Probability Based Assessment of Bridges

Dr. Alan O'Connor

Department of Civil Engineering

Trinity College Dublin

alan.oconnor@tcd.ie

Structure of Presentation

1. Introduction
2. Probability based Assessment
3. Practical examples of application of probability based methods to existing bridges
    i. Storstroem Road + Rail Bridge
    ii. Bergeforsen Railway Bridge
4. Conclusions

1. Introduction: Owner/Manager Perspectives

An common problem among bridge owners/managers is the need to reduce spending whilst attempting to operate and maintain an increasingly ageing bridge stock which is subject to a loading intensity for which, in many cases, it was not designed.

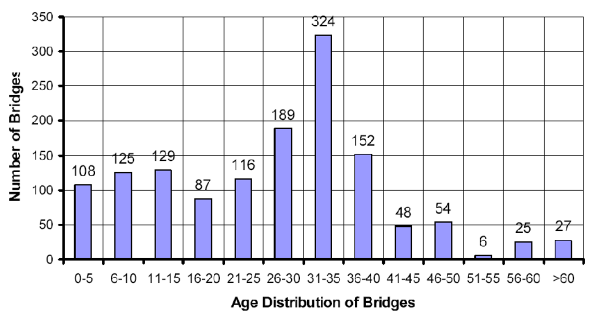
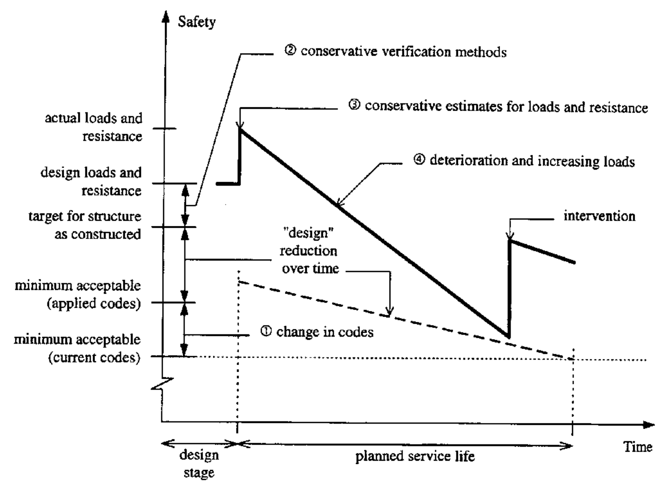
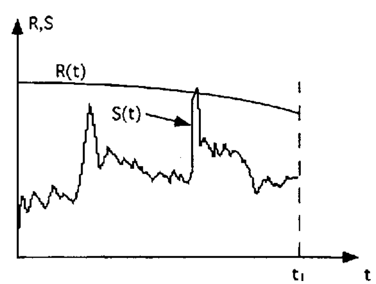


Figure 1 - Age distribution of DRD bridges. About 50% of the bridges are 25-40 years old.





1. Introduction: Owner/Manager Perspectives

The problem is compounded by the ever increasing trend in motorway traffic frequency, which was seen to double in the decade 1992 – 2002 and by the debate regarding the need to increase legal weight limits for trucks and trains and/or to provide special routes/networks which they can use.

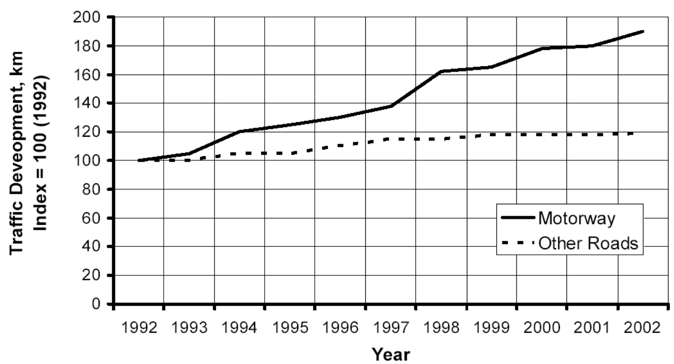


Figure 2 - Motorway traffic (in kilometres driven) has doubled from year 1992 – 2002.

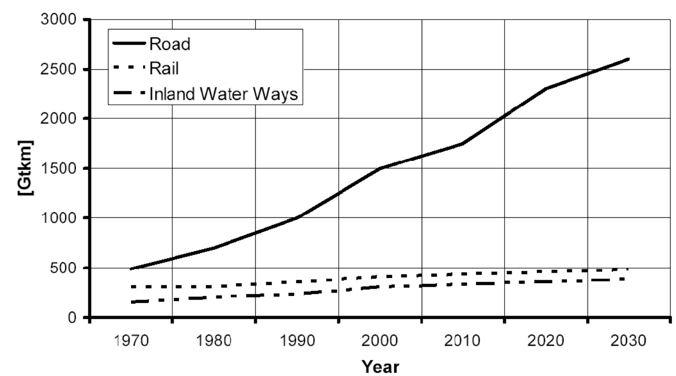


Figure 3 – Records and forecast of the development of total continental freight transport in Europe 1970-2030

1. Introduction: Owner/Manager Perspectives

So how can infrastructure owners/managers deal with ageing/deteriorating infrastructure, subjected to increasing loads and load frequencies, for which it was never designed, with reducing budgets and yet ensure code compliance, i.e. min safety requirements?

1. Introduction: Strategy – Get In Behind the Code!

EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN 1990

April 2002

ICS 91.010.30

Supersedes ENV 1991-1:1994

English version

Eurocode - Basis of structural design

Eurocodes structuraux - Eurocodes: Bases de calcul des structures

Eurocode: Grundlagen der Tragwerksplanung

This European Standard was approved by CEN on 29 November 2001.

CEN members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration. Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the Management Centre or to any CEN member.

This European Standard exists in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CEN member into its own language and notified to the Management Centre has the same status as the official versions.

CEN members are the national standards bodies of Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, Malta, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and United Kingdom.

EUROPEAN COMMITTEE FOR STANDARDIZATION
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EUROPÄISCHES KOMITEE FÜR NORMUNG

Management Centre: rue de Stassart, 36 B-1050 Brussels

Ref. No. EN 1990:2002 E

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.

... tifying compatible load ... 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.

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

1. Introduction – Safety Criteria

Legally:

- Don't necessarily have to fulfill the specific requirement of the general code as long as overall requirement for the safety level are satisfied.
- Safety is determined in terms of β which is formally defined in terms of the allowable probability of failure as:

$$\beta = -\Phi^{-1}(p_f)$$

for which $\Phi^{-1}(\cdot)$ is the inverse function of the standardised normal distribution.

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

Reliability Class	Minimum values for β	
	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

Table 2 – Reliability Classes Specified by the Eurocodes (EN 1990)

Consequence Class (Reliability Class)	Description	Examples of buildings and civil engineering works
CC3 (RC3)	High consequence for loss of human life	Grandstands, public buildings
CC2 (RC2)	Medium consequence for loss of human life	Residential and office buildings
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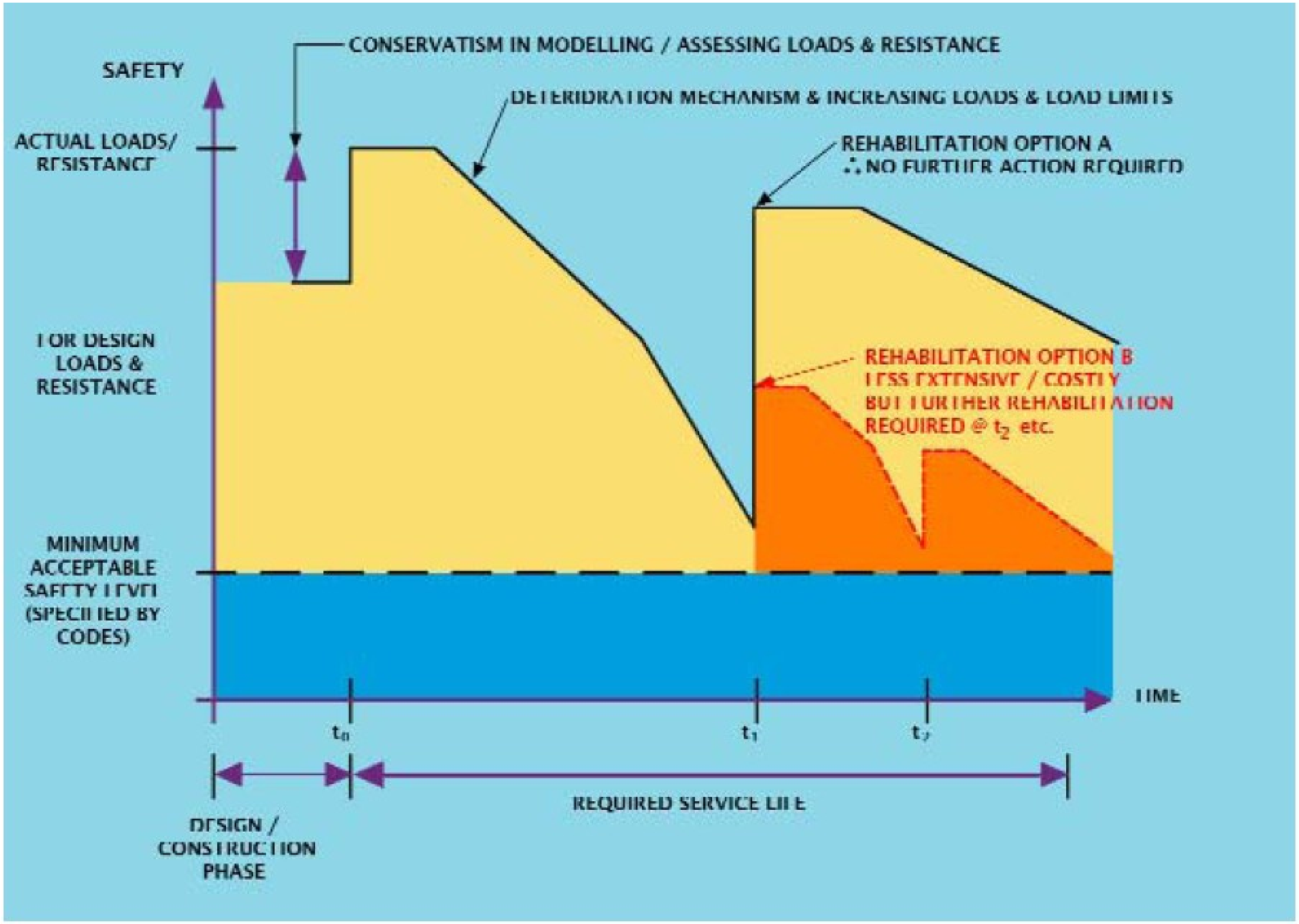
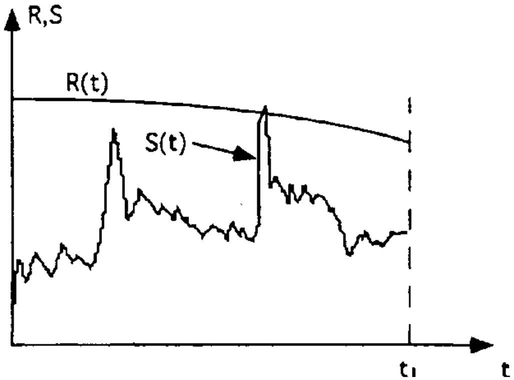
1. Introduction – Safety Management

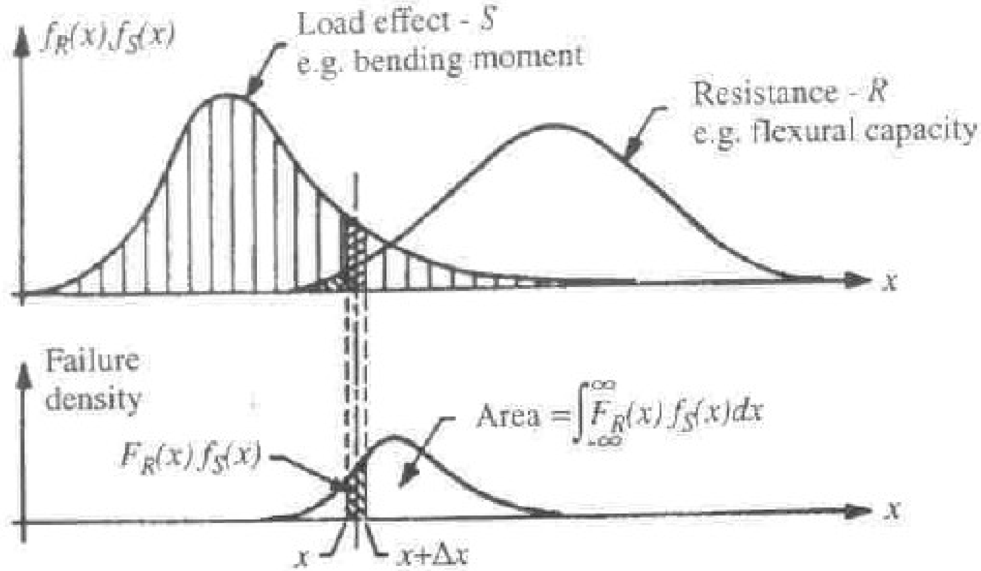


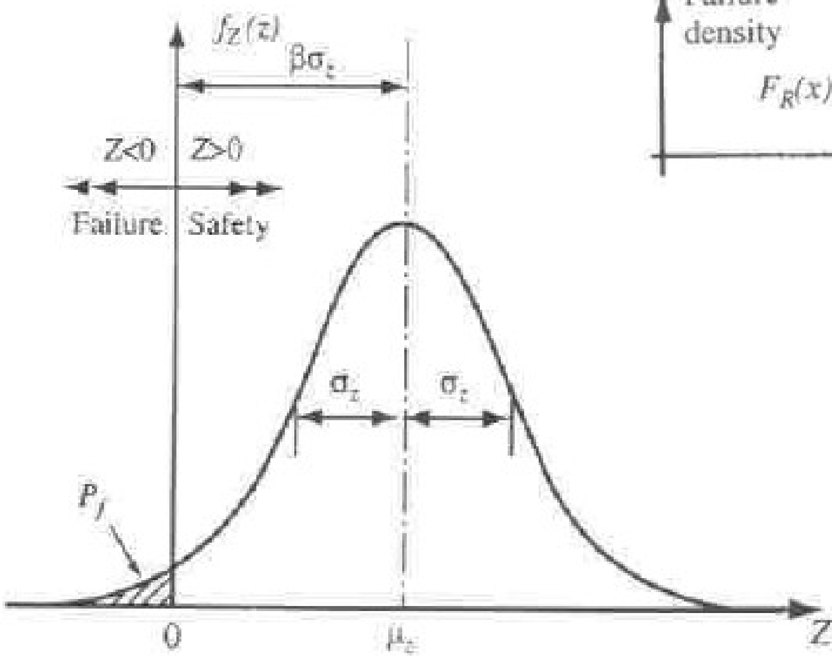
Basis of Probabilistic Design & Assessment

2. Probability Based Assessment (PBA) – Structural Reliability

Structural Reliability Theory – Basis of Design Codes and Partial Safety Factor



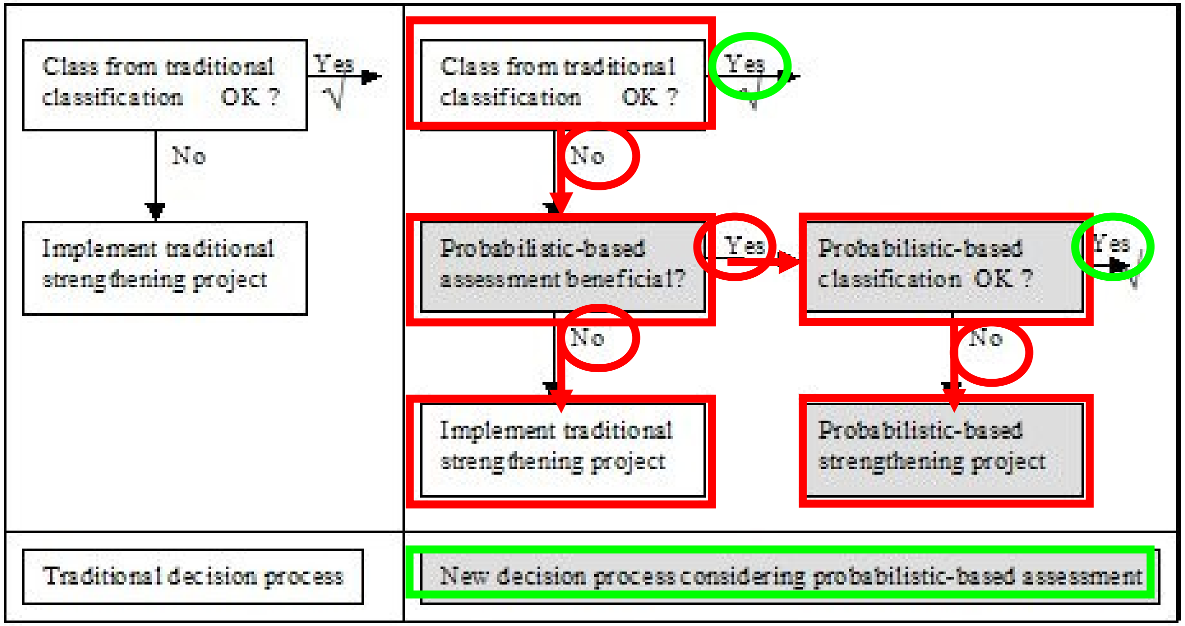




$$p_f = \Phi\left[\frac{-(\mu_R - \mu_S)}{(\sigma_S^2 + \sigma_R^2)^{1/2}}\right] = \Phi(-\beta)$$

2. PBA: Decision Strategy

The strategy for deciding to perform probabilistic assessment may be explained by a revised decision process highlighted:



2. PBA: Generalised vs Individual Approach

Practically the revised decision strategy may be explained in terms of the difference between adopting a generalised or individualised approach to the assessment of structures which prove critical.

<u>The general approach:</u>

Based on codes for bridges

- New bridges
- Existing bridges

Generalisation

- Partial safety factor format
- Load specification
- Many types of bridges

Benefit

- Efficient and easy to use

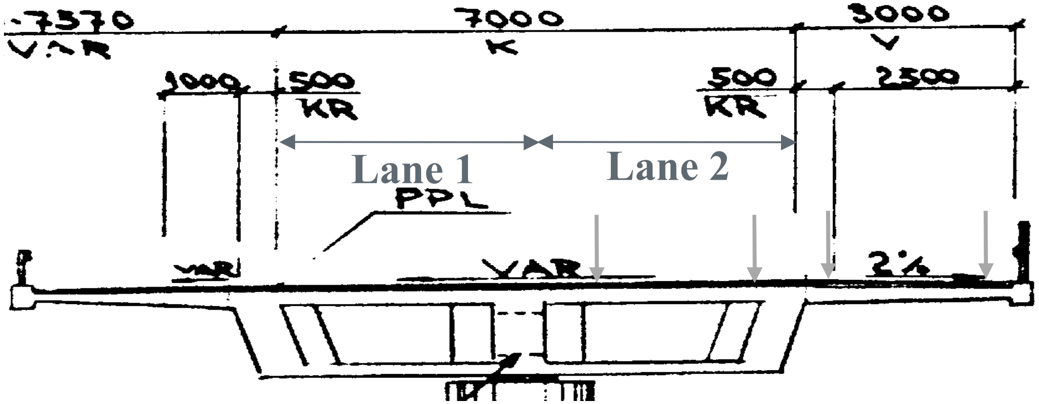
Drawback

- Costly in case of lack of capacity

2. PBA: Generalised vs Individual Approach

Conservative combination of extreme cases

- Conservative capacity models
- Conservative response models
- Conservative load magnitudes
- Conservative location of loads
- Conservative impact factors
- Conservative occurrence models



Example: Conservative load modelling

2. PBA: Generalised vs Individual Approach

Conservative combination of extreme cases (Hrastnik Experiment, FP5 SAMARIS)

- Conservative impact factors
- Conservative occurrence models

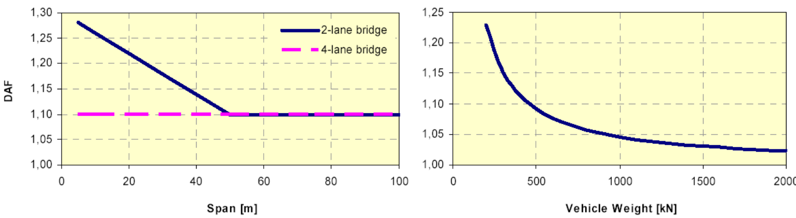
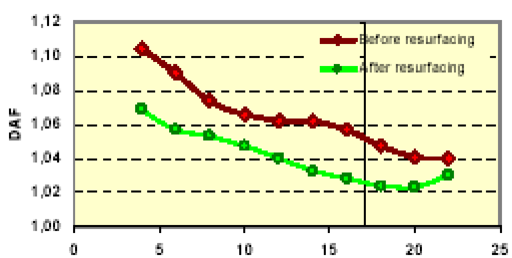


Figure 1 - Allowances for dynamic amplification incorporated in the Eurocode (left) and Danish recommendations for reduction of DAF with vehicle weight (right)

Figure 3 – Hrastnik bridge - side and top views



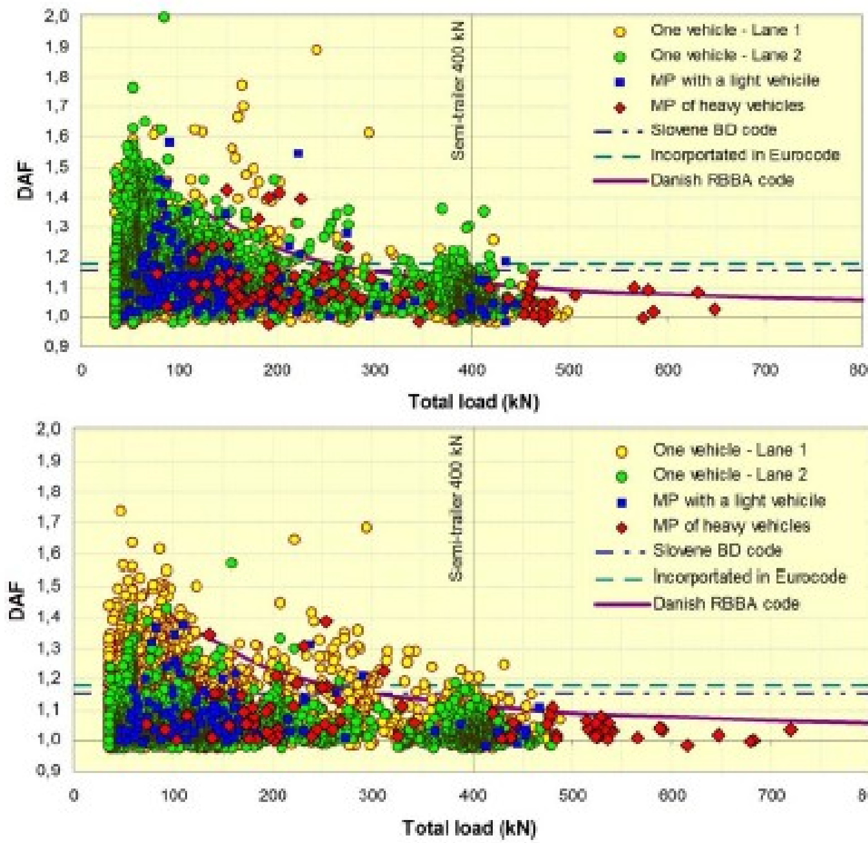


Figure 6 - Measured DAFs of loading events before (above) and after resurfacing of the pavement (below), compared to the bridge design and Danish RBBD codes

2. PBA: Generalised vs Individual Approach

<u>The individual approach:</u>

Concept:

- Don't necessarily have to fulfill the specific requirement of the general code
- Overall requirement for the safety level must be satisfied. Where safety is determined in terms of β which is formally defined in terms of the allowable probability of failure as:

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Concept:

- Don't necessarily have to fulfill the specific requirement of the general code
- Overall requirement for the safety level must be satisfied. Where safety is determined in terms of β which is formally defined in terms of the allowable probability of failure as:

Purpose:

- Cut strengthening or rehabilitation costs without compromising the safety level

Method:

Probabilistic-based assessment

Uncertainties of the specific conditions:

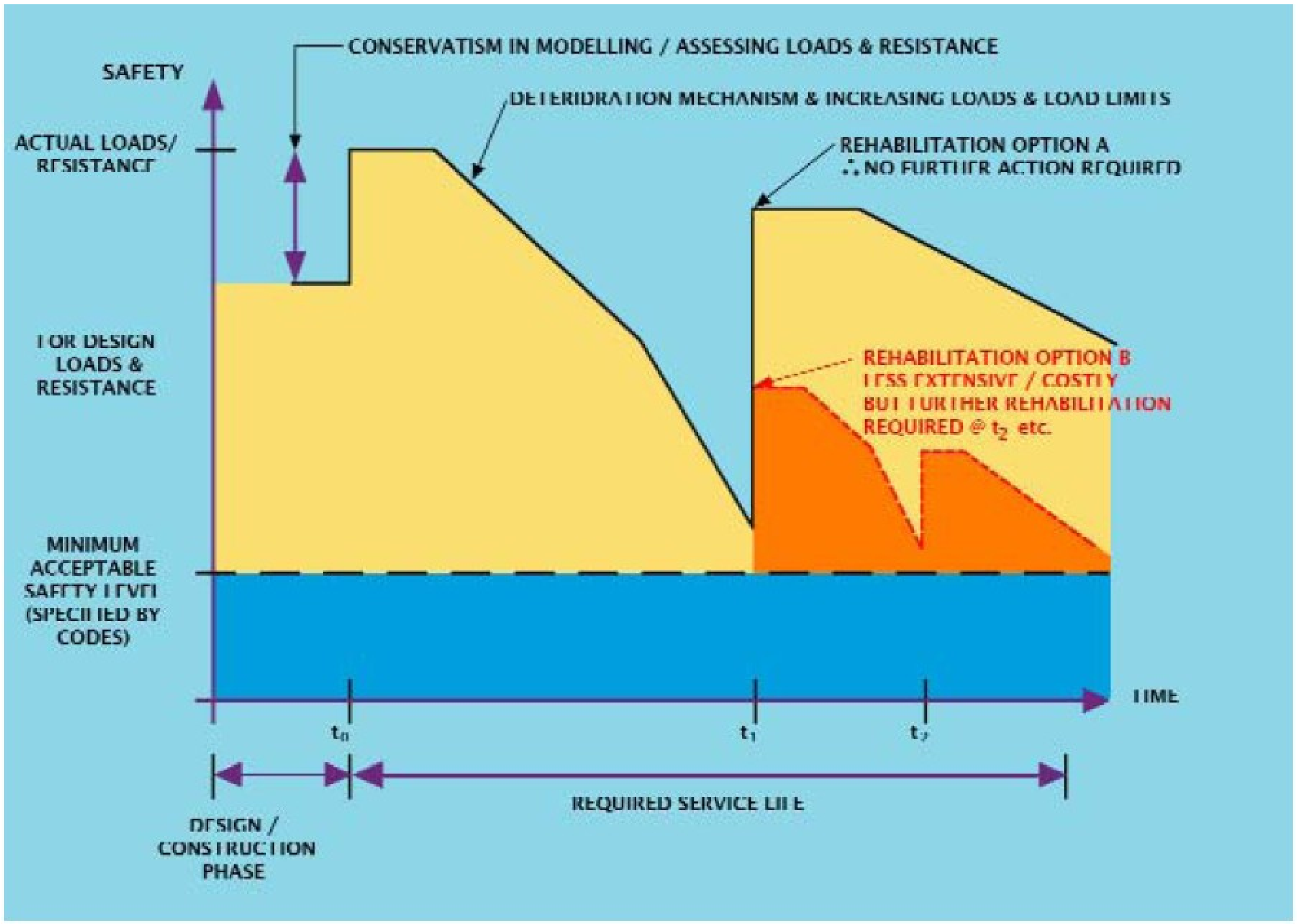
- Traffic load
- Capacities
- Models
- Updating based upon inspection results & load history information

Bridge specific "code" is obtained

REQUIRED SAFETY LEVEL IS NEVER COMPROMISED

2. Probability Based Assessment

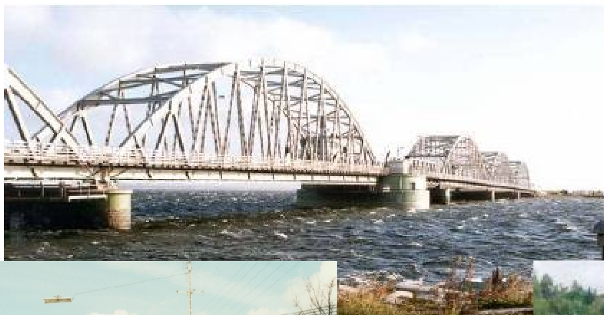
The individual approach:

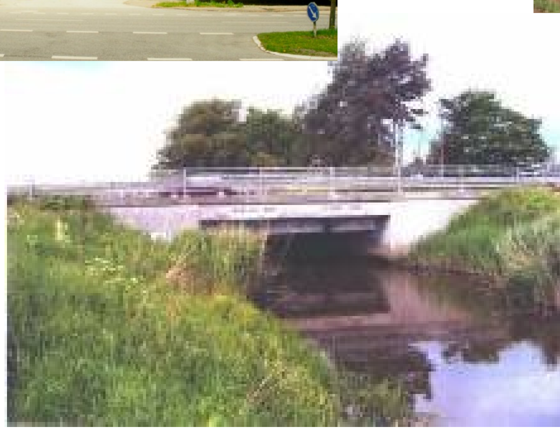


Basis of Probabilistic Design & Assessment

3. Examples of Practical Application

In the following practical application of the methodology outlined is presented in the context of road & rail bridges assessed in Denmark and Sweden.





3. Examples of Practical Application

ii. Storstrom Bridge

- The 3.2 km long Storstroem Bridge connects the Danish Island of Zealand with the southern Danish islands of Falster and Lolland.

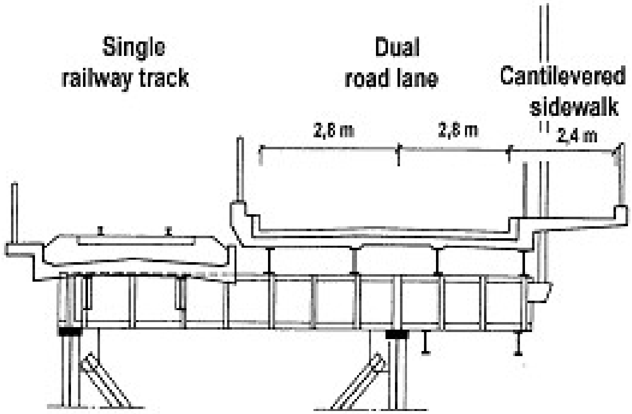
- The contract for the building of the bridge was given to the British company Dormann, Long & Co., who also fabricated the main steel structure (The contract was awarded to a British company as a political move to offset the significant trade deficit which had developed between the UK and Denmark at his time due to Danish pork exports).

- The bridge opened in September 1937.

3. Examples of Practical Application

ii. Storstrom Bridge

- The bridge carries dual road lanes and a single railway track and a cantilevered sidewalk for pedestrians.



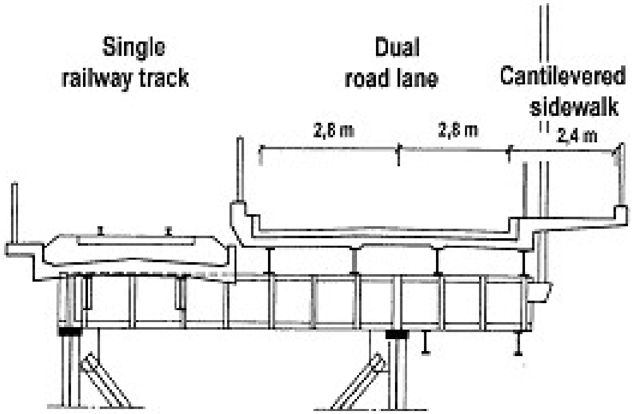
- Until 1985 when the Faroe Bridge opened, Storstroem Bridge was the only fixed connection between Zealand and the southern Danish Islands. The Faroe Bridge carries only cars.

- Today the Storstroem Bridge carries only local traffic with an average annual daily traffic (AADT) of about 8000 vehicles.

3. Examples of Practical Application

ii. Storstrom Bridge

- The main deck slab of the 3.2 km long Storstroem Bridge has suffered serious deterioration to both the concrete and reinforcement.
- Replacement of the bridge would be extremely costly especially when considered in connection with the possibility of the construction of the Femern Bridge at some point in the future.
- Thus, the DRD would like to postpone any decision on a strategy for the Storstroem Bridge until a decision about the Femern crossing is made. However, at the same time the DRD must ensure that the structure has sufficient structural safety for both vehicles and pedestrians at all times.

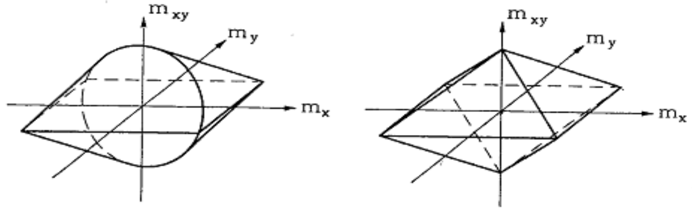


3. Examples of Practical Application

ii. Storstrom Bridge: Integration of Plastic & Probabilistic Methods

The program PROCON is used for the plasticity-based assessment of the bridge. This program, developed at RAMBØLL, consists of a finite element formulation for limit analysis of perfectly plastic plates using triangular elements. The flexural load carrying capacity of concrete slabs is calculated according to the yield criterion which is adopted in the Eurocode (Eurocode 1995).

$$-(m_{Fx}^{+}-m_x)(m_{Fy}^{+}-m_y)+m_{xy}^2 \leq 0 \quad -(m_{Fx}^{-}-m_x)(m_{Fy}^{-}-m_y)+m_{xy}^2 \leq 0$$



Yield Criterion Linearised Yield Criterion

(According to Equations)

In a limit analysis the nodal loads are made up of two contributions, a fixed load p_0 and a variable load λp_1, scaled by the load factor λ. The equilibrium equations are of the form:

$$H_m = p_0 + \lambda p_1$$

3. Examples of Practical Application

ii. Storstrom Bridge: Results of Assessment

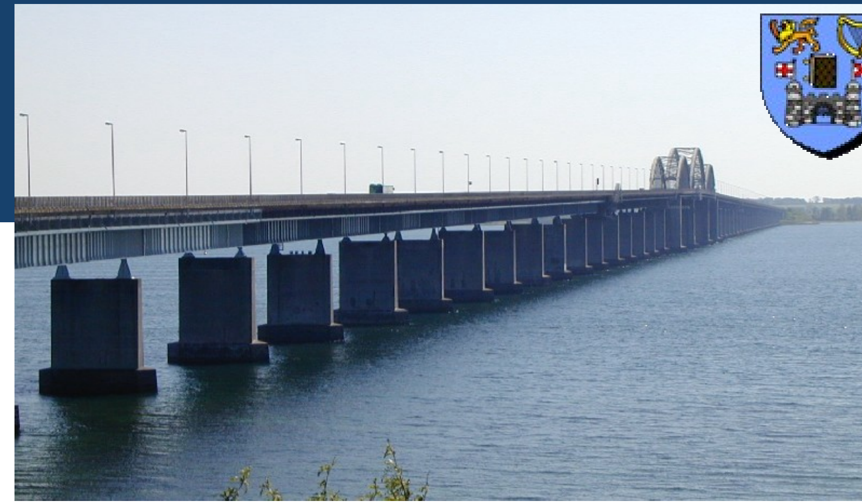
Deterministic assessment of the deck slab using PROCON for combined dead and live load produced a maximum load factor of 0.61. This implies that the slab is incapable of sustaining the applied load. The recommendation would therefore involve costly rehabilitation of the structure.

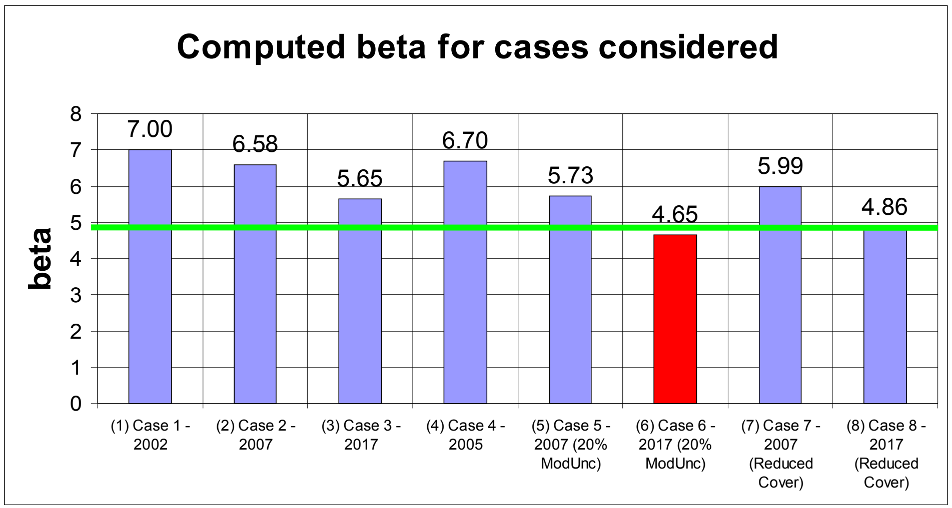
Probabilistic Assessment including deterioration modelling, with deterioration models updated based upon inspection results performed at the bridge could document sufficient capacity.

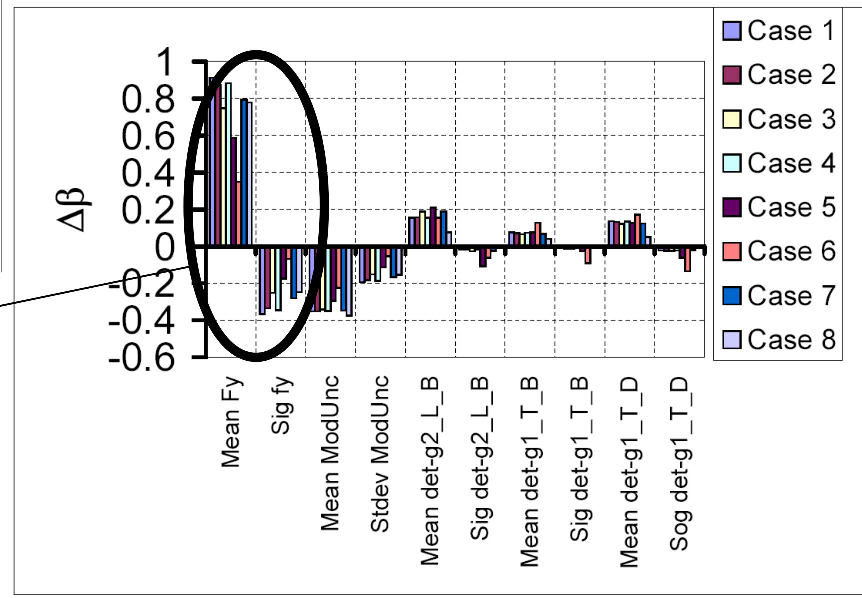
Table 5 - Results of deterministic and probabilistic assessment; O'Connor et al (2004).

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	$p_f = 6.92 \times 10^{-7}$ $\beta = 4.83$

Storstrom Bridge Denmark (2008)





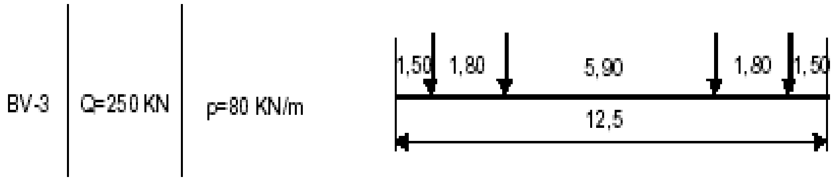


Updating of parameters through e.g. inspection results can reduce uncertainty and improve β, or vice versa (i.e. Intelligent Assessment, Structural Health Monitoring)

3. Examples of Practical Application

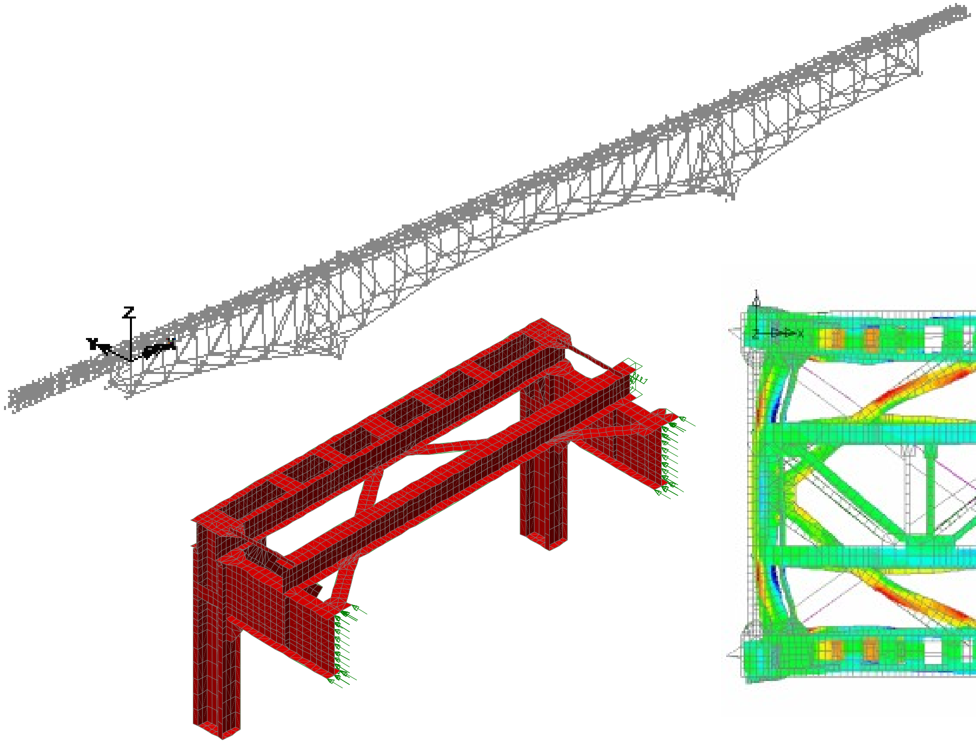
iv. Bergeforsen Railway Bridge, Sweden

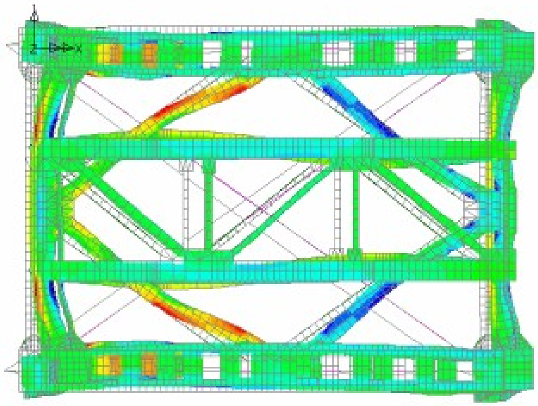
Bridge constructed in 1923
Superstructure span configuration: 42+84+42 = 168m
Side spans 22.5m + 11.6m
Total bridge length = 202.1m
Required to assess for Swedish BV-3 load model



3. Examples of Practical Application

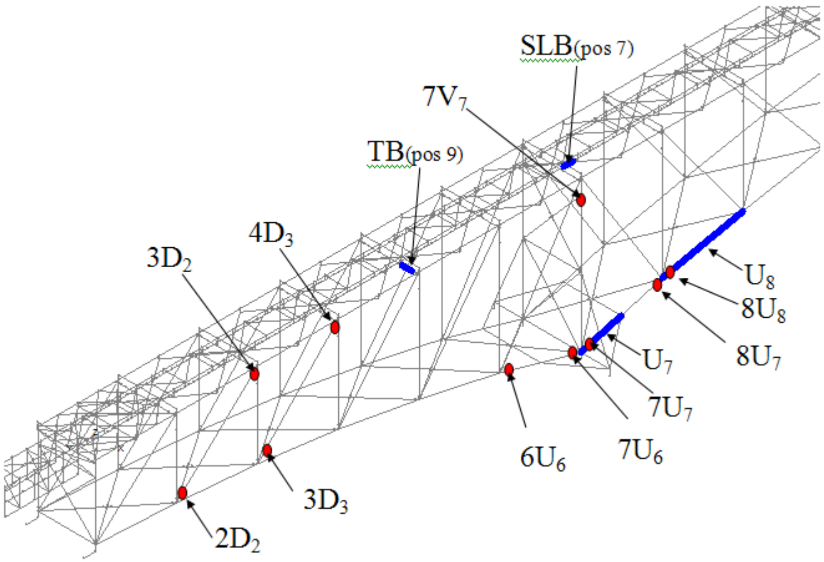
Structural analysis was performed using an FE model calibrated against a shell and volume element model constructed for specific critical locations.





3. Examples of Practical Application

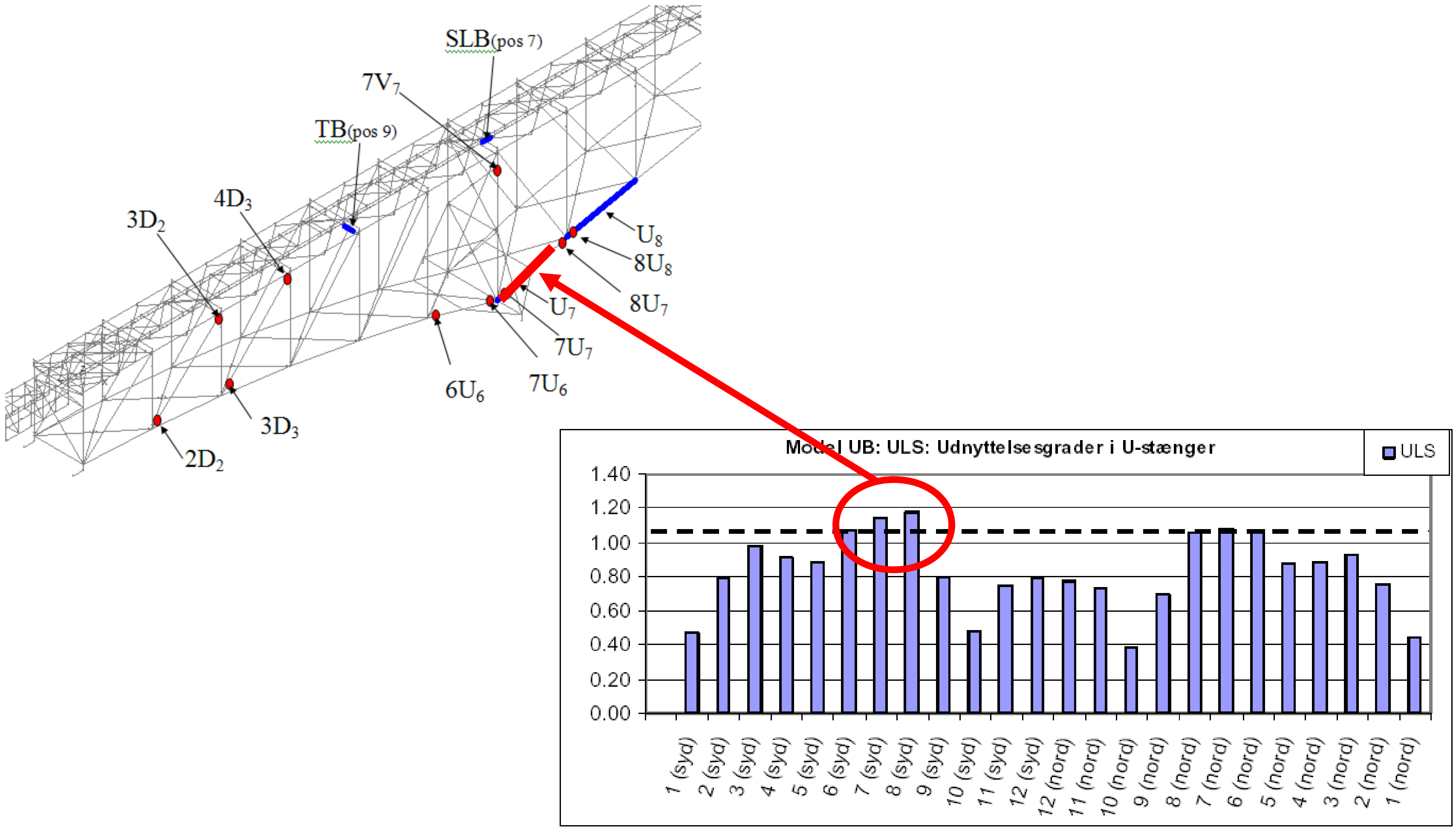
Deterministic assessment - results



- SLS capacity demonstrated deterministically
- FLS capacity demonstrated deterministically by Rainflow analysis
- ULS capacity could **NOT** be demonstrated at certain elements + joints as follows

3. Examples of Practical Application

Deterministic assessment - results



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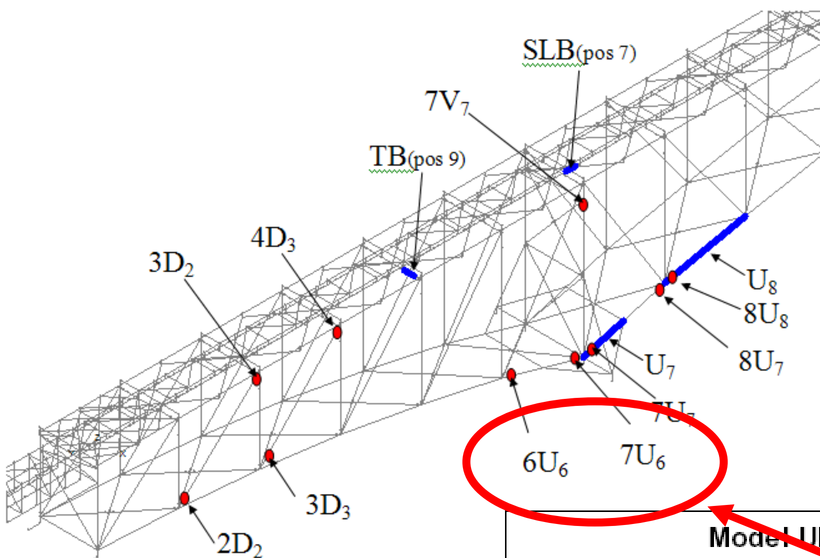
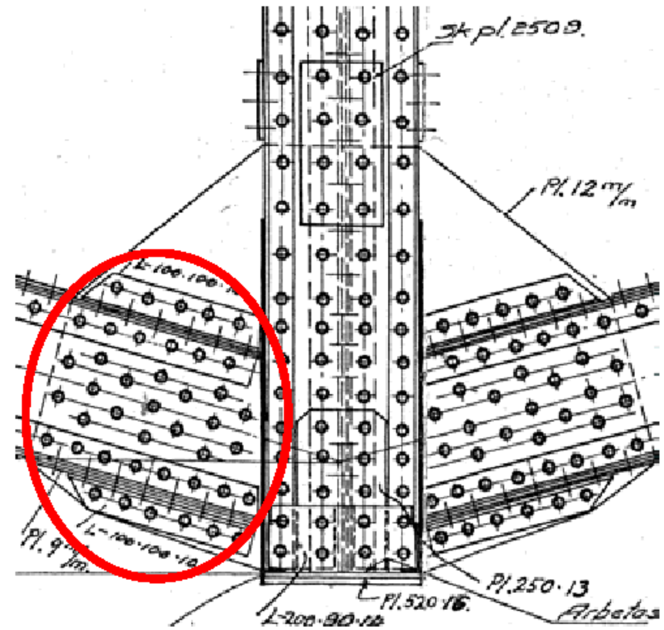
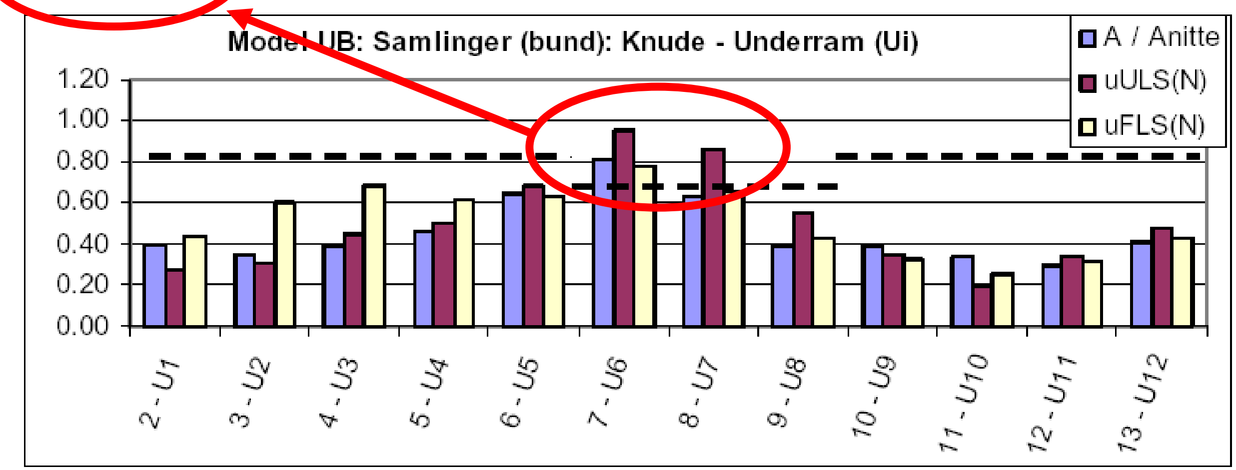




(a) Connection 7-U_6



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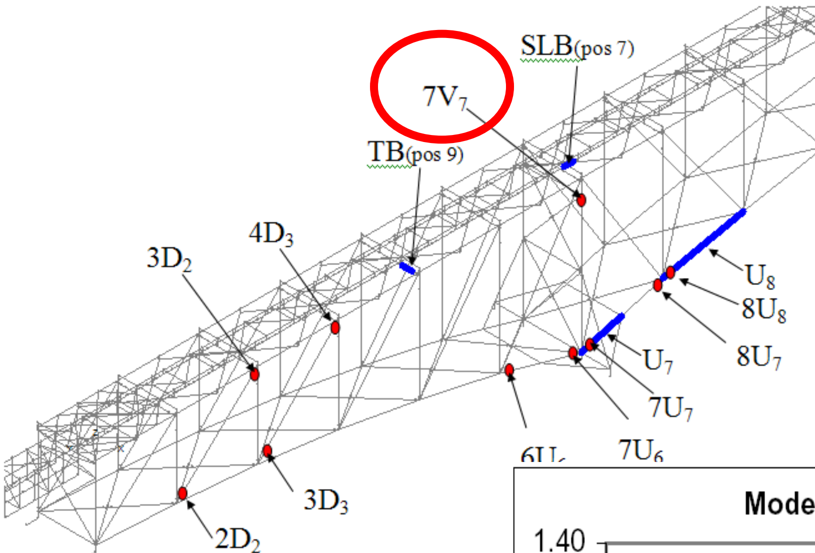
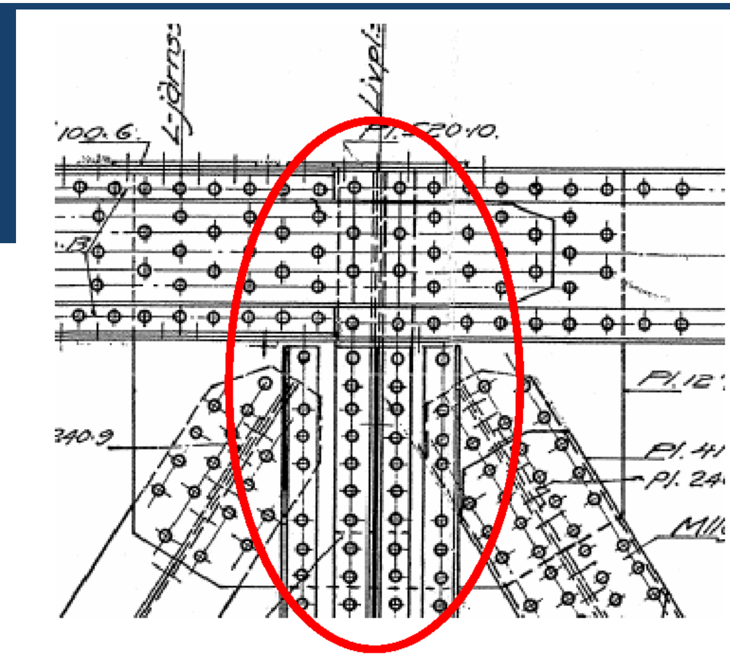
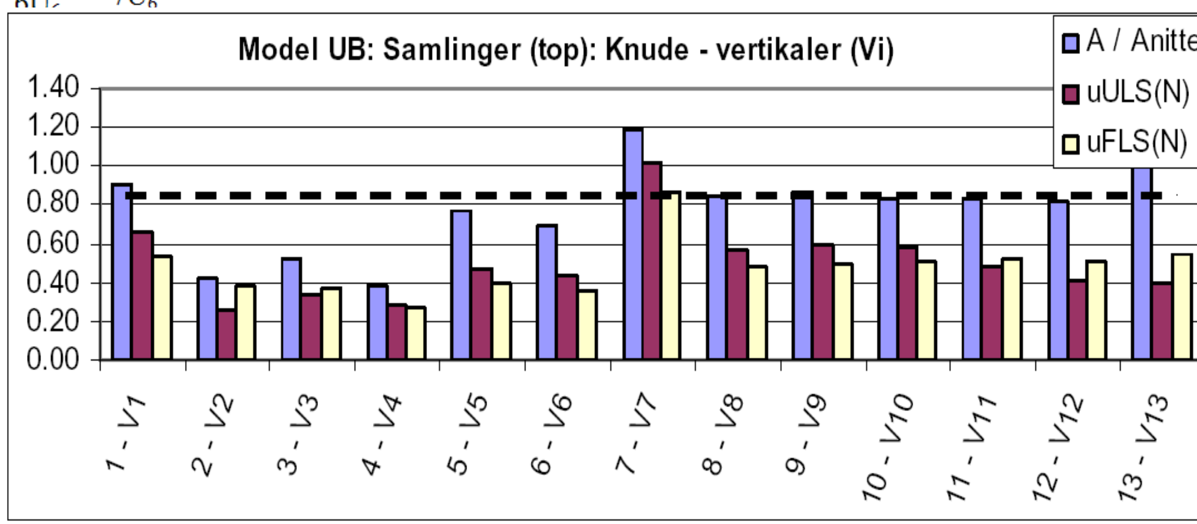


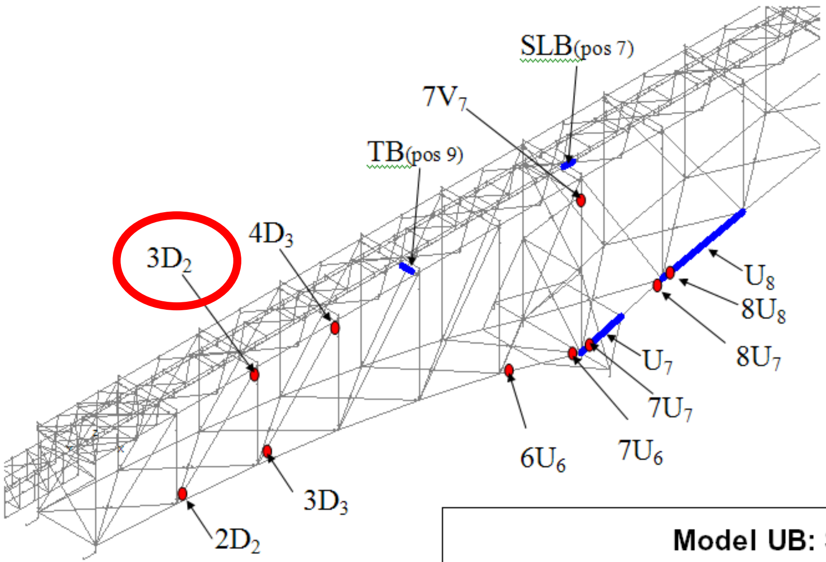


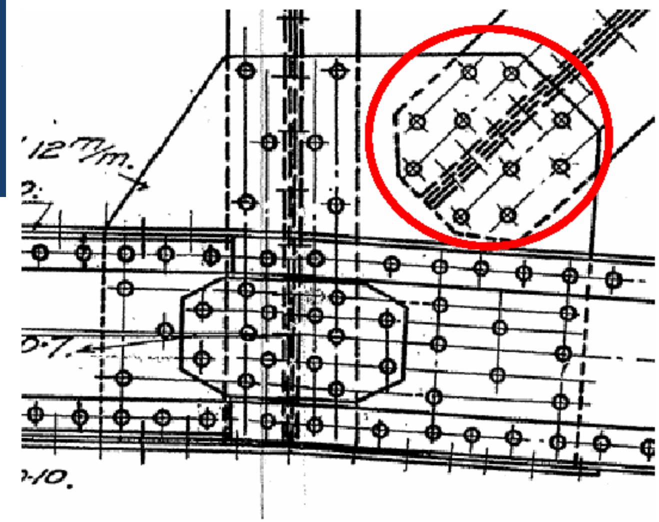
(a) Connection 7-V_7



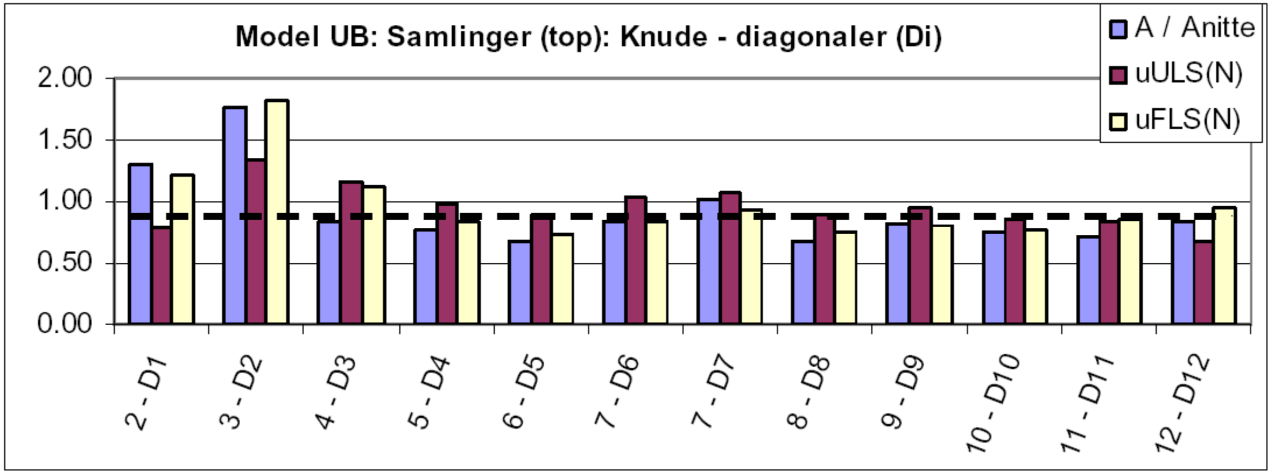
3. Examples of Practical Application

Deterministic assessment - results



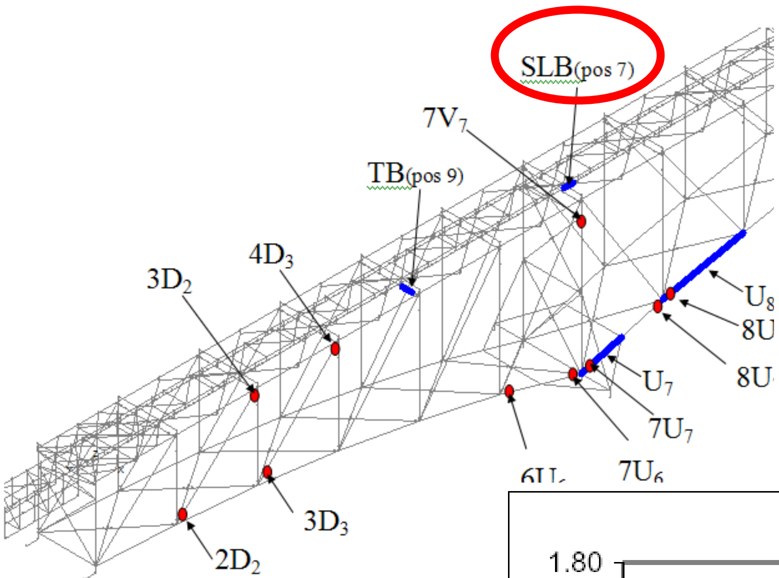


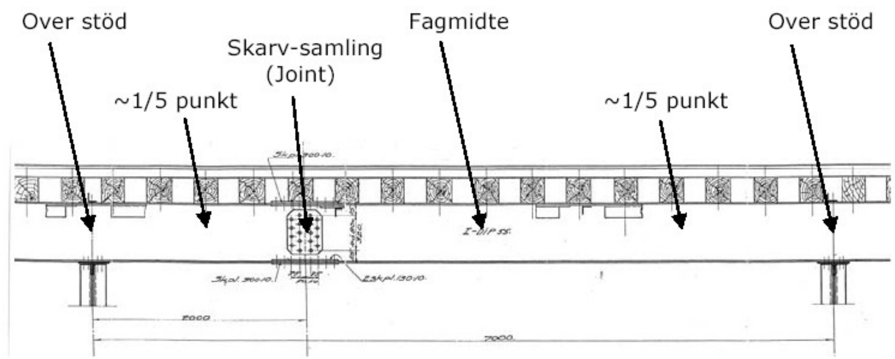
(a) Connection 2-D_2



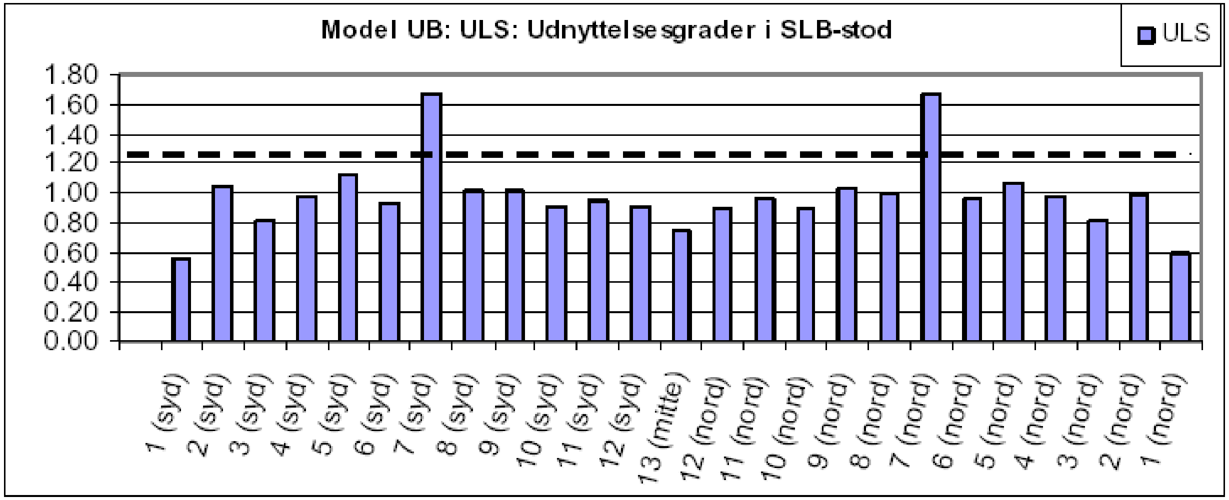
3. Examples of Practical Application

Deterministic assessment - results





Figur 6-1 Opstalt af DIP55-profiler.



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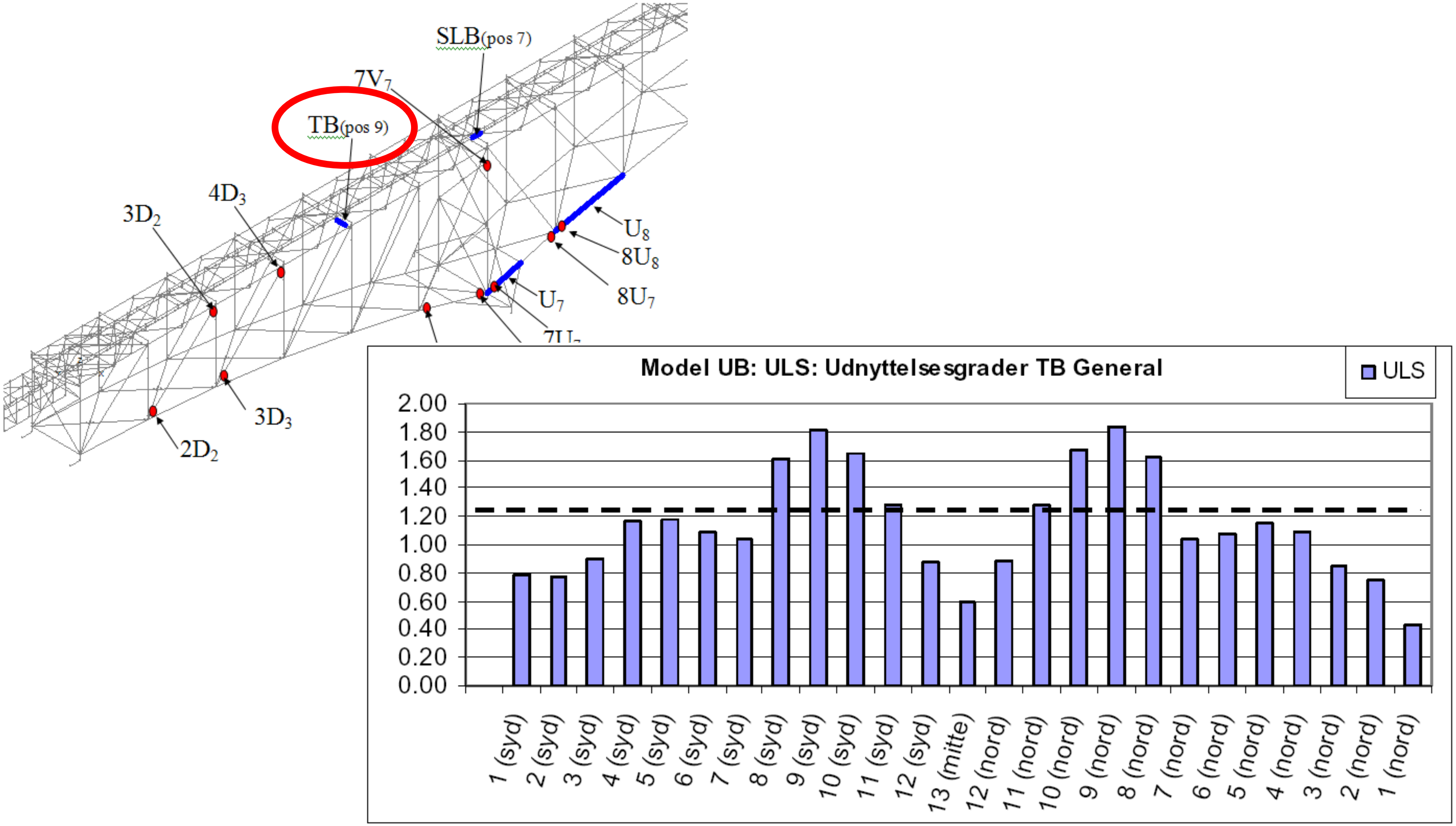

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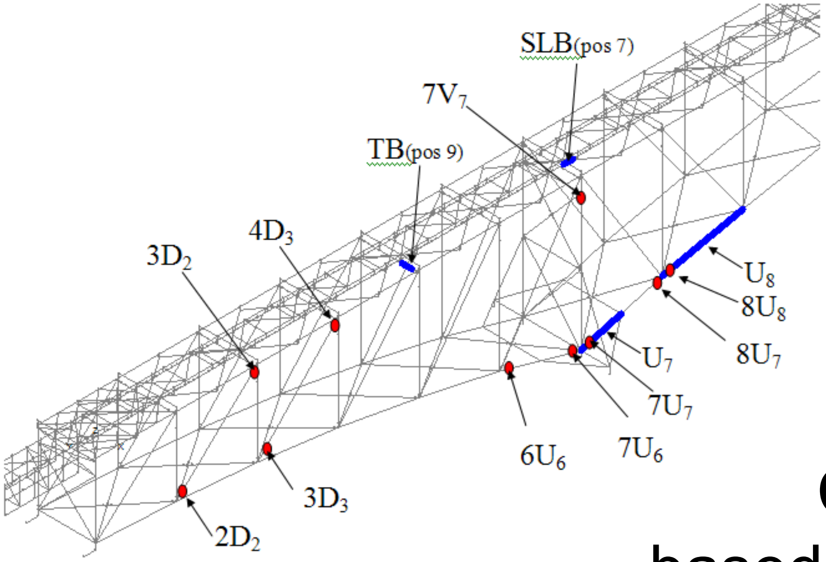


Concluded that probability based assessment should be performed at these critical locations!

3. Examples of Practical Application

Requirement for Safety Level

2 :114 Säkerhetsindex

Säkerhetsindex, β, definierat enligt ISO 2394-1998, *General Principles on the reliability for Structures*, skall för en byggnads-del vara
$\geq$ 3,7 för säkerhetsklass 1,
$\geq$ 4,3 för säkerhetsklass 2,
$\geq$ 4,8 för säkerhetsklass 3. *(BFS 1998:39)*

Limit State for
Elements

$g \leq 0$ where $g = f_y - |\sigma|$

σ is induced Navier Stresse due to applied loads = $\sigma_{Fx} + \sigma_{My} + \sigma_{Mz}$

Riveted Joint Connections

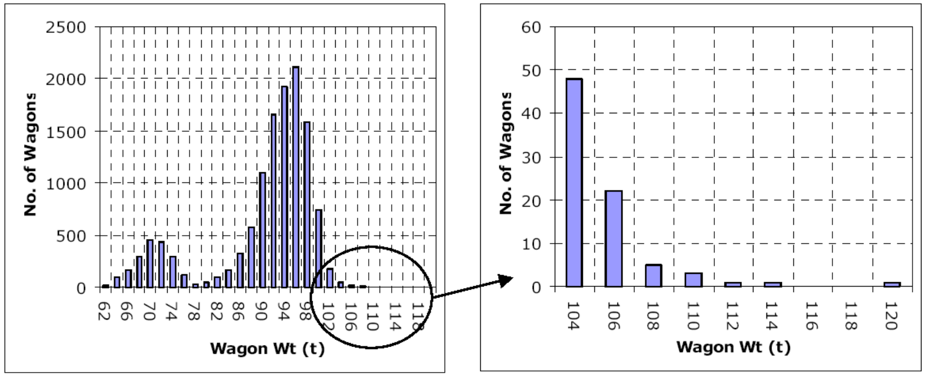
$g \leq 0$ where $g = 0.85 \cdot 0.6 \cdot f_u - |\tau|$

to allow for rivet misalignment BV583.11

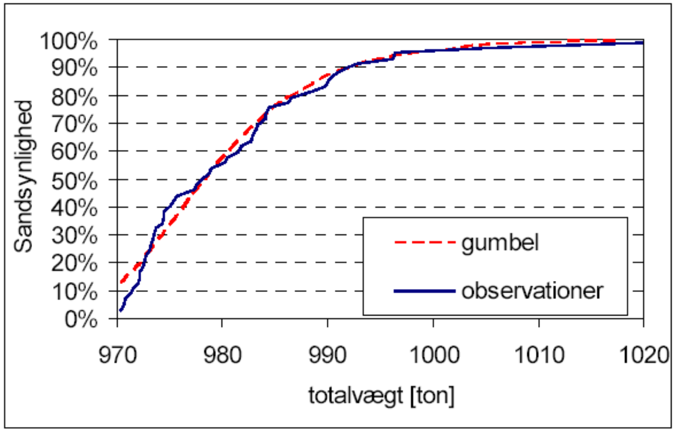
3. Examples of Practical Application

Load & Load Effect Modelling - Train Load

Based on measurements it was possible to fit a standard statistical extreme distribution fit to measured data in order to determine the extreme distribution of the train load.



It was determined that the Gumbel extreme value distribution provided the best fit to the measured data.



3. Examples of Practical Application

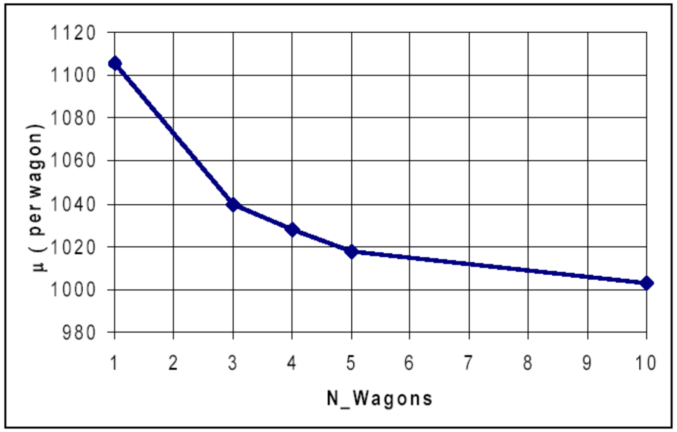
Load & Load Effect Modelling - Extreme Train Load

The parameters of the Gumbel EVD were evaluated based upon the number of wagons considered.

EVD based on	μ (kN)	σ (kN)	CoV (%)
1 Wagon	1105.9	16.9	1.53
3 Wagons	3119.2 (/3=1040)	36.4	1.17
4 Wagons	4111.7 (/4=1028)	44.1	1.07
5 Wagons	5090.2 (/5=1018)	49.5	0.97
10 Wagons	10030.1 (/10=1003)	91.9	0.92

Modelling the trains in this way reduces the conservatism associated with modelling the EVD based upon 1 wagon!

Model uncertainty on wagon weight was assumed 10%, i.e. ‘Small’ from DRD Guideline due to extremely low CoV ranging from 1.52 – 0.92%.



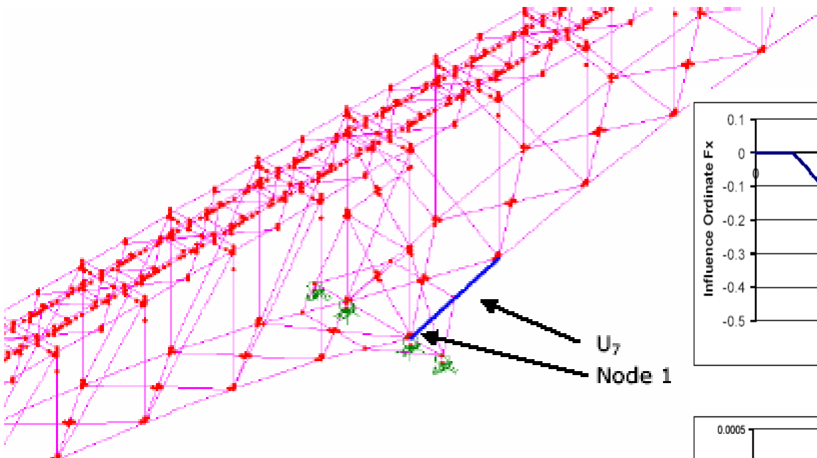
3. Examples of Practical Application

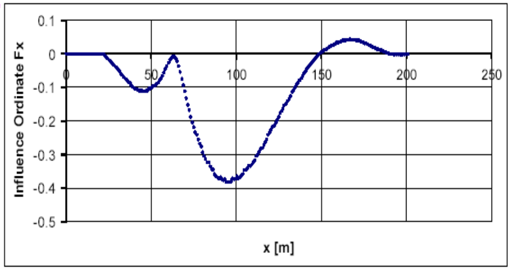
Load & Load Effect Modelling - Extreme train load

Element U_7 utilisation ratio 1.102 at Node 1.

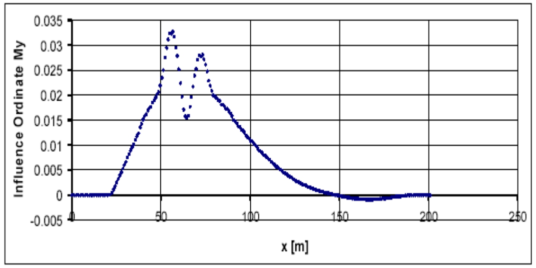
68% of this was due to F_x, with 31% due to primary bending M_y and 1% due to secondary bending M_z. Totally controlled by GLOBAL EFFECTS!

Modelling of EVD Train Load by group of 10 wagons (10x12.5=125m) appropriate

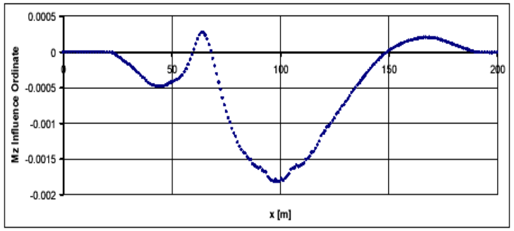




(a) F_x (68%)



(b) M_y(31%)

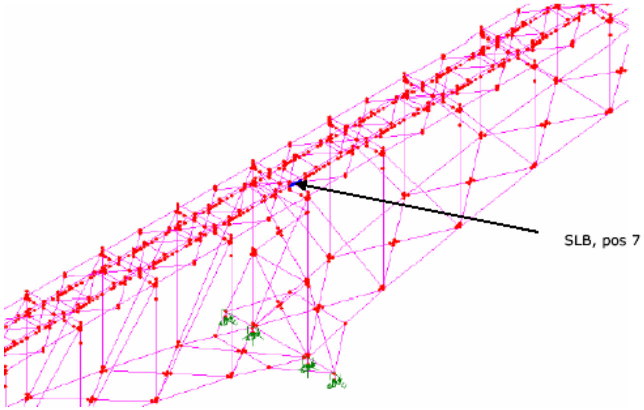


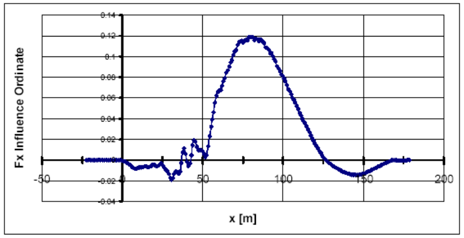
(c) M_z (1%)

3. Examples of Practical Application

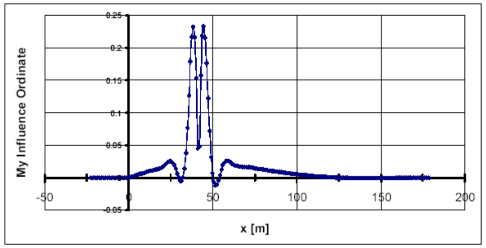
Load & Load Effect Modelling -Extreme train load + dynamic amplification of static load effect

- Element SLB, pos 7 utilisation ratio 1.635.
- 16% of this was due to F_x, with 65% due to primary bending M_y and 19% due to secondary bending M_z. Controlled by combination of Local + Global effects.
- high deterministic utilisation ratio due to requirement to model dynamic amplification based upon local effects only (resultant dynamic amplification factor = 1.53 vs. 1.06 for global effects).
- probabilistic computation of dynamic amplification considers each Navier Stress component individually applying local dynamic amplification factor to local effects and global dynamic amplification to global effects.

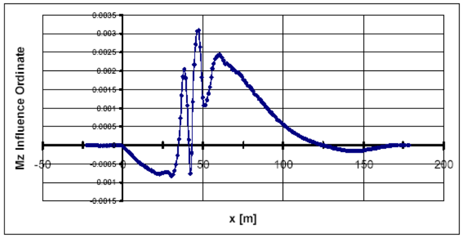




(a) F_x (16%)



(b) M_y (65%)



(c) M_z (19%)

3. Examples of Practical Application

Elements

β_{U_7} = 5.67 > 4.8

β_{U8} = 5.19 > 4.8

$\beta_{SLB.posn7}$ = 4.66 < 4.8

$\beta_{TB,posn17}$ = 4.81 > 4.8

Joints

β_{6-U_6} = 6.38 > 4.8

β_{7-U_6} = 4.51 < 4.8 (Remedial action necessary)

β_{7-U_7} = 4.06 < 4.8 (Remedial action necessary)

β_{8-U_7} = 6.01 > 4.8

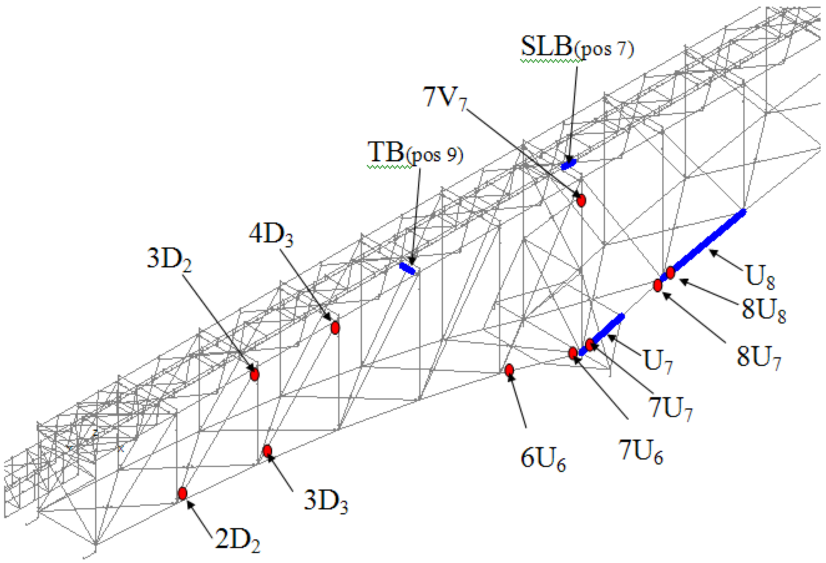
β_{7-V_7} = 6.31 > 4.8

β_{2-D_2} = 4.42 < 4.8 (Remedial action necessary)

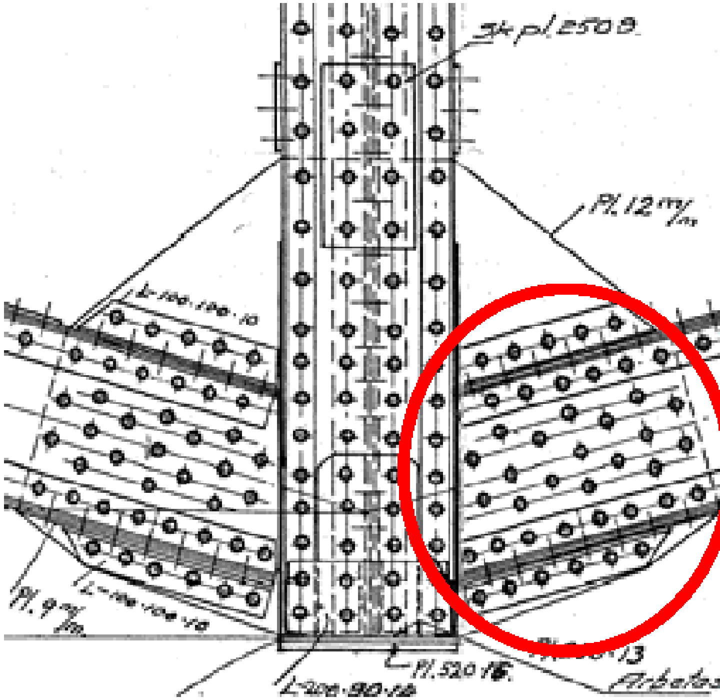
β_{3-D_2} = 4.56 < 4.8 (Remedial action necessary)

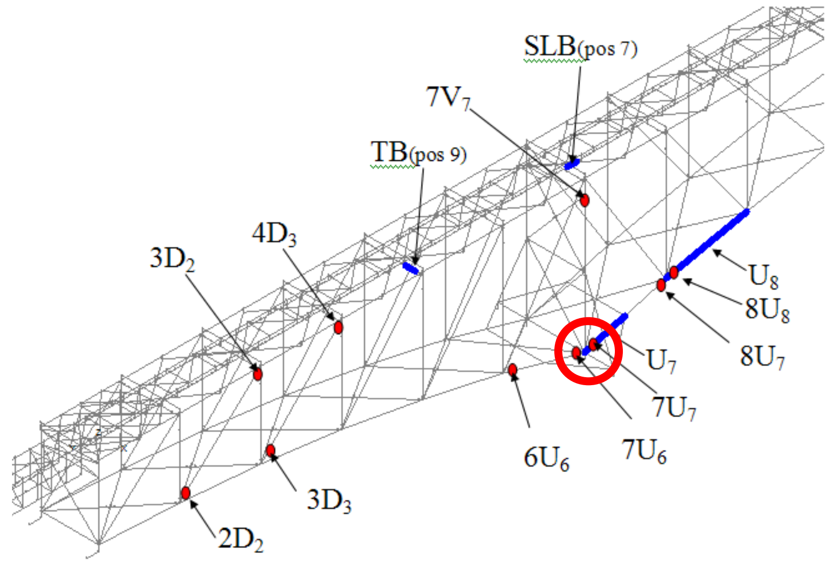
β_{3-D_3} = 5.18 > 4.8

β_{4-D_3} = 5.32 > 4.8

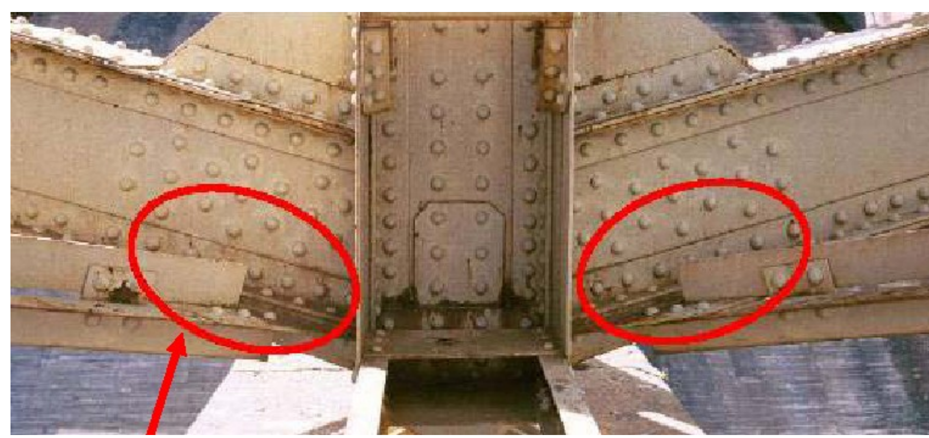


3. Examples of Practical Application





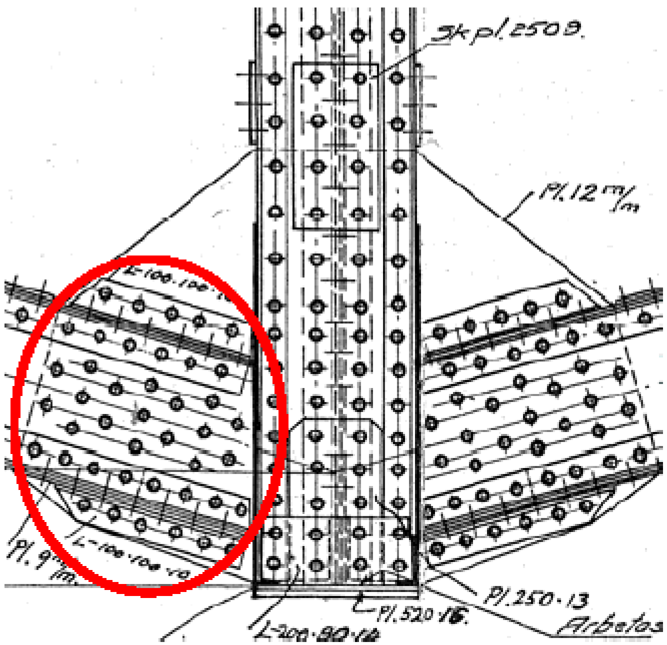
(a) Connection 7-U_7



3. Examples of Practical Application

Elements

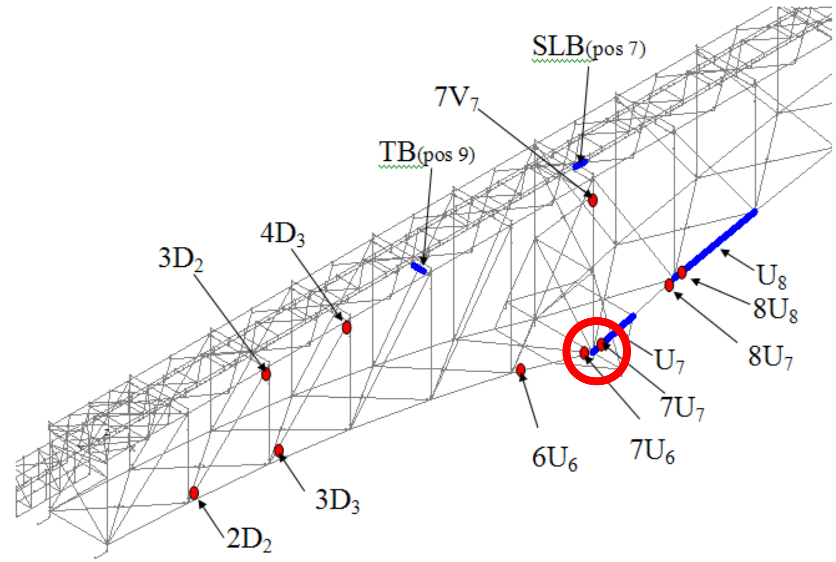
β = 5.67 > 4.8

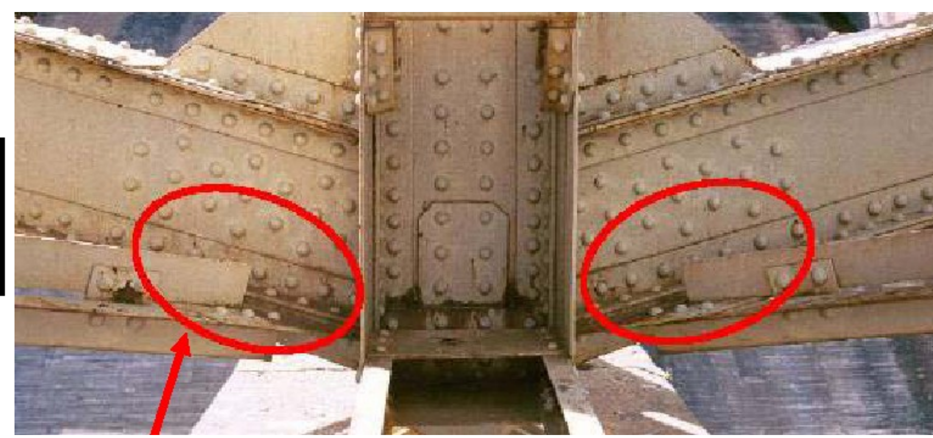


(a) Connection 7-U_6

β_{3-D_3} = 5.18 > 4.8

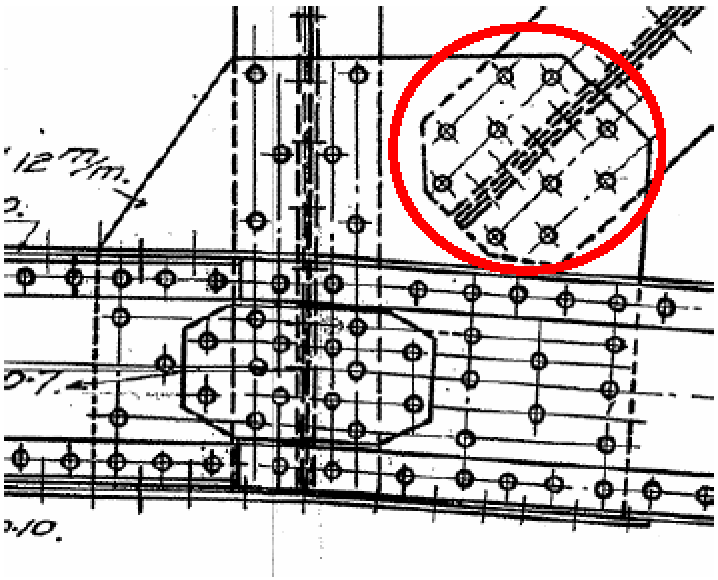
β_{4-D_3} = 5.32 > 4.8





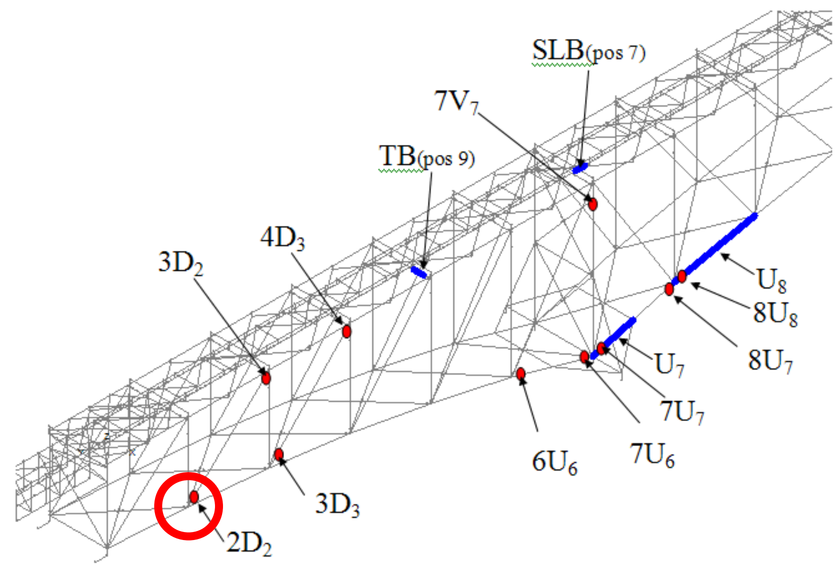
3. Examples of Practical Application

Elements



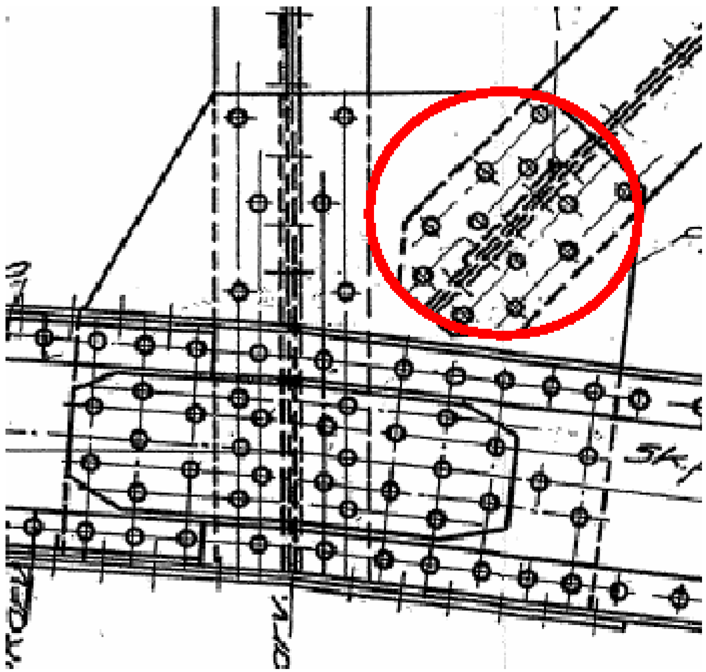
(a) Connection 2-D_2

β_{4-D_3} = 5.32 > 4.8



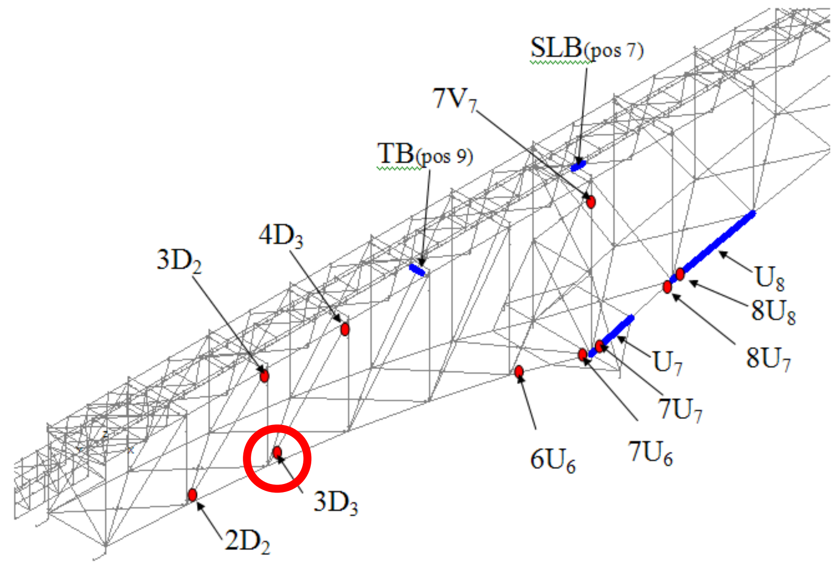
3. Examples of Practical Application

Elements



(a) Connection 3-D_3

β_{4-D_3} = 5.32 > 4.8



3. Examples of Practical Application

Elements

β_{U_7} = 5.67 > 4.8

β_{U8} = 5.19 > 4.8

$\beta_{SLB.posn7}$ = 4.66 < 4.8 (M_z = 0, $\beta_{SLB.posn7}$ = 5.85)

$\beta_{TB,posn17}$ = 4.81 > 4.8

Joints

β_{6-U_6} = 6.38 > 4.8

β_{7-U_6} = 4.51 < 4.8 (Remedial action necessary,

Proposal A β_{7-U_6} = 6.05, Proposal B β_{7-U_6} = 7.80)

β_{7-U_7} = 4.06 < 4.8 (Remedial action necessary,

Proposal A β_{7-U_7} = 5.62, Proposal B β_{7-U_7} =7.11)

β_{8-U_7} = 6.01 > 4.8

β_{7-V_7} = 6.31 > 4.8

β_{2-D_2} = 4.42 < 4.8 (Remedial action necessary,

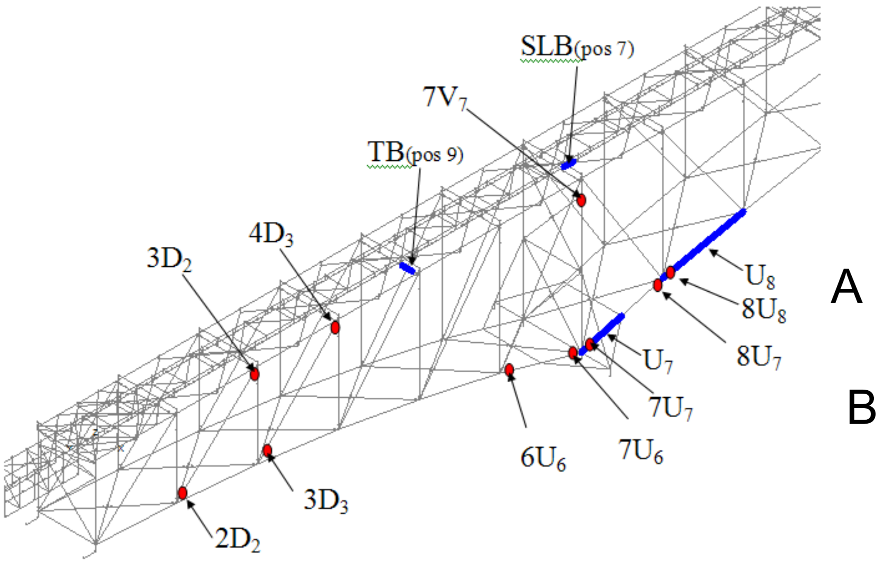
Proposal A β_{2-D_2} = 6.25)

β_{3-D_2} = 4.56 < 4.8 (Remedial action necessary,

Proposal A β_{3-D_2} > 4.8)

β_{3-D_3} = 5.18 > 4.8

β_{4-D_3} = 5.32 > 4.8



3. Examples of Practical Application

Elements

β_{U_7} = 5.67 > 4.8

β_{U8} = 5.19 > 4.8

$\beta_{SLB.posn7}$ = 4.66 < 4.8 (M_z = 0, $\beta_{SLB.posn7}$ = 5.85)

$\beta_{TB,posn17}$ = 4.81 > 4.8

Joints

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Proposal A β_{3-D_2} > 4.8)

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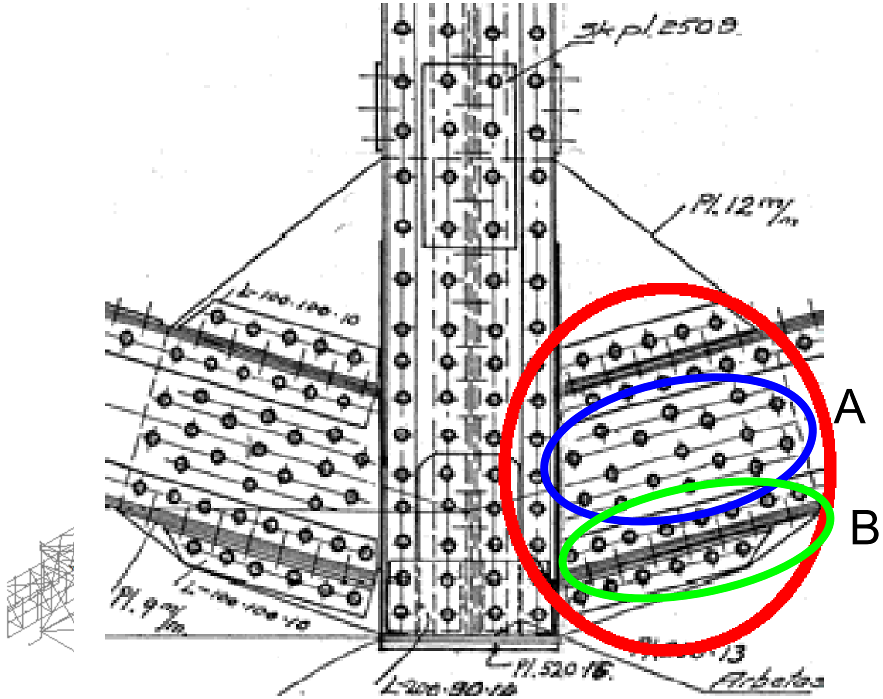
β_{4-D_3} = 5.32 > 4.8



Option A = Replace rivets in zone A with 27mm dia. Bolts

Option B = Replace rivets in zone B with 27mm dia. Bolts

(a) Connection 7-U_7

3. Examples of Practical Application

Elements

β_{U_7} = 5.67 > 4.8

β_{U8} = 5.19 > 4.8

$\beta_{SLB.posn7}$ = 4.66 < 4.8 (M_z = 0, $\beta_{SLB.posn7}$ = 5.85)

$\beta_{TB,posn17}$ = 4.81 > 4.8

Joints

β_{6-U_6} = 6.38 > 4.8

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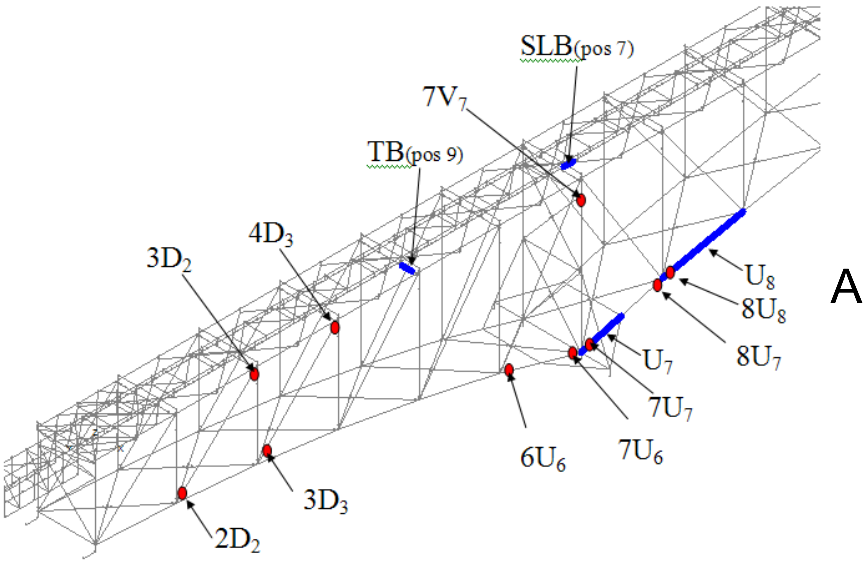
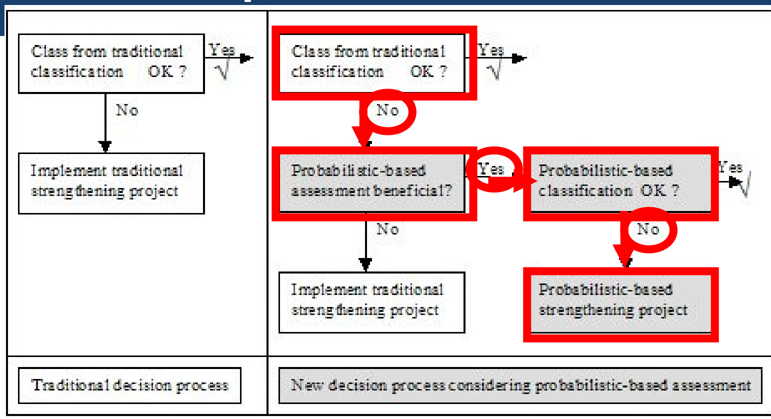
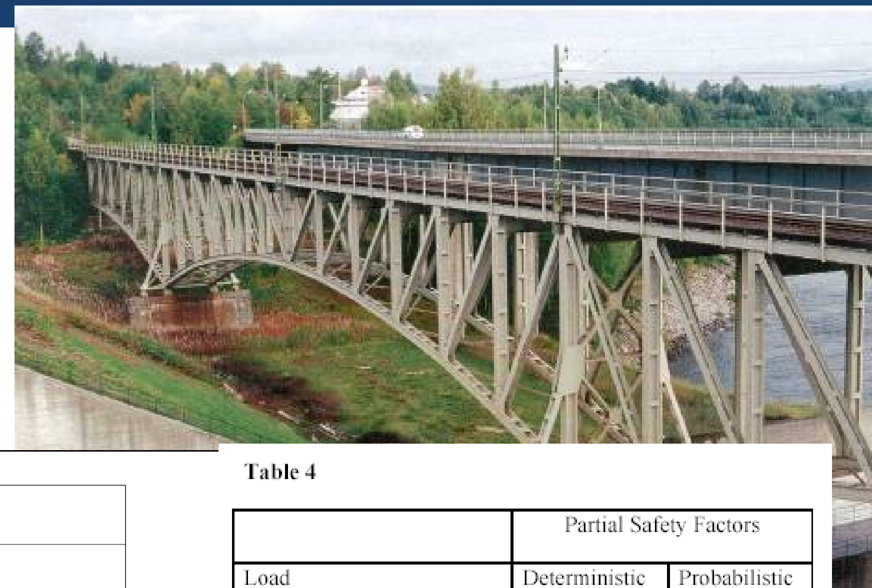


Similar options considered for other joints which had failed to demonstrate sufficient capacity. Results indicated that in all cases sufficient safety could be achieved.

3. Examples of Practical Application





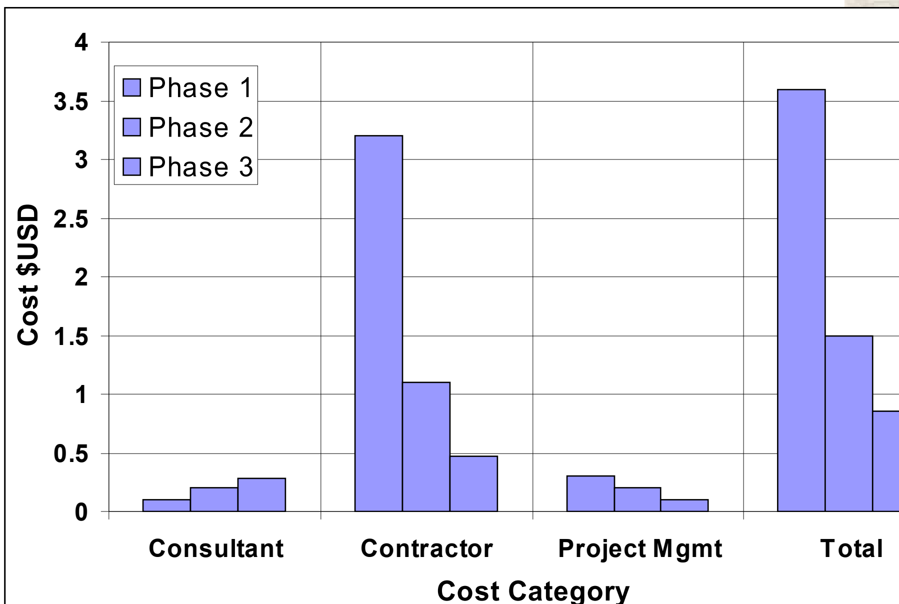


Table 4

	Partial Safety Factors	
Load	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

4. Conclusions

Problem:

1) Lack of load carrying capacity or exceedance of structural/performance limit state due to
   - weak bridges
   - deteriorated/(ing) bridges
   - Increasing loads

2) Low budgets for strengthening and/or rehabilitation where required

Idea:

Demonstration of higher capacity through Probabilistic safety assessments incorporating better calculation/response models

Principal Motivation:

Cost saving through Budget Optimisation

4. Conclusions

- Case studies are presented to demonstrate to practical application of probability based assessment to existing bridges.
- In the cases where sufficient capacity could not be demonstrated the probabilistic methodology can be used to optimise the rehabilitation process.
- 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 in Denmark and Sweden is provided from national codes combined with the Nordic committee recommendations (NKB 1978) and the Eurocodes.
- There are no practical or technical obstacles in applying probability-based assessment 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 avoiding the need for costly strengthening and replacement of existing bridges.
- It has become the policy of the Danish Roads Directorate and Banverket that the probability-based approaches should be more frequently applied in the future.

4. Conclusions

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Probability-based bridge assessment

A. O'Connor PhD, CEng, MIEI and I. Enevoldsen MSc, PhD

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
		TOTAL	40,400,000