Tampere University

Jännitettyjen betonipalkkien yhdistetyt rasitukset - tutkimuksesta käytäntöön

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Topic of today!

Background

- The research started in 2017 with preliminary review of finnish bridge stock
- What happens if tendons in a prestressed bridge are broken and how the situation can be analyzed?
  - There is increasing concern of the state of prestressed structures globally as ruptured strands are becoming more common
- What current methods can be used to predict structural behaviour or are there more refined methods for assessment and are applicable for engineering use?
- Many experimental tests:
  - Re-anchoring and bond of ruptured strands
    - https://doi.org/10.1002/suco.202000351
  - Small-scale load tests of prestressed beams under bending and torsion
    - https://doi.org/10.1016/j.engstruct.2023.115606
    - https://doi.org/10.1016/j.engstruct.2024.119053
  - Large-scale load test of prestressed beams under bending, torsion and shear
    - https://researchportal.tuni.fi/en/publications/analyzing-structural-behavior-of-prestressed-continuous-beams-wit

THE STUDIED FIELDS

- Interaction of bending, torsion and shear in prestressed structures
- Structural effects of prestressing strand failure
- Stress redistribution of continuous structure in ULS
- Re-anchoring of grouted tendons
- Signs of strand failure under SLS loads

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Combined actions

- Interaction between bending, torsion and shear is essential in design of bridge structures due to the nature of the loads and large span-to-height ratios
- From a scientific point of view, however, the issue is not fully resolved – at least not for prestressed structures
- Beam experiments with torsion from 1960s to this day were collected to a database
  - Amount of experimental research data on concentrically prestressed beams with combined actions is very small

DATABASE

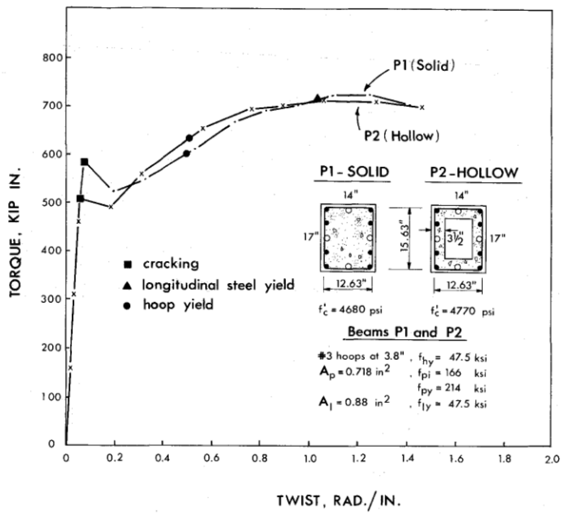
1084 beams:
- 149 hollow
- 935 solid

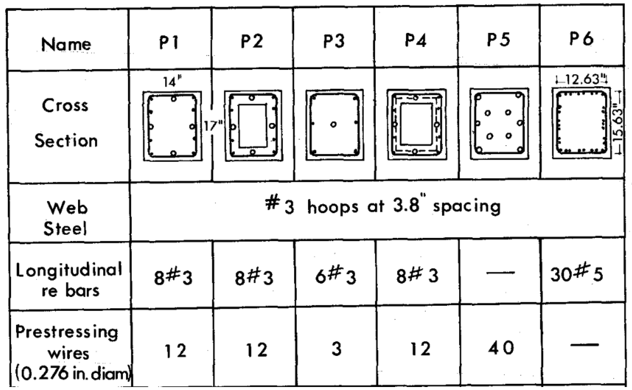
118 prestressed beams:
- Pure torsion: 54
- Bending and torsion: 39
- B + T + Shear: 25

On average from year 1977

Prestressing steel mainly centrally placed

Cross-section areas 0.01…0.37 m^2
Mean:
- concrete strength 34.1 MPa
- longitudinal reinforcement ratio 1.8 %
  - with eccentricity of 0.78 ± 0.44
- transverse reinforcement ratio 1.1 %



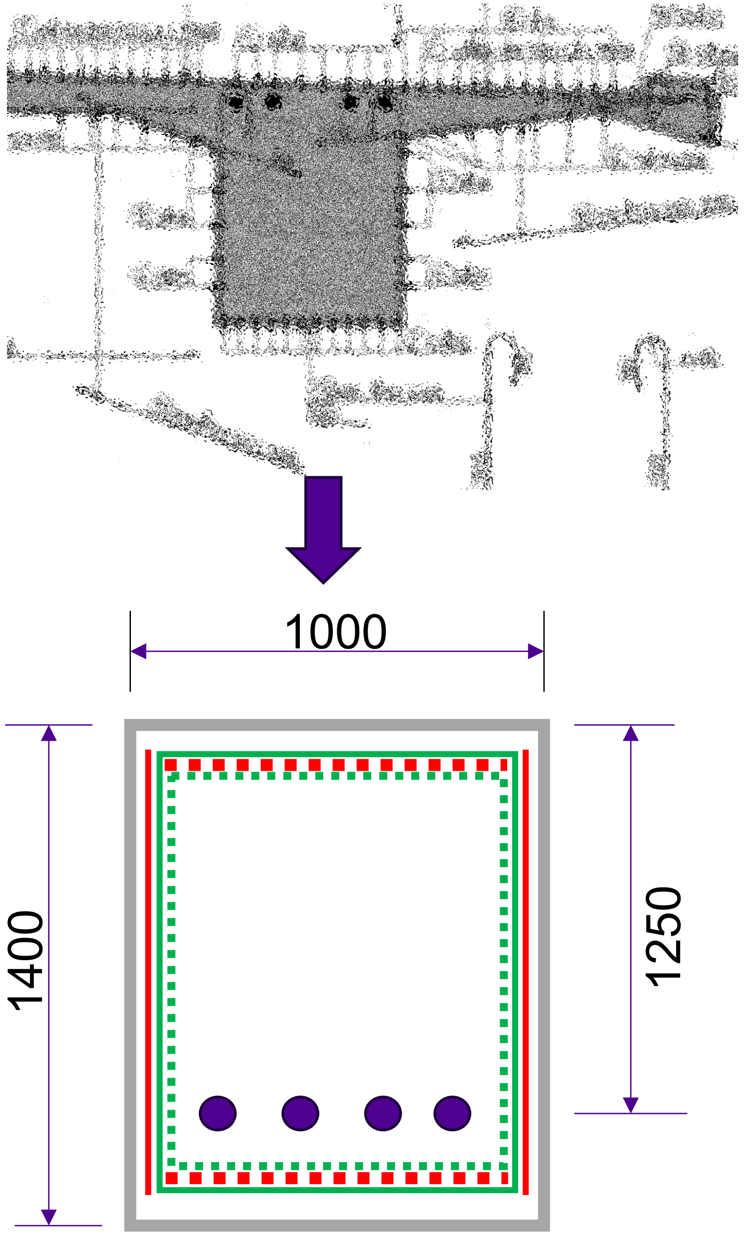


Name	P1	P2	P3	P4	P5	P6
Cross Section						
Web Steel	#3 hoops at 3.8" spacing					
Longitudinal re bars	8#3	8#3	6#3	8#3	—	30#5
Prestressing wires (0.276 in. diam)	12	12	3	12	40	—

Kuvien lähde:
https://doi.org/10.15554/pcij.05011978.54.73

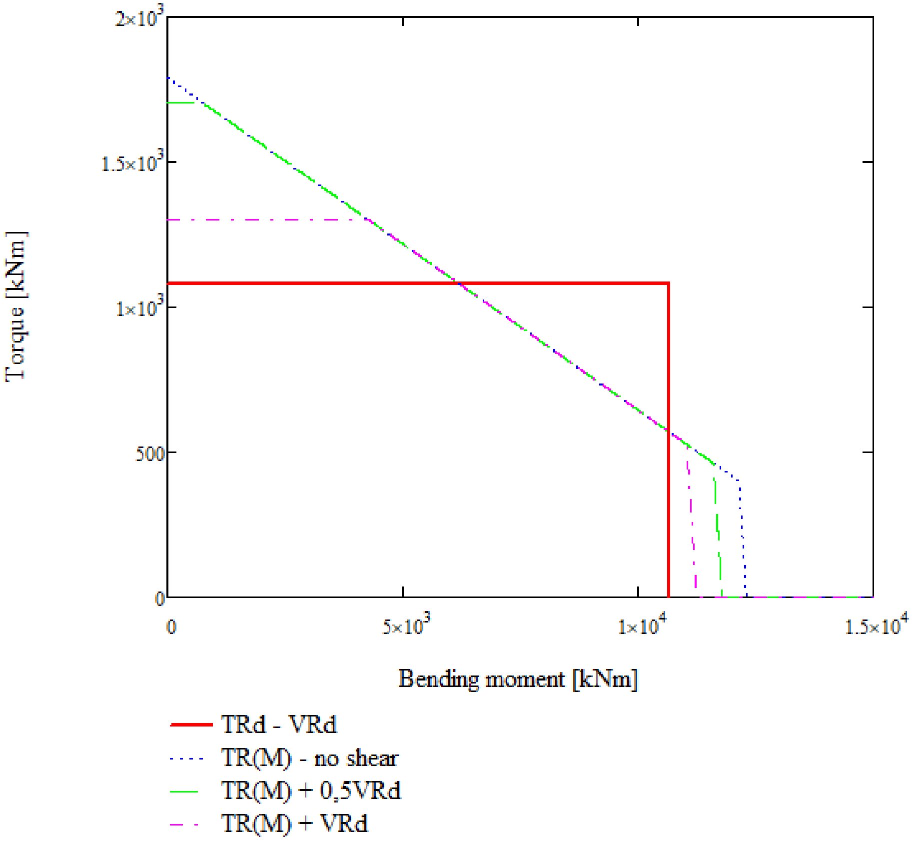
Calculation example

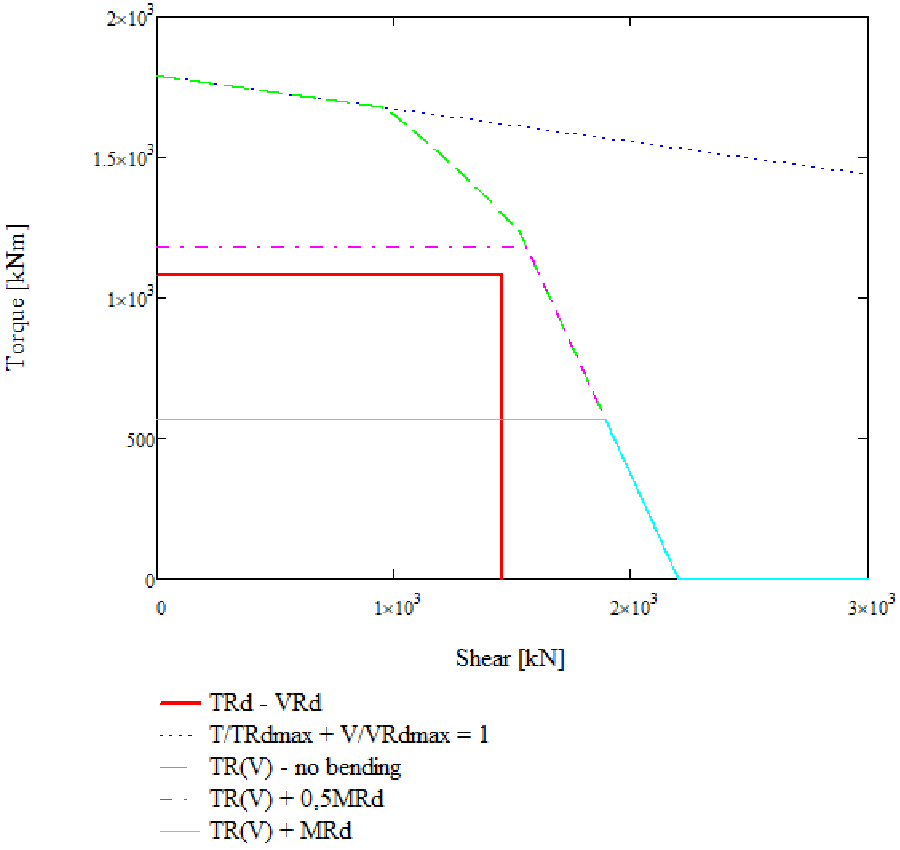
- Simplified rectangular prestressed concrete cross-section close to middle support
- Concrete: f_{cd} = 23 MPa
- Tendons: f_{pd} = 1454 MPa
- Rebars: f_{sd} = 454 MPa (concrete cover 40 mm)
- Separate and combined strengths in bending, shear and torsion with:
  - NCCI 2
  - CEB-FIP Model Code 1978
  - Eurocode (1st gen, 2005) EN1992-1-1 + EN1992-2



- Longitudinal rebars for shear: 2x3140 mm^2 (~2x10d20)
- Longitudinal rebars for torsion: 3400 mm^2 (~17d16)
- Tendons for bending: 4x1800 mm^2 @900 MPa
- Hoops for torsion: d16 c/c 150 (1340 mm^2/m)
- Links for shear: 2d16 c/c 300 (1340 mm^2/m)

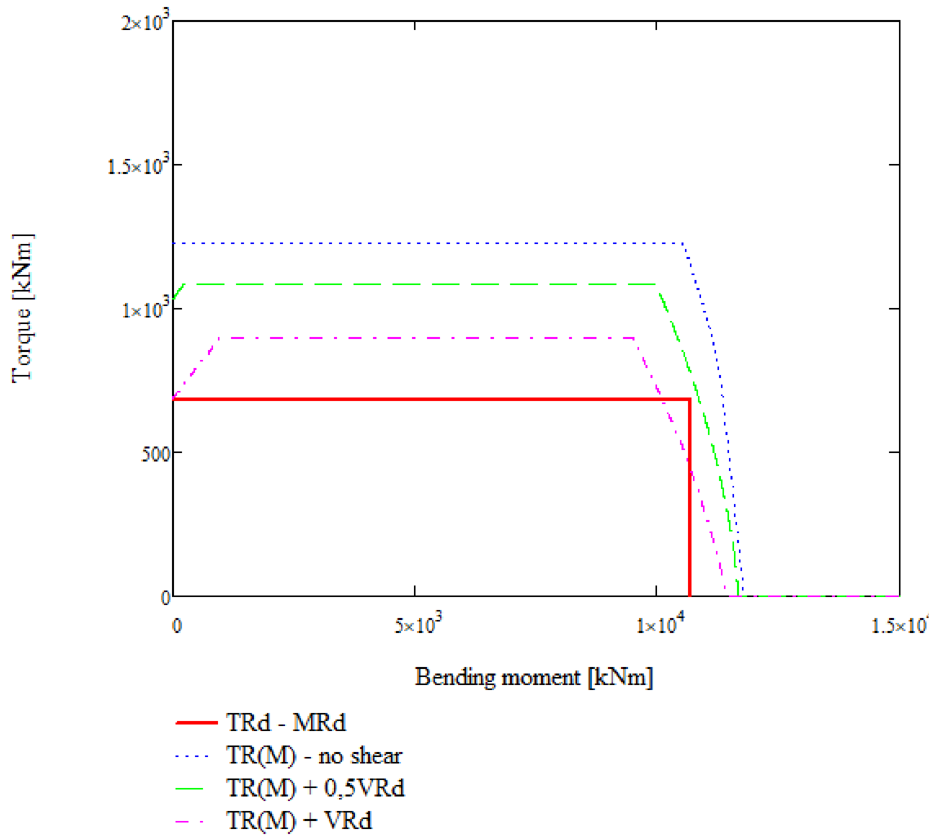
Bending, Torsion & Shear – NCCI 2

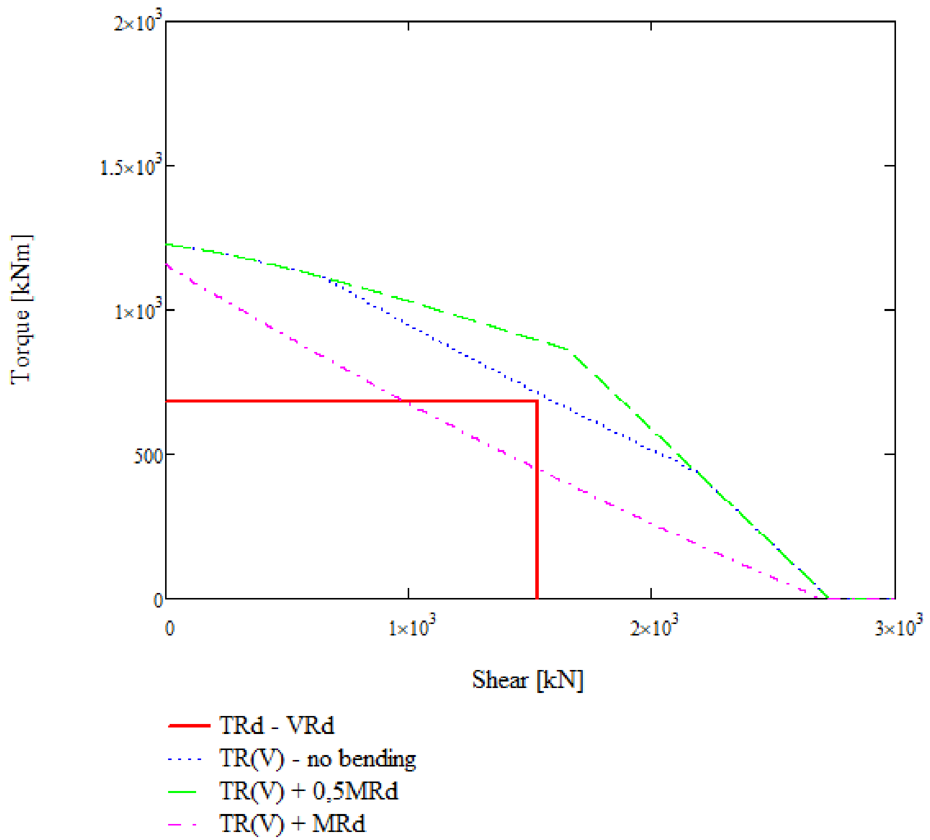




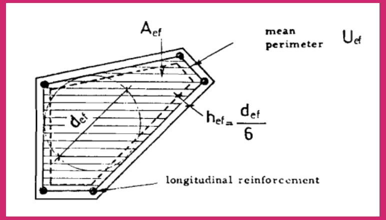
- Concrete contribution is large in shear
  - cot(θ) = 1
- In torsion 1/3 < cot(θ) < 3
  - Is superposition of reinforcement areas applicable?
- A_{ef} is calculated from the centerline of longitudinal reinforcement
- No rules accounting for prestressing steel as longitudinal reinforcement in shear or torsion
- Compression from bending is not allowed to relieve longitudinal tensile stresses from torsion
- Longitudinal reinforcement for shear not tied to cot(θ)
- Large cut-off with
  - $T/T_{Rdmax}+M/M_{plRdmax}=1$
  - $T/T_{Rdmax}+V/V_{umax}=1$

Bending, Torsion & Shear – Model Code 1978



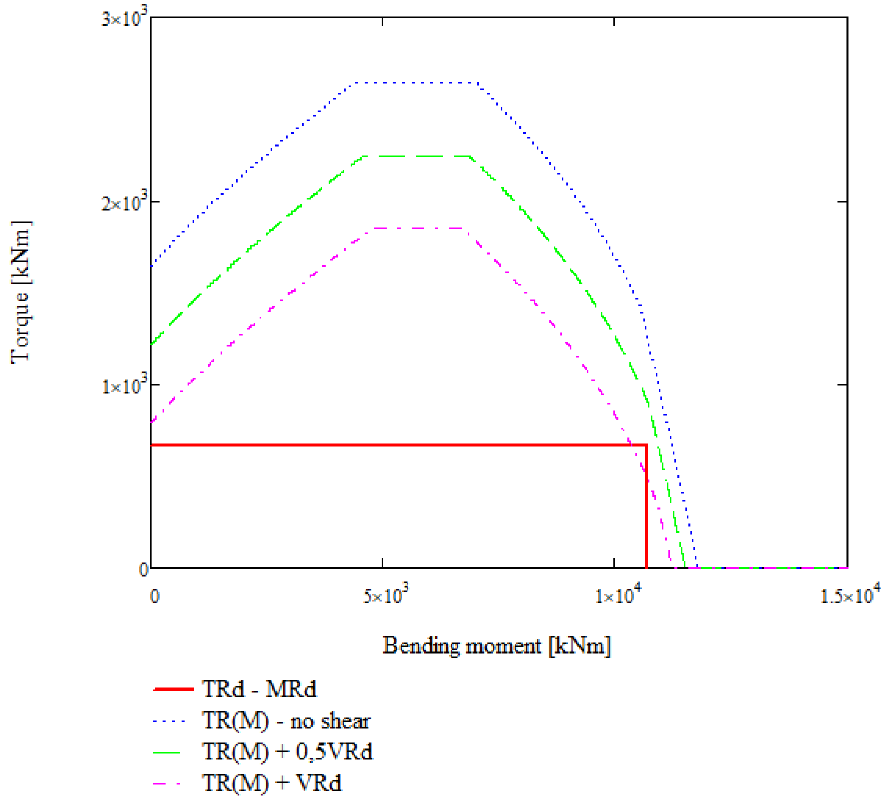


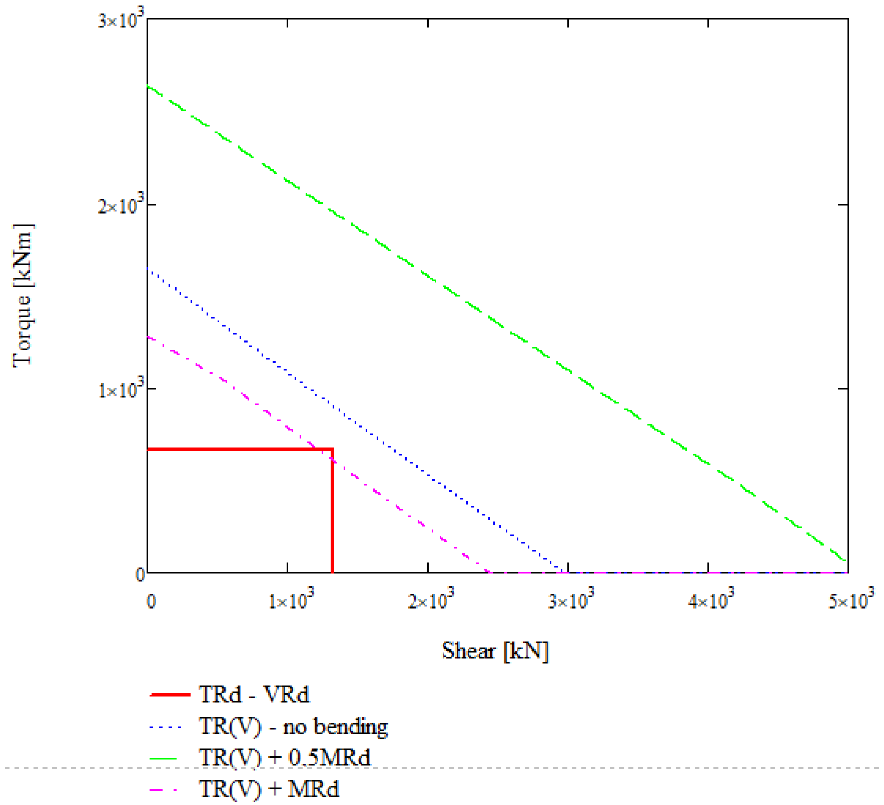
- $3/5 < \cot(\theta) < 5/3$
- A_{ef} calculation:



- Prestressing steel can be accounted for as longitudinal reinforcement in torsion
- Concrete contributes in torsion and shear resistances – but not in the interaction calculations
- Longitudinal reinforcement for shear not tied to cot(θ)
- Longitudinal reinforcement for torsion can be reduced in the flexural compression zone
- No cut-off from maximum values bending moment and torsion
  - Warning of too high principal compressive stresses in compression zone

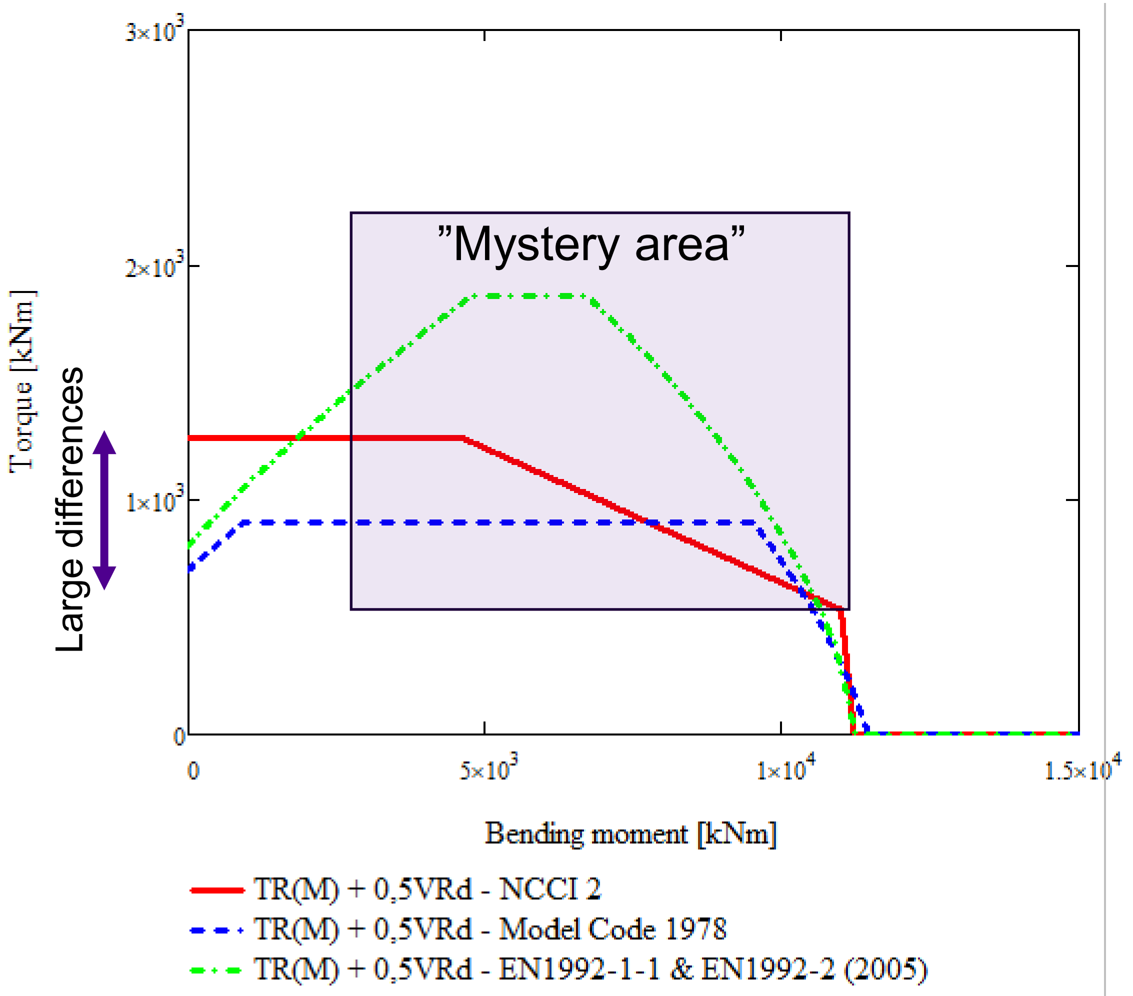
Bending, Torsion & Shear – 1992-1-1 + 1992-2 (2005)





- $1 < \cot(\theta) < 2{,}5$
- $A_{ef} = A/u$
- No contribution from concrete
- All longitudinal and transverse reinforcement tied to cot(θ)
- Prestressing steel can be accounted for as longitudinal reinforcement in torsion
- Longitudinal reinforcement for torsion can be reduced in the flexural compression zone
- No cut-off from maximum values bending moment and torsion
  - Only shear and torsion

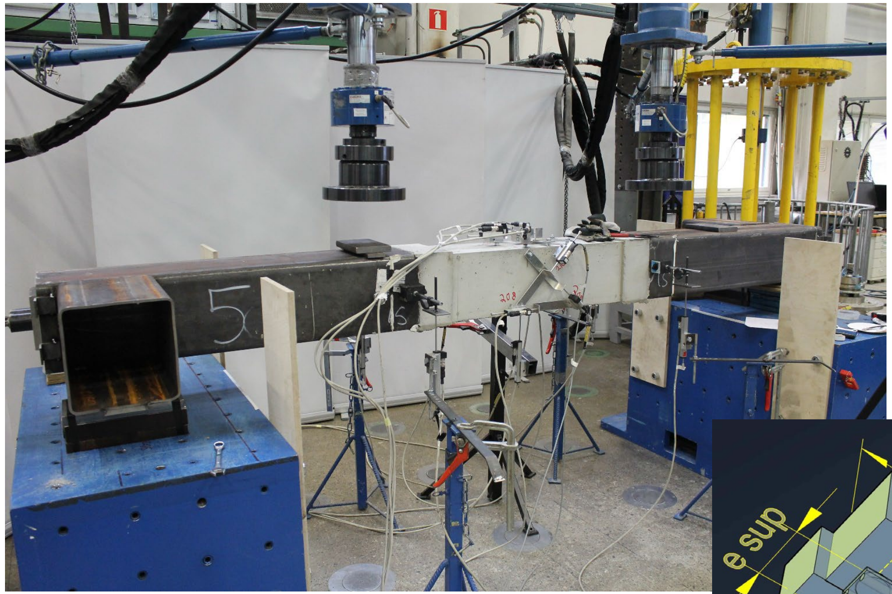
Calculation example - conclusion

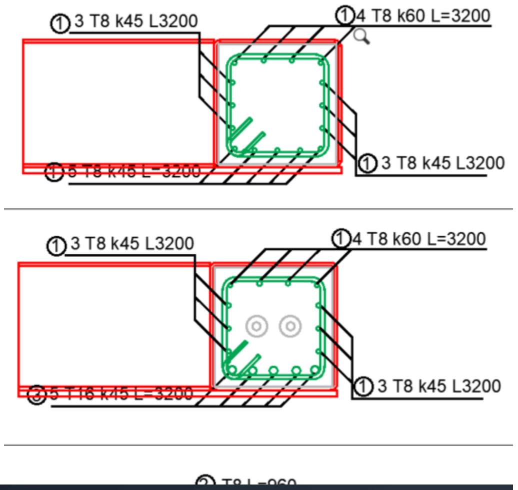


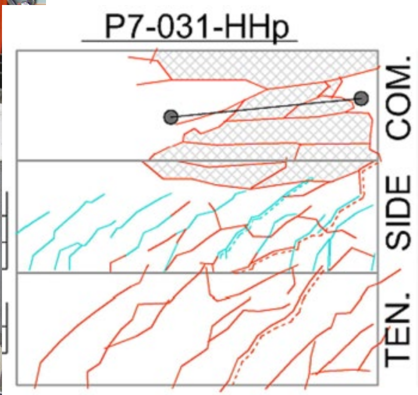
- The "mystery area" has been researched with:
  - Small scale bending-torsion experiments
  - Developement of *Plasticity based space truss model with variable compression panel thickness* (PB-TM)
  - Collecting 92 experiment results from literature for model calibration
  - Development of *Strain based space truss model* (SB-TM)
  - Large scale experiments continuous prestressed beams with bending-torsion-shear interaction

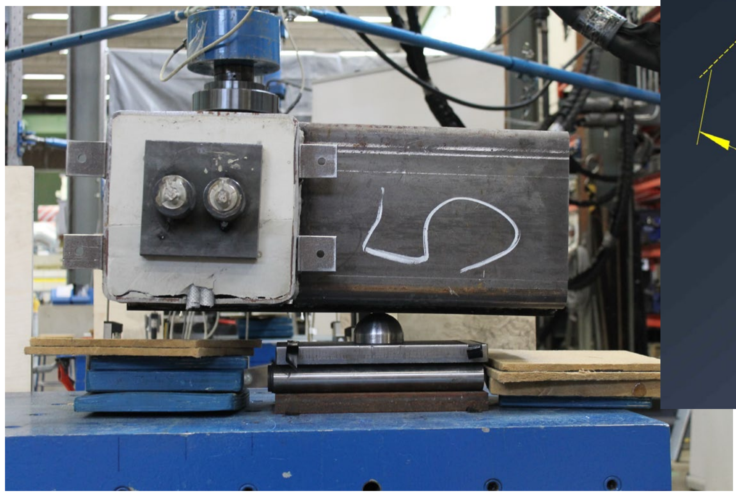
Small scale experiments

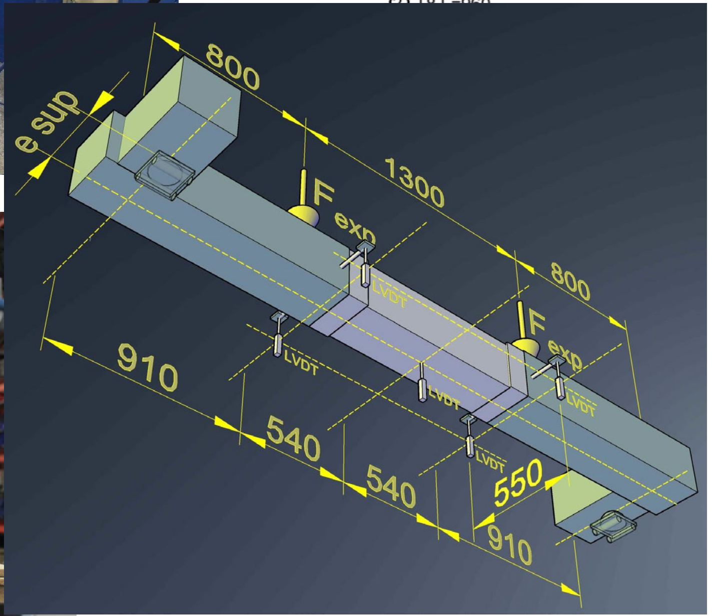
- 8 beams with different reinforcement setups
  - Lighlty and heavily reinforced, prestressed
- Sudden fracture of concrete on compressive side was evident in heavily reinforced beams, while the beams were not overreinforced for bending





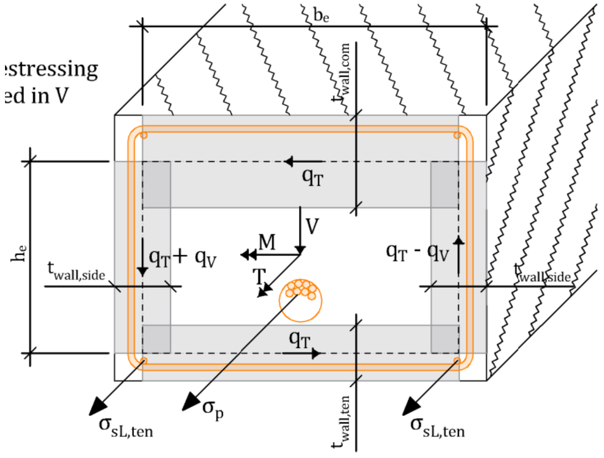




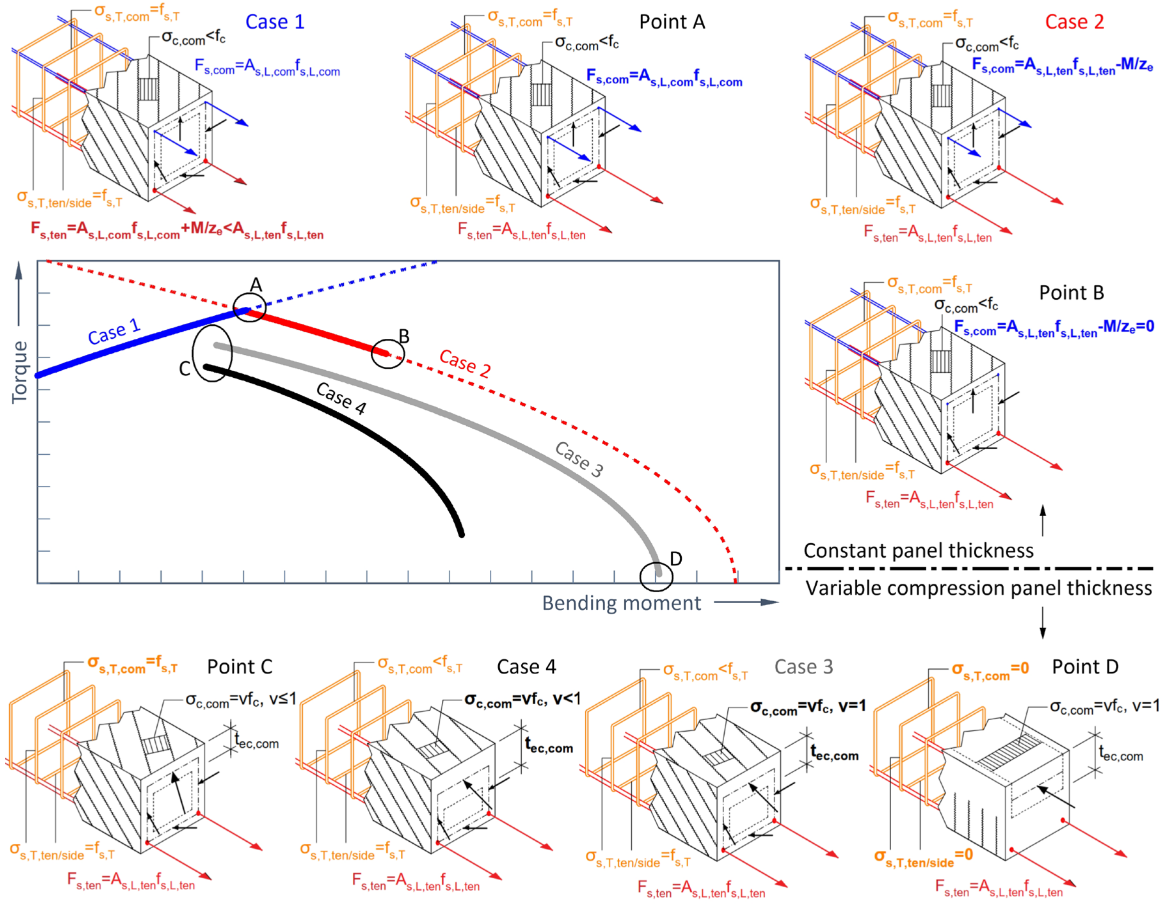


Plasticity-based space truss model (PB-TM)

- Combining the aspects from plasticity based bending model and space truss model for torsion
- The transverse strain of the top panel is derived from force equilibrium of the panel forces
- Created from the results of load tests on 8 beams with heavy reinforcement and prestressing



- $t_{wall,side/ten} = k_{wall}*(A_c/u_c)$,where k_{wall} is variable taking account the T/M -ratio and longitudinal mechanical reinforcing ratio, and A_c and u_c are the area and perimeter of the concrete cross-section
- $\sigma_{sT,ten/side} = \sigma_{sL,ten/side} = f_{sy}$, $\sigma_{sT,com} < f_{sy}$, $\sigma_{sL,com} = 0$
- $\sigma_p = \min(\sigma_{p0} + f_{sy}; f_{p0,02})$
- $\sigma_{c,side/ten}$ and $\theta_{side/ten}$ are determined from equilibrium with σ_{sT} and q
- $\theta_{com} = \mathrm{atan}(q_T*b_e/N_L)$, where $N_L = M/z_e$ and z_e is the internal lever arm for bending
- $\sigma_{c,com} = \upsilon_c(\varepsilon_{1,com})*f_c$, where $\varepsilon_{1,com}$ is determined with transverse equilibriun in ultimate state and Mohr's circle assuming $\varepsilon_{2,com} = \varepsilon_{cu}$
- $t_{wall,com}$ determined so that cross-section is in equilibrium



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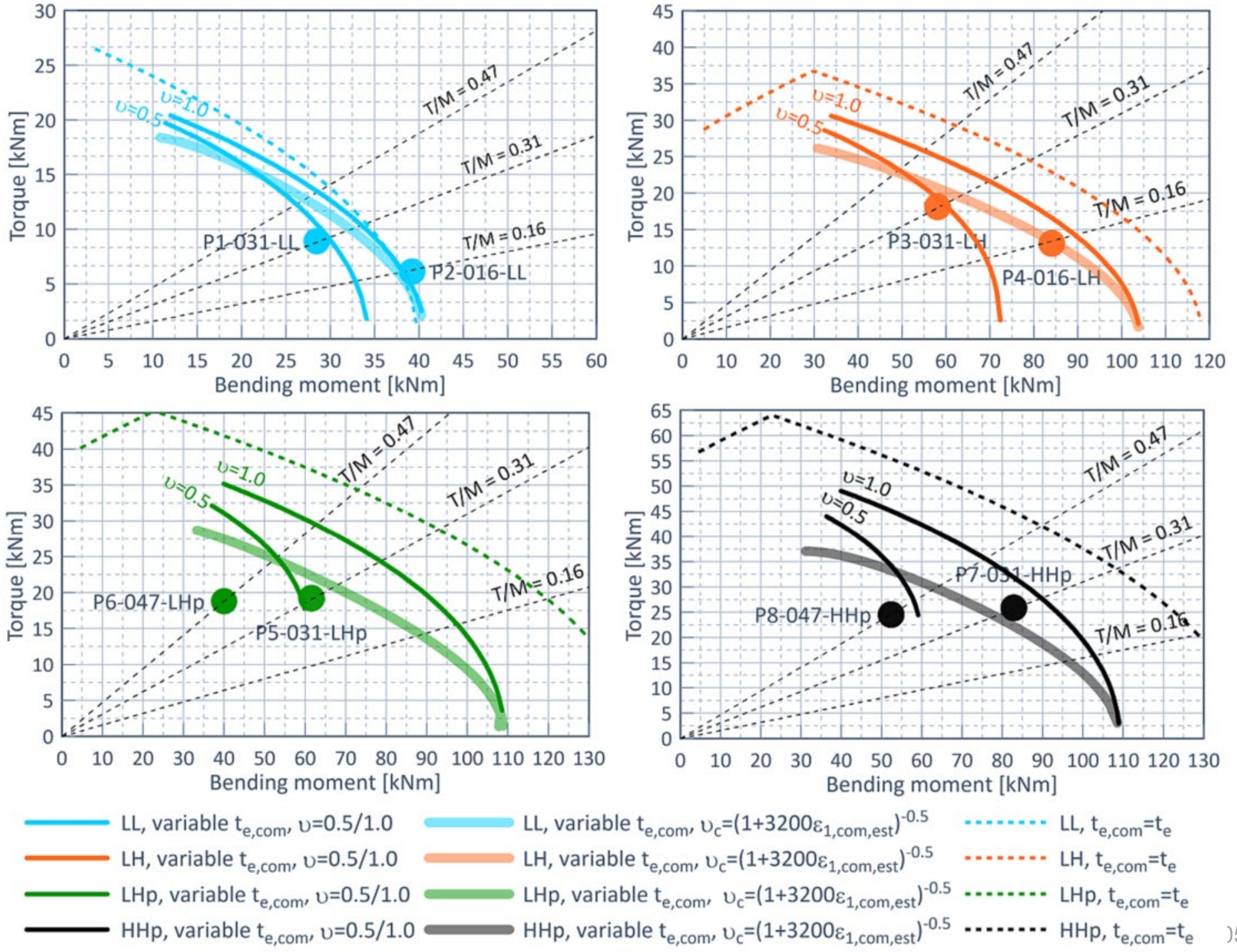
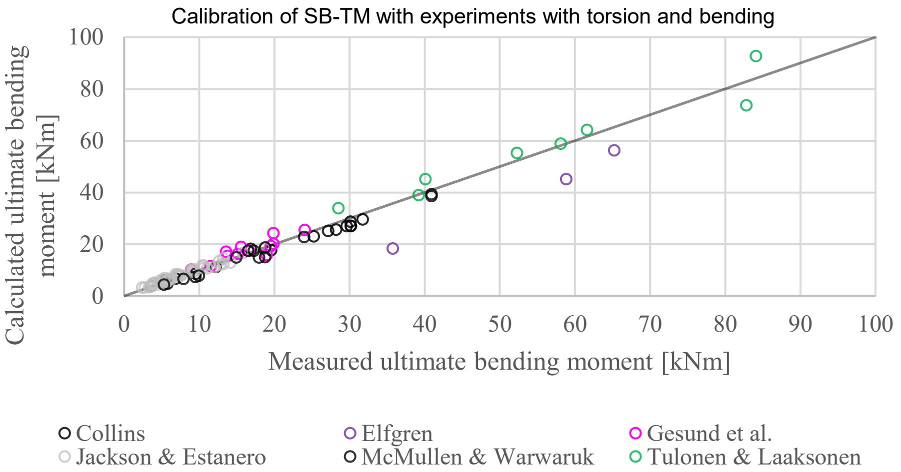
Plasticity-based space truss model (PB-TM)

- The test resultsod small scale experiments were over-estimated with model without concrete softening or variable compression zone thickness
- Concrete softening factor was adjusted with test results

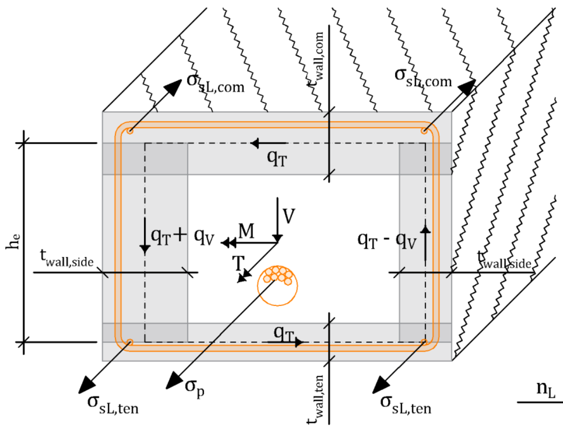


Strain-based space truss model (SB-TM)

- Based on solving the strain state of given combinations of torsional shear flow q and cross-section bending curvature κ
- Non-linear material properties and non-linear nested iterative solving of the panel forces
- Full load-deformation response calculation is possible
- The model was used to adjust the PB-TM parameters to achieve better match with experimental results from the data base

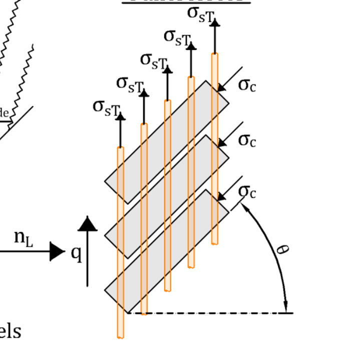


Strain based truss model (SB-TM)



- $q_T = T / (2A_0)$ where A_0 is the dashed line
- $q_V = V / (2h_e)$
- The vertical component of pre (tendon inclination) is account

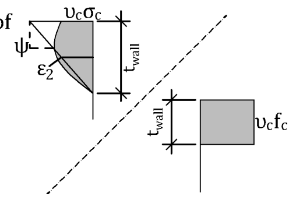
Panel forces

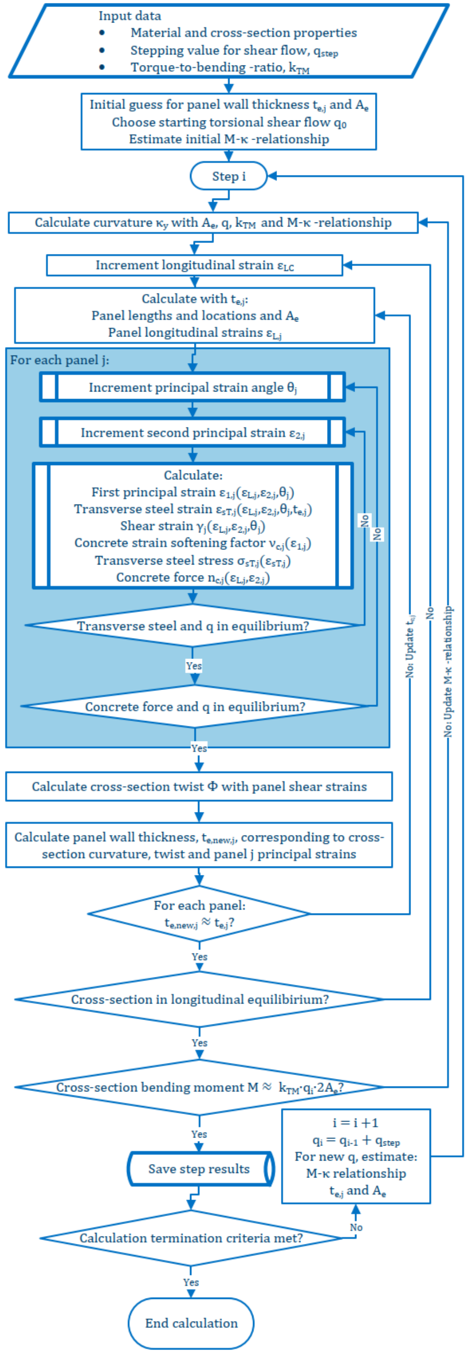


- Longitudinal strain $\varepsilon_L(z) = \kappa * z + \varepsilon_{L0}$
- $\sigma_{sL,ten/com}$ and σ_p are determined from material models with $\varepsilon_L(z)$
- t_{wall} for each panel is determined from ε_2 and panel curvature ψ, which is a function of cross-section twist Φ and curvature κ
- Cross-section twist is calculated from shear deformation of panels
- ε_2 and θ are determined for each panel so that force equilibrium and strain compatibility is fulfilled
- $\sigma_c = \upsilon_c(\varepsilon_1) * \sigma_c(\varepsilon_2)$ for each panel
- ε_{L0} is iterated so that cross-section is in equilibrium

Concrete softening factor

$$\upsilon_c(\varepsilon_1) = 1/(1+1600*\varepsilon_1^{0.5})$$

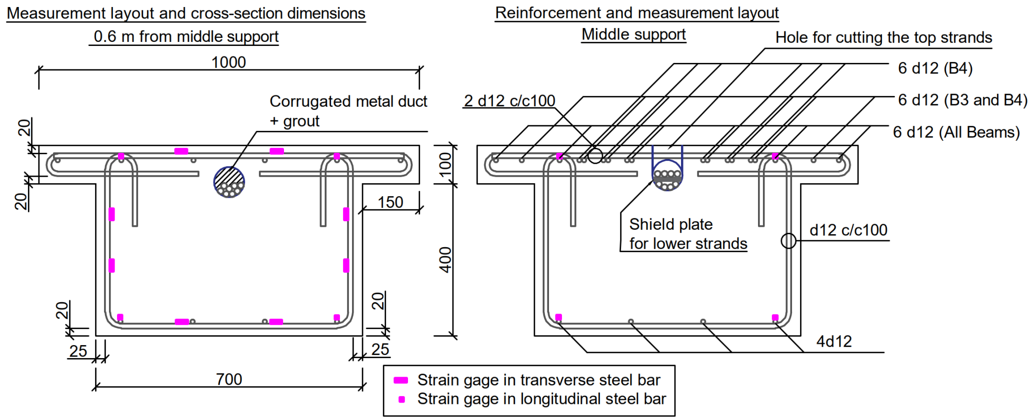


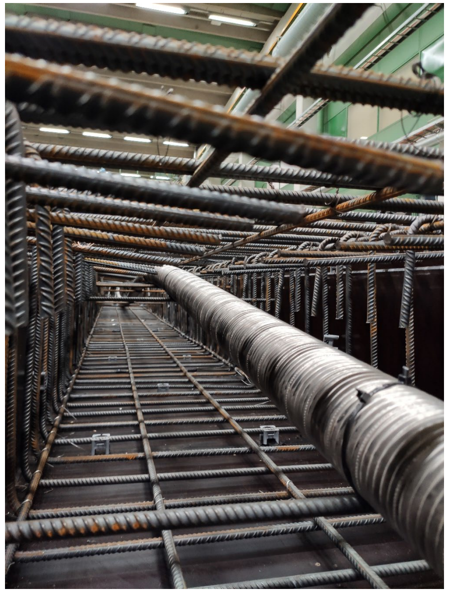


Large scale experiments

- Four 20 meter long two span post-tensioned concrete beams were loaded to failure with 9-point loading
- The structure represented a typical highway overpass
- In some of the beams, half of the prestressing strands were cut at the support to simulate tendon breakage
- Tests were conducted in 2021 at Tampere University Structural Engineering Laboratory

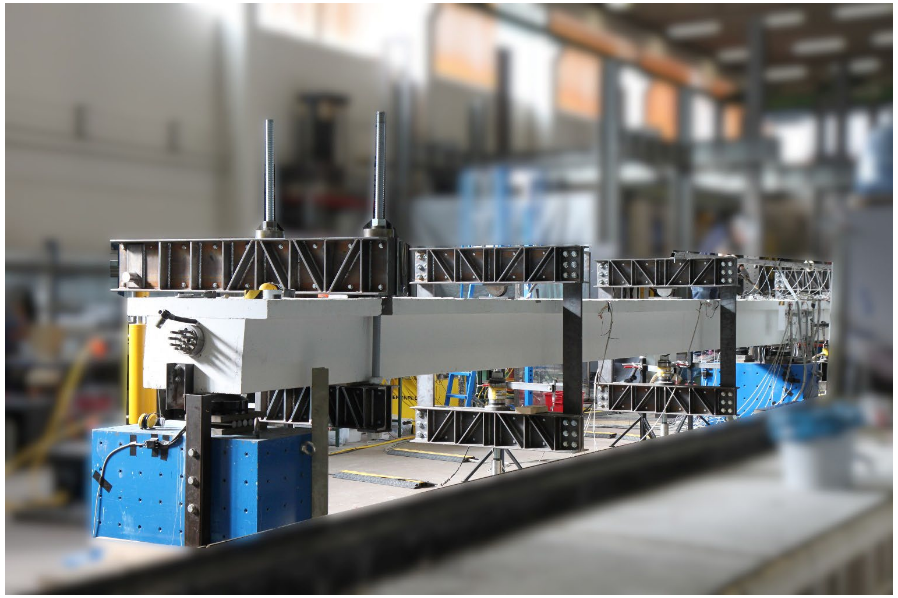
Four beams:	continuous with two 9.7 m spans
Cross-section:	0.7x0.5 m rectangle with small overhangs
Concrete:	mean cylinder strength 34…38 MPa
Tendons:	parabolic profile with 8 x 150 mm^2 strands @ 900 MPa inside a grouted corrugated steel duct, $f_{p0.01}$ = 1600 MPa
Reinforcement:	bottom 4 x d12, top 6 x d12.
	hoops d12 c/c 100
	Top soffit at the middle support, B1&B2 6 x d12 mm, B3: 12 x d12, B4: 18 x d12 mm, f_{yk} = 519 MPa

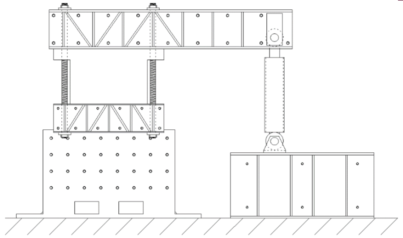


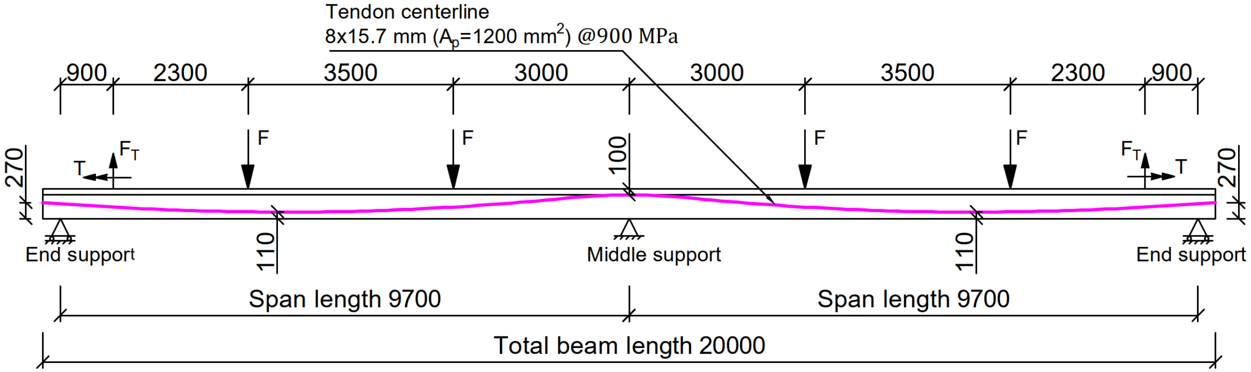


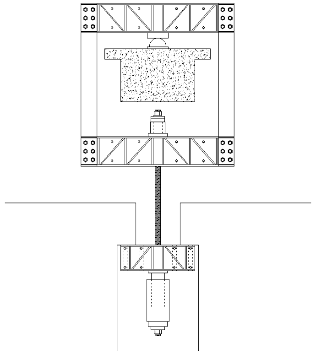
Test setup and instrumentation

- Each beam was heavily instrumented
- Beams were loaded with four vertical loads at the span and two torsion loads at the beam ends
- Some measurements were started when the beams were lifted to the supports and continued through the prestressing to the failure load







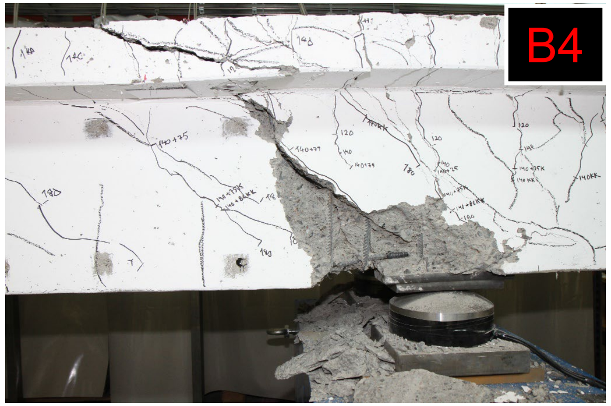


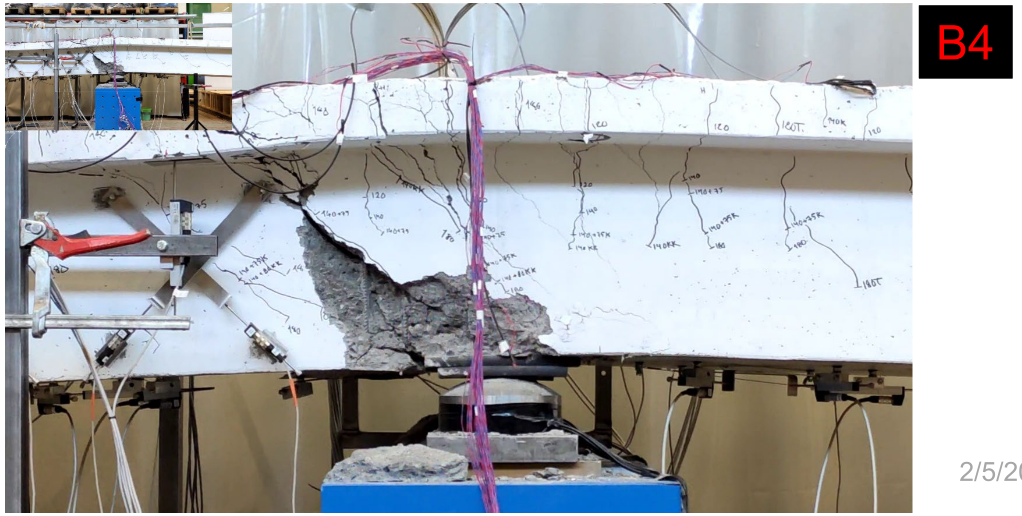
Instrumentation per beam:

- 80 rebar strain gauges
- 41 concrete surface strain measurements with LVDT
- 18 LVDTs to measure deflections and rotations
- 4 bearings with support reaction measurement
- 4 force transducers for vertical load measurement
- 2 instrumented hydraulic jacks for torsion load measurements

Beam experiments: Failure modes

- All of the beams showed heavy cracking at the middle support
- The failure of all beams was combination of bending, torsion and shear
- The beams with the heaviest reinforcement, B1 and B4, failed in brittle manner
  - Cracking and spalling was observed in the compressive soffit near the middle support
  - Soon after large diagonal crack appeared onto the side and concrete spalled off
- The failure modes of beams B2 and B3 were more ductile
  - No concrete spalling of the side face, but spalling and diagonal cracking at the compressive soffit





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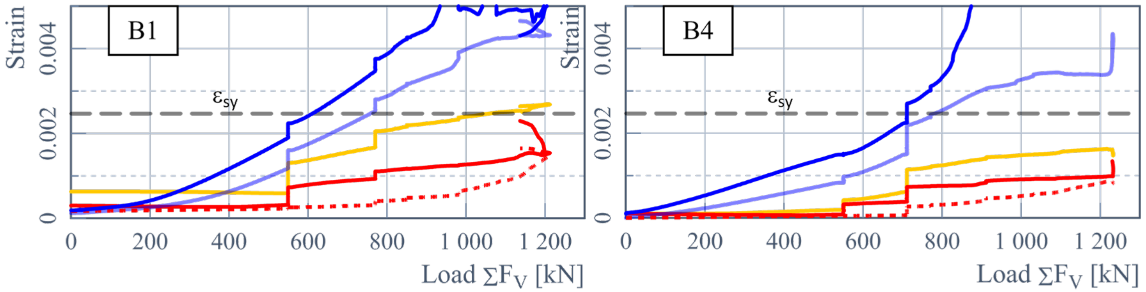
Comparison with the calculated results

- Accuracy of both models is very good
- SB-TM estimates that the failure occurred in a section somewhere between the middle support and 0,6 m from middle support
  - This is an area where the cut strands have not yet fully re-anchored
  - Supported by hoop strain measurements (no yielding at 0,6 m) and visual observation of the failures
- PB-TM estimates failure location bit further from the support – slightly underestimates the ultimate strength

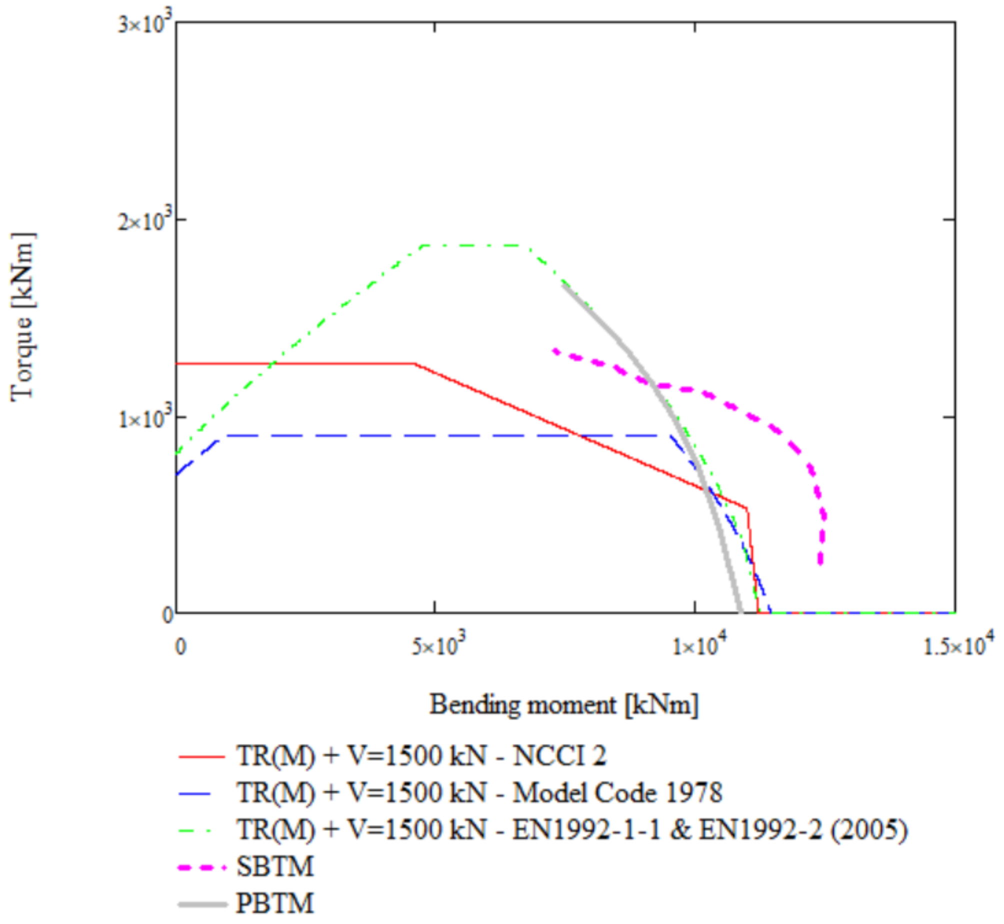


Results from middle support – torsion and peak moment only	SB-TM M_{exp}/M_{Rcalc}	PB-TM M_{exp}/M_{Rcalc}
B1 (8/8 strands + 6 rebars)	1.09	1.19
B2 (4/8 strands + 6 rebars)	1.15	1.30
B3 (4/8 strands + 12 rebars)	1.19	1.29
B4 (4/8 strands + 18 rebars)	1.09	1.17

Results 0,6 meters from middle support – torsion, shear and bending moment	SB-TM M_{exp}/M_{Rcalc}	PB-TM M_{exp}/M_{Rcalc}
B1 (8/8 strands + 6 rebars)	0.90	0.99
B2 (4/8 strands + 6 rebars)	0.95	1.04
B3 (4/8 strands + 12 rebars)	0.98	1.08
B4 (4/8 strands + 18 rebars)	0.93	1.00

Calculation example revisited

- PBTM follows eurocode approach quite closely – failure dominated by yielding of longitudinal and transverse reinforcement
  - No significant strain softening of the concrete
- SBTM gives larger bending capacities – mainly due to non-linear and strain hardening material properties
  - Resistances with higher torque are lower as yielding of the transverse steel dominates the failure
- Conclusions (in this case):
  - Failure is not governed by crushing of concrete as estimated with NCCI2
  - Assumption of full yielding of all the longitudinal and transverse reinforcement may be give too high resistances



Conclusions

- The presence of torsion can lead to more brittle failure than expected due to greater concrete stresses and lower concrete strength caused by shear strains
- The current design methods for torsion and shear are not intuitive to use for combined actions and lack a coherent connection to the physical behavior of real structures – especially if the structure is heavily reinforced
- The presented analysis methods provided accurate results but are computationally demanding – more design-oriented tools are required
- On-going research is concentrating on applying the models developed for different design cases and to extend the capabilities of models

Thank you for your attention!

Questions?

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