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Review paper

Risk management in civil engineering

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ABSTRACT

Risk is involved in the whole lifecycle of a structure: design, construction, utilization, and demolition. There is a close connection between reliability and risk. Contemporary building codes introduce consideration of reliability in structural design. Here, the concept of risk takes into account the level of consequences of a failure. Structural engineers, who are used to deterministic calculation procedures, are often unfamiliar with the uncertainties associated with risk analysis. An overview of the basic principles of risk management in civil engineering is presented in this paper.

1 The concept of risk

Risk can be seen as a concept invented by humans to help them understand and deal with the dangers and uncertainties of life [1]. In general, the concept of risk is considered in ISO 31000:2009 [2, 3], where risk is defined as “the effect of uncertainty on objectives”. ICE/ISO 31010 [4] summarizes a number of techniques that can be used to improve the understanding of risk and how uncertainty is taken into account. The document also provides references to other documents where particular techniques are described in more detail.

Risk analysis supports decision making in various activities. In 2010, the European Commission published a Working Document - "Guidelines for Risk Assessment and Mapping for Disaster Management", which sets a general framework for disaster prevention and proposes measures to minimize the impact of disasters. The guidelines take into account existing EU legislation and Eurocodes. The document contains research results in the field of risk assessment and risk mapping of major natural and man-made disasters, based on existing good practice in Member States at the time. In 2019, a report [5] was published, based on the aforementioned guidelines, with the aim of providing scientific support to EU Member States in the preparation of a National Risk Assessment. The document provides tools and methods for risk assessments related to specific hazards and assets: drought, earthquake, flood, terrorist attacks, biological disasters, critical infrastructure, chemical accidents, nuclear accidents and Natech accidents (Natural Hazards Triggering Technology Accidents).

Structural engineers predominantly use deterministic calculation procedures and feel uncomfortable with the fact that risk analysis in practice can mean different things depending on the professionals doing the analysis and the client's requirements [6]. In this regard, the book [7], intended for both engineers and students, provides clear definitions and instructions for conducting risk analysis and is a useful text for structural.

Risk R is often estimated by the expected value E(L) of the consequences L (i.e., losses):

$$R = E(L) = \sum_i p(L_i) \cdot C(L_i) \tag{1}$$

Here L_i represents a particular loss *i* related to something valuable to humans, $p(L_i)$ is the probability of L_i, and $C(L_i)$ is the measure of that loss (commonly expressed in monetary units). The event of loss is a random variable (for example, the number of affected people), and it is conditional on the event designated as the failure. The failure is “non-conformance to some defined performance criterion”, [8]. There may be a number of failure modes F_j corresponding to the established performance criteria.

The probability $p(L_i)$ is obtained by conditioning on the failure modes:

$$p(L_i) = \sum_j p(F_j) \cdot p(L_i | F_j) \tag{2}$$

where $p(F_j)$ is the probability of a failure mode F_j, and $p(L_i | F_j)$ is the related conditional probability.

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Each failure mode is a result of an event H_k - hazard (a single initiating event). Introducing conditional probabilities $p(F_j|H_k)$, expression (1) is extended to:

$$R = E(L) = \sum_k p(H_k) \cdot \sum_j p(F_j|H_k) \cdot \sum_i p(L_i|F_j) \cdot C(L_i) \tag{3}$$

where $p(H_k)$ is the probability of hazard H_k occurrence.

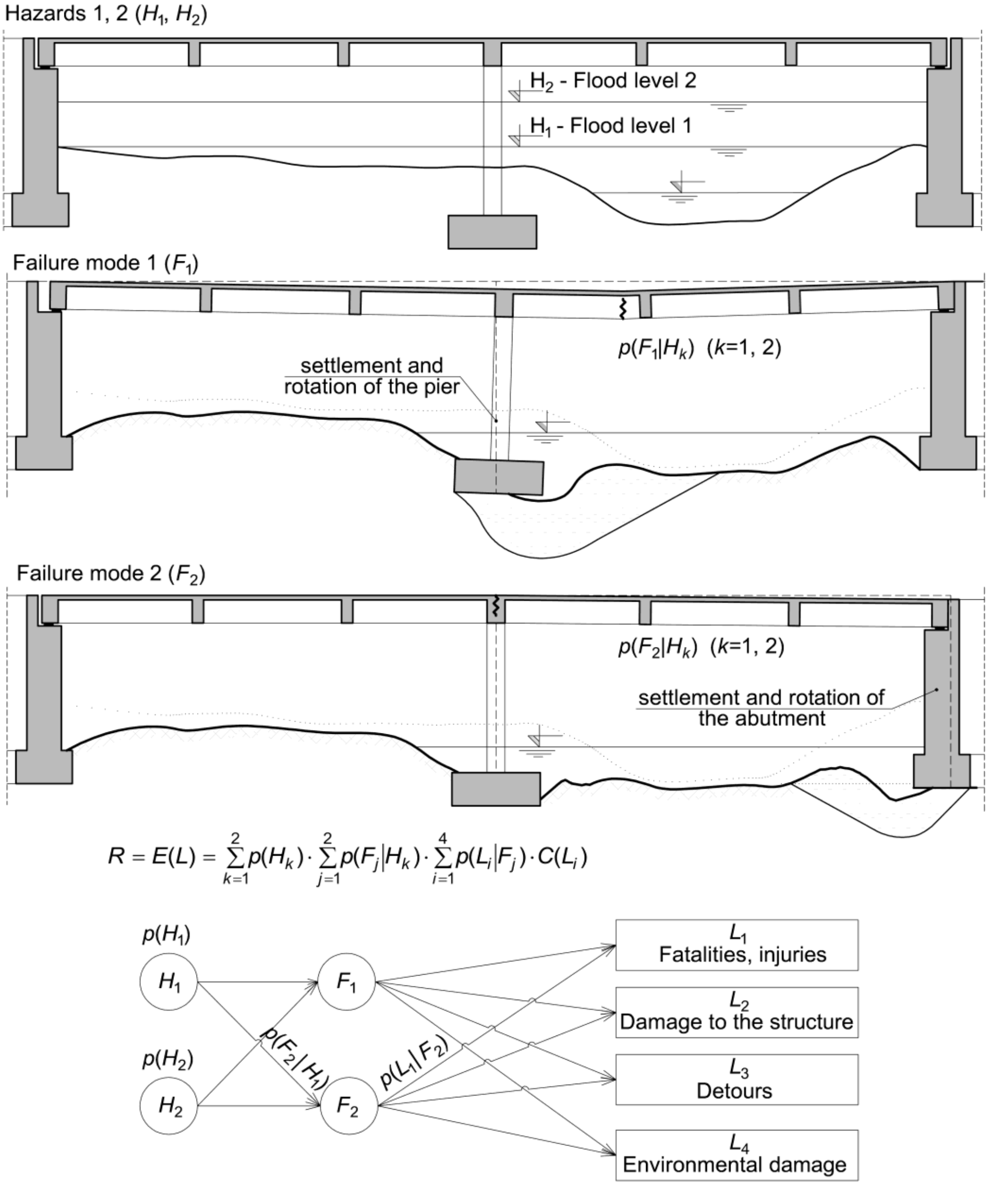

Figure 1. Example of the risk assessment

An example of the risk assessment is illustrated in Figure 1 [9]. A bridge structure is exposed to two hazardous situations that may cause two failure modes (related to local scour at substructures), leading to four types of losses.

Civil engineers are constantly facing risk in their practice (in conceptual design, construction, and maintenance), which is due to diverse uncertainties related to loads, design models, material properties, construction procedures, and environmental impacts. Risk cannot be avoided, given the uncertainties of future events, but it can be reduced by risk mitigation measures. Rational measures require adequate risk assessment. Risk assessment provides a basis for rational decision-making in the context of uncertain and/or incomplete information [10].

2 Framework for risk management

ISO 31000 [2, 3] provides general framework for risk management. General principles on risk assessment of systems involving structures are presented in ISO 13824 [11]. The risk management process, applicable in civil engineering, is presented in Figure 2.

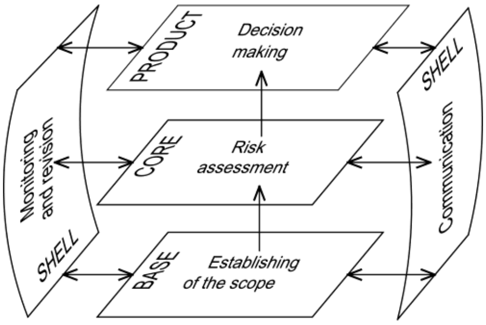

Figure 2. Framework for risk management (adapted from [2])

2.1 Establishment of the scope

The essential step within risk management is the establishment of the scope (context). It comprises:

- definition of the system (Figure 3);
- setting the time frame;
- setting the level of risk analysis (qualitative, semi-quantitative, quantitative, or probabilistic);
- identification of stakeholders (e.g., investor, designer, contractor, owner, user, society, etc.) and their responsibilities;
- setting the acceptance criteria.

The system to be considered is the totality of all objects, events, consequences, assumptions, agreements, and constraints that are necessary for a particular risk assessment. Within the system, the definitions of all elements are provided, and all relevant facts are collated (information, data, expertise, models, etc. [12].

The definition of the system is essential to establishing exposure, vulnerability and robustness. Due to the properties of the considered system, specific sequences of events (scenarios) arise that cause direct and indirect consequences [13].

Direct consequences refer to the losses related to individual elements of the system and their vulnerability. Vulnerability ($V_{j,k}$) can be interpreted as the conditional probability of a specific failure mode as a result of a specific hazard:

$$V_{j,k} = p(F_j | H_k) \tag{4}$$

Several systems with different levels of complexity are presented in Figure 3 with examples of direct/indirect losses. Narrowing the boundaries of the system (1 → 4) enables detailed modelling of system properties. The use of detailed models followed by expansion of the system boundaries (4 → 1) results in a significant increase in the complexity. The complexity is also significantly affected by the selected time frame and the level of risk analysis (see section 2.2). Within risk management, “the level of complexity should be tailored to the decision at hand and the quality of data that supports the decision analysis” [14].

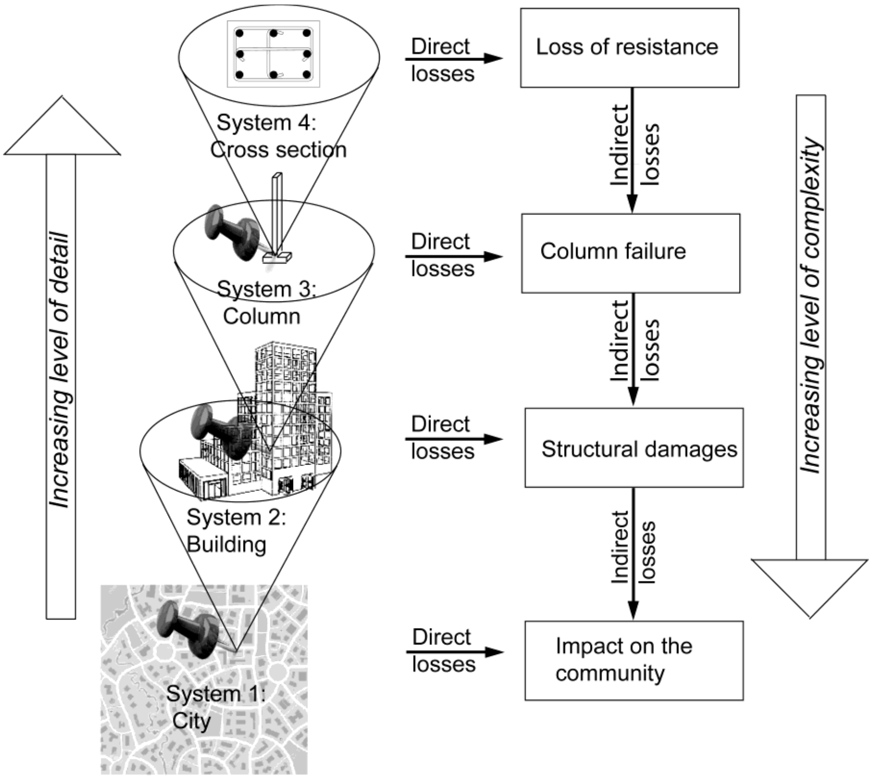

Figure 3. Systems with direct/indirect losses and the level of complexity

A system can exhibit various failure modes. They can be related as a series, while some of them may comprise the simultaneous (parallel) occurrence of certain failure events. An example of possible structural failure modes for a restrained beam is shown in Figure 4.

Indirect consequences refer to losses beyond the direct consequences and are usually associated with the loss of system functionalities. A structural system is said to be robust if the structure will not lose its functionality at a rate or extent that is not proportional to the cause of structural damage [13]. Robustness represents the ability to withstand the propagation of losses throughout the system, and is a function of system properties like redundancy, ductility and load redistribution, but it also depends on failure consequences [15].

Consequences are categorized in classes which relate to cost bearer (internal, e.g. owner, and external, e.g. users or society) and by tangibility (tangible, e.g. material loss, and intangible, e.g. fatalities). Categories are obtained combining classes of losses that are presented in Figure 5 (category “direct-external-intangible” is marked for example).

Risk acceptance criteria denote acceptable limits to the probabilities of certain consequences of an undesirable event and are expressed in terms of annual frequencies. Risk acceptance criteria are generally determined by the specialists but may reflect the risk attitude of a particular decision-maker. “These criteria are normally determined by the authorities to reflect the level of risk considered to be acceptable by people and society”, [16]. Rational risk acceptance criteria should be based on socioeconomic considerations.

The problem with making decisions about risk acceptance is that the group that pays for safety measures frequently differs from the group that benefits from them. Those who do not directly pay for the safety measures want very strict rules, and vice versa [17]..

Societal risk criteria are presented as curves on *F-N* plots (usually log-log scales) that show the relationship between the annual frequency *F* of accidents with *N* and more fatalities. These curves have been developed for various industrial fields. The mathematical expression for an *F-N* criterion curve contains the risk aversion factor α, and may be expressed as:

$$F = k \cdot N^{-\alpha} \qquad (5)$$

where *k* is the constant and the risk aversion factor α = 1 ÷ 2, [14-16]. Value α = 1 denotes a risk-neutral attitude. An example of F-N curve is shown in Figure 6.

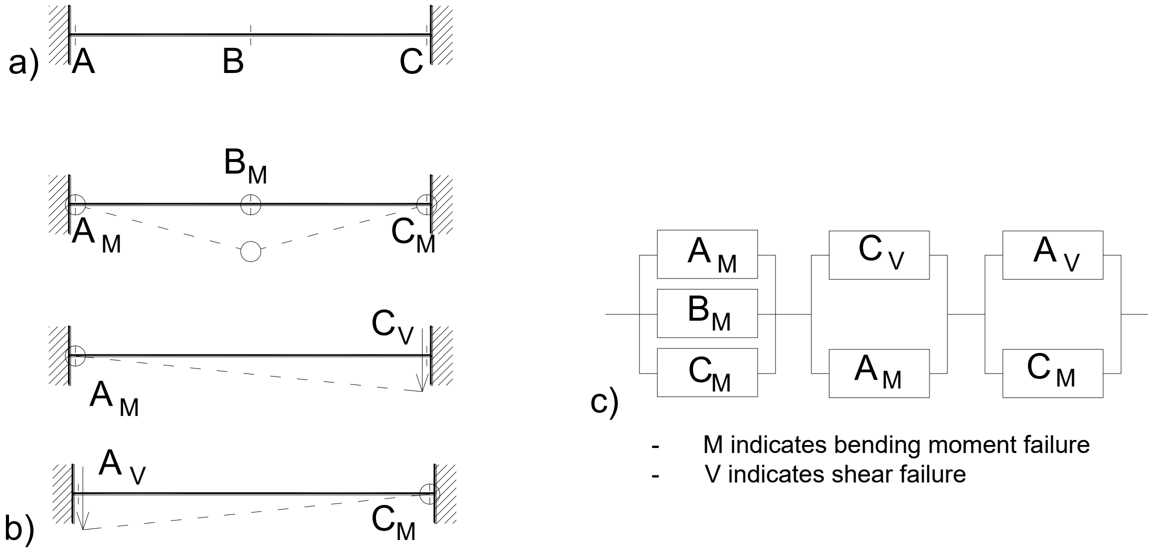

Figure 4. Illustration of some structural failure modes: a) structural system, b) corresponding failure modes and c) block diagram for systems reliability analysis

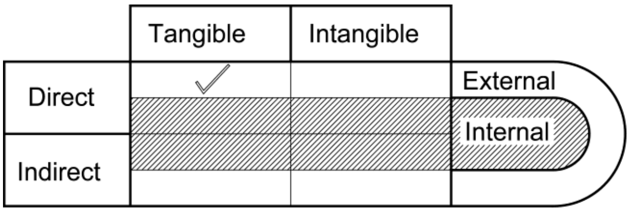

Figure 5. Categorization of losses

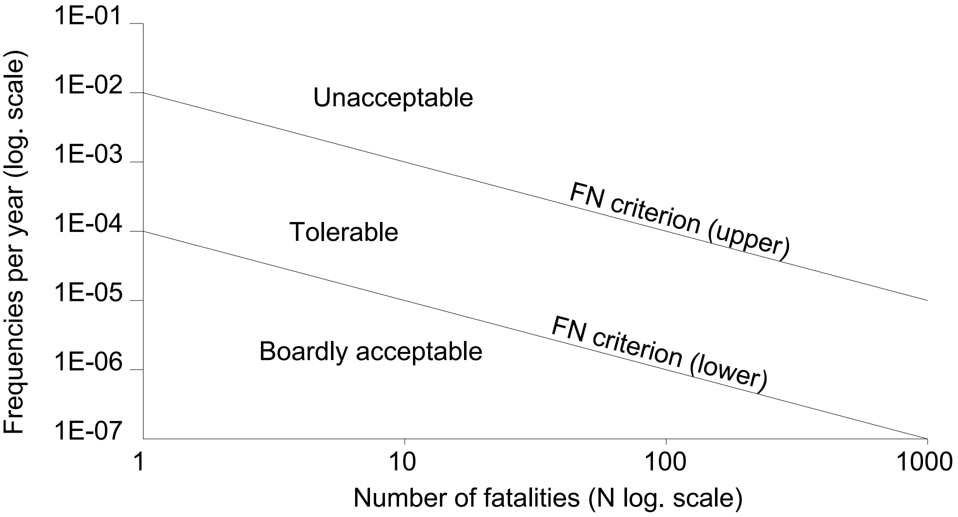

Figure 6. Example of F-N criterion lines (adapted from [7])

2.2 Risk assessment

Risk assessment involves three steps: identification, analysis, and evaluation of risks. Identification of relevant hazards and consequent losses is performed within the established context (Section 2.1). Risk analysis is carried out by an appropriate method in accordance with a defined level. A risk matrix is usually used for a qualitative or preliminary analysis. The modified risk matrix, involving pre-defined failure mode probabilities, is used for semi-quantitative analysis [21]. For quantitative and probabilistic risk analyses, the event tree, the fault tree, or the Bayesian network [4, 7, 8] are commonly applied. The last step of a risk assessment is evaluation, which is necessary for a decision about the risk treatment.

Identification of hazards (i.e., initiating events) and hazard scenarios, followed by identification of the type and extent of related consequences (losses), is an essential prerequisite for the risk analysis. Hazard scenarios establish the chain of events leading to specific losses.

The hazards may originate from various causes:

- natural (e.g., earthquake, flood, landslide);
- human activities (e.g., impact of vehicles, overload, fire);
- malicious attacks (e.g., bomb explosions, vandalism);
- human errors (e.g., design or construction errors, misuse);
- negligence (e.g., lack of inspection or maintenance).

Hazard identification procedures may vary from the simple use of a list of threats or extensive tables for a formal identification process to a detailed expert study as an interdisciplinary process. Selected hazards should be documented as a part of the risk assessment, and explanations should be provided for the omitted ones.

Design codes and recommendations address in detail only some of the abovementioned hazards (e.g., earthquake, fire, impact, etc.). Human errors and negligence are also acknowledged, but besides general requirements for quality control and supervision, the codes usually do not provide detailed instructions. Inaccuracy in design models and uncertainty in input data are partially covered by safety factors.

These factors are calibrated based on target values of the reliability index β which is the ratio of the expected value to the standard deviation of the performance function [10, 22-25].

Consequences (losses) may be related to various domains:

- human safety (e.g., fatalities, injuries, damage to important facilities);
- property (e.g., damage to structures, contents, and surroundings);
- economics (e.g., loss of income, cost of detours or delays);
- environmental (e.g., pollution, environmental damage);
- social (e.g., loss of reputation, increase in public fears).

The method of *risk analysis* is selected in accordance with a defined level: qualitative, semi-quantitative, quantitative, or probabilistic.

A qualitative risk assessment is the starting point for any risk analysis, providing a risk ranking and identification of credible event scenarios for further, detailed analysis. It is based on the comprehensive experience or studies of experts and does not involve mathematical calculations. Results are commonly expressed in a risk matrix Figure 7.

In Fig. 7, consequences are classified as “low”, “medium” and “high”, similarly to CC1, CC2 and CC3 in Annex B of EN1990 [21]. The time frame has to be specified within the selected context. For example, the occurrence of a scenario that is “occasional” in 50 years might be “remote” in a single year. The classification presented in Fig. 7 is the starting point for decision making. If the risk is “intolerable”, risk mitigation measures are mandatory, or the planned activity is to be cancelled. In the case that the risk is “broadly accepted”, no action is required. Between these regions, there is the wide zone referred to as ALARP (“As Low As Reasonably Practical”). The words “Reasonably practical” refer to the costs of risk mitigation measures. Only general risk mitigation measures (i.e., verified in common practice) can be suggested by the qualitative risk assessment.

In the simplest quantitative risk assessment, the occurrence rate of the initiating event, conditional probabilities, and the corresponding value of losses, are the point estimates. The effects of the uncertainties in inputs and their interdependency should be assessed in sensitivity analyses. A quantitative approach with point estimates can

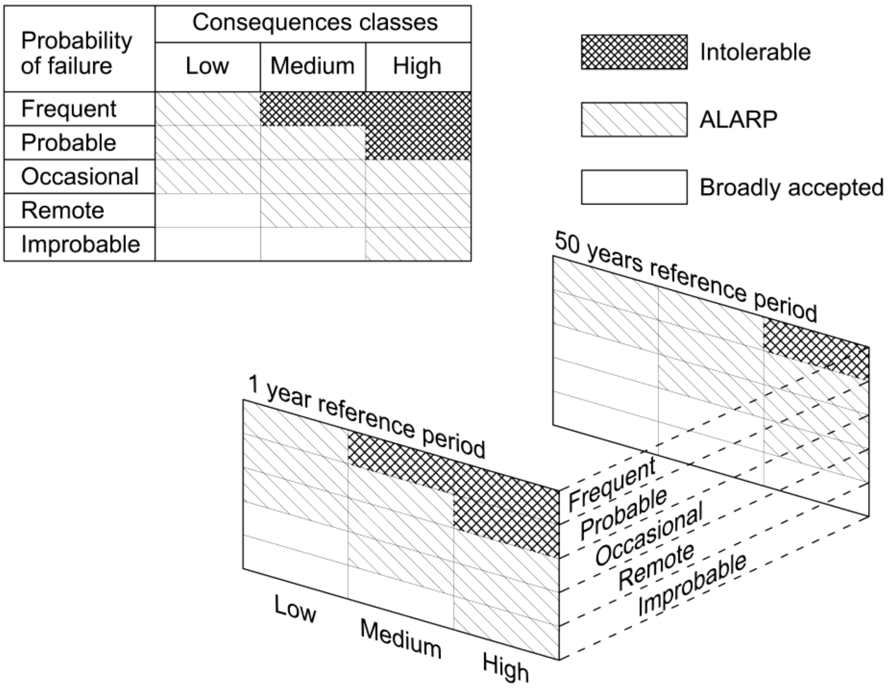

Figure 7. Example of risk matrix and impact of the reference period

be used in cases where uncertainties have no significant influence on decision-making. Probabilistic risk assessment is used when the sensitivity analyses indicate that uncertainties in the input estimates cannot be neglected. The events (including losses) are treated as random variables.

Available historical data can be used for the selection of probability distributions and the estimation of distribution parameters, but a high amount of reliable data is required. Reliability analyses of elements and systems are the next steps in the probabilistic risk assessment. The most complex risk assessment involves time-dependent reliability analysis of various limit states and time-dependent modelling of losses related to the spectrum of consequences.

Switching from qualitative to quantitative risk assessment is suitable only where it is reasonable and feasible. Reasonable means that the cost of doing a quantitative analysis is not high compared to the value of solving the problem. Feasible refers to the availability of computing tools, information, and data.

The simplest way of evaluating *risk* is qualitative: high, medium, or low risk (risk matrix, Fig. 7). A more comprehensive result of the risk analysis provides the spectrum of losses with estimated probabilities in the prescribed time frame.

2.3 Decision making

There are four basic options to deal with risk: acceptance, transfer, avoidance, and risk reduction (i.e. mitigation). If all of the prescribed performance goals (e.g., Dutch risk- driven concept named RAMSSHE€P comprises Reliability, Availability, Maintainability, Safety, Security, Health, Environment, Economics (€) and Politics [26-28]) are fulfilled, then the risk is accepted. Risk transfer is a measure that involves the contractual shifting of a particular loss from one stakeholder to another (e.g., insurance company). Avoidance is the act of staying away from a risky situation. Acceptance, transfer, and avoidance are already decisions.

The combination of decision theory and risk assessment enables consideration of alternatives to reduce risk. Basically, risk mitigation measures aim to reduce the probabilities of a scenario and/or the probabilities of losses. The spectrum of measures ranges from knowledge improvement to changes in system characteristics. Knowledge about statistical characteristics (i.e., adequate probability distribution and its parameters) of hazards and/or the state of the system is updated by research and/or inspections (i.e., risk mitigation through improvement of knowledge).

Risk mitigation through changes in the system´s characteristics may be achieved by:

- limiting the use of the structure (avoiding overload and reducing the probabilities of losses);
- strengthening the components of the structure (reducing vulnerability) and/or
- increasing the redundancy of the structural system (increasing robustness).

Every risk mitigation measure incurs costs. Optimization should be supported by data concerning efficiency of measures and related costs. Within the framework of optimization, losses can be expressed in monetary units. In this context, the monetisation of fatalities is a particularly delicate issue. There are several approaches: Societal Value of Statistical Life (SVSL), Societal Willingness to Pay (SWTP), Implied Cost of Averting a Fatality (ICAF), Societal Life Saving Cost (SLSC), compensation to be paid for death by accident…[29-32] . A systematic review is given in [33].

2.4 Communication, monitoring, and revision

Communication, monitoring, and revision are ever-present activities in risk management. Communication and discussion are continuous and iterative processes that are conducted to provide, share, or exchange information about risk between the decision-maker and other stakeholders. Communication procedures are of essential importance when high probabilities of large social losses are anticipated, in order to prevent or reduce such consequences.

Monitoring and revision imply constant feedback of information from the considered system in order to evaluate the efficiency of the risk mitigation measures and propose modifications if necessary.

3 Structural reliability and risk mitigation measures

Contemporary design standards and codes follow the principle that the more severe the consequences, the lower the failure probabilities should be accepted. Risk-informed decisions are incorporated into the codes.

3.1 Structural design codes

Statistical analysis of load and material data resulted in the concept of partial safety factors. Safety factors for individual failure modes of structural components are calibrated using an appropriate failure probability related to the accepted risk. It is usually suggested that structures should be designed with sufficient robustness (e.g., by strengthening key elements, selecting ductile materials, or providing sufficient redundancy) [16]. The reliability of a robust structural system is expected to be at least equal to the reliability of system components.

The main tool proposed in Annex B of EN 1990, [21, 22] for the management of structural reliability is modification of partial factors depending upon:

- consequences of a failure;
- design supervision differentiation;
- quality control and inspection during execution.

The purpose of reliability differentiation is the socio-economic optimization of the resources required for a construction project, taking into account all expected consequences of failure and the cost of construction [21].

3.2 Risk over the life cycle of the structure

The comprehensive decision process covers all aspects of the life cycle of structures:

- planning (conceptual design);
- design;
- construction;
- service (including inspection, maintenance, and repair or rehabilitation) and
- demolishing.

A decision-maker can apply risk mitigation measures that are inherent to a particular phase of the life cycle to reduce risk. However, the best effect is achieved when it is applied at the strategic level and during conceptual design. Different hazards, losses, or risk mitigation measures are specific for each phase of the life cycle [34].

3.2.1 Risk in design

“Good engineering practice involves looking beyond minimum prescriptive code requirements and considering the risk from low-probability, high-consequence events, regardless of whether the event is an ‘accidental’ or ‘normal’ load.” [35]

In the design phase, it is necessary to consider all subsequent phases in the life cycle of the structure.

These phases are implicitly considered in design codes through the chosen reference period for the design loads and general guidelines: ‘The structure will be adequately maintained’ and ‘The structure will be used in accordance with the design assumptions’, [21]. This implies that the designer should recommend a maintenance regime and emphasize the loads anticipated in the design to the owner. The owner or user should provide appropriate maintenance and prevent overloading or misuse of the structure.

A number of studies of failures in structural engineering have shown that most of the failures producing economic consequences originated in the planning phase, while the failures and errors leading to fatalities and injuries are connected to the construction phase [32].

Designers and practitioners should recognize safety hazards during the design phase. The review paper [36] refers to the various possibilities of considering the safety of workers during the construction or maintenance of civil engineering works in the context of registered accidents at work.

Planning in the early phases of a project is the best way to control risk in design and construction. That includes:

- preliminary investigations for conceptual design (reducing the uncertainties related to site conditions, environment, ground condition, etc.);
- expected utilization of the structure and anticipated loads;
- anticipated construction method;
- supervision requirements, and
- quality control requirements.

3.2.2 Risk during construction

Risk analysis is incorporated into well-established project management. Risk management is currently considered a mandatory and integral part of successful project management [37], which must be continuously implemented during the entire execution of the project [38].

Within the framework of project management, the project life cycle ends when the final structure is handed over to the owner.

The construction phase is a complex activity that is frequently the most critical phase in project management due to the uncertainties that might lead to additional design and planning activities during project implementation, with negative effects on costs or schedule. Besides, the construction could be adversely affected by environmental changes, natural disasters, and/or unforeseen geological conditions. It is estimated that a large percentage of projects (more than 70 %) fail to be realized on time, within budget or with the expected level of quality [39].

A review of the literature on construction project risk management reveals that force majeure risks and those related to workers are rarely studied, according to [38]. However, many cases of failure involving injuries and fatalities were recorded during construction: “It is estimated that there are around 60,000 construction fatalities occurred worldwide each year (ILO 2006)” [40] The construction sector employs about 6-10% of the workforce in industrialized countries, but 20-40% of fatal accidents at work occur in this sector. This trend is even worse in developing countries [41]. A recent review paper [42] provides a systematic overview and detailed analysis of the content of published studies related to risk identification in construction over the last three decades.

Temporary works, e.g., scaffolding or shoring for excavations, often receive less attention than permanent works. Loading on temporary structures may be inadequately foreseen. Furthermore, most structures are more susceptible to instability in the assembly stage than when completed. A combined effort of designers, constructors, and adequate supervision, including quality control, is required to ensure that proper sequencing of construction works is achieved while material weakness, temporary structural instability, or overload are avoided [34]. These actions, together with compliance with health and safety regulations during construction work, are risk mitigation measures in the construction phase.

3.2.3 Risk during the service life of a structure

The service phase is the longest period in the life cycle of a structure.

During the service life, structural failures usually do not occur due to ageing processes since they may be, to some extent, controlled by maintenance. More frequently, the effects of extreme events (earthquake, flood, extreme wind, landslide, etc.), or their combination, result in partial failures or total collapse. Intensities and occurrence probabilities of extreme events, as well as direct and indirect losses, mostly depend on the geographic location of the structure. There is abundant literature on risk estimation due to extreme events, usually involving case studies [14, 18, 35, 43-55]. Multiple hazards were considered in [56-60].

If the functionality of the structure is reduced, indirect losses may in some cases, exceed the value of the structure. To avoid such losses, inspections, maintenance, and, if necessary, repair or rehabilitation actions are to be carried out during the service life of the structure. Inspections can be of various types: visual, direct measurement, non-destructive testing, response measurements, or even a proof load. They are aimed at detecting damages, but the probability of damage detection depends on the type of inspection and the type of damage or hazard that has caused the damage. For example, damages caused by accidental actions or natural disasters will probably be detected, while corrosion of an inaccessible component may not be. The methodology for maintenance management and risk management is the same.

Risk-based inspection planning implies frequent and/or more reliable inspection of elements that have a high failure probability and elements whose failure may cause excessive consequences. It is assumed that if damage is indicated, particular action will be taken either to reduce the consequences (e.g., evacuate the structure or restrict its use) or to reduce the probability of failure (e.g., make repairs). “Reliability analysis, coupled with economic decision theory, has been recognized as one of the most effective tools for assessment of optimal inspection and maintenance plans” [61]. An overview of several procedures for the reliability assessment of existing structures may be found in [62].

The prioritization of inspection and maintenance activities can be based on quantitative risk analysis. Probabilistic, time-dependent analysis can be used to evaluate and optimize inspection and maintenance costs. Different maintenance strategies may be compared using a risk-based approach. Uncertainties about cost-related items may also be included. Bayesian updating offers a suitable framework for incorporating available information into risk-based maintenance. The mentioned approaches are elaborated in the literature [61, 63-78]..

4 Conclusion

The risk approach can be used to rank the structural design alternatives, construction alternatives, maintenance procedures, or prioritize interventions on existing structures. An advanced risk approach can be used for decision-making regarding design and construction activities, for inspection, monitoring, or maintenance to prevent structural deterioration, and for disaster preparedness.

Risk management is not one man's job and requires a multidisciplinary approach. It is also a continuous process and usually requires a vast amount of reliable cost and performance-related data, statistical operations, and, in some cases, considerable computer simulation capabilities.

Contemporary design codes enable management of risk in the design phase. The best effect on cost savings is achieved when risk management is applied during conceptional design. During construction supervision, adequate quality control and compliance with health and safety regulations are common risk mitigation measures. After construction and for existing structures, risk-based maintenance should be applied. Guidelines for risk-based assessment of existing structures are envisaged in the further development of the Eurocodes.

Acknowledgments

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