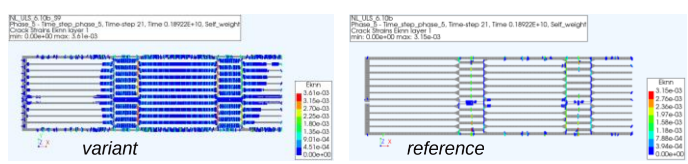
different start, similar ending

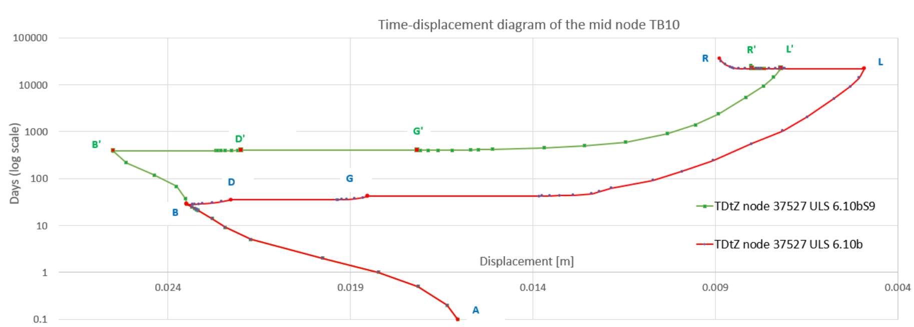


variant 9: 1 year waiting time before cast-in activation

much more cracking in cast-in…

… but not of influence for failure mechanism or failure load





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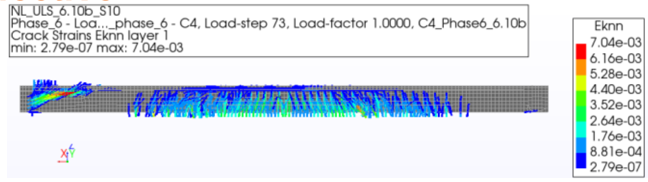
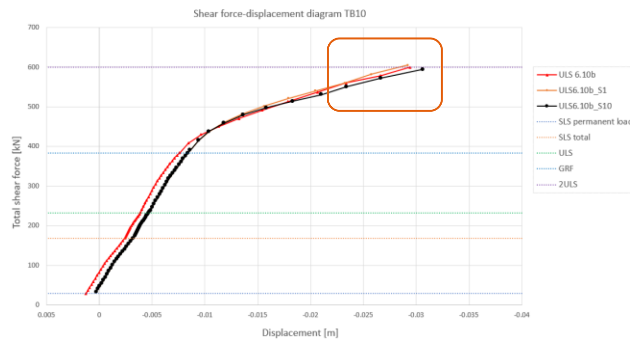
variant 10: shear reinfo less effective

more localization of shear crack



slight increase in development of shear deformation at 2.0×ULS



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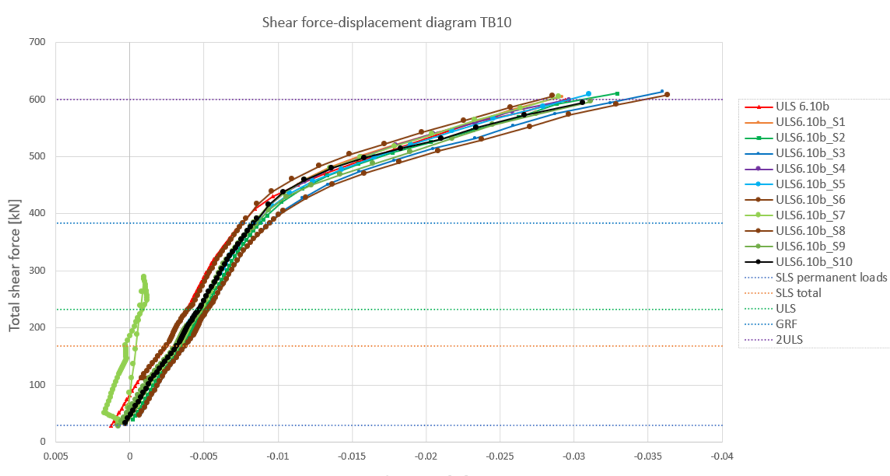
wrap-up: all variants. shear force vs shear displacement

no variation shows significant differences in load-displacement diagram before 2.0×ULS…

… despite differences in structural respons (onset of cracking, amount of cracking)



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at the end of the day…

conclusions and lessons learned

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conclusions and lessons learned

There's life after the onset of a shear tension crack

- NL FEA shows large 'hidden' margin after shear-tension crack development with inclined prestress elements
- UC drops from 1.85 to 0.56

In this case the added value of an integral calculation is questionable

- Governing girder from quick scan proves indeed governing
- Redistribution via deck slab to adjacent girders only after failure of governing girder

The usual suspects for sensitivity analysis don't result in large variation in outcomes (maybe prestress yield strength would have been the better choice…)

Mind autotying: useful feature but is there a solution for T-shaped connections?

NL FEA adds much value. But how about solid elements and advanced creep modelling? For the problem at hand:

- 3D modelled girders perform similar to 2.5D modelled girders
- A simplified modelling of creep and shrinkage results in the same failure load and mechanism as the advanced model

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