NRA
An tÚdarás um Bóithre Náisiúnta
National Roads Authority

duratiNet

Maintenance and Decision Tools

Dr Albert Daly, National Roads Authority
Dr Alan O'Connor, Trinity College, Dublin

European Union
European Regional Development Fund
Investing in our common future
ATLANTIC AREA Transnational Programme

Activity 2

Maintenance, repair and decision tools

- *Difference repair, maintenance strategies*
- Methodologies to support decisions on repair and maintenance
- Requirements for the optimisation of maintenance and repair

End-product

✓Web version
✓Printed version

Presentation layout

1. Problem definition
2. Probability-based maintenance optimisation
3. Case studies – Practical application
4. Conclusions

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5TH Transnational Workshop
Vigo, January 2011

1. Problem definition

EU GDP growth linked to Freight Growth

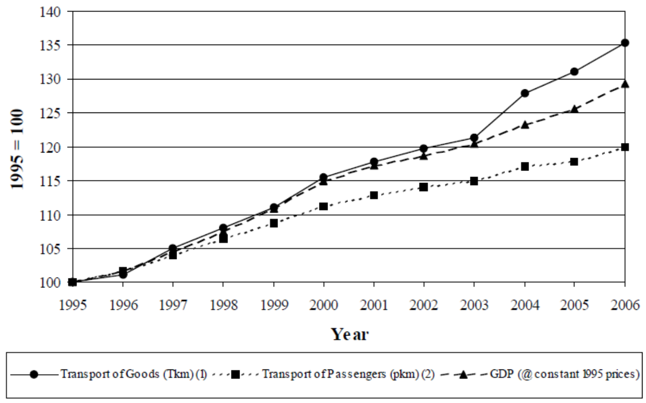

Figure 2 - Evolution of transport demand and GDP in the EU-25 for period 1995 – 2006 (Eurostat; DG Transport and Energy, 2008).

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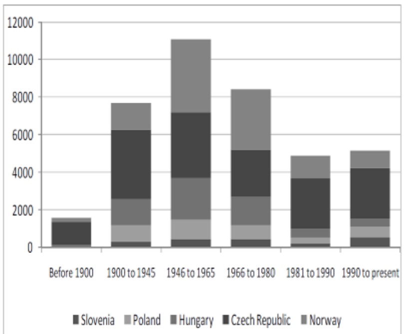
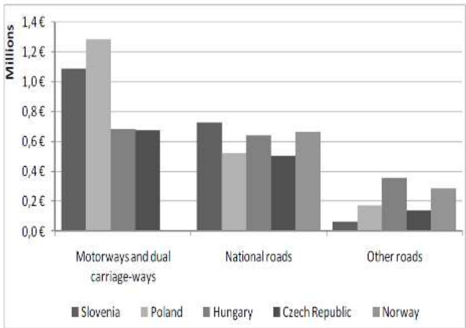
Transnational Programme

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

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

Storstroem 1937, 3.2km

2. Probability-based maintenance optimisation

Legal Basis – Eurocode 1 Basis of Design

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

EUROPEAN STANDARD | EN 1990
NORME EUROPÉENNE
EUROPÄISCHE NORM | 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

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.

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

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

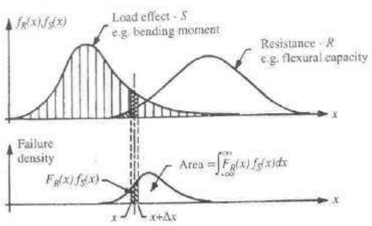
(7) For a particular verification load cases should be selected, identifying compatible load arrangements, sets of deformations and imperfections that should be considered simultaneously with fixed variable actions and permanent actions.

(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:

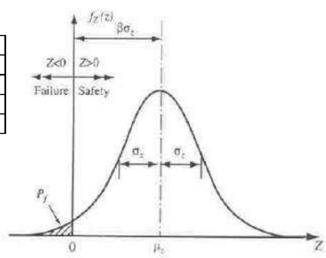
Cut strengthening or rehabilitation costs **without** compromising the safety level

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

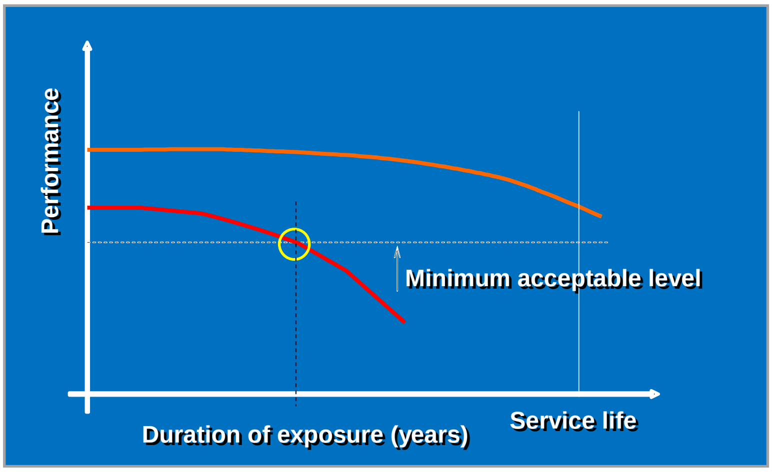
Reliability Class	Minimum values for β	
	1 year reference period	50 year reference period
CC3 (RC3)	5.2	4.3
CC2 (RC2)	4.7	3.8
CC1 (RC1)	4.2	3.3

B = 5.2 ➔ $p_f = 1.0 \times 10^{-7}$

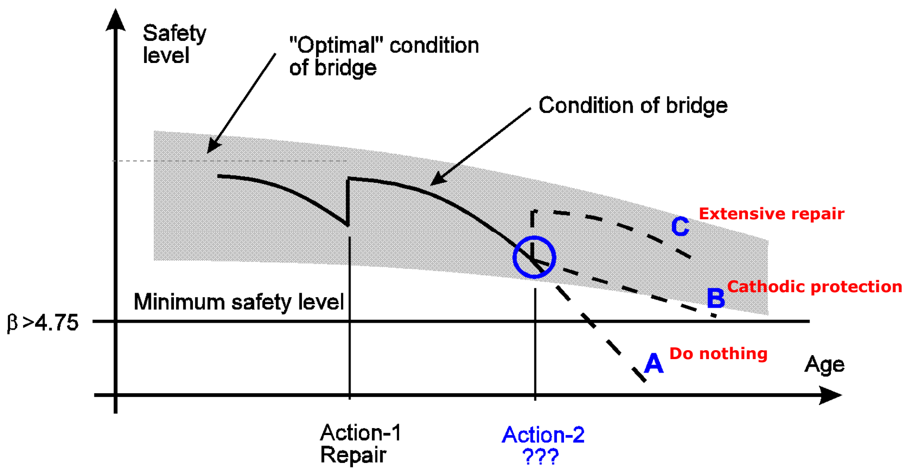
Essentially a bridge-specific "code" is obtained



Decision making process



Decision making process



3. Case Studies

(i) 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.

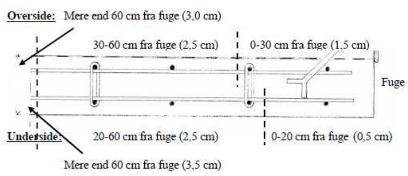
Storstrom Bridge: Results of Assessment

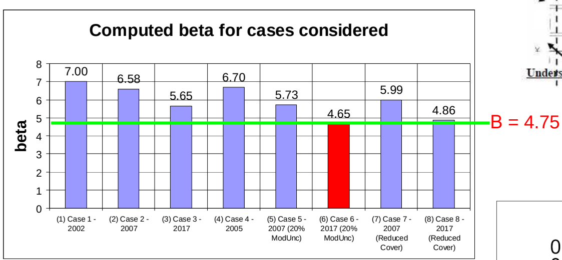
Deterministic assessment of the deck slab using PROCON for combined dead and live load produced a maximum load factor of 0.61. This implies that the slab is incapable of sustaining the applied load. The recommendation would therefore involve costly rehabilitation of the structure.

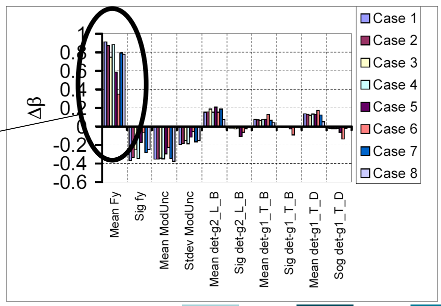
Probabilistic Assessment including deterioration modelling, with deterioration models updated based upon inspection results performed at the bridge could document sufficient capacity.

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





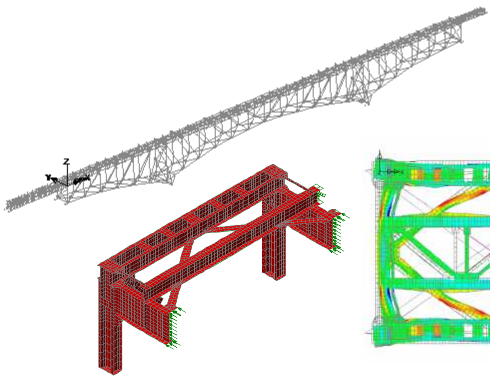


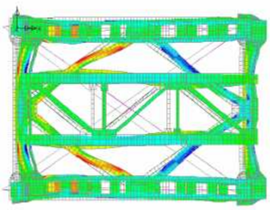
Updating of parameters through e.g. inspection results can reduce uncertainty and improve β, or vice versa (i.e. Intelligent Assessment, Structural Health Monitoring)

(ii) Bergeforsen Railway Bridge, Sweden

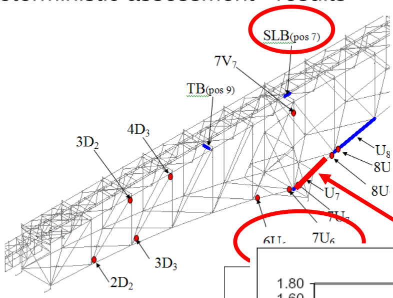
Bridge constructed in 1923
Superstructure span configuration: 42 + 84 + 42 = 168m
Side spans 22.5m + 11.6m
Total bridge length = 202.1m
Required to assess for **Heavier Trains**

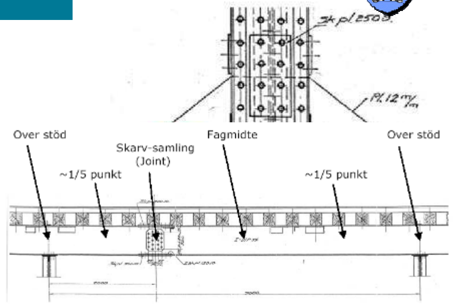
Structural analysis was performed using an FE model calibrated against a shell and volume element model constructed for specific critical locations.





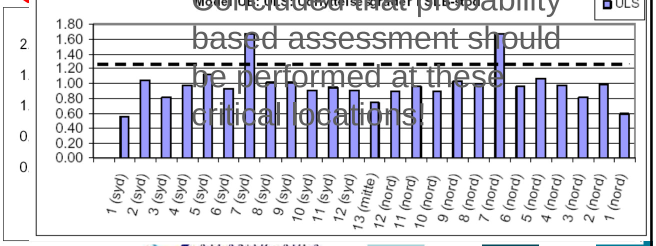
Deterministic assessment - results





Figur 6-1 Opstalt af DIP55-profiler.

(a) Connection 7-U_6



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

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

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

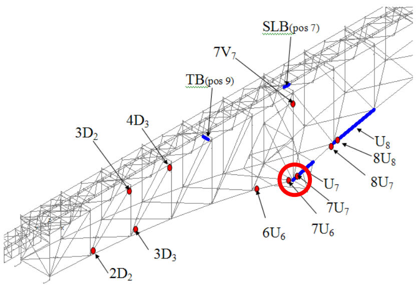
β_{7-V_7} = 6.31 > 4.8

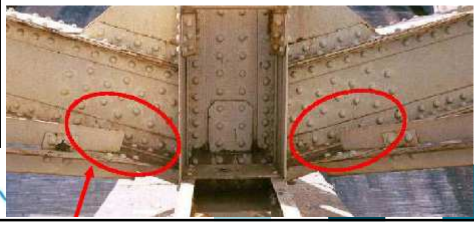
β_{2-D_2} = 4.42 < 4.8 (Remedial action necessary)

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





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,

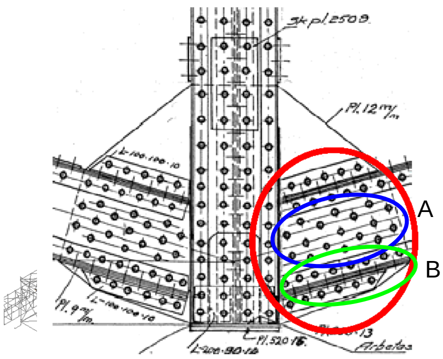
Proposal A β_{2-D_2} = 6.25)

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



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

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

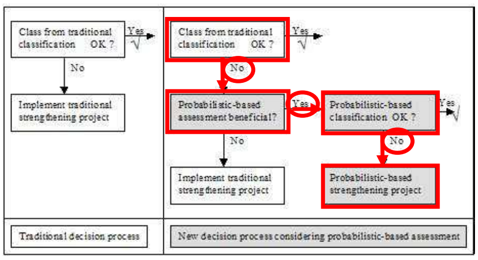
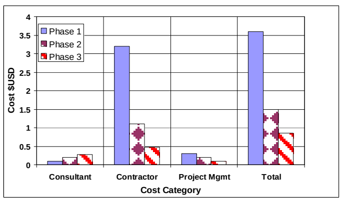


Table 7 - Results of deterministic and probabilistic assessment; O'Connor et al (2004).

	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



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

Actvity 7

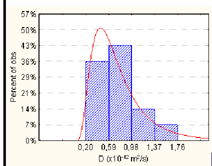
Case studies

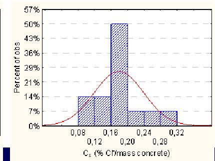
BARRA Bridge (Portugal)

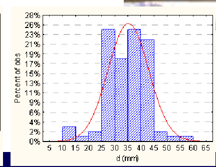
Ferrycarrig Bridge (Ireland)

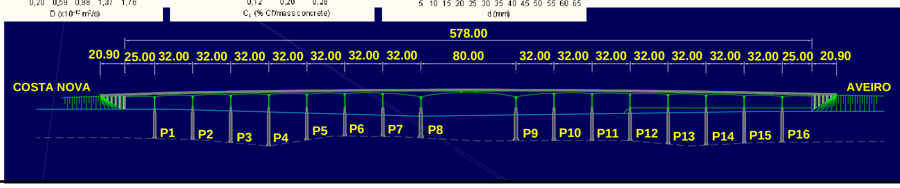
Barra Bridge

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









Ferrycarrig Bridge, Wexford, IRELAND

History of the structure:

- **Constructed 1980, 8 spans of 15.7m, carrying N11 over Slaney**
- **Principle Inspection carried out in 2002 using EIRSPAN procedures**
- **All components visually examined**
- **Structure in fair condition**

Except for…

- **Extensive cracking found in cross-heads and south abutment**
- **Crack widths up to 3.5mm**
- **Larger cracks at exposed end of cross-heads**
- **Cracking not attributed to any specific deterioration mechanism**

Ferrycarrig Bridge, Wexford, IRELAND

- Crosshead 1: OPC mix + standard formwork
  (standard repair - acted as control for other repair systems)
- Crosshead 2: as in Crosshead 1 + increased cover
  (to examine the benefits of increasing cover)
- Crosshead 3: as in Crosshead 1 + surface treatment
  (to examine the effect of surface impregnation)
- Crosshead 4: GGBS mix
  (use of ground granulated blast furnace slag as an addition to OPC to improve durability)
- Crosshead 5: as in crosshead 1 + mixed-in corrosion inhibitors
- Crosshead 6: same as Crosshead 4
- Crosshead 7: same as Crosshead 1

4. Conclusion

- Probabilistic approach provides a rational addition to the present approach to structural repair and management
- Case studies are presented to demonstrate to practical applications.
- In **NO** way has the safety of the structure been compromised.
- Justification provided from national codes and the Eurocodes.
- 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.

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Go raibh míle maith agat

Acknowledgements:

Alan O'Connor
TCD, Dublin

Rest of DuratiNET team