Structural Engineering Documents

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3rd reviewed and extended Edition

Jörg Schneider
Ton Vrouwenvelder

Introduction to Safety and Reliability of Structures

Including free access to
Variables **P**rocessor Software **FreeVaP**

International Association for Bridge and Structural Engineering (IABSE)

Jörg SCHNEIDER

Born in 1934 in Cologne, Germany, Jörg Schneider received his civil engineering degree from the Swiss Federal Institute of Technology Zurich (ETHZ) in 1958. He was an assistant at ETH from 1959 to 1963 and then joined the firm of Stahlton AG, where he was involved in the design and development of prestressed and precast concrete structures.

Since 1967 he has been professor for Structural Engineering at ETHZ. His research interests include safety and reliability of structures, with special emphasis on human error. He retired from ETHZ in 1999.

He joined the IABSE in 1968 and was active in many of its committees and one of its vice-presidents from 1993 to 2001. He has been a member of the Joint Committee on Structural Safety from 1979 to 2002 and its president from 1990 to 1994. In 1998 he received the Dr.h.c. by the University of Natural Resources and Life Sciences, Vienna. In 2002 he was elected honorary member of IABSE.

In 1999 Jörg Schneider founded, together with a few friends, the consulting office Risk&Safety AG, Aarau, Switzerland.

Ton VROUWENVELDER

Ton Vrouwenvelder was born in 1947 in The Hague, the Netherlands. He received his diploma in civil engineering at the Technical University of Delft in 1970 cum laude. As a junior researcher he worked at the Applied Mechanics Division till 1977 and then moved to the Concrete Department of TNO-Bouw.

In 1987 he became part time professor at Delft University, gave courses in structural mechanics and started up a course on probabilistic methods in civil engineering together with professor Han Vrijling.

He has been involved in national and international research and consultancy projects as well as in the development of standards codes for design and assessment of buildings and civil engineering structures (Dutch standards as well as ISO standards and Eurocodes). In particular he has been involved in the development or Eurocode 1990 and ISO 2394. He is a member of the Joint Committee on Structural Safety since 1982 and served as its president in the period from 1999 till 2005. In 2011 he received the C. Allin Cornell CERRA Award.

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Preface

The book you hold in your hands is based on IABSE's Structural Engineering Document SED 5, published in 1997 upon request of Working Commission I of the IABSE and supported by the Joint Committee on Structural Safety (JCSS) in order to advance the use of reliability methods in structural engineering. The book offers a short, informative, and more educational type of text and figures on safety and reliability analysis in structural engineering. It is intended both for students and practising engineers and aims to keep things understandable and to explain concepts and procedures by simple examples rather than by digging deep into the theory. Thus, almost no proofs are given. It is hoped that this book serves its purpose in furthering a topic which is gaining more and more attention and finding increasing application in practice.

The text and figures are based on parts of the lecture course "Sicherheit und Zuverlässigkeit im Bauwesen" given by *J. Schneider* in the 90th to 3rd year students in the Civil Engineering Department of the Swiss Federal Institute of Technology, Zurich (ETHZ). This course was very much influenced by a short course given in Zurich by *A. Nowak* in *1987*.

Translations from the German were done by *E.G. Prater* of ETHZ, and *Hillary Hart* of the University of Texas at Austin, U.S.A. A number of members of IABSE's Working Commission I and of the JCSS carefully read the text pointing out mistakes and suggested shortening and amending here and there. Among those whose help is gratefully acknowledged are *T. Vrouwenvelder* and *R. Rackwitz.*

SED 5 was well received in 1997. A 2nd edition was printed in 2006, and, grace to the permission of *M. Petschacher*, was supplemented with a free educational type of Variables Processor software, *FreeVaP*, in order to help in understanding the subjects treated.

The second edition was sold out in 2016. In view of the facts that the book turned out to be very attractive for starters who do not want to be overwhelmed by too heavy mathematics, and that the book sells well, IABSE decided to print a third edition.

However, during the last 20 years quite some progress was observed and the first author found himself not really up-to-date anymore to cope with all of these developments. He was very happy to find in the second author a good friend of former times and a person fully knowledgeable in all necessary fields to bridge all gaps. In good co-operation of the undersigned a number of new chapters were introduced and additions and corrections here and there were made resulting in some 40% increase of volume. And, again, access to the software mentioned above was ensured.

The feedback by the reviewers of the manuscript was well received and is gratefully acknowledged. A very special thank-you of the authors goes to Mikael Breastrup for his very careful look at the contents of this book and for bringing quite a number of larger and smaller blunders, errors and mistakes to the surface. This greatly enhances the value of this book for an inexperienced reader as she or he is not unnecessarily puzzled by errors in the book itself, once there is a beginning of real understanding.

We wish this book a good start into the next decade.

Zurich, Spring 2017

Jörg Schneider, Zurich
and
Ton Vrouwenvelder, Delft

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1. Dealing with Hazards

1.1 Main concepts

In this chapter the most important terms in structural safety and structural reliability are discussed and defined. In so doing, a rather broad approach to the safety of structures and related topics is taken.

1.11 Safety

Society expects that the occupants and users of buildings and structures and persons in their vicinity or area of influence are safe. People expect that the failure of buildings and structures is extremely rare and they consciously rely on the professional care and expertise of those involved in the planning, design, analysis, detailing, construction, and maintenance of structures.

The definition of the term *safety* must consider these facts and expectations. Thus, in this book, safety is defined as follows:

- The term safety is primarily related to the safety of people affected by structural failures.
- Adequate safety with respect to a hazard is ensured provided that the hazard is kept under control by appropriate measures or the respective risk is limited to an acceptable value.
- Absolute safety is not achievable.

Safety in the above sense – as opposed to the term *risk* – is obviously a *qualitative* term. Safety is achieved if the risk of damage to persons is reduced to comparatively small and thus acceptable values. The definition includes the safety of these groups:

- the workers at the site,
- the users of a structure or a facility,
- other persons in the vicinity of a structure, a facility or the environment at large.

It is important to note that in the above definition, it is not the structure the facility or the environment as such that is designated safe, but rather the people in the respective area of influence.

Safety problems attached to items, systems, facilities or events generally can be identified by simply asking the question: "Are persons endangered if this item, system, or facility fails or this specific event occurs"? If the answer is „yes“, then utmost care is requested.

Typical safety problems, therefore, result from the failure of a residential or commercial building, or a bridge, but they can also result from events such as train collisions, the sinking of ships. Also the collapse of a fuel tank endangering the human environment, etc., might fall in this category. Considered in this way, the collapse of an empty tower on a lonely hill during prolonged snowstorms is not a safety problem, being sure that, in such circumstances, no one is in the area.

1.12 Reliability

Reliability is defined as the probability that an item or facility will perform its intended function for a specified period of time, under defined conditions. The item under consideration could be a

2. Information Processing

2.1 Elementary probability concepts

Probability analysis is of great importance in dealing with risks. Although this book is not the right place to give a thorough introduction to probability theory, it is nevertheless necessary to summarise the most important concepts and principles. A more detailed discussion can be found in the literature (see, e.g., *Bernardo & Smith, 1994; Castillo, 1988; Lindley, 1965; Miller, 1990; O'Hagan, 1994; Papoulis, 1965; Tribus et al., 1969)*.

2.11 Events

The following are examples of what is meant by the term *event:* ... a pump is not working properly within a given period, ... the wind velocity within a given period exceeds a certain value; ... the steel strength of a pipe is below a given value; ... a hazard is detected in good time; ... the result of a series of chemical reactions (e.g., a chain reaction); ... a person dies in a traffic accident; etc.

An event that cannot be subdivided is called an *elementary event E*. The space in which a particular event occurs is called the *event space Ω* (fig. 2/1).

The symbol A∪B describes the union of the events A and B, represented by the shaded area. The corresponding verbal expression is "A and/or B". Fig. 2/1 demonstrates this in a so-called Venn-diagram (John Venn, an English logician, 1834 – 1923).

By the symbol A∩B the intersection of the events A and B is meant, again represented by the shaded area. The corresponding verbal expression is "both A and B" (Fig. 2/1).

Events can be independent of one other: e.g., A = not reaching a specified steel strength in a pipe and B = the fact that the pipe is painted blue. Events can, of course, also depend on one other: e.g., A = not reaching a specified steel strength and B = the fact that the pipe has burst. Thus, attention has to be paid to possible dependencies.

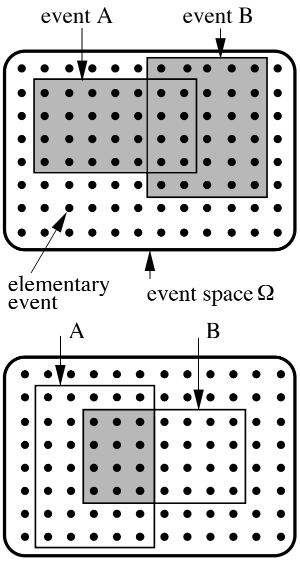


Fig. 2/1: Venn diagrams

2.12 Probabilities

a) Classical probability

Classical probability is given by the simple relationship:

$$p = \frac{\text{number of successful elementary events}}{\text{number of possible elementary events}} \qquad (2.1)$$

3. Basic Variables and Modelling

3.1 Introduction

A whole range of problems in civil engineering can be described by the comparison of two stochastic quantities: one, some sort of solicitation or stress (hence called the S variable); the other, a corresponding capacity or resistance (hence called the R variable). The following examples illustrate the point:

R	S
flow capacity of a river bed	discharge of the river
flow capacity of a sewage pipe	discharge of waste water
bending resistance	existing bending moment
permissible deflection of beam	existing deflection of beam
soil cohesion and shear strength	stresses in soil due to external loads
traffic capacity of a road junction	intensity of traffic

As a rule it is expected that the quantity on the left, the R variable, is at least as big as the quantity on the right, the S variable, so that no failure occurs. In terms of the examples: the river does *not* overflow its banks, the beam does *not* fail, the slope does *not* become unstable, the traffic does *not* come to a standstill, there is *no* electrical power failure, etc. From the examples it follows that such comparisons might consider a situation, or be a matter of time.

Checking for structural safety, e.g., traditionally follows *deterministic* patterns. In principle, a defined value r_d of the resistance of a structural component is derived from a number of characteristic values. In a similar manner a defined value s_d representing the action effects is derived from a number of characteristic values of actions. In order to check for safety or failure these two single values r_d and s_d are then compared.

The *deterministic* or *semi-probabilistic* form of the safety condition reads:

$$r_d \geq s_d \tag{3.1}$$

Sometimes a conscientious engineer repeats such an analysis in order to test the sensitivity of the result to variations of the input values. This is a step in the right direction, but it is often cumbersome and does not result in a good overview.

In the *probabilistic* approach advocated here the quantities that influence the problem are introduced as variables with their distribution types and their respective parameters. All load and resistance factors are dispensed with. Their function, however, is partially accounted for by so-called model variables.

Using R and S as variables in the above sense, the normal or desired state can be formulated as follows:

$$R \geq S \tag{3.2}$$

or rearranged:

$$R - S \geq 0 \tag{3.3}$$

4. Reliability Analysis Methods

4.1 Preliminary remarks

Among other requirements structures have to exhibit the following most important features:

- safety
- serviceability

Both requirements related to some predefined period of time (durability) should be achieved by minimum cost (economy). Similar demands are also placed on other technical systems.

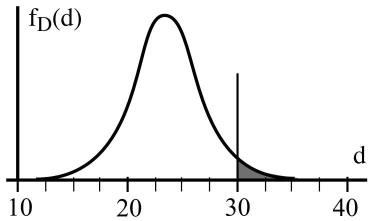


Fig. 4/1: Probability density of D

Each requirement can be formulated using a so-called *limit state condition,* which can generally be written as:

$$G(a_0, X_1, X_2, ... X_n) \geq 0 \tag{4.1}$$

The X_i represent the random variables, which describe both the problem and the requirements for a particular basis of assessment (see section 3.21). Random variables are not always physical values like dimensions, strengths, loads, etc., but could well be abstract values, such as the opinion of a group of people about the admissible value of a beam deflection. In fig. 4/1, such an opinion is shown in the form of a probability density: Only the shaded part of all questioned people would be prepared, in the case investigated, to accept a beam deflection of $d \geq 30$ mm. How such variables are derived was discussed in section 2.14.

The so-called *limit state equation* separates the acceptable region from that which is characterised as failure:

$$G(a_0, X_1, X_2, ... X_n) = 0 \tag{4.2}$$

Failure is defined by the *failure condition* as:

$$G(a_0, X_1, X_2, ... X_n) < 0 \tag{4.3}$$

Of interest in the present connection is the *probability of failure* p_f. This can be written as follows:

$$p_f = P[G(a_0, X_1, X_2, ... X_n) < 0] \tag{4.4}$$

There are many methods for determining these failure probabilities or the corresponding reliability indices, each method having its own level of sophistication. Quite often the following subdivision is used, starting with the highest level:

- *Level III:* limit state functions and distribution functions for the random variables are introduced without any approximation; calculations are usually based on Monte Carlo simulation (see 4.2) or straight forward numerical integration;
- *Level II:* the amount of calculation efforts is reduced by adopting well chosen linearization techniques, usually the so called First Order Reliability Method; the degree of accuracy may strongly depend on the details of the problem at hand;

5. Assessment, Judgement and Quality Assurance

5.1 Risk versus Safety

The notion "Safety" describes the state of a system operating with an acceptably small level of risk. Risk is, if necessary, reduced to values below this acceptable level by appropriate safety measures, which often are quite costly. Since long it's known that absolute safety cannot be achieved.

Establishing levels of acceptable risk is a matter for society at large and, thus, can have a significant political dimension. However, in the absence of political direction, it is the public authorities, representing society, who attempt to fix the observable criteria in an absolute manner. For risks judged to be below some acceptance level, and quite generally for risks where no such level is defined, authorities intervene, e.g., by requiring industry to implement ever more costly safety measures.

One thing, however, is clear: "... if our priorities in managing risks are not cost-effective, we are, in effect, killing people whose premature deaths could be prevented ..." (*Okrent*, *1980)*. Thus, in the end, keeping the risk for life and limb of people below acceptable limits in a cost-effective way is of prime concern.

5.11 Risk is a multifaceted concept

a) Randomness in risk analysis

In technical contexts, the term risk is generally understood as a function of the consequences of a possible event and of the occurrence frequency of such an event. The simplest function for relating the corresponding values is the product of these quantities. In fig. 5/1, therefore, risk is shown as a rectangle, defined by the two quantities.

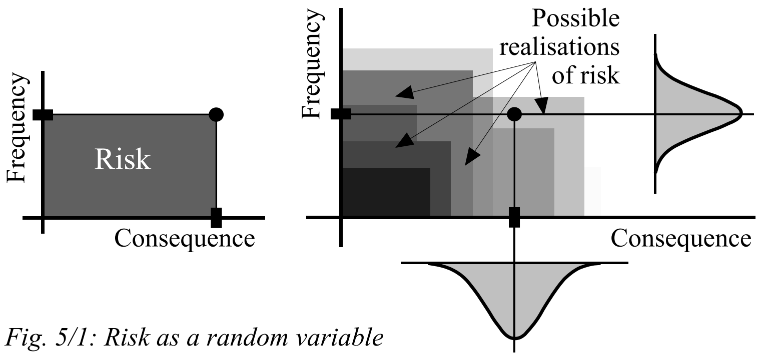


Fig. 5/1: Risk as a random variable

Admittedly, neither the consequences nor the frequency of an event can be known accurately in advance. Both are random variables, which, particularly for infrequent events, are poorly based on statistics. This uncertainty is represented in Fig. 5/1 by the probability density functions (pdf's) for frequencies and consequences. Naturally, if the input values are randomly defined, then the product of both variables is a random quantity as well, described by its expectation and its variance. This should be recognised.

In those situations one may consider the risk as a random variable and when comparing risks take the expectations. Another option is to define the risk directly as the expectation of the consequences, taking all uncertainties on board. To some extent it is just a matter of wording.

6. Outlooks

In the previous chapters the presentation of the theory and in particular the mathematics have been kept as simple as possible. The advantage of such an approach is that it is very accessible, the disadvantage is that many useful applications of the theory cannot be explained. In this section, however, an outlook to more advanced applications will be presented, in the hope that readers will become enthusiastic and find their ways to more advanced literature.

6.1 Probabilistic analysis and Finite Element Models

Finite Element Models (FEM) is a quite common tool for engineers to assess the response of a structure under various static as well as dynamic loading conditions. As a FEM calculation is cumbersome in itself, the use in combination with reliability theory needs to be quite limited.

The outcome of a FEM calculation depends on the discretisation scheme. A finer mesh, as a rule, will lead to more accurate results. This type of (in)accuracy should also be taken care of, in addition to the randomness of loads and structural properties. It adds to the uncertainty of the results, but will not be elaborated further here.

6.11 Semi-probabilistic static analysis

a) Standard practice: linear analysis

In practice one usually undertakes a semi-probabilistic static linear analysis for every individual load case and next find stress resultants in every critical point by superposition using the combination rules specified in the code. If all *unity checks* (defined as the generalised stress resultant divided by the corresponding resistance value) are below 1.0, the structure is considered to meet the safety standards.

Even though this may look simple and straight forward, there are still debates on, e.g., the value of the Modulus of Elasticity: either mean value, characteristic value or design value and (in the case of concrete) cracked or uncracked condition. Other points of discussion are the proper inclusion of dynamic effects in case of wind or earthquake loading and the proper schematisation of structural connections and boundary conditions, both physically and from a reliability point of view.

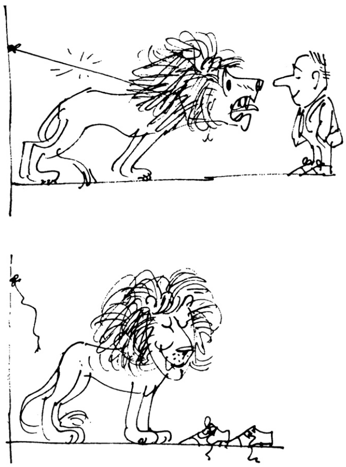
b) Nonlinear analysis

If for a certain structure a linear analysis is considered as inadequate, nonlinear FEM analysis may be used to get a less conservative estimate of the load bearing capacity of the structure. Note that superposition in nonlinear analysis is not possible anymore, so one has to perform the calculation for all possible hazard scenarios. The recommended strategy is to do a linear analysis first and restrict the nonlinear analysis to the scenarios for which the linear analysis gives unfavourable results.

The debate on the use of values for material properties in the semi-probabilistic analysis is now extended to all yield and hardening or softening parameters of the material. Some experts prefer to use mean values for all random material properties and have a global resistance factor at the end; others prefer to use design values for all random properties. The problem is that it is not always

7. Appendix

Just as a joke (or is it a warning?) here something to think about:



Cartoon by courtesy of *Dicke, 1975*

7.1 Murphy's Law

"If anything can go wrong, it will!"

O'Toole (whoever this was) replied by:

"Murphy was an optimist."

Corollaries:

- Nothing is as easy as it looks.
- Everything takes longer than you think.
- If there is a possibility of several things going wrong, the one that will cause the most damage will be the first one to go wrong.
- If you perceive that there are four possible ways in which a procedure can go wrong, and circumvent these, then a fifth way will promptly develop.
- Left to themselves, things tend to go from bad to worse.
- Whenever you set out to do something, something else must be done first.
- Every solution breeds new problems.
- It is impossible to make anything fool proof, because fools are so ingenious.
- Nature always sides with the hidden flaw.

See: https://en.wikipedia.org/wiki/Murphy's_law
and many other sources.

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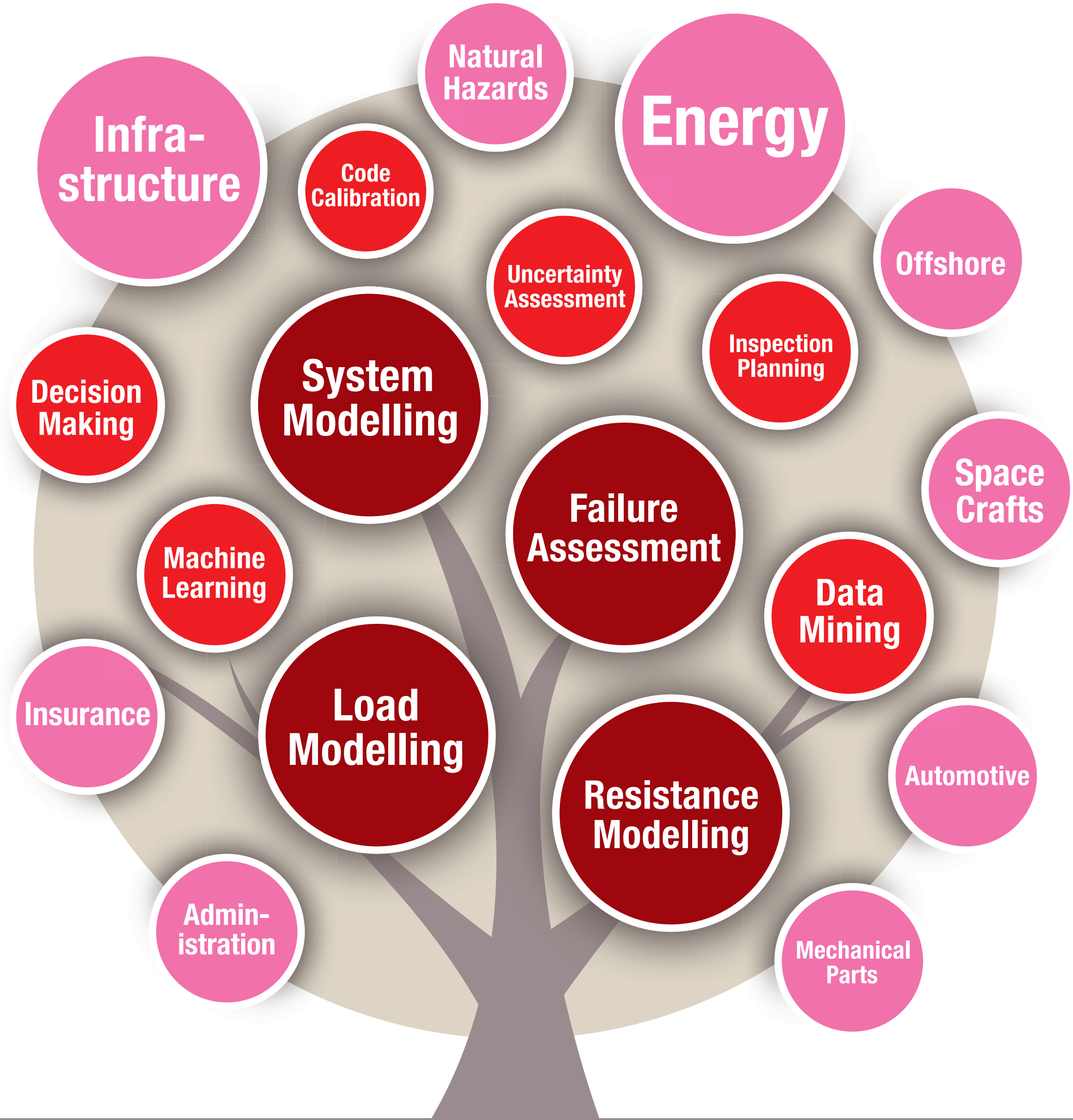

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The International Association for Bridge and Structural Engineering (IABSE) is a scientific / technical Association comprising members in 100 countries and counting 51 National Groups worldwide. Founded in 1929 it has its seat in Zurich, Switzerland. IABSE's mission is to promote the exchange of knowledge and to advance the practice of structural engineering worldwide. IABSE organizes conferences and publishes the quarterly journal Structural Engineering International, as well as conference reports and other monographs, including the SED series. IABSE also presents annual awards for achievements in structural engineering.

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Introduction to Safety and Reliability of Structures

Society expects that buildings and other structures are safe for the people who use them or who are near them. The failure of a building or structure is expected to be an extremely rare event. Thus, society implicitly relies on the expertise of the professionals involved in the planning, design, construction, operation and maintenance of the structures it uses.

Structural engineers devote all their effort to meeting society's expectations efficiently. Engineers and scientists work together to develop solutions to structural problems. Given that nothing is absolutely and eternally safe, the goal is to attain an acceptably small probability of failure for a structure, a facility, or a situation. Reliability analysis is part of the science and practice of engineering today, not only with respect to the safety of structures, but also for questions of serviceability and other requirements of technical systems that might be impacted by some probability.

The present volume takes a rather broad approach to safety and reliability in Structural Engineering. It treats the underlying concepts of safety, reliability and risk and introduces the reader in a first chapter to the main concepts and strategies for dealing with hazards. The next chapter is devoted to the processing of data into information that is relevant for applying reliability theory. Two following chapters deal with the modelling of structures and with methods of reliability analysis. Another chapter focuses on problems related to establishing target reliabilities, assessing existing structures, and on effective strategies against human error. The last chapter presents an outlook to more advanced applications. The Appendix supports the application of the methods proposed and refers readers to a number of related computer programs.

This book is aimed at both students and practicing engineers. It presents the concepts and procedures of reliability analysis in a straightforward, understandable way, making use of simple examples, rather than extended theoretical discussion. It is hoped that this approach serves to advance the application of safety and reliability analysis in engineering practice.

The book is amended with a free access to an educational version of a Variables Processor computer program. FreeVaP can be downloaded free of charge and supports the understanding of the subjects treated in this book.

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