“SRA into SRA” – Structural Reliability Analyses into System Risk Assessment : activities of an ESReDA Project Group

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ABSTRACT: this paper gives an overview of the integration of structural reliability analyses into system risk assessment, by looking for the difficulties faced in practical applications of these methods, and discussing the valuability of possible solutions. The first issue investigated is the existence of alternative probabilistic models in case of poor physical modelling. Two possible solutions are discussed: the gamma process and the statistical Cox model. The second issue is the use of structural reliability assessments in the decision-making process related to structural integrity. Firstly, the links between structural reliability assessments, reliability target values, social acceptance of risks, are investigated. In particular, the definition of risk measures by quality of life measures is proposed and may have advantages for engineers, but the existence of an optimal safety is questionable. Finally, three practical methods applied to specify reliability target values for structures are presented: implicit method, expert judgment and cost-benefit balancing.

1 INTRODUCTION

Developed European societies are getting more and more sensitive to risks, especially due to technological devices and industrial facilities. Safety requirements apply to every kind of industrial or public facilities.

The reliability of structures is an important safety issue. It is the result of a global and consistent process affecting every step of the structural life cycle: design, manufacturing, installation, operation, maintenance policy, lifetime evaluation…All the measures taken at each of these steps have an impact on the “practical reliability” of the structures.

To give confidence in the reliability level of the structures, or simply to comply with the regulatory requirements in some cases, this reliability level has sometimes to be evaluated.

In this regard, structural reliability analyses enable to perform more rational risk evaluations: they are an alternative approach to traditional deterministic evaluations for taking account of all the uncertainties affecting the parameters characterizing the physical state of the structure and its environment (load fluctuations, variability of material properties). They are considered as a promising research area, both for theoretical developments and for industrial applications. In the last decades they have been increasingly applied in many industrial branches. Although they constitute a helpful tool for safety and reliability assessments, some questions arise when using them in an industrial context:

- Are they the only probabilistic framework for degradation modeling? Can they be applied to all degradation phenomena?
- In most cases industrial companies have to ensure the safety of both their facilities (considered as systems) and the components constituting these facilities, especially the structures; how to make sure that these two requirements can be met consistently? That target reliability levels for structures are acceptable considering the failure consequences on the facility and its environment? And that reliability assessment for complex structures and systems is performed adequately?

These two distinct issues have been investigated in the framework of the ESReDA Project Group: “SRA into SRA” (i.e. “Structural Reliability Analyses into System Risk Assessment”). ESReDA (European Safety & Reliability Data Association) is a European excellence network, whose objective is to promote and harmonize European research, application and training in the fields of dependability of industrial facilities. In particular, ESReDA has an everlasting activity in Structural Reliability through some of its Working Groups that issued common books (Thoft-Chrstensen et al. 1998, Lannoy et al. 2004). The participants in the Project Group are from institutes, universities as well as industrial companies. They come from European countries such as Austria, Denmark, Czech Republic, France.

This paper gives an overview of selected group activities dealing with the aforementioned issues. The positions expressed in each paragraph reflect the opinion of their author.

2 IDENTIFICATION, MODELLING AND CONTROL OF DEGRADATIONS

This chapter has been basically written by André Lannoy, with a significant contribution of Henri Procaccia.

Degradation can be defined as the continuous deterioration of the characteristics of a SSC (System, Structure or Component) that could impair its ability to function within acceptance criteria. In the context of ageing of industrial facilities, the modelling of degradations is widely considered as a prioritary topic for research and development in the near future. Indeed the main stakes related to this topic are very important from a safety and maintenance point of view:

- the structural reliability assessment,
- the reliability based design of passive components,
- the optimisation of condition based maintenance,
- the optimisation of in service inspections,
- the reduction of risks and maintenance costs.

2.1 *Degradations as an indicator of physical ageing*

This generally concerns passive equipment (structures, pipes, pressurized containers, etc.). The ageing process is generally associated with a mechanism of degradation of the material with which it is made.

It has to be mentioned that the degradation does not lead automatically to a failure and a loss of function for the equipment: for example, some types of corrosion will cause a through-wall crack (measurable effect) which can lead to more serious leakage or, more serious still, fast fracture (failure mode).

Optimization to prevent this type of occurrence will involve condition-based maintenance or in-service inspection, which must make it possible preventively to detect the start of a deterioration triggered by a degradation process, and its propagation, before an actual break. Once a degradation has been observed (through monitoring), it is sufficient to perform the preventive tasks that will prevent the failure.

2.2 *Modelling of degradations as a risk analysis problem*

The main steps are the following:

- step 1: to identify the degradation mechanism concerned,
- step 2: to evaluate the degradation evolution with time or with covariates describing the use of the equipment,
- step 3: to find mitigation actions avoiding or postponing the degradation of the SSC,
- step 4: to control and to provide information permittting the three first steps.

In the sequel some considerations about steps 1, 2 and 3 are presented.

2.2.1 *Step 1: identification of the degradation mechanism*

- At the design stage, FMEA (Failure Modes, Effects Analysis) which is an inductive method of analysis of a SSC for the systematic study of causes and effects of failures can be used.
- During operation, the evolution of degradation mechanisms identified at the design stage has to be controlled, new degradation phenomena may also appear**.**

As far as we know, today, two methods are available and have been used, more or less, in the nuclear industry:

- the PMDA-PIRT methodology (Proactive Materials Degradation Assessment- Phenomena Identification and Ranking Table), developed by the US Nuclear Regulatory Commission (Wilson, Boyack, 1998),
- the AVISE methodology (“Anticipation du Vieillissement par Interrogation et Simulation d'Experts”) developed by (Bouzaïène-Marle, 2005).

Once degradation mechanisms and components for potential future degradation are identified, it can be possible:

- to better understand the current degradation mechanisms,
- to optimize periodic inspection and continuous monitoring techniques,
- to define maintenance procedures or to optimize the replacement of SSCs.

2.2.2 *Step 2: evaluation of the degradation kinetics*

The physical understanding of degradation mechanisms is a key issue for degradation modelling. However, other approaches can sometimes be applied, and two families of degradation models can be considered:

- firstly, mathematical models based on the physical understanding of the degradation mechanism: the estimation of the parameters of the model is determined from experimental records during tests, or also from operating experience data, in particular from degradation measures observed during in service inspections, on the basis of physical laws; then two subcases

of modelling can be considered: in the subcase of deterministic modelling, the input parameters of the model are considered as fixed, and are generally taken as pessimistic representative values; in the subcase of probabilistic modelling, the input parameters are considered as random variables, and the output is for instance a probability of degradation threshold upcrossing; this is the typical framework used in Structural Reliability assessments including degradation modelling;
- secondly, statistical degradation models; estimation of parameters is only done from operating experience data; this statistical modelling can be proved difficult, taking into account the characteristics of data in an industrial context: a very small sample of inspection data, a high proportion of incomplete data and censored data, successive inspections not really carried out in the same areas, 100% complete inspection generally not possible or too costly, measurement errors due to instrumentation, operating times difficult to collect or to estimate.

Various classes of models correspond to this type of modelling. One class is the random processes modelling the evolution of degradation as a function of time. The gamma process is one particular example. It can modelize the degradation of a component submitted to shocks having an aleatory intensity at random times. This process is an increasing one. The increments are independent and during a time interval they follow a gamma law (Roussignol, Bérenguer et al, 2002).

Note that the generalized gamma process can suit for the initiation and for the propagation of a defect, the kinetics can indeed vary with time (Nikulin, 2005). Note also that this type of modelling only accounts for the operating time or the age of the structure.

Parameters of the gamma process are difficult to assess, in particular in our industrial context of operating experience with always right censored data.

2.2.3 *Step 3: control, mitigation actions, monitoring or condition based maintenance*

To follow the kinetics of degradation and to detect possible ageing is very important, not only from a safety point of view but also for a profitability target. Condition based maintenance enables to secure the continuous follow up of a component in operation, with the objective to anticipate the failure by taking action just before the degradation reaches a limit threshold.

It is consequently necessary to find a correlation between the state of degradation of the component and one or several measurable physical variables, for instance physical parameters, crack depths,...

The Cox model (or proportionnal hazard modelling) is the product of the basis hazard by an exponential factor incorporating the effects of a number of explicative influent variables called covariates.

The model works relatively well (Nikulin, 2005):

- when the values of covariates are not very far from the usual experimental values of these covariates,
- preventive maintenance is very often efficient and there is no ageing effect perceptible,
- the use of an approximate model, simple like the Cox model, can be preferred to the use of another model considered better, but sophisticated and difficult to explain and to interpret physically.

3 HOW SAFE IS SAFE ENOUGH?

Whereas deterministic analyses immediately provide the statement whether the integrity of the analysed structure is acceptable or not, structural reliability analyses provide failure probabilities or reliability indices related to this integrity. And these probabilities do not enable by their own to state whether the structural integrity is acceptable or not. For these probabilities to be integrated in the decision-making process related to structural integrity, it is necessary to specify acceptance criteria based on the knowledge of these probabilities. In many cases these criteria may appear as the comparison of the failure probability to an acceptable failure probability (considered as a target value, as a reliability objective, or a minimum value). In any case, the definition of the acceptance criteria involves risk considerations, and especially risk assessments.

These links between structural reliability assessments, reliability target values, risk assessments of passive components and of the industrial systems in which they are integrated, social acceptance of risks have been investigated in the working group: although structural reliability analysts are not entitled to fix the reliability targets themselves, they have to care for the use of their reliability analyses in the decision-making process assessing the structural integrity.

Some of these issues are presented in this part. The first three paragraphs have been written by Dirk Proske. They investigate the issue of the definition of risk measures by quality of life measures, of the existence of optimal safety and of the global management of risks including risk assessments. The last paragraph has been written by Alaa Chateauneuf. It describes various practical methods applied to specify reliability target values for structures.

3.1 *Quality of life measures as risk measures*

Since the first application of the term risk in the 14th century many efforts have been undertaken to define risk in robust numerical terms. For the case of loss of life, mortalities were applied as early risk measure already in the 19th century. Since then many different risk measures have been developed, such as Fatal Accident Rates, (Frequency - Number of fatalities) curves or Lost Life Years. In the field of structural engineering mainly risk parameters of zero order are used, such as probability of failure, which do not consider explicitly loss of life (or only to certain extent). The same is true for the field of natural hazards were hazard maps are developed, also not giving damage or loss numbers. This will change according to the requirements of the European Union by the introduction of risk maps for natural hazards and for tunnels. However the application of such parameters is mainly a question of jurisprudence: Civil engineers avoid giving exact number of life losses, since they are personally responsible for the work. Besides such a problem, all the risk parameters experience some drawbacks. For example (Frequency - Number of fatalities) curves, first developed for the investigation of nuclear power plant safety and radiation safety, are very useful for technical and natural risk assessment, but not for health risks. Here in medicine beside some very specific risk parameters, mainly Lost Life Years are used which are not only able to consider the loss of life, but also cover diseases and injuries.

If one deeply looks into the risk rankings of the different risk measures, one finds that the highest risks to humans are social and health risks. Just as a rule of thumb: poor people even in a rich country die several years before the average of the population. This fact is also true for unmarried people (Proske 2008).

This result describes very clearly how humans do decisions: first they try to prevent social risks. They are looking for work, they are moving to their family and so on. But such behaviour is often not considered in the simplified risk assessment. Therefore risk measures have not only to consider an exact cause and damage, they have also to consider living conditions.

This yields as to quality of life measures. There exist many different ways to define quality of life. For a complete list of definitions please consult Proske (2008). As examples, the WHOQOL (1995) group has defined: “Quality of life is ‘individuals’ perceptions of their position in life in the context of the culture and value systems in which they live and in relation to their goals, expectations, standards and concerns.” The term quality of life measures has a long history. Already Romans discussed “vitae qualitas”, then in the beginning of the 20th century economists start to discuss quality of life, in medicine quality of life is a common terms since the middle of the 20th century and since a decade also engineers consider quality of life in terms of the Life Quality Index (Proske 2008).

The major advantage of the quality of life measures is that they are a very broad concept. One can consider the efficiency of a mitigation measure such as seat belt in a car or an adjuvant therapy for a cancer patient and can compare both. This advantage turns also out to be a disadvantage over the long term run. Currently in medicine more than 1,200 quality of life measures are known. Which parameter is the correct one for a specific case remains to be a difficult question? Therefore in some fields the enthusiasm about quality of life parameters already declines, such as in medicine. However on the other hand, we have no other goal of treatment than asking people how well they are. Since most of the quality of life measures in medicine are surveys, many subjective elements can and have to be considered in contrast to engineering quality of life measures which are heavily based on overall economic indicators.

3.2 *Subjective Risk evaluation*

For engineers, an important purpose of the application of proofs of safety, independently from the specific numerical term, is the clearance of personal responsibility. For example, if an engineer applies a current code of practice, it does not mean that the structure is safe or that the code is true, it only means that the engineer has fulfilled his duty.

Therefore safety or risk evaluations do not necessarily have to comply with the subjective risk evaluation. Even worse, subjective risk evaluation may result in changes of the code, even if the structure was considered as safe based on the former code. Therefore subjective risk evaluation has to be considered to provide sufficient safety measures. Much work has been carried out in this field in the 1970 and 1980 during the rapid growth of the nuclear power industry (Fischhoff et al. 1981, Slovic 1999). In general, it is accepted that a bias exists between subjective risk ranking and objective risk ranking based on historical data. Many different causes have been identified for this discrepancy such as knowledge about the risk or fearfulness.

However a strong item should be pointed out here, which is not often considered in subjective risk assessment. Subjective risk assessment is heavily related to psychological and social effects. Such effects can currently only be investigated by surveys. On the other hand, engineers mainly use numerical models with strong causal relationship to investigate their products and proofing safety. The difference between the two types of models can be clearly stated: Whereas we have in physics Newton’s law of motion, we have nothing comparable for societies (Arrows 1951, Proske 2008). This effect may also limit the application of the different quality of life parameters since they were developed related to certain types of systems or certain types of science.

Therefore in the field of subjective risk estimation, engineers face the problem to consider effects such as trust, benefit, control and or other soft items in numerical terms. Under real world conditions such subjective and social factors heavily influence decisions. For example, after the failure of the hall in Bad Reichenhall in Germany the federal minister for constructions wanted to change the laws for such halls. Considering the fact, that for about 23 million houses/offices/halls in Germany less than one is lost per year and considering further that people are exposed usually more then 20 hours per day, a singular numbered loss of people in Germany due to structural collapse may be negligible and the Fatal Accident Rate is extremely low. However people do not understand such numbers: Houses are vital technical products. Imagine one year 10 halls may fail killing 150 children. People will not send there children to sport halls, perhaps even to schools anymore and society may stop functioning properly. Such consequences could be seen very clearly in the financial crisis 2008 were loss of trust in financial facilities nearly causes a breakdown of the global financial system.

One should drop the overall idea of optimal safety using numerical risk measures even applying quality of life measures, since this may give inadequate solutions due to major assumptions about system behaviour. A solution to this problem will be a greater focus on robustness and the decrease of vulnerability.

3.3 *Vulnerability and protection measures*

A very specific approach has been developed for the field of natural hazards in Mountain regions. Due to insufficient data, it is extremely difficult to estimate the return period and intensity of future events. For example, whereas for earthquakes often historical data up to 2,000 years exists, not much data exists for avalanches, debris flows, landslides and rock falls. Beside that, such phenomena are strongly exposed to changes of the population, here to climate changes. If data exists for several hundred years, it is usually not known, whether that data build up one population.

Therefore the Integral Risk Management cycle has been developed. Such a cycle considers risk assessment, mitigation measures, disaster management and post disaster management. It does not pretend, that something such as optimal safety is the goal. Instead it clearly states the limitation of the used models by permanent improvement shown by a cycle. Therefore Integral Risk Management seems to be a superior solution to risk assessment alone. (Kienholz et al. 2004).

3.4 *Target reliability*

The specification of target reliabilities for structures and industrial systems is mandatory for safety requirements and qualification, for both design of new systems and life-cycle management of existing ones. These target reliabilities affect not only the safety levels, but also the socio-economic utility and the socio-political vision of risk acceptability. Naturally, the selection of the target reliability depends directly on the failure consequences (e.g. fatalities, direct and indirect economic losses, environmental damage and pollution, etc.), which are often difficult to estimate, especially when life-cycle is considered for operating systems. Therefore, the reliability allocation still remains a delicate task as it concerns not only the engineering field, but also the economic and political fields, where the priorities and the society preferences are quite different.

The specification of the target safety level should take account for the following factors:

- The method of modeling uncertainties in safety assessment. For example, Quantitative Risk Assessment takes account for human factors, which may lead to accidental loads and abnormal resistance, while Structural Reliability Analysis is limited to safety analysis under “normal” conditions (randomness is often limited to loads, materials and geometry);
- The nature of the failure modes: instantaneous or progressive (*warning indications*), component and system modes, residual strength considerations, etc. In the system approach, the relevant structure is assumed to be composed of different physical components (members, joints, ...) which may have various failure modes, e.g. different collapse, fracture or fatigue modes;
- The possible consequences of failure, in terms of: risk for life, injury, economic losses, level of social inconvenience (disturbance of occupants and activities), loss of the reputation of the owner/operator/decision-maker, affecting the future business (economic or moral), and sustainability considerations (reduction of waste and recycling of materials);
- The expenses and efforts required to reduce the risk of failure;
- The reference period to be considered for safety targets. When considering fatalities, the target is set for failure probabilities per unit time, in order to ensure the same risk at any time, independently of the service in-

stance. When considering economic losses, the service lifetime is taken as a reference period in cost benefit considerations.

To specify the target reliability for a system, three approaches can be applied, namely: implicit method, expert judgment and cost-benefit balancing.

3.4.1 *Implicit method*

Traditionally, target reliabilities in engineering have been set implicitly by calibration at past and present practice (Rackwitz, 2002). The profession agrees that this cannot give totally wrong numbers because those developments for appropriate targets had already a long history, where trial and error techniques have led to almost optimal sets of suitable quality assurance rules. This procedure cannot be applied to new and specific structures and systems, due to low feedback and non-homogeneous cost/reliability distribution for various components of the same system.

The implicit method is based on either the comparison with existing codes of practice or the analysis of existing *acceptable* structures. This approach aims at ensuring the same reliability level for new and old installations. It is globally accepted by all the decision-makers as it does not, at least theoretically, imply additional risks for the society. In fact, this method represents the basis for the calibration of the Eurocodes, where the Joint Committee for Structural Safety (JCSS 2001) proposed to standardize the probability distributions for loading actions and material properties.

The drawback of this method lies in the specification of target reliabilities for new and innovative systems, as no reference is available for comparison. Moreover, the integration of socio-economic needs, especially those related to safety cannot be easily incorporated.

3.4.2 *Expert judgment*

More modern approaches define a so-called ALARP region for risk (As Low As Reasonably Practicable) located between risks which are clearly acceptable and unacceptable. Usually this is defined in a log-log plot of the occurrence probability of adverse events versus their consequences. The regions of risk are mostly determined from data on failures. It is noted that different industries tend to define different ALARP risks reflecting their experience and also their special demands. The empirical nature of this approach is evident, as it is based on expert judgment on risk acceptability (e.g. mortality rates, environment damage, economic losses, etc.), supplied by experience gained from operation feedback. For instance, the rule given by ISO recommendations (ISO, 2006) on the admissible failure probability is given in Equation (1):

$$P_f = \Pr\left[death / failure\right] \;\leq\; 10^{-6} / year \qquad (1)$$

The target can also be set in terms of the number of fatalities N:

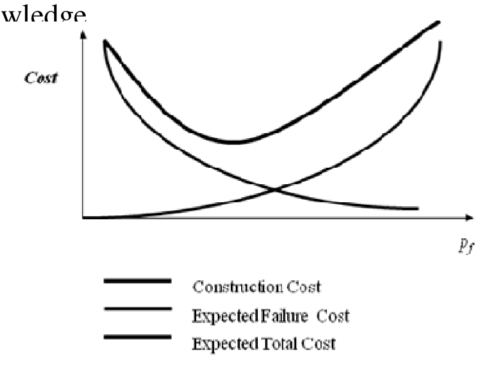
$$P_f \leq A\, N^{-\alpha} \quad / year \qquad (2)$$

with $A = 0.01$ *(or 0.1)* and $\alpha = 2$.

Although this approach allows for reliability target specifications for new systems, it arises large difficulties in specifying the model parameters, which are very sensitive to the society evolution and to political factors.

3.4.3 *Cost-benefit balancing*

The optimization of the cost-benefit balance can be seen as the most rational way of setting the reliability targets, through the maximization of the utility function of the system. The balance between the expected benefits and the potential losses due to failure, allows us to define the optimal target for old and new systems, as shown in the figure. Although this approach is rational, it still remains sensitive to society preferences and political factors, especially when human lives and indirect costs (propaganda effects, image of the company, confidence of the users, etc.) are involved. Progresses are required in this field in order to provide robustness in dealing with practical engineering problems, with imperfect state of knowledge.



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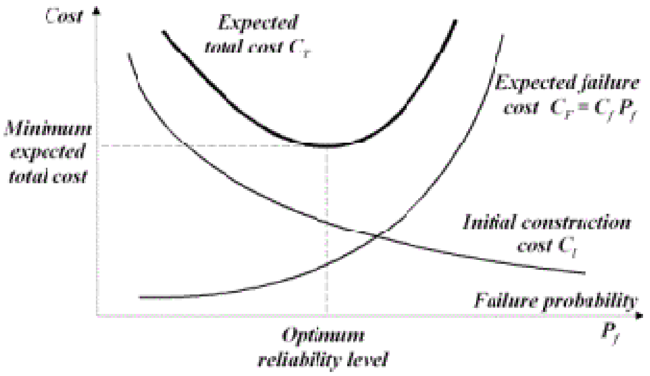

Figure 1. Optimum setting of reliability target on the basis of minimum total cost.

3.4.4 *Component reliability allocation*

Engineering structures generally consist of many components arranged in series and/or parallel systems. The failure consequences are mainly related to system collapse rather than to component failure. Therefore, the target reliability is set at the system level. In other words, the system reliability has to satisfy the target, i.e. $P_f^{sys} \leq P_f^T$ (P_f^{sys} being the failure probability of the system and P_f^T is the admissible failure probability), whatever the component reliability levels, at least theoretically.

The reliability allocation for the various components can be performed on the basis of either expert judgment or total cost optimization. The latter can be formulated as follows:

$$\begin{aligned} &\min_{d,P_f^i} C_I(d) + C_f\ P_f^{sys}(d, P_f^i) \\ &subject\ to: P_f^{sys} \leq P_f^T \qquad (3) \\ &and: P_f^i \leq P_f^{\max} \end{aligned}$$

where $C_I(d)$ is the initial cost, C_f is the failure cost, P_f^{sys} and P_f^i are respectively the failure probabilities for the system and for the i^{th} component, P_f^T is the target probability for the system and $P_f^{\max}$ is the maximum allowed failure probability for the components. In this problem, the optimization parameters are not only the design parameters *d*, but also the reliability levels of the different components; i.e. P_f^i. The solution allows us to allocate the most economical component reliabilities without affecting the system reliability.

4 CONCLUSION

Two distinct issues related to the use of Structural Reliability Analyses in an industrial context have been investigated in the framework of the ESReDA Project Group: "SRA into SRA" (i.e. "Structural Reliability Analyses into System Risk Assessment"):

- Are they the only probabilistic framework for degradation modeling? Can they be applied to all degradation phenomena?
- In most cases industrial companies have to ensure the safety of both their facilities (considered as systems) and the components constituting these facilities, especially the structures; how to make sure that these two requirements can be met consistently? That target reliability levels for structures are acceptable considering the failure consequences on the facility and its environment?

Regarding the first issue, alternative solutions are available for the modeling of degradation or degradation kinetics, if only a poor physical model exists. In this case, stochastic processes like the (generalized) gamma process possibly including covariates may provide a possible solution to model the degradation evolution, although difficulties may arise when calibrating the process parameters. For kinetics modeling, the use of the Cox statistical model may be relevant and has been performed in industrial applications. In any case, it is necessary to get a sufficient amount of data.

Regarding the second issue, the links between structural reliability assessments, reliability target values, risk assessments of passive components and of the industrial systems in which they are integrated, social acceptance of risks, have been investigated. In particular, the definition of risk measures by quality of life measures is proposed and may have advantages for engineers, but the existence of an optimal safety (an implicit assumption of these approaches) is questionable since it does not account sufficiently for subjective risk perception. Finally, it appears that risk assessments are not sufficient to manage risks: the global management of risks includes risk assessments, but also relies on mitigation measures, disaster management and post disaster management.

Finally, the three practical methods applied to specify reliability target values for structures are presented: : implicit method, expert judgment and cost-benefit balancing. The first one is based on either the comparison with existing codes of practice or the analysis of existing *acceptable* structures. It is globally accepted by all the decision-makers. These three approaches are complementary as the obtained reliability levels reflect a certain confidence in the way to deal with system safety (qualitative information, imprecise quantitative data, etc.). It could be proposed to combine these three approaches, and to introduce some Bayesian tools for setting an expert system for decision making relative to safety targets for engineering systems.

Finally, this paper gives an overview of the integration of structural reliability analyses into system risk assessment, by looking for the difficulties faced in practical applications of these methods, and discussing the valuability of possible solutions.

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