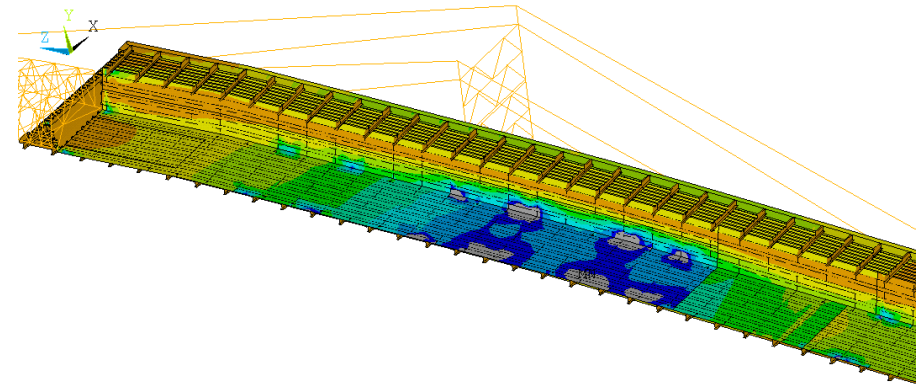
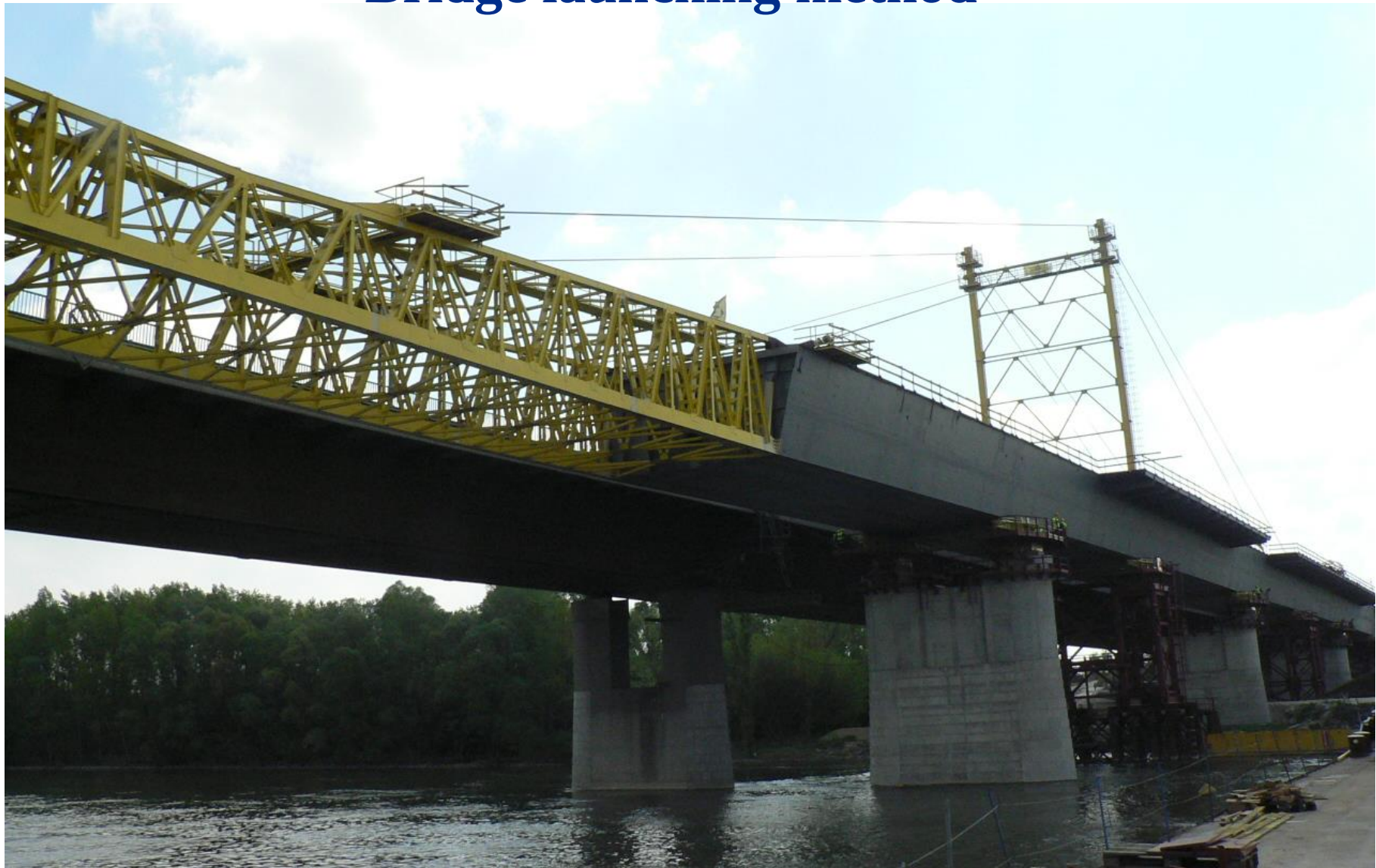


FEM based design of bridges

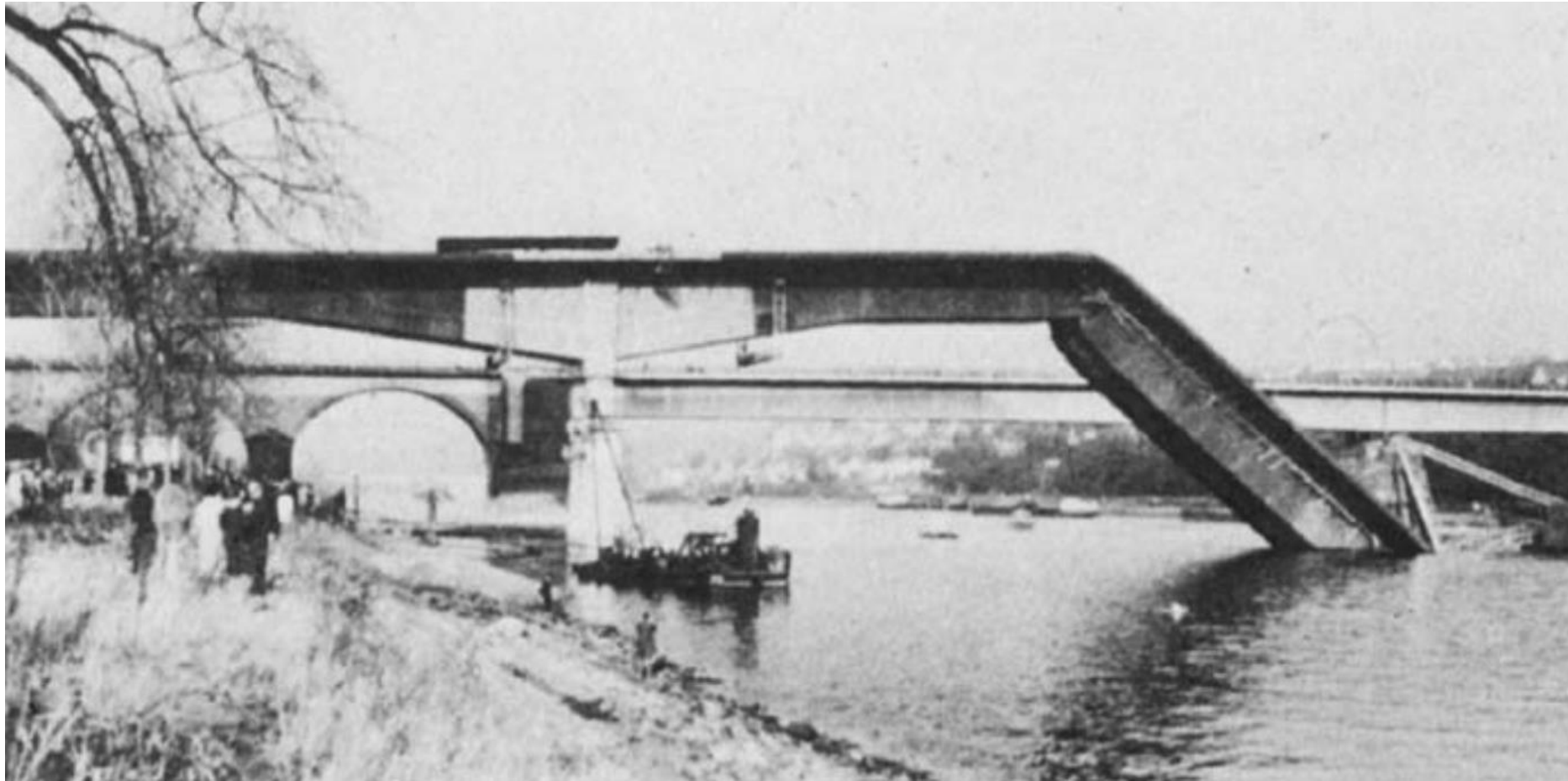


Balázs Kövesdi, PhD
Associate Professor
BME Dept. of Structural Engineering

Bridge launching method



Buckling failure of stiffened plate – Koblenz bridge

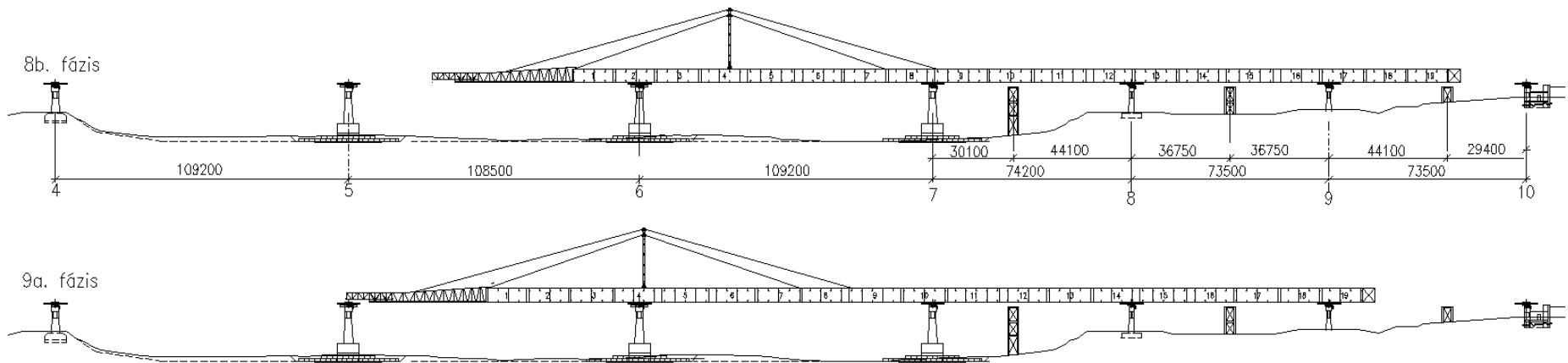


Patch loading check for local load introduction



Launching check of the Háros Danube bridge

Simulation of the launching process – static check of the superstructure and the launching device

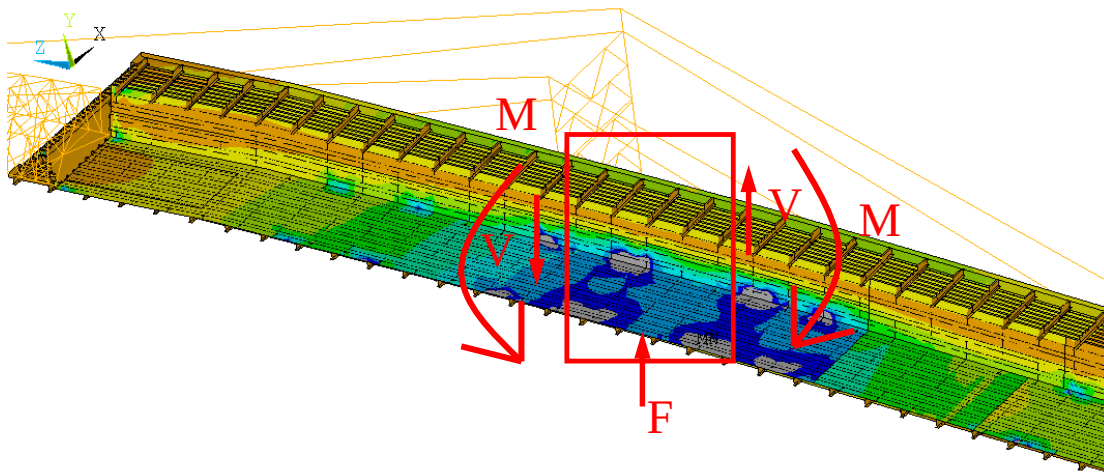


Problems to be solved:

1. Ultimate resistance of stiffened plate for $M+V+F$
2. Patch loading resistance check by hand calculation does not fit the requirements



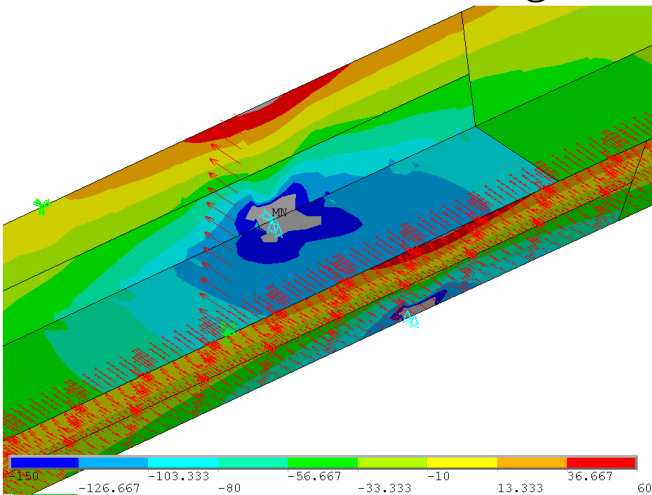
Small stiffeners applied



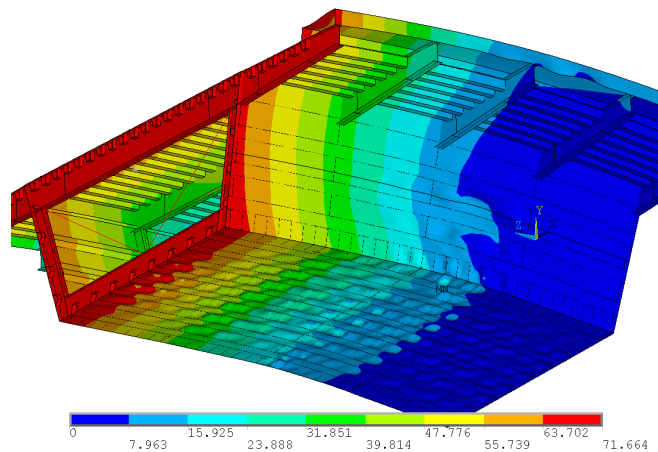
Check of the superstructure

Method: **GMNI analysis**

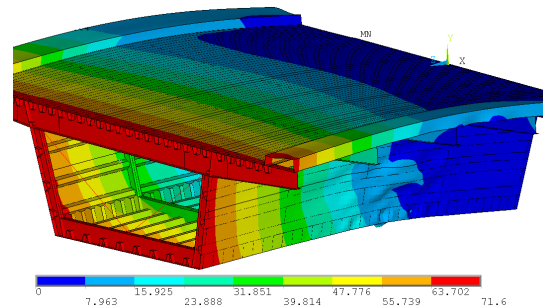
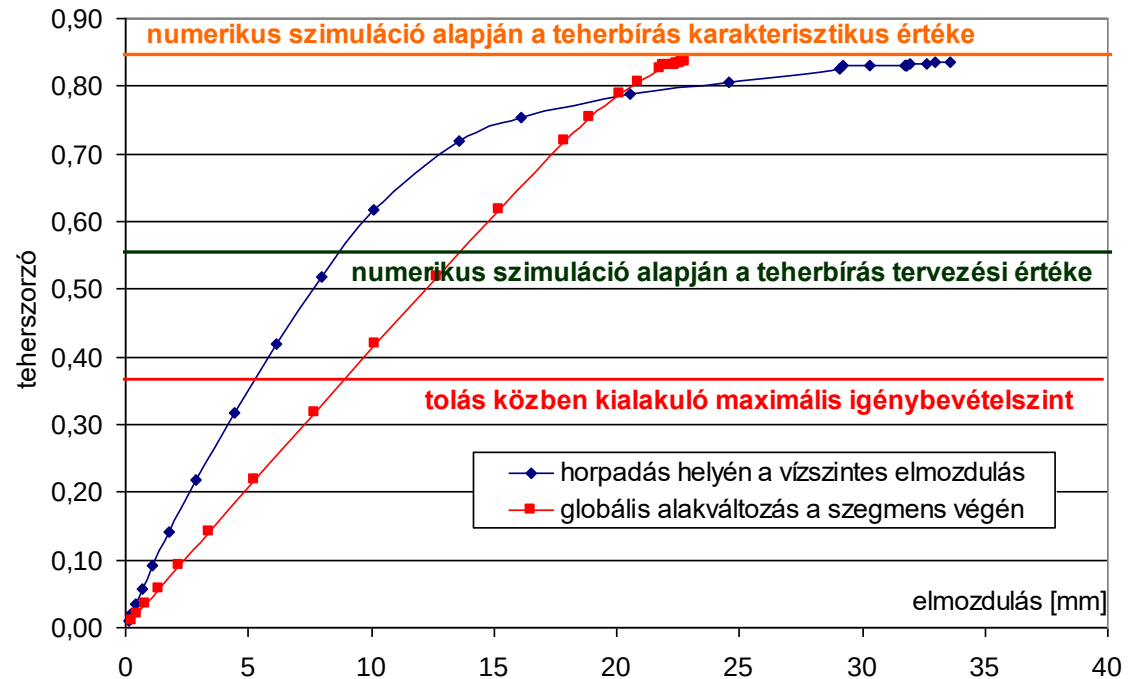
Ultimate normal stress diagram



Failure mode



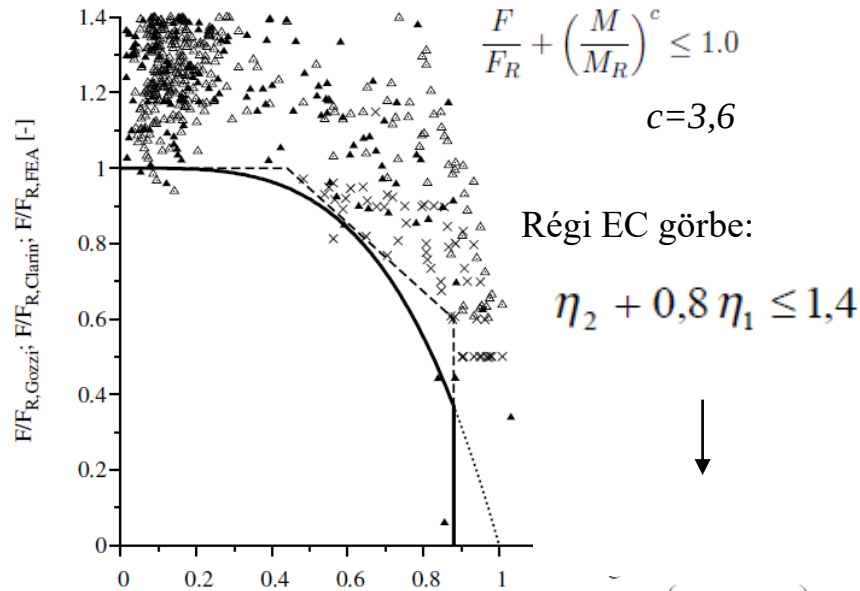
Result of the numerical simulation – 7/c phase



Interaction of bending and shear buckling

Background of the research

New interaction curve for F-M
(Kuhlmann/Braun)



Currently in the EN 1993-1-5

Combined equation for F-M-V:

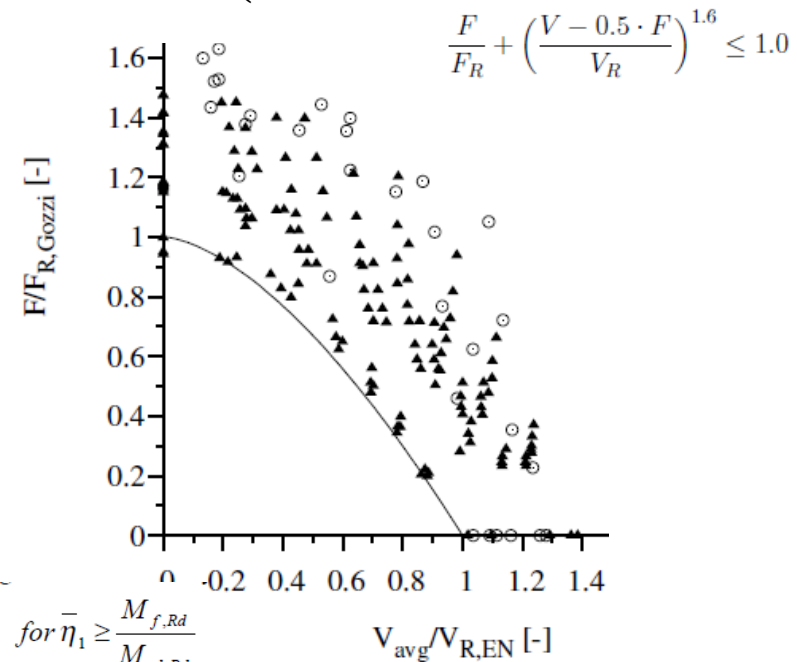
$$\frac{F}{F_R} + \left(\frac{M}{M_{pl,R}}\right)^{3.6} + \left(\frac{V_{avg}}{V_R}\right)^{1.6} \leq 1.0$$

→ proposed Amendment

- New curve was previously verified in F-M and F-V planes separately.

Aim of the research: Verification of the developed new F-M-V interaction surface in the 3D domain.

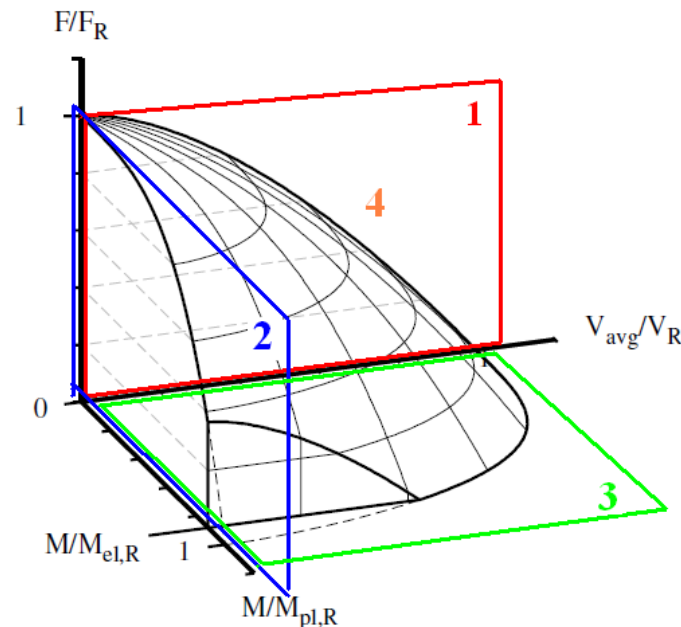
New interaction curve for F-V
(Kuhlmann/Braun)



$$\bar{\eta}_1 + \left(1 - \frac{M_{f,Rd}}{M_{pl,Rd}}\right) (2\bar{\eta}_3 - 1)^2 \leq 1.0 \quad \text{for } \bar{\eta}_1 \geq \frac{M_{f,Rd}}{M_{pl,Rd}}$$

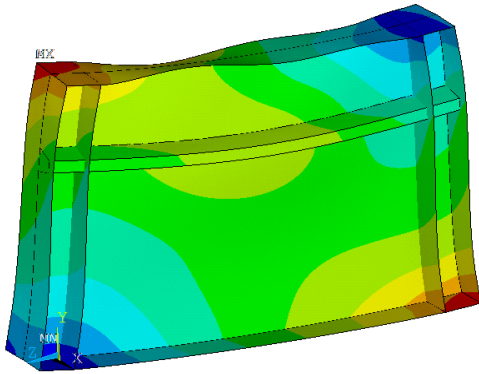
Strategy of the research

1. Numerical model development
 2. Model verification (based on experimental results of COMBRI project)
 3. Calculations in F-V plane (1)
 4. Calculations in F-M plane (2)
 5. Calculations in M-V plane (3)
 6. Calculations in the F-M-V domain (4)
- Aims: - model verification
- prove the F-M-V interaction curve in the planes: F-V; F-M; V-M interaction
- Aim: validation of F-M-V interaction surface

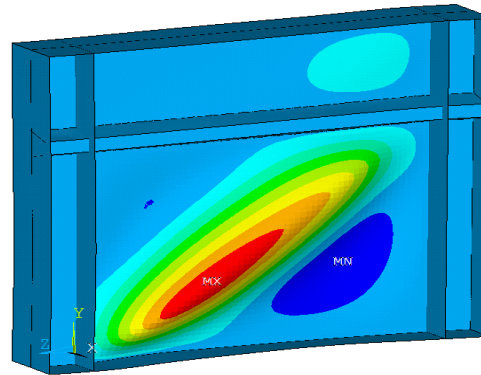


Analysed failure modes

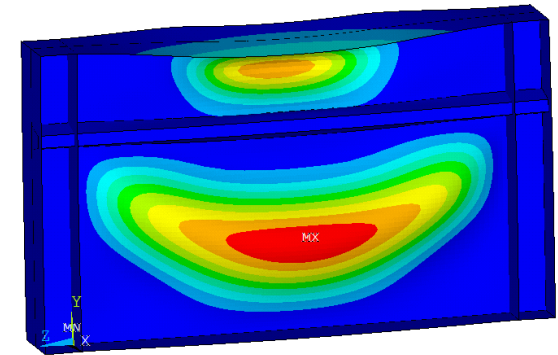
Bending



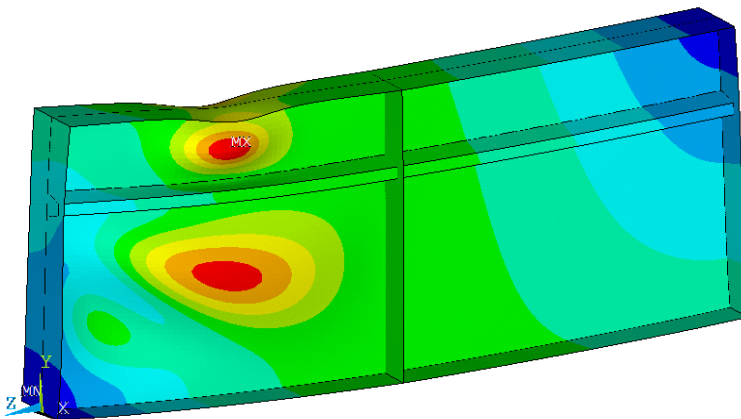
Shear buckling



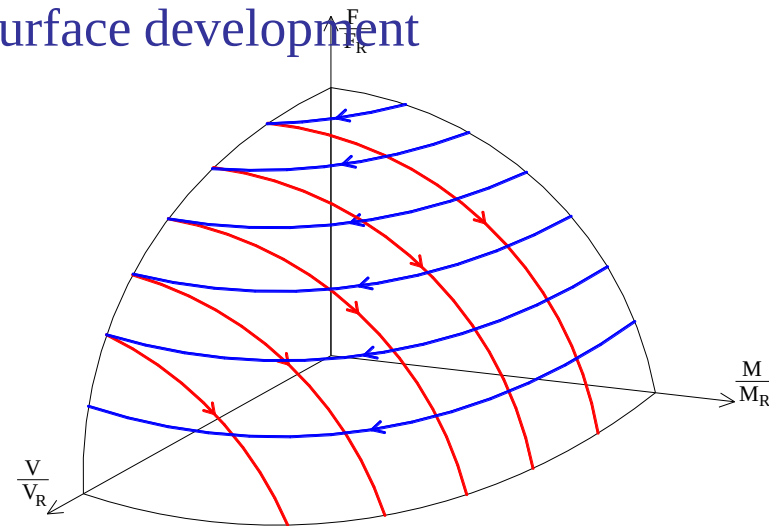
Patch loading



Combined failure modes

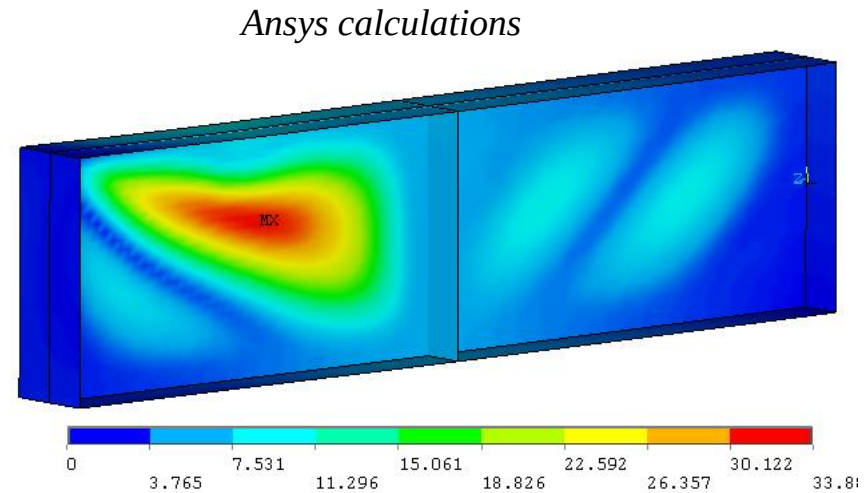
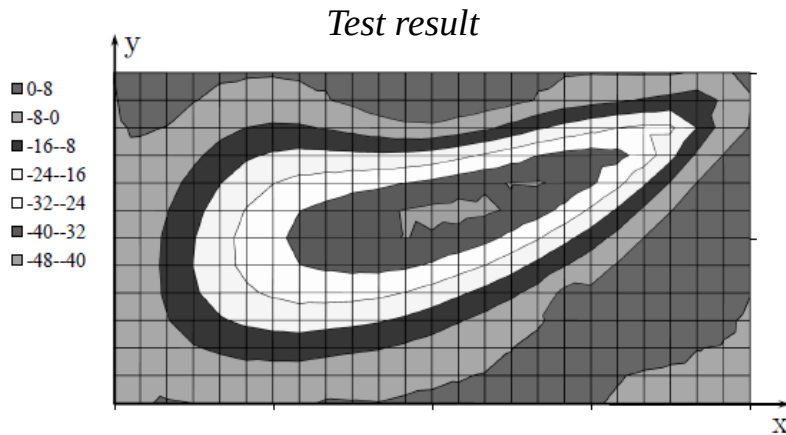


Interaction surface development

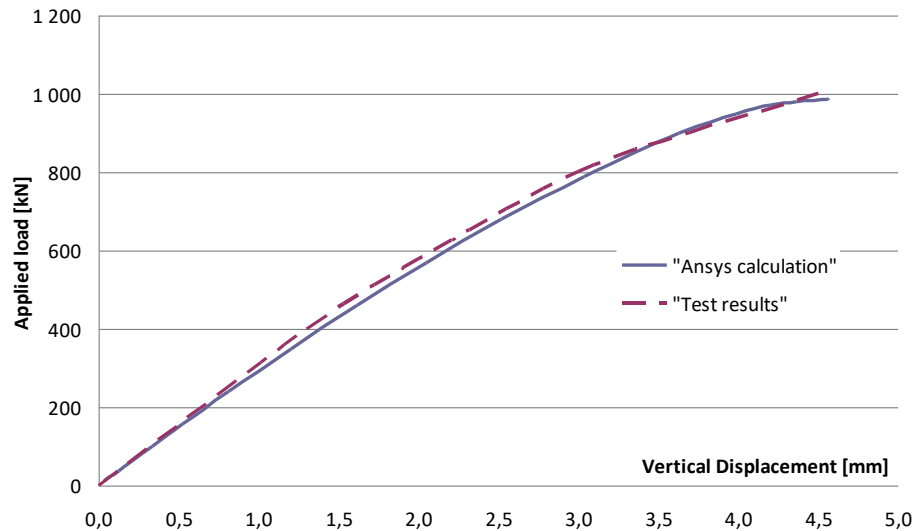


Model verification

Failure mode:



Comparison of load-displacement diagrams

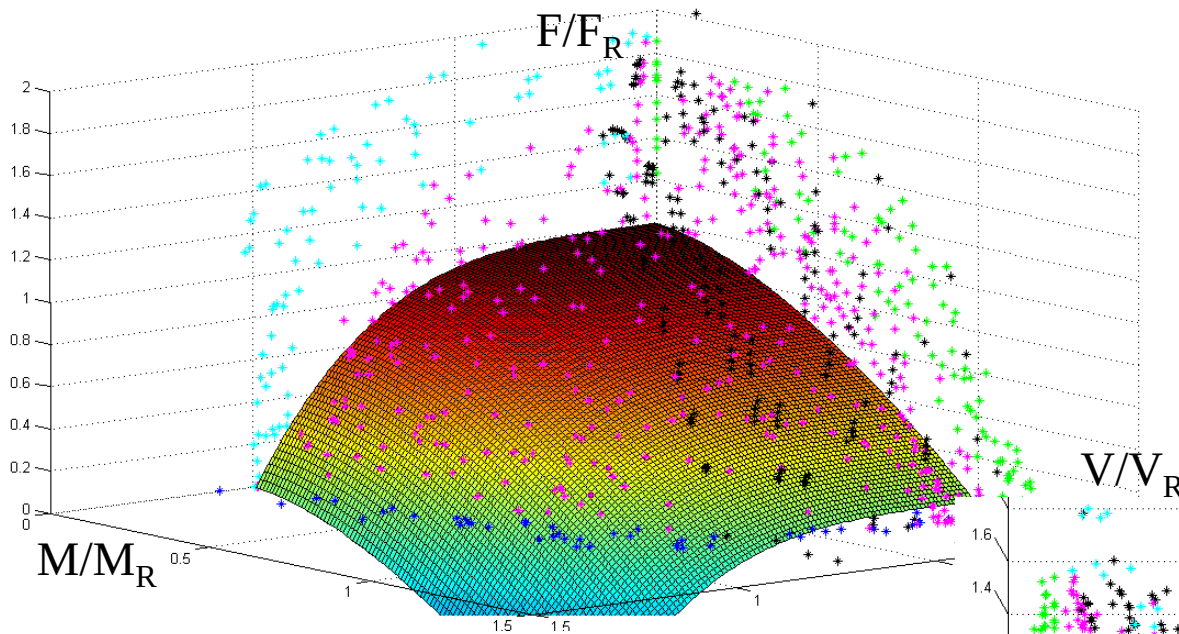


Comparison of ultimate loads

Test specimen	Used imperfection	Test result	Ansys calculation	ratio
SP600	eigenshape	846	835	0,99
SP1200	hand defined	1030	1012	0,98
	eigenshape		988	0,96

F - M - V interaction

evaluation according to EC calculated resistances ($M_{pl,R}$)



used interaction curve:

$$\frac{F}{F_R} + \left(\frac{M}{M_{pl,R}} \right)^{3.6} + \left(\frac{V_{avg}}{V_R} \right)^{1.6} \leq 1.0$$

M_R : EN1993-1-5 $M_{pl,Rd}$

V_R : EN1993-1-5 $V_{w,Rd}$

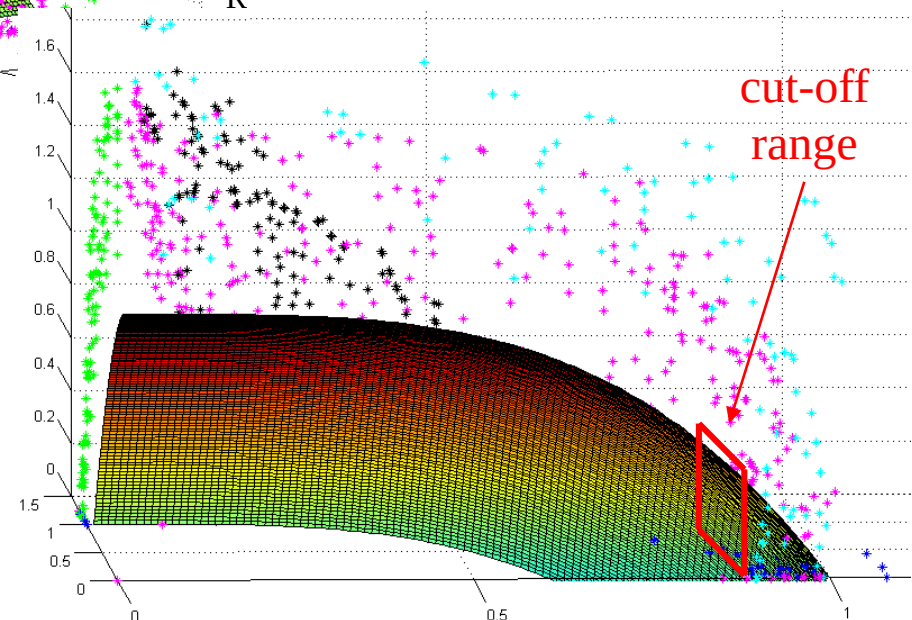
F_R : latest proposal of Chacón

- no points inside of the interaction surface

- only in the cut-off range



all results are on the safe side



Patch loading resistance

Resistance model according to EN1993-1-5 szerint

$$F_{Rd} = \frac{f_{yw} L_{eff} t_w}{\gamma_{M1}}$$

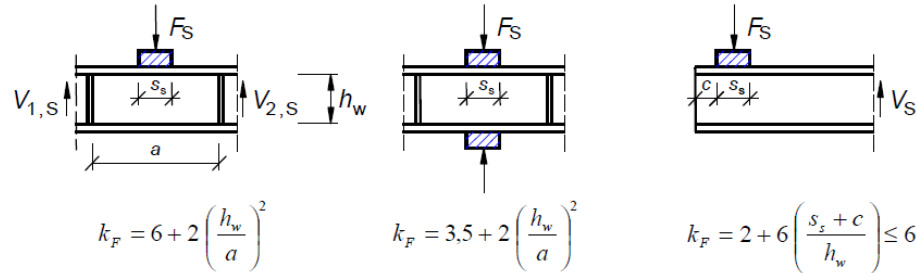
where: $L_{eff} = \chi_F \ell_y$

$$\ell_y = s_s + 2 t_f (1 + \sqrt{m_1 + m_2})$$

$$\chi_F = \frac{0.5}{\bar{\lambda}_F} \leq 1.0$$

$$\bar{\lambda}_F = \sqrt{\frac{\ell_y t_w f_{yw}}{F_{cr}}}$$

$$F_{cr} = 0.9 k_F E \frac{t_w^3}{h_w}$$



Effect of the longitudinal stiffener implemented in k_F

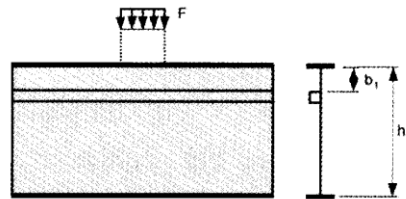
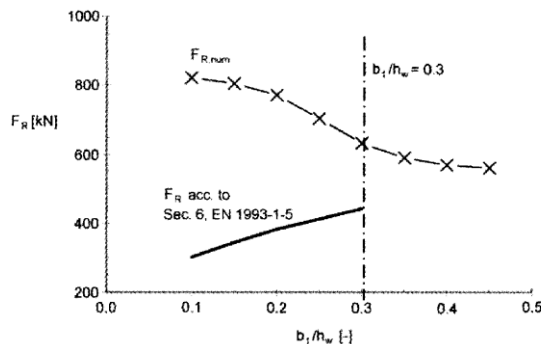
For webs with longitudinal stiffeners k_F may be taken as

$$k_F = 6 + 2 \left[\frac{h_w}{a} \right]^2 + \left[5.44 \frac{b_1}{a} - 0.21 \right] \sqrt{\gamma_s} \quad (6.6)$$

where b_1 is the depth of the loaded subpanel taken as the clear distance between the loaded flange and the stiffener

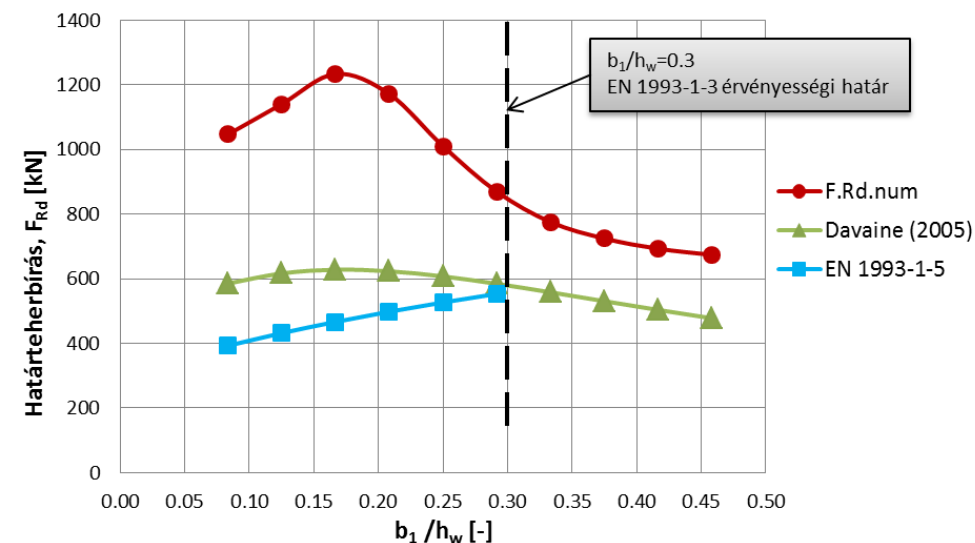
$$\gamma_s = 10.9 \frac{I_{s\ell,1}}{h_w t_w^3} \leq 13 \left[\frac{a}{h_w} \right]^3 + 210 \left[0.3 - \frac{b_1}{a} \right] \quad (6.7)$$

Resistance model - real resistances



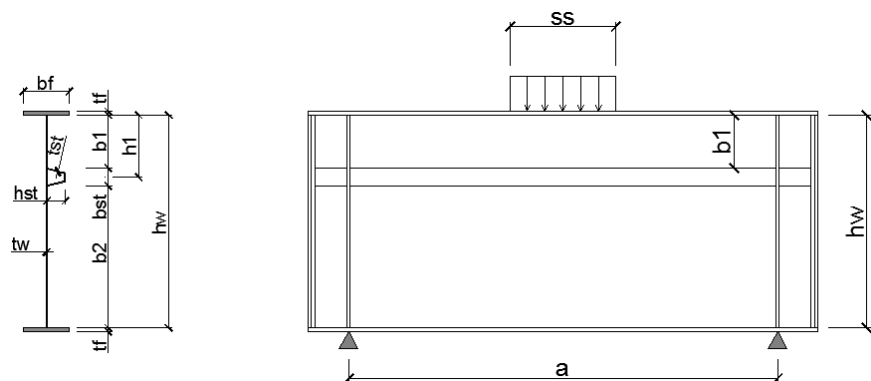
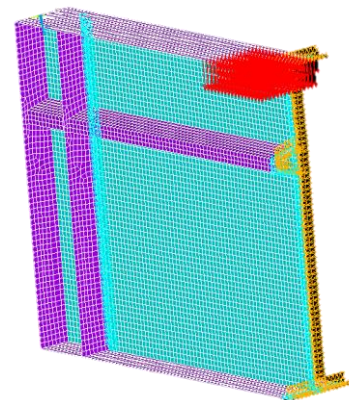
- - Large difference between resistance model and real resistances,
- Character is wrong
- ↓
- Correction of the design method

Comparison with previous correction methods

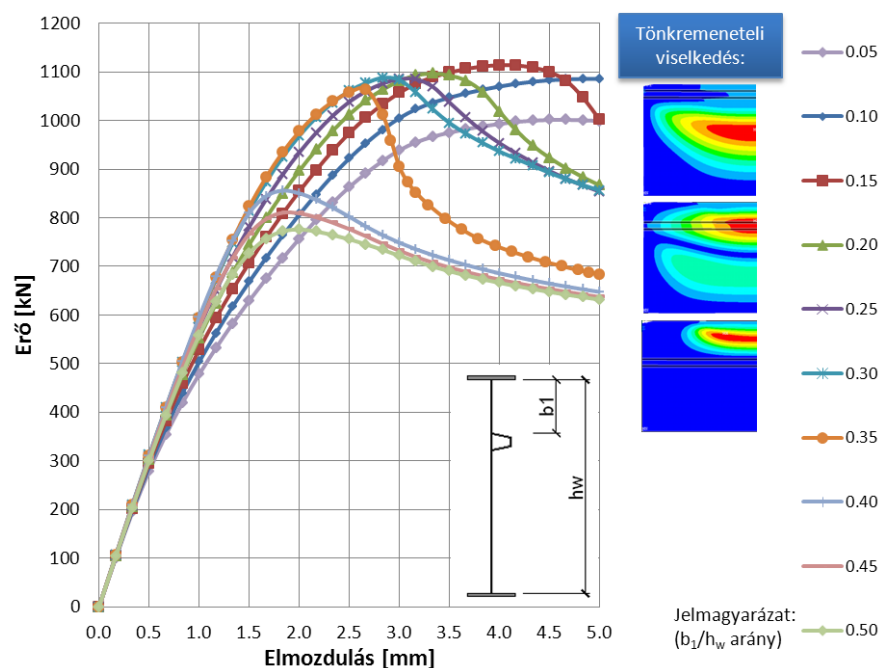


→ Further improvements needed

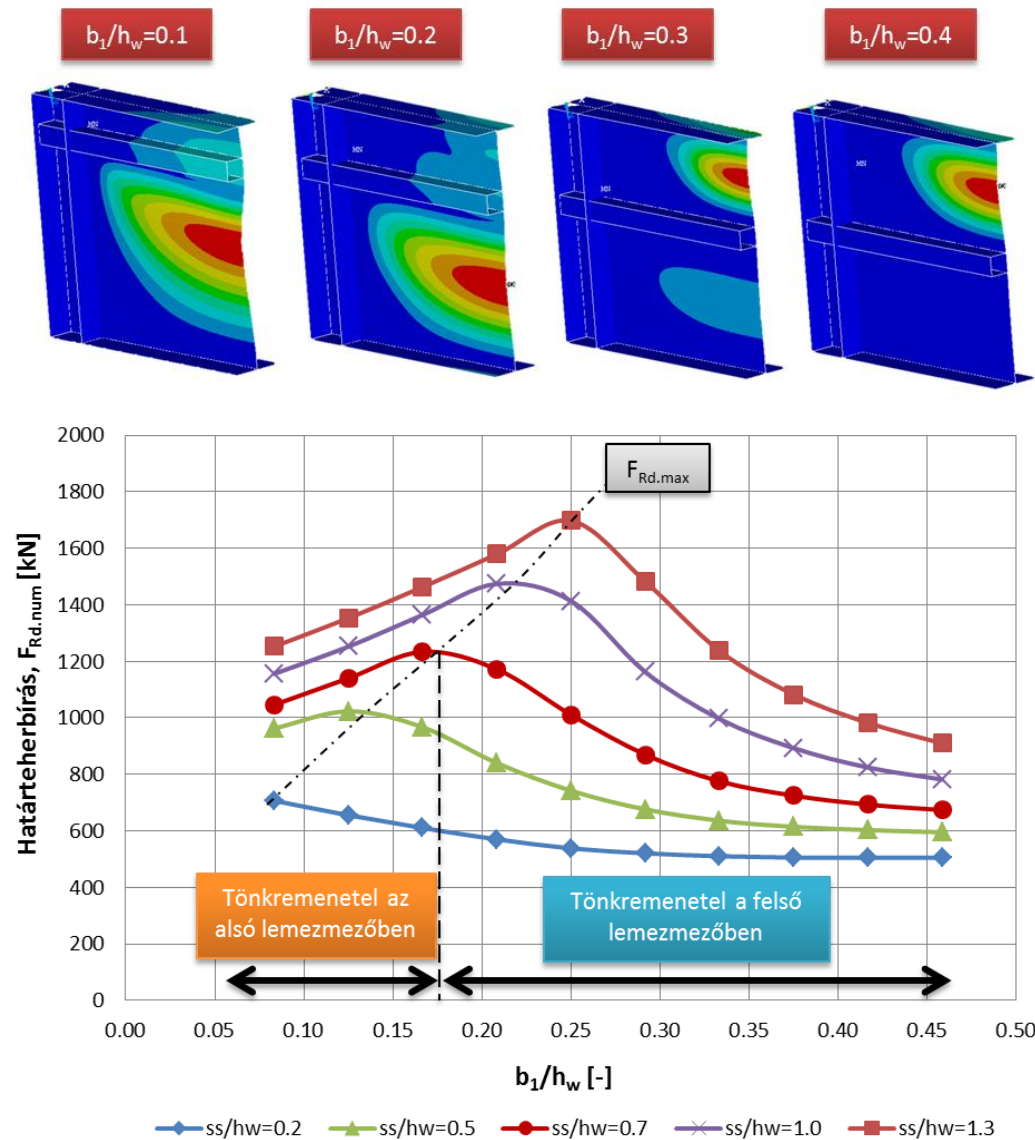
Numerical model development and calibration



Verification based on laboratory experiments



Observed failure modes



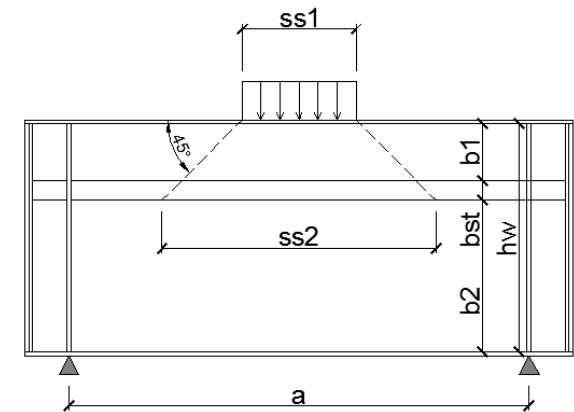
Design method development

- Correction of the buckling coefficient of the EN 1995-1-5

$$k_F = 6 + 2 \cdot \left(\frac{h_w}{a} \right)^2 + \left(5,44 \cdot \frac{b_1}{a} - 0,21 \right) \cdot \sqrt{\gamma_{st}}$$

- Based on numerical parametric study:

- Stiffener effect: $\gamma_{st} \geq 13 \cdot \left(\frac{a}{h_w} \right)^3 + 210 \cdot \left(0,3 - \frac{b_1}{a} \right)$
- Buckling coefficients:



Upper sub-panel

$$k_{F1} = 4 + 2,3 \cdot \frac{s_{s1}}{b_1}$$

$$F_{cr1} = 0,9 \cdot k_{F1} \cdot E \cdot \frac{t_w^3}{b_1}$$

$$l_y = s_s + 2 \cdot t_f \cdot (1 + \sqrt{m_1})$$

$$F_y = f_{yw} \cdot t_w \cdot l_y \leq f_{yw} \cdot t_w \cdot a$$

Lower sub-panel

$$k_{F2} = \left(6 + 9 \cdot \frac{s_{s2}}{b_2} \right) \cdot \sqrt{\frac{h_w}{a}}$$

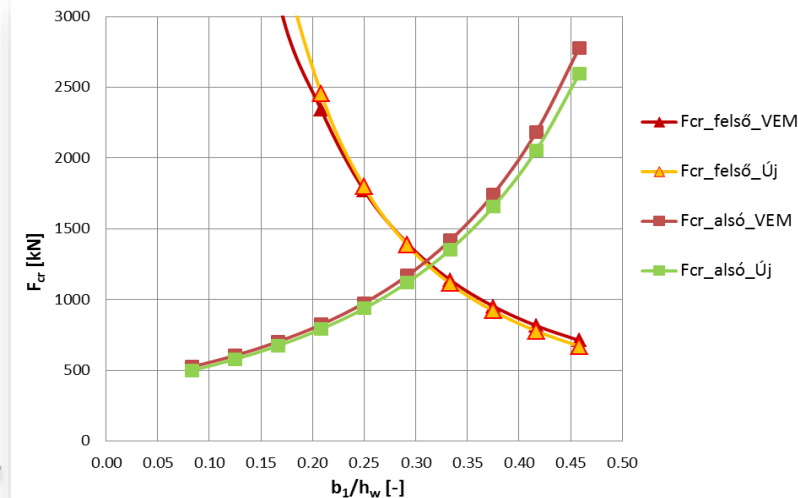
$$F_{cr2} = 0,9 \cdot k_{F2} \cdot E \cdot \frac{t_w^3}{b_2}$$

$$l_y = s_{s2} + 2 \cdot t_f \cdot (1 + \sqrt{m_1})$$

$$F_y = f_{yw} \cdot t_w \cdot l_y \leq f_{yw} \cdot t_w \cdot a$$

$$F_{Rd} = \min(F_{Rd.1}; F_{Rd.2})$$

Comparison with numerical results



Launching methods

- Launching on long way path
- Launching on short way path
- Launching on local equipments

Launching on long way path



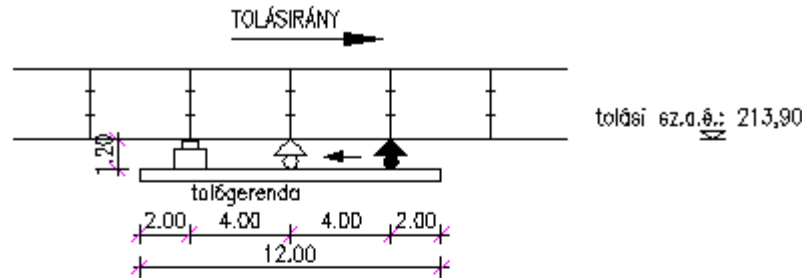
Launching on long way path

Application of provisory truss bridge → Continouse launching path



Launching on short way path

A.) Sajtós emelés, kocsi hátrahúzás

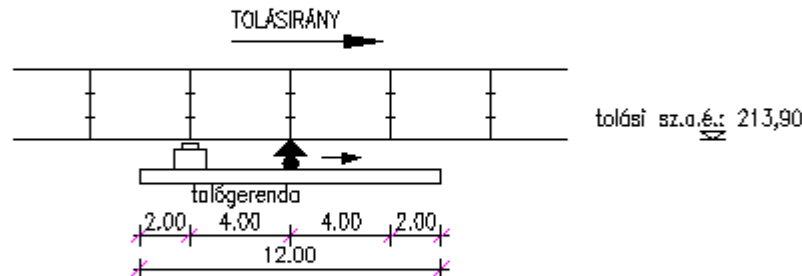


4 meter launching

2 x 4 meter launching girder

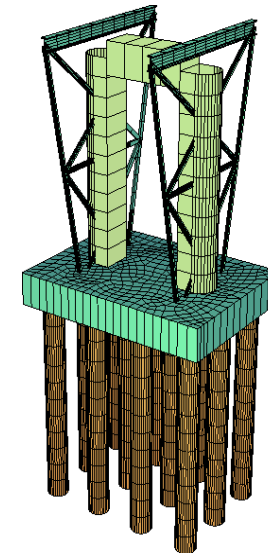
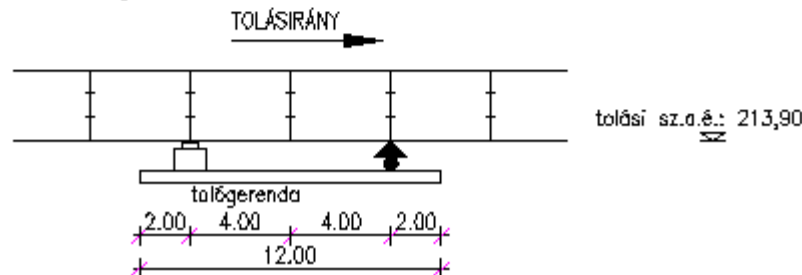
Independent frame with bases

B.) Kocsira terhelés, 4m előretolás

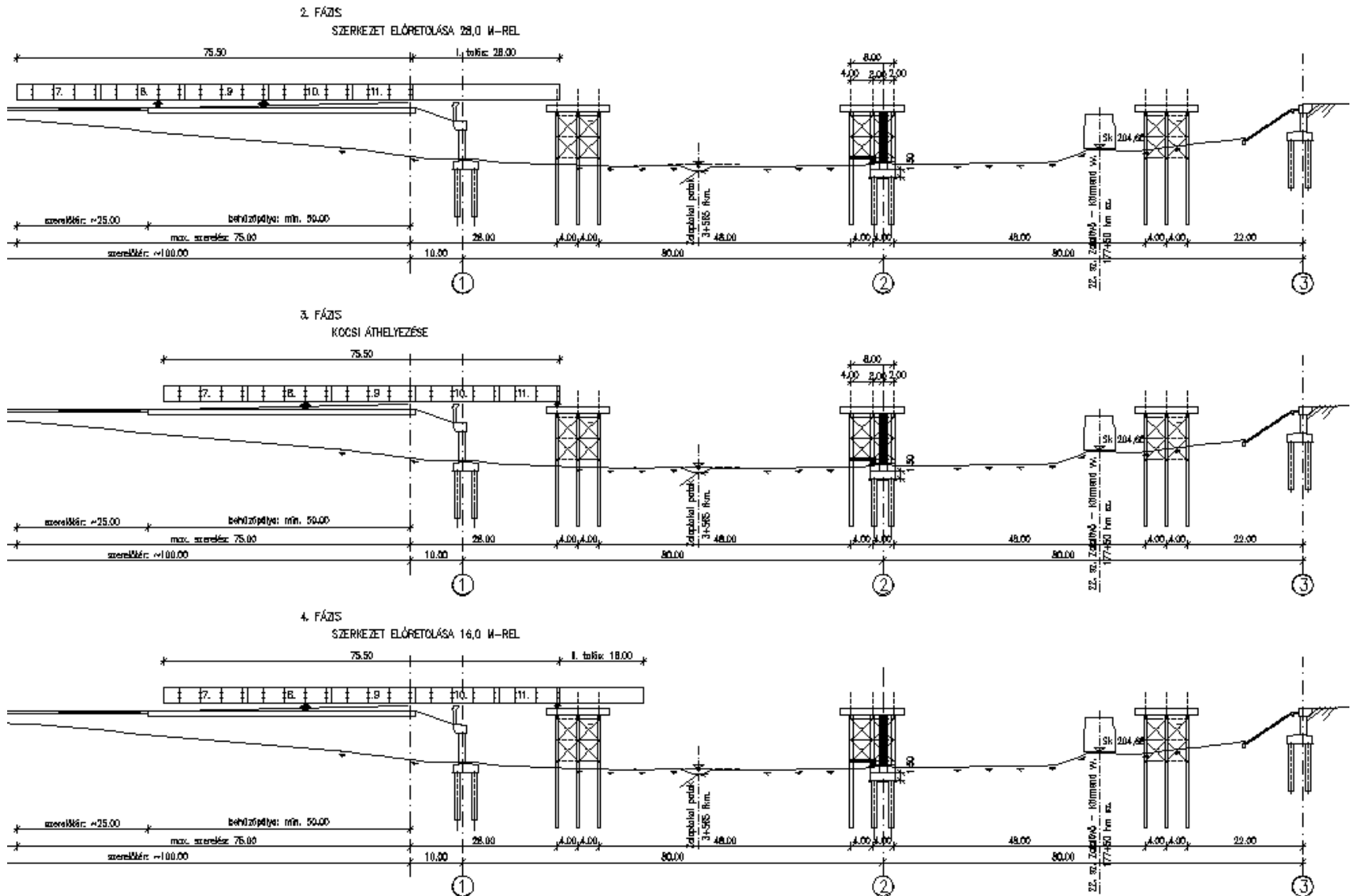


transversal force introduction at cross girdres, no stability problem

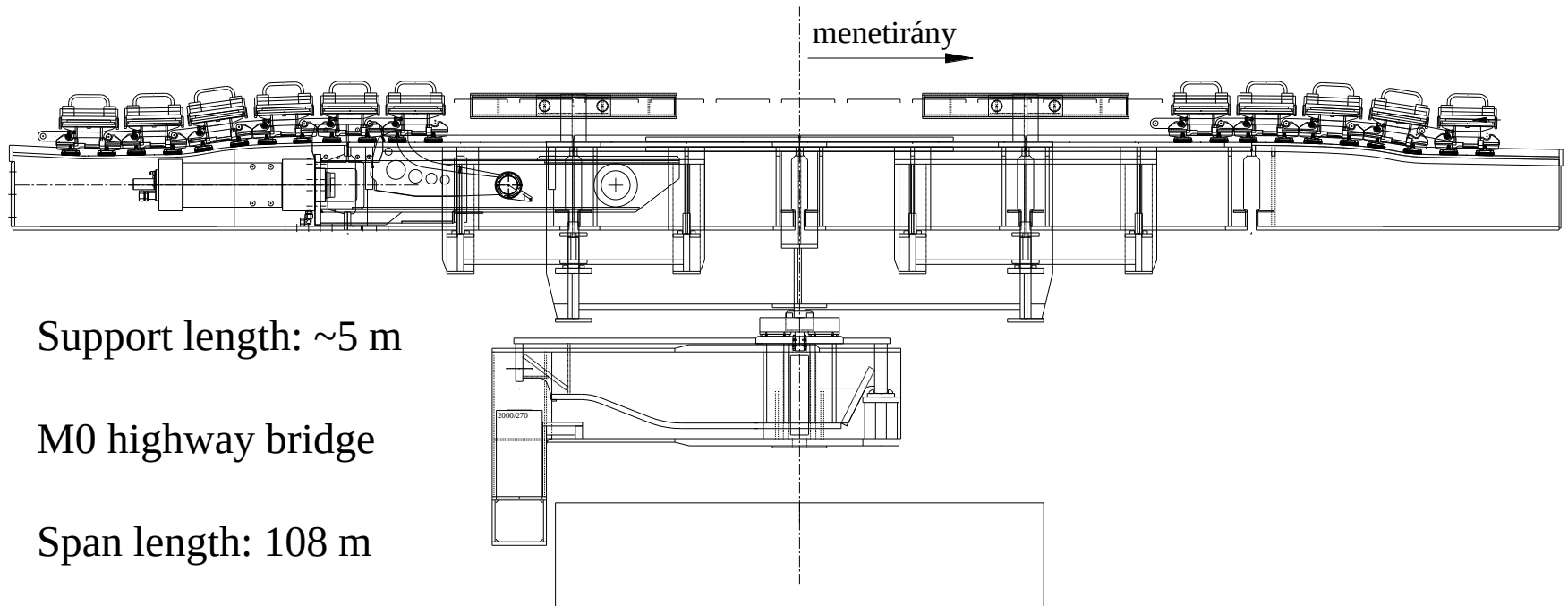
C.) Tolás vége



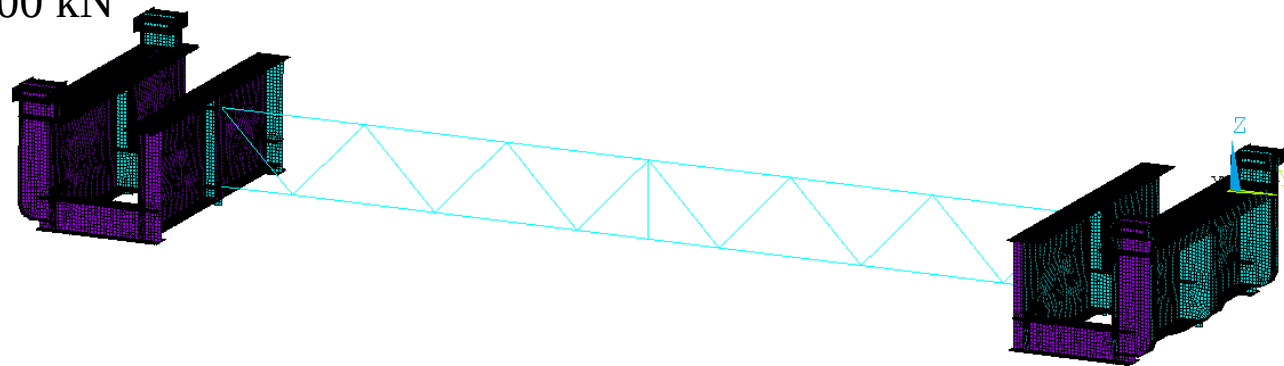
Launching on short way path



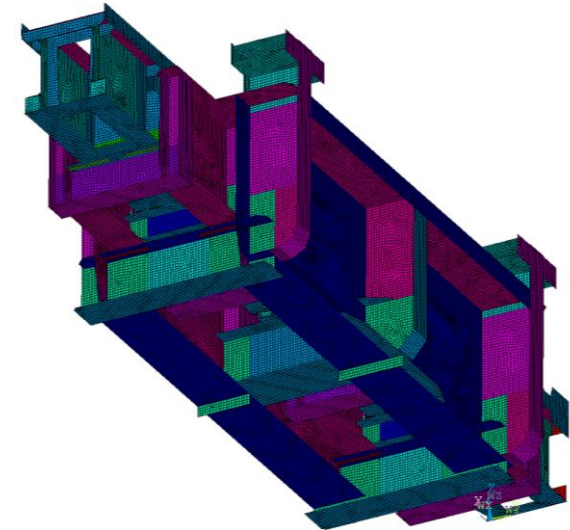
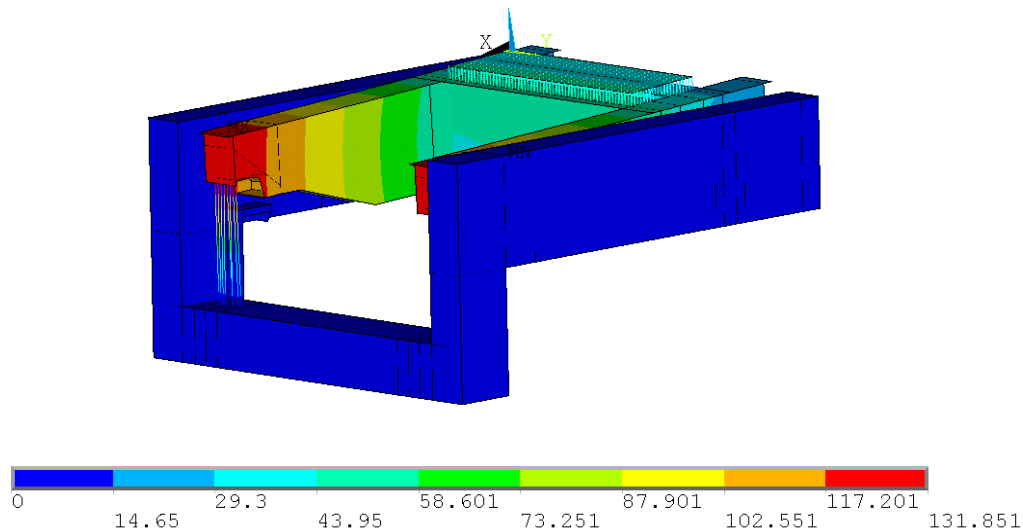
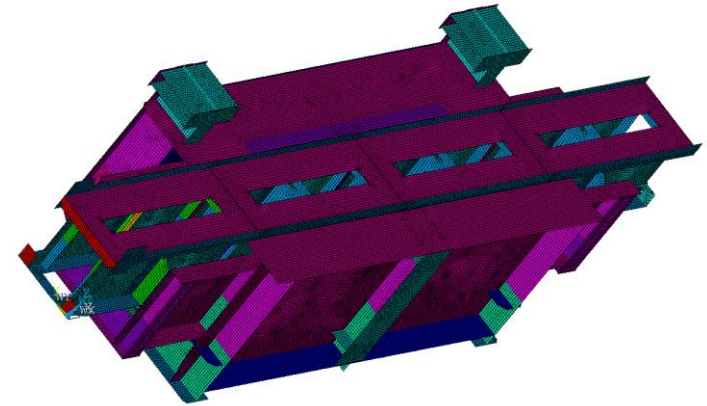
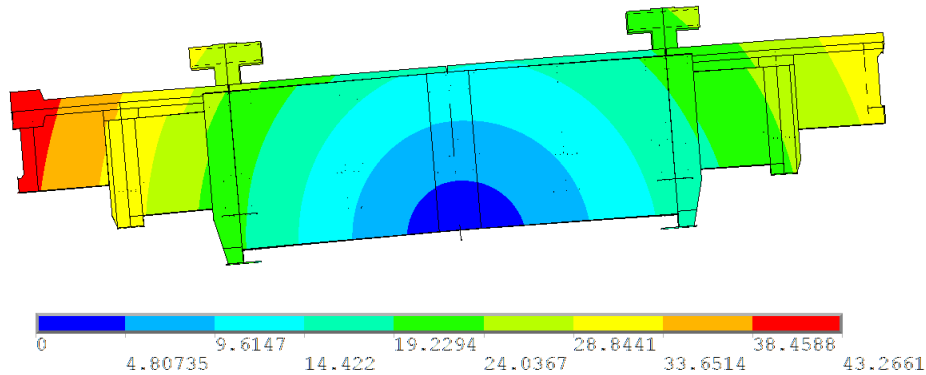
Launching on local equipments – long ss



- Support length: ~5 m
- M0 highway bridge
- Span length: 108 m
- Max reaction force: 2x6000 kN



Launching on local equipments – long ss



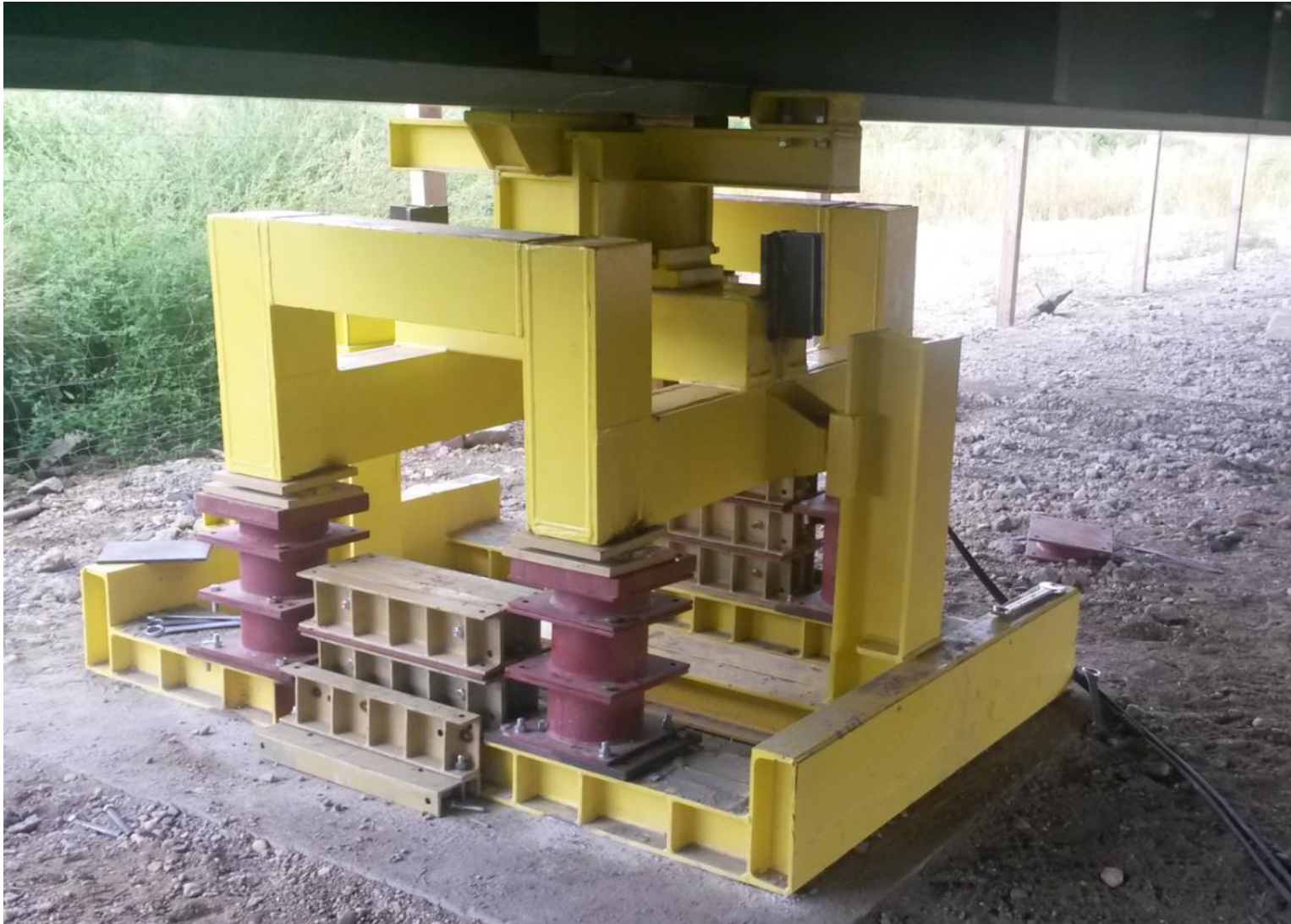
Launching on equipments – long ss



Launching on local equipments – short ss



Launching on local equipments – short ss



Launching on local equipments – short ss



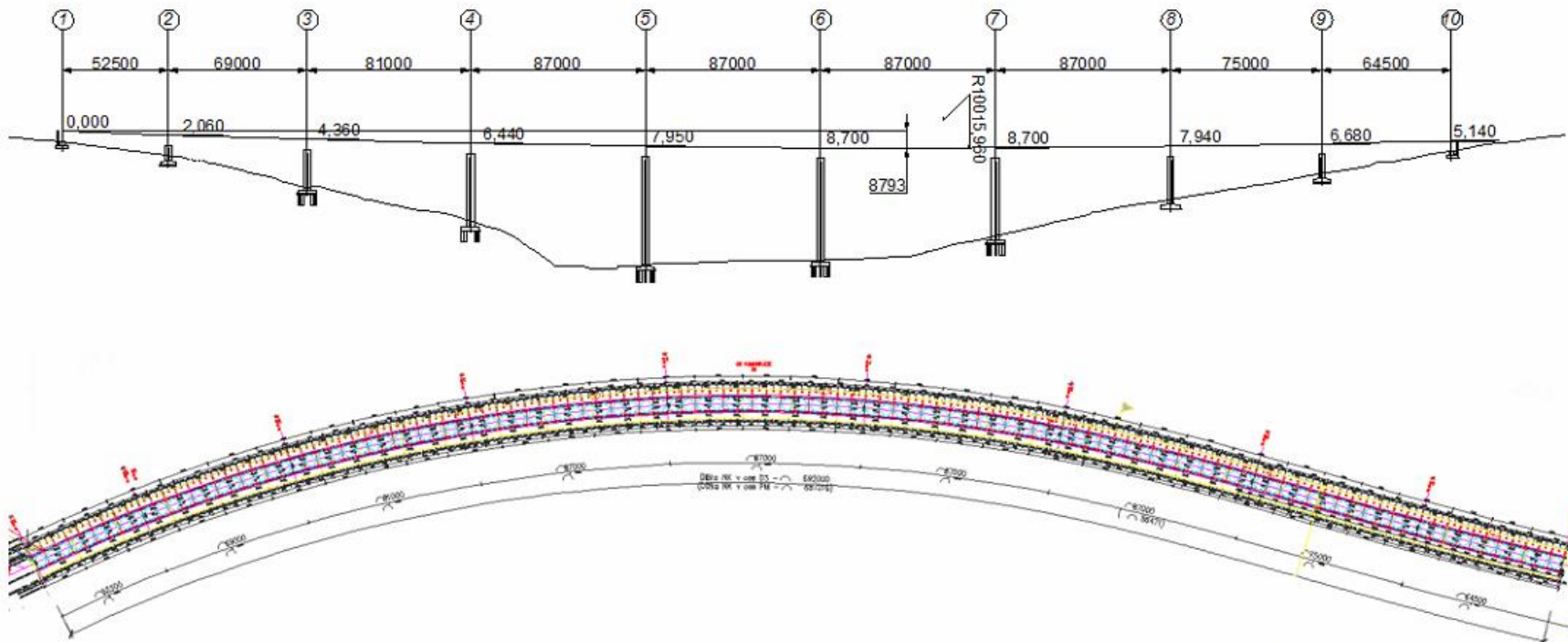
Launching on local equipments – short ss



Design and development of the launching process of the highway bridge “Čadečka”



Geometry of the highway bridge



- a new highway bridge has been erected on the SK D3 highway between 2014-2015
- bridge crosses the highway over a valley with 700 m width
- in a maximum height of ~60 meters
- unique, complex geometry
- top view two third of the bridge is located in a right arch of a circle ($R=700$ m)
- one part is a transient arch
- short part is straight and the end of the bridge is located in a transient arch

Task of the authors

complex bridge geometry + high piers



decided by the launching manufacturing process



eliminated or minimized the necessary work on the piers and made the largest safety and fastest way for erection



due to complex geometry



steel part is launched



concrete deck at final location

task of the authors:

- design the launching process
- design the launching equipments
(launching truss and hydraulic jack system)
- static check of superstructure and
the launching equipments
- manage and execute the launching process



Layout of the superstructure

composite girder bridge having 9 spans

span lengths: $52.5 + 69.0 + 81.0 + 4 \cdot 87.0 + 75.9 + 64.5 \text{ m} = 690 \text{ m}$

designed by the SHP (Brno) company

erected by the Promont s.r.o. (Krásno nad Kysucou) company

cross-section:

two steel I-girders with longitudinal stiffeners and with transversal ribs

cross bracing system and two (upper and lower) wind bracing systems

main girder distance: 6700 mm

web depth of 4400 mm

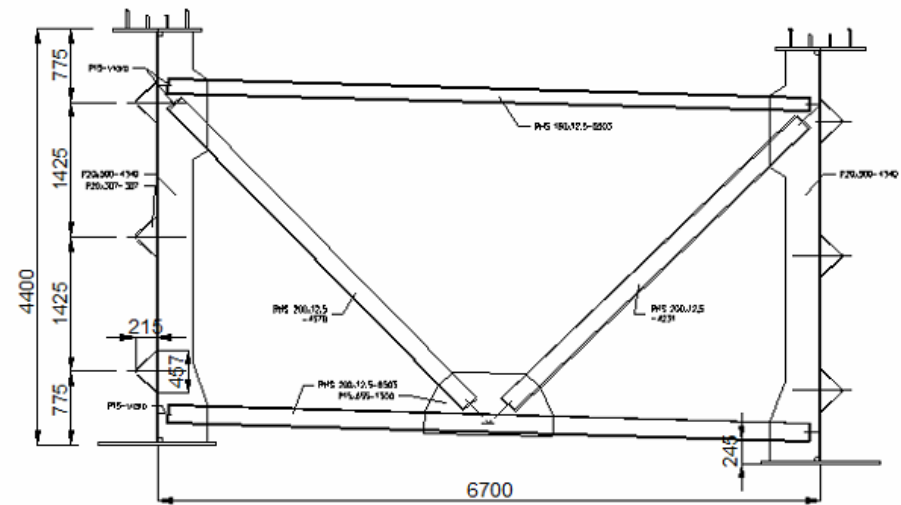
upper flange: 900 x 25 – 60 mm

lower flange: 1200 x 30 – 95 mm

rib distance: 3000 mm

steel material: S420 (S460)

specific weight: 38 kN/m



Strategy of the launching process

two dominantly different part from geometrical point of view



launching from the two ends simultaneously



continuous removal of the launching truss



sinking of the cross-section to be connected (reduction of stresses)



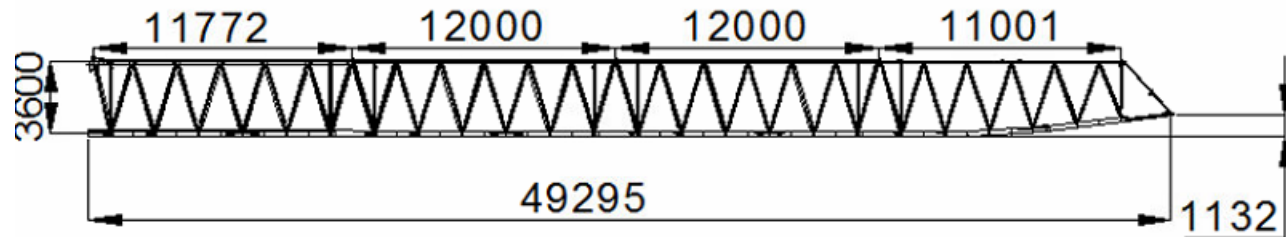
welding of the two parts and lifting back the cross-section



Layout of the launching truss

Launching truss: nominal length of 48.0 m

to reduce the negative bending moments at the cantilever stages



Optimized geometry:



- wind load (2.5 kN/m^2)
- curved shape
- flexibility by launching
- minimized weight
- minimized bending moment



Numerical modelling of the launching process

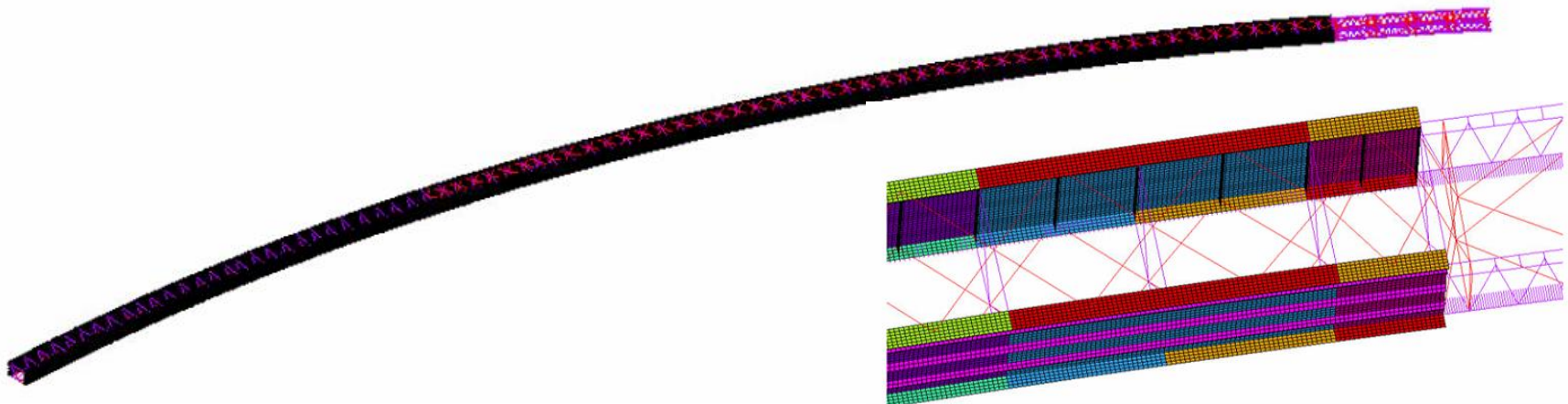
Modelling aims:

- stress and stability check of the superstructure
- maximum horizontal and vertical reaction forces acting on the launching devices

Modelling steps:

1. launching simulation is performed step-by-step within 1 m increment.
2. load carrying capacity of the launching truss is also checked.
3. horizontal and vertical reaction forces are determined to check and eliminate the possible overloading of the launching devices.

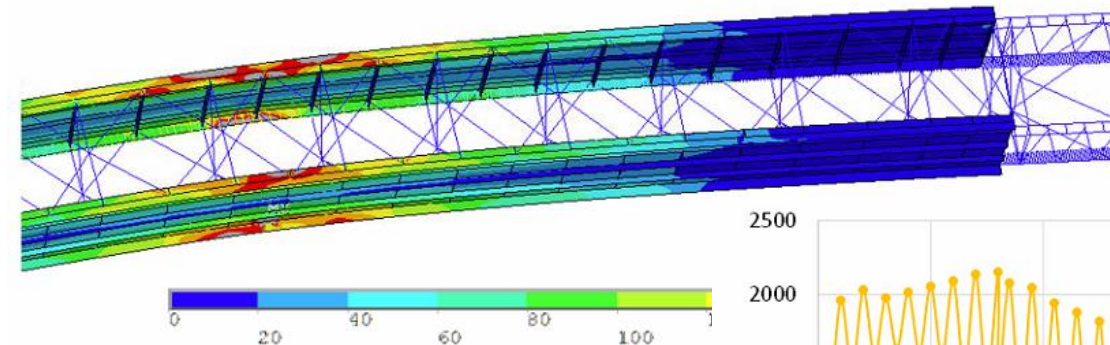
Developed model: shell + beam model on movable elastic spring supports



Numerical modelling of the launching process

Considered actions:

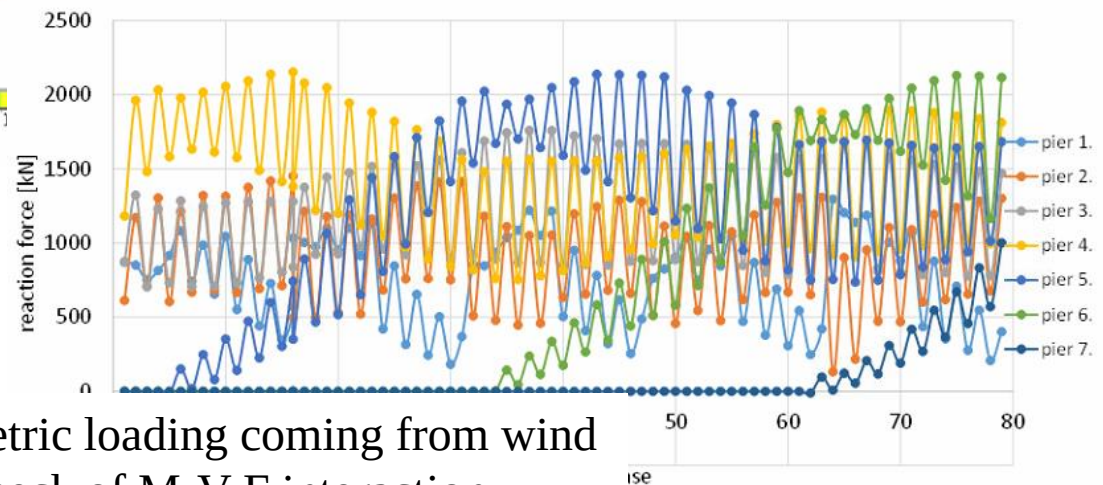
- self weight of superstructure
- loads coming from deformation of the bridge (launching path geometry)
auto-recalculation for all launching steps (1 m increment)
- wind load: $2.75 \text{ kN/m}^2 + 0.55 \text{ kN/m}^2$
- temperature load: $+15/-5^\circ \text{ C}$



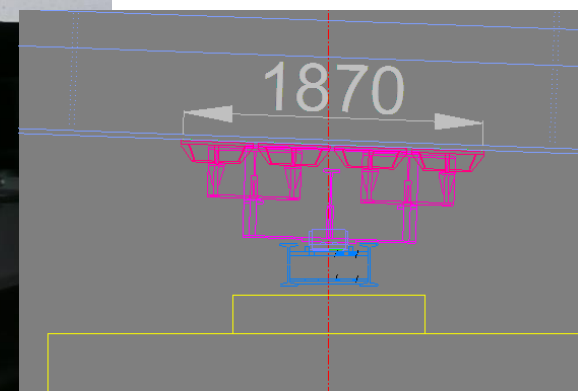
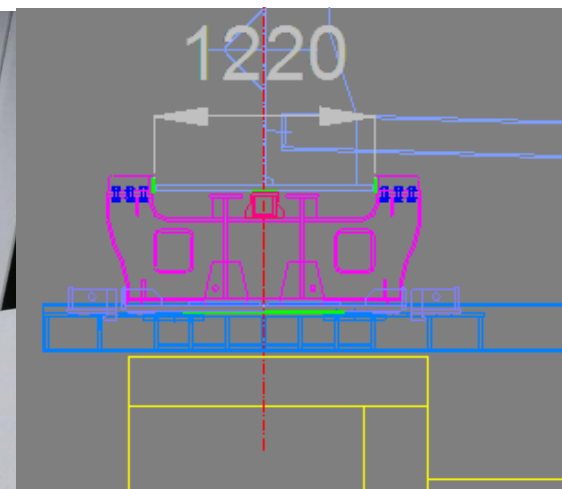
Stress diagram to check the superstructure and the launching device.

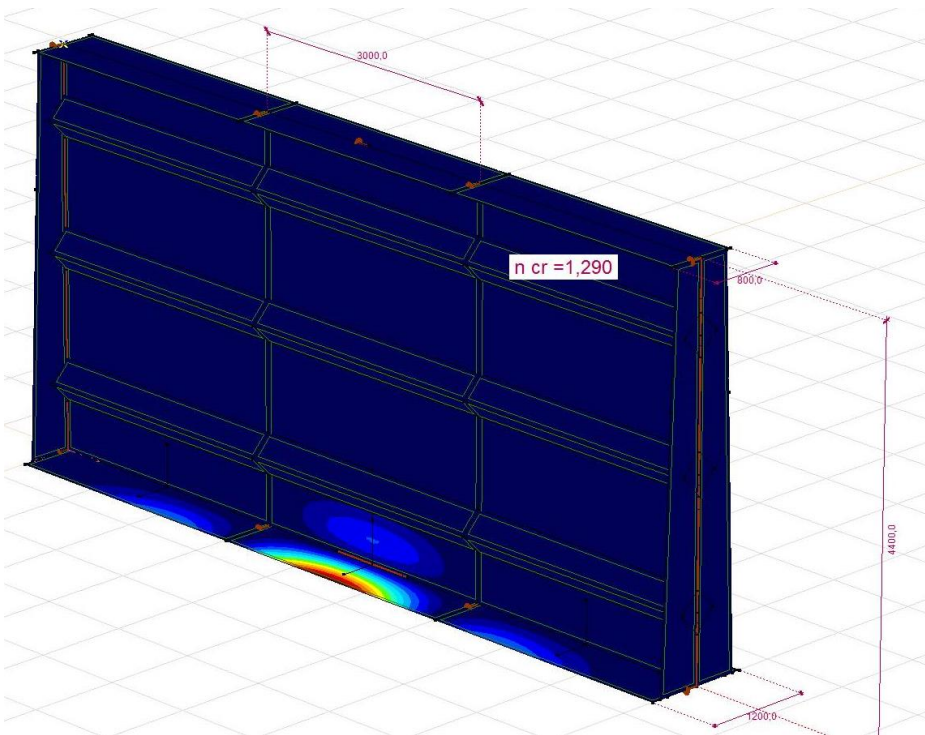
Largest problems: - asymmetric loading coming from wind
- static check of M-V-F interaction

Reaction force diagram for design of launching device



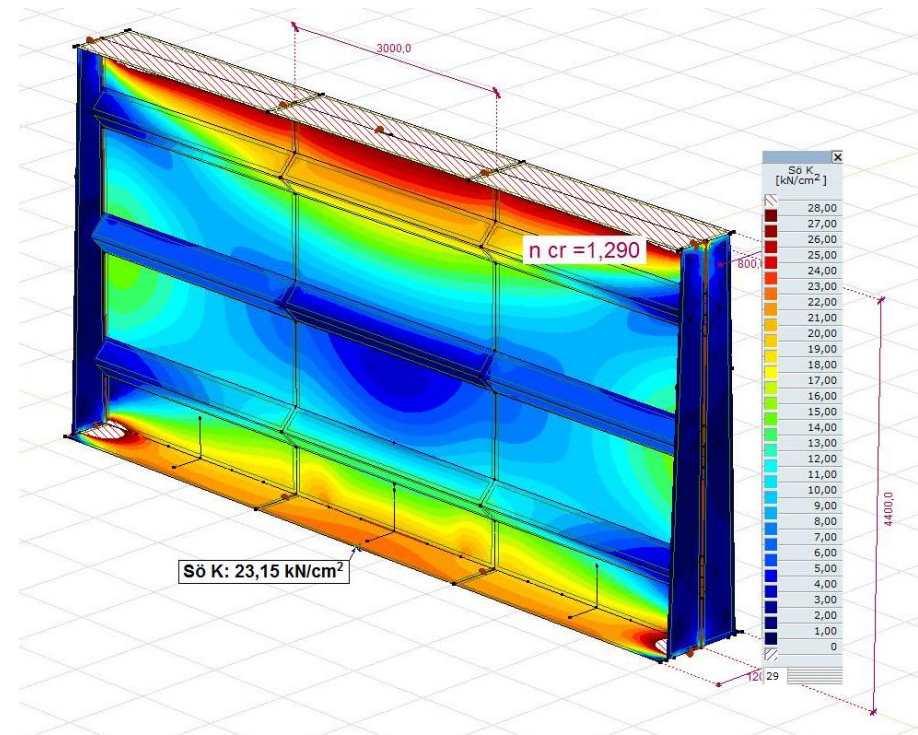
Lateral supports on the launching device





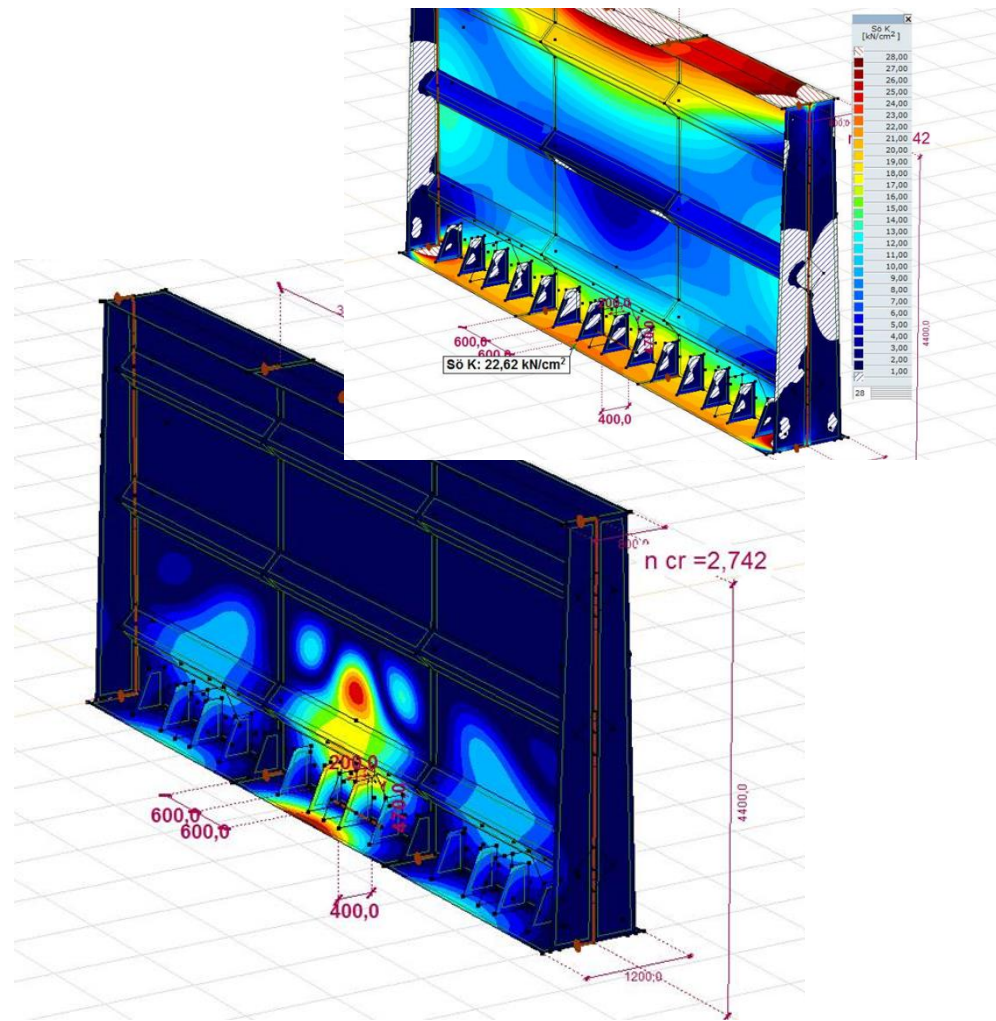
Patch loading check

Reaction force: 2800 kN (at 2,0 m length)



Result of the calculation:

$$\lambda = 83 \quad \alpha = 1,88 (!!!)$$



Calculation result:

$$\lambda = 58 \quad \alpha = 3,2 (!)$$

Determination of the drive force

correct determination of the drive force is a safety issue

between the piers 1-7: downhill with a slope of 4,5%,

between the piers 7-10: downhill with a slope of 2,0%.

theoretical minimum sliding coefficient: 3-4%



bridge could be launched with almost zero drive force



braking system needed



correct determination of drive force

$$V = V_F + V_E + V_K$$

where: V_F is the force coming from friction,

V_E is the force coming from the change of the potential energy of the structure,

V_K is the force needed for acceleration of the structure.

Determination of the drive force

V_F : from the friction coefficient and the sum of the reaction forces

vertical and **horizontal** reaction forces as well

friction coefficient depends on: the launching device,
the applied materials and oils.

non-moving structure: 0.06-0.19, moving situation: 0.02 – 0.05

V_E determination: from the change of the potential energy

$$\Pi_{(x_1)} - \Pi_{(x_0)} = V_E \cdot (x_1 - x_0) \quad \text{where: } V_E = \frac{d\Pi_{(x)}}{dx}$$

$$\Pi = \frac{1}{2} \cdot \int_{S_0} EI_s \cdot \rho^2 \cdot ds - \int_{S_0} g_s \cdot y \cdot ds$$

Conclusion:

V_E can reach 1.5-2% of the total reaction force, which can explain the observations and the degradation of the drive force in case of the real launching process.

V_K compared to the another two components by the current launching velocities is negligible.

Execution of the launching process



Execution of the launching process



Execution of the launching process



Execution of the launching process



Execution of the launching process



Execution of the launching process





Thank you for your attention!