



# Maintenance and Decision Tools

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European Union  
European Regional  
Development Fund

Investing in our common future



## Presentation Layout

1. Problem Definition
2. Probability Based Maintenance Optimisation
3. Case Studies – Practical Application
4. Conclusions

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# 1. Problem Definition

For a given structure how do we decide upon the optimal maintenance strategy as a function of age, condition, importance, **required remaining life** etc. in a robust/repeatable manner, avoiding generalisation/excessive conservatism such that our maintenance budget is optimised???

e.g. Victoria Falls 1905,

*Storstrom 1937, 3.2km*



# 1. Problem Definition

## EU GDP Growth linked to Freight Growth

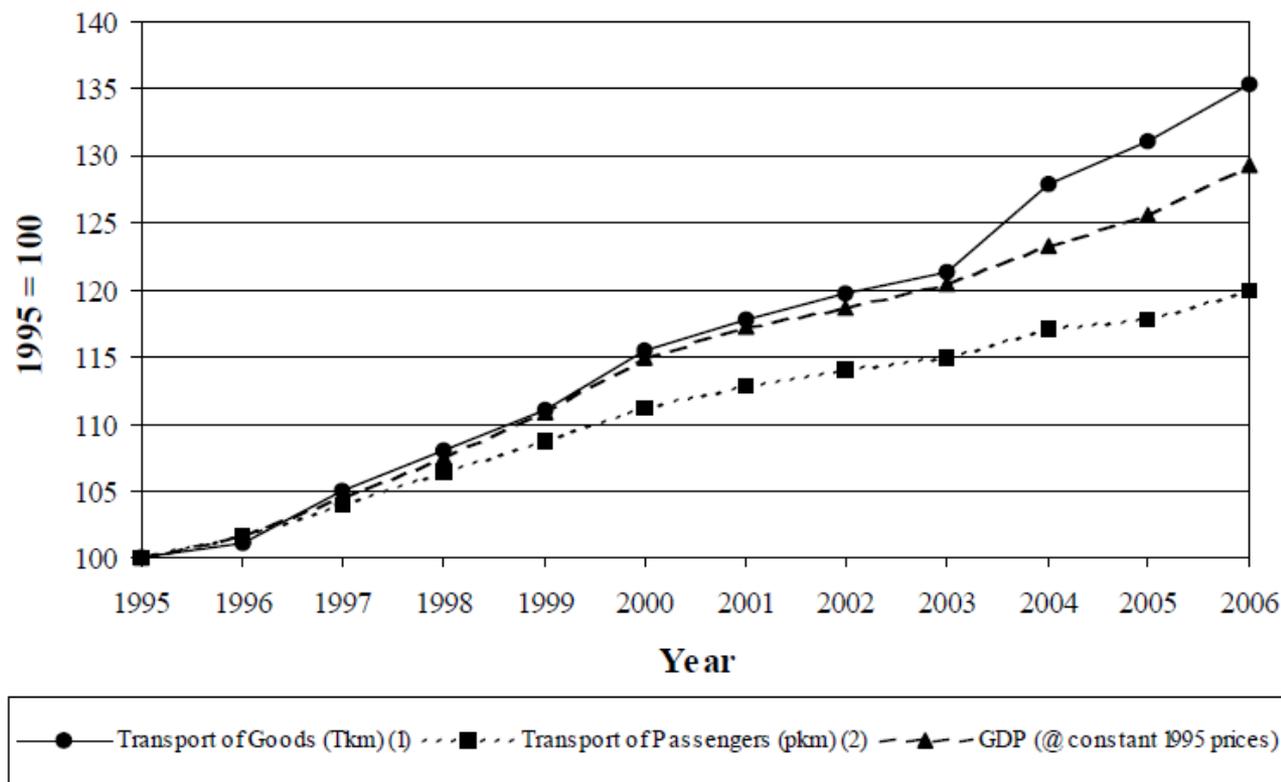
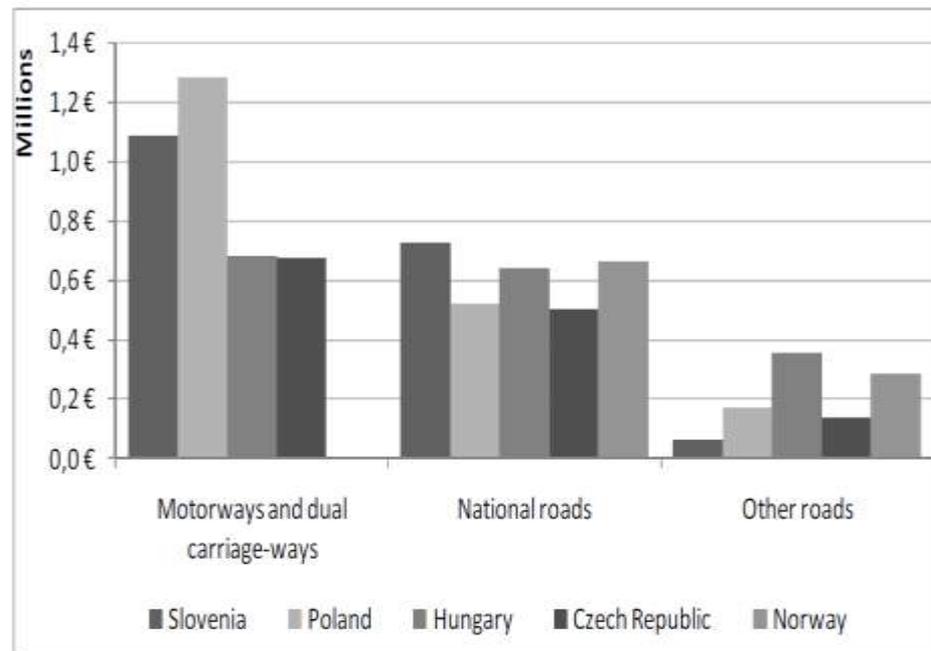
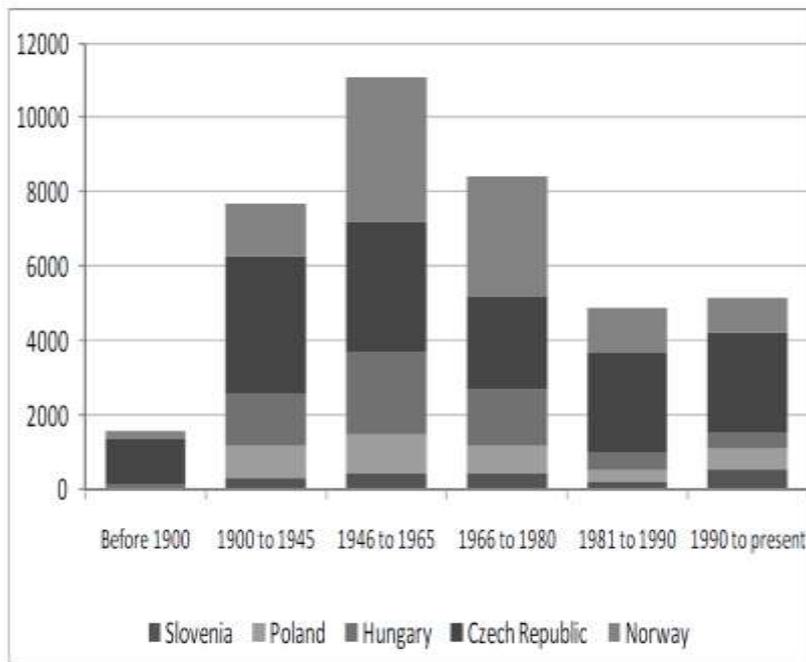


Figure 2 - Evolution of transport demand and GDP in the EU-25 for period 1995 – 2006 (Eurostat; DG Transport and Energy, 2008).

## 1. Problem Definition



Number of bridges built during various times

Replacement costs of bridges on various types of road

Aleš Žnidarič, Vikram Pakrashi, Eugene OBrien, Alan O'Connor, A Review of Road Structure Data in Six European Countries, Proceedings of the ICE, Journal of Urban Planning and Design, In Press

## 2. Probability Based Maintenance Optimisation

Legal Basis – Eurocode 1 Basis of Design

Safety Level NEVER Compromised – **Rather Individually Evaluated & Optimised**



### 3.5 Limit state design

(1)P Design for limit states shall be based on the use of structural and load models for relevant limit states.

(2)P It shall be verified that no limit state is exceeded when relevant design values for

- actions,
- material properties, or
- product properties, and
- geometrical data

are used in these models.

(3)P The verifications shall be carried out for all relevant design situations and load cases.

(4) The requirements of 3.5(1)P should be achieved by the partial factor method, described in section 6.

(5) As an alternative, a design directly based on probabilistic methods may be used.

NOTE 1 The relevant authority can give specific conditions for use.

NOTE 2 For a basis of probabilistic methods, see Annex C.

(6)P The selected design situations shall be considered and critical load cases identified.

(7) For a particular verification load cases should be selected, identifying compatible load arrangements, sets of deformations and imperfections that should be considered simultaneously with fixed variable actions and permanent actions.

(8)P Possible deviations from the assumed directions or positions of actions shall be taken into account.

(9) Structural and load models can be either physical models or mathematical models.

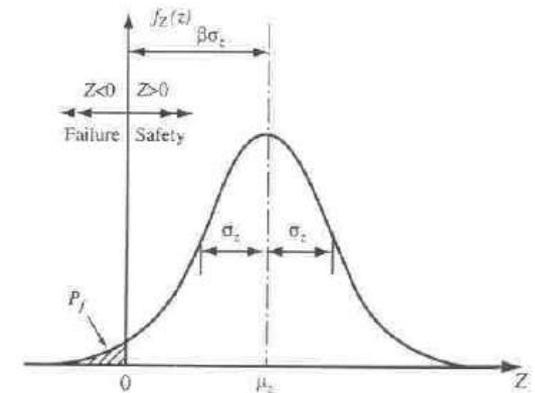
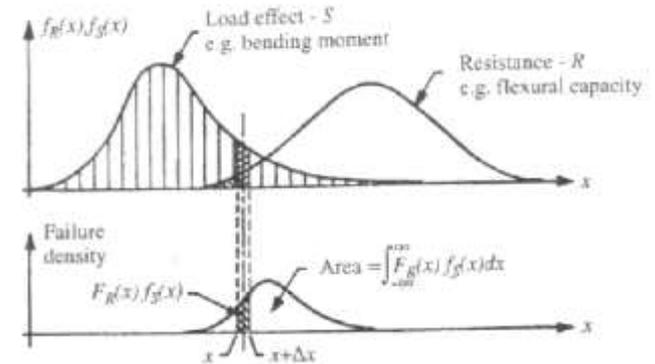
# 2. Probability Based Maintenance Optimisation

Statistical Modelling of:  
 Loads  
 Resistances  
 Uncertainties  
 Updating based upon results of tests/inspections

Purpose:  
 Cut strengthening or rehabilitation costs **without**  
 compromising the safety level

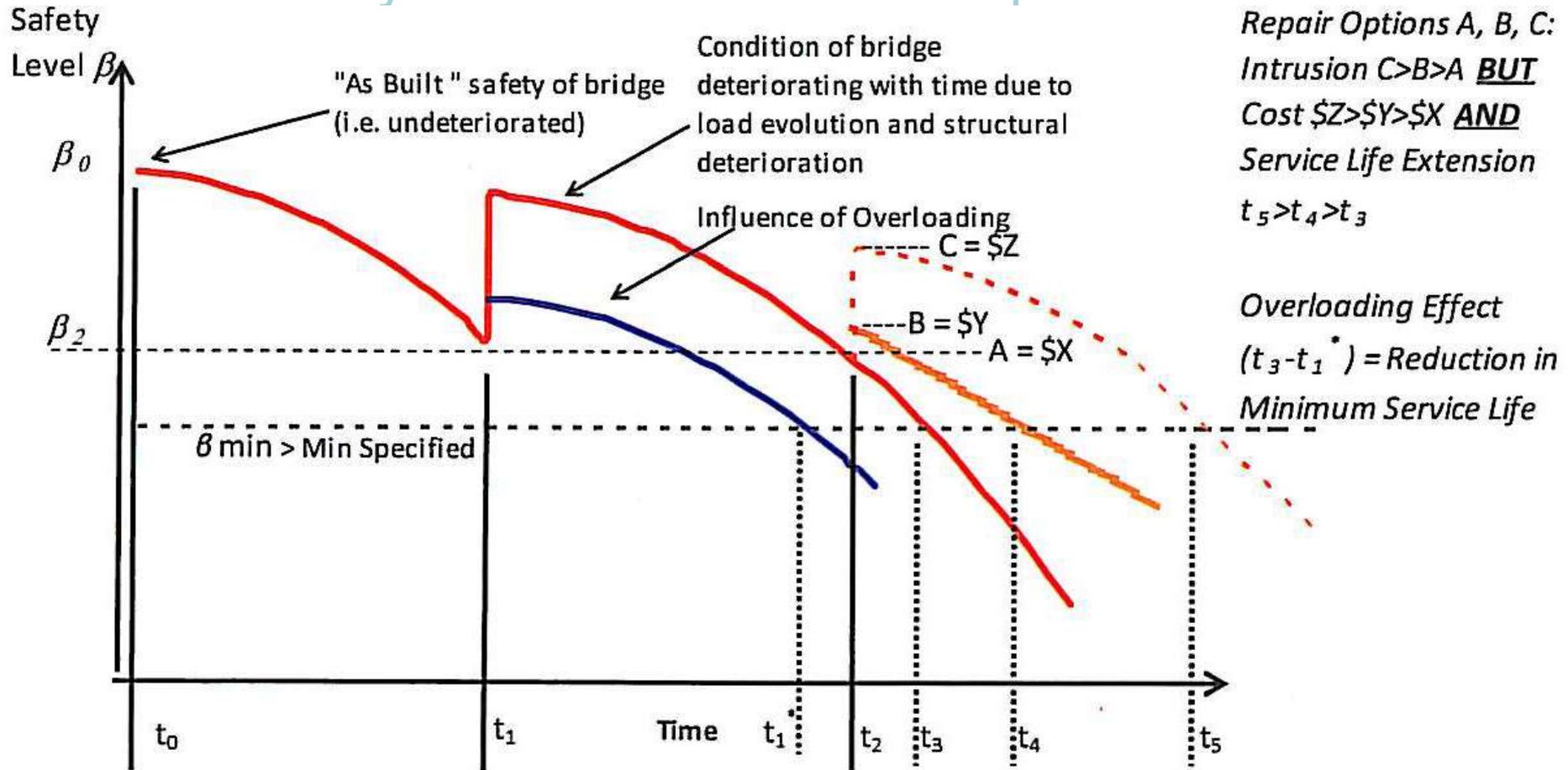
Table 1 – Minimum Safety Levels Specified by the Eurocode (EN1990:2002)

Reliability Class	Minimum values for $\beta$	
	1 year reference period	50 year reference period
CC3 (RC3)	5.2	4.3
CC2 (RC2)	4.7	3.8
CC1 (RC1)	4.2	3.3



**Essentially a Bridge specific “code” is obtained**

## 2. Probability Based Maintenance Optimisation



## 3. Case Studies

### (i) Storstrom Bridge

- The 3.2 km long Storstrom Bridge connects the Danish Island of Zealand with the southern Danish islands of Falster and Lolland.
- The contract for the building of the bridge was given to the British company Dormann, Long & Co., who also fabricated the main steel structure (The contract was awarded to a British company as a political move to offset the significant trade deficit which had developed between the UK and Denmark at his time due to Danish pork exports).
- The bridge opened in September 1937.





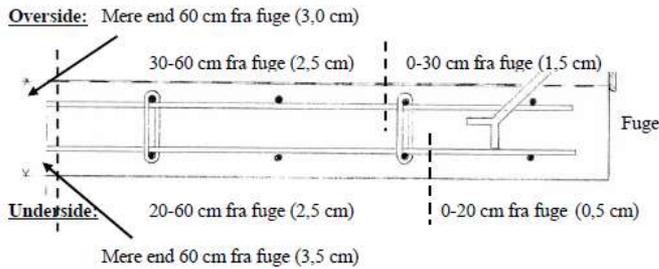
## Storstrom Bridge: Results of Assessment

Deterministic assessment of the deck slab using PROCON for combined dead and live load produced a maximum load factor of 0.61. This implies that the slab is incapable of sustaining the applied load. The recommendation would therefore involve costly rehabilitation of the structure.

Probabilistic Assessment including deterioration modelling, with deterioration models updated based upon inspection results performed at the bridge could document sufficient capacity.

Table 5 - Results of deterministic and probabilistic assessment; O'Connor et al (2004).

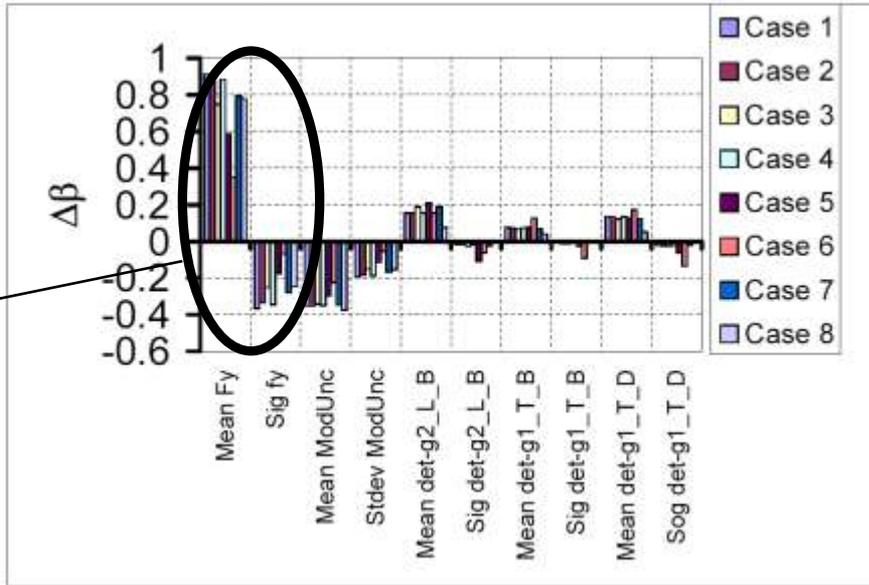
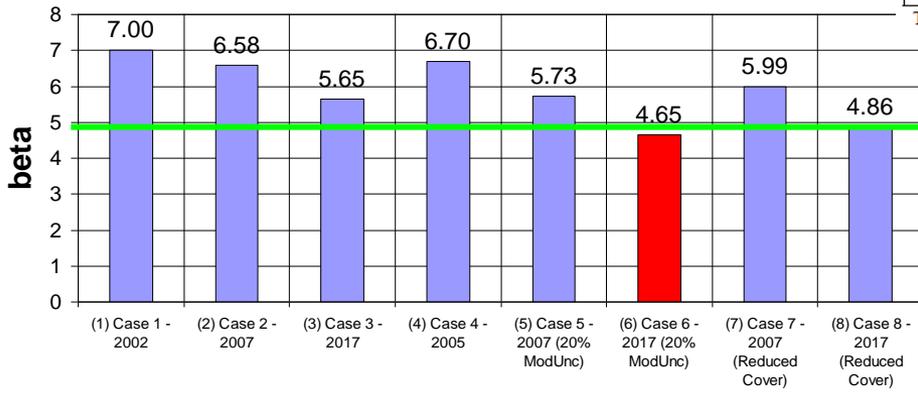
Load Combination	Self Weight + KL10 Live Load
Deterministic plastic load carrying capacity	61 %
Probabilistic Assessment: No deterioration	$p_f = 2.94 \times 10^{-13}$ $\beta = 7.20$
Probabilistic Assessment: Stochastic modelling of deterioration according to inspections results	$p_f = 6.92 \times 10^{-7}$ $\beta = 4.83$



	Område A (O.S. midt)	Område B (O.S. kant)	Område C (U.S. midt)	Område D (U.S. kant)
<i>Langsgående:</i> 0-30 cm 0-20 cm	N(91;16)	N(74;20)	N(91;16)	N(73;14)
30-60 cm 20-60 cm	N(95;6)	N(95;6)	N(95;6)	N(85;17)
Storre end 60 cm	N(95;6)	N(95;6)	N(95;6)	N(95;6)
<i>Tværgående:</i> 0-30 cm 0-20 cm	N(95;6)	N(86;12)	N(95;6)	N(85;14)
30-60 cm 20-60 cm	N(95;6)	N(95;6)	N(95;6)	N(95;6)
Storre end 60 cm	N(95;6)	N(95;6)	N(95;6)	N(95;6)

Tabel 7-3 Bestemte stokastiske modeller af armeringens tværsnitsareal i år 2002.

## Computed beta for cases considered



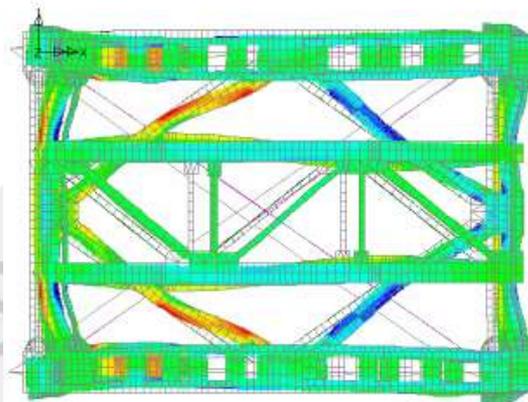
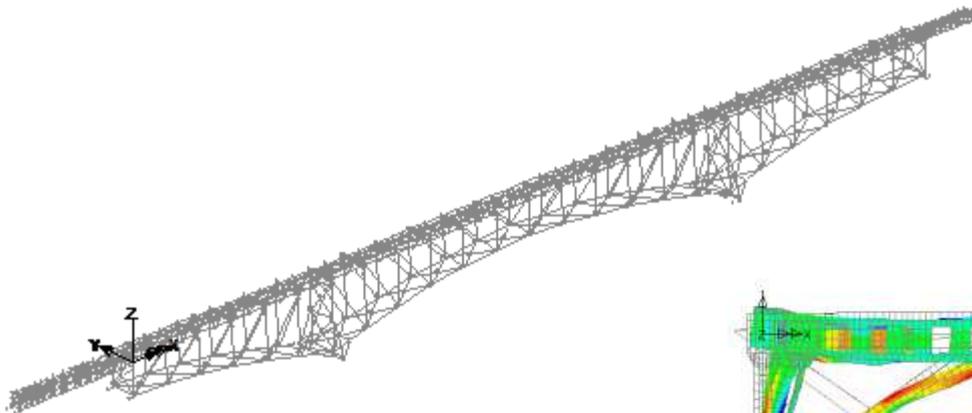
Updating of parameters through e.g. inspection results can reduce uncertainty and improve  $\beta$ , or vice versa (i.e. Intelligent Assessment, Structural Health Monitoring)

## (ii) Bergeforsen Railway Bridge, Sweden



Bridge constructed in 1923  
Superstructure span configuration:  $42+84+42 = 168\text{m}$   
Side spans  $22.5\text{m} + 11.6\text{m}$   
Total bridge length =  $202.1\text{m}$   
Required to assess for **Heavier Trains**

Structural analysis was performed using an FE model calibrated against a shell and volume element model constructed for specific critical locations.

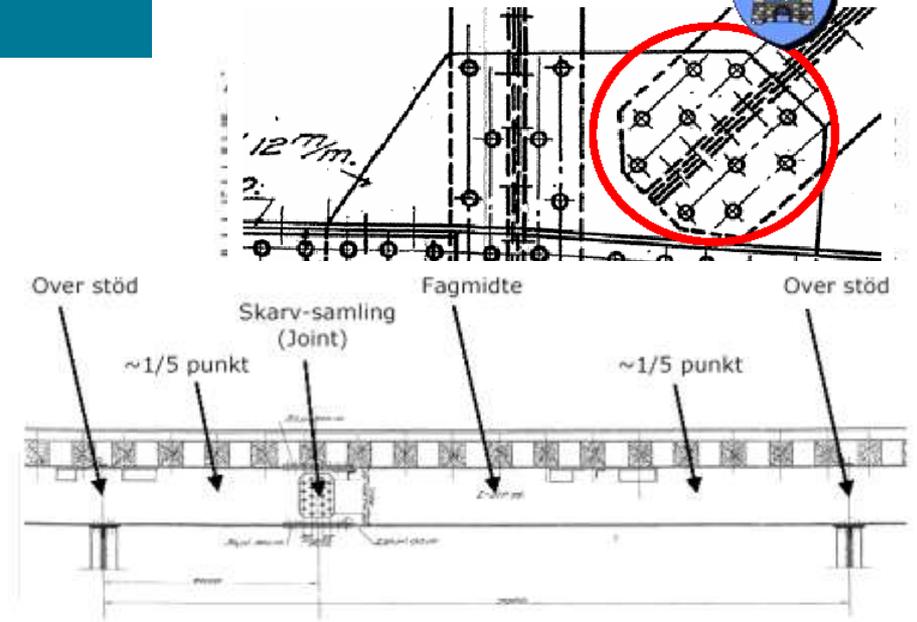
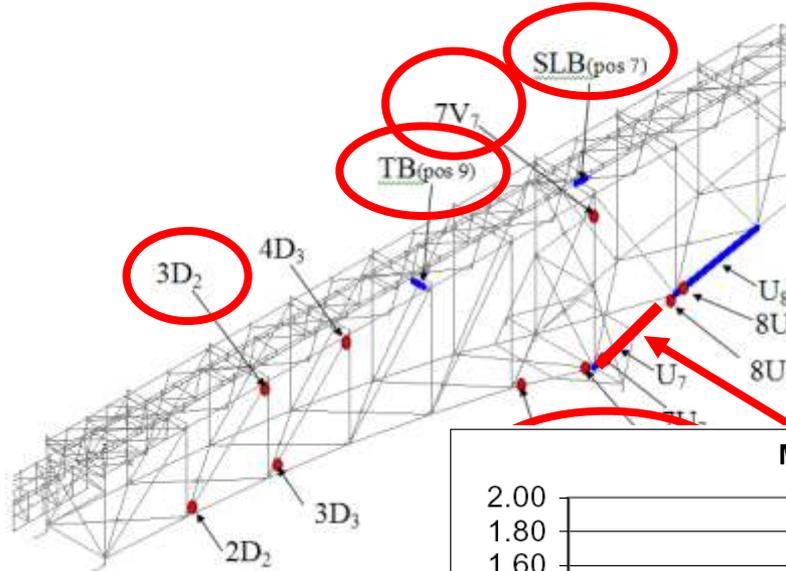


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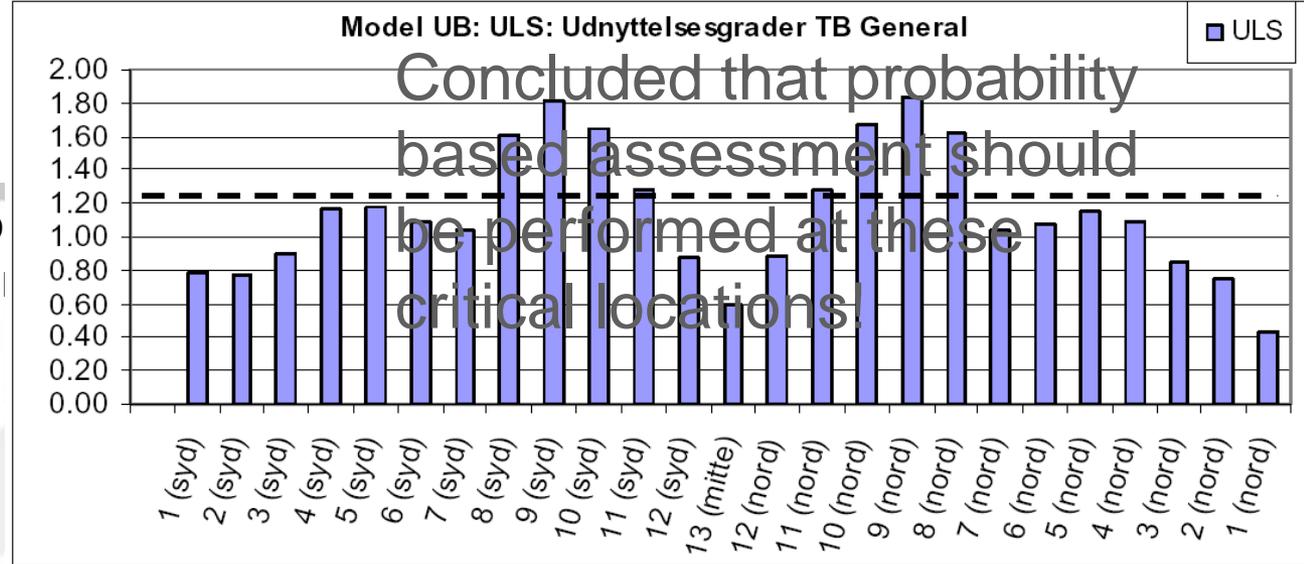
## Deterministic assessment - results

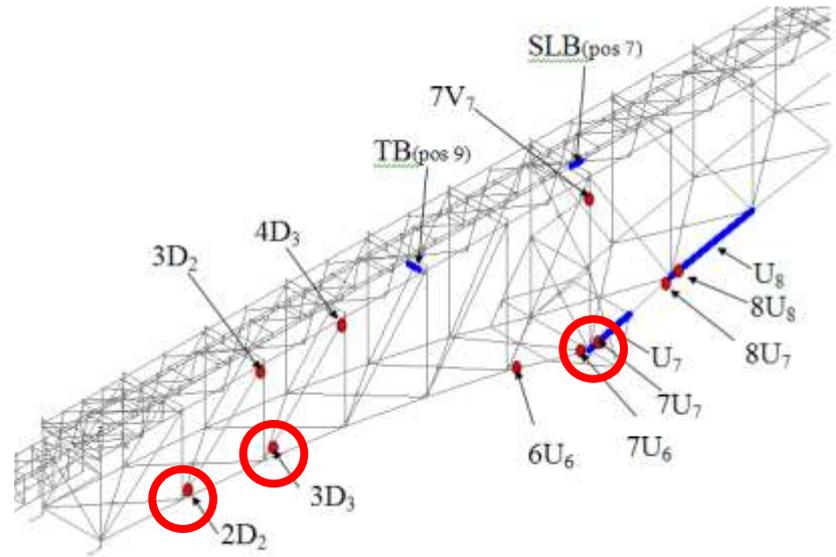
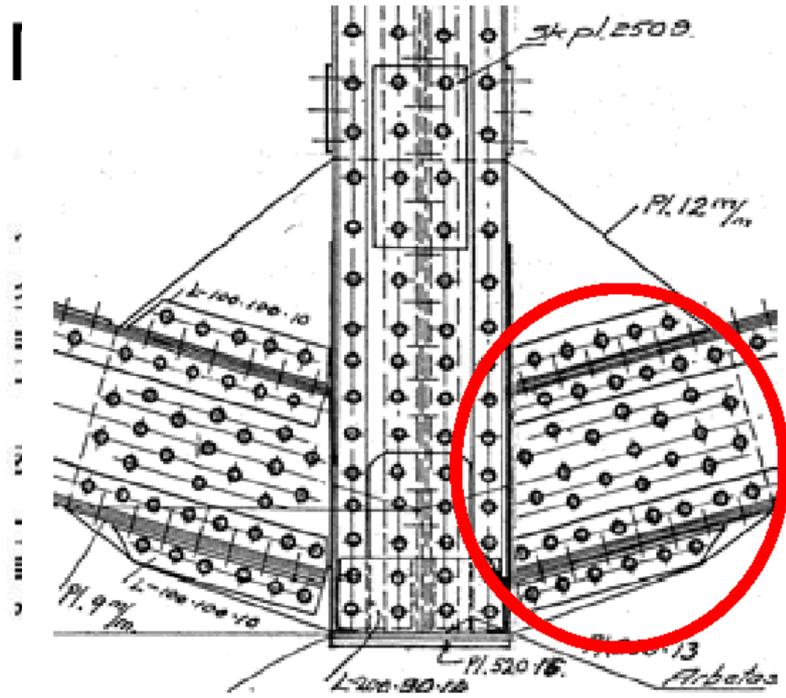


Figur 6-1 Opstalt af DIP55-profiler.

(a) Connection 2-D<sub>2</sub>

- SLS capacity demo
- FLS capacity demo
- ULS capacity could joints as follows





(a) Connection 7-U<sub>7</sub>



## Elements

$$\beta_{U_7} = 5.67 > 4.8$$

$$\beta_{U_8} = 5.19 > 4.8$$

$$\beta_{SLB, post7} = 4.66 < 4.8 \quad (M_z = 0, \beta_{SLB, post7} = 5.85)$$

$$\beta_{TB, post7} = 4.81 > 4.8$$

## Joints

$$\beta_{6-U_6} = 6.38 > 4.8$$

$$\beta_{7-U_6} = 4.51 < 4.8 \quad (\text{Remedial action necessary})$$

Proposal A  $\beta_{7-U_6} = 6.05$ , Proposal B  $\beta_{7-U_6} = 7.80$

$$\beta_{7-U_7} = 4.06 < 4.8 \quad (\text{Remedial action necessary})$$

Proposal A  $\beta_{7-U_7} = 5.62$ , Proposal B  $\beta_{7-U_7} = 7.11$

$$\beta_{8-U_7} = 6.01 > 4.8$$

$$\beta_{7-V_7} = 6.31 > 4.8$$

$$\beta_{2-D_2} = 4.42 < 4.8 \quad (\text{Remedial action necessary})$$

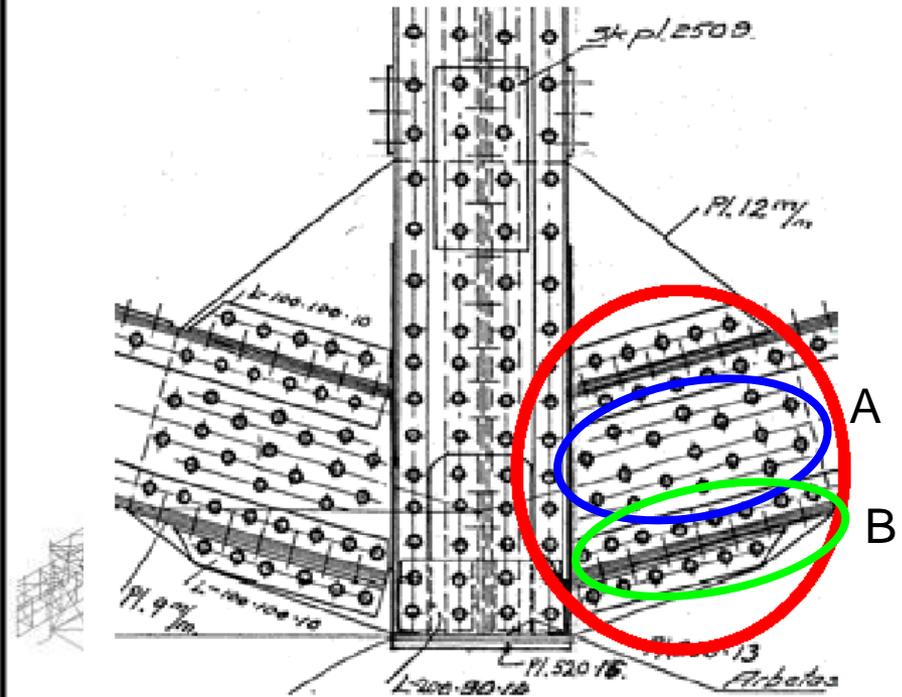
Proposal A  $\beta_{2-D_2} = 6.25$

$$\beta_{3-D_2} = 4.56 < 4.8 \quad (\text{Remedial action necessary})$$

Proposal A  $\beta_{3-D_2} > 4.8$

$$\beta_{3-D_3} = 5.18 > 4.8$$

$$\beta_{4-D_3} = 5.32 > 4.8$$



Similar options considered for other joints which had failed to demonstrate sufficient capacity. Results indicated that in all cases sufficient safety could be achieved.

(a) Connection 7-U<sub>7</sub>

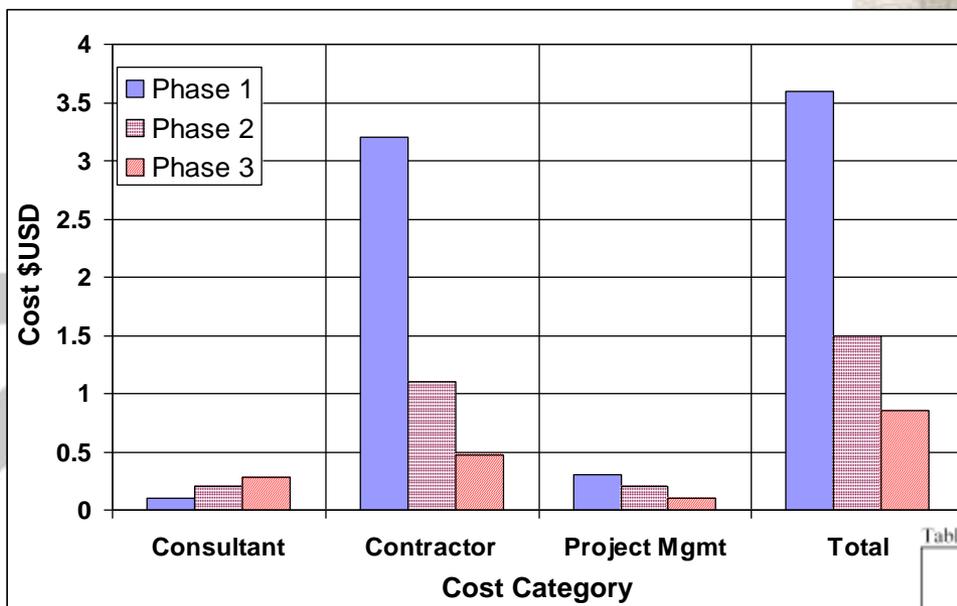
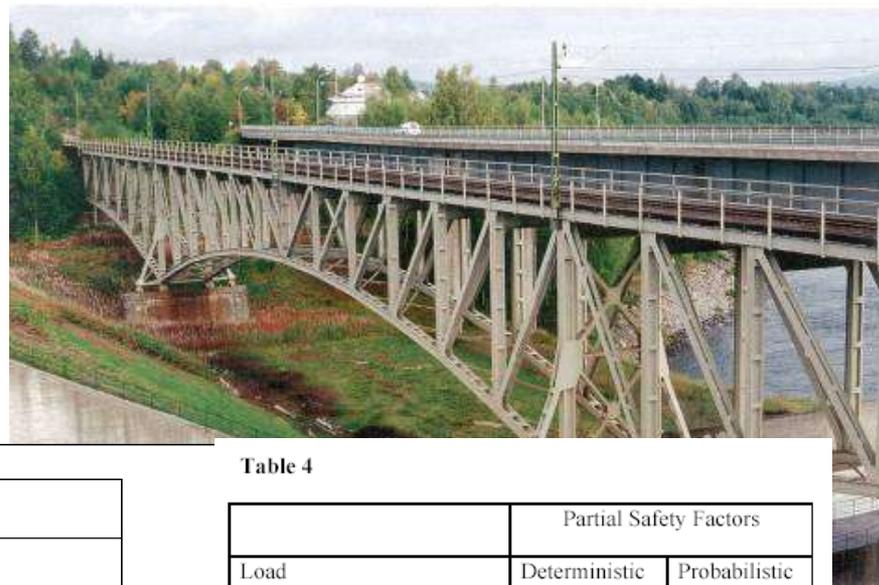
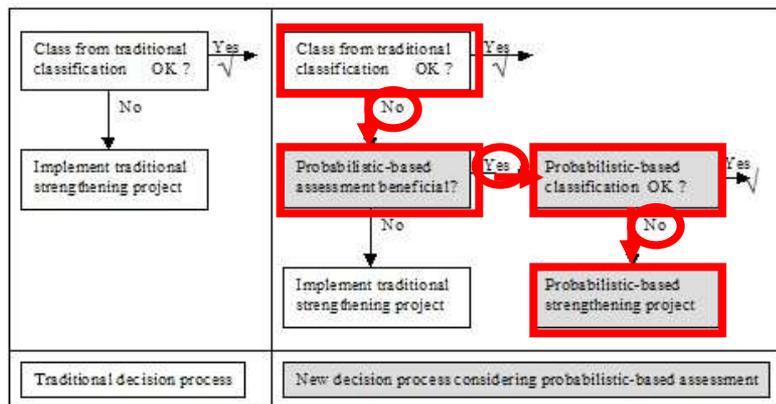


Table 4

Load	Partial Safety Factors	
	Deterministic	Probabilistic
Dead Load	1.0	1.03
Superimposed Dead Load	1.0	1.02
Train Load Global	1.3	1.21
Train Load Local	1.3	1.20
Dynamic Factor Global	1.08	1.05
Dynamic Factor Local	1.47	1.32

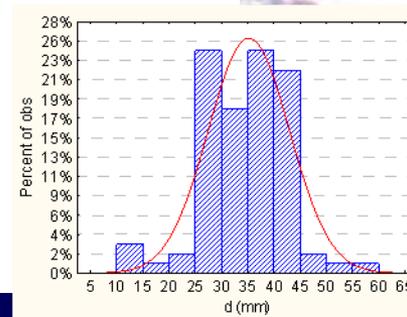
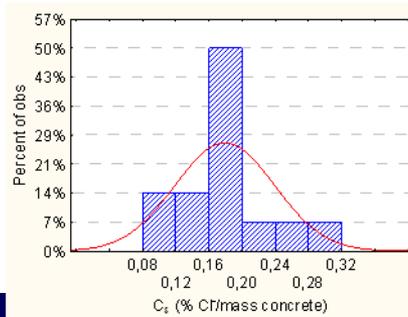
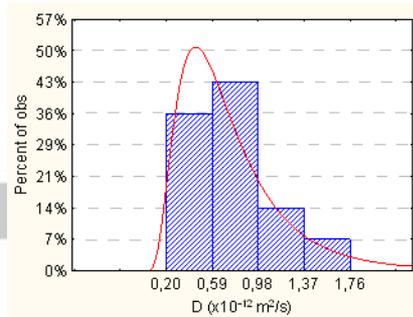
Table 7 - Results of deterministic and probabilistic assessment; O'Connor et al (2004).

	Phase 1 Deterministic Assessment (\$USD)	Phase 2 Advanced Deterministic Assessment (\$USD)	Phase 3 Probability Based Assessment (\$USD)
Consultant Fee	\$0.1ml	\$0.2ml	\$0.28ml
Contractor Fee	\$3.2ml	\$1.1ml	\$0.47ml
Project Management	\$0.3ml	\$0.2ml	\$0.1ml
Total Cost	\$3.6ml	\$1.5ml	\$0.85ml

## 3. Case Study

### (iv) Barra Bridge

- 578m, 17 Span structure
- Opened 1975
- Structure rehabilitated based upon deterministic assessment following extensive experimental investigation
- Probabilistic assessment underway as part of DuratiNet



An example of savings to date (>€40,000,000):



Table 2 – DRD savings from probability based assessment

Bridge	Result of Deterministic Analysis	Probability-based assessment	Cost Saving € EUR
Vilsund	Max $W$ = 40 t	Max $W$ = 100 t	3,200,000
Skovdiget	Lifetime ~ 0 years	Lifetime > 15 years	12,000,000
Storstroem	Lifetime ~ 0 years	Lifetime > 10 years	16,000,000
Klovtofte	Max $W$ = 50 t	Max $W$ = 100 t	1,600,000
407-0028	Max $W$ = 60 t	Max $W$ = 150 t	1,200,000
30-0124	Max $W$ = 45 t	Max $W$ = 100 t	400,000
Norreso	Max $W$ = 50 t	Max $W$ = 100 t	400,000
Rødbyhavn	Max $W$ = 70 t	Max $W$ = 100 t	400,000
Åkalve Bro	Max $W$ = 80 t	Max $W$ = 100 t	1,200,000
Nystedvej Bro	Max $W$ = 80 t	Max $W$ = 100 t	1,600,000
Avdebo Bro	Max $W$ = 80 t	Max $W$ = 100 t	2,400,000
		<b>TOTAL</b>	<b>40,400,000</b>



## 4. Conclusion

- Case studies are presented to demonstrate to practical application of probability based approaches in optimal maintenance planning for existing bridges.
- In **NO** way has the safety of the structure been compromised rather a bridge specific code has been derived.
- The justification for the application of probability-based methods to bridges is provided from national codes and the Eurocodes.
- There are no practical or technical obstacles in applying probability-based techniques.
- A clear advantage of the approach lies in its ability to incorporate bridge specific information and bridge specific safety modelling.
- Applying the probability-based approaches can result in considerable monetary savings by optimising maintenance strategies for existing bridges.