Betonipalkin murto taivutuksen, leikkauksen, väännön ja normaalivoiman yhteisvaikutuksesta - Tutkimushankkeen päätulokset

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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
  - Small-scale load tests of prestressed beams under bending and torsion
  - Large-scale load test of prestressed beams under bending, torsion and shear

Topic of today!

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
- Related previous research by authors:
  - Bending and torsion tests of heavily reinforced and prestressed beams
  - Re-anchoring of bundled strands inside corrugated steel duct with voids

DATABASE

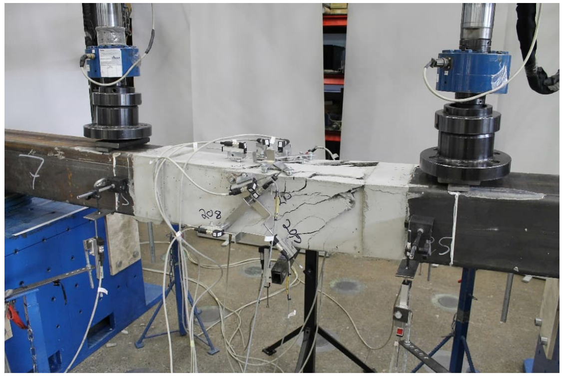
1084 beams:
- 149 hollow
- 935 solid

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 %



https://doi.org/10.1016/j.engstruct.2023.115606
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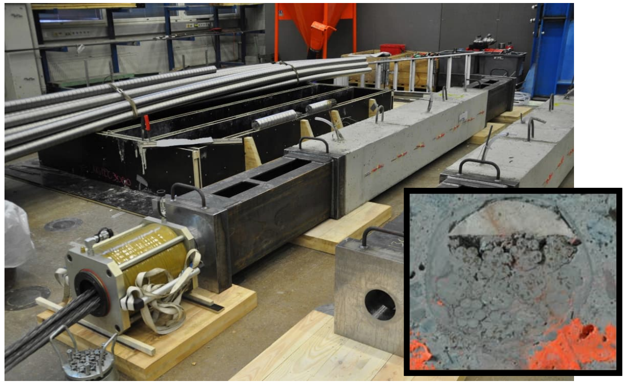
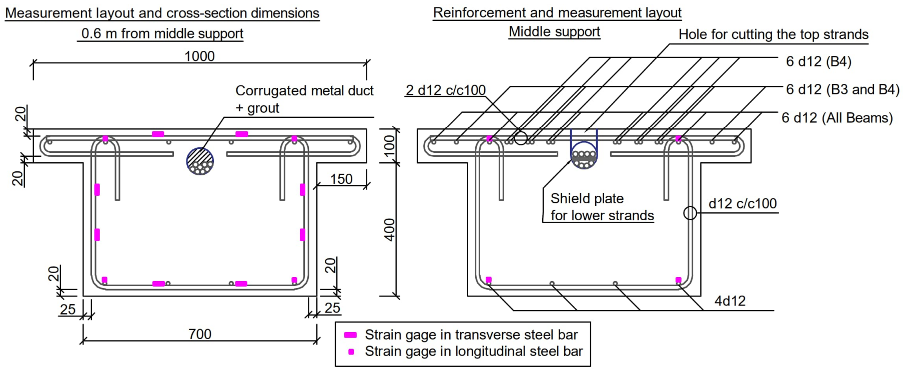


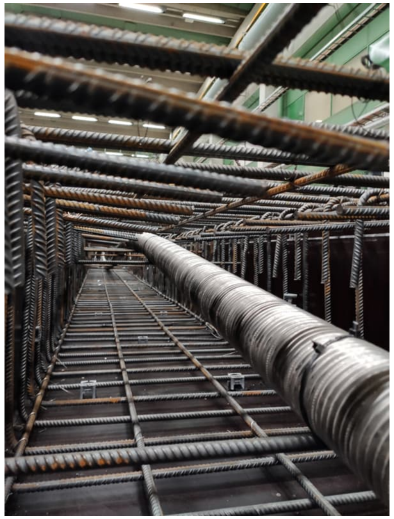
https://doi.org/10.1002/suco.202000351

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

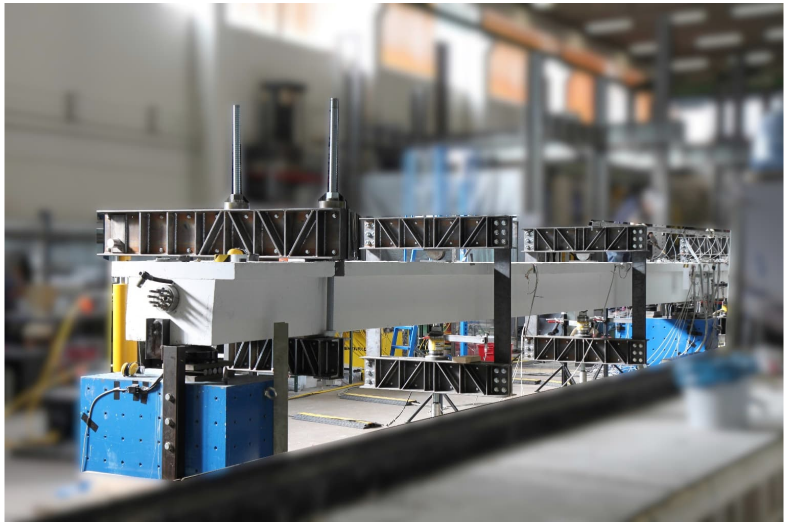
Four beams:	continuous with two 9.7 m spans
Cross-section:	0.7x0.5 m rectangle with small overhangs
Concrete:	mean cylinder strength 34…38 MPa
Tendons:	parabolic profile with 8 x 150 mm^2 strands @ 900 MPa inside a grouted corrugated steel duct, $f_{p0.01}$ = 1600 MPa
Reinforcement:	bottom 4 x d12, top 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





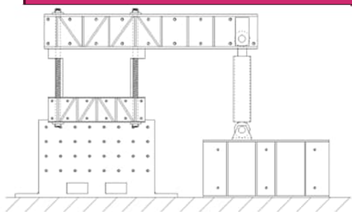
Test setup and instrumentation

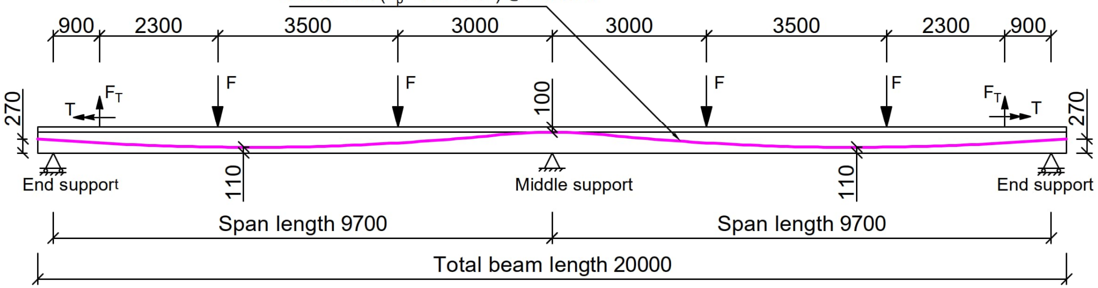
- Each beam was heavily instrumented
- Beams were loaded with four vertical loads at the span and two torsion loads at the beam ends
- Some measurements were started when the beams were lifted to the supports and continued through the prestressing to the failure load

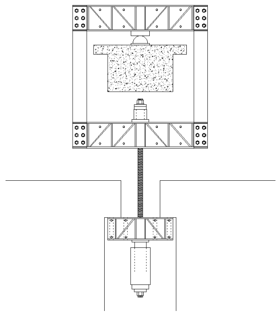


Instrumentation per beam:

- 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







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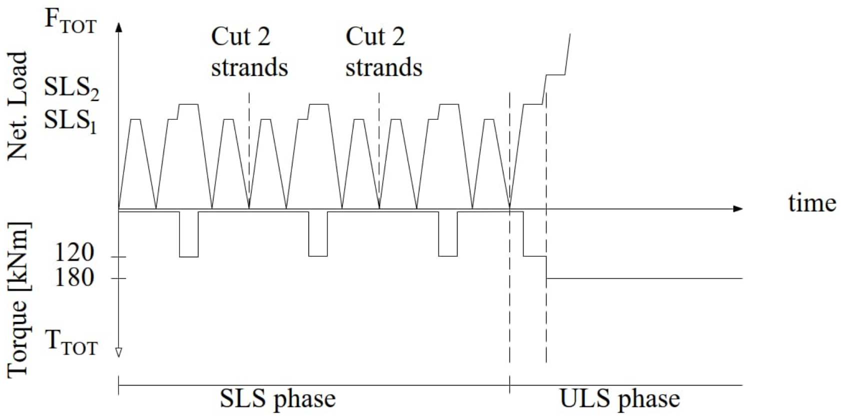
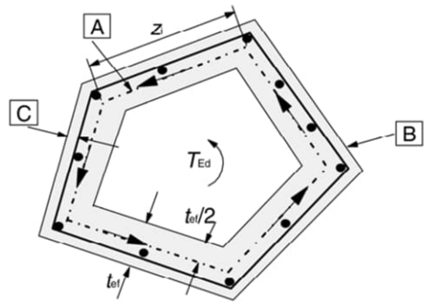
Conduction of experiments

- The loading consisted of SLS and ULS phases
  - Stresses in the SLS phase were intended to correspond to the stress level of a bridge loaded with Eurocode traffic loads
  - In ULS phase, load was increased until structural failure was achieved
- The strands were gradually cut from the middle support during the SLS phase
  - The first beam, B1, acted as reference where no strands were cut
- Torque was present in some SLS stages, and constant in the ULS phase



Methods for analysis

- Reference model with classical beam theory and non-linear material models
- Sectional analysis for bending-torsion-shear interaction with:
  - EN1992-1-1
  - Plasticity based space truss model (PB-TM)
  - Strain based space truss model (SB-TM)



A – keskiviiva

B – tehollisen poikkileikkauksen ulkoreuna, piirin pituus u

C – betonipeite

	Torsion	Shear
Transverse	$\tau_{t,i} t_{ef,i} = \frac{T_{Ed}}{2A_k}$ $V_{Ed,i} = \tau_{t,i}\, t_{ef,i}\, z_i$	$V_{Rd,s} = \frac{A_{sw}}{s} z f_{ywd} \cot\theta$
Longitudinal	$\frac{\Sigma A_{sl} f_{yd}}{u_k} = \frac{T_{Ed}}{2A_k} \cot\theta$	$\Delta F_{td} = 0{,}5\, V_{Ed}\, (\cot\theta - \cot\alpha)$
Concrete	$T_{Rd,max} = 2\, \nu\, \alpha_{cw}\, f_{cd}\, A_k\, t_{ef,i} \sin\theta \cos\theta$	$V_{Rd,max} = \alpha_{cw}\, b_w\, z\, \nu_1\, f_{cd}/(\cot\theta + \tan\theta)$
Interaction	$T_{Ed}/T_{Rd,max} + V_{Ed}/V_{Rd,max} \leq 1{,}0$ (2) Väännön ja leikkauksen vaikutukset sekä kotelo- että umpisauvoissa voidaan laskea yhteen, kun oletetaan sama arvo puristussauvan kaltevuuskulmalle θ. Kohdassa 6.2.3 (2) esitetyt kaltevuuskulman θ rajat ovat myös täysin käyttökelpoisia leikkauksen ja väännön yhdistelmän tapauksessa. Puristuspaarteissa pääraudoitusta voidaan pienentää vallitsevaan puristusvoimaan verrannollisesti. Vetopaarteissa väännön edellyttämä pääraudoitus lisätään muuhun raudoitukseen. Pääraudoitus jaetaan yleensä sivun pituudelle z_i, mutta pienehköissä poikkileikkauksissa se voidaan keskittää tämän pituuden päihin.	

CEB-FIP Model Code 1978

If torsion is combined with a large bending moment, such a combination can cause critical principal stresses in the compression zone, particularly in beams having box sections. In such cases, the principal compressive stress can be calculated from the mean longitudinal compression due to flexure and from the tangential stress due to torsion, taken as being equal to $T_{sd}/2A_{ef} h_{ef}$. The stress so obtained should not exceed 0,85 f_{cd}.

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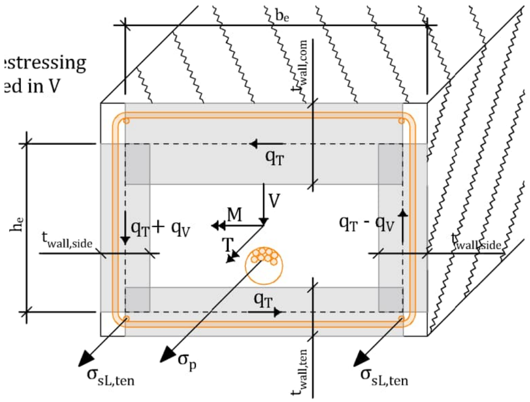
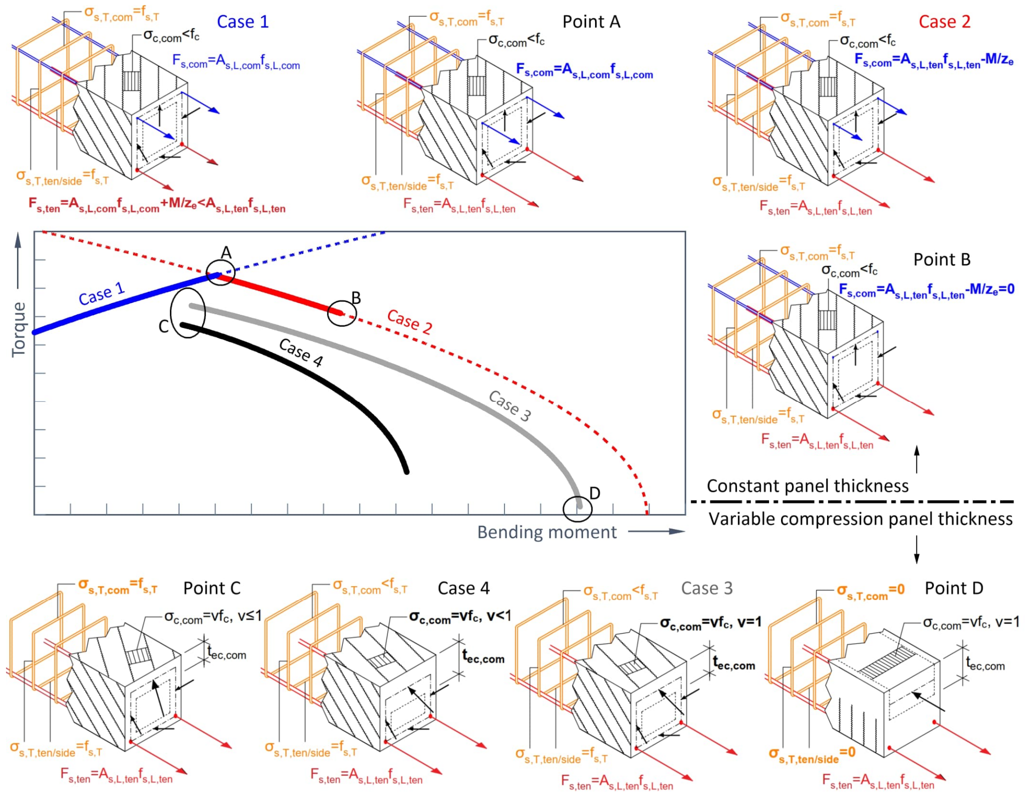
Plasticity-based space truss model

- 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
- Adjusted and verifiedfor bending and torsion with SB-TM and database of experiments



- $t_{wall,side/ten} = k_{wall} * (A_c/u_c)$,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 equilibrium 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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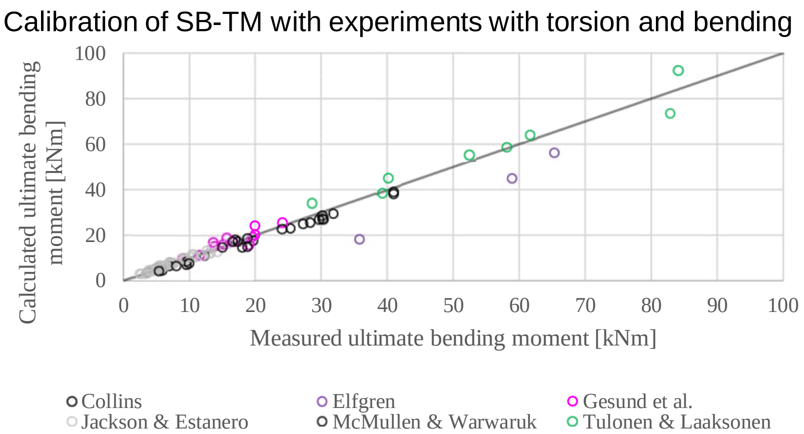
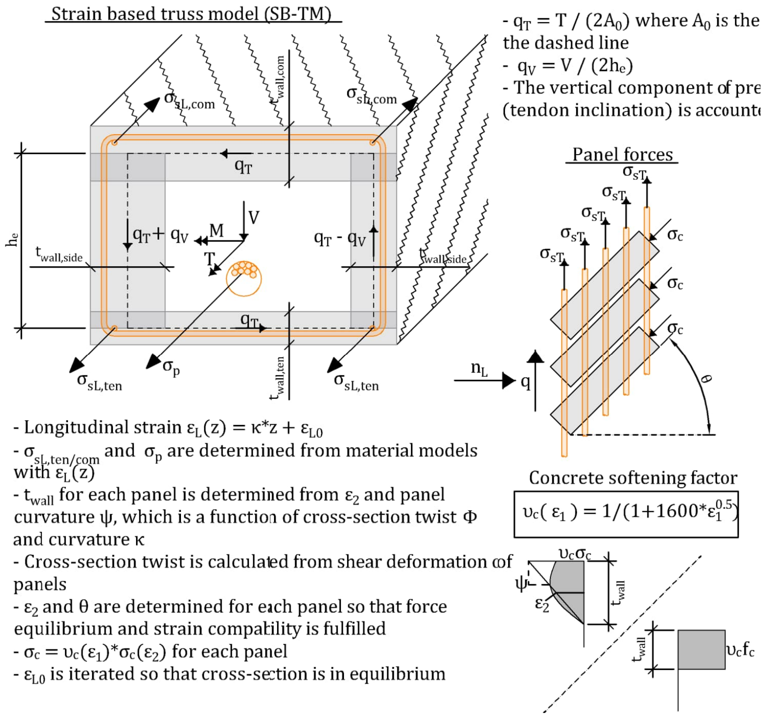
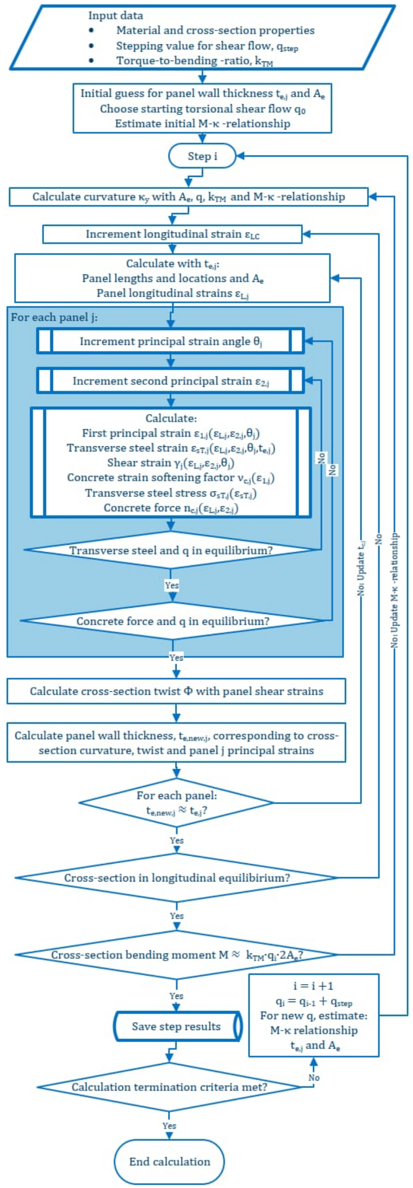
Strain-based space truss model

- 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
- Computionally heavy







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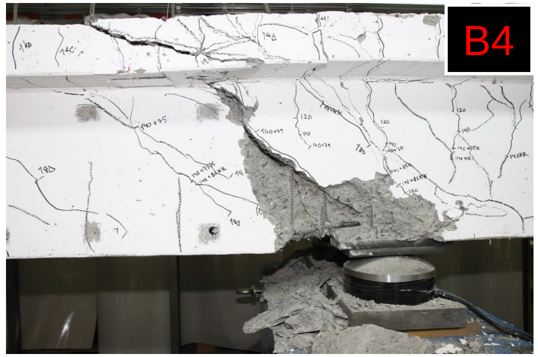
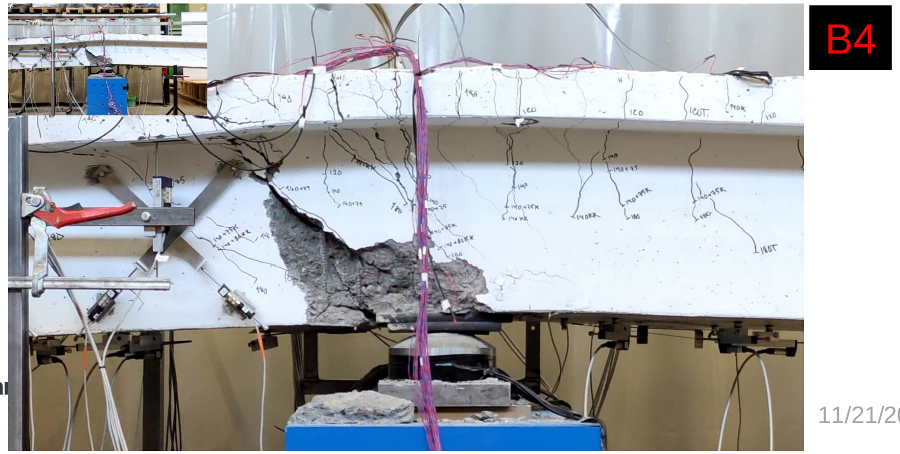
Beam experiments: Failure modes

- 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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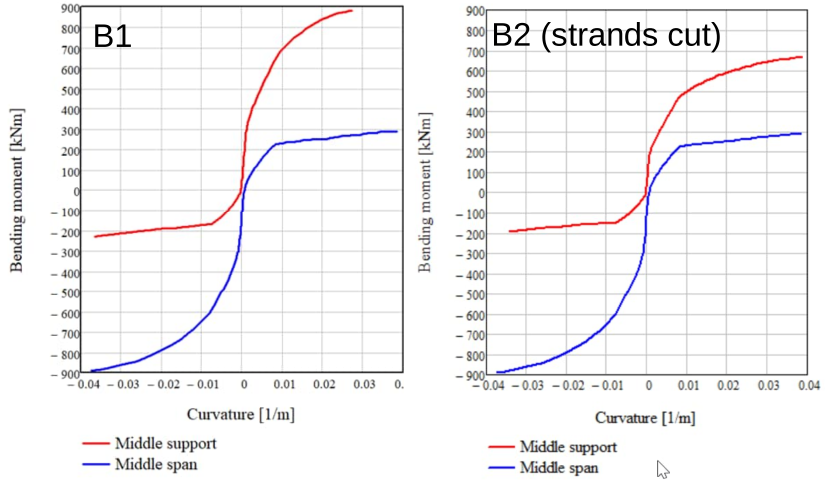
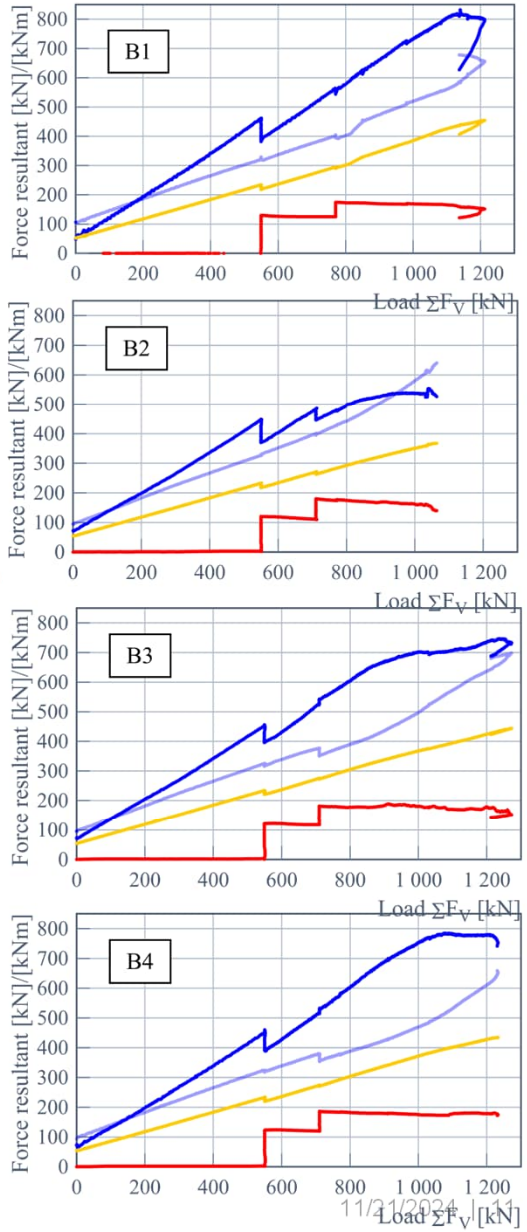
Beam experiments: Failure loads

- The failure loads of all beams was determined by the resistance in the middle support area
  - The loss of 50 % of the prestressing strands lowered the ultimate load only by 12 %
- The load capacity of beams B1 and B4 were almost the same, so the additional 12 d12 reinforcement compensated for the cutting of four 150 mm^2 strands
- Maximum bending moment was achieved with lower than maximum load due to some load redistribution
  - The shearing-type failure of the concrete in the side face at the support limited the rotation capacity

Calculated moment-curvatures (without torque or shear)





Torsion and shear capacities to EN 1992-1-1

Pure torsion: 386 kNm (cot θ = 1.68, simultaneous yielding of hoops and crushing of concrete, demand of longitudinal force: 909 kN)

Pure shear: 1037 kN (cot θ = 2.5 yielding of hoops, demand of longitudinal force: 2592 kN)

Shear with 180 kNm torsion: 712 kN (cot θ = 2.5 yielding of hoops, demand of longitudinal force: 2431 kN)

Longitudinal yield capacity of total reinforcement at the support: B1 2501 kN, B2 1547 kN, B3 1899 kN, B4 2251 kN

Vertical component of prestressing force at 0,6 m from 4° inclinination: 75 kN

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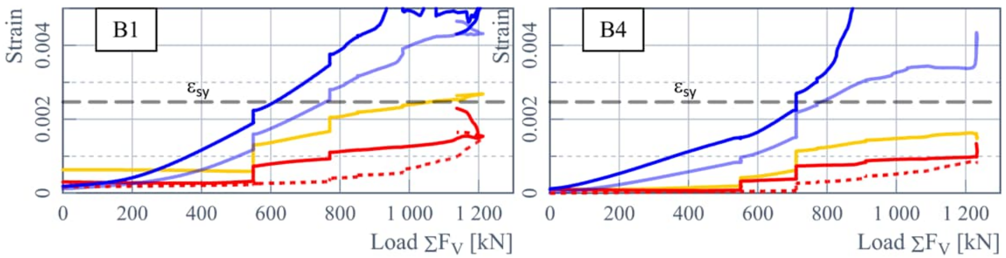
Comparison with the calculated results

- 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

Conclusions

- Combining the effects of bending, torsion, shear is essential in predicting the ultimate load of prestressed beam
- The negative effects of tendon breakage can be reduced by having statically indeterminate structure where bending stress redistribution is possible – effects of shear and torsion may however dominate failure – sufficient ordinary reinforcement is needed
- 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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