State of the Art of Methodologies for Safety Assessment of Aging Structures

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Abstract

The assessment of the safety of aging structures is mandatory to ensure appropriate operations of industrial systems. The needs of coherent and adapted methodology become more and more significant in various engineering fields, knowing the large number of equipment and their actual ages, on one hand, and the limitations of re-investment capacity, on the other hand. The project IMdR P10-2[1]: "Methodologies of safety assessment of aging structures – panorama and benchmarking", to which seven subscribers have participated: AMETHYSTE, BUTAGAZ, CETIM, EDF, INERIS, RTE and SNCF, has as an object to identify the existing scientific methodologies, which are applied in different industrial fields, in order to highlight the main concepts, and the requirements in terms of data and skills. For each family, the level of uncertainty control and the risk consideration are identified. A benchmark composed of three industrial examples (atmospheric tank, pressurized pipe and steel structure), based on real data, is established for comparison of the different methodologies, in terms of data acquisition, uncertainty analysis and risk consideration in managing and monitoring the state of the structures.

Keywords: Structural Safety, Ageing Structures, Risk Analysis, Risk-based Inspection, Degradation Models.

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1. Introduction

Due to significant accidents in the past decades, society evolutions and improved regulations regarding risk perception and management, the structure and industrial system managers have to pay attention to the health monitoring of the state of safety of systems for which they are responsible. The recent developments of various methodologies, more or less specific to the concerned industrial sectors, do not allow to have a consistent and complete view of the available methods and tools for the safety assessment of existing structures. This assessment requires the accurate knowledge of the state of the structure itself, its history, its environment and the possible internal and external evolutions with time. The relevance of the assessment cannot be possible unless a realistic representation of uncertainties and their effects on the state of the structures, the environment, the degradation mechanisms and the management system itself (i.e. inspection, monitoring, maintenance, repair and rehabilitation). In addition to diagnostic activities, allowing to assess the present state of the structure, the prognostic works aim at evaluating the degradation processes and the residual lifetime from the technical-economic point of view.

The managers need a methodology defining a general and systematic framework, to orient the activities toward the high-risk components , through the assessment of the failure modes, their occurrence probabilities and consequences, in a first step, and then through the integration of analysis and inspection results within the decision-making process, on the second time. The applied methodology should be also take benefits of the available feedback in technical databases, field and engineering experience (managers, engineers and operators) and risk assessment models, as well as the experiences in other industrial fields and consulting.

The goal of the assessment consists in providing the decision-maker with qualitative and quantitative information, which can be handled to improve the risk management. The assessment activities consist in the risk analysis, including hazard identification, the estimation of undesirable event occurrence probability and the evaluation of corresponding consequences, on one hand, and the risk assessment, including the specification of risk acceptability levels and the comparison of alternatives and options, on the other hand.

Whatever the applied methodology, the first step in the assessment consists in the inventory of the structural system and its representation in terms of sub-systems, structure units, components and elements. The assessment starts from the lowest level, i.e. element level, and the aggregation allows us to constitute the higher levels. In order to focus on critical components, it is usually recommended to proceed in two steps : a first step of quick survey, often visually or based on feedback analysis, of the general state of components, and a second step of deep analysis oriented to critical components that have been identified in the first step.

In this framework, the project described herein aims at identifying the applied methodologies in different industrial fields, at describing the fundamental concepts, the application conditions, advantages and limitations. It also aimed at proposing some improvement activities and links between existing methodologies. A benchmark constituted of three industrial examples has been established in order to allow for comparison of various methodologies, in teems of data, uncertainty considerations and risk assessment.

2. Risk management

The safety assessment is a technical and scientific process allowing to model and to quantify the risks related to predefined situations. The risk assessment aims at answering three questions: what could go wrong? What is its likelihood? What are the consequences? The risk management can be achieved by monitoring and appropriate decision-making. The risk communication should be adapted to the audience: medias, public, politicians, technicians and scientists.

The safety assessment of structures aims to:
- maintain the integrity of the asset and it function;
- improve and maintain its reliability;
- maintain the safety of working space and the affected zone;
- optimize the availability and more generally the performance and the service;
- ensure the serviceability conditions;
- reduce the investment and intervention costs.

The risk management includes all the processes allowing operators, managers and owners to make decisions for safety, modify regulations and choose system configurations on the basis of assessment results in order to maintain safety and to better control the possible risks (Lannoy et al., 2005). The risk management facilitates the decision-making on the basis of safety assessment, in addition to other factors: economic, social, political, environmental, legislative, reliability, productivity and security. Noting that such an assessment is not only useful for safety, as it provides also various information to optimize the industrial performance in terms of availability and cost reduction.

The international norm ISO 31000 (ISO 31000) defines the risk management process according to five main steps (figure 1):
1. Establishment of the context and definition of the system;
2. Identification of risks (hazards, uncertainties and consequences);
3. Risk analysis (requirements, capacities, likelihood, consequences, measures);
4. Risk assessment;
5. Risk treatment (mitigation, elimination, transfer)

There steps should interact with expert opinions, consulting and communication, on one hand, and are subjected to regular monitoring and revision procedures, on the other hand.

To perform risk analysis, it is necessary to:
- identify the internal and external hazards;
- evaluate its frequency;
- evaluate the consequences;
- evaluate the risk;

- identify the preventive and corrective actions,
- evaluate their efficiency
- make decisions and control the monitoring of actions, in addition to feedback development and enhancement.

Different steps should also be considered to determine the risk acceptability: define the alternatives or options, specify the objectives and the efficiency measurements, identify the consequences of alternatives, quantify the values of consequences, and evaluate all the alternatives in order to allow for better choices and decisions.

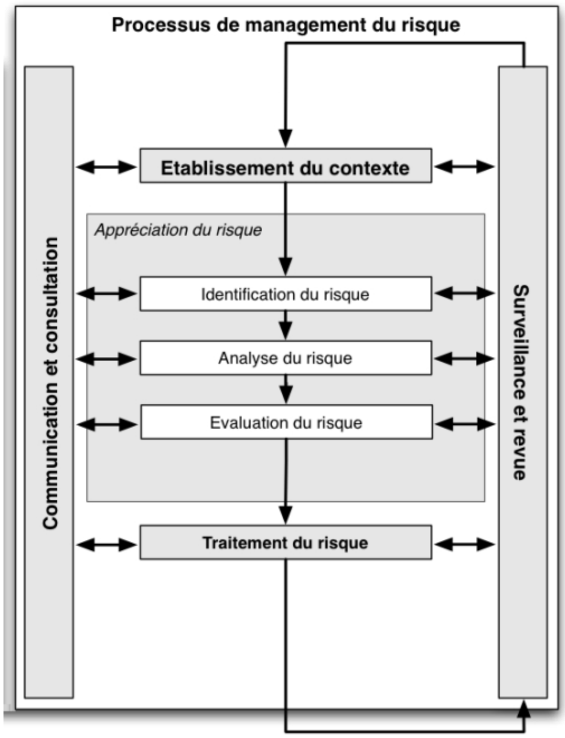

Figure 1. Process of risk management according to ISO 31000

The safety assessment should be observed regarding the considered goal among the four performance criteria:

- Serviceability (capacity to fulfil the required functions);
- Safety (absence of unexpected damage to persons, equipment's or environment);
- Durability (absence of unexpected performance degradation);
- Compatibility (fitting the requirements of the activity: industrial, regulations, governmental, social and environmental).

In general, the assessment methodologies can be either qualitative or quantitative. Although the qualitative methods use mainly the expert opinions to identify and evaluate the hazard probabilities and consequences, the quantitative methods are based on the statistical methods and the appropriate databases (Altenbach, 1995). The choice of a qualitative or quantitative approach depends on the availability of data and models for the hazard evaluation and the analysis tools available to the risk management team. However, it is to observe that the quantitative analysis should always be preceded by qualitative analysis, particularly to apprehend the context and to facilitate the physical understanding of the system.

3. Safety assessment of existing structures

The identified methodologies in this project are grouped into three categories:

- Condition-Based Methodologies (Faddoul et al., 2011), in which the assessment is carried out by attributing scores to the condition states relative to each component, during inspections or expertise. These scores allow us to valuate the health indexes of structures, components and elements, and therefore leading to appropriate rating of the structure and to prioritization of actions to be performed. This approach is rather deterministic and qualitative. It requires mainly simple observation data.
- Risk-Based Methodologies (API 581, 2008), in which the consequences and the failure probabilities are obtained through a referential specific to each industrial field, in order to assess the risk. The degradation phenomena and the inspection reliability are also taken into account in the risk assessment, and for the residual life estimation, in order to plan the inspections. This approach is semi-probabilistic, involving qualitative and quantitative procedures. It requires to build an appropriate database for the failure rates and the influence of various factors on the evolution of the state of the considered structure.
- Reliability-Based Methodologies (Ditlevsen et al. 2005; Aoues et al., 2013), in which the accurate analysis of structural reliability is performed with respect toe ach failure scenario at the present and predicted states; the random degradation phenomena are also considered in this analysis. The expected total life-cycle cost of the structure allows the optimization of the inspection and maintenance plan under budget and reliability constraints (Sahraoui et al., 2013). This approach is purely probabilistic and quantitative. It requires full statistical data on materials and state of the structure, in addition to precision mechanical behavior models.

The main steps of these methodologies will be shortly described in the following sections.

3.1. Condition-based methodology

The application of the condition-based methodology, based on the qualitative or quantitative guidelines, constitutes a simple procedure for the assessment of the general state of existing structures, by the mean of observation of its degradation level. The method is carried out according to the following steps (figure 2):

1. The decomposition of the structure in terms of structural units, components and elements. This inventory does not take account for logical, functional and mechanical relationships between elements, except the protection relationships against the environmental and mechanical aggressiveness;

2. Establishment of guidelines for element types, in which different types are described with their possible degradation mechanisms and defects ;
3. Establishment of guidelines for conditions states for each degradation mechanism. The qualitative and/or quantitative indications allows the inspectors to easily associate the and in the less variant way, the percentage of the element in each condition state;
4. Establishment of guideline for « critical findings » in order to cover the degradation mechanisms associated to local behavior, such as fatigue ; these findings induce alarms for the action prioritization;
5. The aggregation rules for various condition states are defined for each type of degradation, according to the obtained score (usually the maximum degradation score is considered, rather than the average one); This approach admits the same weighting for all the degradation mechanisms, and only the affected percentages determine the condition state of the element;
6. The assessment of the structure is based on the computation of a number of indexes (e. health index, rating index, sufficiency index, distress index, etc.)on the basis of the condition states of each type of degradation in each element of the structure, on one hand, and the other socio-economic parameters, on the other hand;
7. The prognostic of the future condition state is based on the Markov chain model using the transition matrices which are evaluated either by expert opinion elicitation, or by field feedback from the last inspections of the structure ; a guideline for the environment allows the calibration of the degradation rate according to the nature of the element protection ;
8. The prioritization of interventions is then established according to the structural indexes and the other associated economic parameters (e.g. loss of element value, costs of damage, repair, failure and rehabilitation, etc.).

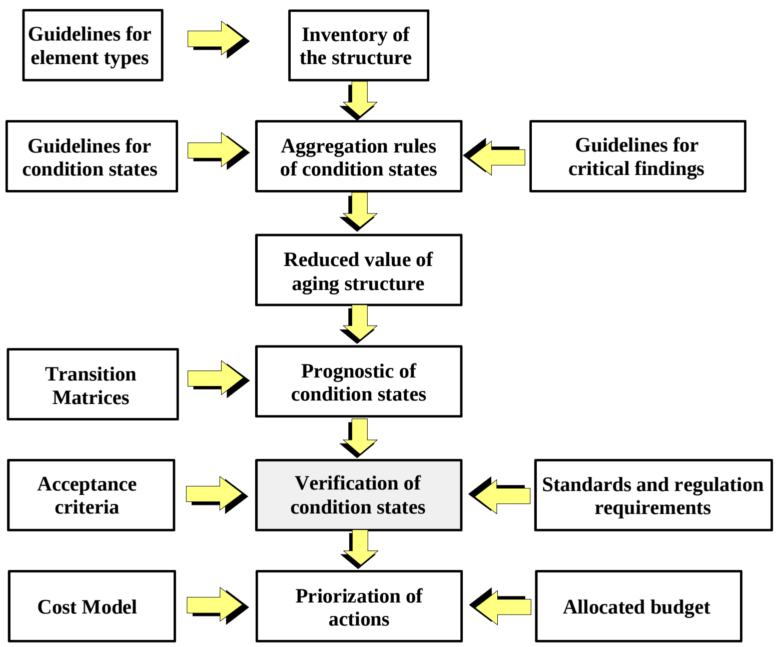

Figure.2. Flowchart of Condition-Based Methodology.

3.2. Risk-Based Methodology

This methodology consists in assessing the risks associated to each component and equipment, on one hand, and considering the results to define the frequency and quality of inspections, on the other hand. The following steps are applied (figure 3):

1. Selection of components, sub-systems and systems: this selection is based on the feedback and on the expert judgments, regarding the component to be considered and similar components. The grouping per element type or by degradation type can be very useful for the analysis. The rating according to the replacement cost can be performed in order to determine their relative importance;
2. Development of the consequence tree for each sub-system failure: the combination of feedback, engineering judgment and expert opinions allows us to define the failure consequences of sub-systems in terms of consequences associated to their constitutive components; The engineering judgments and experts opinions are often based on physical modeling when available, in order to estimation the failure consequences (e.g. diffusion of toxic gas, etc.). It is to note that the components do not contribute equally in the sub-system behavior. The classes of consequence costs are established in this approach.
3. Estimation of the failure probability for components: on the basis of experience feedback or subjective probability from expert (the qualitative approach is based on the approximation of physical and structural conditions of individual components, in order to attribute the failure probabilities); for each component, a probability is associated to the damage extent (and could be also related to its severity). When the logical representation as a « series system » is considered, the failure probability of subsystems is obtained by the maximum probability of its components ;
4. Computation of failure costs: the failure cost is estimated in terms of relative importance of components, the costs of maintenance and the damage level (direct and indirect costs of consequences). A metric should be defined for the contribution of each component in the total failure costs. For each consequence type, the failure cost of subsystem can be calculated by the weighted sum of costs associated to the constitutive components. The risk is then evaluated by the consequence costs and by the component importance, one hand, and by the corresponding failure probability, on the other hand.
5. Decision analysis: the above steps are performed for each subsystem of the structure and the system. The components are ranked according to their individual risk levels. The levels of accepted risk are defined by expert judgment and the results are represented in the risk matrix.

In this methodology, the risk estimation should be continuously updated according to monitoring results, influence, cost revision and experts' interventions. This updating allows also the refinement of the estimation of component failure probabilities and their impact on the structural integrity, and consequently the establishment of more precise planning of main inspections.

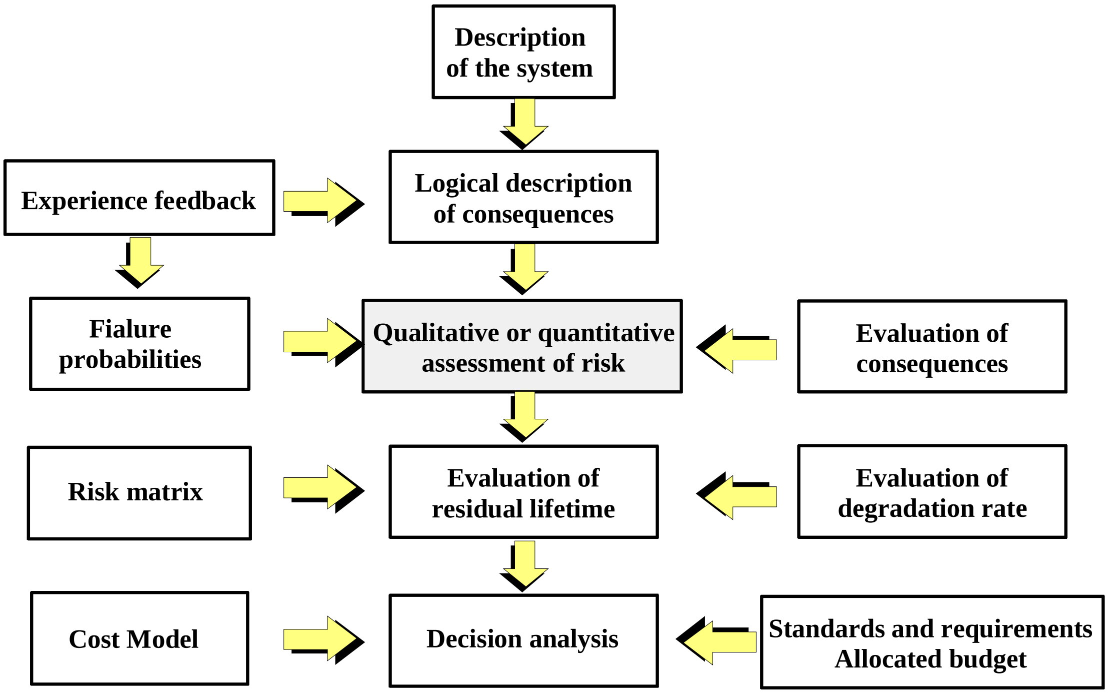

Figure 3. Flowchart of Risk-Based Methodology.

3.3. Reliability-Based Methodology

This methodology is based on the coupled reliability-mechanical modeling with sophisticated mechanical, logical and probabilistic behavior of the structure, completed by degradation and failure consequence analysis and cost formulation to define the utility function (Ellingwood 1996, JCSS 2001). This approach provides hence the largest and sophisticated framework for system representation, including its operation and environment. The main steps are as following (figure 4):

1. Identification of the structural system and establishment of the event tree ;
2. Quantitative analysis of the failure tree branches : the occurrence probabilities of the components are evaluated by the reliability methods based on the mechanical behavior, and the operating conditions are then identified;
3. Identification of hazards and logical description of the failure scenarios (as series and parallel systems) allowing the quantitative evaluation of the failure tree, where the experience feedback can also be used to update the information;
4. Quantitative evaluation of the probabilistic assessment of the residual lifetime distribution, and evaluation of consequences, of risk and of utility function ;
5. Probabilistic modeling of inspection results in order to take account for their precision and corresponding uncertainties ;
6. According to the available information on the residual lifetime, the computation of consequences and risks, the decision analysis is performed to define the intervention planning and the risk mitigation measures. The impact of these operations on the residual lifetime is reevaluated in order to improve the quality of intervention plan. The decision is based preferably on cost-benefits optimization, under reliability and risk constraints.

This methodology is fully quantitative and implies the use of physical and mechanical models for degradation and for the consideration of functional interdependence. The data related to the structure, the environment and the inspections are statistically considered and modeled by probability distributions which are used as input in the computation model. The qualitative information van is integrated by using Bayesian approaches to update the quantitative data. The risk is quantitatively evaluated without any particular reference grid.

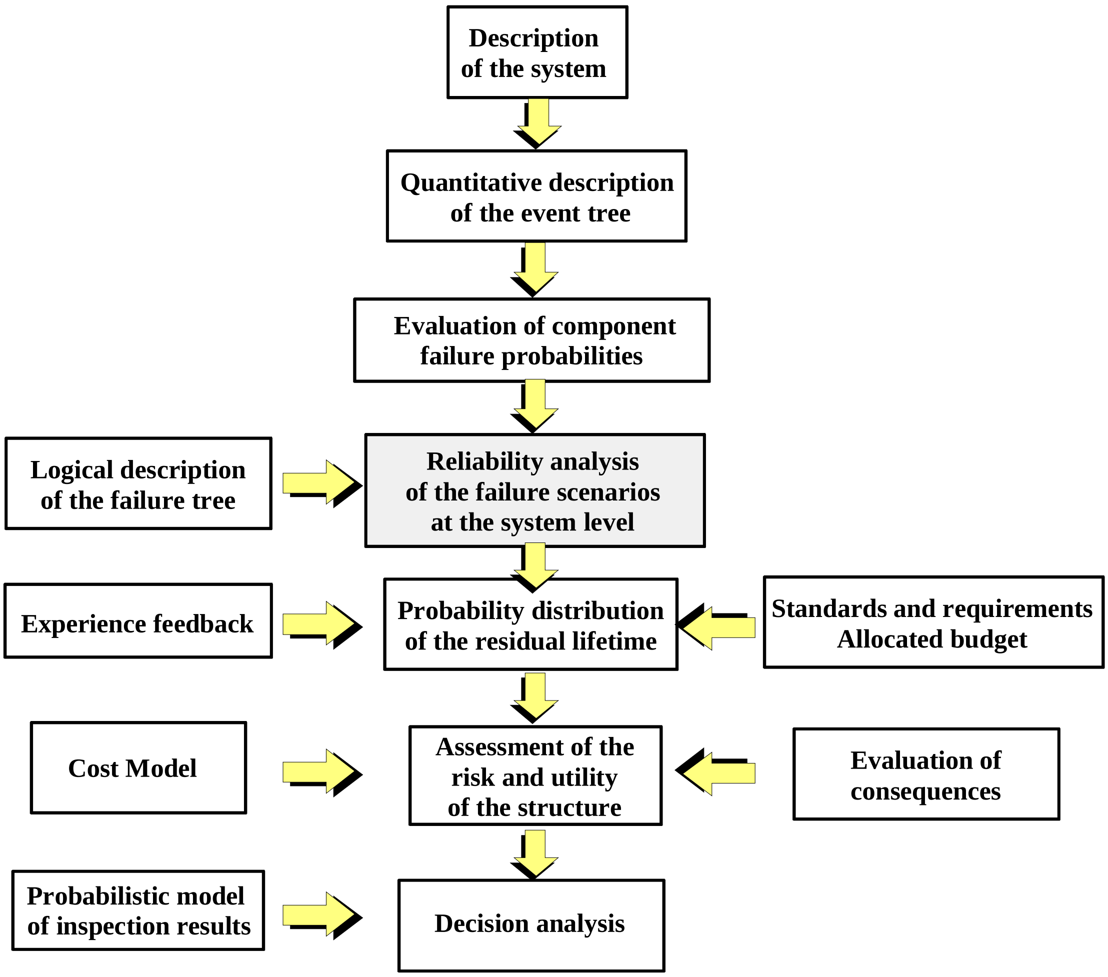

Figure 4. Flowchart of Reliability-based methodology.

4. Benchmark of various methodologies

The methodologies described in the previous section are now applied to three industrial examples: atmospheric tank, pipe under pressure and riveted steel joint, in order to compare their performance and to identify their practical limits and possible improvements.

4.1. Atmospheric tank

The safety assessment is carried out for a steel atmospheric tank for oil industry. The tank, built 50 years ago, is subjected to uniform corrosion at the bottom plate and the wall. The applied methodologies are:

- Deterministic approach based on allowable values;
- Risk-based Inspection methodology according to the qualitative approach;
- Risk-based Inspection methodology according to the quantitative approach;
- Reliability-based methodology, based on the mechanical analysis of the corroded plates and joints.

The deterministic regulations allow us to compare the measured values with the allowable values. These latter admit a reduction of the safety margin for the case of aging structures, compared to the initial design requirements. However these reductions are not associated with the structure age. These methods do specify neither the inspection interval, nor the safety level of the installation.

The risk-based analysis considers the failure probability and consequences. The assessment of the tank in terms of available data shows a high risk level, as shown in figure 5. This method provides the inspection interval according to the acceptable risk which is arbitrary defined to represent the financial risk that the company can afford. However, it is note possible to optimize the intervention plan.

The reliability analysis is an extension of the risk-based method, where the uncertainties are quantified in a consistent way. This approach takes into account, not only the experience feedback, but also the predictive behavior models. The specification of the optimal intervention time is based on the minimization of the total maintenance cost, as shown in figure 5 where the optimum is found at 17 years after the last inspection.

Although these methods lead to similar conclusions regarding the state of safety of the tank, they give different results in terms of residual lifetime, with direct impact on the inspection planning. The application of quantitative methods show the very large impact of environmental consequences, leading to very large costs related to pollution.

Probabilité	Matrice de criticité			
Elevée	L	H	E	E
Moyenne	L	M	H	E
Faible	N	L	M	H
Négligeable	N	N	L	M
Conséquences	Négligeables	Faibles	Moyennes	Elevées

Criticité
E Très élevée
H Elevée
M Moyenne
L Faible
N Négligeable

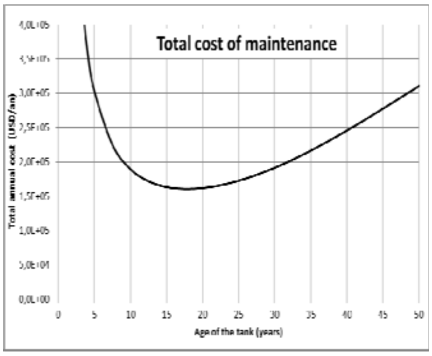

Figure 5. Risk level and total maintenance cost.

4.2. Pipe under pressure

In this case study, the safety assessment is carried out for a pipe under pressure subjected to atmospheric corrosion (Bryla et al., 2012), corresponding to the class C4 in the norm ISO-9223. The pipe wall thickness measurements have been performed on different parts of the pipe, showing a low corrosion rate, but with dispersion that cannot be neglected. Three approaches have bee applied:

- The deterministic approach based on the margin factor evaluation under pessimistic assumptions. This approach could not allow the clear justification of the structural integrity, knowing the large range of variations.
- The semi-probabilistic approach in which the characteristic values are introduced in the computation of the margin factors.
- The probabilistic approach, based on the statistical analysis of data and the specification of the reliability target. This approach provides the residual lifetime with respect to the target reliability level.

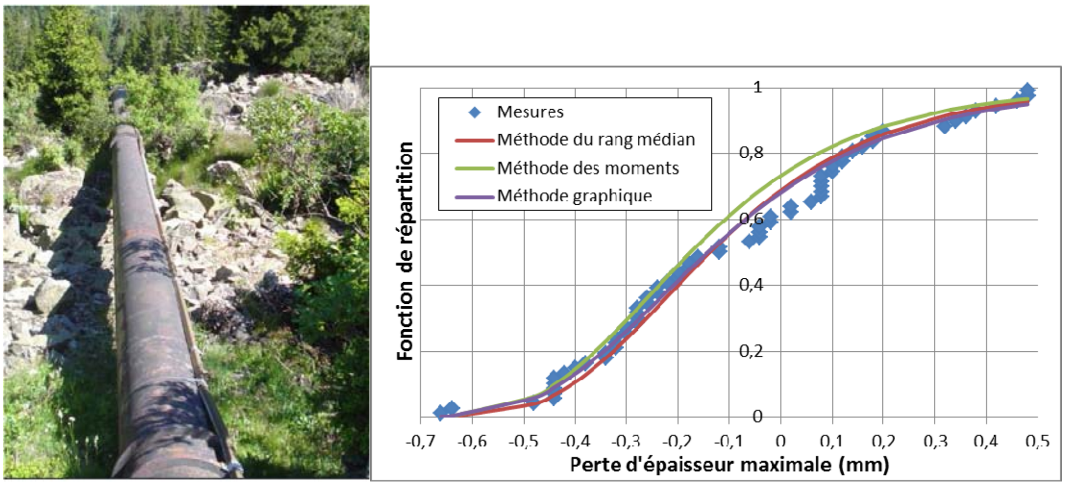

Figure 6. Pipe under pressure and CDF of the thickness losses by corrosion.

The deterministic approach leads to a minimum safety factor of 1.16 for nominal conditions at design and operation. This safety factor becomes insufficient when pessimistic assumptions are considered. For the corrosion class C4, the estimation of the residual lifetime leads to the range between 0 and 145 years when different corrosion rates are considered; the value of 43 years can be adopted by taking average corrosion rate for this class.

The semi-probabilistic approach is based on the characteristic values at the quartile of 5% or 95%, according to the type of the variable (i.e. resistance or loading effect). The safety factor is also low when pessimistic assumptions are considered and the inspection interval is difficult to specify properly.

The probabilistic approach considers the various random variables in the structural system, including material properties, corrosion rate, and the corroded thickness measurements by inspections. These variables are defined by appropriate probabilistic models. The specification of the residual lifetime is now based on the admissible reliability level, corresponding to 10^{-4} in this application. The residual lifetime is found to be equal to 60 years for the class C4.

These analyses show clearly the interest of real data acquisition and the use of various inspection techniques (destructive and non destructive). The inspection data are better used in the probabilistic approach, allowing to assess properly the structural safety.

4.3. Riveted steel joint

A steel joint of a railway bridge is considered under the effects of fatigue and corrosion. Contrarily to the above two examples, there are very few historical data on this bridge. The safety assessment has been conducted according to the following methods:

- The deterministic method based on the safety factor, given by the ration between the applied and allowable stresses.
- The Condition-Based Methodology, allowing the definition of the condition states of the structures and the health index of its components.
- The semi-probabilistic methodology based on the partial factors which are computed according to the Eurocode 3 part 1.8.
- The Risk-Based methodology, based on the qualitative approach.
- The reliability-based methodology, based on the failure probability computation for the limit state functions, involving the mechanical behavior of the structure.

Figure 7. Steel bridge and evolution of the damage factor

The deterministic approach compares the applied maximal stress with the material strength. The safety factor is obtained by the ration of these two stresses. Under the maximum loading, this factor is equal to 3.92 for rivets under tension and 1,14 for rivets under shear. The deterministic analysis estimates the residual lifetime by 16 years, given that the observed corrosion is less than 3mm.

The condition-based methodology defines the degradation states and the health index of the bridge. The condition state is found to be poor for the superstructure, satisfactory for the substructure and good for the deck. The structure should be repaired but there is no emergency for the moment.

The application of the Eurocode 3 allows us to check the various failure modes of the joint. The design rules are evaluated under old and new loading conditions. The joint is accepted for the large majority of load cases, except when the joint is assumed completely rigid and the Eurocode loads are applied. The consideration of corrosion reduces significantly the safety factors.

The risk-based methodology is applied according to the qualitative approach. Under low probability and high consequences, the bridge is ranked as « high risk ». Assuming corrosion of class C5, the residual lifetime is estimated as 11 years, with inspection to be planned at 9 years. The reliability-based methodology considers the bridge as safe when the old loading model is used and unsafe when the new loading model is applied. Under the admissible probability of 10^{-3}, the residual lifetime is estimated by 20 years.

5. Improvement issues

The available methodologies offer to the manager a wide range of adaptation possibilities that can be defined according to the onsite, the needs, the data, and the other practical issues. The existing methods have often been developed in a particular engineering field in terms of objectives, constraints and culture of the industrial field, on one hand, and the sensitivity techniques and scientific background of working groups, on the other hand. There manager can find either practical but incomplete methods, or very sophisticated method but unusable for real systems. The golden rule consists in evaluating the interests gained by the use of more complex approaches, with respect to their impact on the final decision and the associated confidence. In other words, it is useless to apply complex methods when the data uncertainties cover the accuracy gained or when the final decision is insensitive to the improvement of parameter estimation.

In general, the safety assessment methodologies should be applied in a progressive procedure, with the possibility of enriching them in terms of the structural or components risks. Although the condition-based methodologies allows us to make quick ranking of elements according to their condition states, the reliability-based methodology provides accurate evaluation of safety, with the cost of sophisticated mechanical, physical and probabilistic modeling. This method could be interesting only for critical components. The risk-based methodology could be seen as a compromise between the above approaches. Whatever the applied method, the quantitative approaches should be preferred to the qualitative methods, because of the lack of argumentation and robustness of the decision. From the practical point of view, it is necessary to develop a computer system for asset management, in order to allow for capitalization of knowledge, and efficient and dynamic updating of the safety assessment.

The main improvement issues of the existing methodologies can be listed as following:

- The elaboration of probabilistic framework ensure the coherence between the risk assessment and the prediction of the residual lifetime ;
- The improvement of the structural system modeling in order to take account for component interdependence and interaction between the failure scenarios.

- The improvement of the robustness of the risk matrix concept, in order to reduce the arbitrary part in the class definitions for probability and consequences.
- The development of appropriate methodology for rare scenarios and without degradation historical data.
- The standardization of the probabilistic modelling of degradation for the main phenomena (e.g. fatigue, corrosion, wear, creep, etc.) and their interaction ;
- The improvement of the probabilistic modeling of inspections and the local as spatial uncertainties, especially in case of non destructive testing and with the possibility of using different techniques for the same degradation.

There is a significant margin of progress to make the existing methodologies more attractive and more efficient regarding the decision-making for safety and for life-cycle optimization. The ideal methodology should combine the decision analysis, the advanced probabilistic and reliability methods, the failure and damage consequence evaluation, and the mechanical and physical behavior models for residual strength analysis. The various sources of uncertainties should be considered within the decision process related to defect data, types of material, loading and environment, maintenance plan, and mechanical and financial models.

6. Conclusion

The safety assessment methodologies of existing structures follow the same philosophy in considering degradations and failure consequences, but differ in the adopted approaches to reach this target. The choice of a specific methodology is not an easy task, which explains why large number of methods can be found in literature. The most commonly applied methods are supported by strong industrial fields. (e.g. petroleum and bridge engineering).

The identification and the application of these methodologies allowed us to highlight the fundamental concepts and assumptions, to identify the needs in terms of data, level of uncertainties and to assess the risk management procedures. This project has also the goal of making links between the various methodologies for the safety assessment and management, and for the life-cycle optimization of assets in mechanical and civil engineering.

7. Acknowledgement

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