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ETEVÄ-BRIDGES:

Structural robustness of post-tensioned bridge in case of tendon failure

Presentation 5.2.2025

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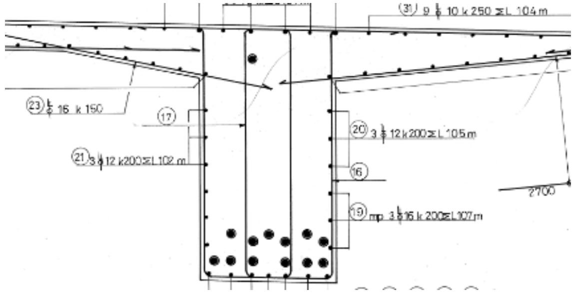
Background and motivation

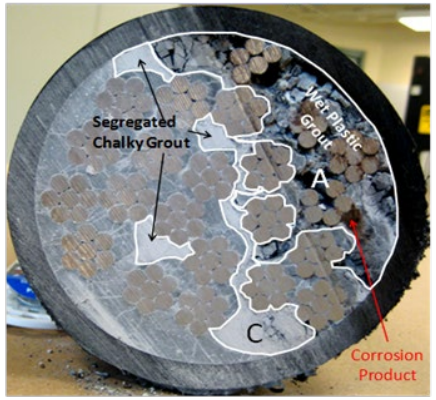
Motivation and background

- Pre- and post-tensioning is common method for construction of demanding concrete structures
    - 9 % of Finnish bridge population (ca. 1700 pcs.) is post tensioned
    - The prestressed bridges cover 34 % proportion of overall length of all bridges
    - Major part of prestressed bridges in Finland is built after 1990’s
    - Increasing traffic loads place new demands on structures
- Tendon corrosion problems due to hydrogen embrittlement
    - A few tendon grades are prone to hydrogen corrosion, and all grades are more prone to corrosion in comparison to normal reinforcement steel
    - How strucure performs if tendon strands break?
    - 60-90 % of capacity of beam bridges is carried by tendons
    - The corrosion problem of prestressing steel is global. The cases are reported around the world.



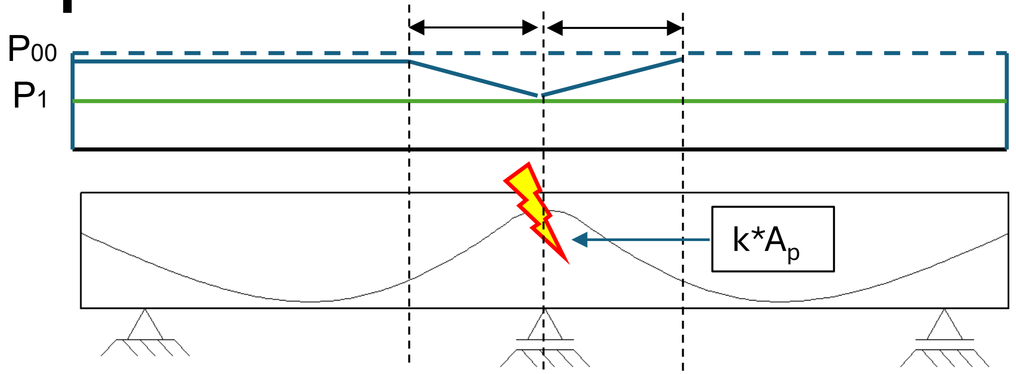
Research problem

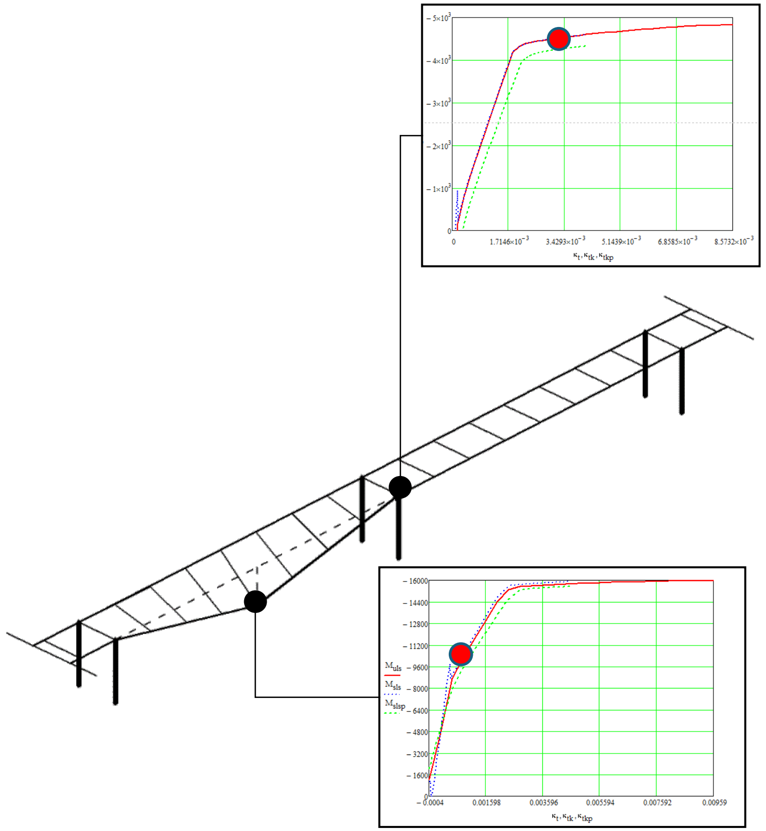
- If the grout has not filled the tendon ducts completely:
    - The corrosion can initiate
    - Possible effect on bond and re-anchoring behaviour
    - Is it possible to take advantage of tendon re-anchoring in grout in case of poor grouting and tendon failure?
- If the tendon corrosion has propagated:
    - Is the safety level of structure still adequate, is sudden collapse possible without warning?
    - Is it possible to notice early signs of tendon damage?
- There's only a little research considering a structural behaviour of real structures in case of internal post grouted tendon failures.



Robustness of bridge, concepts

- Local – cross-sectional ability to withstand damage
  - Capacity of intact tendons
  - Capacity of reinforcement
  - Crack-before-failure behaviour
- Global – Structural behaviour in system level
  - Moment redistrubution in longitudinal and transversal direction
  - Rotational capacity
  - Post-critical capacity of cross-section





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Research project and methodology

Articles of dissertation

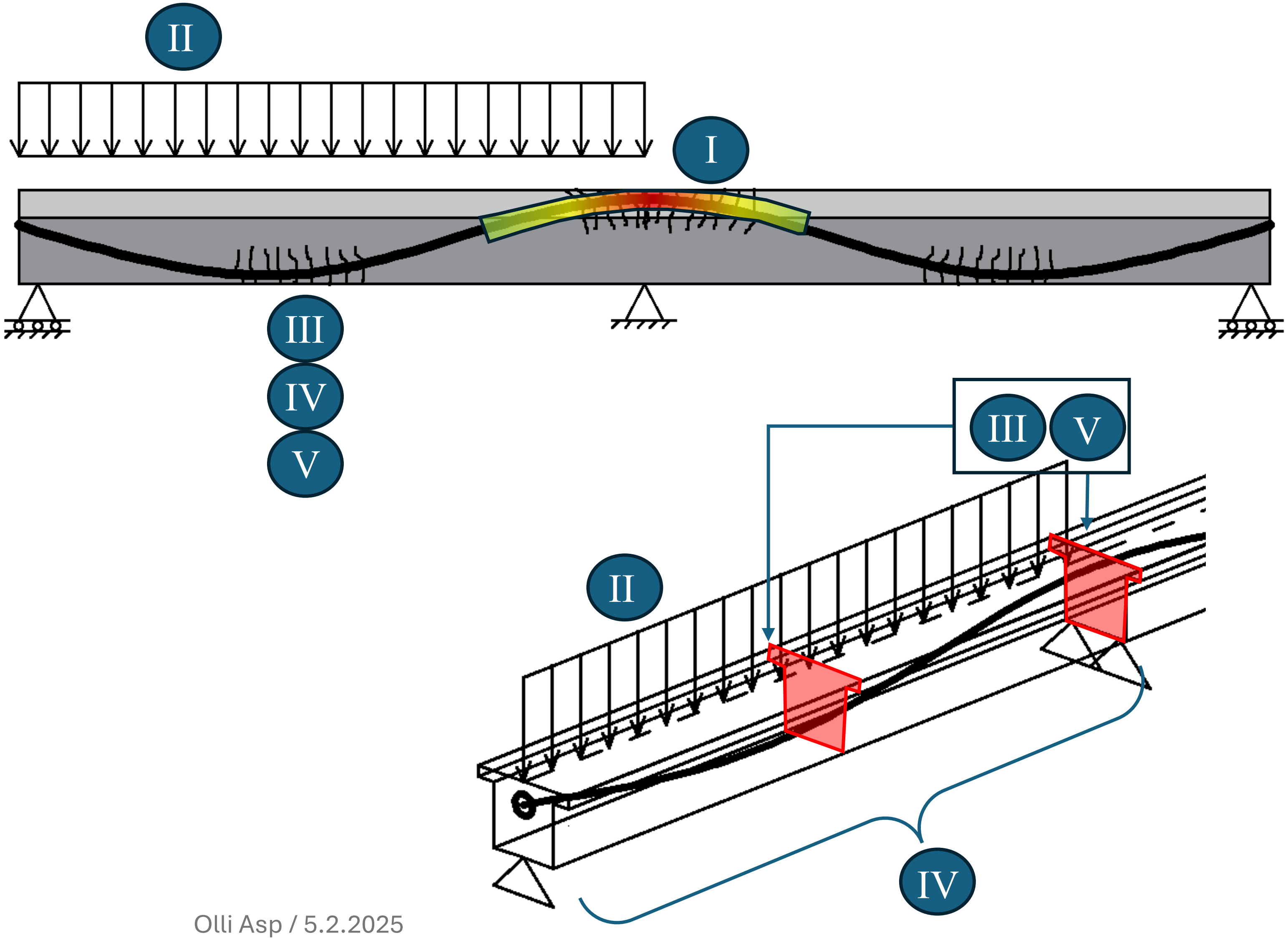
I Bond and re-anchoring of tendon in case of strand failure

II Evolution of traffic loads and characteristics affecting on road bridge structures

III Redundancy and reliability levels of grouted PTC-cross-section in case of tendon failure

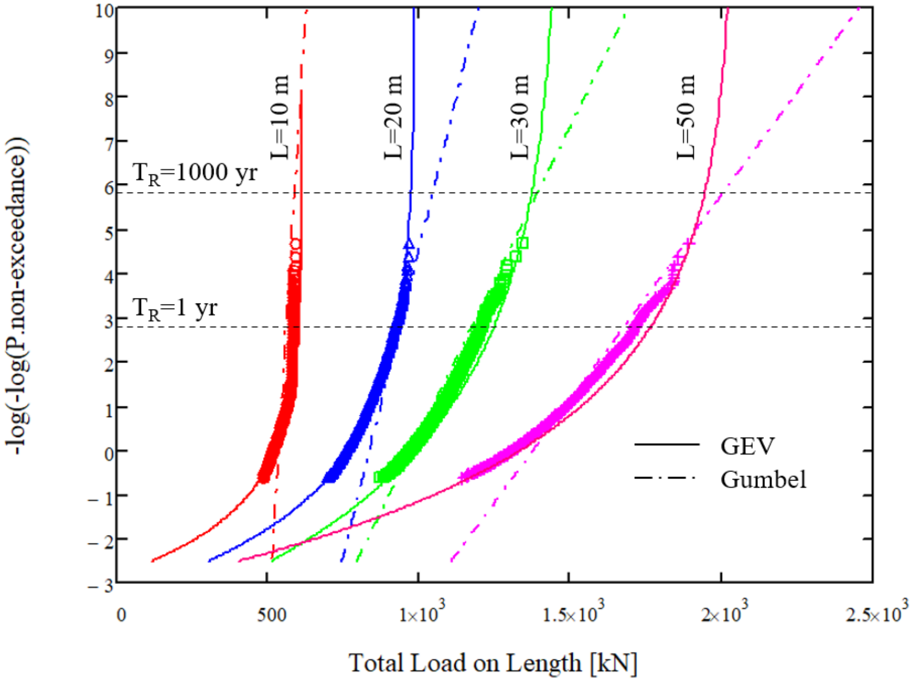
IV Pre-Failure behaviour and robustness of PTC structure in case of middle support tendon failure

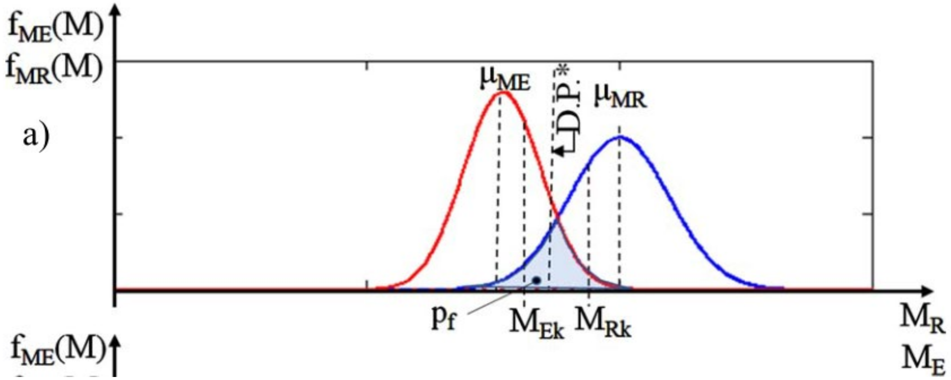
V Bond and re-anchoring effects at PTC cross section



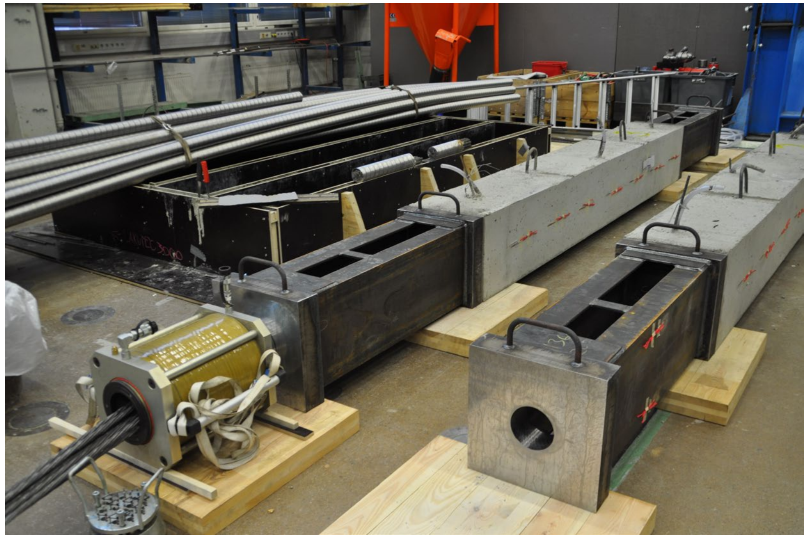
Methodology

Simulation and reliability analysis

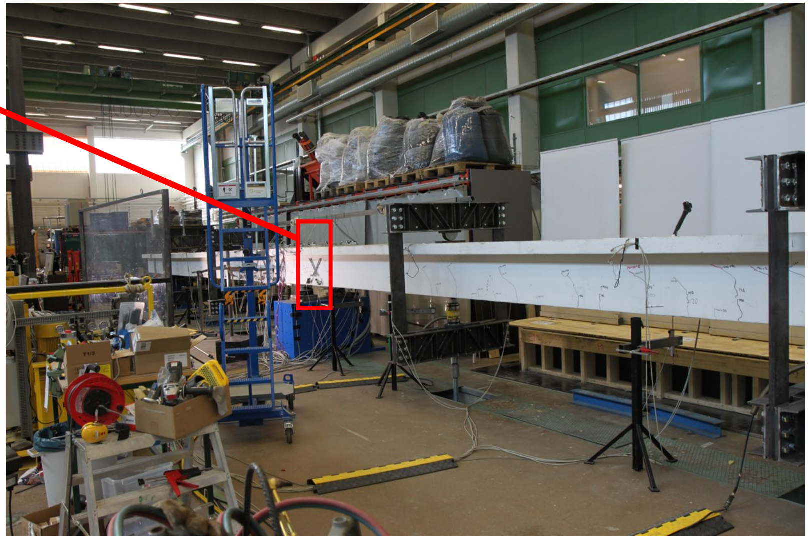




Experimental research



Notch at middle support top to flame cut the strands



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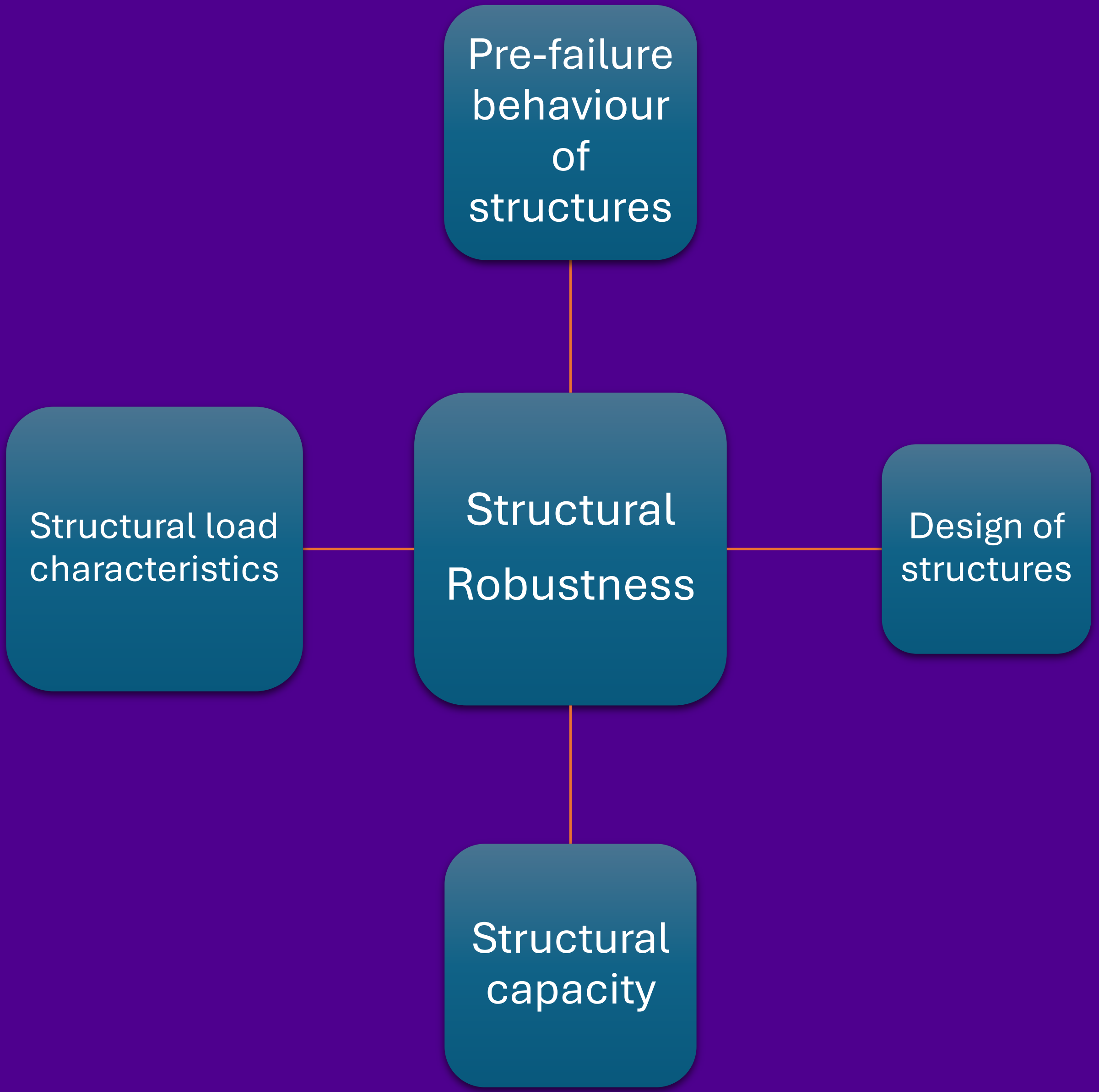
Results


Pre-failure behaviour of structures

Structural load characteristics

Structural Robustness

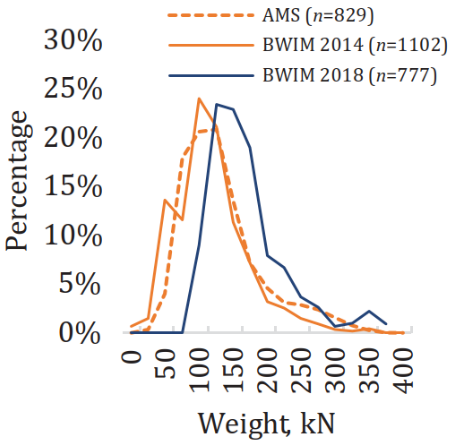
Design of structures

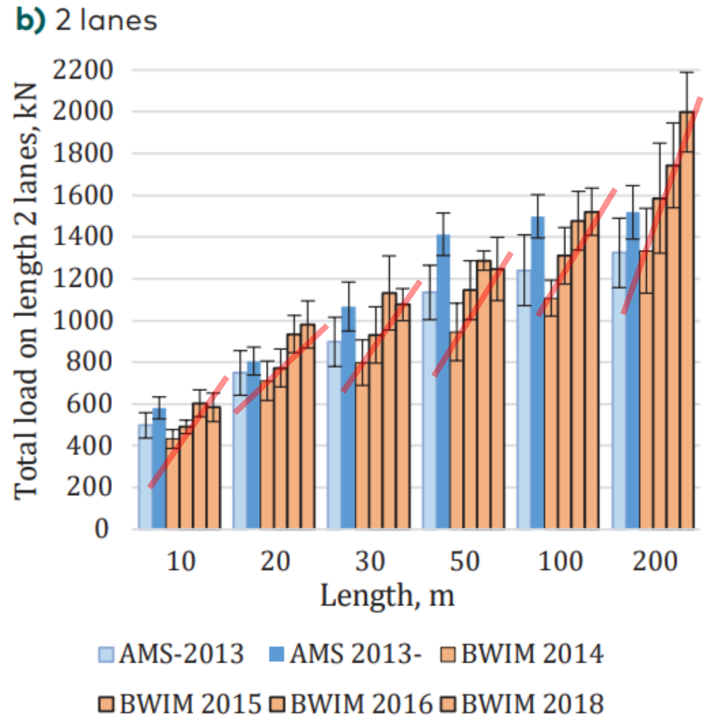
Structural capacity

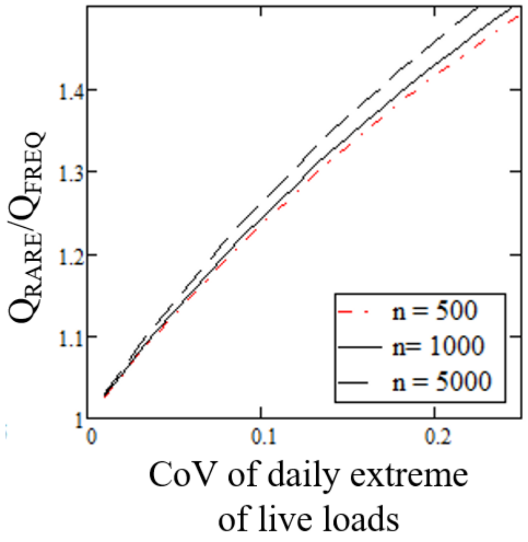
TRAFFIC LOAD MODEL CALIBRATION AND COMPARISON TO EVOLVING TRAFFIC LOADS IN 2014–2018

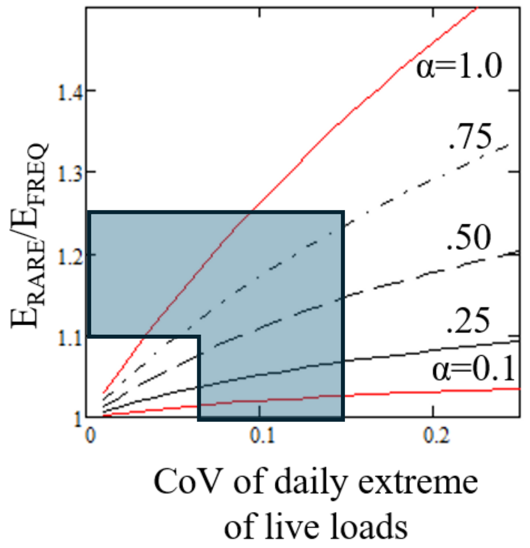
Key results:

- Statistical characteristics of traffic load effects and evolution of traffic loads due to legislation change in 2013
- Methodology and key aspects for construction of traffic load model based on simulation for further use
- The ratio between **rare and frequent** load is found to be **1.1..1.3.**
- The selected conservativeness of background simulations of LM1-2014 has vanished during monitoring period between 2014 and 2018
- While average traffic load effects increased approximately 10 % , the coefficient of variation remained.









Bond and re-anchoring tests of post-tensioned steel tendon in case of strand failure inside cement grouting with voids

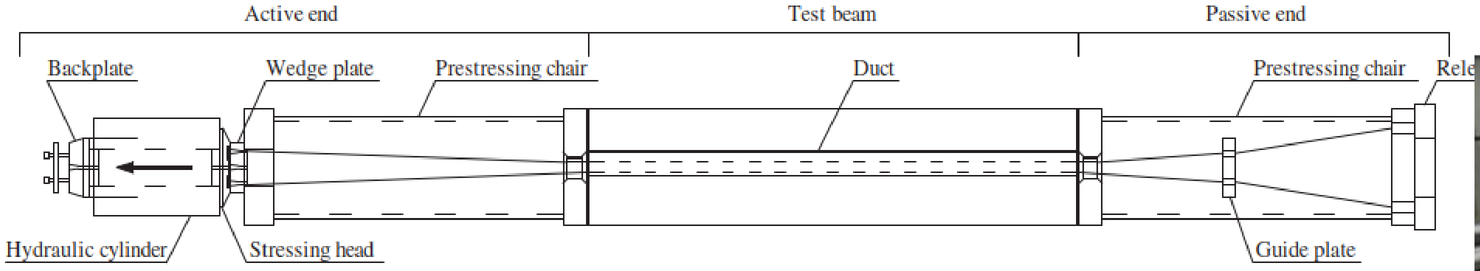
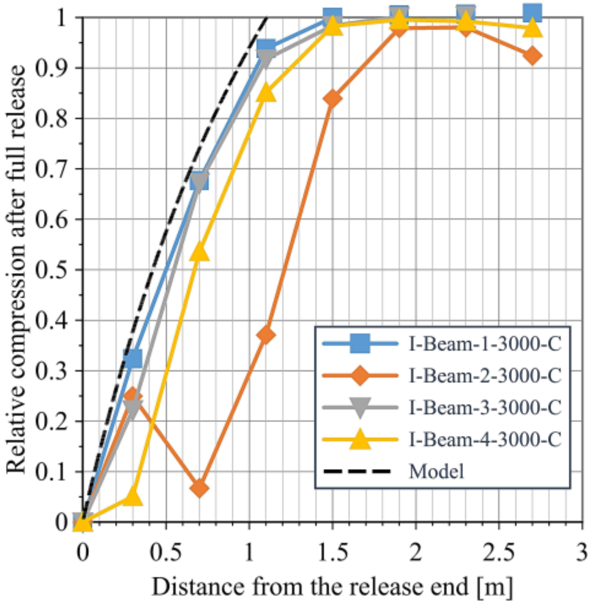
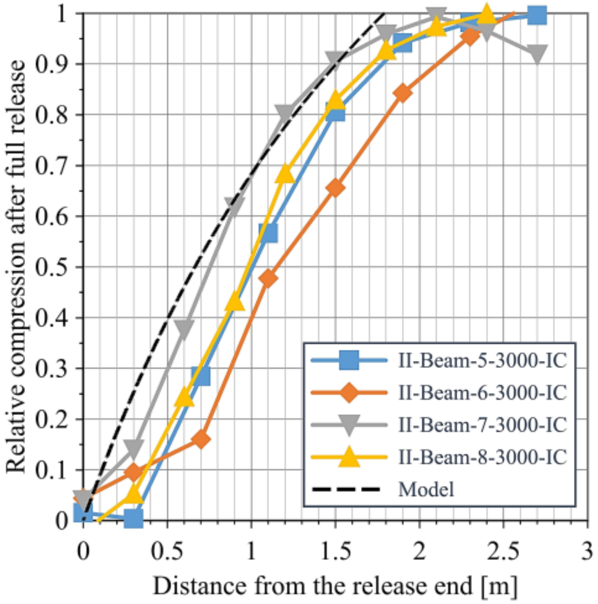
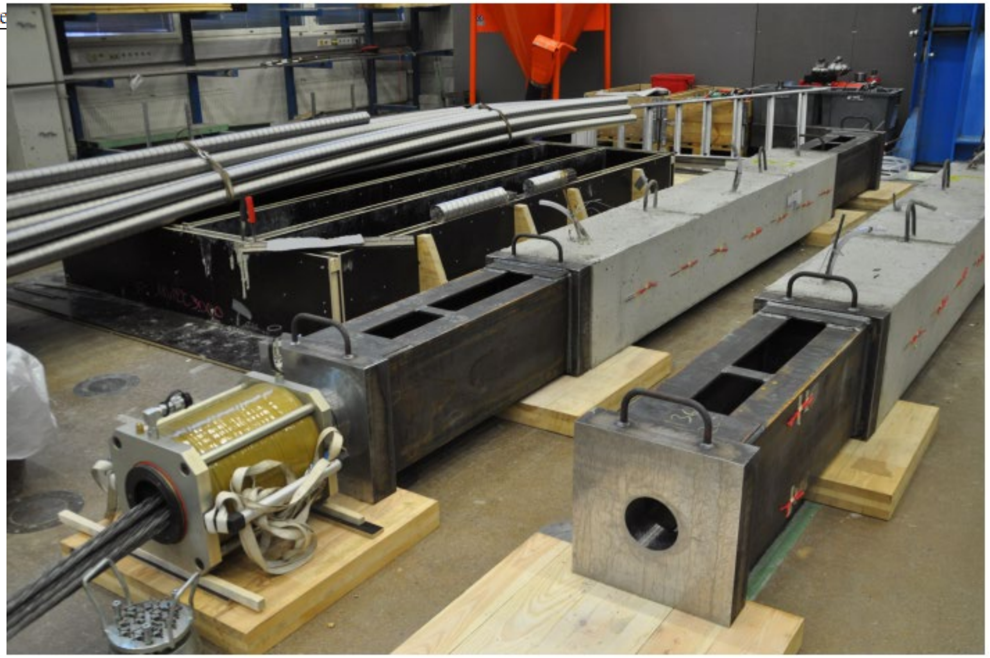


FIGURE 1 Schematic drawing of test setup



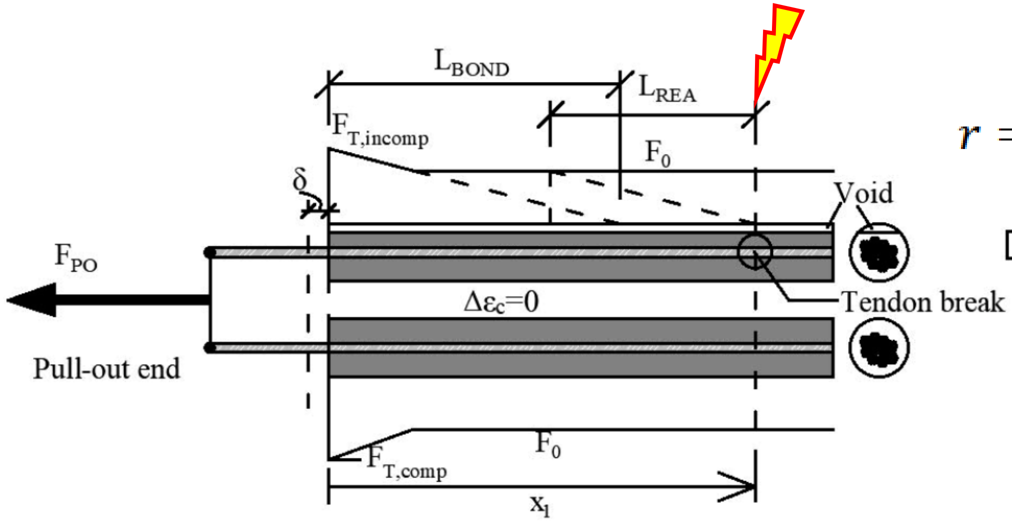




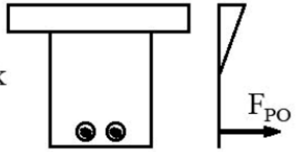
Key results:

- Re-anchoring length and calculation method for bundle of strands in complete and incomplete grout, verification and parameters for calculation
- Verification of the effect of overlapping bond and re-anchoring lengths
- With poor grouting the re-anchoring length increases **from 1.3 meters to 1.7 meters.**

Bond and re-anchoring tests of post-tensioned steel tendon in case of strand failure: Redistribution model of tendon forces in Pull-out

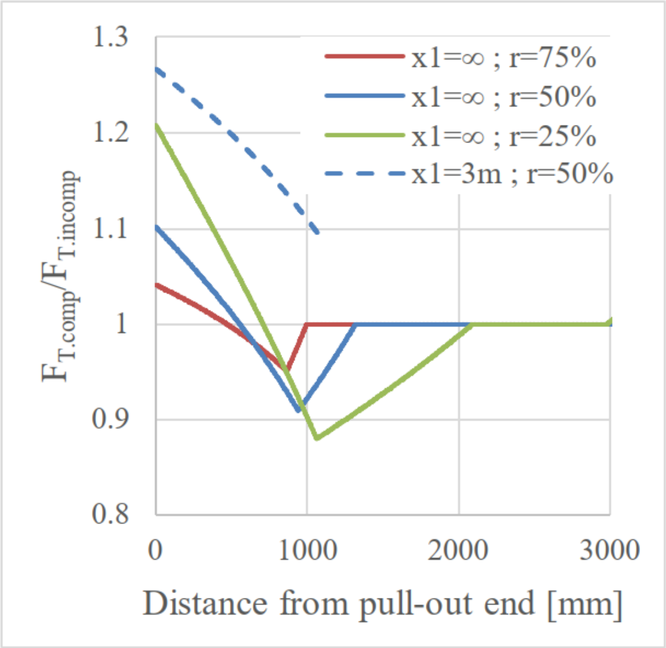


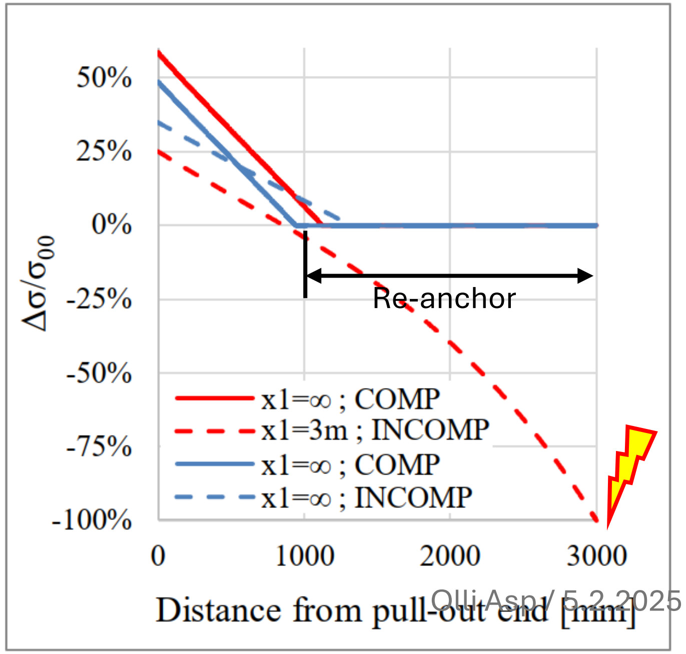
$$r = \frac{q_{b.incomp}}{q_{b.comp}} = \frac{(\tau_b \times p_{bp})_{incomp}}{(\tau_b \times p_{bp})_{comp}}$$



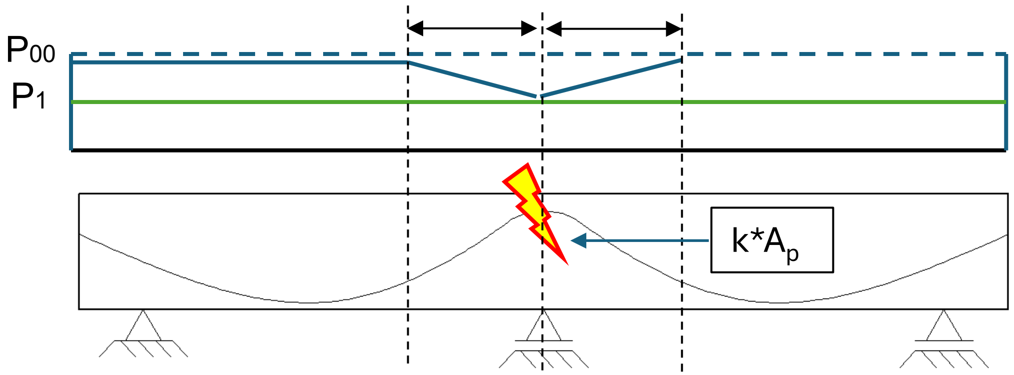
Key results:

- Force distribution between tendons with complete and incomplete grout in case of external force, from 10..20%
- Poor grouting conditions increase slip of poorly grouted tendons during pull-out → more force on complete grouted tendons.
- Tendon broken in proximity of pull-out section the overlapping of re-anchoring increased ratio of slip / force applied and therefore increased deformation of structure. Leading to more aggressive force redistribution +30 %

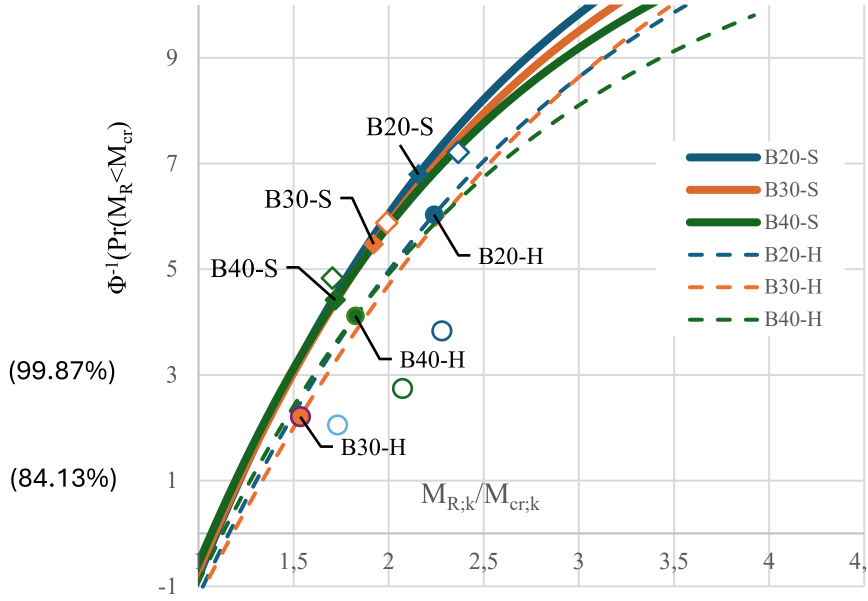


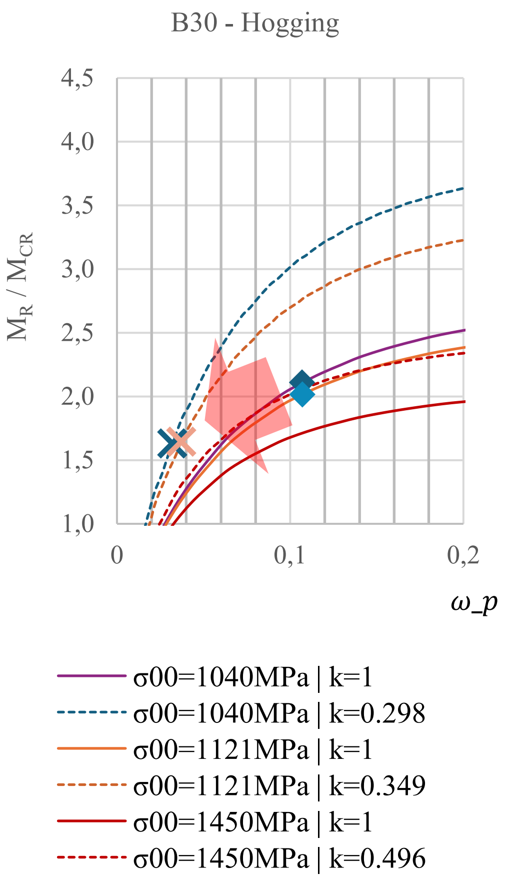


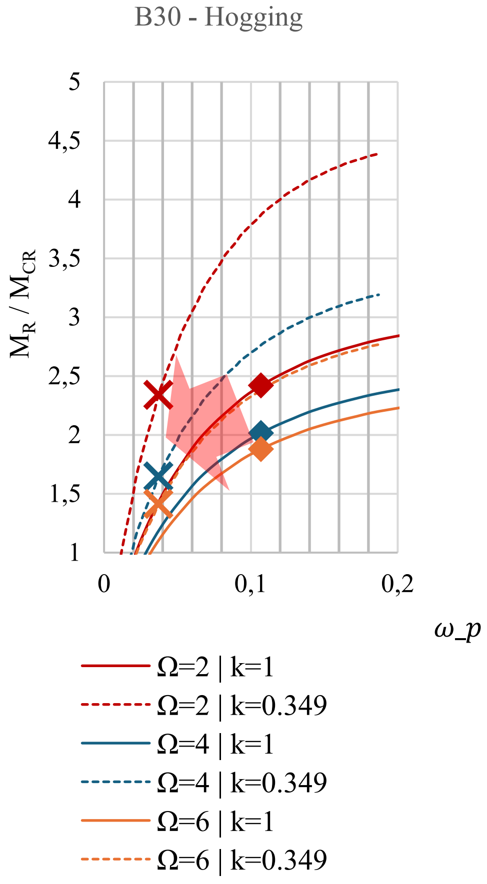
Redundancy and reliability levels of analysis method of post-tensioned and grouted concrete cross-section in case of tendon failure



Probability of $M_R > M_{cr}$ as function of $M_{R.k}/M_{cr,k}$







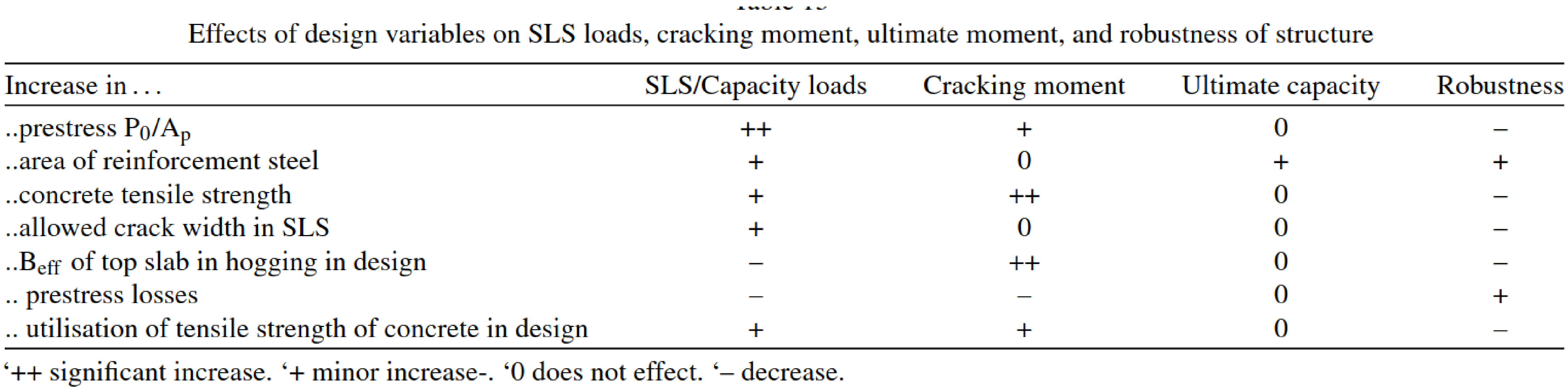
Effects of loss of PT-steel area

$$\Omega = \frac{\omega_p}{\omega_s} = \frac{A_p \cdot f_{pk}}{A_s \cdot f_{sk}}$$

Redundancy and reliability levels of analysis method of post-tensioned and grouted concrete cross-section in case of tendon failure

Key results:

- Case studies show that the **ratio between failure and cracking moment remained in order of 1.5** also with tendon loss, which verifies adequate crack before failure behaviour as typical ratio between **frequent and rare loads are in order of 1.1 and 1.3.**
- The limits of crack width and decompression in different SLSs increase the reliability and robustness of a bridge in ULS, also in case of tendon failure
- Sensitivity analysis proved different design variables on the robustness of a structure in case of loss of tendon area. The results are presented in a Table 13 that can be used to identify suspicious structures in a bridge stock population.

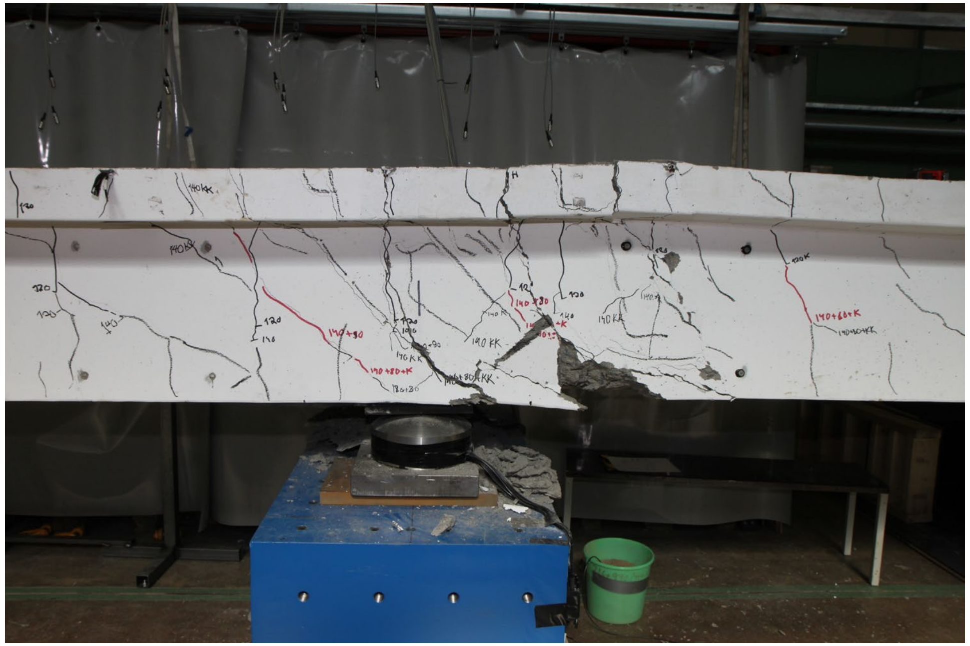


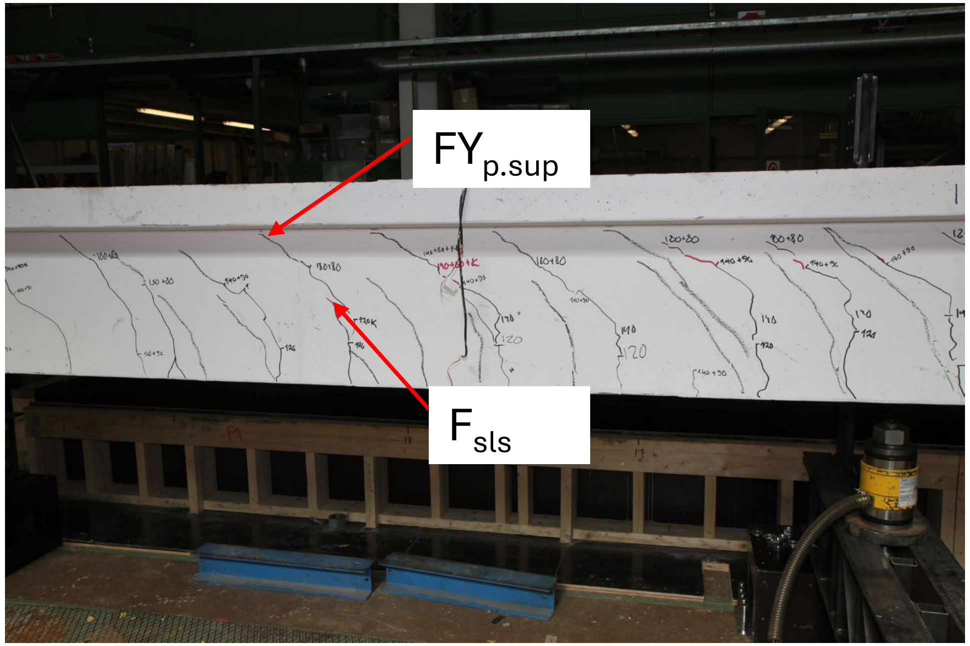
Effects of design variables on SLS loads, cracking moment, ultimate moment, and robustness of structure

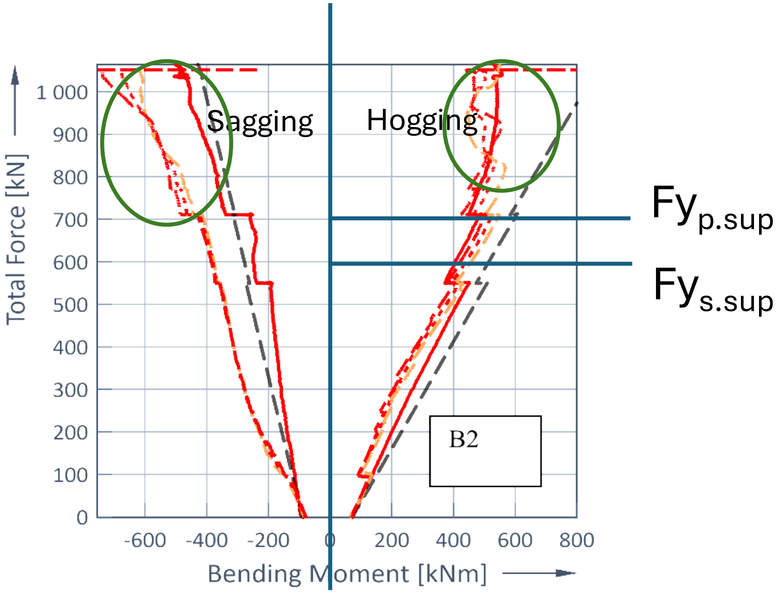
Increase in . . .	SLS/Capacity loads	Cracking moment	Ultimate capacity	Robustness
..prestress P_0/A_p	++	+	0	–
..area of reinforcement steel	+	0	+	+
..concrete tensile strength	+	++	0	–
..allowed crack width in SLS	+	0	0	–
..B_{eff} of top slab in hogging in design	–	++	0	–
.. prestress losses	–	–	0	+
.. utilisation of tensile strength of concrete in design	+	+	0	–

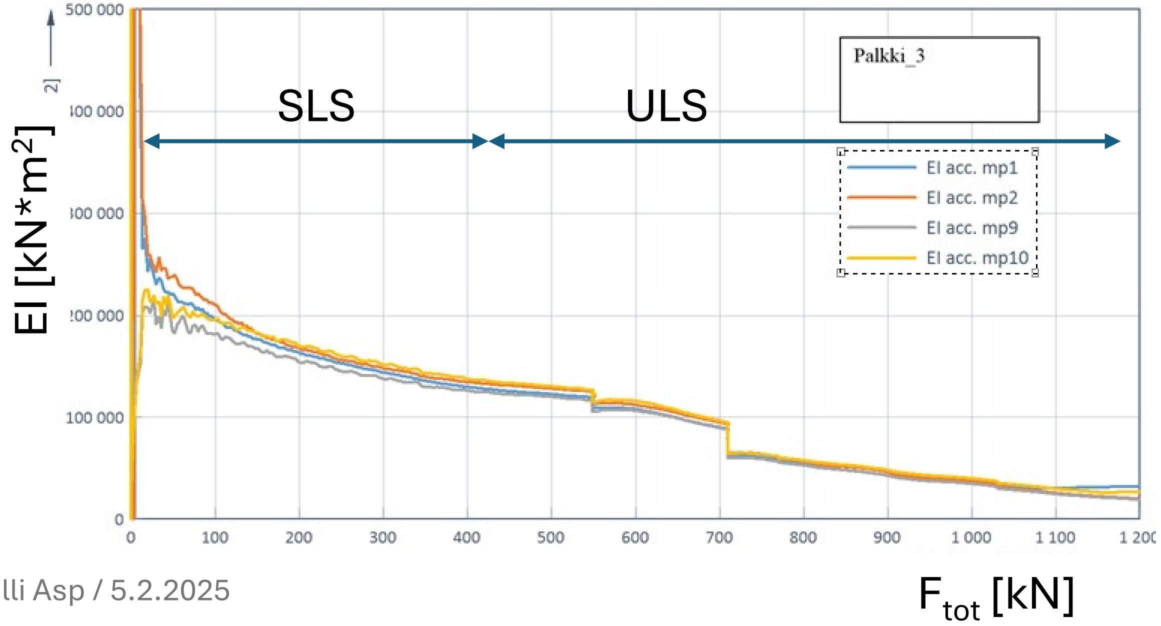
‘++ significant increase. ‘+ minor increase-. ‘0 does not effect. ‘– decrease.

Pre-failure behaviour of continuous post tensioned and post grouted beam in case of tendon failure



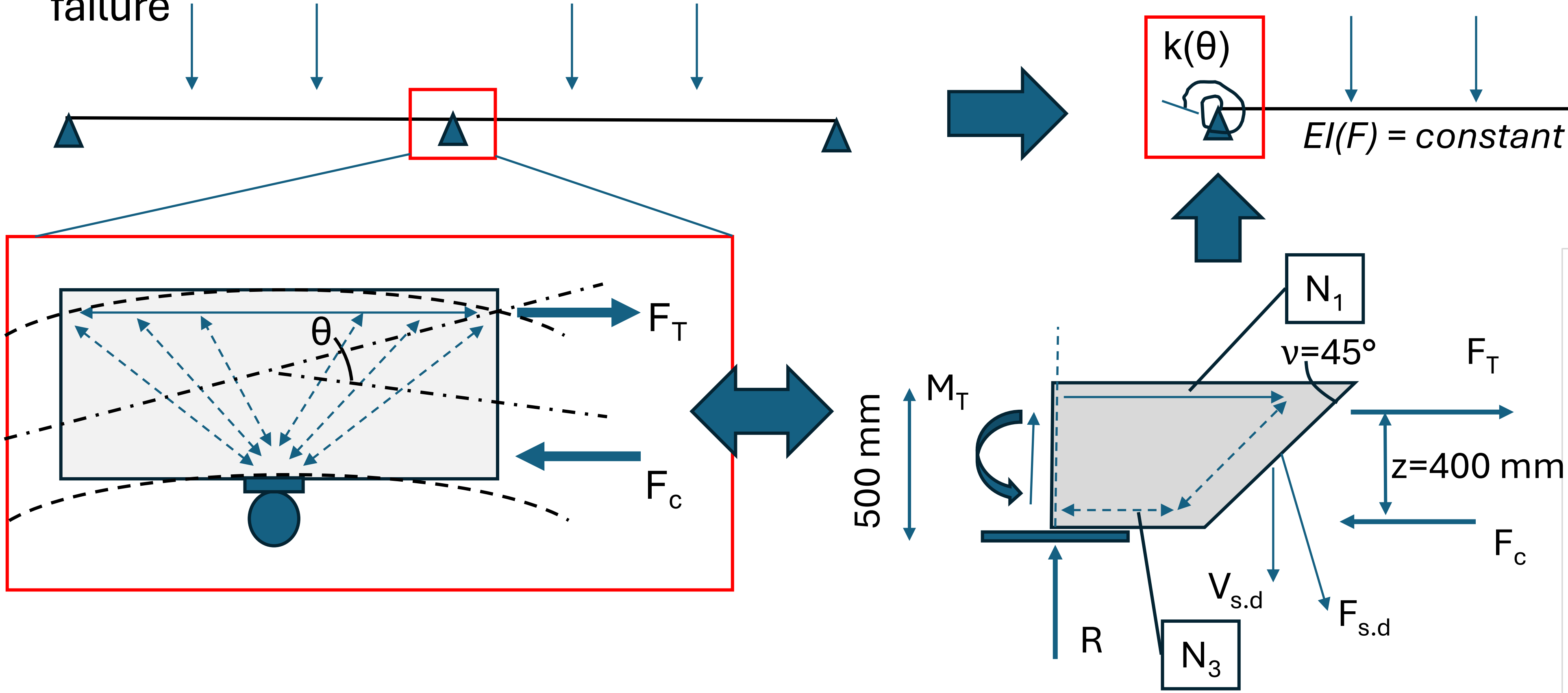


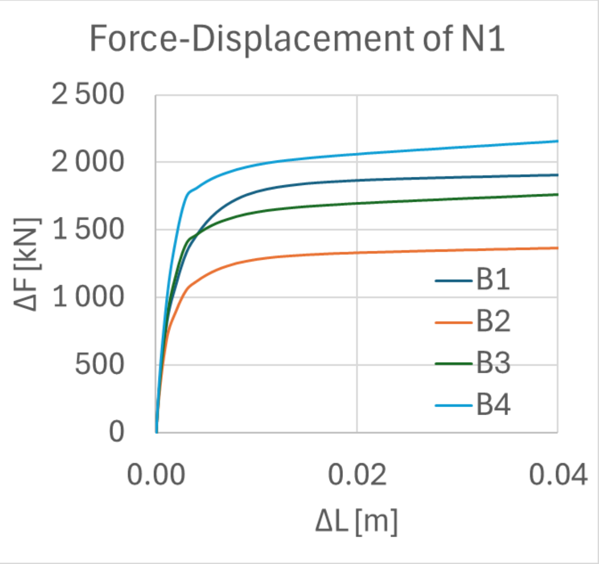




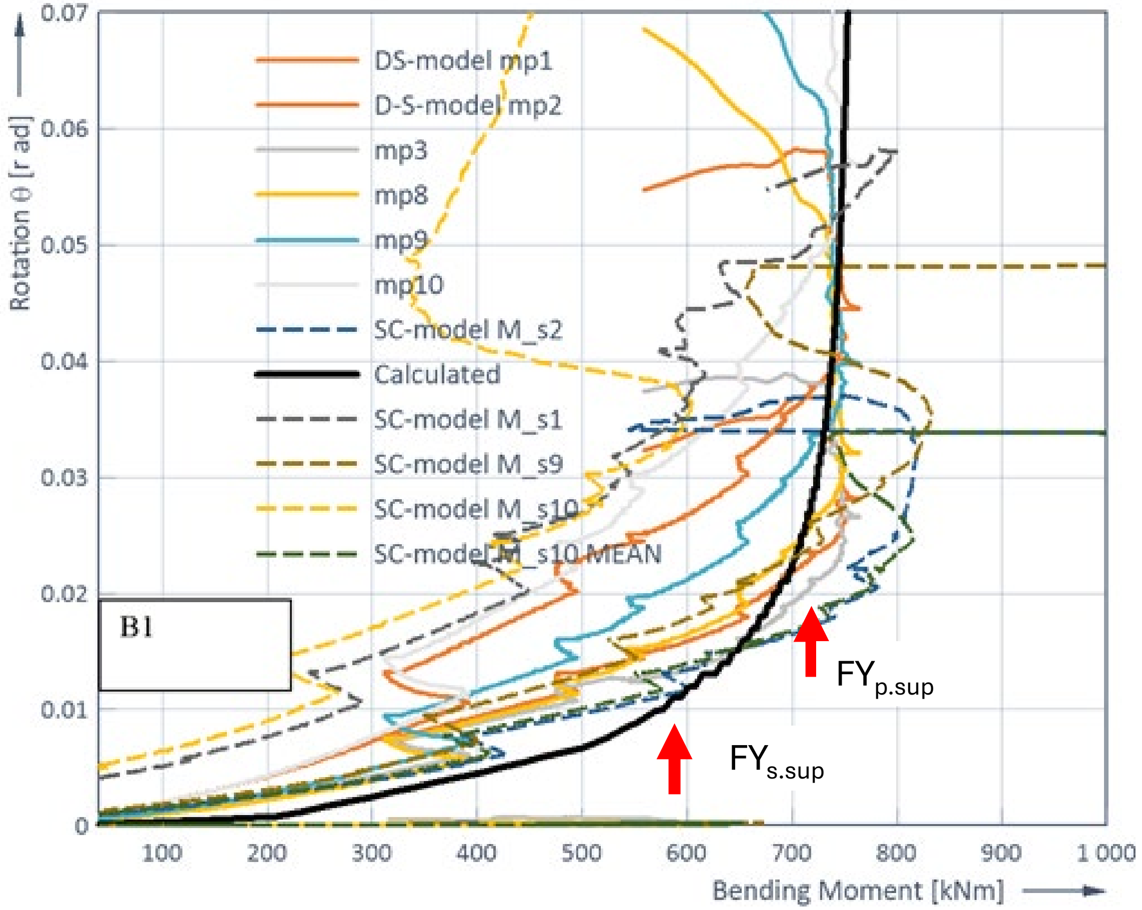
Olli Asp / 5.2.2025

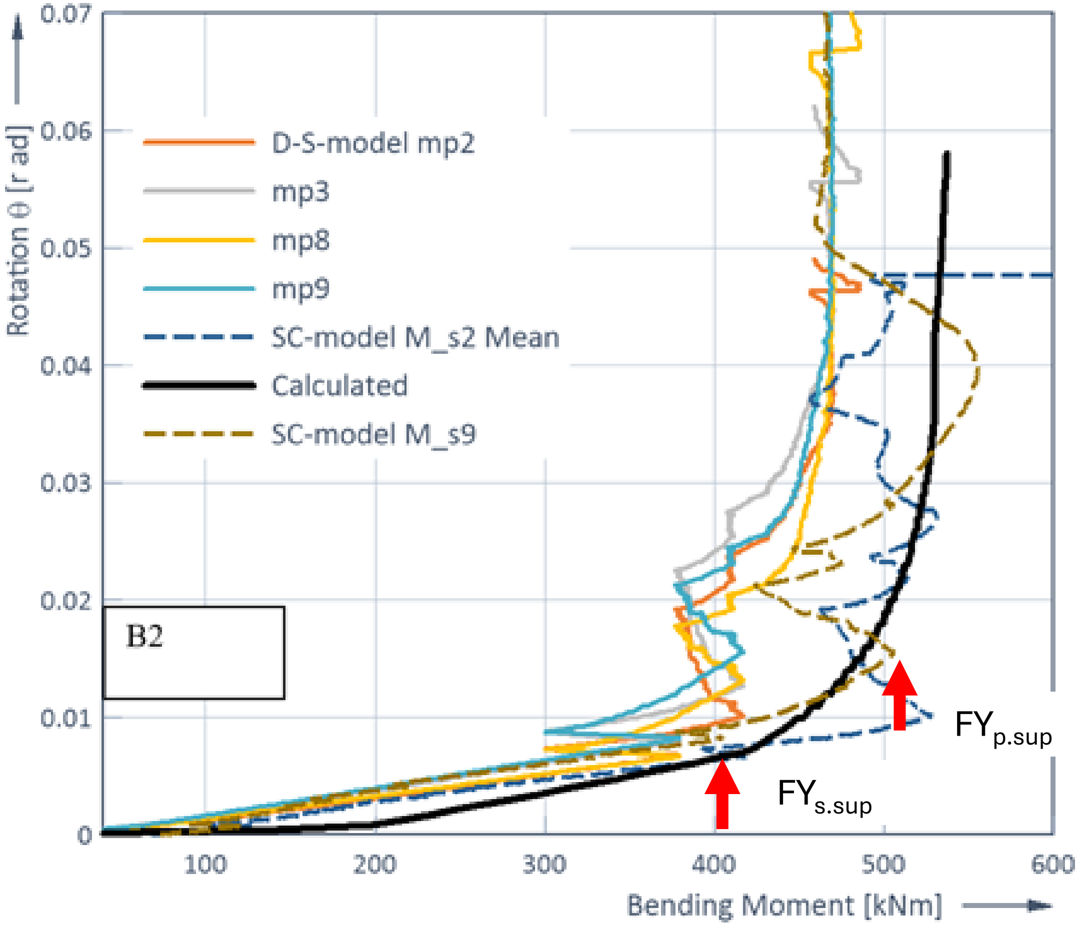
Pre-failure behaviour of continuous post tensioned and post grouted beam in case of tendon failure




Force-Displacement of N1

Pre-failure behaviour of continuous post tensioned and post grouted beam in case of tendon failure – Measured vs. modelled Moment-Rotation relationship on middle-support



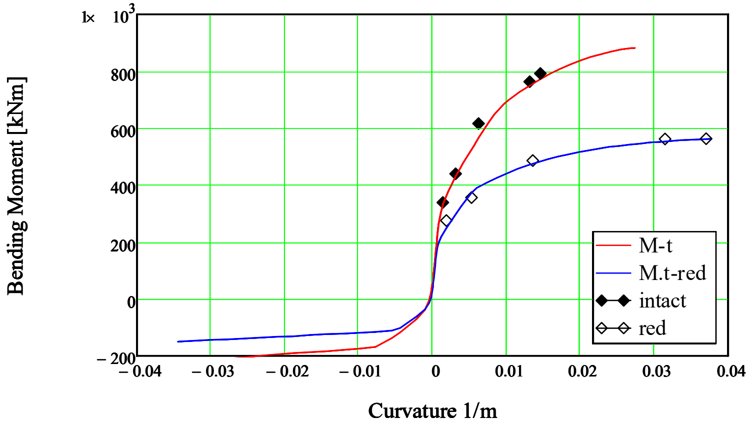


Pre-failure behaviour of continuous post tensioned and post grouted beam in case of tendon failure

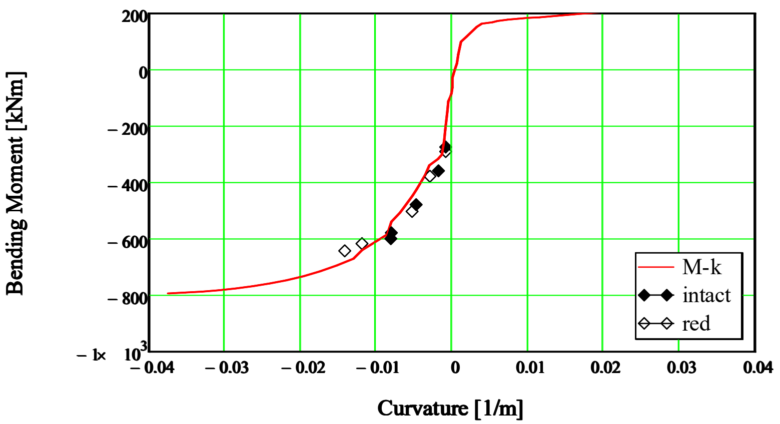
Key Results:

- Strong moment redistribution from middle support to field, due to tendon reduction in ULS.
- Low utility ratio of bending moment in field while ultimate at support ca. 70 % of ULS
- The amount of reinforcing steel has beneficial effect on robustness and ductility, the FU/Fy$_{sup}$ ~1.4 and FU/FY$_{span}$~ 1.15
- Recommendations and simplifications for analysis purposes: Strut-and-tie model for middle support action under tendon failure.

Hogging



Sagging



F=1040 kN

Results and conclusions

- The failure of tendon causes local effects which may have effects on global behaviour, in typical post grouted PTC bridge in Finland
  - This is due to re-anchoring capability of tendon, while there is at least some grout around strands
- The original design and used limit states have strong effect on robustness of structure in case of tendon failure.
  - The bridge designed with stricter SLS design criteria have also higher redundancy in ULS
- The ultimate capacity is significantly reduced due to loss of tendon. The cracking is highly probable due the fact that the M_R/M_{CR}-ratio remains almost the same despite the tendon loss.
  - The assumption in cross section ductility analysis leads that the cracks of cross section caused by tendon loss, needs to open multiple times with frequent load before the ultimate load occurs. This helps to recognize the upcoming failure and helps to redistribute the moments due to change in flexural stiffness
  - The moment redistribution due to hinge formation is observed the high enough rotational capacity increases robustness in global scale.
- The allowed cracking of ageing structures in use reduces the reliability of structure at ultimate. This should be considered while allowing higher loads on ageing bridges.

Thank You for your attention!

Questions?