Fehmarnbelt Fixed Link – Bridge Design
Presentation of Concept Design
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Content of the presentation

1. Situation at start of 2011
2. Concept Design October 2010
3. Approach Bridges
4. Main Bridge
5. Risk studies and safety aspects
6. Planning of construction
7. Main construction cost and manpower resources
8. Expected project development
1. Situation at start of 2011

- Design started April 2009 with reference to treaty DK – D (09/2008)
- Concept designs for tunnel and bridge completed
- Environmental data collection (2 years) are concluded
- Preliminary environmental evaluation available
- Evaluation of all results leads to the recommendation by Femern A/S to Transport Minister: > Immersed Tunnel
- Information meetings in Germany and Denmark during January
- Transport Minister/Trafikudvalg to comment on recommendation at start of February

**Recommendation Immersed Tunnel confirmed on 1st February**

- The preferred solution is now the Immersed Tunnel and the alternative solution the Cable Stayed Bridge
2. Concept Design October 2010

The design was developed in the following steps:

1. Data collection and basis for design
2. Investigations of options
3. Preliminary concept designs
4. Concept Design March 2010
5. Revised Concept Design July 2010 (Variant 1) including options
6. Final Concept Design October 2010 (Variant 2)
7. Harmonisation between tunnel and bridge
8. Completion of Safety Concept development
9. Preliminary evaluation of environmental impacts
Location and importance of Fixed Link

- Connection rated as important TEN-T project by EU
- Main railway connection to Scandinavia (Sweden)
- Railway capacity for heavy goods will reach limits soon (old Lillebælt bridge)
- Railway link Helsingør-Helsingborg (HH) in future required
- Bottle necks:
  DK: Storstrømsbroen
  D: Fehmarnsundbridge; B 207 widened (A1 only up to Heiligenhafen)
Preferred corridor for connection

Corridor as result of spatial resistance investigations and of connection between possible landing points on Fehmarn (4) and Lolland (4)

Red connection is the chosen route for the bridge in the preferred corridor
Main requirements to Concept Design

Main challenges – besides Design Basis development, general risk studies and identification of optimal foundation concepts – were:

- Investigation of corridor/route and alignment
- Navigation in Fehmarnbelt
  - Safety of bridge structures
  - Size, number and arrangement of navigation channel(s)
- Operational risk analysis (ORA)
- Negligible changes to water flow in Fehmarnbelt
- Optimization of approach bridges (girders and piers)
- Concept development for cable stayed and suspension bridge
- Erection concept for approach bridge and main bridge including time plan and cost estimate
Foundation locations

Area of ground improvement: Approach bridge Fehmarn + Main bridge
Ground improvement alternatives

1. Deep Cement Mixing (Japanese method)

2. Steel pile inclusions
   a) driven or vibrated steel piles
   b) concrete pile inclusions ("bored pile type")

Foundation, Fehmarn

Steel piles Ø 2m
Ground improvement with concrete pile inclusions

Concrete pile inclusion:

1. construction method similar to bored pile with casing of varying length depending on soil conditions, e.g. shorter in Palaeogene Clay and longer in other layers

2. construction sequence changed to first dredging, then ground improvement

Typical caisson 24m x 30m
Environmental impact considerations

Main view points are:

1. Impact on water exchange with eastern Baltic Sea
2. Permanent loss of foundation areas (marine growth compensates ?)
3. Disturbance of harbour porpoise (marsvin) population in German FHH-Area
4. Impact on bird migration across bridge (barrier effect)
5. Increased danger of spill of oil or chemicals (collision of ships)
6. CO$_2$ emission during construction and operation

Preliminary evaluation results:

>> Bridge acceptable seen environmental-technically

>> Bridge may be difficult seen environmental-legally
Water exchange through Fehmarnbelt

- Exchange between North Sea and Baltic Sea uses Lille Bælt (10%), Store Bælt (60%) and Øresund (30%)
- Ingress of salty water important; acceptable are 0.1 to 0.2% reduction (changes due to climate changes ca. 10 times larger!)

Via Nordica 2012 - Fehmarnbelt Bridge
Impact areas in Fehmarnbelt (footprint)

Impact at coast with temporary construction harbours

Grey area = temporary
Red area = permanent

Impact in the Belt area of main bridge
Possible compensation for permanent impacts

West Bridge, pier 52
Area for marine growth substantially larger than area covered by bridge!
> Marine growth on piers future feeding ground for harbour porpoises.

East Bridge, western pylon
Protected areas in Fehmarnbelt neighbourhood

- Nakskov Fjord (DK008X242)
- Stenrev sydvest for Langeland (DK008X200)
- Femern Belt (DK008X260)
- Mariboæerne (DK008X087)
- Krenkorup Haveskov (DK008X240)
- Redbyhavn
- Smålandsfanvandet nord for Lolland, Guldborg Sund, Bøtte Nord, Hylekrog-Rødsand (DK006X238)
- Slaberhuk (DE1533-301)
- Sundwiesen Fehmarn (DE1532-321)
- Küstenlandschaft vor Großenbrode und vorgelagerte Meeresbereiche (DE1632-392)
- Sags-Bank (DE1733-301)

Marsvin

Eider duck

Via Nordica 2012 - Fehmarnbelt Bridge
Risk for ship accidents per year (index figures)

VTS system reduces total risk substantially!

Source: Risk assessment results for variations in reference scenario, 7. January 2011
**CO₂ emission from bridge construction**

**Variation of specific material emissions**

- **B1**: steel low; cement low
- **B2**: steel high; cement low
- **B3**: steel high; cement high
- **B4**: steel average; cement low
3. Approach Bridges

Approach bridge Fehmarn  5,748 m
Approach bridge Lolland  9,412 m
Bridge section
4 lanes, 2 side lanes, 2 tracks
Width roadway                     22.1 m
Width deck                        23.1 m
Depth of girder                   12.9 m
Improvement of water flow

Piers and pylons (1999) with section change to caissons at -2 m > local vortices developed!

Joint moved to +4 m and shaft now continuous
Pier arrangement (standard piers)

- Pier type II; 185 MN collision load
- Caisson up to + 4m
- Pier shaft from + 4m
- Weights:
  - Caisson max 8,200t
  - Shaft max 4,400t
Girder cross section approach bridge

- Concrete deck road 22.1m wide
- Depth 12.9m
- Diagonals at every 20.0m
- Track area 12.2 m wide
- Depth bottom chord 2.2 to 2.5m (accessible)
- Dehumidification system incl. diagonals
- Windshields
Ship collision with approach bridge pier - model

Global IBDAS model for bridge
Local ABAQUS model for pier
HOB collision 20,000 DWT ship
\( v = 5.1 \text{ m/sec } (185 \text{ MN}) \)
Peninsula and landing on Fehmarn
Peninsula and landing on Lolland
4. Main Bridge (Cable stayed bridge)

Total length: 2,414m
Overview of Main Bridge

- Vertical navigation clearance 65.0m plus 1.2m reserve for climate change
- HOB collision forces: pylons 790 MN, piers 540 MN
- Rectangular crossing of T-route (axis centre pylon = T-route)
- High point roadway +82.2 m, railway +72.3m
Overview of pylons

Centre pylon

Outer pylon
Pylon caissons

Centre pylon
- cylindrical shape, diameter 74m
- water filled

Outer pylon
- elliptical shape, axis 94m/54m
- sand filling
Cable stayed bridge

Main spans: 724 m
Pylon height: 272 m
Girder cross section main bridge

- Top and bottom chord accessible
- Dehumidification arrangement for whole section incl. diagonals
- Diagonals to introduce cable forces
- Wind shields
Deformation criteria for girder

Crit 1: Maximal deformation and inclination of main bridge
Crit 4: Maximal vertical movement at joints
Crit 7: Maximal rotation at joints (vertical plane)
Crit 8: Maximal rotation at joints (horizontal plane)
Crit 9: Maximal transverse slope for tracks and roadway
Crit 10: Maximal gradient of change of slope

Criteria 2, 3, 5 and 6 are not governing for the main bridge.

> All criteria are fulfilled.
Collision protection for piers close to T-route

Anchor- and transition piers of main bridge; totally 4 piers; 540 MN impact
Details of protection structure
Study of impact load capacity

ABAQUS model for basic shear strength of 100 kPa

Steel piles for ground improvement required: pattern 5.0m and 7.5m

Requirement: 540 MN impact load

Result: 250 kPa needed
Options for Suspension Bridges

Suspension bridge with two spans of 1,104 m; Length 3,240 m

Suspension bridge with one span of 1,632 m; Length 3,096 m

Cons: Deformation of suspension bridge at limits (> 7m)  
Resistance to water exchange not known yet  
Longer construction time and higher costs for main bridge
Animation of Suspension Bridge

Suspension bridge with 1,632m span
5. Risk Studies and Safety Aspects

ALARP approach to be applied with precedents principle
Varying benchmarks for roadway and fixed benchmark for railway

The acceptability of risk to users and disruption of the link shall be guided risk associated with comparable infrastructure (precedents principle).

The risk can only be tolerated if cost of risk reduction would exceed the improvements gained. This implies that risk mitigation/alleviating measures complying with a marginal increase in total expected societal benefit shall be introduced.

Evidently negligible risks will be evaluated based on qualitative assessment.
Basis for Operational Risk Analysis (ORA)

- Personal risk to the users of the Link, i.e.
  - Railway users
  - Road users
- Personal risk to third party, primarily on ship traffic passing the bridge
- Personal risk to operation and maintenance personnel
- Risk of damage to Link and user property
- Risk of traffic disruption and disturbance
- Risk of economic loss to third party, primarily the ship traffic passing the bridge
- Risk to the environment from accidents during operation

Operational risk assessment covers:
Coast-to-coast section
Landside sections
  - coast Denmark to toll station
  - coast Germany to neutral section
## Risk categories and main hazards

<table>
<thead>
<tr>
<th>Risk Category</th>
<th>Risk Measure</th>
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</thead>
<tbody>
<tr>
<td>1 Individual risk road, user</td>
<td>Fatalities/passage</td>
</tr>
<tr>
<td>2 Individual risk rail, user</td>
<td>Fatalities/passage</td>
</tr>
<tr>
<td>3 Third party risk</td>
<td>Fatalities/Year</td>
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<tr>
<td>4 Societal risk (composed of 1+2+3)</td>
<td>Fatalities/Year, F-N representation</td>
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<td>5 Maintenance/Inspection personnel</td>
<td>Qualitative assessment</td>
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<td>6 Risk of disruption, road-rail</td>
<td>Days/Year, F-N representation</td>
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<tr>
<td>7 Environmental risk</td>
<td>EUR/year</td>
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</table>

Hazard types to be considered are:

- Train accidents
- Aircraft accidents
- Fires
- Dangerous releases
- Malicious damage
- Road accidents
- Ship accidents
- Explosions
- Natural hazards
- Operation & Maintenance
Ship traffic through Fehmarnbelt

Presently in addition 38,000 ferry passages per year

<table>
<thead>
<tr>
<th>Route Name</th>
<th>2018</th>
<th>2038</th>
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<tbody>
<tr>
<td>H eg</td>
<td>6,689</td>
<td>10,609</td>
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<tr>
<td>T eg</td>
<td>1,418</td>
<td>2,303</td>
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<td>K-O eg</td>
<td>23,491</td>
<td>36,392</td>
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<tr>
<td>Coastal eg</td>
<td>613</td>
<td>847</td>
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<tr>
<td>Coastal wg</td>
<td>474</td>
<td>638</td>
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<td>T wg</td>
<td>35,044</td>
<td>53,833</td>
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<td>Rødby</td>
<td>279</td>
<td>317</td>
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<td>Puttgarden</td>
<td>159</td>
<td>180</td>
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<tr>
<td><strong>Grand Total</strong></td>
<td><strong>66,168</strong></td>
<td><strong>105,118</strong></td>
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</table>
Risk of disruption due to ship collision

- Disruption risk 2038: Risk comparable to Øresund Bridge
- Design for larger ship collision loads: - Pylons 790 MN - Piers 540 (I), 185 (II, III) and 120 (IV) MN - Girder 44 MN
Simulations of passages at FORCE Institute

- Simulation of passages underneath the bridge under conditions representing reality (varying sea state, wind, visibility, traffic etc.) as much as possible
- Performed by pilots and captains from the merchant marine
- Concluding evaluation
Safety Concept

• The Safety Concept is developed in collaboration with the organisations involved in emergency situations in Denmark and Germany

• The involved organisations are:
  Police
  Fire brigade
  Emergency doctors
  Ambulance service
  Special forces for handling accidents with dangerous goods

• Several discussion rounds have taken place and a final version of the Safety Concept (document in 3 languages) is expected to be available in Mai 2011

• Space requirements for emergency case handling are combined and coordinated with the toll station in Denmark (custom and border control) and the border control area in Germany
Main safety feature for operation

External staircase every 400m at both sides including elevator
Preparations for operation and self-rescue
Scenario: train catches fire – rescue steps
Provisions for operation, maintenance and rescue
6. Planning of Construction

Major assumptions for the construction planning:

- 5 main contracts $< 2\cdot10^9$ USD
  - Landworks Fehmarn + Peninsula
  - Substructure of approach bridges
  - Superstructure of approach bridges
  - Main bridge (cable stayed bridge)
  - Landworks Lolland + Peninsula

- Further contracts will cover railway structures, technical installations, toll station (Lolland), visitor centre, etc.

- Cost estimate to be prepared as contractor will do, e.g. identify optimal sequence of activities and find efficient, low cost production facilities

- Temporary construction harbours and pre-fabrication yards to be included
Consequences of major assumptions

- Prefabrication of bridge elements to largest possible extent results in:
  
  **Approach bridge**
  - Prefabricate piers comprising shaft and caisson as 1 piece or 2 elements
  - Assemble composite girder in full length, float it in on barge and erect it

  **Main bridge**
  - Prefabricate pylon caissons and float them in
  - Construction of pylons on top of caisson in-situ
  - Assembly of 20m long segments and erection in free cantilevering method

- Prefabrication of elements is deemed to be cost/risk/time optimal for:
  
  **Approach bridge**
  - Caisson and pier shaft in Poland
  - Steel structure 1. step in China + sea transport; assembly and deck concreting in Poland

  **Main bridge**
  - Caissons in dry dock and in Fehmarn Belt
  - Steel structure 1. step in China + sea transport; assembly for erection in Poland
Prefabrication of approach bridge elements

- Caissons and pier shafts
- Transport of steel parts
- Temporary harbour at coast
- Assembly of superstructures
HLV 'Svanen'

- Self-propelled double-pontoon floating crane for transport and erection of bridge elements
  
  - Lifting capacity: 8,700 t
  - Length: 102.8 m
  - Width: 71.8 m
  - Lifting height: 74.5 m
  - Draft: 4.5 m
  - Centric loading point
  - Previous jobs: West Bridge, Confederation Bridge, Øresund Bridge, Offshore operations

> 'Svanen' is one example; several floating cranes available, new ones are coming
Construction sequence for piers

- Standard erection of caisson and pier shaft
- Shallow water piers will be prefabricated and erected in one piece
Erection of superstructure approach bridge

Joint 40m in span: better fit at bearing, welding easier, bending moment at pier location
Prefabrication for main bridge

Caissons in dry dock up to 10 m

Assembly for steel erection

Extension of caissons to full height

Caisson ready for submerging
In-situ construction of main bridge in Fehmarnbelt

Construction of pylon (climbing form) and start of steel girder erection

Free cantilevering of bridge girder
7. Main Construction Cost and Manpower Resources

Result of cost estimate

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<tr>
<td>Fehmarn Landworks + Peninsula</td>
<td>164.2</td>
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<tr>
<td>Substructures approach bridges</td>
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<td>Superstructures approach bridges</td>
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<td>Cable stayed main bridge</td>
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<td>Lolland Landworks + Peninsula</td>
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<td><strong>Construction costs (1)</strong></td>
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<td>Railway tracks and installations</td>
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<td>Mechanical + electrical installations</td>
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<td>Construction risk add-on</td>
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<td><strong>Total construction costs</strong></td>
<td><strong>3,579.5</strong></td>
<td><strong>26.7</strong></td>
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NPV value for O&M costs
669.7 Mio Euro (120 years)
**Time schedule: Status January 2011**

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<th>2009</th>
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- Time planning assumes today construction start in 2014
- Construction period 5½ years with reserve for climbing of pylon legs and testing of technical installations
Animation of Bridge Solution
Sunset at Fehmarnbelt

Thank you very much for your attention