

BRIDGE ENGINEERING MEETS FOOTBALL

[SAFETY AND REHABILITATION OF EXISTING STADIUM STRUCTURES]

Dansk Ståldag
November 14, 2024

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Monitoring & Analyses of Existing Structures
Ramboll Denmark

AGENDA

- > Overloaded Grand Stand From Crowd Jumping
- > Alternative Rehabilitation Based On Measurements
- > Strengthening Project
- > Full Scale Load Test
- > Recommissioning & Operation
- > Other Stadiums

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- > IABSE Awards 2024 Finalist 😊
- > Gala in Zürich November 12
...didn't win 😞...



WEMBLEY STADIUM, UK

[1923, proof loading with 2400 soldiers]

BRITISH
PATHÉ

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PATHÉ

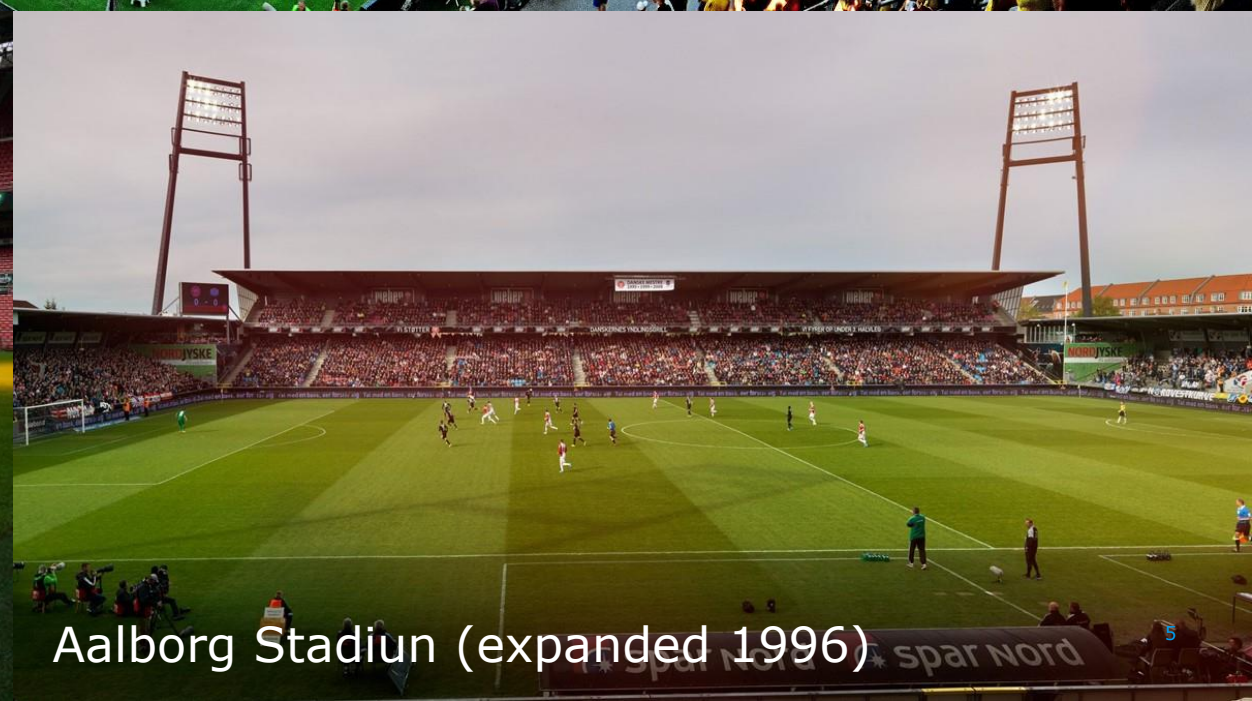
DANISH STADIUMS OF THE 1990ies

[without design code for dynamic pedestrian loading]

Brøndby Stadium (1992,1999)



Parken Stadium (1992)



Aalborg Stadium (expanded 1996)

DYNAMIC PEDESTRIAN LOADING

[Danish design code DS/EN 1991-1-1 DK:NA 2013]

> First incorporated in the DS-410 update of 1999, derived from German ISO standard

> Includes 3 load harmonics (load frequency '**np**' + 2 upper harmonics),

$$q_L(t) = F_P \left[1 + \sum_{j=1,2,3} \alpha_j K_j \sin(2\pi j n_p t + \varphi_j) \right]$$

> Modal load amplitudes '**αj**' – constant with load frequency (α1=1.6, α2=0.1, α3=0.2)

> Magnitude reduction factor '**Kj**' – account for correlation of the loading between the number of active people

> Constant with load frequency

> Full correlation of people jumping (at first load harmonic)

NIJMEGEN TERRACE COLLAPS

[October 15 2021, Netherlands]



BRØNDBY
STADIUM

OVERLOADED
GRAND STAND
FROM
COORDINATED
JUMPING

LOWER SOUTH SIDE STANDING TERRACE

[Nedre Sydsiden ståtribune]

14 m

14 m

> CONSTRUCTED 1992

> PREFABRICATED/PRESTRESSED CONCRETE ELEMENTS

> INDEPENDENT SIMPLY SUPPORTED TERRACE TT-ELEMENTS

[HIGH SLENDERS - LENGTH 14 M 1ST NATURAL FREQUENCY 5,4 HZ]

> 6 SPANS, 17 ROWS PER SPAN, APPROX. 100 LONG BEAMS

VIBRATION MEASUREMENTS 2018

[1.9g, 45mm amplitude, 138% ULS utilization]



SAFETY ASSESSMENT

[cause of immediate restrictions]



>INSTALL CHAIRS

Reduce static load
Limit jumping

>CLOSE CENTRAL SECTIONS

Historical high loading
Disperse dedicated fans

>REDUCE CAPACITY

From 4700p to 2750p

STRENGTHENING

> APPLICATION OF EUROCODE LOAD MODEL:

- Natural frequency to be increased to approx. 7.5-8.0 Hz
- Stiffness must be added to all TT-elements
 - Larger height
 - Smaller spans

> ESTIMATED COST

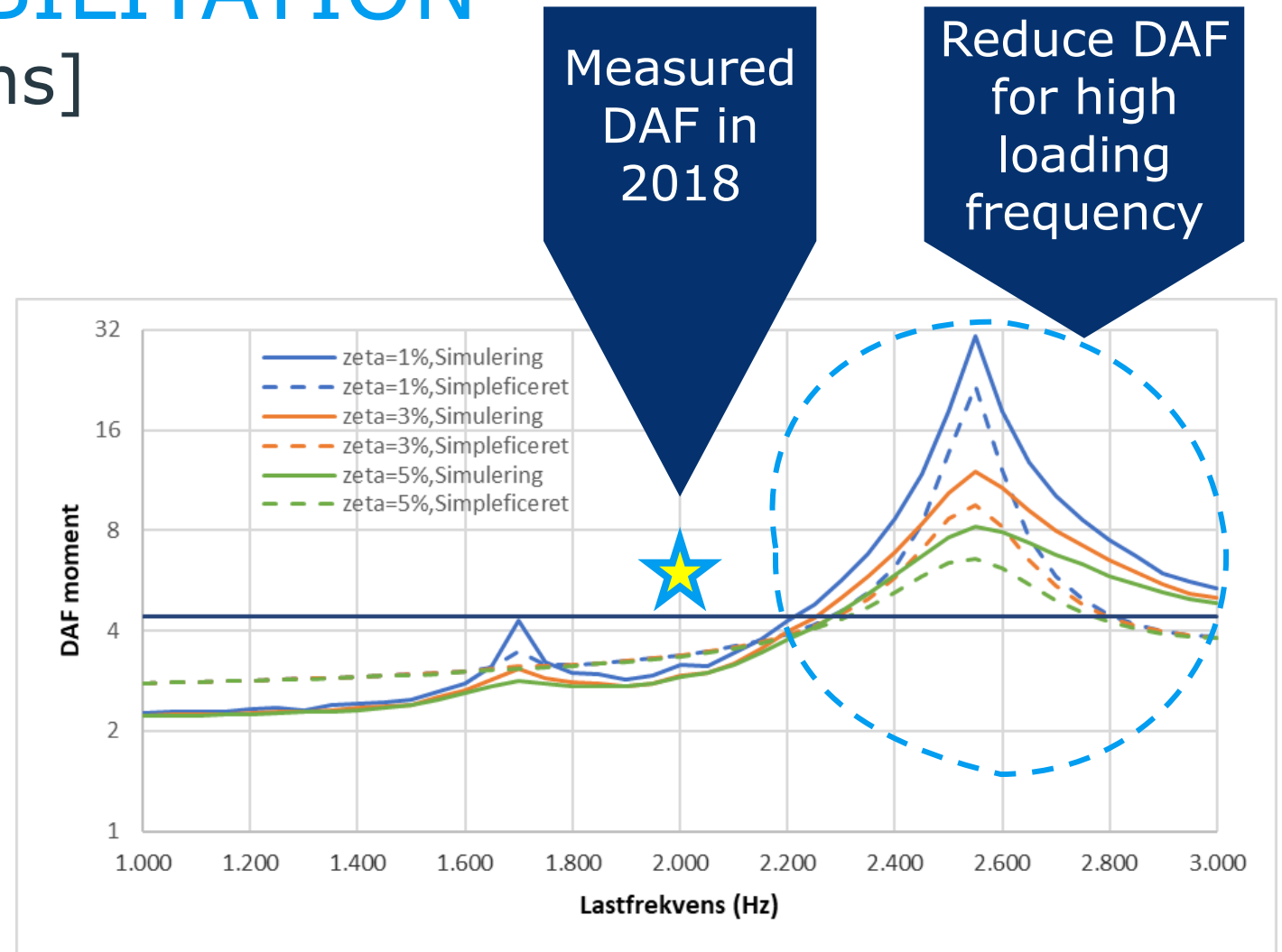
- Replacement of TT-elements: 20-25 mio. dkk
- Full strengthening to code: Costs higher than replacement

ALTERNATIVE REHABILITATION BASED ON MEASUREMENTS

ALTERNATIVE REHABILITATION

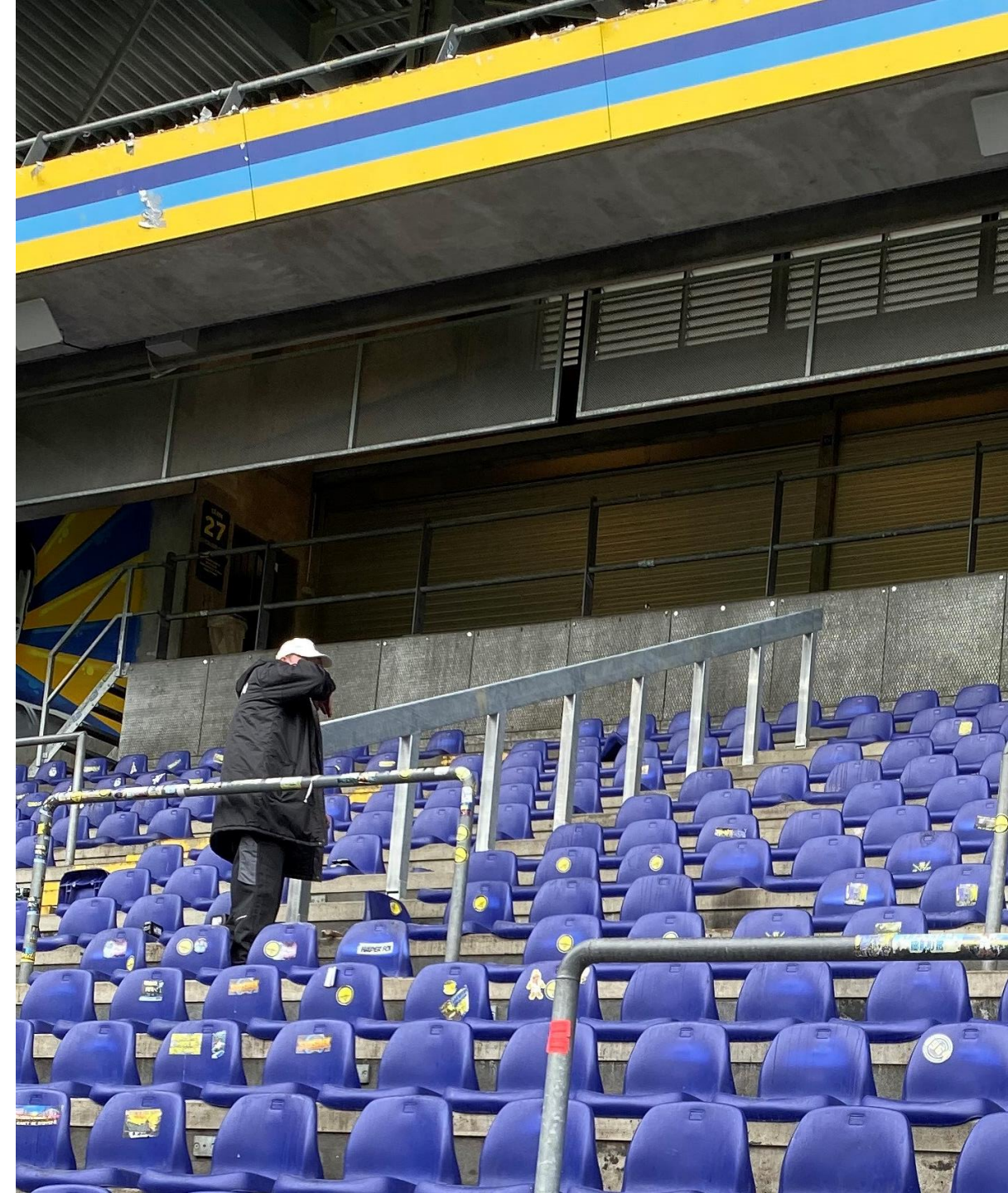
[How to remove restrictions]

- > Keep existing grand stand open at minimum cost and required safety level
- > Rehabilitation based on measurements of actual response of terrace elements
- > Challenge conservative design code
 - > Not fully correlated at load frequency
 - > Reduced for increased load frequencies
- > Future operation constraints
 - > Accept limits on use – no concerts!
 - > Keep track of loading – monitor!



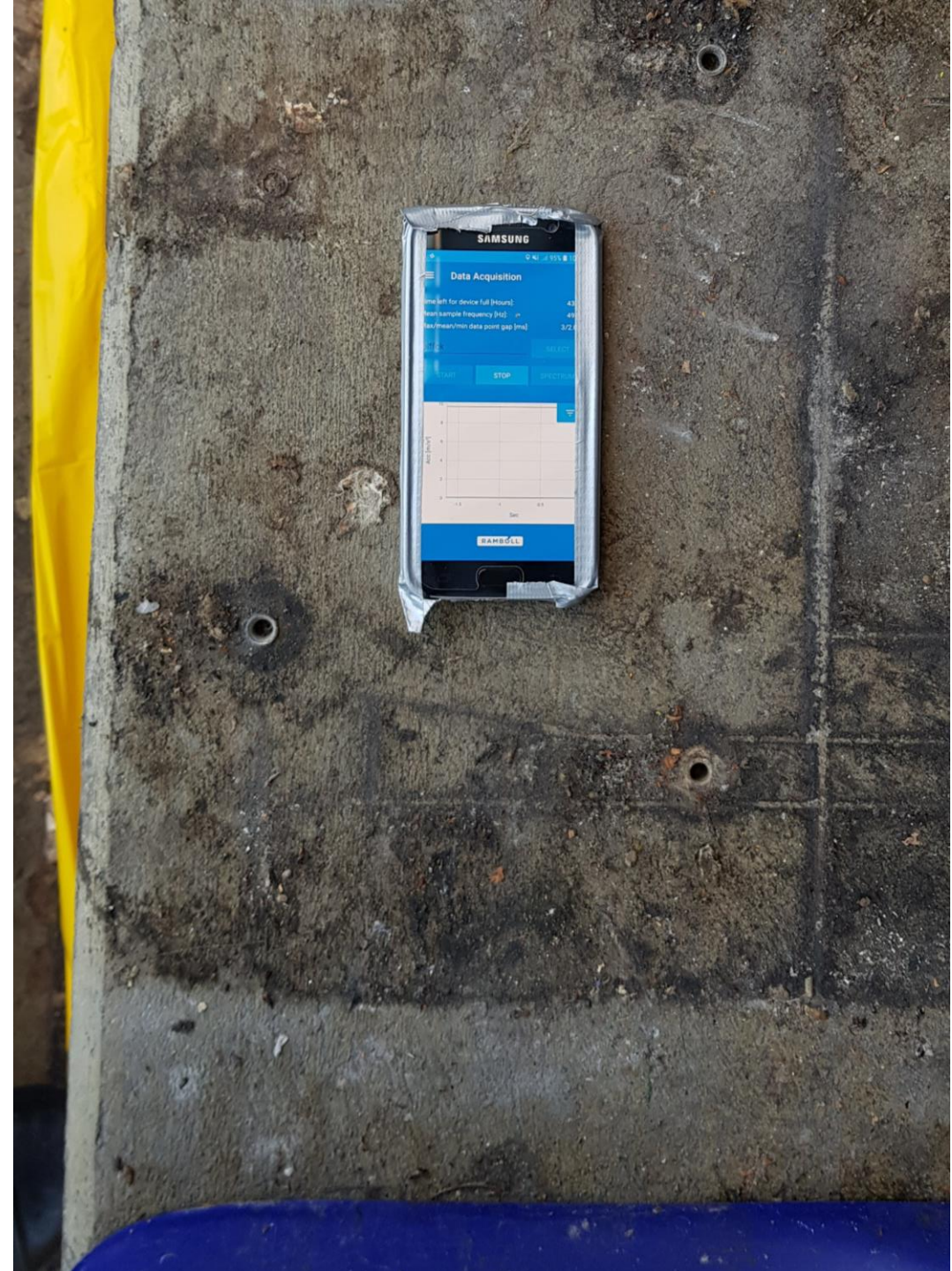
REHABILITATION BASED ON MEASUREMENTS

- > Strengthening solution guided by measurements – magnitude, correlations, variations, outliers
- > Connection of terrace elements by cross bracings
- > Validation by monitoring before-and-after



SMART PHONE MONITORING

[Cost effective]



DIC VIBRATION MEASUREMENTS

[GoPro camera, Brøndby-SJE 30/10 2019]



STRENGHTENING PROJECT

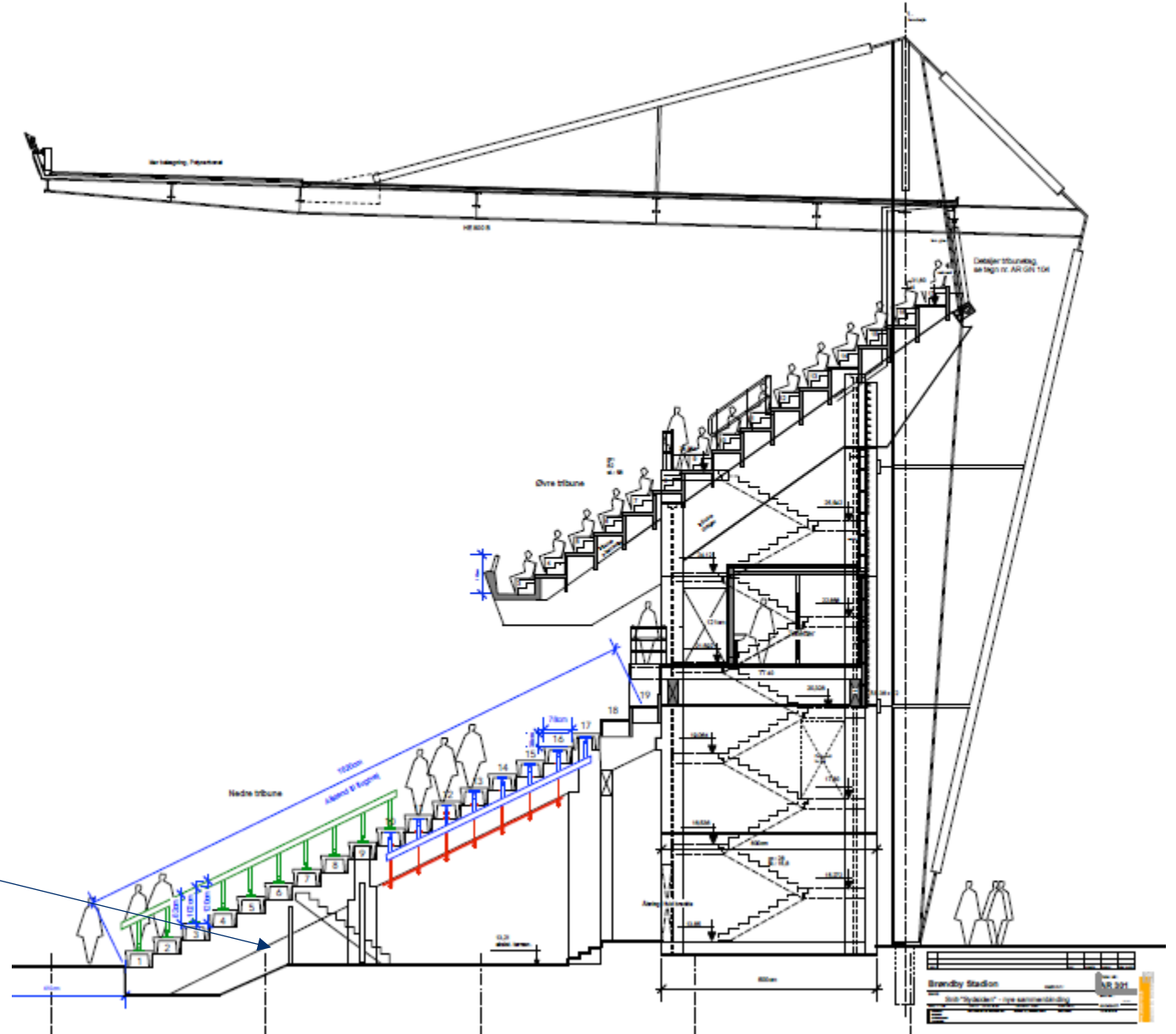
NEW STEEL STRUCTURES

**TRANSVERSE STIFFENER
BELOW DECK, ROW 10-17**

**TRANSVERSE STIFFENERS
PARAPHETS, ROW 1-10**

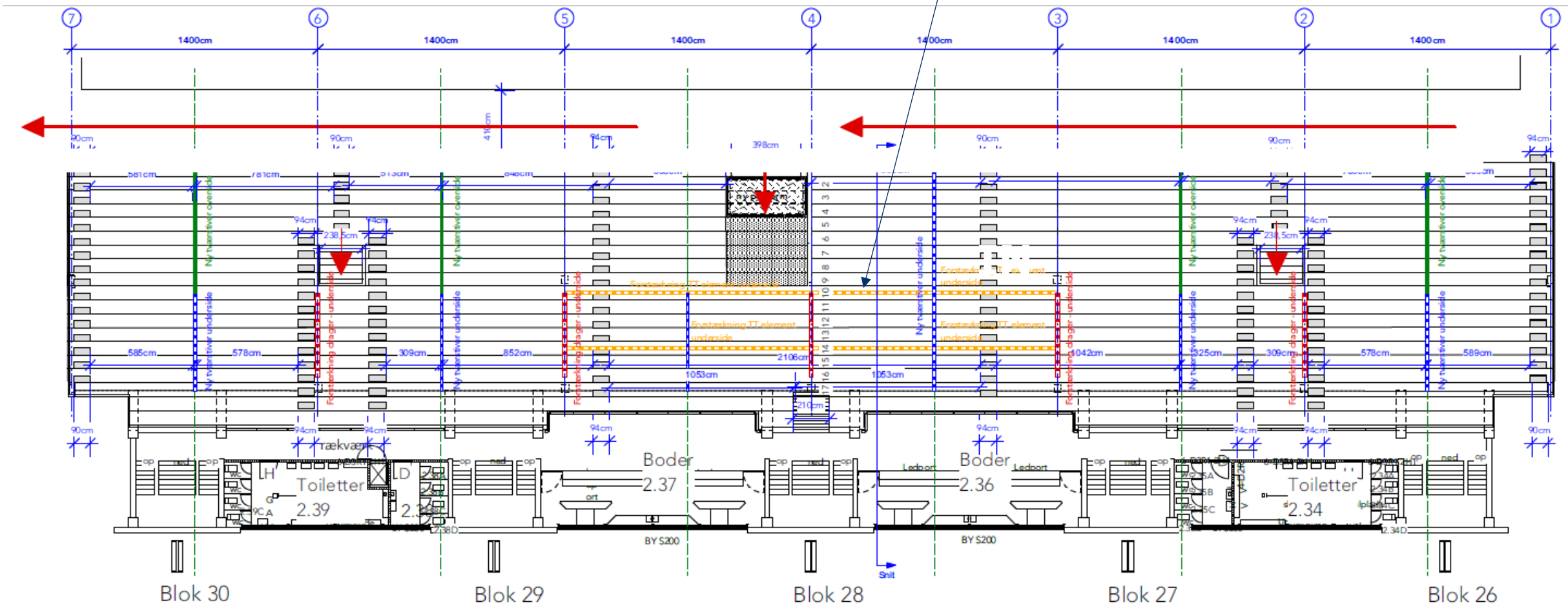
**MAIN GIRDER REINFORCEMENT
UPPER, ROW 9-17**

**MAIN GIRDER SUPPORT
LOWER, ROW 1-9**

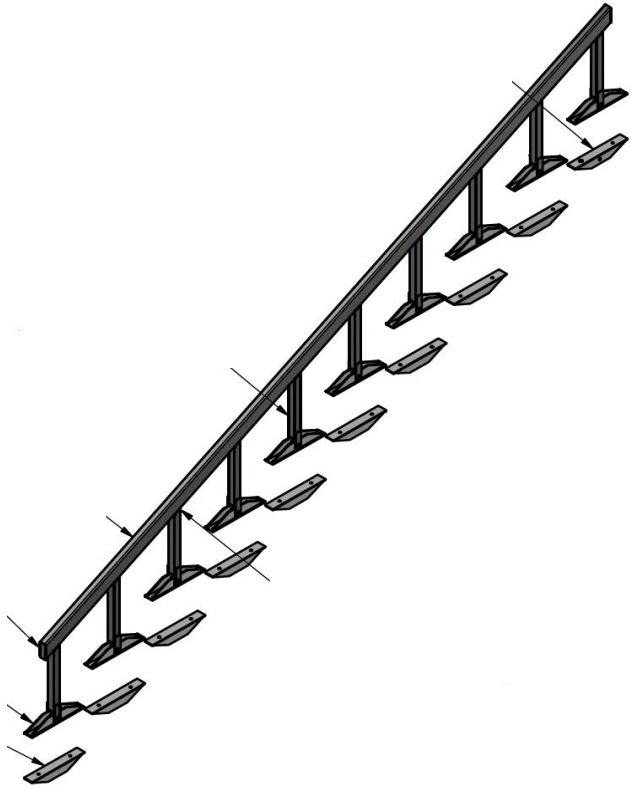


NEW STEEL STRUCTURES

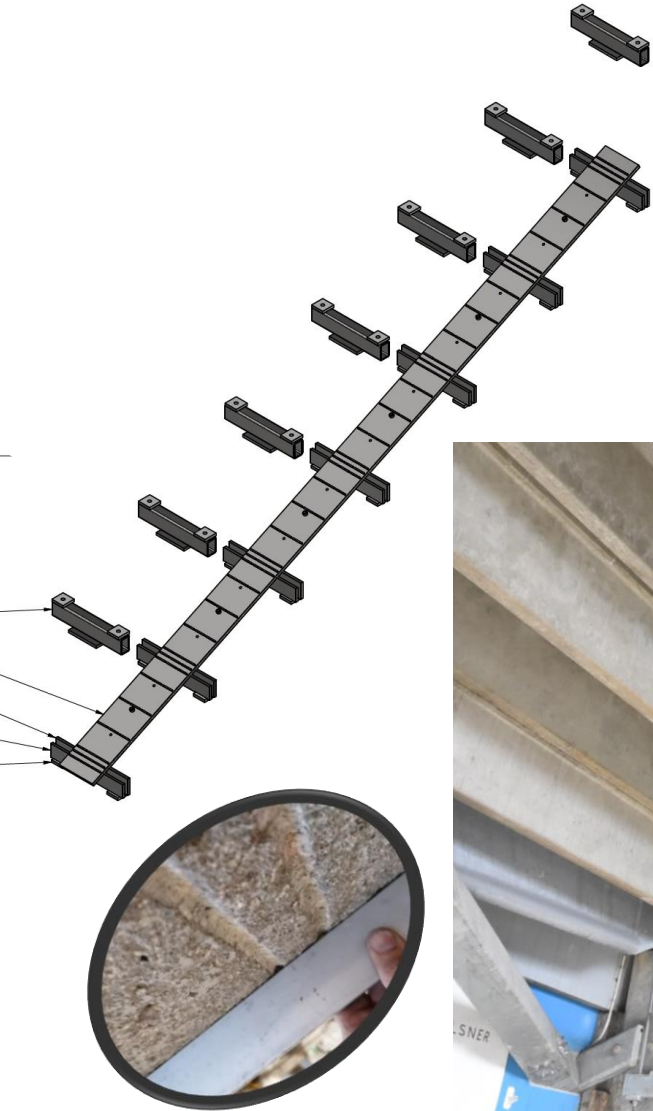
LONGITUDINAL 14 M BEAMS
IN CENTRE SPANS BEHIND GOAL



Transverse beams upper parapehets row 1-9



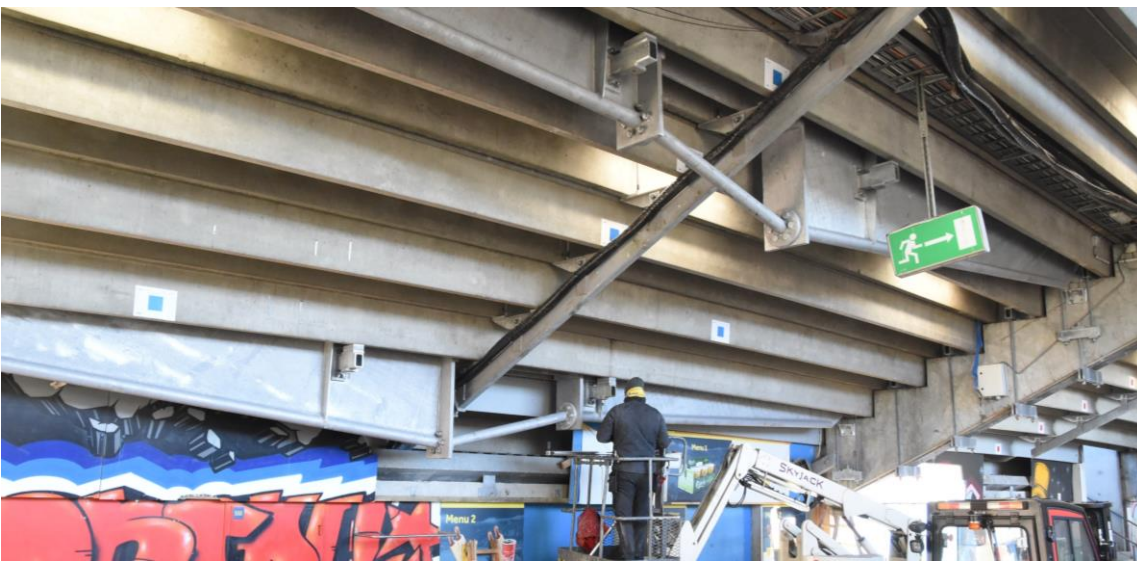
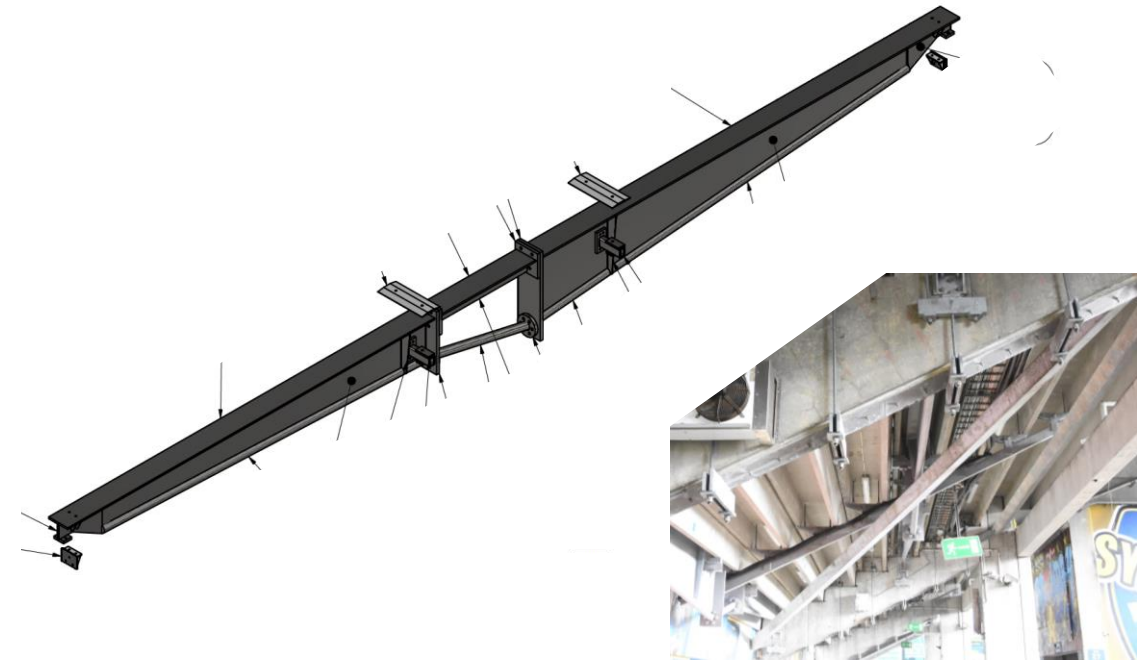
Reinforcement of upper main girders (row 9-17)



Ramboll



14 m longitudinal beams



FULL SCALE LOAD TEST

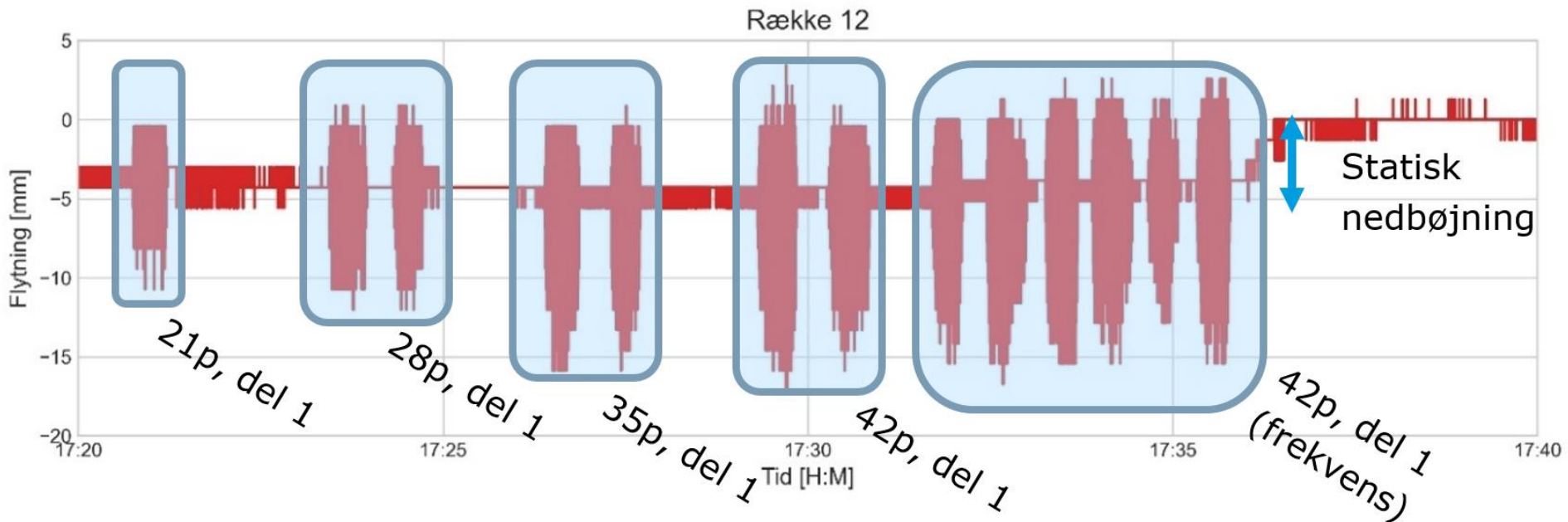
FULL SCALE LOAD TESTING WITH 350 PEOPLE



- > Allows for controlled/variable load intensity and frequency, and validation of effect of '14m beams'
- > Load testing aimed at reestablishing full capacity – in-game monitoring maintained for later validation.
- > Load testing in 2 critical/representative sections with/without '14m beams'
- > Simultaneous excitation of 8-17 elements due to cross bracings (21-42 people/elements)
- > Monitoring with accelerometers and DIC GoPro cameras

FULL SCALE LOAD TESTING WITH 350 PEOPLE

- > Preparation is king! – 350 supporters moving/jumping/stopping for only a limited period of time
- > 20 load tests of 20 seconds over ~2 hours (legs hurting – zero jumping in 1½ years due to Corona ☹)
- > Authentic atmosphere – jumping to the sound of music ☺



FULL SCALE LOAD TESTING

[350p, 9 rows, ~ 1.8 Hz]

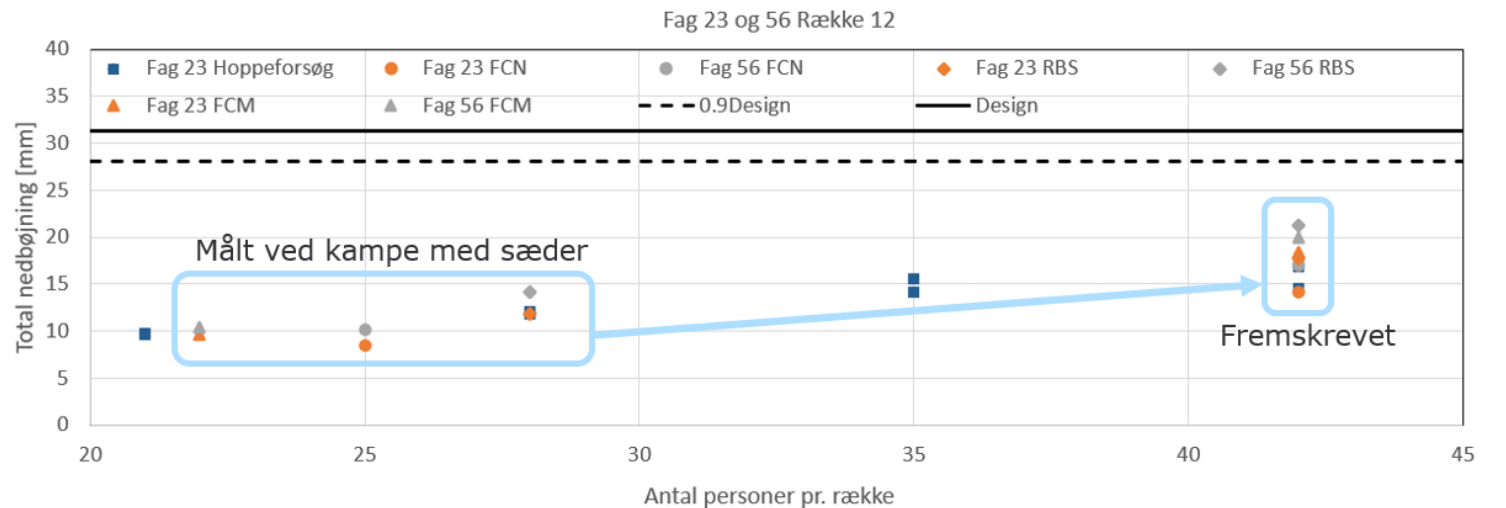
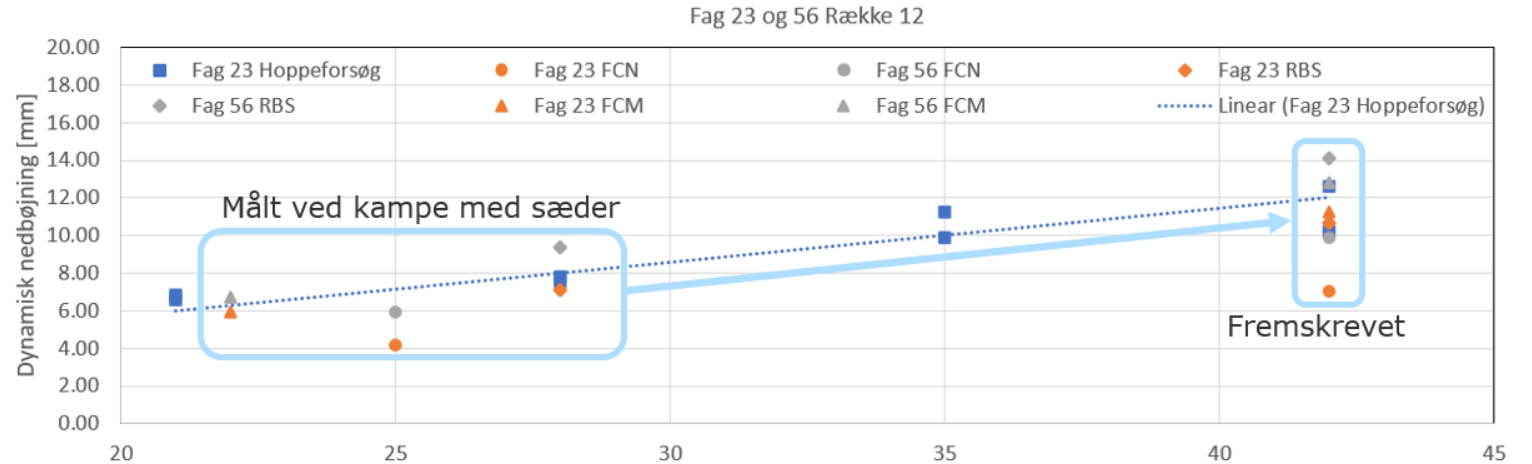


RECOMMISSIONING & OPERATION

VALIDATION BY IN-GAME MEASUREMENTS

[Vibration measurements extrapolated]

- > 2750 people and seats installed
- > Extrapolation by 1:1 with #people to
- > Estim. 21mm total with 4700 people
- > 75% of acceptance criteria – good 😊!



RECOMMISIONING

[standing terrace again 😊]

- > Back to full capacity – 4700 supporters & no seats
- > Brøndby-FCK, Sunday October 24 2021 (result 3-1 😊)
- > Max total deflections 22 mm in central spans
- > +20% increase compared to load testing – was expected



PERMANENT MONITORING

[proactive maintenance]

- > Permanent monitoring of vibrations for continuous safety
- > Cost-effective monitoring system with RamVib smartphones
- > Remote online access, automatic cloud upload and analysis



A SUCCESSFUL REHAB CASE

[doesn't sell newspapers]

- > Sustainable solution – strengthening of existing structures rather than replacement enabled by structural monitoring
- > Cost effective solution – savings of 70% / 12-14mDKK
- > EUROCODE dynamic pedestrian loading model conservative!
- > Existing structures need bespoke solutions!

Rådgivere redder Brøndbys tribuner med hoppeforsøg og studier af slagsange



(Illustration: Robert Hendel / Gonzales Photo / Ritzau Scanpix)

Fans var ved at hoppe tribunerne på Brøndby Stadion i stykker. En udskiftning var forestående, men studier af slagsange og hopperi har vist, at forstærkning og overvågning er nok.

Af [Ulrik Andersen](#) [Følg @UAndersen](#) 21. nov 2021 kl. 12:00 [1](#)



Spændingen var i top, da FCK 24. oktober gæstede Brøndby Stadion til endnu et opgør, og hjemmeholdets tilhængere heppede intenst på deres helte. Men det var ikke kun på tribunerne, spændingen var stor. Under dem gik ingeniører fra rådgivningsfirmaet Rambøll rundt med øjnene rettet opad:

PARKEN STADIUM COPENHAGEN

- Constructed in 1992
- Extensive coordinated jumping on B-stand registered/measured in februar 2023, exceeding design loads
- Jump ban from march 2023
- Larger scale vibration test as part of strengthening project
- Strengthening solution in development



Bright
ideas.
Sustainable
change.

RAMBOLL

