# Latest developments in long span bridges

Henrik Polk - Technical Director
Bridges International, COWI



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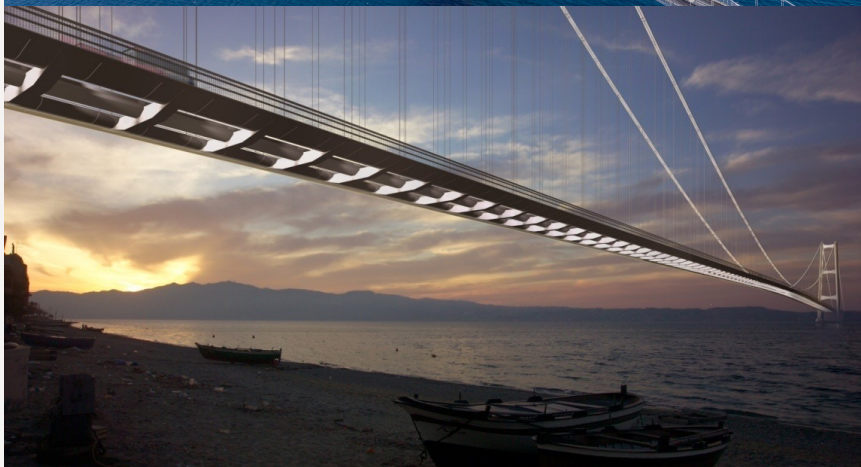
# Long span bridges – own references

- Cable stayed bridges - built
  - Tappan Zee - 370m, New York 2017 (prepared for railway)
  - Russky Bridge – 1104m, Russia 2012
    present world record
  - Chong Ming Yangtze River Bridge – 730m, China 2009
  - Sutong Yangtze River Bridge – 1088m, China 2008
  - Öresund bridge, - 490m Denmark 2000 (road and railway)
- Cable stayed bridges – not built yet
  - Bjørnafjorden Floating Bridge, ½ span of 430m, Norway
- Hybrid bridges (combined suspension- and cable stayed bridge) – built
  - Yavuz Sultan Selim Bridge – 1408m, Türkiye 2016
    present world record
- Floating bridges – not built yet
  - Bjørnafjorden Floating Bridge – 5400m, Norway

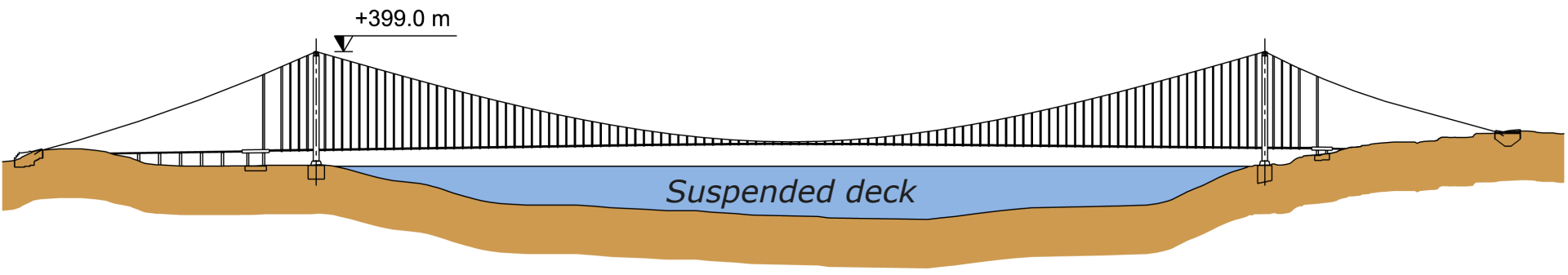
# Long span bridges – own references

- Suspension bridges - built
  - 1915 Çanakkale Bridge – 2023m, Türkiye 2022 present world record
  - Osmangazi Bridge – 1550m, Türkiye 2016
  - Maputo-Katembe Bridge, Mozambique 2018
  - Great Belt – 1624m, Denmark 1998
  - Chacao Bridge – 2x1100m, Chile (under construction)
  - Zhanggao Bridge – 2300m, China (under construction)
  - ShiZiYang Suspension Bridge – 2180m, China (under construction)
- Suspension bridges – not built yet
  - Messina Strait Bridge – 3300m, Italy
  - Halsa Fjord Suspension Bridge, 2000m, Norway
  - Sula Fjord Suspension Bridge, 2000m, Norway
  - Vartdalsfjorden – 2250m, Norway



# New straits to pass – span lengths

- Cable stayed bridges - max span length of 1104m since 2012 (Russky Bridge)
  - Appears as max span length has been reached
- Hybrid bridges – max span length of 1408m since 2016 (Yavuz Sultan Bridge)
  - Bridge type substitutes a suspension bridge where vertical deck stiffness is essential – e.g. carrying a railway line
- Suspension bridges - max span length of 2023m since 2022 (1915 Çanakkale Bridge)
  - New bridges under construction increasing max span length to 2300m in 2026-28
  - If construction of the Messina Bridge gets stated in 2025, max span length will become 3300m
  - Hypothetical - Gibraltar Crossing with 5000m main span

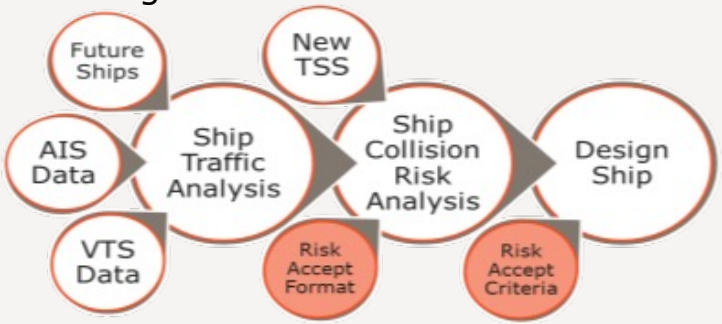


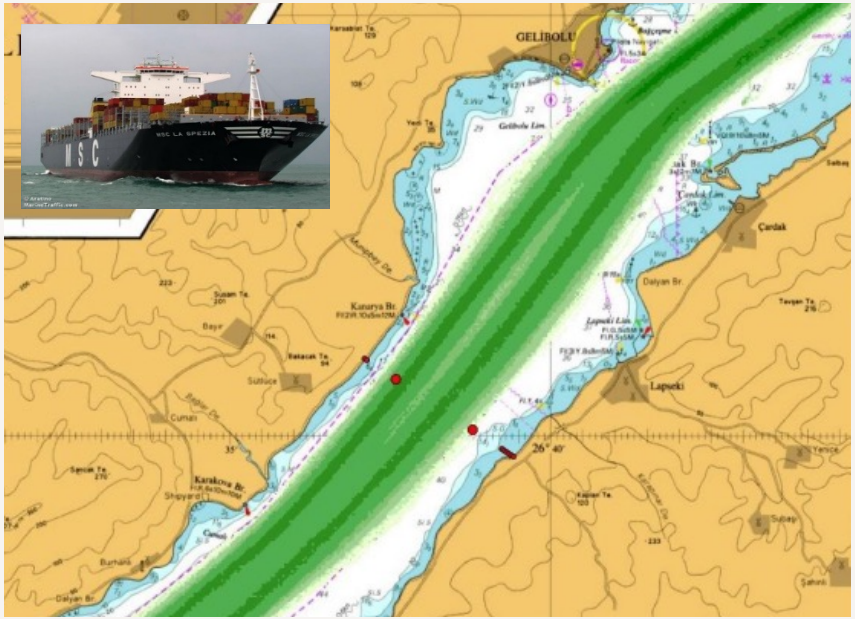
# New straits to pass – span lengths

- Straits of up to 5400m width - new concepts being developed for floating bridges
- Interest from many sides, but it will take time to mature the projects
- Main challenges are (Bjørnafjorden Bridge, Norway):
  - Relatively high waves in combination with long period swell (15-30s)
  - Floating bridges are not covered by the Eurocode system
  - Complex correlation between wind and waves for bridge superstructure
  - Ship impact – global impact, locally at piers, girder and pontoon walls
  - Hydrodynamic pontoon design and risk of flooded pontoons
  - Complex fatigue loading due to combined waves, wind and traffic
  - Complex erection – long prefabricated bridge sections towed to site and connected
  - All in all - complex design and construction

# New straits to pass – ship traffic

- Larger ships and increased ship traffic
- Çanakkale Bridge used as example
  - 44,000 registered vessels passing the strait per year – potential increase
  - The traffic today includes 260,000DWT bulk carriers, 167,000DWT oil tankers and 16,000TEU container ships
  - The navigation clearance is 1600m wide by 70m high



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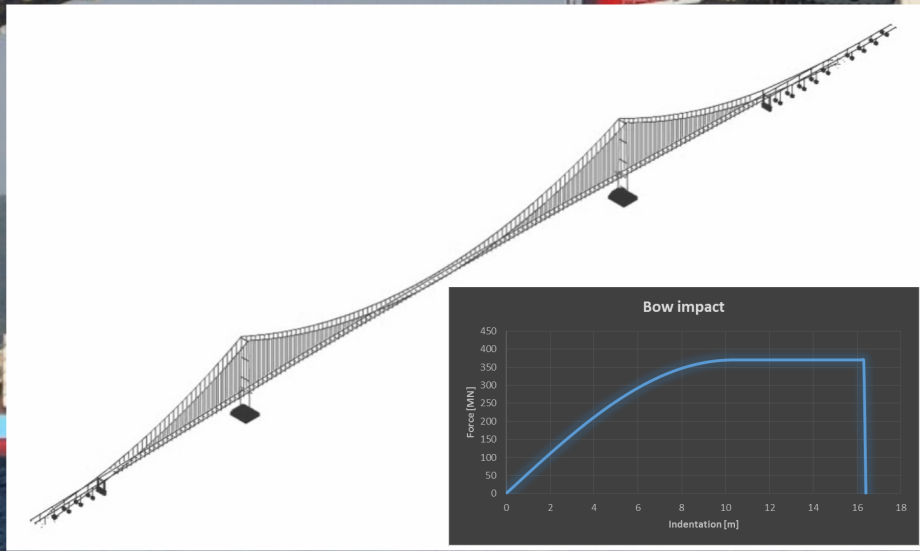
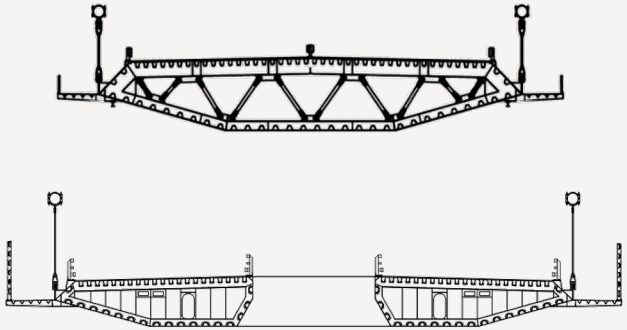
# New straits to pass – ship traffic

- Consider and design robust substructures
  - Dynamic analysis performed in global FE-model to obtain the sectional forces from the global effect of the impact load
  - Strict design criteria introduced to achieve minimal damage of non-accessible parts of foundations under accidental loads
  - Lower part of steel tower and concrete plinth design are governed by ship impact



# New straits to pass – stability of steel box

- Increasing main span length giving challenges in respect to secure the deck flutter stability
  - Simplified - flutter instability might happen at low wind speed if the 1st torsional frequency becomes too close to the 1st vertical frequency
  - Increase torsion stiffness – make the steel box higher, or even better widen the steel box, or separate the steel box into two
  - Mono-box girder - feasible up to typical 1800-2000m (2300m for Zhanggao Bridge) dependent on wind conditions and special additions
  - Twin-box girder – typical beyond 1800-2000m





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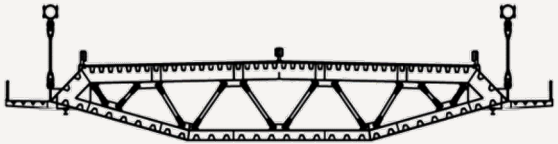
# New straits to pass – mono-box aerodynamic

- Flutter wind speed becomes a challenge for long span single box girders
  - Keep angle of inclined bottom flange reasonable low
  - Install guide vanes at the corner between bottom flange and inclined bottom flange - guiding the wind round the corner and thereby reduces vortex shedding
  - Active design of safety barriers and parapets
  - Vertical steel plate positioned at centre of deck and at bottom
  - By above active measures the Zhanggao Bridge has been able to stretch the mono-box up to 2300m



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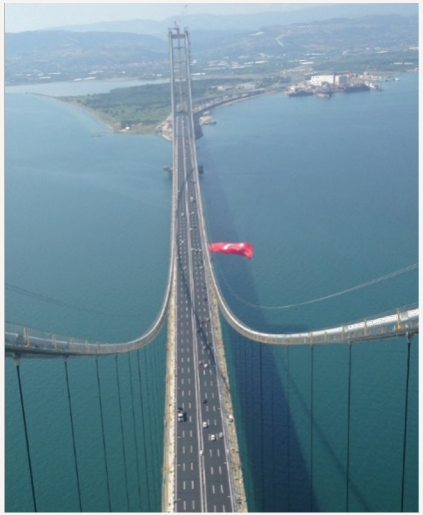
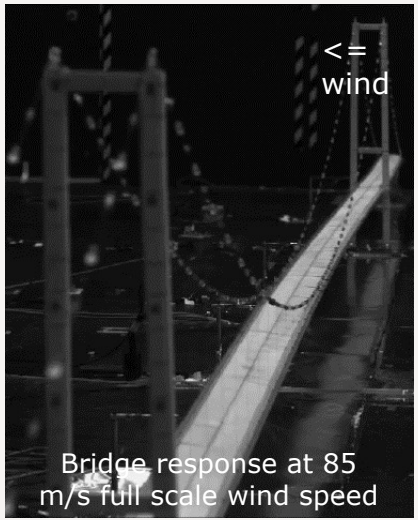
# New straits to pass – stability of mono-box

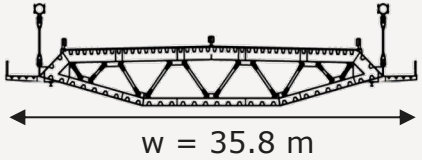
› Typical mono-box girder layout - Osmangazi Bridge

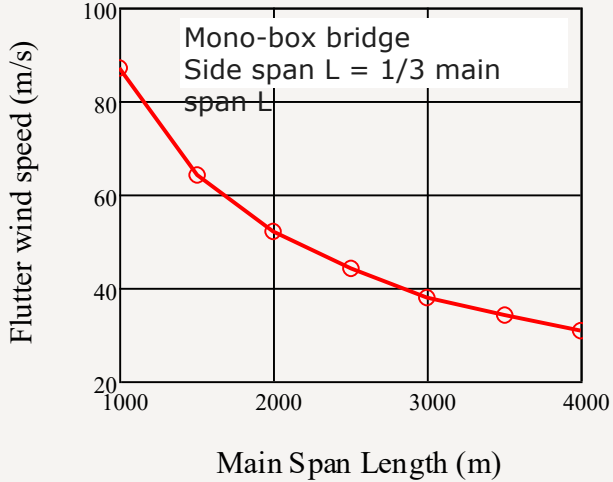
Main span L = 1550 m



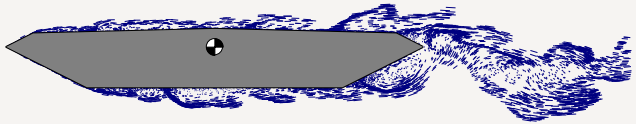
1:220 scale full bridge wind tunnel model




- Flutter wind speed requirement: 58 m/s



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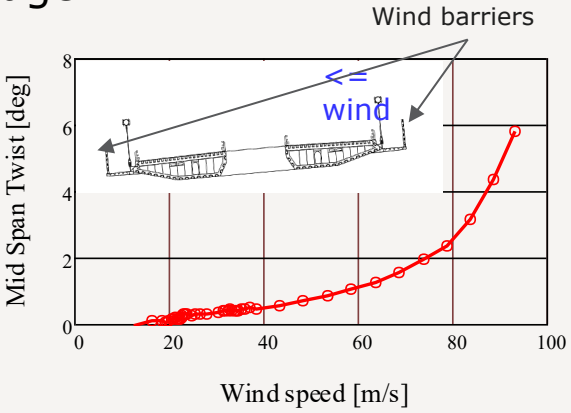
# New straits to pass – stability of twin-box

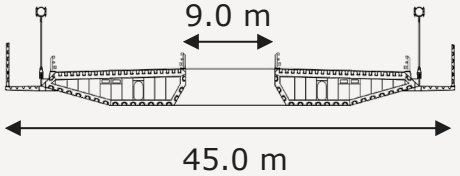
› Typical twin-box girder layout - 1915 Çanakkale Bridge

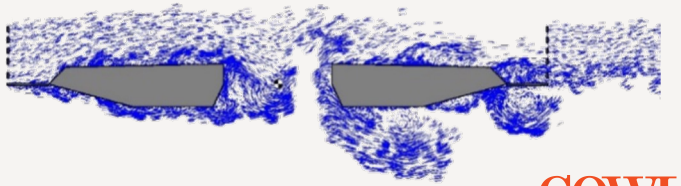
Main span L = 2023 m

1:190 scale full bridge wind tunnel model


- Flutter wind speed requirement: 69 m/s





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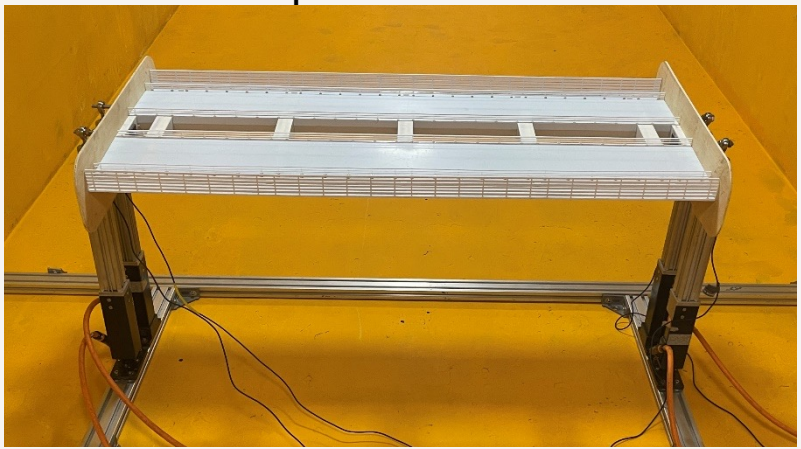
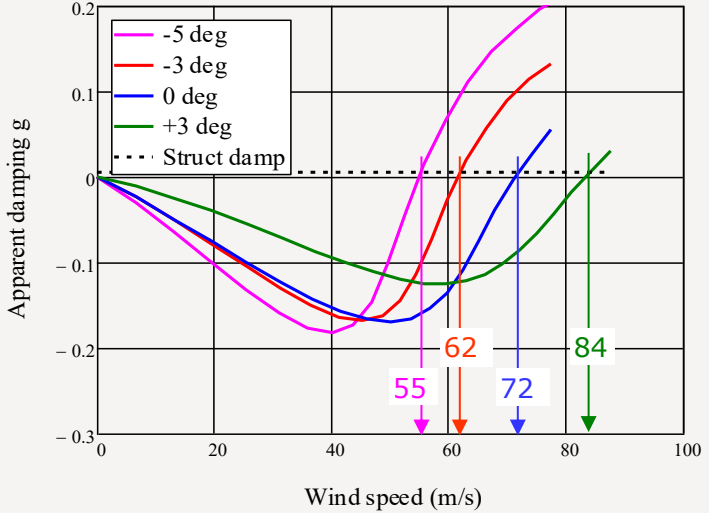
# New straits to pass – twin-box aerodynamic

- Flutter wind speed as function of deck angle of rotation relative to horizontal
- The "nose-up effect"






- Higher wind speed – the more the deck will twist - "nose up effect"
- Higher wind speed - the more the deck will rotate making the deck even more stable



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# New straits to pass - aerodynamic and wind tunnel tests

- Aerodynamic modelling and testing of long-span bridges are essential obtaining the correct dynamic response of the bridge structure
- Testing is necessary to investigate:
  - Wind force coefficients (CD,CL,CM) and derivates
  - Vortex shedding
  - Galloping
  - Flutter instability

# New straits to pass - aerodynamic and wind tunnel tests

- Typical wind tunnel testing:
  - Tower section model (1:80 scale)
  - Full tower model (1:225) and tower erection stages
  - Deck section model at 1:60, followed later by 1:30
  - Hanger vibration (1:1) and wake galloping
  - Full bridge model (1:190) and deck erection stages


Scale 1:225, Tower


Scale 1:60, Deck


Scale 1:30, Deck

Scale 1:190, Full Bridge



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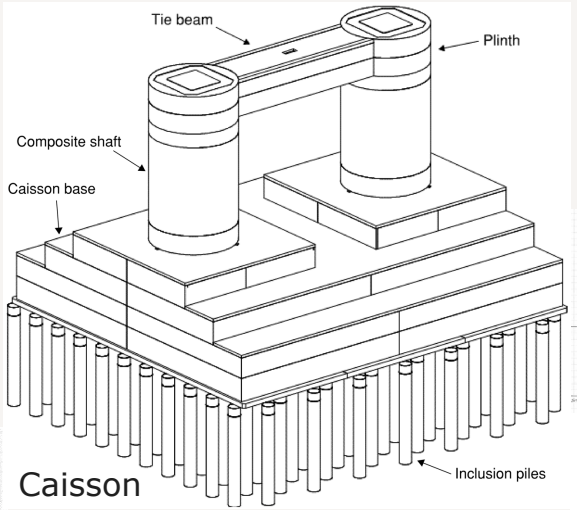
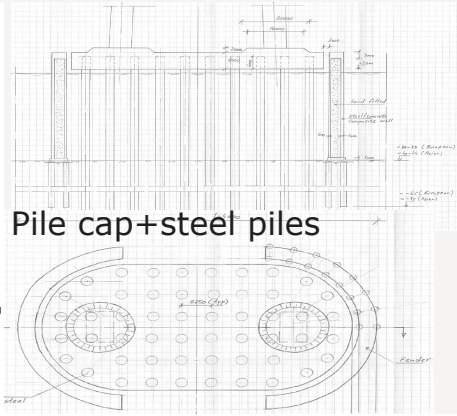
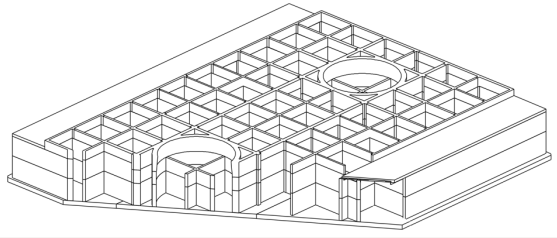
# Environment – tower foundation

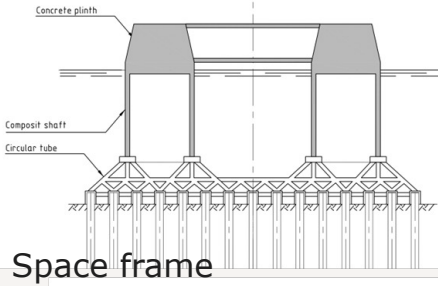
- Tower foundations – often placed in water with pour ground conditions
  - Investigate different concepts and evaluate in respect to experience, ship impact, seismic, track record, quantities, risk etc.
    - Open dredged wells
    - Pile cap + steel piles
    - Space frame
    - Caisson



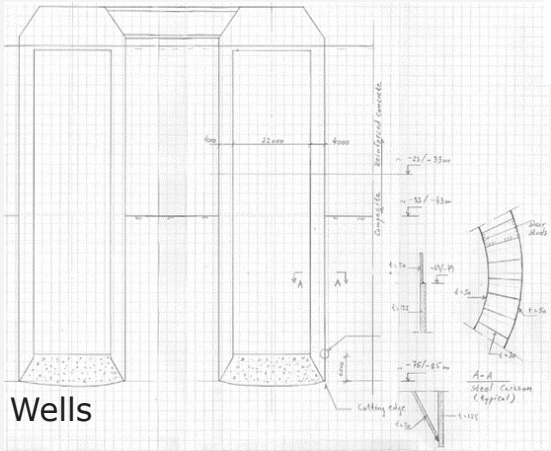
Caisson

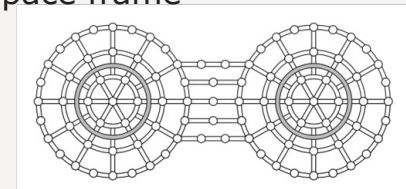

Pile cap+steel piles



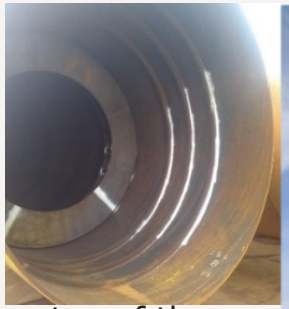


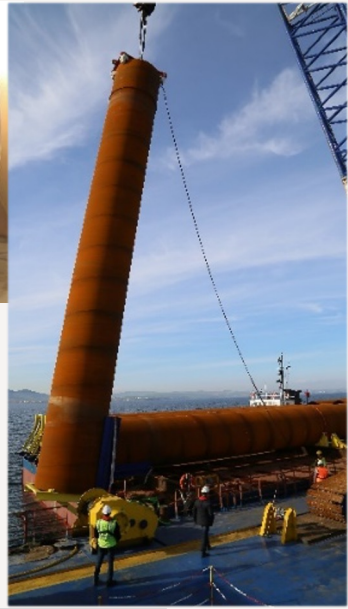
Space frame


Wells

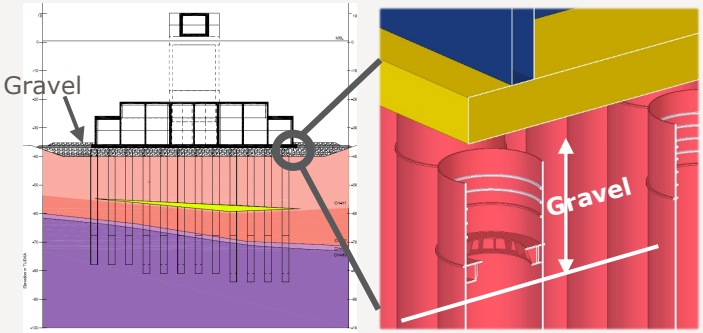


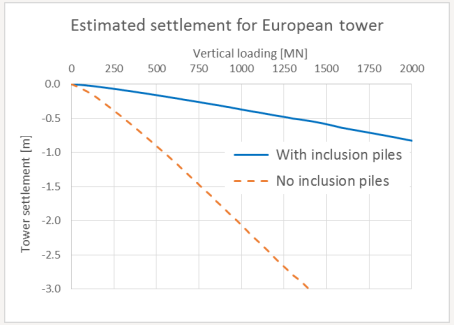
# Environment – tower foundation

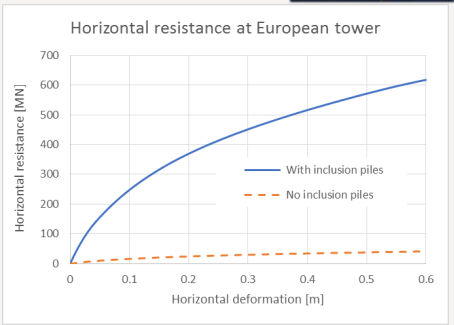




- Often it ends with a caisson solution
  - Robust for ship impact
  - Robust for seismic overloading – can slide on the gravel bed placed on top of the inclusion piles
  - Fast construction off site, work in parallel with construction site
- Long steel inclusion piles are driven into the seabed
- Caisson is placed on a gravel bed on top of steel inclusion piles
- Settlement reduced and lateral resistance increased



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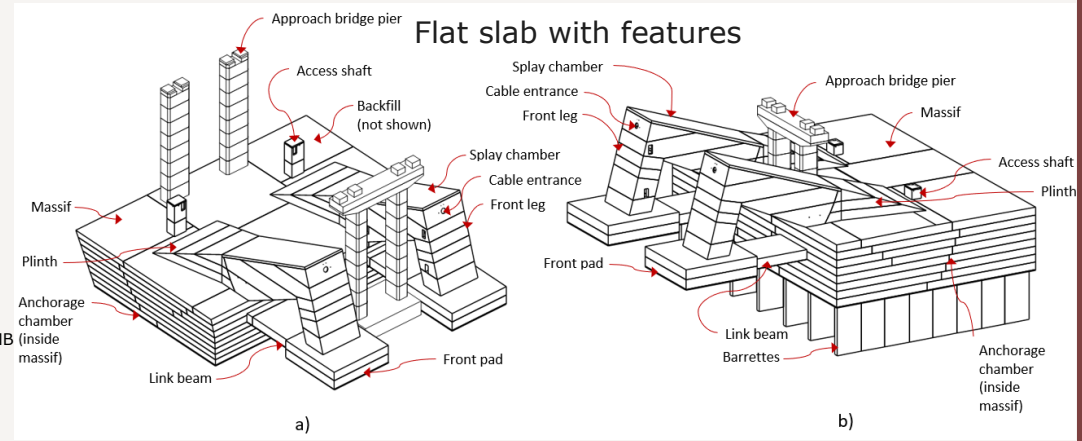
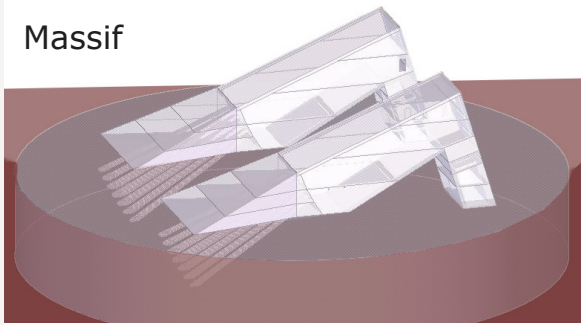
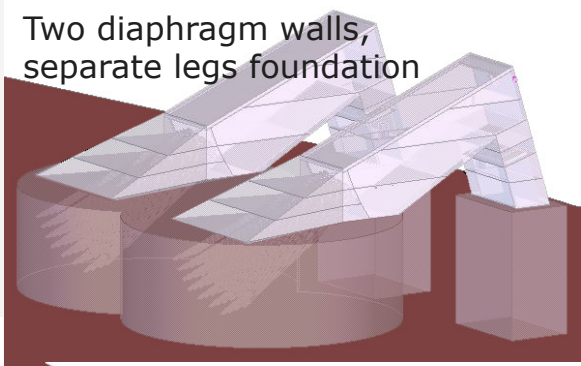
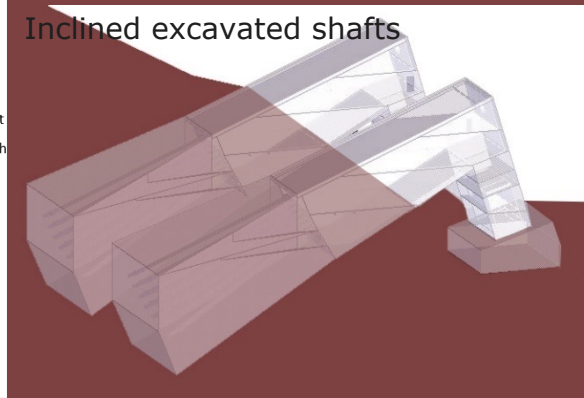
# Environment - anchor blocks

- Anchor block foundations – often placed in water or at shoreline also with pour ground conditions
  - Investigate different concepts and evaluate in respect to experience, ship impact, seismic, track record, quantities, risk etc
    - Massif inside diaphragm wall circle
    - Two overlapping diaphragm wall circles, front legs on separate foundations
    - Inclined shafts excavated and refilled with reinforced concrete
    - Flat slab with features



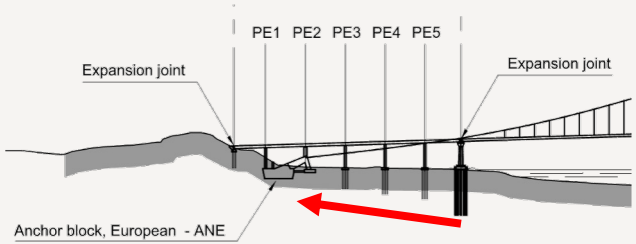



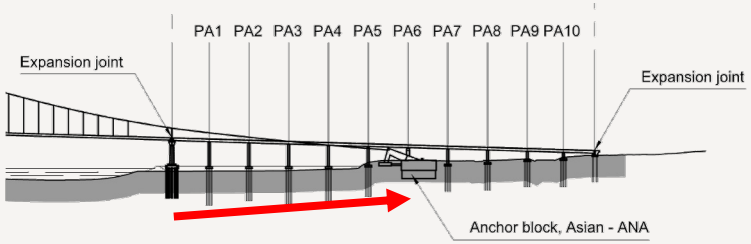



# Environment– anchor blocks

- Ended moving anchor block "up" and some 300m further inland and choose the slab solution with features
  - Flat massif with individual front legs
  - Backfill can act as counterweight
  - Diaphragm walls to increase shear capacity
  - Excavation without major temporary support
  - Concrete quantities reduced by 50% and thereby also saving in construction time
  - Additional costs are longer main cables and tie down arrangement at side span piers (modified bridge articulation)



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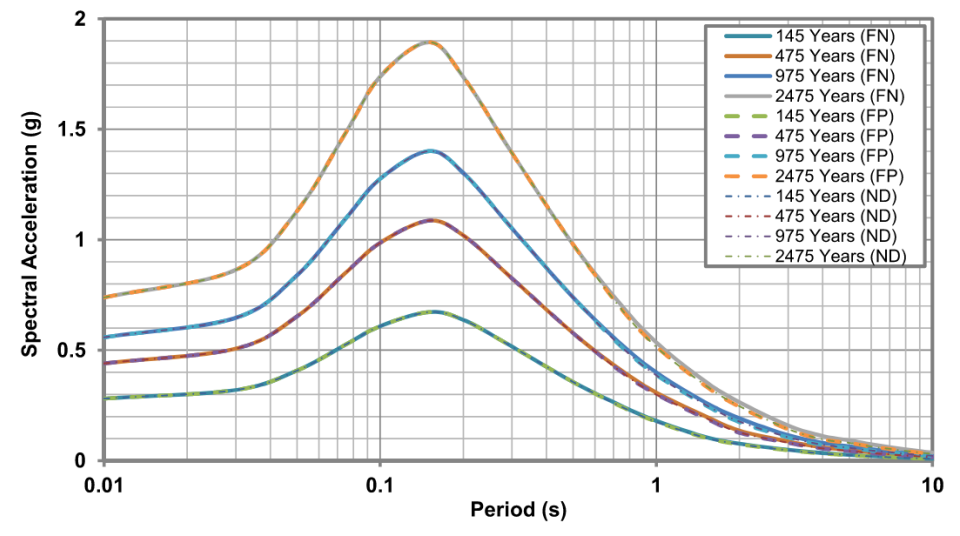
# Environment - seismic analysis

- Design criteria typical considers 3 potential events:
  - Functional evaluation earthquake (FEE) – 145 year return period
  - Safety evaluation earthquake (SEE) – 975 year return period
  - No-collapse earthquake (NCE) – 2475 year return period
    - For inaccessible substructures a stricter requirement is often introduced following the SEE



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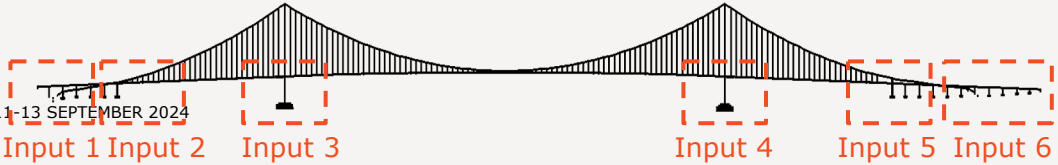
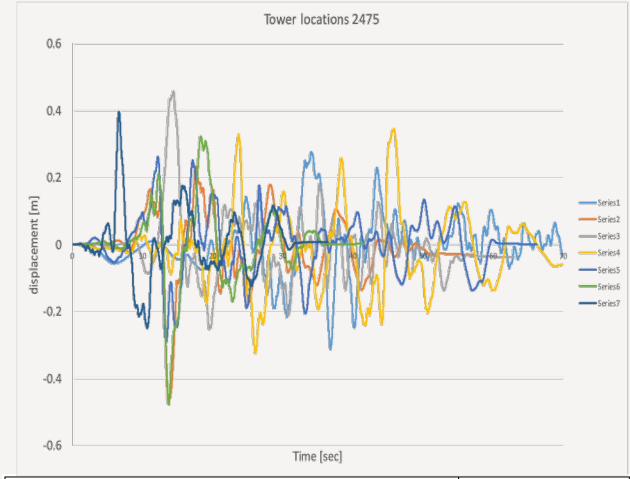
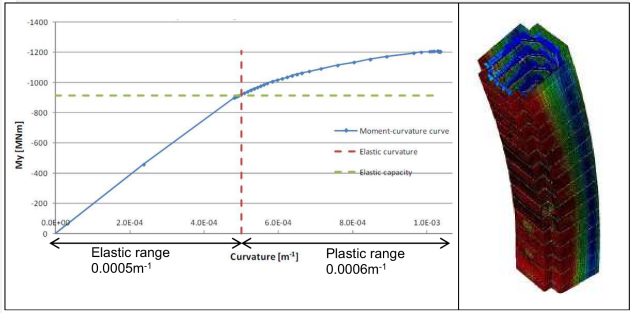
# Environment - seismic analysis

- Important to investigate the non-linear behavior using 7 sets of earthquakes - EC then allows to use average for design
  - Time-displacement actions in three directions at six main bridge supports - see figure below
  - The analyses to verify sufficient capacity of bridge inclusive hydraulic buffers, tower wind bearings, end stops and soil-structure interaction
  - Anchor blocks and tower caissons often partly governed by seismic
  - Towers (steel) govern partly by seismic when in “high seismic zones”




Tower – plastic design in NCE



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# Traffic loading - road

## Global road traffic loading - uniformly distributed load (UDL)

- Loaded lengths < 200 m, UDL = 81.8 kN/m
  - Eurocode 1991-2 load model 1, 2 and 3

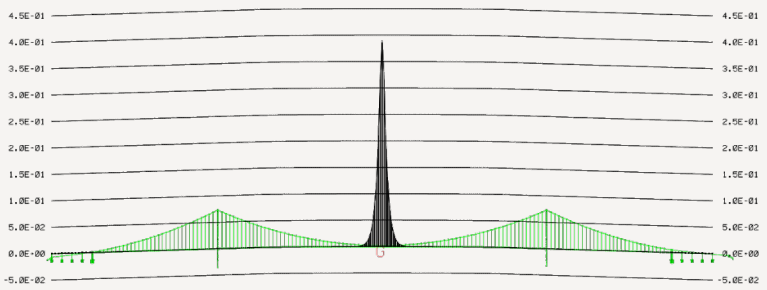
(1) Load models defined in Clause 6 should be used for the design of road bridges with loaded lengths less than 200 m.

NOTE 1 200 m corresponds to the maximum length taken into account for the calibration of Load Model 1 (see 6.3.2). In general, the use of Load Model 1 is safe-sided for loaded lengths over 200 m.

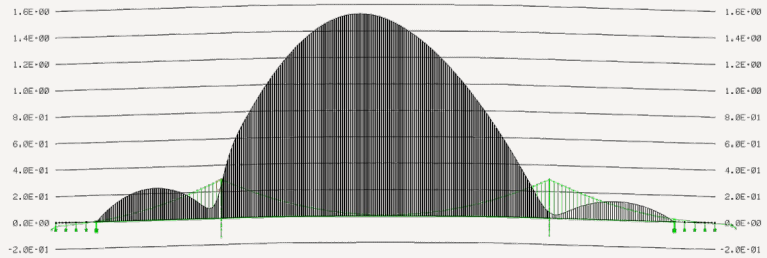
NOTE 2 Load models for loaded lengths greater than 200 m can be defined in the National Annex.

## Eurocode miss reduction in road traffic loading for long span bridges

- Loaded lengths > 200 m - UDL = 58.8 kN/m
  - By using EN 1991-2 SE-NA (TRVK Bro 11 - taking effect of long loaded length into account)



Influence on normal force in hanger



Influence on normal force in main cable



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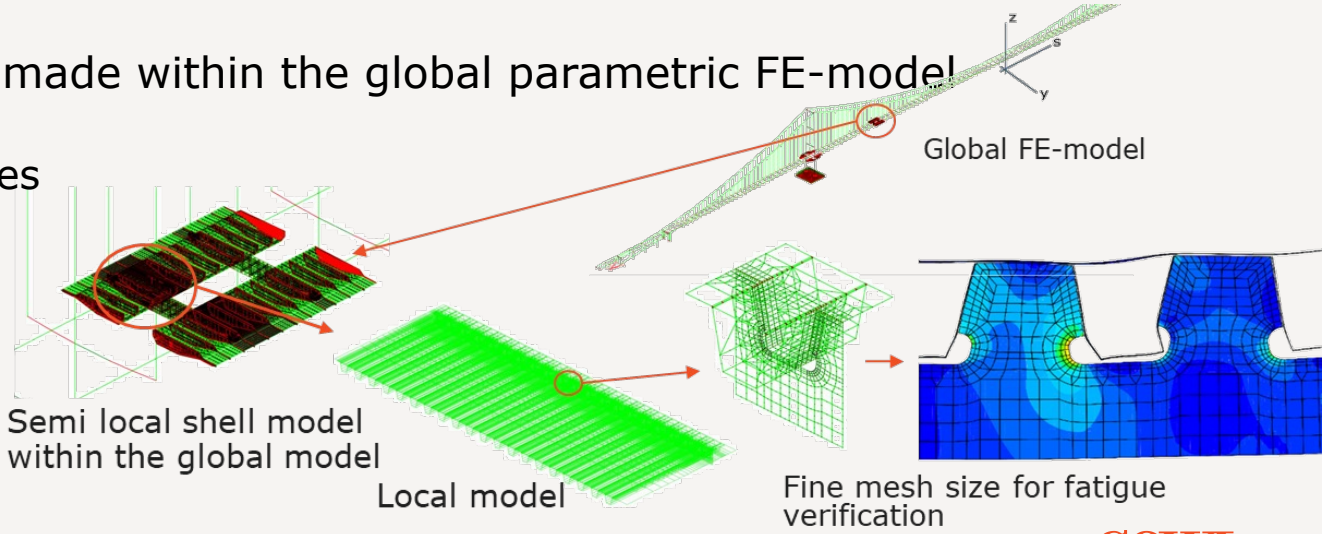
# Traffic loading – road fatigue

- Optimised deck design for modern cable supported bridges require detailed fatigue verifications of the orthotropic steel deck
- The detailed fatigue verifications should be based on full stress histories for individual vehicles
- The full verification is made within the global parametric FE-model
- Verification using the normal fatigue categories or the more refined hot spot method
- How to improve fatigue life will be presented in coming slides



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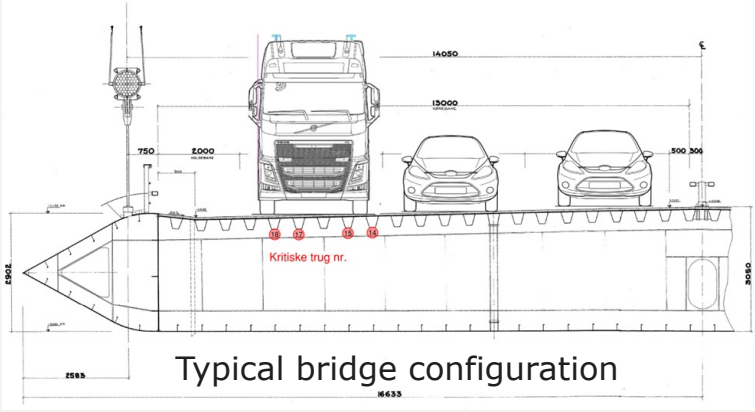
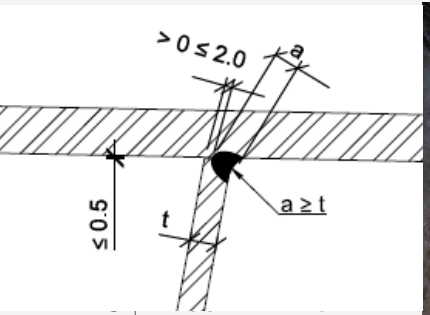
# Traffic loading – impact from fatigue

- Many long span bridges experience fatigue problems after 20-50 years in service
  - Deck plate typical 12mm and trough 6mm
  - Cracks often initiate at diaphragms in heavy lane near the expansion joints and propagates into the deck structure over the years
  - Heavy traffic increases rapidly
  - New axle configurations with increased loading
  - Welding techniques, requirements and NDT have however also improved since designs



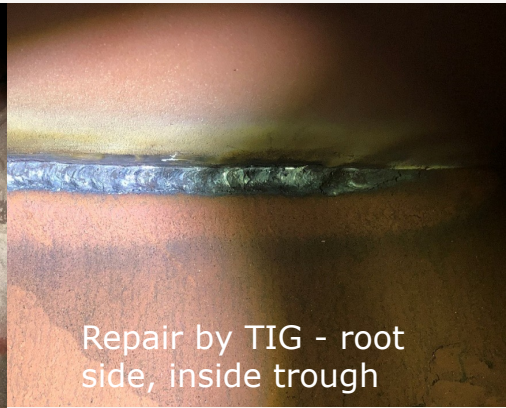
Typical bridge configuration



Typical trough to deck detail

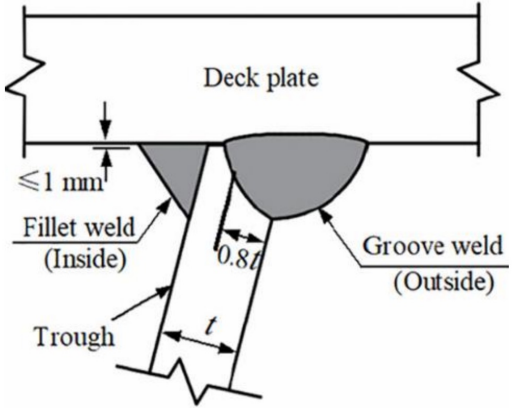

Crack propergates from diaphargm

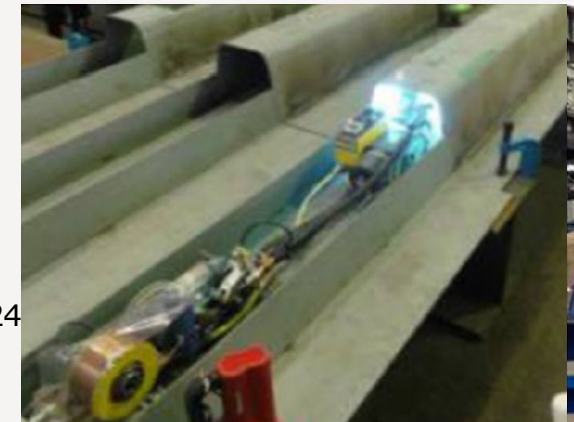

Repair by TIG - outside trough

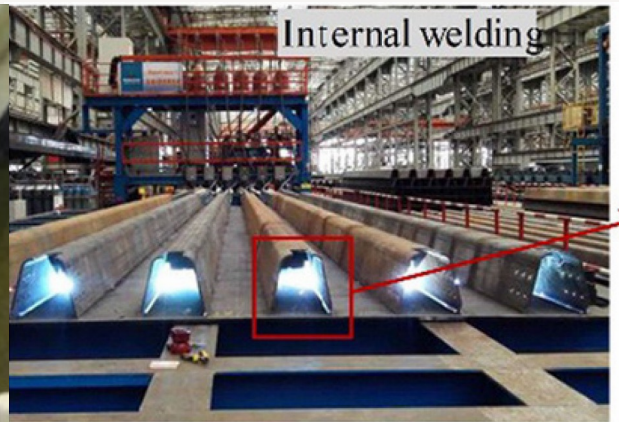

Repair by TIG - root side, inside trough

# Traffic loading – improve fatigue durability

- Increase deck plate and troughs in heavy lanes to say 14-16mm deck plate (perhaps even more) and 7-8mm troughs – already done for most new designs
- Double-sided welding of troughs to deck – being done China
  - Own preliminary investigations suggest 50% increase in design life
  - Perhaps above can also be done for repair works when asphalt shall be renewed. Troughs shall then be continuously without inside obstructions. This could be a problem for bolted troughs

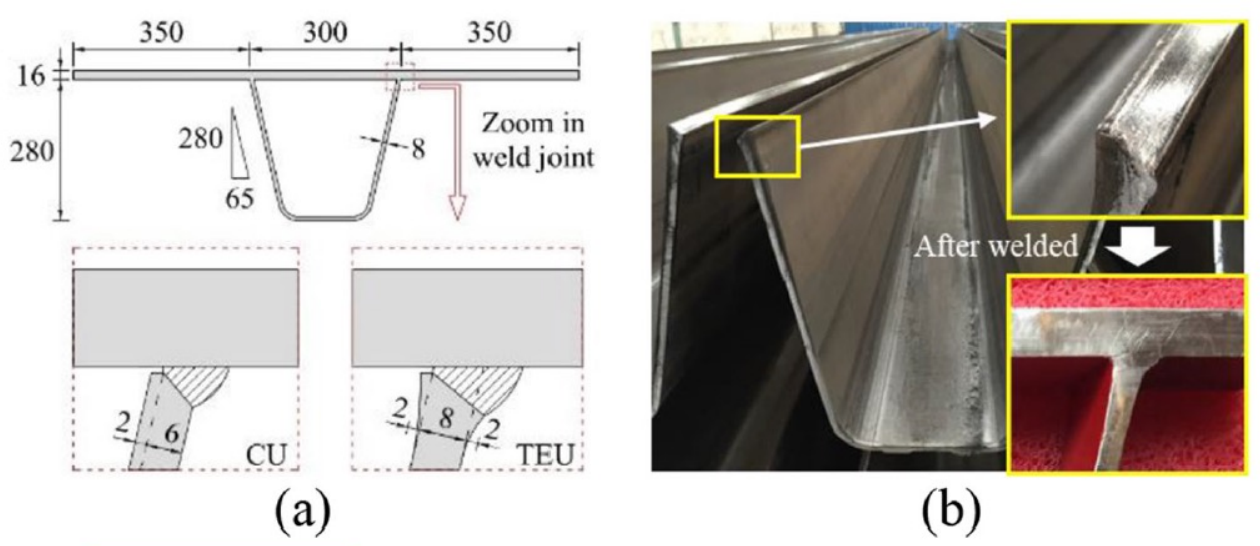





# Traffic loading – improve fatigue durability

- Thickened edge of troughs from 8mm to 12mm
  - Partial weld, fully welded from one or two sides



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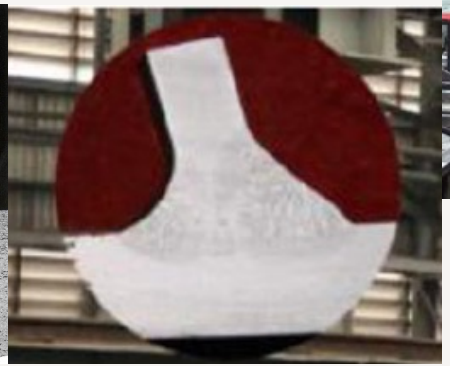
# Traffic loading – improve fatigue durability

- Better weld quality by new welding techniques - robot welding, laser hybrid welding and automated NDT methods
  - Improve weld uniformity and quality
  - Fully welding of deck to trough joints from one or two sides
  - Automated NDT – less defects
  - Use of Artificial Intelligence (AI) in welding and NDT process



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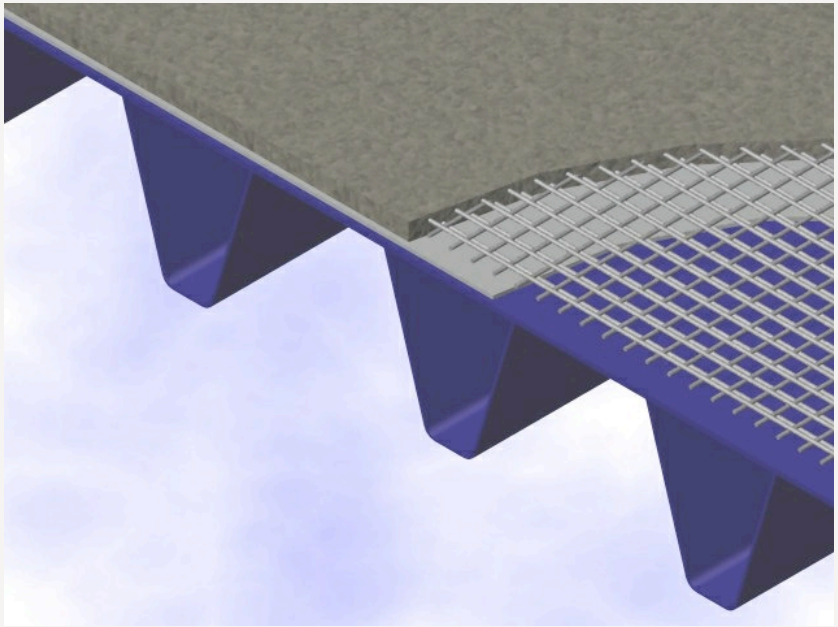
# Traffic loading – improve fatigue durability

- Increase deck stiffness and improve its isotropic properties
  - No light break through alternatives have yet been found to replace the light 70 year old "orthotropic steel deck"
  - Use stiffer asphalt types
  - Use high performance concrete – fibre or stainless steel net





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# Traffic loading – rail and rail fatigue

- A stiff deck structure is essential when designing long span bridges for rail traffic
- High truss girder structure is often used, alternatively the new hybrid bridge type
- Complex analyses to be performed:
  - Simulating trains passing over bridge structure by use of dynamic properties for the trains
  - Verification of the bridge performance
  - Train derailment and overturning
  - Comfort analysis
- Railway fatigue
  - In principle as for road



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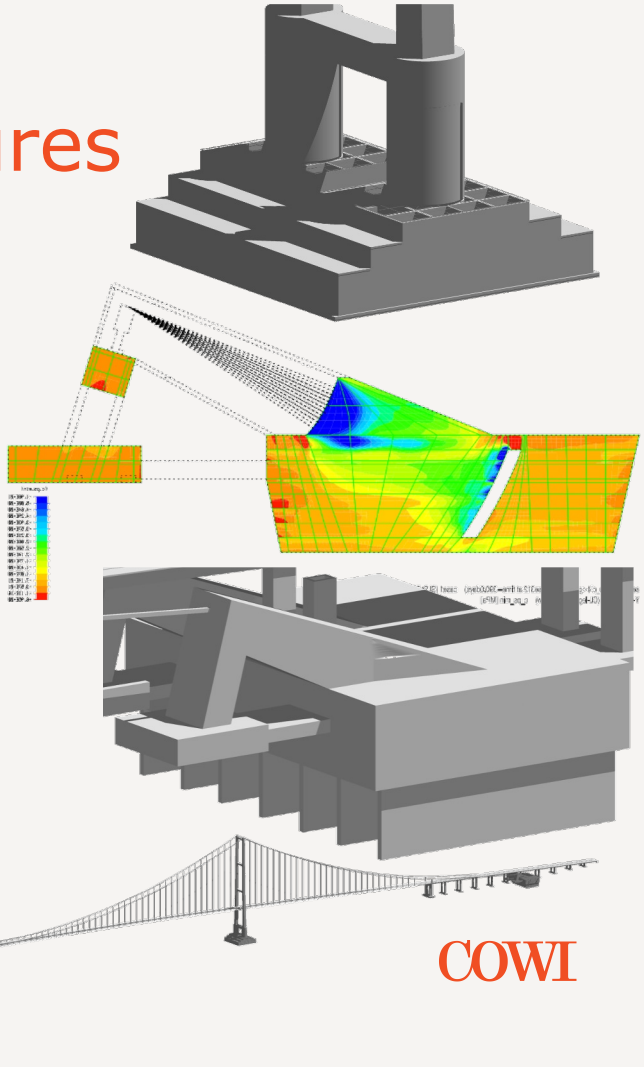
# Materials – concrete substructures

- The concrete substructures are designed and optimised directly in the global FE-model
  - Modelling in one global parametric FE-model with integrated local models
  - Boundaries becomes correct when having only one FE-model
  - Automatic load application – beneficial for all models
  - Tower foundations – often done by shell modelling
  - Anchor blocks – often done by combination of 3D-solid modelling and shell modelling





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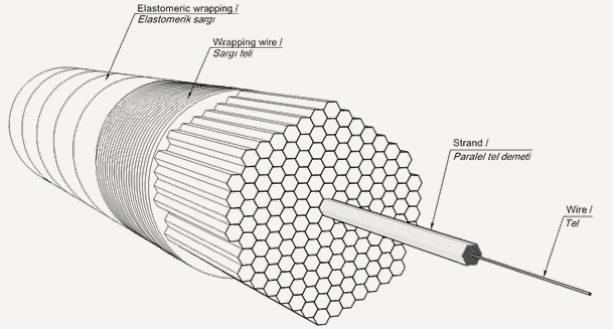
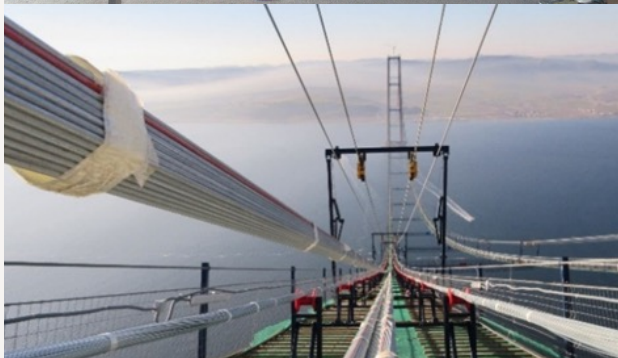
# Materials – cable structures

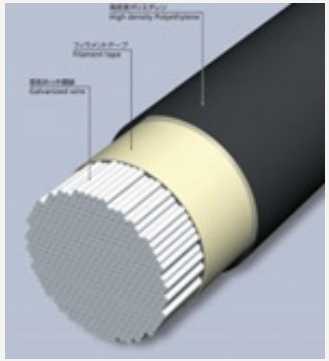
- Cable structures consist of main cables, splay- and tower saddles and hangers
  - Main cable
    - Up to 80% of loading in main cable is bridge self-weight, remaining almost from traffic – keep deck self weight to a minimum
    - Air spinning replaced by Prefabricated Parallel Wire Strands (PPWS)
    - Less number of strands gives faster erection - coils of 120 tons used for the Çanakkale Bridge
    - Each strand is pulled from one anchor block to the other giving faster cable erection compared to air spinning
    - Strand is hexagon shaped and has a red wire – easy to see if twisted
    - Wires - breaking strength of 1960MPa, but 2060MPa and 2160MPa might soon come into designs. 2060MPa already used in China
    - The main cable (D=850mm for Çanakkale Bridge, D= 1150mm for Zhanggao Bridge) is often protected by elastomeric wrapping and dehumidified ensuring a long design life
    - Main cable diameter can be increased beyond 850mm without major challenges. Already being done I China



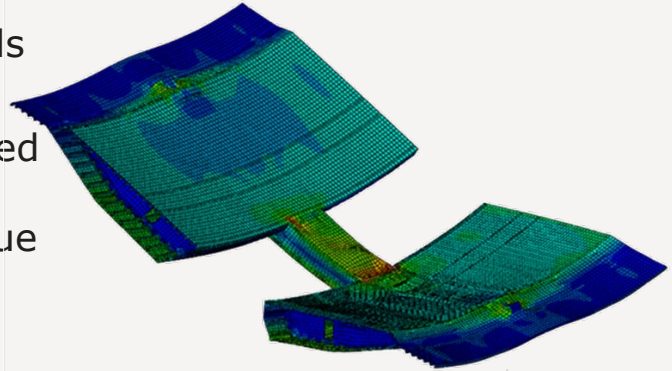
# Materials – cable structures

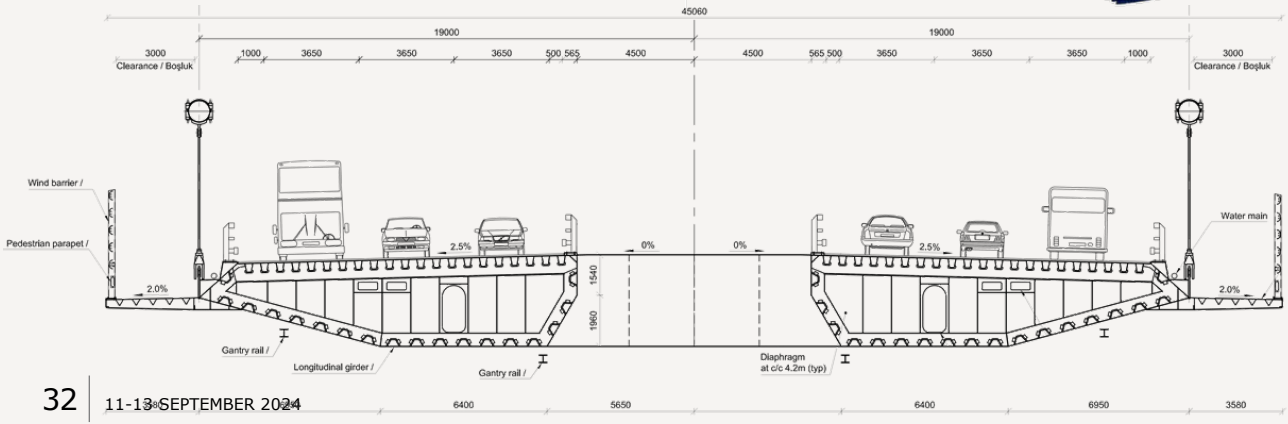
- Splay saddles, tower saddles and clamps
  - The trough parts are often manufactured in high strength cast-iron (G24Mn6+QT2/3) in combination with welded steel plates S460. Be careful not to go too thin in casting thickness
- Hangers
  - Parallel Wire Strand (PWS) type is used covered by HDPE sheeting (often in strength 1770MPa). PWS is stiffer than lock-coil cables earlier used

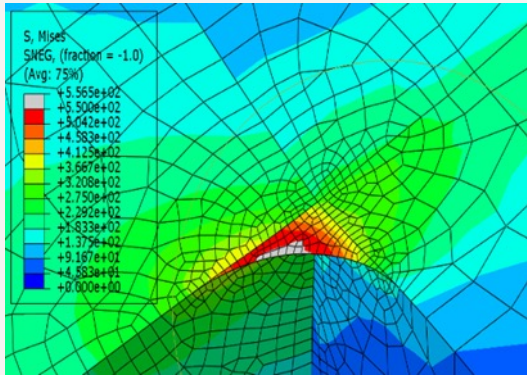


# Materials – steel structures

- Most common steel materials utilised are S355 to S460
- S550 was however introduced on the Çanakkale Bridge to overcome corner stresses due to Vierendeel effect of the twin-box girder





# Materials – steel structures

- S680 was utilised in splice plates connections of the Çanakkale tower
- It is foreseen that milling of steel plate within the range S355 to S460 can be done without reduction in yield strength due to thicknesses increase
- The high-performance steel mills can already deliver above increased quality, but contractors are reluctant as one might narrow the competition
- Alternatively use S500 which was introduced 2019 in EN 10025-4
- Another way is to use actual yield strength documented in the certificates. This has already partly been utilised
- Less use of materials means less $CO_2$





EN 10025-4:2019+A1:2022 (E)

**Table 4 — Mechanical properties – Tensile test properties at room temperature**

| Designation | | Minimum yield strength $R_{eH}$ [a] MPa | | | | | | Tensile strength $R_m$ [a] MPa | | | | | Minimum percentage elongation after fracture [b] % $L_0 = 5{,}65\sqrt{S_0}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Nominal thickness mm | | | | | | Nominal thickness mm | | | | | |
| Steel name | Steel number | ≤ 16 | > 16 ≤ 40 | > 40 ≤ 63 | > 63 ≤ 80 | > 80 ≤ 100 | > 100 ≤ 150 | ≤ 40 | > 40 ≤ 63 | > 63 ≤ 80 | > 80 ≤ 100 | > 100 ≤ 150 | |
| S275M<br>S275ML | 1.8818<br>1.8819 | 275 | 265 | 255 | 245 | 245 | 240 | 370 to 530 | 360 to 520 | 350 to 510 | 350 to 510 | 350 to 510 | 24 |
| S355M<br>S355ML | 1.8823<br>1.8834 | 355 | 345 | 335 | 325 | 325 | 320 | 470 to 630 | 450 to 610 | 440 to 600 | 440 to 600 | 430 to 590 | 22 |
| S420M<br>S420ML | 1.8825<br>1.8836 | 420 | 400 | 390 | 380 | 370 | 365 | 520 to 680 | 500 to 660 | 480 to 640 | 470 to 630 | 460 to 620 | 19 |
| S460M<br>S460ML | 1.8827<br>1.8838 | 460 | 440 | 430 | 410 | 400 | 385 | 540 to 720 | 530 to 710 | 510 to 690 | 500 to 680 | 490 to 660 | 17 |
| S500M<br>S500ML | 1.8829<br>1.8839 | 500 | 480 | 460 | 450 | 450 | 450 | 580 to 760 | 580 to 760 | 580 to 760 | 560 to 750 | 560 to 750 | 15 |

[a] For plate, strip and wide flats with widths ≥ 600 mm the direction transverse (t) to the rolling direction applies. For all other products the values apply for the direction parallel (l) to the rolling direction.

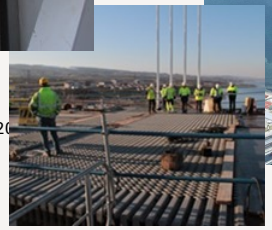
[b] For product thickness < 3 mm for which test pieces with a gauge length of $L_0 = 80$ mm shall be tested, the values shall be agreed upon at the time of the order.

# Bridge articulation system

An optimised design requires that the articulation system is considered correctly in the global FE-modelling

- Bridge articulation system:
  - Expansion joints – often at bridge ends
  - Vertical and lateral bridge bearings at bridge ends
  - Lateral wind bearings at towers
  - Hydraulic buffers and end stops for control of the longitudinal displacements of the deck - located at towers or bridge ends







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# Bridge articulation system

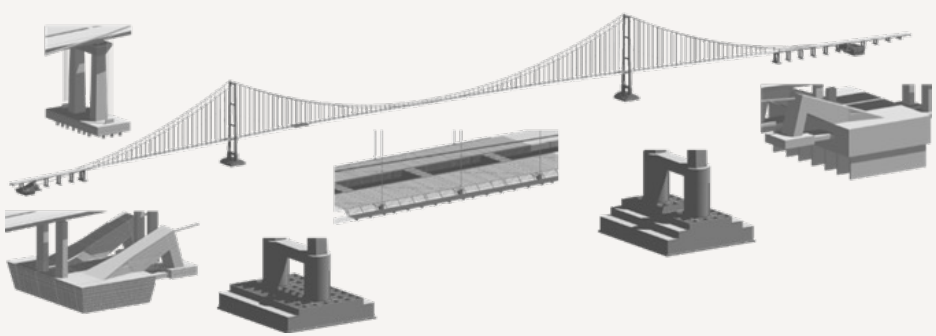
Long span bridges give large movements for in-service loads (traffic, temperature, wind) and seismic actions

- Hydraulic buffers:
  - restrain bridge deck for fast passing trucks and buffeting wind
  - reduction of movements giving extended lifetime of sliding elements
  - allow free movement of deck for temperature and static traffic loads giving reduced reaction forces in the structures
  - viscous damping during seismic events dissipating energy and controlling movements and forces
- Hydraulic end stops:
  - limit expansion joint movements to a manageable level

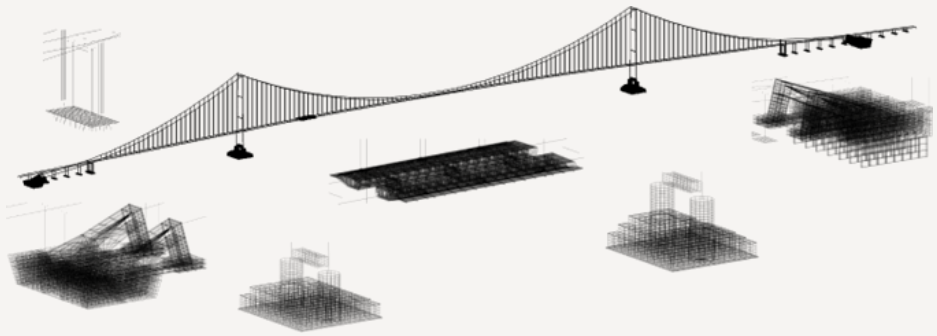
# FE-modelling – global, semi local and local

The global parametric FE-model using a combination of beam, shell and solid elements

- Local models are activated inside the global model with correct loading/boundary conditions
- Fast design updates and changes giving a refined and optimised design
- Fast output with consequences - quantities and $CO_2$



geometrical model



element model



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# Design conditions

- Long span signature bridges - often more complex
- Design shall have less impact on environment
- Optimised pricing, fast and safe construction
- Example here taken from 1915 Çanakkale Bridge:
  - Close collaboration between designer & contractor
  - Extensive focus on alignment, anchor block location, layout and quantities. In parallel decide on tower foundation layout, fabrication and floatability
  - Parallel works streams – e.g. installation of inclusion piles and casting of caissons
  - Being able to design and construct in parallel
  - Steel towers, main cable and deck segments prefabrication in large units. Fast erection on site using huge tower cranes, floating cranes and special made lifting gantries



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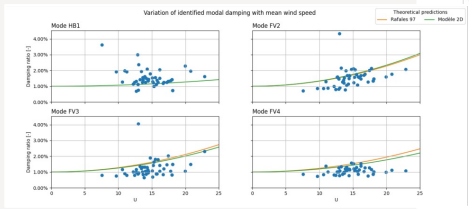
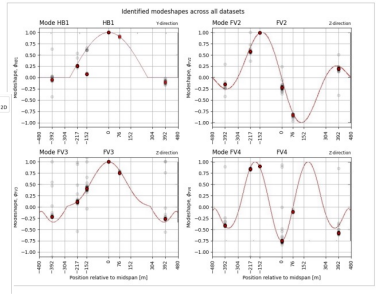
# Operational conditions

- Longer service life and service life extension for existing bridges
  - Install dehumidification of main cables and deck
- Structural health monitoring and digital twins
  - A fundamental requirement for carrying out proactive operation and maintenance is to be able to predict the bridge performance
  - The aim is also lower maintenance costs
- Less bridge downtime
  - Installation of wind screens and control bridge dynamics in windy conditions, dynamic traffic signs etc.
- Maintenance having less impact on environment



# Thanks