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Thoft-Christensen, Palle

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CHAPTER 95

ON INDUSTRIAL APPLICATION OF STRUCTURAL RELIABILITY THEORY[1]

P. Thoft-Christensen
Aalborg University, Aalborg, Denmark

INTRODUCTION

For the last two decades we have seen an increasing interest in applying structural reliability theory to many different industries. However, the number of real practical applications is much smaller than what one would expect. At the beginning most applications were in the design/analysis area especially for high-risk structures as used in the offshore and nuclear area. However, in many countries code calibration is now performed on a probabilistic basis. An important example is the new EUROCODE. A relatively new and very promising area for application is probabilistically based management systems for inspection and repair of structures, and for justification of the lifetime extension of structures.

This paper is mainly based on the ESReDA Working Group report [1] and the ESReDA seminar proceedings [2], and Thoft-Christensen [3].

1. ESReDA WORKING GROUP

In May 1995, ESReDA established a Working Group on *Industrial Application of Structural Reliability Theory*.

The aims and scope of the working group are:

- to promote industrial application of structural reliability theory in Europe,
- to advance European co-operation in the field of industrial application of structural reliability theory,
- to stimulate research and development of industrial application of structural reliability theory,

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[1] Proc. IFIP WG7.5 Conference on "Reliability and Optimization of Structural Systems", Krakow, Poland, May 1998, pp. 51-66.

- to further the dissemination and exchange of information on industrial application of structural reliability theory.

The Working Group published a report in October 1997 [1] and, also in October 1997, organised a seminar on "Industrial Application of Structural Reliability Theory" in Paris, France. During the seminar 18 papers were presented; see the proceedings [2].

2. NUCLEAR INSTALLATIONS

This section is based on Chapman, Pitner & Persoz [4], Morilhat [5], Brinkman [6], Cilik & Hrázký [7], and Baker & Chapman [8]. In these papers several important applications of structural reliability are presented:

- SRRA (Structural Reliability Risk Assessment)
- PRAISE (Piping Reliability Analysis Including Seismic Events)
- Probability of Failure and Fatigue Monitoring for Life Extension
- Maintenance Optimization and Life Prediction of Steam Generator Tube Bundle

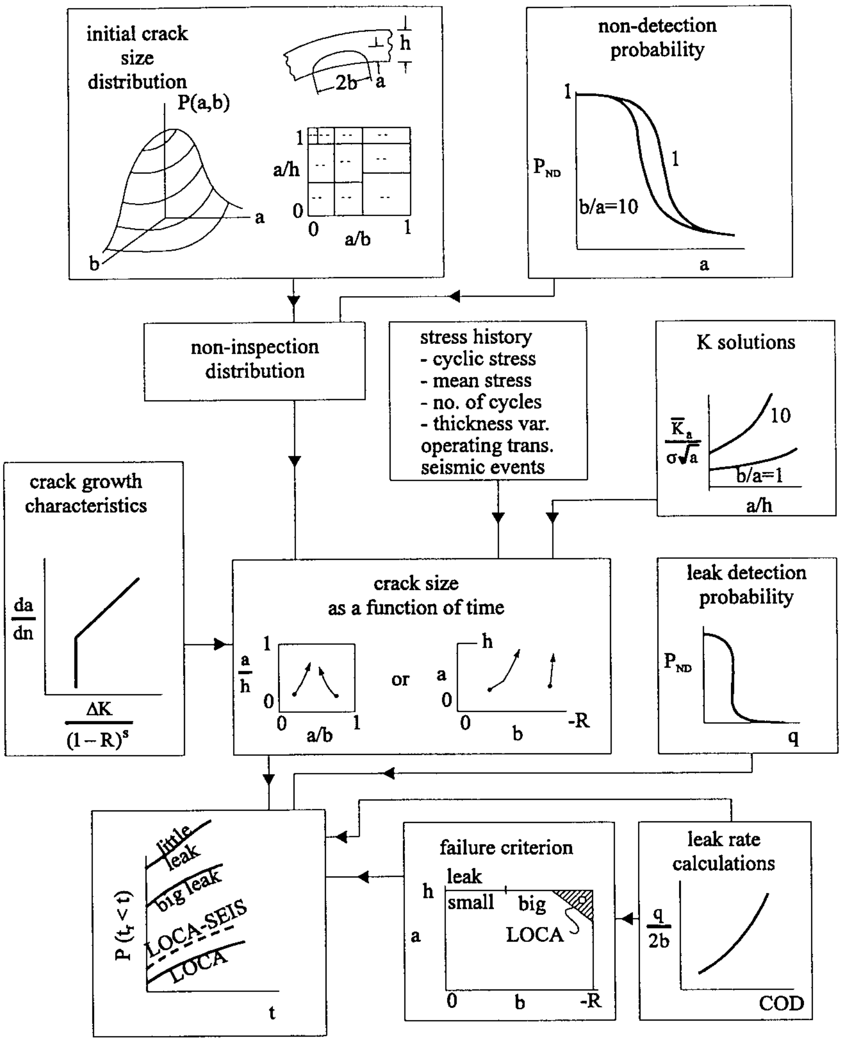


Figure 1. Schematic diagram of steps in analysis; PRAISE code (from [4]).

- In-Service Inspection as a Confidence Builder
- Integrity Analyses of Reactor Vessels
- Risk Based In-Service Inspection
- Failure Probability of Steam Line Components
- Failure Probability of Power Transformers
- LOCA (Lose of Coolant Accidents)
- Rupture Probability Calculation using Probabilistic Failure Mechanics
- Risk Based Optimization of In-Service Inspection
- Failure Probability Distributions for Pipe Welds

Probabilistically based structural integrity analysis has been used for many years in the nuclear industry. It started as early as 1980-81 with the computer code PRAISE (Piping Reliability Analysis Including Seismic Events) developed by the United States Nuclear Regulatory Commission. Later it was expanded to include stress corrosion cracking initiation and growth to failure, see figure 1. Since then, more similar codes have been developed. The basic principle in these codes is to use the deterministic equations and to apply statistical distributions to uncertain quantities. Thereby, instead of giving a single yes or no statement to any given failure criterion (the deterministic approach), the probabilistic approach provides a probability of that criterion being met.

A typical example on application of structural reliability theory within the nuclear industry is shown in figure 2. The probability of failure per year of a vessel is approximately 2.2×10^{-8} and is dominated by a circumferential weld. However, including the smaller details of the condensate will increase this very low probability of failure to 2.5×10^{-6}. The results of these assessments show that the probability of failure depends significantly on the vessel details.

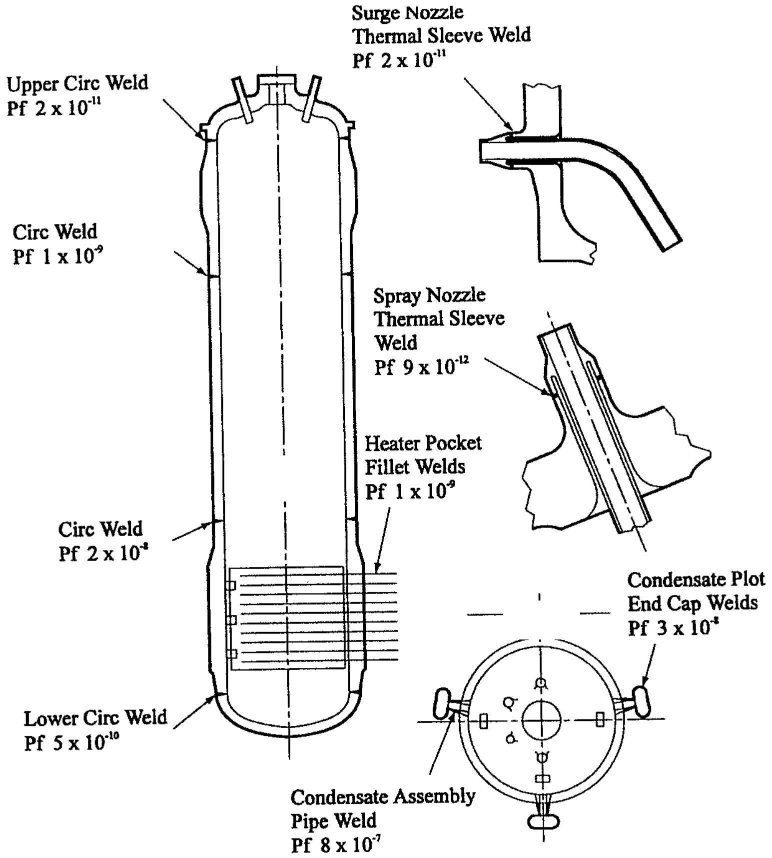


Figure 2. Evaluation of the probability of failure for vessel welds (from [4]).

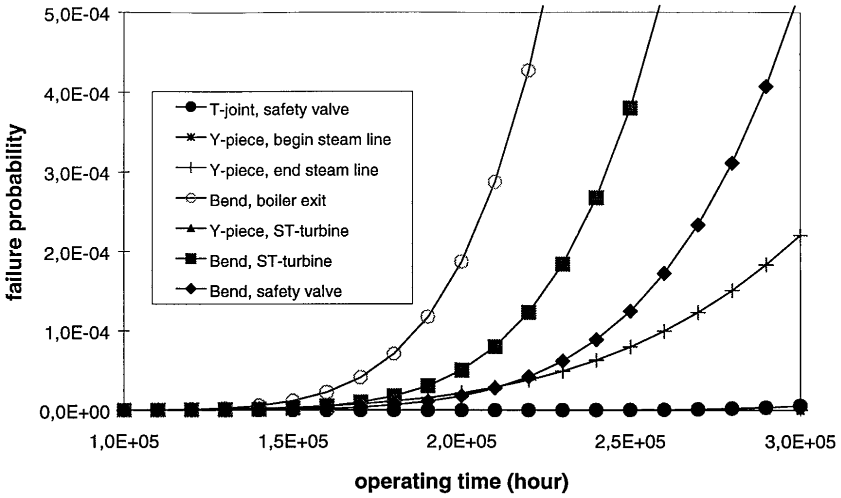


Figure 3. Failure probability as a function of operating time for steam components; $T = 549^{o}$C (from [6]).

Another example from this area is presented in figure 3, where the failure probability as a function of operating time for steam line components in a power plant is shown.

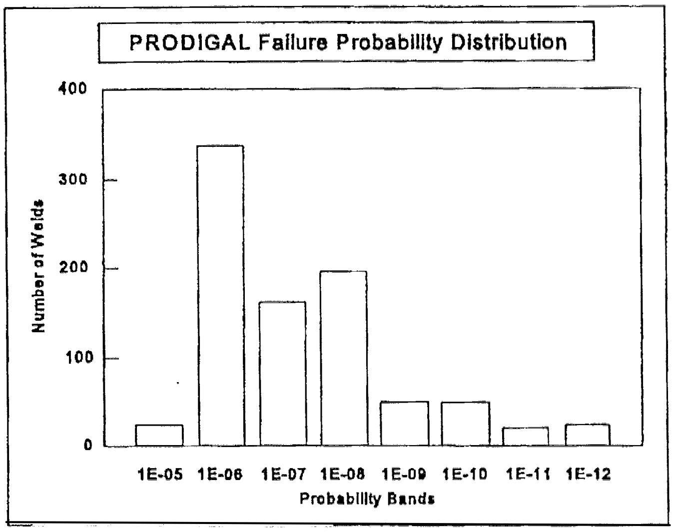


Figure 4. Typical pipe weld failure probability distribution (from [8]).

Rolls-Royce and Associates, UK has developed a probabilistically based fracture analysis computer software called PRODIGAL to enable individual, site specific, weld failure probabilities to be quantified. The distribution of failure probabilities for 877 pipe welds from a typical PWR plant using PRODIGAL is shown in figure 4.

3. OFFSHORE STRUCTURES

This section is based on Hagen & Mørk [9], Sigurdsson, Cramer & Hagen [10], Mørk [11], Sigurdsson [12] and Thoft-Christensen [13]. In these papers several important applications of structural reliability are presented:

- Probabilistic design of Offshore Structures
- Code Calibration
- Pipeline Free Span Design
- Design Guidelines
- Requalification of Offshore Platforms
- Decision Measures and Ranking of Alternatives
- Probabilistic Collapse Analysis of Jacket
- Reliability Based Optimization of Fire Protection.

Reliability based optimization of fire protection of offshore subsea pipelines are often installed in areas of irregular seabed topography and in deep water. Therefore, free spans in such pipeline systems may occur and submarine currents or wave induced flow velocities may cause significant dynamic excitation of the free span sections. Further, amplified response due to resonant fluid-structure interaction may cause fatigue damage.

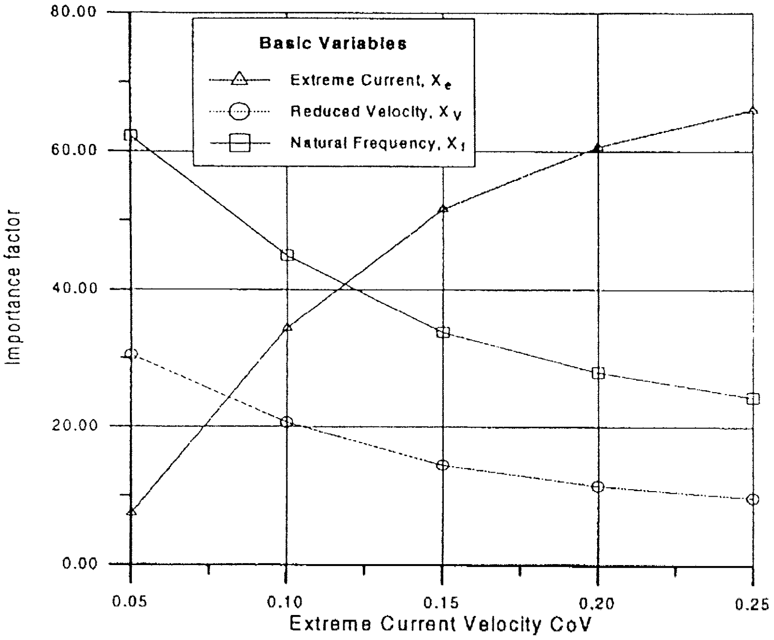


Figure 5. Onset criteria for cross-flow VIV. Importance factors for base case (from [9]).

Offshore subsea pipelines are often installed in areas of irregular seabed topography and in deep water. Therefore, free spans in such pipeline systems may occur and submarine currents or wave induced flow velocities may cause significant dynamic excitation of the free span sections. Further, amplified response due to resonant fluid-structure interaction may cause fatigue damage.

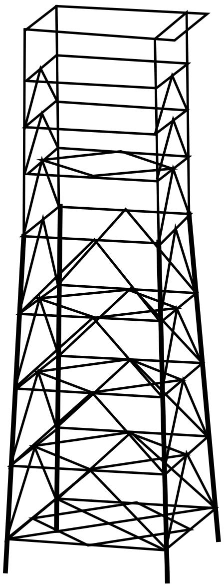
In 1994 the joint industry R&D MULTISPAN project was established by a number of companies and institutions to provide rational criteria for free spans. In figure 5 the importance factors from a calibration study are shown as functions of the extreme current variability corresponding to safety class Normal. In the new DNV Design Guidelines the safety factors shown in table 1 are recommended.

Table 8: Recommended safety factors

Safety Class	**Low** *Temporary*	**Normal** *in-service*	**High** *in-service*
γ_T	1.7	2.0	2.3

Table 1. Recommended safety factors in DNV'96 (from [9]).

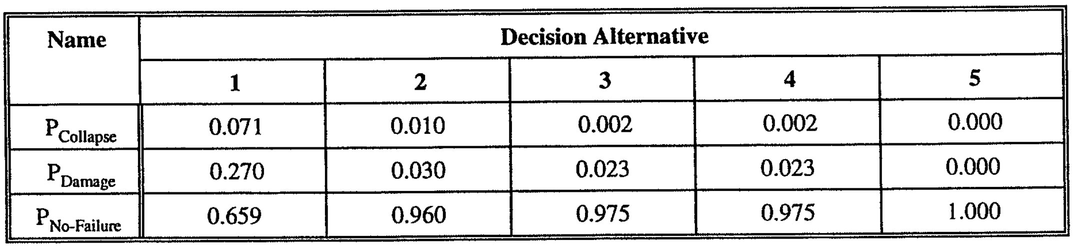
An important application of structural reliability theory in the offshore area is requalification of platforms. One of the objectives of a requalification is to establish that



the structure is fit for its purpose over the residual service life. The requalification procedure presented in reference [10] is illustrated for the jacket structure shown in figure 6.

The jacket was designed in the sixties on the basis of data which have been changed later. In reference [10] five requalification alternatives are defined. In brief, alternatives 1-4 are different modifications of the structure to reduce the loading and, except for alternative 3, demanning of the platform. Alternative 5 is platform elimination of the structure and replacing it by an underwater connection of the pipelines passing the platform. The probabilities of collapse, damage and no-failure are shown in table 3 for all five alternatives.

Fig. 6. Offshore jacket structure (from [4]).



Name	**Decision Alternative**				
	1	**2**	**3**	**4**	**5**
$P_{Collapse}$	0.071	0.010	0.002	0.002	0.000
P_{Damage}	0.270	0.030	0.023	0.023	0.000
$P_{No\text{-}Failure}$	0.659	0.960	0.975	0.975	1.000

Table 2. Annual occurrence probabilities for the five selected alternatives (from [10]).

A final example of application of structural reliability in offshore engineering is given in reference [13], where reliability based optimization of passive fire protection is discussed and software modules are developed.

4. BRIDGES AND TRANSPORTATION

This section is based on Thoft-Christensen & Middleton [14], Marty, Perroud & Farges [15], Das [16], Nowak, Szerszen & Park [17], and Middleton & Thoft-Christensen [18]. In these papers several important applications of structural reliability are presented:

- Reliability Assessment of Concrete Bridges
- Reliability Assessment of Steel Bridges
- Deterioration Modelling
- Reliability Based Bridge Management Systems
- Whole Life Assessment of Bridges
- Bridge Load Models
- Reliability Assessment of Mechanical Car Components
- Assessment of Suspension Arms

Several highway authorities have identified the potential for applying reliability based methods for assessing existing bridges, see reference [16]. For bridge management purposes it is important to know the performance of a bridge in future years under different maintenance regimes. Therefore, whole life assessment rules are being developed. Reliability analysis is being extensively used to develop these rules, see figure 7.

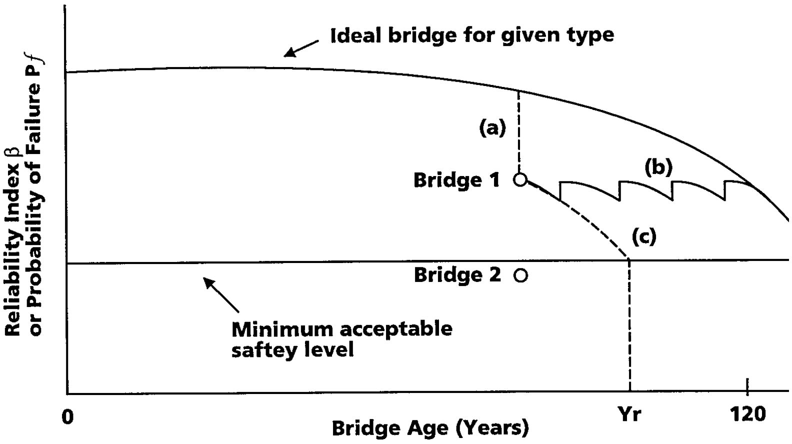


Figure 7. Whole life assessment rules (from [16]).

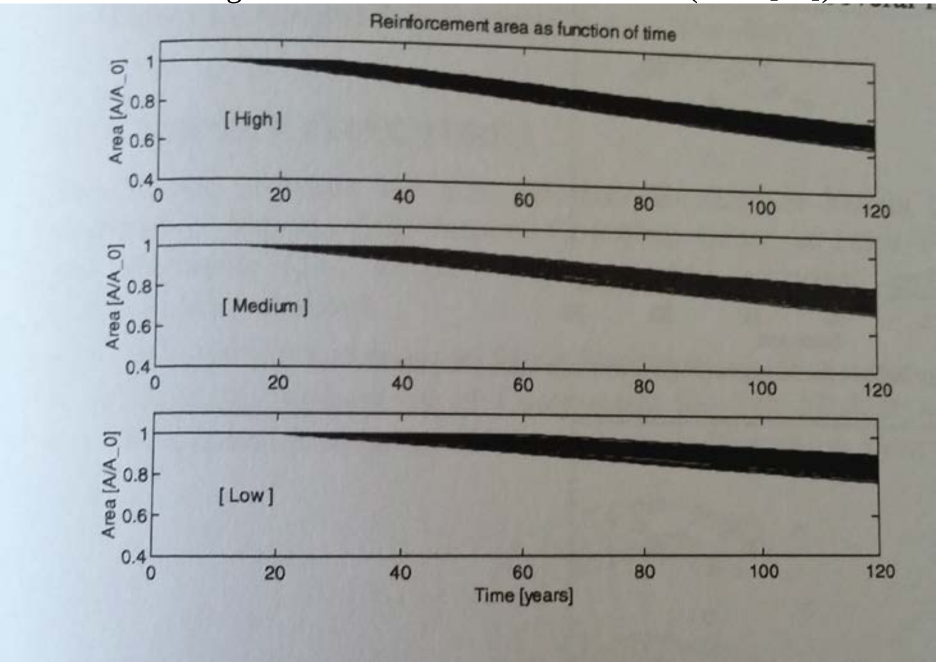


Figure 8. Normalised reinforcement area A / A_0 as a function of time for low, medium, and high deterioration (from [14]).

One study is the development of reliability based codes of practice for the structural analysis of bridges. The goal is to develop a methodology with which e.g. a typical short span concrete bridge could be realistically assessed, taking into account the age of the structure and different levels of deterioration. Several models can be used to model the deterioration of reinforcement steel in concrete slabs. However, there seems to be a general agreement that a model based on Fick’s law of diffusion can be used satisfactorily in most cases.

In reference [14] three levels of deterioration are proposed: low deterioration, medium deterioration and high deterioration. In figure 8 the sample realisations of the history of the reinforcement area for deterioration models low, medium, high are shown for a specific case. The following example is used to illustrate the applied methodology.

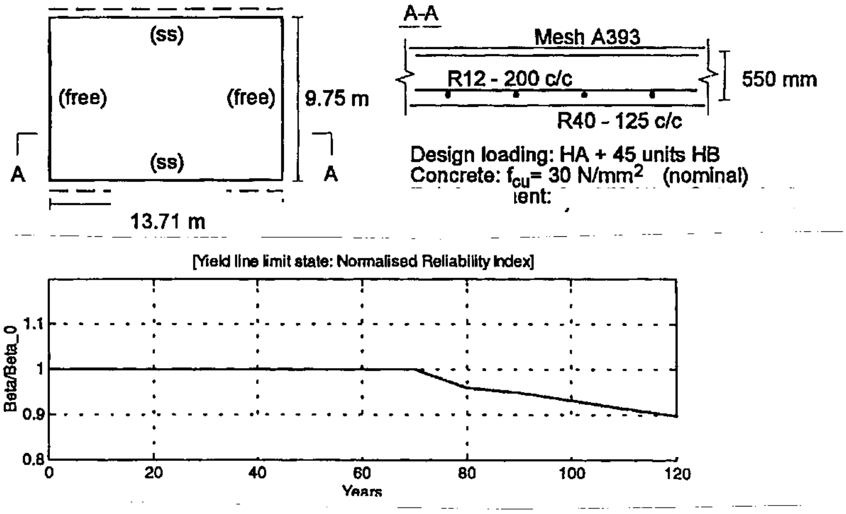
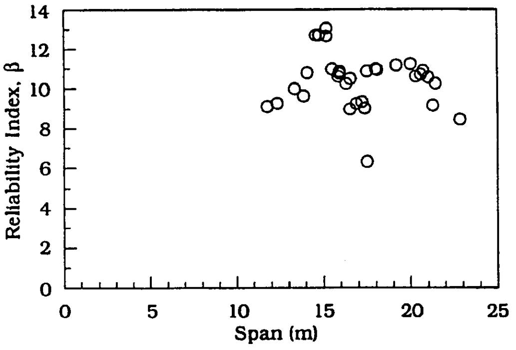
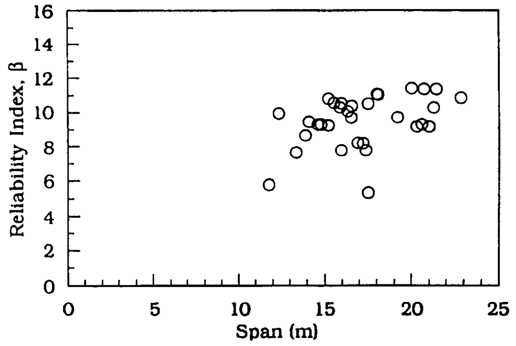


Figure 9. Bridge data and reliability assessment (from [14]).

Reliability analysis of steel bridges has been discussed in reference [17] for bending moment and shear failure, se figure 10.



. Reliability Indices for Moment (High Corrosion after 120 years).



Reliability Indices for Shear (High Corrosion after 120 years).

Figure 10. Reliability indices for moment and shear (from [17]).

Deterministic and probabilistic ranking of six concrete bridges has been compared in reference [18]. The result of the investigation is that there is very little difference in using deterministic and probabilistic ranking, see table 3.

Bridge No.	**Factor of safety (Deterministic)**	**Reliability Index**	**No.of stochastic variables**
1	1.41	3.65	14 b.v.'s*
2	1.42	3.72	22 b.v.'s
3	1.54	4.21	19 b.v.'s
4	1.4.8	5.66	30 b.v.'s
5	1.74	5.87	14 b.v.'s
6	2.50	10.6	44 b.v.'s

*b.v. = basic variable

Table 3. Comparison of deterministic and probabilistic ranking of bridge safety (from [18]).

Structural reliability has been used extensively in the automobile industry. As an example, a suspension arm from the Peugeot 306 is discussed in reference [15], see figure 11. It is shown that the reliability of the suspension arm is so high that it can be made lighter or re-used on a heavier vehicle.

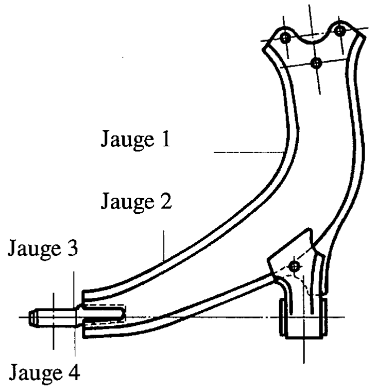


Figure 11. Peugeot 306 Suspension Arm (from [15]).

5. AEROSPACE STRUCTURES

This section is based on A.M. Moreno-Gonzàlez & Martin [19], Gerez, Moreno-Gonzàlez & Maggio [20], Moreno-Gonzàlez, Gerez, & Perez-Torres [21], Klein [22] and Marchante [23]. In these papers several important applications of structural reliability are presented:

- Reliability Assessment of Space Structures
- Reliability Assessment of Components like Test Modules and Cardan Joints
- Risk Based Evaluation of Launch Vehicle Propulsion Systems

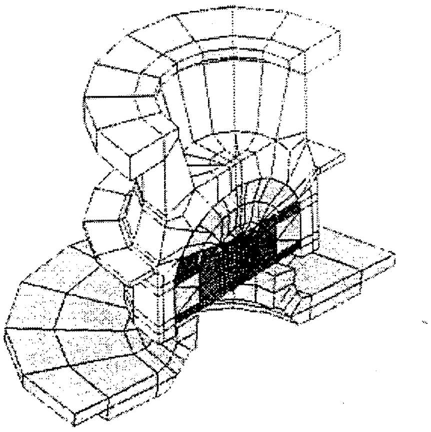


Figure 12. Cardan Joint Finite Element Model (from [19]).

- PRA (Probabilistic Risk Assessment) of Space Shuttle Subsystems like Power Units, Main Propulsion Pressurisation Systems and Catastrophic Failure Frequency
- Risk Analysis of Solid Rocket Booster
- Reliability Analysis of an Aluminum-Lithium Tank
- Assessment of Loads on Space Structures.

Probabilistic design is becoming the most common tool in space system design. As an example of a component used in spacecrafts, the reliability of a cardan joint is discussed in reference [19], see figure 12.

The overall cost of a launch system consists of several factors such as the expected potential due to catastrophic failure, the manufacturing costs, and the operational costs. The potential for catastrophic failure can be evaluated by a probabilistic risk assessment. In reference [20] the risk evaluation methodologies traditionally used in the aerospace industry are discussed and demonstrated on the US Space Shuttle. Traditional risk analysis was used in the early stages of the Shuttle project. Traditional risk analysis only gave a qualitative estimate of the risk of loss of mission and catastrophic loss of vehicle, and of the major single point failures in the propulsion system design. However, the Challenger accident made it clear that a quantitative risk analysis is needed. At that time Probabilistic Risk Assessment (PRA) was being extensively applied by the nuclear power industry to evaluate risk levels. The PRA methodology is a scenario-based technique which characterises accident sequences in an event tree format. Therefore, implementing a similar general strategy, the aerospace industry began applying PRA techniques to manned space vehicles. The capabilities of PRA clearly show that PRA has certain advantages over traditional reliability and safety analysis techniques.

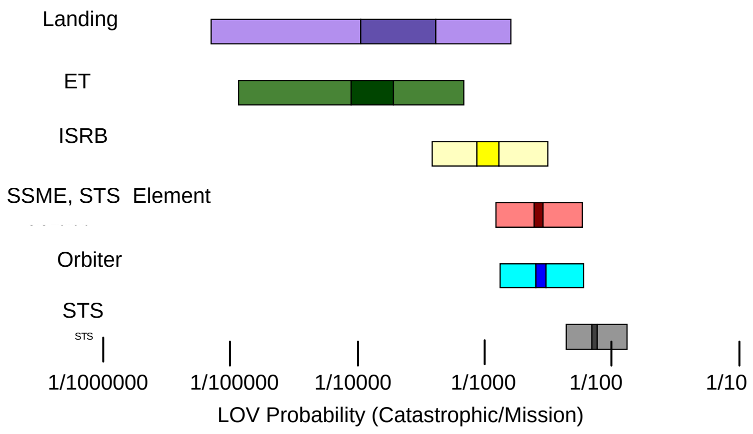


Fig. 13. LOV (Loss-of-Vehicle) risk uncertainty distributions for the total shuttle mission (from [20]).

Using importance analyses, the contribution of each system component to the vehicle loss frequency can be estimated. This can also be used to evaluate the risk reduction effectiveness of a proposed modification to components, equipment or subsystem of the Shuttle. Figure 15 shows the LOV (Loss Of Vehicle) risk uncertainty distributions for total Shuttle missions for each of the main subsystems (STS, Orbiter, SSME (Space Shuttle Main Engines), ISRB (Solid Rocket), ET (External Tank), and Landing).

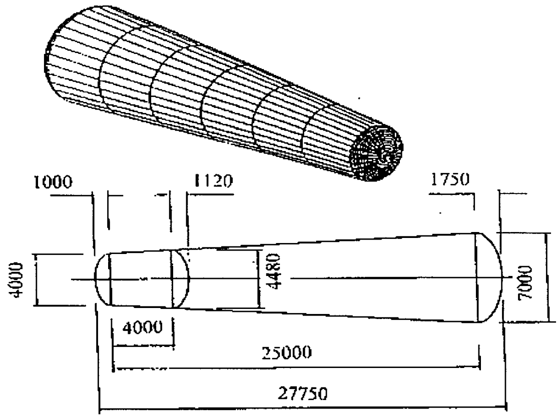


Figure 14. Reference Tank Geometry (from [21]).

To ensure safety of space missions without using excessively large structures requires the use of system reliability analysis techniques. In reference [21] a structural reliability analysis methodology and its application to the conceptual design of an Al-Li cryogenic tank as part of the Future European Space Transportation Investigations Programme (FESTIP) is presented, see figure 14. The failure modes used and the estimated failure probabilities are indicated in table 4.

Eq. no.	Zone	Failure probability	Description
1		$<1\times10^{-5}$	Stress waffle 5 (x direction). Top rib
2		$<1\times10^{-5}$	Stress waffle 5 (y direction). Skin
3	Waffle 5	0.0095	Buckling of ribs waffle 5 (x direction)
4		$<1\times10^{-5}$	Buckling of skin waffle 5 (x direction)
5		0.0038	Buckling of skin waffle 5 (y direction)
6	Dome	$<1\times10^{-5}$	Stress dome (x direction)
7		$<1\times10^{-5}$	Stress dome (y direction)
8	Weld	$<1\times10^{-5}$	Stress dome (x direction)
9		$<1\times10^{-5}$	Stress dome (y direction)
10	Ring	$<1\times10^{-5}$	Stress ring (x direction)
11		$<1\times10^{-5}$	Stress ring (y direction)

Table 4. Failure modes and failure probabilities (from [21]).

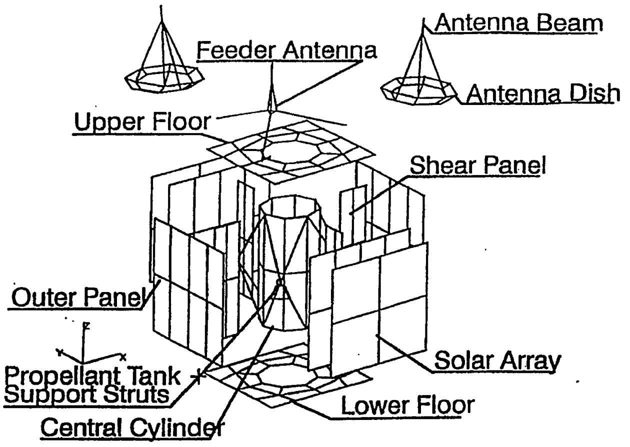


Figure 15. Telecommunication Satellite (from [22]).

A global overview of Scatter/Reliability in Spacecraft Structural Engineering is given in reference (22). In reference (22) materials, loads, safety factors and failure modes are presented in detail. Different fatigue and fracture approaches are also given. The scatter variables of a telecommunication satellite are obtained by Monte Carlo simulation.

6. HYDRAULIC STEEL STRUCTURES

This section is based on van Manen, A.C. Vrouwenvelder & van Foeken [24], López-Hernández, Diaz & Moreno-González [25], Vrijling & van Gelder [26], Nederend [28]. In these papers several important applications of structural reliability are presented:

- Probabilistic Design of Storm Surge Barrier
- Design Codes for Hydraulic Structures
- Reliability Assessment of Dams
- Failure Analysis of Dams
- Reliability Analysis of Breakwaters
- Lifetime Analysis of Breakwaters

Application of structural reliability theory in the design and assessment of hydraulic engineering structures and flood defense works in the Netherlands was enhanced during the damming of the Eastern Scheldt. Advanced techniques to assess the structural reliability were used during the design stage as well as during construction of the Eastern Scheldt Storm Surge Barrier; see figure 16.

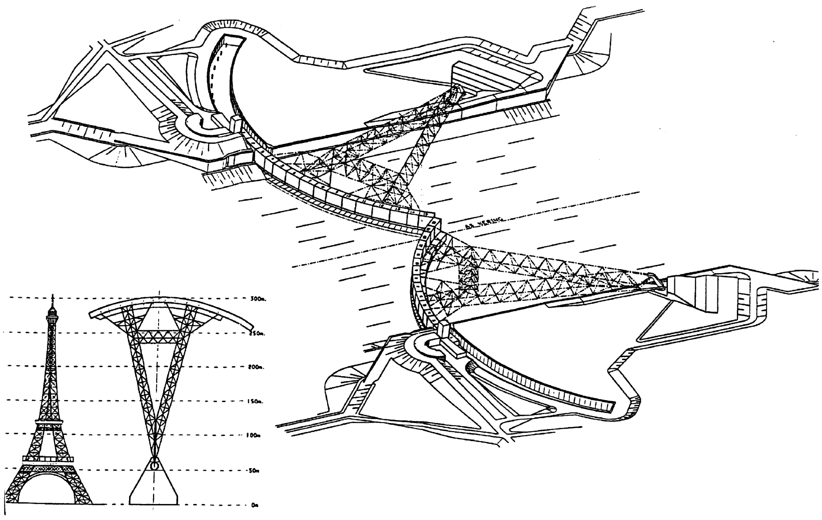


Figure 16**.** Storm Surge Barrier in the New Waterway near Rotterdam (from [24]).

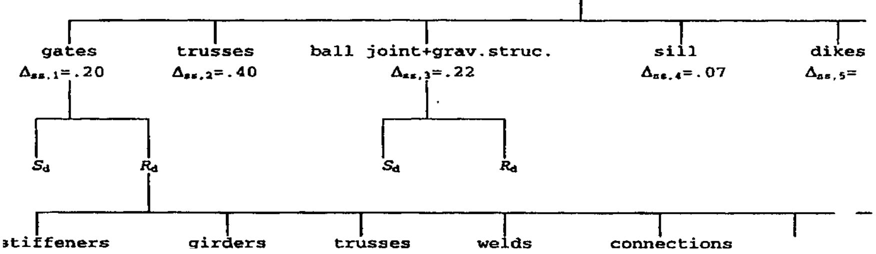


Fig. 17. Distribution of failure probability to substructure and the design point approach for some substructures (from [24]).

A target failure probability of 10^{-6} per year for the main event "failure of the barrier" was chosen. The target failure probability was then split up into target reliabilities for the different substructures by using the following equation

$$\Phi\left(-\beta_{\mathrm{ss}}\right) = \Phi\left(-\beta_{\mathrm{barrier}}\right)\ \Delta_{\mathrm{ss},i}$$

Correlation between substructures is neglected. The value of $\Delta_{\mathrm{ss},i}$ has been defined by the structural engineer (designer) for each substructure and varies between zero and one. A part of the adopted distribution is shown in figure 17.

Analysis of the reliability of dams is performed to quantify the frequency of possible failures of the dams. Risk analysis is performed to evaluate the potential consequences of risks. Failures are grouped according to type of dam, height and type of foundation and are analysed in terms of the source of the information, type of degradation, time of failure relative to the age of the dam, methods used to evaluate the damage and the corrective measures taken, see reference (25). As mentioned, the purpose of the reliability study of a dam is to perform a quantitative evaluation of dam safety in terms of failure probability expressed as failures/year. Therefore, the first step is to identify possible causes of dam failure. The required data include the type of dam, characteristics of the floodplain and terrain, and the existence or not of dams further upstream. The next step is to quantify the possibility of occurrence. The global failure probability is then obtained from the failure probability for each individual cause of failure. The most commonly used approach is based on the collection of experimental data on dam behaviour, e.g. the ICOLD database. The failure is then analysed in terms of the source of the information, type of degradation, time of failure relative to the age of the dam, methods used to evaluate the damage and the corrective measures taken. This database was used to evaluate the failure probability of the dams discussed in this document. The annual frequencies of failure were obtained for the three Spanish dams considered in reference [25] are shown in table 5.

	Annual frequency of failure (incidents/year)
Entrepeñas	2.09×10^{-6}
Buendía	2.16×10^{-6}
Bolarque	5.79×10^{-6}

Table 5. Annual frequency of failure (from [25]).

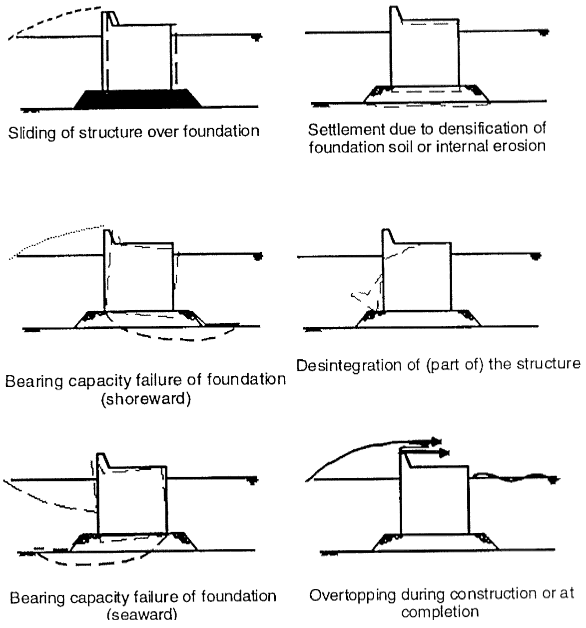


Figure 18. Overview of failure modes for vertical breakwaters (from [26]).

Vertical breakwaters are used to protect harbour basins against wave action. The most important failure modes for a breakwater are shown in figure 18, see reference [26]. When studying the probabilistic design of breakwaters it is important to discern between inherent uncertainty (randomness) and uncertainty related to the lack of information (statistical and model uncertainty). In reference [26] these uncertainties and human errors and their effect on the lifetime reliability are described.

7. FATIGUE ASSESSMENT

This section is based on Solomos [28] and Sigurdsson, Cramer & Lotsberg [29]. In these papers several important applications of structural reliability are presented:

- S-N Fatigue Modelling
- Fatigue Crack Growth
- Modelling
- Fracture Mechanics Approach
- Fatigue assessment of Aluminium Alloy
- Inspection Updating
- Application to offshore Jackets

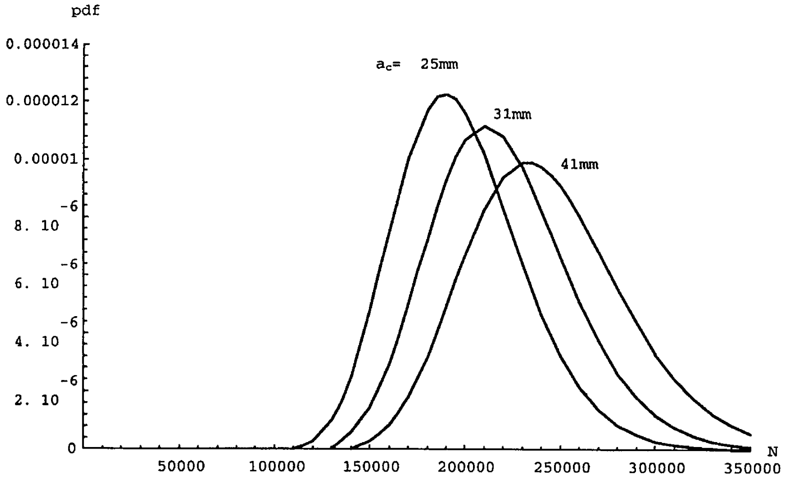
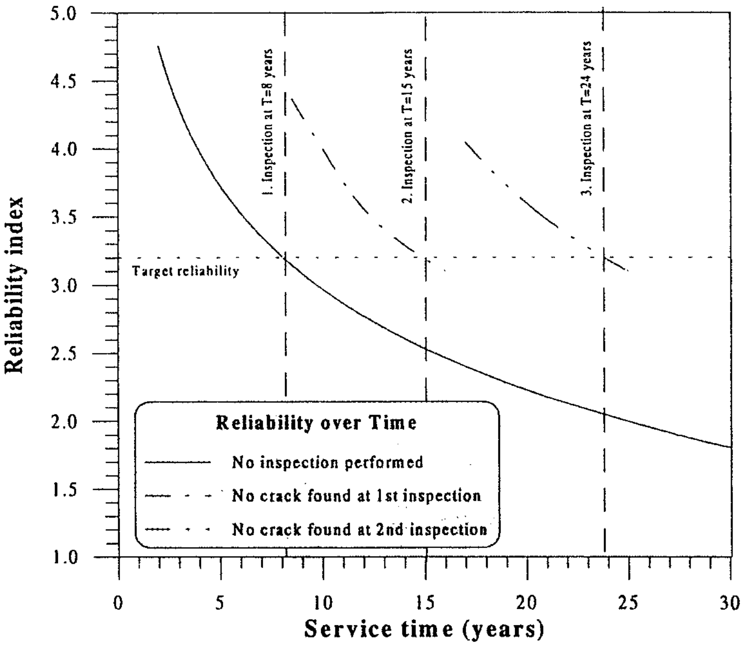


Figure 19. Analytical probability distribution of first-passage time for several critical crack sizes (from [28]).

A Markov model for fatigue crack growth and its application on specimens of T2024-T3 aluminium alloy has been investigated in reference [28]. Analytical probability distributions of crack size level and analytical survival probability curves for critical crack sizes have been developed. Further, probability distributions of first-passage time have been estimated for several critical crack sizes are estimated, see figure 19.



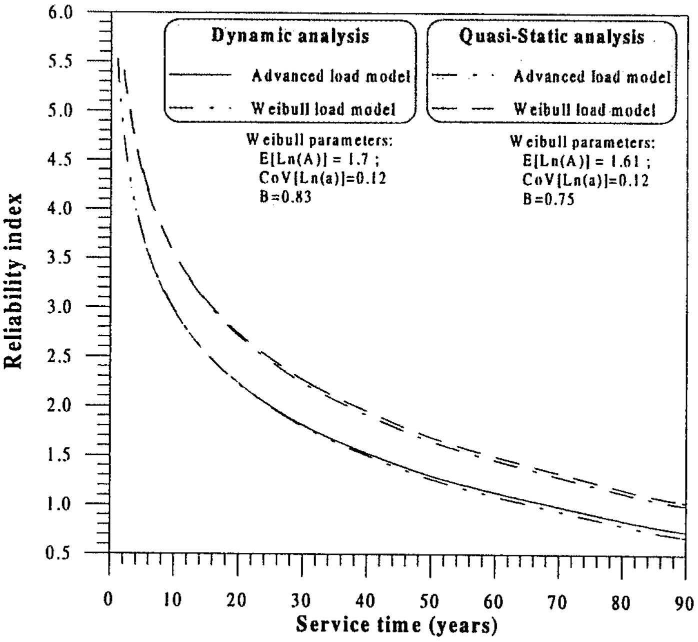


Figure 20. Estimated S-N fatigue reliability of the critical joint and estimated updated fatigue reliability having inspections with no crack detection as functions of the service time (from [29]).

In reference [29] an example of the fatigue assessment of an eight-legged North Sea jacket structure located at 107 m water depth is presented. The analysis is a level III reliability analysis, where the joint probability distribution of the uncertainty parameters is applied in the computation of the estimated fatigue failure probabilities. The assessment of the reliability and the updated reliability having inspections is shown in figure 20.

8. ENERGY

This section is based on Lassen [30], Dimou, Koumousis & Solomos [31], and Hopkins [32]. In these papers several important applications of structural reliability are presented:

- Reliability Based Inspection Strategies for Gas Turbine Engine Components
- Optimization of Expected Life Cycle Costs
- Cost Minimisation for an Aero engine Compressor Disc
- Reliability Based Optimal Design of Wind Mill Towers
- Reliability Analysis of Tower Shells
- Limit State Design of Transmission Pipelines
- Interactive Maintenance Strategy for Pipelines

Analysis and inspection cost minimization are carried out in reference [30] on an AM-355 martensitic stainless compressor disc from a military aero engine. These discs are vulnerable to fatigue damage due to cracks which initiate at the tie bolt holes. The cumulative probability of disfunction has been assessed as a function of service and for different numbers of inspections, see figure 21.

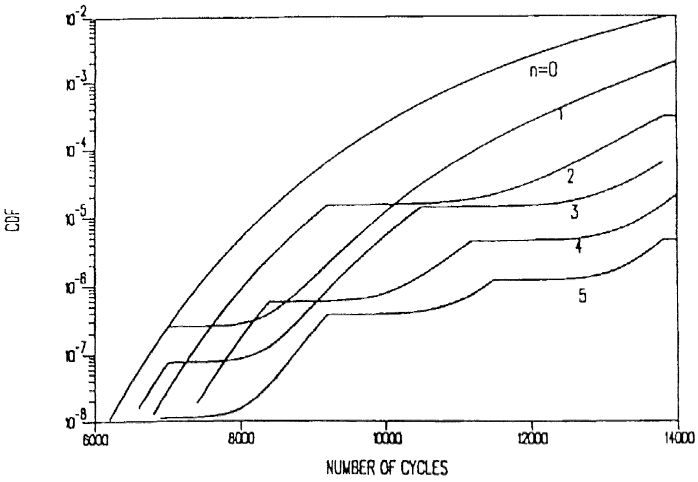


Figure 21. Cumulative probability of disfunction as a function of service life. Effect of ECI with different number of inspections n (from [30]).

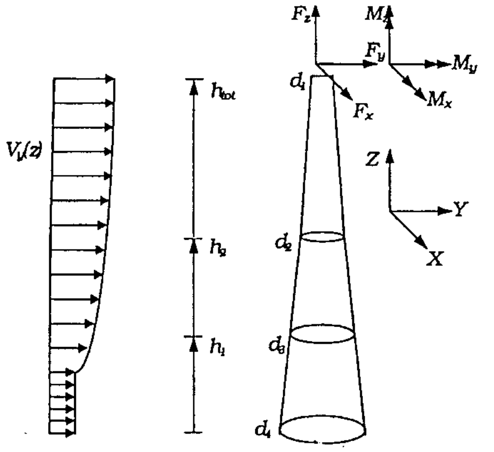


Figure 22. Schematic presentation of the loads on the structure (from[31]).

Reliability based optimal design of wind mill towers has been studied in reference [31]. A new approach is proposed for the evaluation of the reliability indices of the tower segments using the theory of random fields. The optimal design formulation is formulated as a non-linear mathematical programming problem. Ultimate stress and buckling stress constraints and their respective reliability indices are considered in all critical sections of the tower segments.

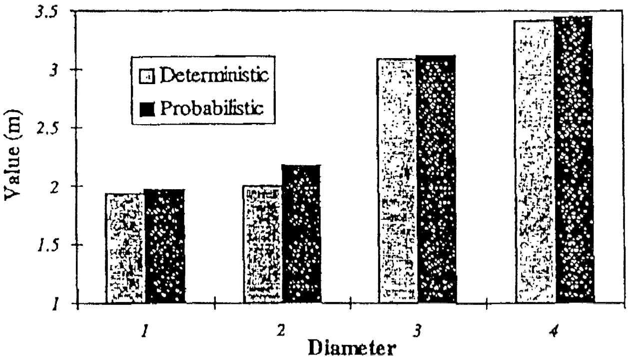


Figure 23. Comparison of optimal diameter results for the minimum cost design problem (from [31]).

The consequence of the introduction of the probabilistic constraints is studied, see figure 23. It can be seen that the introduction of the probabilistic constraints penalises the optimal output from the analysis.

The practical application of structural reliability theory and limit state design concepts to new and in-service transmission pipelines has been investigated in reference [32]. The overall framework for updating a pipeline using structural reliability theory is shown in figure 24. The framework accommodates all engineering aspects of the uprating, ranging from consideration of increased compressor capacity (or pumps) to checks of the suitability of valves at the uprated pressures. In the paper a proposed maintenance strategy is shown. The strategy allows a total control of performance of a pipeline, and the number of failure can be controlled accordingly.

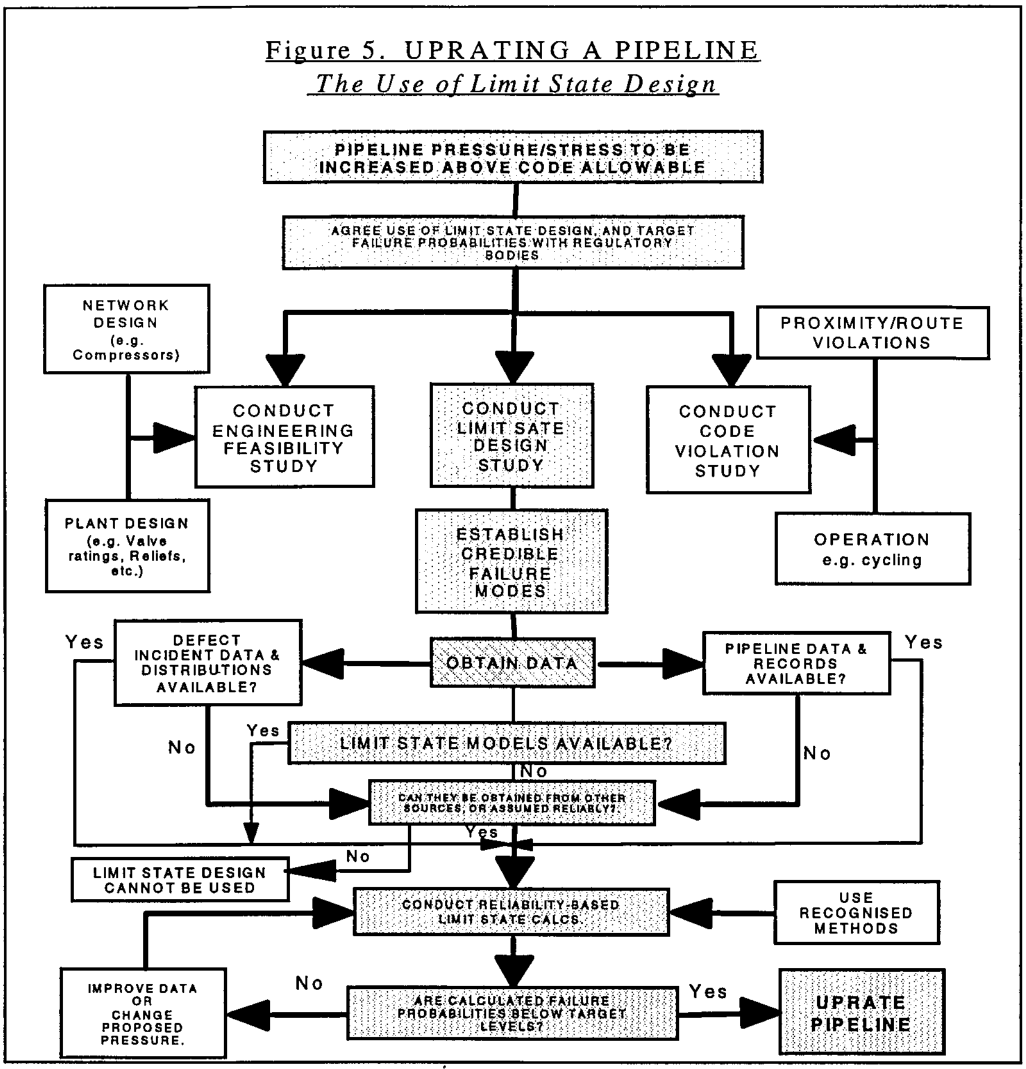


Figure 24. Updating of a pipeline (from [32]).

9. CONCLUSION

In this paper it is shown that modern structural reliability theory is being successfully applied to a number of different industries. This review of papers is in no way complete. In the literature there is a large number of similar applications and also application not touched on in this presentation.

There has been some concern among scientists from this area that structural reliability theory is not being used by industry. It is probably correct that structural reliability theory is not being used by industry as much as it should be used. However, the work by the ESReDA Working Group clearly shows the very wide application of structural reliability theory by many different industries. One must also have in mind that industry often is reluctant to publish data related to safety and reliability.

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