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SEMINAR

X

Safety Concepts

Concepts de sécurité

Sicherheits-Konzepte

Co-chairmen:	
(morning session)	J. Ferry Borges, Portugal
	J. Pechar, CSSR
(afternoon session)	L. Östlund, Sweden
	J. Brozzetti, France
Introductory Papers:	"Sicherheit als sozio-ökonomisches Optimierungsproblem"
	T. Schneider, Switzerland
	"Risk Management – The Realization of Safety"
	C. Bøe, Norway
	"Safety, Building Codes and Human Reality"
	F. Knoll, Canada
Coordinator:	J. Schneider, Switzerland

(The Introductory Papers are published in the Introductory Report of IABSE 11th Congress in Vienna 1980)

Opening Remarks

JULIO FERRY BORGES
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I am most pleased and honoured to co-chair this first part of the Seminar on Safety Concepts.

The papers to be presented cover both the problems of theoretical probabilistic reliability and of quality assurance applied to structural engineering.

I do hope we shall have a fruitful discussion.

Although at present probabilistic reliability and quality assurance are two distinct disciplines, their fundamental aims are the same and they use several similar concepts. As a step for their unification it is important that they are dealt with jointly. Furthermore, all these activities should be viewed under the general framework of the organization of the construction industry.

I welcome the initiative of IABSE of dealing with these subjects in its Anniversary Congress.

General Survey on the Theme and the Seminar Procedure

C. BØE
Dr. Eng.
Det Norske Veritas
Oslo, Norway

Meine Damen und Herren,

I am sorry that I shall not be able to proceed in the language of our host country, but I ask our hosts to forgive me as I continue in English. To have such language problems is a practical detail which has to be coped with in a large international conference. I know our host has sorted this out admirably.

However, in this session we have another language problem, if you like. That is - or rather was - the selection of the title of theme for the safety session. The final title is - as you know quite well - Safety Concepts. The theme could however, quite easily have been entitled: Safety methods, Safety formats, Safety measures, or Safety codes. Now, you will at once recognize that the alternative titles may be more specific, precise, or concrete. Perhaps, you will say, even more to the point than the chosen one when viewed from the stark realities of practical life.

On the other hand you may recognize that the alternative titles are more narrow in scope. And that is precisely the point: In organizing the session we would like to look into the problem in a very wide context. So - that is the reason for the title of this session, and let us bear in mind this wish of the organizers, when we hear the various papers being presented, and when we enter into the discussion later today. Let us in this session deal with safety in the widest possible context.

A look at the fundamental elements of safety concepts in this wide context may give us some key-words for a formal structuring:

- The goals, or objectives.
- The process of realization, or the safety measures and how they are deployed.
- The organizational and structural codes.

You will find these three key-words in the three introductory reports which I hope all of you have read carefully. There is some overlap, of course, but on the whole we will find that this is one way of phrasing the cornerstones of safety concepts. Let us now take a closer look.

Safety is always at the mercy of economy. I have not yet seen any cases or any areas where this is not true. I do not, however, say that there is a constant conflict between safety and economy. It is more like a constant problem of trade-off between demands for safety and demands for economy. This is clearly implicit in the papers you are going to hear in this session today. And this is where the objectives are important. Left unconsciously to the driving forces behind all business enterprises, safety comes last - if at all. The clear statement and analysis of objectives assist us in deciding what is our practical aim. This gives safety a fair chance in the constant trade-off with economy, because in advance we can decide on priorities in situations, where it is difficult to remember ambiguous public demands and high level safety requirements.

Having decided on - or more likely, at least analyzed - the safety objectives, we face the difficult task of realizing our goals. And, believe me Ladies and Gentlemen, few things are more difficult than realizing complex goals, and safety goals are always complex in practice.

Please also believe me when I say that it is equally difficult to breathe life into innocuous statements of high level safety goals, especially political ones. To interprete such goals can be simple, though normally they are not. In this respect, we are faced with the management of risks, and as you will see from the papers, in particular with the prevention of human error.

We can set up quality control or even quality assurance systems. We can define responsibilities quite unambiguously, We can describe the competence and duties of all people involved in the whole building process. We can use the latest scientific knowledge in the dimensioning of structures. We can impose control on data. We can supervise the whole building process. But tell me: Who supervises the supervisor? Who can control greed and laziness? Who can at all times guarantee vigilance, alertness, patience and common sense?

The realization of safety is a fight all the way, especially against human error. We have papers in this session which deal with this problem, but are we on the right track?

I gave you codes as the third key-word. Codes are very important because they are mostly based on law. They are legally based requirements which can be enforced onesidedly. Codes are therefore very important as limits of safety - or rather -limits of risk, which can not be overridden in the trade-off between safety and economy. Codes make up the basis from which safety can stand up to economy.

What then is the basic problem we are facing in this seminar on Safety Concepts? Without knowing the answer each one of you will give to my question, I shall hazard my own.

There seems to be a lack of an overall model for safety concepts which can be used in practical life. An overall model where we can focus the research work done in various places around the world, and in the various areas of our profession. In my introductory report, I have tried to envision such a model. It is certainly not good enough, I know of far better ones. MORT - the Management Oversight and Risk Tree, developed in the USA, is one in particular. But it is very complicated both to show here, and to learn. Furthermore, it is developed in quite another context than this congress covers. Still it is an alternative which is worth while looking into.

Perhaps the main objective of this seminar of Safety Concepts could be to initiate work on such an overall model.

Before I give the word back to the Chairman, allow me to say just a few words on the selection of the papers and their arrangement in this session.

There has been a conscious policy behind the selection of papers in that the contributions that did not fit into the rather broad theme were rejected. This has nothing to do with the quality of the papers. The organizers were very lucky in that as much as 24 papers were received. Obviously, the schedule for the seminar could not accommodate so many papers. A decision was therefore made to reject 8 papers for the reason I have already given. It was not easy to do, because the papers were of good quality, and in a restricted sense, very interesting. Unfortunately, two authors had to resign from presentation of their contributions, due to different reasons.

In arranging the sequence of the selected contributions, it has been attempted to follow some kind of logical train of thought. Firstly, we have the papers more or less dedicated to goals, followed by contributions related to safety measures, the planning of safety and related problems. Finally, we have the papers dealing with design problems in a narrower sense. Please forgive us, if a paper has been placed in a wrong section.

I know that Professor Jörg Schneider, the coordinator for this seminar, has had some difficulties in allocating the contributions to the areas of the introductory reports prepared by Mr. Knoll and myself. It just shows you how difficult safety concepts can be sometimes. As a consequence, the concluding remarks from Mr. Knoll and myself, have both been scheduled to the very end of the formal presentations. We shall then be treating the same contributions, but from our respective personal points of view.

Well now, Ladies and Gentlemen, all that is left for me to say, is to express the wish that we shall have a lively discussion, especially when the free discussion period comes in the afternoon. I am confident that the presentations and, last but not least, you, the audience, will ensure a good discussion.

Thank you for your kind attention. Thank you Mr. Chairman!

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Some Thoughts on Optimization in Civil Engineering

Réflexions sur l'optimisation dans le génie civil

Einige Gedanken zur Optimierung im Bauingenieurwesen

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SUMMARY
The present contribution emphasizes the doubts and open questions that trouble anybody who investigates the optimization of structures under random uncertainties. The technical aspects of such a problem are often secondary in comparison with the weight of social and economic parameters, whose definition is analysed.

RESUME
On présente les doutes et les aspects troublants pour celui qui étudie l'optimisation des structures définies par des paramètres aléatoires. Les aspects techniques du problème sont souvent secondaires par rapport aux aspects économiques et sociaux, dont on analyse la définition.

ZUSAMMENFASSUNG
In dieser Abhandlung werden die Zweifel und offenen Fragen behandelt, mit welchen alle diejenigen konfrontiert werden, die sich mit der Optimierung von Tragwerken bei zufälligen Parametern befassen. Die technischen Gesichtspunkte des Problems sind oft zweitrangig, verglichen mit der Bedeutung sozialer und wirtschaftlicher Parameter, deren Definition untersucht wird.

1. INTRODUCTION

The determination of safety and reliability from a "probabilistic" viewpoint is becoming more and more widely recognized as a rational basis for design of structures and, more generally, of "constructions". Before it can be generally used in actual design, however, it is necessary not only to collect more statistical data and to develop better analytical and numerical procedures, but also to establish unambiguously a few basic principles and methodologies. The discussion and the exchange of opinions between experts of different backgrounds,which will take place at the 11th IABSE Congress on Theme X (Safety Concepts), will certainly be a great occasion in this respect. Therefore, the main aim of this contribution is not to present answers, but rather to formulate doubts and open questions as part of a hopefully stimulating discussion.

2. PROBABILITY OF FAILURE

The first point to be underlined is that, at the very high levels of reliability required in civil engineering, the calculated "probabilities of failure" have no objective, statistical meaning but are rather reference values: as such, they are very important because they allow, when calculated and used in a consistent (and honest) way, quantitative comparisons between alternative designs, thence the "optimization" of the design with respect to some rational "objective function". If this point is not understood from both perspectives, probabilistic methods can become very misleading in civil engineering, or conversely remain at the level of generic, qualitative (and sometimes trivial) statements.

3. EXPECTED UTILITY

In optimization of structures under random uncertainties, the *objective function* is usually identified with the *expected utility*, defined as the expected benefit B, minus the cost of construction and normal maintenance H_I, minus the expected loss L:

$$U = B - H_I - L \qquad (1)$$

In turn, the expected loss L is usually given the form

$$L = H_f \, P_f \qquad (2)$$

where H_f and P_f are respectively the cost and the probability of failure. However, one should not overlook the fact that in most actual cases failure is not a "yes-or-no" event, but rather a "progressive" one, which happens through several "degrees of damage" corresponding to different "limit states" (e.g. minor cracking, unserviceability, major structural damage, catastrophic collapse, ...): sometimes, a type of damage can only occur after another one (e.g. plastic collapse is usually preceded by unacceptable deformations), in which cases one speaks of "limit states in cascade"; other types of damage are completely independent on each other |1| |2|.

Each degree of damage implies a different cost: all corresponding "expected costs" (in general, cost of each damage H_{fi} times probability of that damage P_{fi}; but only the difference of the respective P_{fi}'s must be taken into account in the case of "limit states in cascade") should be summed up to form the expected loss. This is in principle possible, as it has been demonstrated by the writers: in particular the guidelines for selecting the structural design that maximizes expected utility taking account of three limit-states have been illustrated, with reference to a simple example, in Ref. |1|, where a single design pa-

rameter was considered and the "optimal" point was chosen by direct comparison of possible designs. Later, this approach has been extended to more design parameters by means of a suitable procedure |2|, based on the introduction of approximating analytical relations that allow the use of a library optimization algorithm. However much more research is needed to obtain results that can be used in actual design practice:
- quantitative data of sufficient generality on costs of failures are lacking;
- the numerical procedures, still very cumbersome, have not been applied to "concrete" examples;
- further difficulties in the formulation of the "expected loss" can be envisaged if the "damage", rather than increasing in finite steps, is to be considered as a continuous (but certainly non-linear) function;
- the cost of maintenance should also be given a "probabilistic" format;
- etc. etc..

4. CHOICE OF THE UTILITY FUNCTION

Besides improvements in its definition and calculation, the very choice of the "expected utility" as the objective function in structural optimization can be questioned on several grounds. First, each interested party (owner, contractor, prospective tenant, the society at large) may have a different view of what is the "benefit" to be expected or hoped from a construction, and evaluate differently the costs and the losses. Also, each party has a maximum amount of damage (monetary or other) whose risk is willing or capable of affording: therefore a "minimax" design rule should be in some way integrated into the "maximum utility" concept |3|.

Perhaps, the objective function should not be the "expected utility", but some sort of "characteristic utility" corresponding to a predetermined probability of being attained ... Furthermore the interests of all parties should be taken into account, with appropriate weights. All these questions certainly go well beyond the usual playing grounds of structural engineers, but we must contribute to their answers.

5. DEPENDENCE ON ECONOMICS

In decision theory the utility approach is regarded as an axiomatic method. One states a set of axioms on the effects of his "strategies" and on the behaviour of the environment, so that some decisional rules can be derived |3|. However the above utility approach to the structural optimization problem contains implicitly a dependence of the technical problem on the economical trends at the time of design. So the maximum utility design depends on the present interest rate and on the present ratios between the monetary values of the different elements (material, labour, personal property involved by a failure, ...) that define the problem. Some case-studies |1||2| showed that thus different optimal designs are obtained, that generally correspond to different safety degrees.

With reference to the steel portal frame of Fig. 1, some of the results obtained in Ref. |2| are plotted in Figs. 2 and 3. They were determined under the assumptions that the mechanical and geometrical properties of the frame are deterministic, while both loads are random variables distributed according to an extreme law of type II (maxima). In Fig. 2 the expected utility U is plotted versus the *probability of failure* rate P_{f1} per year, *failure* being defined by either the buckling of the right-hand pin-ended column or the development of two plastic hinges, involving a collapse mechanism. The economical loss when total failure occurs is denoted by H_f. An excessive permanent deformation limit state was also considered in the calculations: the loss associated with its occurrence is denoted by H_d. The curves shown represent the envelopes of the curves (P_{f1},U) obtained during the performance of the last step of the numerical optimization procedure proposed in Ref. |2|. It is worth noting that each of these curves was obtained allowing the value of the design parameters s_1, s_2, s_3 (see Fig. 1) to vary within a cube (in the s_1, s_2, s_3 space) of side 1.25 cm. This cube was the smaller neighbourhood of the maximum utility point considered by the optimization algorithm that consists in gradually reducing the cube side from 20 cm to 1.25 cm, to restrict the optimal design point.

Comparison of the curves obtained for different values of the interest rate γ illustrates clearly the dependence of the maximum utility design on the economical trends at the time of design. For instance, if γ is assumed equal to 15% instead of 5%, for both the considered cases $H_d = 3$ and $H_d = 15$ the initial steel weight of the structure decreases by about 10%, the maximum expected utility increases by 0.5%, but the probability of failure per year increases from $3x10^{-7}$ to $3x10^{-6}$ approximately. This result was obtained under the assumption that in both cases, a successful structure yields the same total benefit B^o;however, if the same yearly benefit is assumed, the only consequence is a higher total benefit for the structure characterized by a lower interest rate, and Ref. |1| pointed out a very little dependence of the optimal design on the variable B^o.

If the optimum design is regarded as the most suitable distribution of the available resources capable of providing safety to the analysed structure, the discussed utility approach must be completed by a constraint on the failure probability relevant to the maximum utility design. Without this constraint, in fact, the solution of structural optimization might be an economical optimum that defines a design unsatisfactory (unsafe) from a social requirement viewpoint.

6. SENSITIVITY TO PERTURBATIONS

It may be of interest to indicate a possible handicap, sofar not examined to the writers' knowledge, of structures designed to the "maximum expected utility" rule. It is known in deterministic structural theory that an apparent "optimal" design can be very sensitive to structural "imperfections" or other forms of "perturbations" |4|. Perhaps, a "probabilistically optimal" design might result very sensitive to human gross errors, and other abnormal events, usually neglected in the calculations.

This possibility is evident also from Figs. 2 and 3. In the design parameter space, some of the different descent paths from the optimal design point (in a neighbourhood such as the analysed cube of side 1.25 cm) involve very little decreases of the expected utility. But, in the same neighbourhood, there are also some other descent ways that lead to very small (sometimes negative) values of the objective function. In other words, the structural problem is very sensitive to some sort of perturbation, and a high *risk* is associated with the optimal design. To avoid this danger, one can search the maximum expected utility point in the design parameter space in order to define the region of the satisfactory designs, but, once the optimum is determined, the stability of the solution must be investigated and, if necessary, improved.

7. TAKING ACCOUNT OF INTANGIBLES

Some of the contradictions between "expected utility" and "maximum acceptable damage" can be removed if it is understood that some damages cannot be assigned a "price" in monetary terms: human life is the foremost example, as it indeed should be obvious. On the contrary, many researchers have tried to include it in the formation of an objective function, obtaining absurd results,as underlined

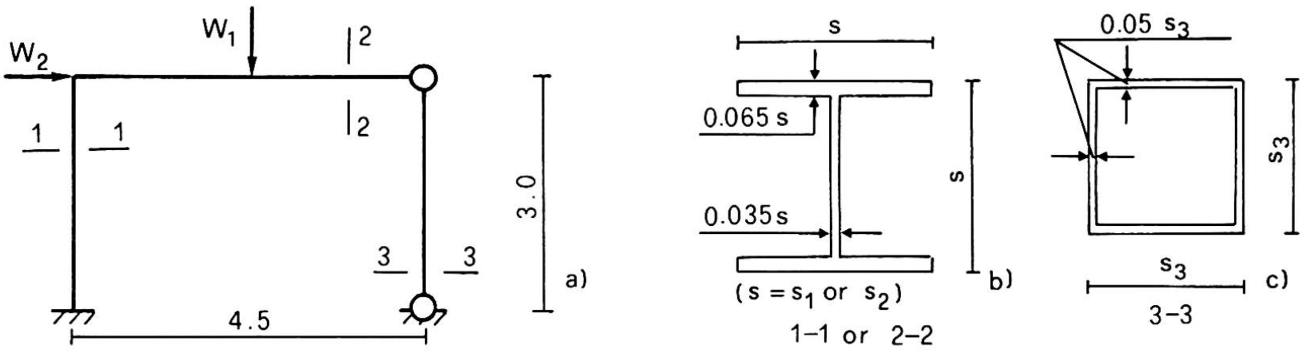

FIGURE 1 (from Ref. |2|) - Example design problem (lengths is meters). Economical parameters: total benefit in case of full success $B^{\circ}=3000$; loss for total failure $H_f=750$ or 1500; loss of excessive deformation $H_d=3$ or 15; interest rate $\gamma=5\%$ or 15%. Monetary unit: 1 kg of steel for B° and U; 1 t of steel for H_f and H_d. Loads: mean values $W_1=2.8$ t; $W_2=0.7$ t; coeff. of variation $c_{W1}=0.1$; $c_{W2}=0.2$.

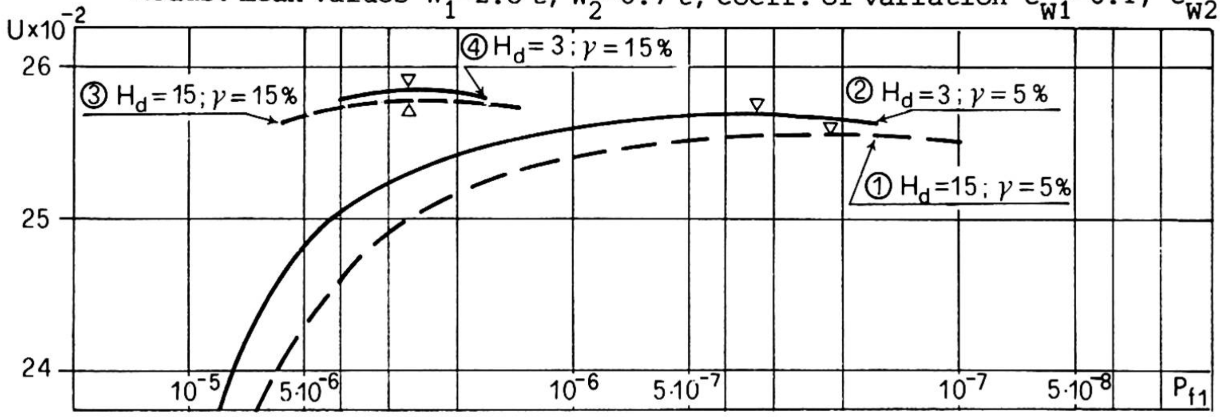

FIGURE 2 - Expected utility U vs. prob. of failure rate P_{f1} per year ($H_f=1500$)

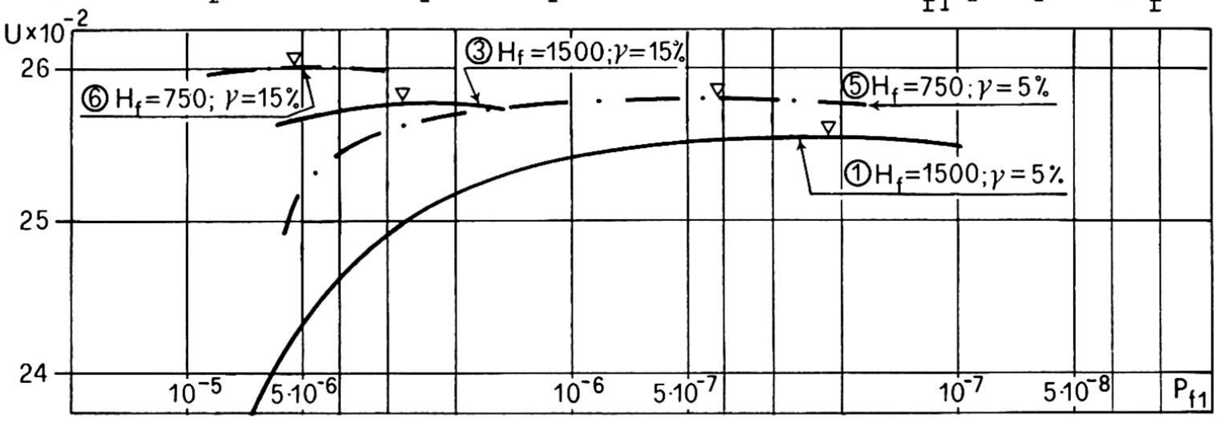

FIGURE 3 - Expected utility U vs. prob. of failure rate P_{f1} per year ($H_d=15$).

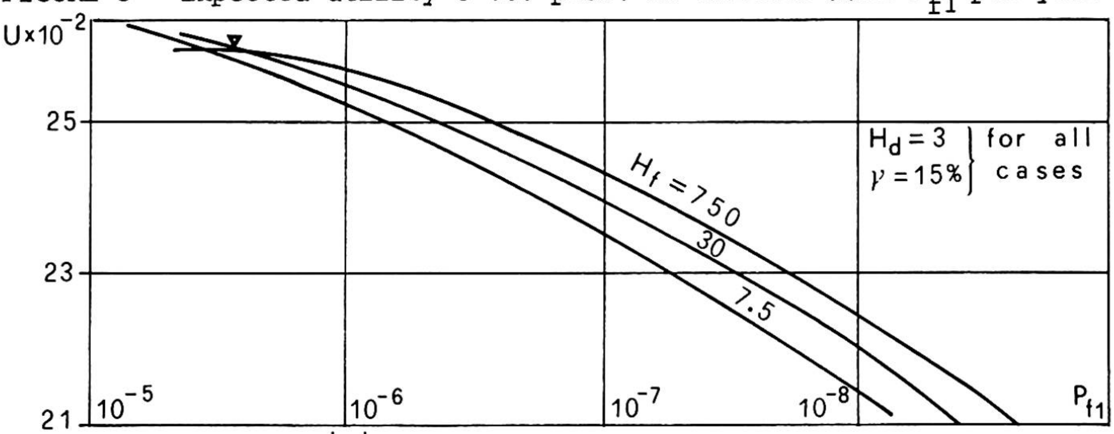

FIGURE 4 (from Ref. |8|) - Expected utility U vs. prob. of failure rate P_{f1} per year; the curves are obtained by following the slowest descent path.

by Grandori |5| and Rosenblueth |6| among others. This occurs also when a "price" of human life is simply thought as an additive term implicitly included in the losses, as in the maximum utility approach of Refs.|1||2|. This point can be illustrated with reference to Fig. 3, which shows, together with the curves ① and ③ , also the analogous curves corresponding to half the loss H_f associated with structural failure (H_f = 750 instead of H_f = 1500); however, in this way a very little modification of the maximum utility design and of the associated probability of failure per year is obtained. In other words, the maximum utility design is not sensitive to human life loss, when this is accounted by a conventional price, unless such high prices are associated with it that the economical aspects of the problem are certainly misrepresented.

A more rational way of formulating the maximum utility design problem avoiding the contradictions emphasized in this Section and in the previous one, is perhaps the one recently suggested in |7|, on which further investigation is in progress |8|. In this approach, one finds first the "economically optimal" design, i.e. the design with the largest expected utility; in this calculation only purely monetary costs must be considered, including those connected with "intangible" quantities. Then, it must be checked that the design so obtained has an acceptably low "probability of failure" (and consequently, the absolute value of the latter loses statistical significance, as already discussed); if so, the design can be varied, in the sense of increasing its "reliability" (i.e. diminishing the risk to human life) while decreasing its expected utility. On the basis of the comparison between the relevant marginal values, considerations of different nature from strict economics will lead to decide how much one is willing to "spend" in terms of utility to save human lives.

Examples of the results that are being obtained in Ref. |8| are shown in Fig. 4, where the expected utility of the structure of Fig. 1 is plotted versus the "probability of failure" (per year): these curves have been obtained by varying the design parameters in such a way that the loss of utility for the same increase in reliability is minimized (slowest descent path). Inspection of Fig. 4 shows that, for instance, for H_f = 750 and γ = 15%, a 10% decrease of the expected utility (from 2600 to 2350 approximately) corresponds to a 100-fold decrease of the "probability of failure" rate (from 0.5×10^{-5} to 0.3×10^{-7}, approximately), and a 20% decrease of utility (to 2100 approximately), to a 1000-fold decrease of probability of failure (to 0.3×10^{-8} approximately). Note also that, while the optimum design is sensitive to the value of H_f, the curves for different H_f's become very close to each other along the descent.

AKNOWLEDGEMENT - The researches referred in this contribution are supported by grants from the Italian National Research Council (C.N.R.).

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X

Optimum Aseismic Design Level of Structures

Dimensionnement optimal des structures contre les tremblements de terre

Optimale erdbebensichere Bemessung von Tragwerken

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SUMMARY
Optimum aseismic design level of structures in urban region is examined from the total cost which involves initial construction cost, aseismic design cost and expected direct structural and secondary social losses due to earthquakes damages. Discussions especially concern effects of social losses and variation of aseismic resistance of structures using a probabilistic approach. Reliability analysis of a system which consists of several structures is also conducted.

RESUME
Le dimensionnement optimal des structures construites en ville est examiné du point de vue des dépenses totales comprenant les frais initiaux de construction, les dépenses engagées vis-à-vis des tremblements de terre, les dégâts à la structure et les pertes sociales causées par les tremblements de terre. L'influence des pertes sociales et la variation de la résistance des structures contre les tremblements de terre sont spécialement discutées à l'aide de la théorie des probabilités. L'analyse de la sécurité d'un ensemble de structures est aussi présentée.

ZUSAMMENFASSUNG
Die optimale Bemessung von Tragwerken in städtischen Regionen gegenüber Erdbeben wird untersucht im Hinblick auf Erstellungskosten, Kosten für die Sicherung gegen Erdbeben, die durch Erdbeben ausgelösten direkten Tragwerkschäden und die weiteren sozialen Kosten. Wahrscheinlichkeitstheoretisch werden speziell die Einflüsse der sozialen Kosten und die Variation des Tragwerkwiderstandes behandelt. Auch die wahrscheinlichkeitstheoretische Analyse von aus mehreren Tragwerken bestehenden Systemen wird behandelt.

1. INTRODUCTION

Since earthquake motions impose strong and random loads on structures, there may be alternative ways to design structures, depending on concepts of safety and practical economic limitations, as stated in the Introductory Report.[1]

A common philosophy of aseismic design under economic restrictions is to design structures to be undamaged for earthquakes expected a few times or more in the life time of the structure and to avoid total collapse and life loss (although permitting structural damage) for earthquakes which are expected once or less in the structure's life time. This aseismic design may be achieved by sophisticated designing of each structural element without much expense in the future.

However, most structures in Japan are now designed for earthquake loads according to structural codes which specify equivalent horizontal and vertical static forces in terms of seismic coefficients K_h and K_v, respectively. K_h is estimated by the product of the standard seismic coefficient K_0 (usually 20% of gravity), regional seismicity coefficient K_1, local soil condition coefficient K_2 and an importance factor K_3:

$$K_h = K_0 K_1 K_2 K_3$$

Thus, K_3 is the only parameter which can possibly reflect ideas of safety and the consequences of secondary socio-economic and human losses due to earthquake damage. In Japan, the range of K_3 is specified as 0.8-1.0 for bridges, 0.5-1.5 for port structures, 0.9-1.1 for railway structures and 1.0-1.2 for building.[2] These ranges are not determined from analytical trade-offs between seismic design cost and expected structural and social losses but from design experiencies considering the practical importance of the structure.

The purpose of this paper is to examine critically the relation between the importance factor and the optimum aseismic level of structures in terms of the total cost which is defined as the sum of contruction cost and structural and secondary losses. Effects of variation of structural resistance and redundancy of a system on the probability of seismic failure are also investigated through reliability analyses.

2. OPTIMUM ASEISMIC DESIGN LEVEL OF A STRUCTURE BY TOTAL COST

2.1 Model of Total Cost

As a measure of optimization, the total cost C_t consisting of construction cost C_i and expected value of direct and secondary losses C_f is adopted., i.e.,[3]

$$C_t/A_0 = (C_i + E[C_f])/A_0 \qquad \text{..............(1)}$$

where

$$C_i = A_0 + A_1 a_{yd}^2 \qquad \text{......................(2)}$$

A_0 is the initial construction cost and it is assumed that aseismic design cost $A_1 a_{yd}^2$ is proportional to the square of designing level a_{yd} which has the dimension of acceleration. The total seismic loss C_f is calculated from the sum of the direct structural loss L_p and secondary socio-economic loss L_s as

$$C_f = L_p + L_s \qquad \text{.........................(3)}$$

L_p and L_s are estimated from maximum ground acceleration of the earthquake and parameters of structural resistances as,

$$L_p = \begin{cases} 0 & (a \leq a_{yd}) \\ C_{f0}/2 & (a_{yd} < a < a_c) \\ C_{f0} & (a_c \leq a) \end{cases} \quad ....(4)$$

$$L_s = K\, C_{f0} \quad ....(5)$$

where

$$\theta = (a_f - a_{yd})/(a_c - a_{yd}), \quad r = a_c/a_{yd} \quad .....(6)$$

The basic concept of losses is schematically illustrated in Fig.1 where a_{yd}, a_f, a_c are yielding (= design level), failure of function level and level of total collapse, respectively. It is assumed that the structural loss between the levels of a_{yd} and a_c is one half of total collapse. In calculation, structural parameters are treated as either deterministic or Gaussian random variables.

Estimation of secondary socio-economic loss L_s is a complex and difficult task, especially when human life is involved.[4] In this study, L_s is simply measured by a parameter K which shows the degree of socio-economic loss as compared to structural loss C_{f0} for purposes of examining its effects on optimum aseismic design level. The social loss is modeled to occur from the level of a_f which is located between a_{yd} and a_c.

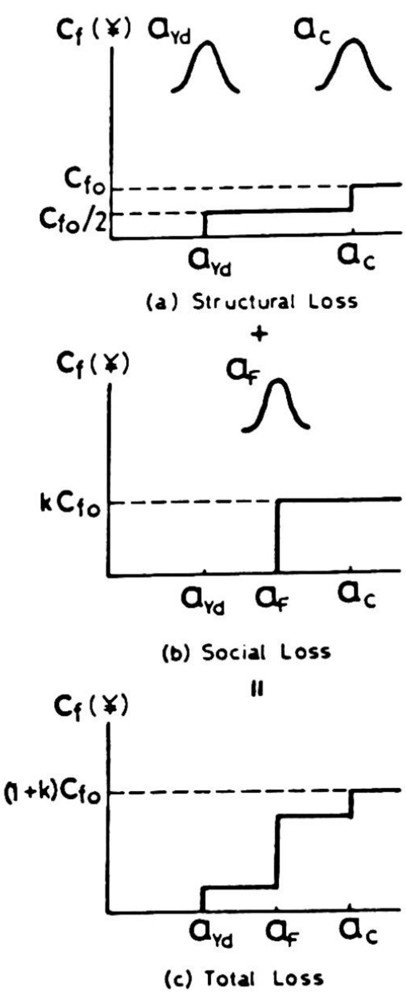

Fig.1 Schematic Illustration of Total Cost due to Seismic Effects

When we know the annual rate λ of earthquake occurrence and probability distribution p(a) of maximum ground acceleration a, the expected value of the total seismic loss C_f is calculated for the case with deterministic resistance as,

$$E[C_f/A_0] = (\lambda/A_0)\int_0^T\int_0^\infty (L_p e^{-\gamma t} + L_s)\, p(a)\, da\, dt \quad ....(7)$$

where γ is a decreasing rate of structural value with time. When structural resistances are random variables, it is necessary to calculate the probability of exceeding the levels of a_{yd}, a_f, a_c from reliability analysis.

2.2 Random Earthquake Loads

Probability density p(a) of maximum ground acceleration is calculated from so called M-Δ (magnitude and epicentral distance) analysis.

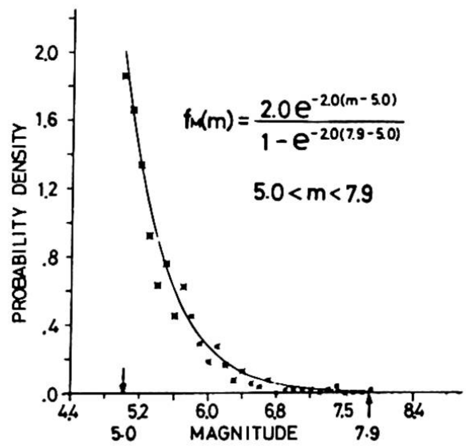

Fig.2 Probability Density Function of Earthquake Magnitude

Probability density $f_M(m)$ of magnitude m of earthquakes is determined from logN-M Curve (N:number of earthquakes) of earthquake occurrence in western part of Japan as

$$f_M(m) = 2.0e^{-(m-5)}/(1-e^{-5.8}) \ldots\ldots\ldots (8)$$

Attenuation of maximum ground acceleration due to epicentral distance Δ is governed by next equation, of which parameters are determined from earthquake data in Japan. [5]

$$a = 0.02\, e^{0.7m}\, \Delta^{-0.8} \ldots\ldots\ldots\ldots\ldots (9)$$

Combination of Eqs.(8) and (9) gives p(a) at any construction site if epicentral distance is given. In this study, local soil conditions which can be included in Eq.(9) are not considered.

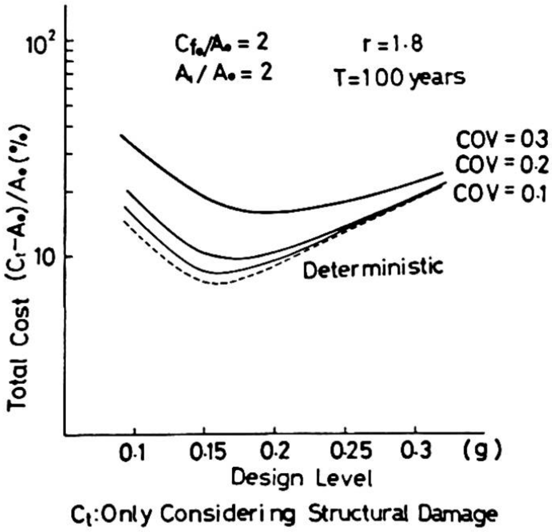

Fig.3 The Normalized Total Cost Without Social Loss

2.3 Calculated Results and Discussions

In Figs.3,4 and 5, the normalized total cost which consists of aseismic design cost $A_1 a_{yd}^2$ and seismic loss C_f is shown against design level a_{yd}. Seismicity parameters are λ=0.05 and Δ=50Km. Values of structural parameters are given in the figures. COV expresses coefficient of variation of Gaussian random structural resistances.

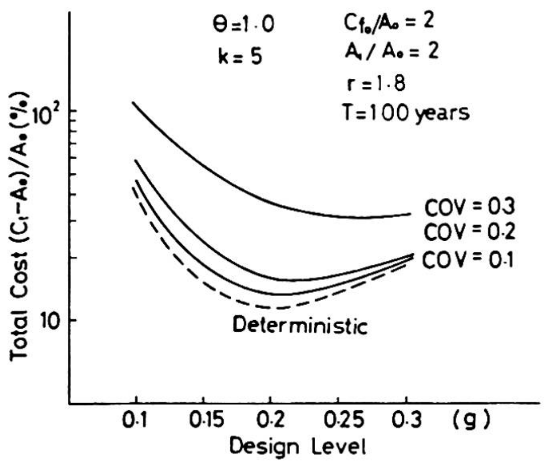

Fig.4 The Normalized Total Cost With Social Loss (K=5)

The total cost without secondary social loss (i.e., K=0.0) is plotted in Fig.3 to show the higher optimum design level for structures with larger variation of resistances. This effects is easily understood from the fact that the larger variation of resistances brings higher probability of failure and hence needs the higher total cost. When design level becomes very high (a_{yd}>0.3g), the probability of failure is reduced greatly and the total cost is almost not affected.

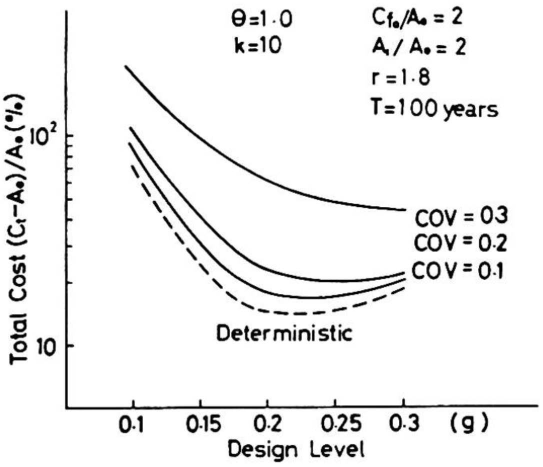

Fig.5 The Normalized Total Cost With High Social Loss (k=10)

In Fig.4, the socio-economic loss L_s which is 5 times as large as the structural loss C_{f0} (K=5) is considered for the same structure in Fig.3. This may be a case of important structures or buildings which are usually used by many people. It is found that the optimum design level is increased 5% in g and the total cost is also increased about 5%, except for a structure with a high variation of resistance (COV=0.3).

In Fig.5, the value of K is increased to 10 to investigate effects of very high secondary socio-economic loss. This may be a case of critical structures or buildings which should be used for purposes of evacuation from fire or rescue operations immediately after earthquake occurence. Both the optimum design level and the total cost are found to be increased by 7-10% as compared to Fig.3, except for the case of COV=0.3 which shows monotonous decrease of the total cost. It should also be noted that the range of optimum design level (=minimum total cost) becomes wide when the social loss and the variation of structural resistances are large. Especially for a structure with K=10 and COV=0.3, it is quite difficult to determine the optimum design level.

The effect of θ, which shows at which level the social loss starts to occur between a_{yd} and a_c, were also examined by numerical results, which are not shown in this paper. They were found to be very small both for the optimum design level and the total cost.

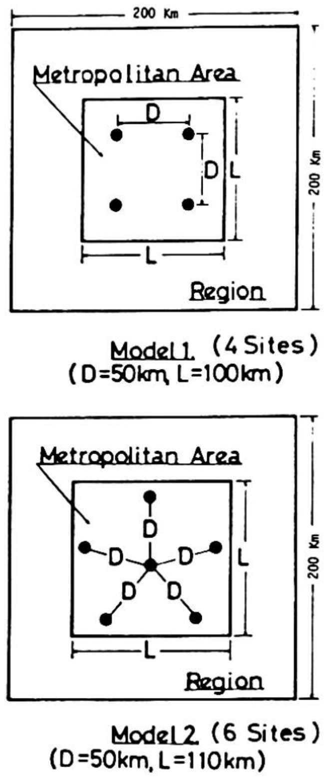

Fig.6 Models of Metropolitan Area and Seismic Region

3.RELIABILITY OF STRUCTURES AS A SYSTEM

3.1 Model of A System and Its Reliability

Just after a big earthquake hits an urban region, important civil engineering structures and public facilities can be considered as a system for emergency operations, such as evacuation and rescue. In this study, a simple system which consists of several structures with the same resistance is considered. Models are shown in Fig.6 where important structures or facilities are located at each site. In a metropolitan area, there are 4 and 6 sites in models 1 and 2 with independent failure modes. Hypocenters of earthquakes are modeled as uniformly distributed in the area and the region.

When the system has no redundancy, reliability of the system becomes a weakest linkage problem. That is, the probability of the system is that of any one of the site. On the other hand, when the system has sufficient redundancy, the probability of failure of it is that of all of the sites.

3.2 Calculated Results and Discussions

In Fig.7, the probability of simultaneous excess of design level a_0 (=0.15g) of model 1 is plotted. Horizontal axis is the least number of sites where the maximum ground acceleration exceeds this level. Continuous lines are probability for 1 year and broken lines are for 50 years. Annual rate λ of earthquake occurence was

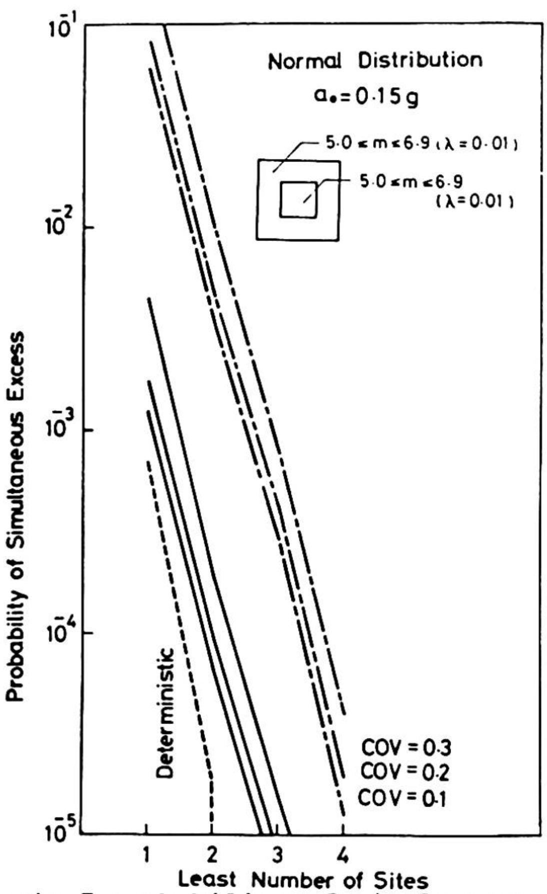

Fig.7 Probability of Simultaneous Excess of a_0 (Model 1)

set relatively small, at 0.01, because of limited epicentral region. Resistance of the sites is also treated as either deterministic or a random variable. It is clearly seen that the probability of simultaneous excess decreases sharply with the number of sites. Probability of failure of at least one of the sites is about 10^4 times higher than that of all of the sites, which verifies the importance of redundancy of these systems. The larger variation of resistance of sites results in a higher probability of failure, as expected.

Effects of the design level on the probability of at least one of the sites of models 1 and 2 on one year are shown in Fig.8. It is important to notice that the probability of failure decreases with different ratios, depending on the variation of resistance. When the sites are deterministic or random (with small variation of resistance), an increase of design level efficiently reduces the probability of failure. On the contrary, an increase of design level of sites with high variation of resistance has a small effect.

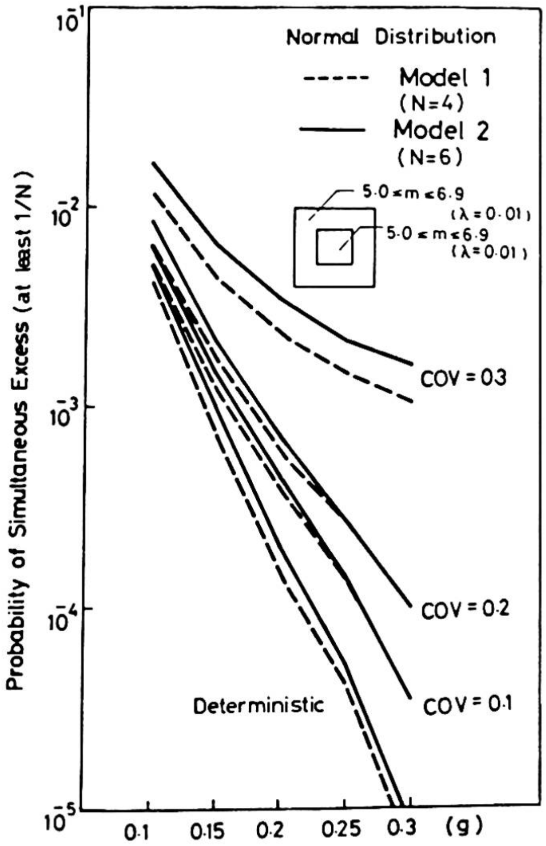

Fig.8 Probability of Simultaneous Excess of a_0 against Design Level

4. CONCLUSION

Optimum aseismic design level of a structure is determined from the total cost, which consists of construction cost and direct structural and secondary socio-economic losses. When the secondary loss of important public structures is assumed to be 10 times as large as the structural loss, the optimum design level is found to be increased by about 10%. This result gives an analytical background to present Japanese aseismic design codes, most of which define a 20% increase in design level for important and critical structures.
Larger variation of structural resistances gives higher probabilities of failure and consequently higher total cost and design level.
High effectiveness of an increase of design level in order to increase the probability of safety can not be expected for structures with high variations of resistance.
The desirability of redundancy is verified to decrease the probability of failure of a system significantly, from reliability analysis of structures treated as a system.

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X

Die optimale Sicherheit oder das akzeptable Risiko bei Bränden in Gebäuden

Optimum Safety or Acceptable Risk in Case of Fire in Buildings

Sécurité optimale ou risque acceptable en cas d'incendie dans des bâtiments

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ZUSAMMENFASSUNG
Bauwerke können und müssen Personen und Sachwerten im Brandfalle eine optimale Sicherheit bieten. Dies gilt namentlich für Objekte, die der Öffentlichkeit zugänglich sind, wie Hotels, Versammlungsstätten, Warenhäuser usw. Wirksame und wirtschaftlich tragbare Lösungen von Brandschutzproblemen lassen sich in der Regel nur mit Schutzkonzepten verwirklichen, die auf klaren Vorstellungen über die Schutzziele für Personen und Sachen beruhen. Ein geeignetes Arbeitsmodell für die Beurteilung der Brandgefährdung und der Ableitung von Schutzzielen und Schutzkonzepten wird erläutert.

SUMMARY
Buildings must and can be constructed in such a manner as to offer an optimum of safety to persons and property. This becomes especially important for buildings accessible to the general public such as hotels, meeting-places, department stores, etc. As a rule, effective and economically acceptable solutions of fire protection problems can only be obtained by concepts based on clear objectives of personal and property protection. A tested method for assessing fire risk and quantifying them with reference to a defined acceptable risk is described.

RESUME
Les bâtiments peuvent et doivent offrir une sécurité optimale aux personnes et aux biens, et cela même en cas d'incendie. Pour les immeubles largement ouverts au public, tels qu'hôtels, salles de réunion, grands magasins etc., cette exigence devient d'une importance primordiale. Des solutions efficaces et économiques ne peuvent en générale être réalisées qu'au moyen d'une méthode basée sur les objectifs de protection pour les personnes et les biens. Un modèle éprouvé pour juger le risque d'incendie et déterminer les mesures de protection est présenté.

1. EINLEITUNG

Personen und Sachwerte in Gebäuden lassen sich gegen die Folgen eines Brandes durch verschiedenartige und verschieden aufwendige Massnahmen schützen. Nach welchen Kriterien werden diese ausgewählt und festgelegt?

Nach der üblichen Vorgehensweise beschafft sich der mit der Planung eines Bauwerkes beauftragte Architekt oder Ingenieur die geltenden Vorschriften und Weisungen der zuständigen Brandschutz-Behörden. Diesbezügliche bauaufsichtliche Forderungen werden aber oft nur mangelhaft verwirklicht, weil entweder das Verständnis für die Notwendigkeit der zu Recht geforderten Schutzmassnahmen fehlt, oder aber die Zweckmässigkeit einzelner Forderungen - manchmal berechtigt - bezweifelt wird. Die Folgen sind Aerger, unerwartete Störfaktoren und Zusatzkosten. Bei diesem Vorgehen bleibt wohl immer eine beträchtliche Unsicherheit bestehen, wie weit das Gebäude den sich darin befindlichen Personen und Sachen im Brandfall Schutz bietet und ob dieses Gebäude - falls es z.B. der Oeffentlichkeit zugänglich ist - die Qualifikation brandsicheres Objekt verdient.

Ein alternatives Verfahren besteht darin, das Ereignis Brand als Gefahr und somit als Lastfall rechtzeitig der Planung und Bemessung eines Bauwerks zu Grunde zu legen. Dies erfordert selbstverständlich Sachkundigkeit, namentlich was die Wahl der massgebenden Gefährdungsbilder, die Definition der Schutzziele und die Auswahl wirksamer und angemessener Schutzkonzepte anbetrifft.

Diese Denk- und Arbeitsweise drängt sich heute insbesondere bei Objekten mit grossen Personen- und Sachwertrisiken auf. Sie wird künftig wahrscheinlich in vermehrtem Masse von Behörden und Feuerversicherern anerkannt oder gar gefordert werden. Dadurch lassen sich die Einzelvorschriften zu Konzepten mit bekanntem Schutzwert kombinieren und sich zudem allfällige widersprechende Forderungen erkennen und eliminieren. Auf das offensichtlich Vorteile versprechende Arbeitsmodell: "Analyse der Gefährdung, Wahl des Schutzkonzeptes nach Zielvorstellungen" soll nachstehend eingegangen werden. Dabei werden auch die Begriffe Gefährdung, Risiko und Sicherheit für die Lastfälle Brand und Explosionen kurz beschrieben.

2. RISIKOANALYSE, EIN ARBEITSMODELL

Die systematische Bearbeitung der Brandschutzprobleme für ein Bauvorhaben umfasst eine Reihe von Aufgaben. Diese rechtzeitig auszuführen und zeitgerecht in die Planung und Erstellung eines Bauwerks einzufügen, ist Voraussetzung, um ein gefordertes Sicherheitsniveau in optimaler Weise zu erreichen.

Brandrisiken mit einer hohen Schadenerwartung sind durch geeignete Schutzmassnahmen in Risiken mit einer verminderten, tragbaren Schadenerwartung zu verwandeln. Das folgende, bewährte Arbeitsmodell führt fast "zwangsläufig" zu wirksamen und angemessenen Schutzkonzepten:

Phase	Arbeit	Ergebnis
1	Gefahren erkennen	Gefahrenplan
2	Gefährdung und Risiko beurteilen quantifizieren und mit akzeptablem Risiko vergleichen	Ist-Zustand, - Gefährdungsbild - Brandproblem
3	Sicherheitsziele formulieren Schutzkonzepte planen optimales Brandschutzkonzept festlegen	Soll-Zustand - mögliche Lösungen - wirksamste und wirtschaftlichste Lösung

3. BRANDGEFAHREN

Ein Schadenfeuer in einem Gebäude wird verhältnismässig geringe Folgen haben, falls es gelingt, den Brand zu lokalisieren und die Ausbreitung der gefährlichen Brandprodukte Hitze, Rauch sowie der toxischen und korrosiven Zersetzungsprodukte zu unterbinden. Zu folgenschweren Ergebnissen führen Brände, die sich ausweiten - von einem Raum auf ein Geschoss, auf mehrere Geschosse und auf ein ganzes Gebäude - und damit in erheblichem Masse Personen und Werte gefährden.

Brände entstehen nicht von selbst. Sie werden verursacht durch Unvorsichtigkeit, fahrlässiges Handeln oder gar Böswilligkeit des Menschen, durch das Versagen technischer Einrichtungen oder durch Umweltgefahren. Leider lassen sich durch alle Vorbeugungsmassnahmen diese Gefahren nie vollständig ausschalten.

Deshalb sind Massnahmen erforderlich, die wirksam Brände zu lokalisieren vermögen, und die den Löschkräften gute Voraussetzungen für die Brandbekämpfung und die Rettung bieten. Zur Brandausbreitungsgefahr tragen nebst dem Gebäudeinhalt (Stoffe, Waren, Einrichtungen) das Gebäude selbst, seine Bauart und die an ihm verwendeten Baustoffe bei.

3.1 Gefahren durch den Gebäudeinhalt

Einige wesentliche Gefahrenfaktoren, mit denen sich die Gefahrenschwerpunkte eines Gebäudeinhaltes zahlenmässig festhalten lassen, sind: Die Brandbelastung in MJ/m2 oder kWh/2 (pro Einheit der Bodenfläche gespeicherte Wärmeenergie, die im Brandfall maximal theoretisch freigesetzt werden kann), die Brennbarkeit (Entzündbarkeit und Abbrandgeschwindigkeit), die Qualmgefahr (durch einige in der Hitze dichten Qualm bildende Kunststoffe), die Korrosionsgefahr durch die Anwesenheit von Materialien, die bei Hitzeeinwirkung grosse Mengen korrosiver Gase und Dämpfe abgeben, und die Toxität durch Stoffe und Waren, die unter Brandeinwirkung giftige oder erstickende Gase und Dämpfe entwickeln oder als starke Gifte anzusprechen sind.

3.2 Gefahren des Gebäudes

Ein Gebäude dient als Schutzmassnahme gegen die Auswirkungen von Rauch und Hitze für die sich im Brandobjekt befindlichen Personen und Güter, sofern bestimmte Voraussetzungen erfüllt sind (Brandabschnitte, Brandzellen, Feuerwiderstand der Tragkonstruktion, abgetrennte Flucht- und Löschangriffswege).

Das Gebäude trägt auch wesentlich zur Brandgefahr bei, weil die Decken und Umfassungswände von Räumen, Geschossen und Gebäuden die Brandprodukte, wie Hitze, Rauch, Feuchtigkeit, korrosive und toxische Gase und Dämpfe einschliessen. Der entstehende Wärmestau lässt die Raumtemperatur mehr oder weniger rasch ansteigen. Der Wärmestau ist wesentliche Ursache für die oft sehr rasch einsetzende Brandausbreitung (Feuersprung, Flash-over Bedingungen).

Weitere Brandgefahren ergeben sich durch die Bauweise eines Gebäudes: Ein brennbarer Innenausbau begünstigt die schnelle Brandentwicklung in einem Raum, brennbare Wand- und Deckenkonstruktionen erleichtern bei fehlenden Unterteilungen die Brandausdehnung auf ein ganzes Gebäude.

Eine Zusammenstellung von gebäudebedingten Gefahrenfaktoren enthält [1]. Im weiteren orientieren Fachpublikationen regelmässig über die an Brandobjekten festgestellten baulichen Mängel.

4. BRANDGEFAEHRDUNG - BRANDRISIKO

4.1 Brandgefährdung

Die vorher dargestellten "potentiellen Gefahren" bedrohen oder gefährden die im Gefahrenbereich sich befindlichen Personen und Sachen. Ein Zusammenwirken mehrerer Gefahrenfaktoren erhöht die Gefährdung; geeignete, gegen die erkannten Gefahren getroffene Schutzmassnahmen verringern sie. Deshalb ist es naheliegend, den Begriff der Brandgefährdung wie folgt zu definieren:

$$\text{Brangefährdung} = \frac{\text{potentielle Gefahren}}{\text{Schutzmassnahmen}} \quad \text{oder } B = \frac{P}{M} \qquad (1)$$

Die derart definierte Brandgefährdung B kann sich auf einen Raum, auf ein Geschoss oder ein ganzes Brandobjekt beziehen. Sie ist als objektbezogene Grösse personen- und sachwertneutral.

4.2 Schadenerwartung

Das zu erwartende Schadenausmass - die sog. Schadenerwartung - schliesst die Zahl der bedrohten Personen bzw. den Wert der gefährdeten Sachwerte oder die zu erwartenden Folgeschäden ein. Die Schadenerwartung S_E ist demzufolge abhängig von der Brandgefährdung B, der Zahl der gefährdeten Personen H und deren von der Gebäudenutzung her gegebenen Brandempfindlichkeit p (mangelnde Mobilität, Ortskenntnisse und Selbsthilfemöglichkeit) bzw. der gefährdeten Sachwerte V und deren Zerstörbarkeit d (durch Rauch, Feuchtigkeit, Hitze etc.).

Mit diesen Grössen kann die Schadenerwartung als Funktion dargestellt werden

- für Personen: $S_{E,H} = f\ (B, H, p)$ (2)

- für Sachen: $S_{E,V} = f\ (B, V, d)$ (3)

4.3 Brandrisiko

Ein weiterer, im Zusammenhang mit Gefahren und Gefährdungen verwendeter Begriff ist der des Risikos. Während sich die erstgenannten Begriffe auf objektiv feststellbare und zumeist messbare Einflussgrössen stützen, beinhaltet der Risikobegriff aber noch einen grundsätzlich anderen Aspekt, nämlich die nicht exakt erfassbare Eintretenswahrscheinlichkeit (E_w) eines Ereignisses.

Mit den Beziehungen (2) und (3) für die Schadenerwartung ergeben sich die Funktionen:

- Risiko für gefährdete Personen

$$R_H = f\ (S_{E,H}, E_w) = f\ (H, p, B, E_w) \qquad (4)$$

- Risiko für gefährdete Sachwerte

$$R_V = f\ (S_{E,V}, E_w) = f\ (V, d, B, E_w) \qquad (5)$$

Die Ergebnisse dieser Funktionen sind verunfallte Personen oder zerstörte Werte pro Zeitabschnitt (z.B. pro Jahr).

In den beiden Risikofunktionen (4) und (5) erscheinen die selben Grössen B und E_w. Es ist nun naheliegend, ein objektbezogenes, eine normale Sachwert- und Personengefährdung einschliessendes Brandrisiko wie folgt zu bilden:

$$\boxed{R = f\ (B,\ E_w)} \tag{6}$$

Mit einer formelmässigen Auswertung der Beziehung (6) wie sie z.B. in Oesterreich und der Schweiz [2, 3] seit einigen Jahren bekannt ist, lässt sich jedes Bauobjekt in Abhängigkeit von Bauweise, Gebäudeinhalt und vorhandenen Schutzmassnahmen nach der spezifischen Schadenerwartung oder dem durch die Schadeneintrittswahrscheinlichkeit mitgeprägten Brandrisiko klassieren.

5. DAS AKZEPTIERTE BRANDRISIKO

Eine gewisse Gefährdung durch Ereignisse mit einer nicht vernachlässigbaren und durch die Statistiken belegten Eintretenswahrscheinlichkeit muss in jedem Objekt in Kauf genommen werden. Es ist deshalb Sache jedes Gebäudeeigentümers und der Behörde, insbesondere bei öffentlich zugänglichen Bauten,wie Hotels, Spitäler, Warenhäuser, Versammlungsstätten, ein zulässiges oder akzeptables Risiko festzulegen.

Sind in einem Objekt Personen in besonderem Masse gefährdet, wie z.B. bei hoher Belegungsdichte (Bürohäuser, Hotels), spezieller Panikgefahr (Warenhäuser, Theater), Fluchterschwerung durch Krankheit und Alter (Spitäler, Heime), Haft (Gefängnisse) oder bauliche Gegebenheiten (Hochhäuser, Tiefgaragen), muss das akzeptable Risiko angemessen reduziert werden.

$$\boxed{R_{akzeptabel} = f\ (B,\ E_w,\ p,\ H)} \tag{7}$$

Es mag auf den ersten Blick als äusserst schwierig erscheinen, zulässige Brandrisiken mit Zahlen zu nivellieren. Doch darf nicht übersehen werden, dass die Oeffentlichkeit oder die "Volksmeinung" mit geringfügigen Abweichungen von Land zu Land limitierte Risiken für viele Nutzungen längst akzeptiert hat. Ein begrenzter Zimmerbrand in einem Hotel wird z.B. akzeptiert; erfasst das Feuer mehrere benachbarte Räume und sind mehrere Todesopfer zu beklagen, wird nach Schuldigen gefragt; das tolerierte Mass ist überschritten. Zahlreiche Publikationen, z.B. auf dem Gebiete der Arbeitssicherheit geben über dieses Thema näheren Aufschluss [4, 5] .

Für die Verantwortlichen für die Planung und den Betrieb eines Gebäudes folgt als logische Konsequenz, sich Klarheit über die möglichen Ereignisse zu verschaffen, die es zu vermeiden gilt.

Die zu vermeidenden Ereignisse führen zu den Zielen für den Schutz von Personen und Sachen im Brandfall. Diese Schutzziele gilt es dann mittels baulicher und gegebenenfalls zusätzlicher technischer und organisatorischer Massnahmen nach einem Brandschutzkonzept oder Sicherheitsdispositiv, das alle massgebenden Gefährdungsbilder des Brandes berücksichtigt, zu verwirklichen.

Die erwähnten rechnerischen Beurteilungsmethoden bieten eine wertvolle Entscheidungshilfe bei der Einschätzung eines Brandrisikos. Ein zu lösendes Brandproblem liegt vor, falls das objektbezogene, vorhandene Risiko R nach (6) grösser ist als das akzeptable Risiko nach (7); Berechnung nach [2] .

6. SCHUTZZIELE - SCHUTZKONZEPTE

Brandschutz-Ziele zu setzen ist eine wesentliche und anspruchsvolle Planungsarbeit. Das Brand-Risiko zu ermitteln, welches der Gebäudeeigentümer, die Benützer und die zuständigen Behörden zu akzeptieren bereit sind, ist keine leichte Aufgabe. Einem Entscheid soll nicht ausgewichen werden, indem Einzelheiten geregelt werden, ohne das Brandproblem in seinen grundsätzlichen Aspekten zu lösen.

Schutzziele müssen so formuliert sein, dass sie der Planer versteht und auch verwirklichen kann. Allgemein gehaltene Sätze wie: "Es müssen alle Insassen des Hotels gerettet werden können" bringen nichts. Notwendig sind Zielvorgaben wie: "Ein Brand im Hotelrestaurant darf die Geschosse mit den Gästezimmern nicht durch Hitze und Rauch beeinträchtigen; ein Zimmerbrand darf sich nicht auf benachbarte Zimmer ausbreiten, die Rauchausbreitung muss auf ein Geschoss beschränkt bleiben".

Grundsätzlich sollen in grösseren Bauobjekten Ziele derart gewählt werden, dass nur der direkt von einem Brand betroffene Bereich geräumt werden muss. Ein optimal brandsicheres Objekt gewährleistet den Personen und Sachen in den nicht direkt vom Brande betroffenen Gebäudeteilen einen sicheren Aufenthalt. Dieses Ziel führt zum sogenannten Aufenthaltskonzept [6, 7], dessen Vorteile offensichtlich sind. Die heute zum allgemeinen Sicherheitsstandard gehörenden Fluchtwege werden dadurch nicht überflüssig. Diese stehen, da sie bei allen voraussehbaren und eingeplanten Brandereignissen nicht durch flüchtende Personen blockiert werden, den Feuerwehren als raschester und recht sicherer Löschangriff zur Verfügung.

Für kleinere Gebäude, Versammlungsräume und für ältere Bauten ohne feuerwiderstandsfähige Unterteilungen in Brandabschnitte und in Brandzellen kommt als Ziel oft nur die sofortige Räumung vor Eintritt einer direkten Bedrohung in Frage. Das daraus abgeleitete "Soforträumungskonzept" nimmt grundsätzlich grössere Verluste an Leben und Sachen in Kauf als das einen Verbleib im Objekt ermöglichende erste Konzept.

7. OPTIMALE SICHERHEIT

Eine optimale Sicherheit weisen Objekte auf, die in erster Linie und mit hoher Zuverlässigkeit gegen einen Grossschaden abgesichert sind. Teilschäden werden akzeptiert, sofern sich daraus keine erhöhten Gefährdungen für Personen und keine wesentlichen Folgeschädengefahren ergeben. Auf der Grundlage dieser klaren Definition lassen sich die Kriterien für die Beurteilung und Klassierung von Bauten aller Art nach ihrer Brandsicherheit herleiten.

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Societal Options for Assurance of Structural Performance

Options sociales et performance des structures

Gesellschaftliche Alternativen zur Sicherstellung des Bauwerk-Verhaltens

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SUMMARY
Several approaches to reduce the incidence of human error leading to the failure of structures to perform adequately are reviewed. It is suggested that only the techniques of control and legal sanction can have a reasonably high probability of effectiveness under all circumstances when seen from a societal viewpoint. Since relatively little quantitative data is available regarding the effectiveness of, and parameters affecting, civil engineering control measures and legal sactions, research in these areas is necessary.

RESUME
L'article considère plusieurs possibilités visant à réduire l'incidence des erreurs humaines conduisant à la ruine des structures. Du point de vue social, seules des méthodes de contrôle et de sanction légale peuvent avoir une probabilité d'efficacité raisonnablement élevée en toutes circonstances. Il est nécessaire de procéder à des recherches dans ces domaines, car peu de données quantitatives sont disponibles quant à l'efficacité des mesures de contrôle et des sanctions légales en génie civil.

ZUSAMMENFASSUNG
Verschiedene Möglichkeiten zur Reduktion menschlicher Irrtümer, welche zum Versagen von Tragwerken führen können, werden besprochen. Es wird behauptet, dass aus gesellschaftlicher Sicht Kontrollmethoden und gesetzliche Sanktionen die einzigen Möglichkeiten sind, um unter allen Umständen einen hinreichend hohen Grad der Zuverlässigkeit im Wirkungsbereich sicherzustellen. Da nur wenig quantitative Unterlagen über die Wirksamkeit von Kontrollmethoden im Bauwesen und von gesetzlichen Sanktionen wie auch über Faktoren, die diese beeinflussen, existieren, ist Forschung in diesen Bereichen notwendig.

INTRODUCTION

It is indicative of the trend in structural engineering that all three introductory reports on the theme "Safety Concepts" concern themselves to a considerable extent with the problem of "human error", the very problem recently acclaimed by Lind [1] as "the greatest outstanding problem in structural safety analysis". That the now generally accepted reliability approach considering loading, material properties and dimensional variation predicts neither real failure rates not deterioration of real structures is well known, as is the futility of increasing the factor(s) of safety to account for these differences. The measures commonly suggested to attack the human error problem have been given in the introductory reports and may be summarized as follows:

1. Education and Training (Risk Analysis).

2. Personnel Selection.

3. Task Complexity Reduction.

4. Control.

5. Legal Sanctions.

All the above measures are oriented towards the better functioning of human operators in tasks such as design, construction, etc. All measures are recommended in the introductory reports. It will be argued in this paper that while each approach is highly desirable, only two (items 4 and 5) are practicable when seen in terms of attempting to ensure the best possible structural behaviour (failure, deterioration, etc.) from the point of view of society. The distinction between that which is desirable and that which it is possible to attain, with any degree of certainty for society, seems to have been largely ignored in discussions on human error.

THE RATIONALITY OF ORGANIZATIONS

The majority of engineers function professionally as part of an organization. The organization is usually dedicated towards one or more specific functions in the construction industry. It seems reasonable to suppose that the people working in such organizations are generally conscious of their professional performance, including their safety record and its maintenance, and that they will normally take steps to rectify whatever deficiencies they perceive. However, it is also well known that under pressure of time, or in difficult contractual or inter-organizational frameworks where "conflict" arises, the rationality of the organization and its functionaries changes [2]. "Short-cuts" are taken and a situation may arise in which procedures and precautions once considered necessary, will no longer be perceived as such by those involved. In effect, the rationality of the organization will be altered as a direct result of the changing rationality of its people acting in response to the perceived external (or internal) environment. Thus, if for example, communications deterioriate, there is a tendency to take umbrage under legalistic interpretation; if time is short, to change practices; if control is lax, or success easily maintained, to slacken off vigilance. The more these effects become evident, inter-organizationally, rather than intra-organizationally, the greater is the likelihood that the common co-operative goal of producing a safe and satisfactory structure will not be attained. The changing rationality of organizations party to a construction project is evident in many cases of complete structural failure. [3]

Consistent with the above viewpoint, it is immediately evident that remedies such as education and training, and attempts to introduce risk analysis, personnel selection, task complexity reduction and internal control systems will only be successful if seen as effective measures by the managements of each organization; in other words, managements must (a) become aware of (perceive) the safety problems which they may be facing, and (b) be convinced of the appropriateness of the remedy [2]. It should also be evident that such perception of need is a fickle thing and may disappear or be seriously reduced in situations of organizational stress or laxity. Similarly, the effectiveness of any measures will be reduced. The concepts introduced above for the performance of an organization may be illustrated using the model of Figure 1, based on the psychology of arousal for individuals.

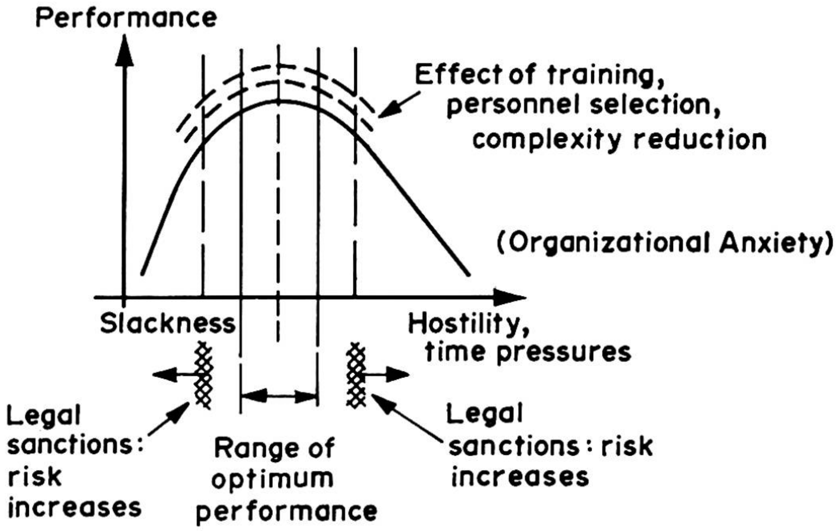

Figure 1 Performance Function

THE REQUIREMENTS OF SOCIETY

The end product of the activities of the construction industry organizations is ultimately a societal object (e.g. a structure), even if held in trust for society through ownership by some particular organization. The people who use the facility, or work there, are generally selected with a fair degree of randomness from society and are entitled to expect the same (or at least very similar) standards of safety for the particular structure as for all other generally similar structures. [This does obviously not apply to certain very specific structures.]

Given that organizational factors will affect the performance of construction industry organizations with respect to safety, and that the resultant safety (and structural performance) is a public matter, the ultimate question is the (not uncommon) one of the conflict of the requirements of social 'good' versus that of private (or organizational) 'good' - how can societal safety (and performance) be maintained, given that organizations possess their own rationality, not necessarily identical to that of the society in which they exist?

ACHIEVING SOCIETAL GOALS FOR STRUCTURES

Let it be assumed for the present discussion that societal structual safety and performance goals can be set (c.f. Schneider [5]).

Although there may be other possibilities, the two avenues commonly used in an attempt to attain acceptable societal goals for structures are external control of design, documentation and construction, and legal sanctions for those held to be responsible for structural performance failure. The effectiveness of either type of procedure in achieving the goal is largely taken for granted, but is strictly unproven. This applies particularly to legal sanctions which, while they may be an effective deterrent to negligent practice, (c.f. arguments over the death penalty for murder) have not as yet been shown to be effective in recognizing possible safety problems, or recognition of limited knowledge, etc. In fact, it would appear that to some extent, at least, the threat of legal action has been quite counter productive.[6,7] The reason for this appears to be that the thrust of legal sanction is directed towards individuals and individual organizations, leading to attempts to avoid responsibility and eventually to a lack of co-operation between organizations. This is of particular relevance in situations where there is already friction between organizations.[3]

External checking and control is a traditional method aimed largely an ensuring compliance with design standards, job specifications, etc. It is commonly assumed to be reasonably effective in detecting design errors and construction mistakes, yet virtually no hard data exists to support this contention. Several different approaches to external checking and control are possible, all apparently in current use. Restricting attention to design checking, these are:

1. completely independent evaluation of final design;
2. step-by-step checking of original design;
3. checking of selected elements of original design;
4. cursory survey for sensibility;
5. acceptance on basis of designer's reputation (i.e. no checking).

The principal frameworks within which design checking operates are [8]: (1) the British-U.S.-Canadian-Australian type system of approval (and checking) by local government officers, sometimes with aid of consultants; (2) the German Prüf-ingenieur system for more significant structures; and (3) the French system based on 10-year liability with design and construction supervised by insurance-company-appointed engineering consultants. Significantly, no comparisons between the effectiveness of these frameworks appears to have been made on the basis of ultimate structural performance. Undoubtedly, to do so would be extremely complex, since local variations due to structural type, design codes, building practices, etc. may well mask differences in checking effectiveness.

Neither legal sanction nor external control can be totally effective. Even where it is theoretically possible to restrain unwise action, or detect poor design or construction, practice indicates clearly that a gap between it and theory will remain. How effective, then, can either of these processes be? For convenience, attention will be restricted in what follows to control processes.

THE LIMIT OF EFFECTIVENESS OF CONTROL PROCESSES

In order to describe the limits to the possible effectiveness of control processes in maintaining societal goals for structures, all contributions to failure of structural performance need to be considered. The various factors have been set out in Table 1.

In the Table, the prospective effectiveness of control processes is a subjective assessment assuming that control is carried out by competent and qualified people in an impartial and independent environment. From the literature on inspector efficiency in visual inspection tasks, it would appear that "high" might represent an 80% detection rate, "low" 20-30%. Naturally control processes in structural engineering are usually more complex than those for quality control

Source of Failure	Corresponding Probability of Structural Failure [8]	Prospective Effectiveness of Control Process
1. Unforeseen events & loads, new forms of structural behaviour, etc.	p_{u1} } ≃25%	low
2. Foreseen events, whose risk is consciously ignored by society, (i.e. the degree of risk sufficiently small, or accepted as inevitable): e.g. large earthquakes; fire.	p_{u2}	-
3. Errors in design concept/construction concept: (includes ignorance of information, oversights, etc.)	p_{u3} } ≃70%	fair - high
4. Errors due to blunders in design (sizing), documentation or construction (includes wilful errors)	p_{u4}	high
5. Natural variability of loads, material properties and dimensions	$p_v \simeq$ 1-10%	low

in an industrial environment on which these figures are based. The actual values for the probability of failure $p_f = p_v + p_u$ depends on the definition of "failure". An insight can be obtained if cases of complete structural failure are considered, rather than other levels of damage or unserviceability. In that case, the calculated likelihood of structural failure due to predictable randomness, p_v (item 5), is known to be at least an order of magnitude lower than actual (observed) failure rates.

From the work of Matousek and Schneider [9] it can be estimated that items 3 and 4 amount to about 70% of all failures; however, their work ignored natural hazards and fire, which are covered here in item 2. Nevertheless items 3 and 4 probably account for at least half of all failures. It is suggested that item 1 is relatively small in a situation of well developed technology. The most important items in a realistic assessment of structural safety are thus items 2, 3 and 4. Of these, the degree of tolerance to certain types of natural hazards is a societal decision; its only relation to control processes is by ensuring that the design concept complies with this decision. This is covered by item 3.

It is now evident that within a given framework of societal decision regarding item 2, the low probability of dealing with item 1 and the existing procedures for dealing with item 5, control processes can play a definite role in items 3 and 4, depending on the resources made available.

A socio-economic model might be invoked to assess optimal relative spending on control measures, given some information about their cost effectiveness, their efficiency and relationships between error detection and structural failure.

THE PLACE OF CONTROL PROCESSES IN STRUCTURAL ENGINEERING

Just as design codes and codes of good practice, construction procedures, etc., have developed in response to the societal need to have sound structures consistently, so it appears it is now time to develop more carefully ways in which society can be ensured that, given the technological tools, design codes, etc., sound structures are still obtained despite the increasing complexity of real conceptualization-design-construction operations.

In, say, aerospace engineering, in which prototypes are usual (to cover lack of technical engineering expertise), the human factor has received much greater attention, due to the need for man to operate the system after it is built. In structural engineering situations, where neither prototype testing, nor service operation is involved, both processes must, in effect, be "built-in" to the structure at the concept-design stage. There is no room for errors in design or construction to be detected in a prototype or to be corrected by an operator.

Seen in this light, the development of a "human factors" or "psychological" branch of structural engineering, to deal with the problem of human error and thus to complement the overtly technical mainstream, seems urgently required.

CONCLUSION

Although a number of strategies are possible to reduce the incidence of structural deficiency or failure caused through human error, only independent control and legal sanctions appear to be viable and enforceable when seen from the viewpoint of society. The effectiveness of other measures, such as education, while highly desirable, are dependent on the uncertain rationality of the organizations performing the task.

A considerable amount of research is required before valid control procedures, and a valid workable framework for such procedures, can be rationally established.

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Concluding Remarks

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I was asked to comment on the first four contributions that seem to have some relation to my introductory report "Safety - a Socio-Economic Decision Problem". The comments should stimulate the free discussion foreseen in a few minutes.

In the introductory report, some basic questions concerning the safety of structures have been put:

. What means "safe"?
. How safe are structures?
. How safe should structures be?

These questions seem to be astonishingly difficult to answer by technical experts. But nevertheless, they are probably the questions in which the general public is primarily interested in.

It looks as if we are not going to be spoilt with answers during this Congress. It is probably rather typical that the attempt to handle the safety problem in a more transparent and out-put oriented way are mainly contributions from not really traditional areas of structural safety.

The approach presented by Dr. Bamert originates from the field of fire protection. In this field, two things are maybe more obvious than in other fields of structural safety. One fact is that we have considerable damages every year. On the other hand, it is obvious that the available means will never allow us to strive for absolute safety. These may be the main reasons that in several countries fire safety has been analyzed rather consequently from an economical point of view. The experience shows that this leads automatically to a more realistic approach than purely technical approaches.

Another attempt to answer the question "How safe should structures be?" comes also from a special field of structural safety. Professor Yamada presents in his paper an approach to seismic safety for structures. Earthquakes also represent a somehow uncommon load for structures. On the other hand, they may affect a very large number of structures simultaneously, thus potentially being able to create a real catastrophe. On the other hand, it is rather obvious that we cannot afford to design all buildings for the maximum loads which have been observed. Earthquake safety is probably one of the most advanced field in structural safety.

Dr. Melchers makes reference to the introductory reports coming from still another side. We gradually realize that human errors are one of the crucial problems remaining to be investigated if we want to improve the safety of structures. But as soon as we start to look at this problem in more detail, we realize that we will not be able to overcome it with our traditional way of thinking. Only if we are able to show the effectiveness and necessity of more controlling measures and legal sanctions, we will be able to impose more measures of this kind on the professional society.

The only paper assigned to this part of the discussion containing a basic approach to structural safety is the paper presented by Augusti and Casciati, I would like to limit my comments to this paper to one point. It is basically plausible to maximize the overall utility of a structure and deduce the optimal safety level from this. Nevertheless, this approach has produced more problems than solutions in most practical applications. The reason is that it is even more difficult to assess the social benefit of technical systems than to assess their safety. But in general, one can observe that the considerable effort which has been made in other fields concerning the safety problem has obviously not found much response in structural safety.

In the introductory report, an approach to answer the above mentioned questions is presented. The two main points are:

. We should introduce a real measure for safety. This has to be a function of the expected losses or damages of a hazardous system.

. We should more consciously be aware that safety decisions are basically social value judgements. These judgements should not be mixed up with the technical analysis of hazardous systems.

But why should we bother about all this if we get along in the traditional way? I would like to put three questions in this context:

. Are we sure that the effort we make to reduce the different hazards of structures are distributed in a optimal way?

. How do we integrate structures in a consistent way into complex technical systems from a safety point of view?

. How do we know which effort we should make for the safety of structures as compared to the effort made to avoid other hazards?

Safety has mainly been regarded as a sub-problem of each single technical activity including hazards. The main effort was oriented to the reliability and operability of the technical system. In the future, safety may increasingly become the primary criterion for the assessment of new technical developments. In this situation, we must be able to answer questions like:

. What means "safe"?
. How safe is a given system?
. How safe should a system be?

We cannot solve the problem of structural safety just from an insider's point of view - we always get lost in more sophisticated, but nevertheless traditional - so-called safety analyses. Let's go ahead answering the above questions from a broader context, from an outsider's point of view. Maybe we get the answers quicker and clearer. I hope this Seminar - even if the answers are not given here and today - will initiate research activities in this sense.

Free Discussion – First Part

In the free discussion to the preceding four contributions, the following persons (listed in alphabetical order) participated

Dr. F. Knoll, Montreal, Canada
Prof. J. Pechar, Prague, Czechoslovakia
Dr. R. Rackwitz, Munich, German Federal Republic
Prof. J. Schneider, Zurich, Switzerland
Prof. C. Turkstra, Montreal, Canada
J. Varsano, Tel-Aviv, Israel
Dr. L.P.C. Yam, London, United Kingdom

Their statements are given below in chronological order:

Pechar: I should like to make some remarks on structural design as a safety measure within an overall safety concept. Sometimes the design problem is simplified to the solution of the safety-cost interaction problem. This simplification is clearly not adequate and acceptable since the notion "safety" does not only cover sufficient bearing capacity and adequate serviceability of structures but also should take into account the influence of structures on the environment and on the user etc. Optimization alone cannot solve the problem. We need probabilistic methods as a tool for improving and quantifying our experience with respect to loads for different structures in different areas for different requirements and conditions and with regard to the behaviour of structures. But design procedures then must be appropriate to their respective task and should take into consideration elastoplastic behaviour of structures, physical and geometrical imperfections (including fabrication and erection tolerances), large deformations etc. and not just only cost-benefit optimization. The limit state design procedure used in Czechoslovakia during the last 12 years seems to correspond quite well to the above mentioned requirements.

Schneider: In preparing the final details for this seminar, I found myself askking "What is the purpose of all this ? Are we on the right track with all these contributions ?" In this context I would like to make some rough, and not very well thought out statements first: The individual wishes to live in his own way. Society, however, lays down certain limitations - unfortunately not the same limitations for everybody. Society also puts financial and other resources into the environment, thus enabling the individual to do, within the given limitations, what he wants, and it is obvious that these resources are limited and differ between different countries. Now life is dangerous and entails risk of life and limb for the individual, who requires society to reduce this risk, although he may voluntarily run much higher personal risks by sports such as mountaineering and other activities. But the reduction of risk is costly and society cannot afford to bring it below a certain level.

We ought then to look for some systematic picture which could be termed the "risk environment" starting with basic risks, such as for example of being killed by hunger, thirst, frost, heat or illness. We there begin to intervene by the distribution of food by means of roads, vehicles, bridges and pipes we build houses to live in, we erect energy plants and distribution systems and provide adequate medical care by setting up hospitals, pharmaceutical industries etc. In doing all this we introduce into the risk environment a multiplicity of additional hazards which lead to accidents in the home, at work and in traffic, and we cause pollution etc. Among all these additional risks the possibiliy of being killed directly or, in a sense indirectly, by failing structures, is one of our special concerns. This rough outline of a risk environment should in my opinion be developed and also numerically quantified.

Using an adequate definition of "safety" as the requirement to reduce environmental risks to life and limb to a level which can be afforded by society, we could then recognize the problem of optimal safety as a distribution problem: invest the given resources of society adequately in the different areas of the risk environment mentioned above in order to obtain minimum risk.

In doing this, some questions arise: How much can society afford to spend to save the life of one of its members ? How much is society willing to spend ? How should safety measures (i.e. risk-reducing measures) be introduced into the risk environment ? What percentage of the available resources could be allotted to the building industry at large and what proportion would go towards structural safety ? How should structural engineers distribute these resources between the planning, design, execution, maintenance and control of structures ? And, finally, are we actually putting our resources into the most effective place to achieve structural safety.

I admit that this all is very vague, but I think that we should reflect a great deal on these questions. Safety concepts, the theme of our seminar, demand a broader view.

Knoll: Housing and structural work is only a very minor portion of the risk environment. If compared to other risks such as the fire hazard or that of traffic accidents, we see that there is not a very great incentive for society to reduce the frequency of structural failure. We must be conscious of this when thinking about the resources society is prepared to provide for the improvement of structural safety.

Rackwitz: Professor Schneider broadened the subject of this discussion to fields as the general risk environment for human beings and to the value system upon which decisions concerning structural safety should be based. Though such subjects are highly interesting we should restrict our discussion to more technical matters. The selection of a value system is not the domain of engineers nor can they decide on a particular system. But, the engineering profession should explicitly state and then report to the society what its criteria are it is using when developing technical safety measures or "local" optimization within the building sector. A basic need, therefore, is to elaborate an appropriate language for a dialogue between society and engineers.

Knoll: I do not think I agree to limit the discussion to simply technical as everything hangs together. Everybody is involved in affecting structural safety as owner, builder, user or merely by accident.

Turkstra: Melchers has suggested that task simplification might help to prevent errors. However, industrial psychologists have evidence that the converse might be true.

People are motivated by an hierarchy of needs starting with basic requirements for food, shelter and security. When a sufficient level of satisfaction of these needs has been reached, people are motivated by more complex factors including "self realization" of the need to fulfill one's self image. In other words, people like to have fun.

Psychologists have suggested "job enrichment" by adding responsibilities and greater skill requirements as a basis for better performance.

Varsano: Referring to Prof. Schneider's conclusions I would like to rise the problem of unexpected loads, which could lead to progressive collapse. This problem is well connected with general safety concepts. The question is to what extent is the society ready to take upon itself, the risk of progressive collapse, and what would the economic influence of such requirement be."

Yam: Our study on progressive collapse in the UK is related to unexpected loads due to gas explosions. Safety measures consist of structural and non-structural strategies. On the loading side, pressures due to internal explosion depend on room geometry, arrangement of furniture, venting and ventilation, and are therefore very difficult to predict. On the resistance side, the important factors include continuity at joints and satisfactory layout of the structure on plan to maintain strength in all possible directions after damage. Our study has also shown that the dynamic response is related to the extent of damage and that making some parts of the structure weak helps to prevent progressive collapse.

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Gefährdungsbilder und Sicherheitsplan

Hazard scenarios and safety plan

Situations de danger potentiel et plan de sécurité

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ZUSAMMENFASSUNG
Der Beitrag beleuchtet die Möglichkeiten, die sich mit den zwei neuen Begriffen für den praktisch tätigen Ingenieur ergeben. Die Gefährdungsbilder, die als Grundlage für die Massnahmeplanung im weitesten Sinne dienen und die im Sicherheitsplan Niederschlag finden, werden anhand eines praktischen Beispiels besprochen.

SUMMARY
The paper discusses the two new notions from the point of view of the practising engineer. The hazard scenarios, which serve as a basis for the planning of measures in the broadest sense and are reflected in a safety plan, are illustrated by an example, which shows the advantages of the hazard scenarios as a realistic way of describing the situation of a structure.

RESUME
L'article présente les possibilités qu'offrent les deux nouvelles notions à l'ingénieur projecteur. Les situations de danger potentiel, qui sont à la base de la planification des mesures et qui sont décrites dans le plan de sécurité, sont illustrées par un exemple.

1. EINLEITUNG

Die zwei Begriffe "Gefährdungsbilder" und "Sicherheitsplan" sind aus den Diskussionen über die Weisung 260 "Sicherheit und Gebrauchsfähigkeit von Tragwerken" des SIA (1) entstanden und im Vernehmlassungsentwurf verankert. Ferner wurden die Begriffe durch das "Joint Committee on Structural Safety" aufgenommen und werden in dessen Arbeit Eingang finden. Die zentrale Bedeutung, die den Begriffen in einem Sicherheitskonzept zukommt, soll im Folgenden vom praktischen Gesichtspunkt aus beleuchtet werden.

Seit über zwanzig Jahren haben sich mehr und mehr Wissenschafter darum bemüht, die Sicherheit von Tragwerken systematischer und rationaler zu betrachten. Dabei wurden Methoden und mathematische Modelle entwickelt, um der Unsicherheit in der Voraussage der Materialeigenschaften, der Bauwerkabmessungen und vor allem auch der Belastungen zu begegnen. Aus diesen Anstrengungen resultierte schliesslich der Begriff der Versagenswahrscheinlichkeit als Mass für die Sicherheit von Bauwerken, sozusagen als "messbare Grösse" der Sicherheit.

Neben all den Vorteilen der systematischen und rationalen Betrachtungsweise haben diese mathematischen Modelle Lücken und Grenzen. Die eine Grenze liegt in der Schwierigkeit, die Unsicherheit der Paramter zu quantifizieren; die andere liegt darin, dass die menschlichen Fehler in der Planung und der Ausführung sowie aussergewöhnliche Einwirkungen sehr schwierig zu erfassen sind. Diese Grenzen zeigen deutlich, wie gross die Lücke von der rein theoretischen Betrachtungsweise zur praktischen Anwendung ist.

Die folgenden Betrachtungen sollen eine Möglichkeit zur Ueberbrückung dieser Lücke aufzeigen.

2. GEFAEHRDUNGSBILDER UND SICHERHEITSPLAN

Vom Gesichtspunkt der Sicherheit beginnt die Existenz eines Bauwerkes in der Planungsphase und endet mit seinem Abbruch. Im Verlaufe dieser Zeitspanne ist das Bauwerk den verschiedensten Gefahren ausgesetzt. Diese Gefahren können in zwei Gruppen eingeteilt werden:

Gefahren menschlichen Ursprungs

- Irrtümer, Fehler, Nachlässigkeiten, etc. im Planungs-, Projektierungs- und Erstellungsprozess
- Ueberlastung durch ausser Kontrolle geratene Nutzung, Unfälle im Betrieb, Brand, Fahrzeuganprall etc.
- Ermüdung oder Zerstörung im Zusammenhang mit mangelhaftem Unterhalt
- Geotechnische Gefahren aus den Bauwerken der Umgebung

Gefahren aus der natürlichen Umwelt

- Wind, Wasser. Schnee, Eis, Temperaturänderungen
- Erdbeben, Erdrutsch, Lawinen, Ueberschwemmungen

In der Regel wirken eine Anzahl dieser Gefahren zur gleichen Zeit auf das Bauwerk ein, eine Tatsache, die als "Gefährdungsbild" bezeichnet werden kann.

Der Begriff "Gefährdungsbild" tritt dabei nicht anstelle der "Lastkombinationen", sondern soll ein wirklichkeitsnäheres Bild der Situation eines Bauwerkes vermitteln.

In (1) wird das Gefährdungsbild folgendermassen definiert:

Die Zuordnung einer ganz bestimmten Gefahr zu einem ganz bestimmten Zeitpunkt- oder -Abschnitt legt ein sog. Gefährdungsbild fest. Die betrachtete Gefahr wird Leitgefahr genannt. Zum gleichen Zeitpunkt mögliche, begleitende Gefahren werden als Begleitumstände bezeichnet und beschreiben mit der Leitgefahr zusammen ein Gefährdungsbild.

Die Leitgefahr wird in extremer Wirkung, Form und Grösse berücksichtigt. Bei der Festlegung der Begleitumstände muss die Dauer der Wirkung der Leitgefahr sowie der Wahrscheinlichkeit des gleichzeitigen Auftretens berücksichtigt werden.

Die so charakterisierten Gefährdungsbilder sind die Grundlage für die Massnahmenplanung im weitesten Sinne. Einzelne Gefährdungsbilder dienen als Grundlage für die Bemessung des Tragwerkes oder für den Nachweis deren Tragsicherheit.

Den in den Gefährdungsbildern beschriebenen Gefahren muss durch adäquate Massnahmen begegnet werden. Einerseits müssen die Nutzungszustände vereinbart und klar umschrieben werden. Andererseits müssen für die wesentlichen Gefährdungsbilder in einem Sicherheitsplan die geeigneten Sicherheitsmassnahmen festgehalten werden.

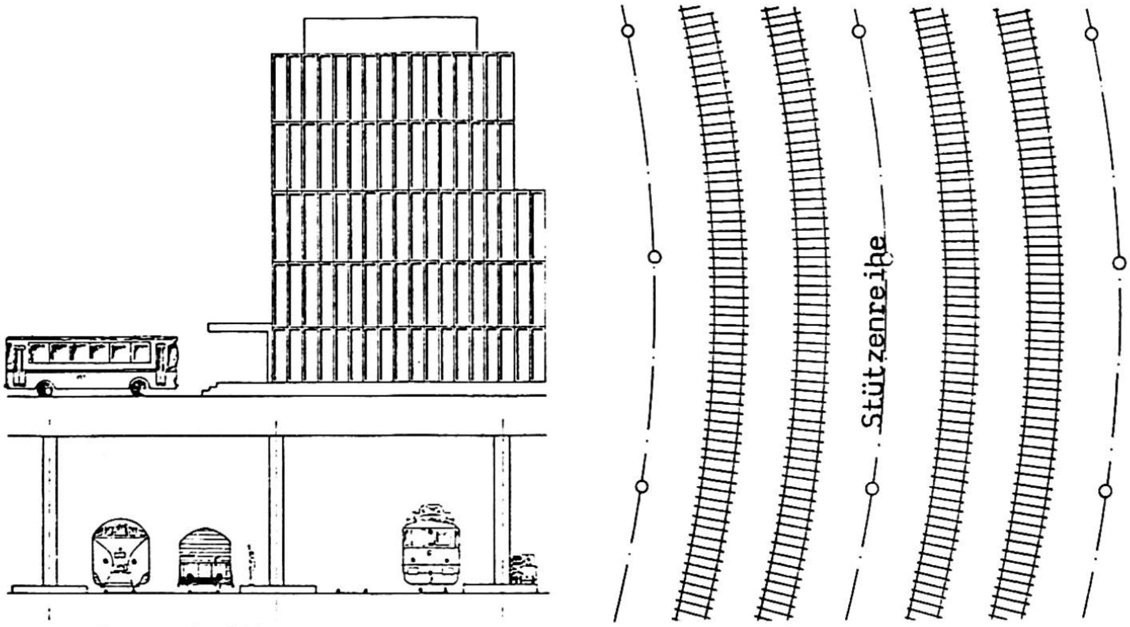
Grundsätzlich bestehen folgende Möglichkeiten von Sicherheitsmassnahmen:

- Elimination der Gefahr durch Massnahmen am Gefahrenherd selbst
- Umgehen der Gefahr durch Aendern der Absicht oder der Tragwerkskonzeption
- Bewältigen der Gefahr durch Kontrollen, Ueberwachung oder Warnsysteme
- Ueberwältigen der Gefahr durch Vorhalten entsprechender Reserven, was bei der Bemessung geschieht
- Akzeptieren der Gefahr als unausweichlich

Anhand des folgenden, stark vereinfachten Beispiels lassen sich einige Aspekte die sich mit dem Begriff Gefährdungsbild zusammen mit dem Sicherheitsplan ergeben, aufzeigen:

Ein Bahnhof, (siehe Fig. 1) dessen Geleiseanlage in einer Kurve liegt, soll mit merhstöckigen Hochbauten verschiedenster Nutzung überdeckt werden. Dabei kommt der Tragkonstruktion, die die aus den Hochbauten resultierenden Lasten aufzunehmen hat, eine besondere Bedeutung zu. Sie wird einerseits aus Stützen bestehen, andererseits aus der Abfangkonstruktion, die die Geleiseanlage überspannen soll. Als Grundlage für eine allfällige Massnahmenplanung und für die Bemessung stehen u.a. sicher folgende Gefährdungsbilder im Vordergrund:

Gefährdungsbild 1:	Leitgefahr	= Anprall eines Zuges infolge Entgleisung
	Begleitgefahr	= Axialkräfte aus der Ueberkonstruktion
Gefährdungsbild 2:	Leitgefahr	= maximale Axialkräfte aus der Ueberkonstruktion
	Begleitgefahr	= ungewollte Exzentrizitäten an den Enden der Stützen und Anprall eines Perronfahrzeuges



Querschnitt Grundriss

Fig. Ueberdeckter Bahnhof

Die zwei Gefährdungsbilder sind ganz grundsätzlich verschieden. Das Gefährdungsbild 1 wird durch die ausserordentliche Einwirkung als Leitgefahr geprägt, wobei

- die Anprallkraft des Zuges infolge Entgleisung kaum bestimmbar, jedoch mit Bestimmtheit enorm gross ist,
- die Entgleistungsgefahr wohl durch besondere Massnahmen wie Leitschienen, erhöhte Sorgfalt bei den Geleisekontrollen etc. verringert, jedoch nicht ganz eliminiert werden kann,
- die Anprallkraft dadurch verringert werden kann, dass die Stützen nicht zwischen zwei Geleisen, sondern auf den Perrons angeordnet werden, was sie jedoch kaum auf eine Grössenordnung reduziert, die mit Widerstand aufgenommen werden kann.

Dies zeigt, dass das Gefährdungsbild 1 kaum Grundlage der Bemessung sein kann, sondern, dass

- eine Massnahmenplanung für das ganze System vorgenommen werden muss,
- die Gefährdungsanalyse zu einem möglichst frühen Zeitpunkt vorgenommen werden muss, zu einem Zeitpunkt, da konzeptionelle Ueberlegungen noch sinnvoll sind.

Im Gegensatz dazu kann beim Gefährdungsbild 2

- die maximale Axialkraft aus der Ueberkonstruktion ziemlich genau bestimmt werden,
- die ungewollte Exzentrizität der Stütze durch entsprechende Kontrollen bei der Ausführung auf ein vorgeschriebenes Mass festgelegt werden,
- die Anprallkraft eines Perronfahrzeuges ohne grossen Aufwand theoretisch oder versuchsweise festgelegt werden.

Das Gefährdungsbild 2 stellt somit eine der Grundlagen zur Bemessung, konstruktiven Durchbildung und für die Kontrolle der Ausführung der Stützen dar.

Laut (1) soll in einem Sicherheitsplan festgelegt werden, mit welchen Massnahmen den Gefahren der wesentlichen Gefährdungsbilder begegnet werden soll. Dabei soll festgehalten werden

- welchen Gefahren durch Elimination derselben begegnet werden soll, z.B. durch Strecken der Geleiseanlage auf eine Gerade oder durch automatische, zwangsweise Beschränkung der Durchfahrtsgeschwindigkeit auf Schrittempo,
- welche Gefahren umgangen werden sollen, z.B. durch stützenfreies Ueberspannen der ganzen Anlage,
- welchen Gefahren das Tragwerk mit seinem Tragwiderstand widerstehen soll, z.B. dem Gefährdungsbild 2 (max. Axialkraft aus Ueberbau, begrenzte Exzentrizität, Anprall eines Perronfahrzeuges),
- welchen Gefahren durch Ueberwachung zu begegnen ist, z.B. durch hohe Anforderung an die Qualitätsüberwachung während der Bauausführung, vermehrte Kontrolle der Geleise und der Signalanlagen sowie der automatischen Zugssicherung,
- sofern bestimmte Gefahren als spezielles Risiko akzeptiert werden, mit welchen Massnahmen eine Gefährdung von Personen ausgeschlossen und das Sachschadenrisiko klein gehalten werden kann, z.B. durch Begrenzen des Schadens an der Abfangkonstruktion beim Wegfall von einer ganzen Stützenreihe.

Für das oben dargestellte Beispiel kann der Sicherheitsplan wie folgt gestaltet werden:

Allgemeine Anweisungen

- Der zentralen Bedeutung der Abfangkonstruktion, d.h. der Stützen und des Trägersystems ist vom Beginn der Planung an besonders Rechnung zu tragen. Insbesondere ist das Tragkonzept so auszulegen, dass es den Ausfall einer ganzen Stützenreihe ohne totalen Kollaps überleben kann, eine Anforderung mit höchster Priorität.
- Die auf die Abfangkonstruktion zu stehen kommenden Hochbauten müssen im Konzept sehr streng auf das oben erwähnte Tragsystem ausgerichtet sein.
- Im überdeckten Bereich dürfen die Geleiseanlagen keine Weichen aufweisen. Die Zugssicherung muss im Einfahrtsbereich eine automatische Geschwindigkeitsmessung und -begrenzung aufweisen.

Anweisungen für die Bemessung

- die Stützen sind u.a. auf die maximale Axialkraft aus der Ueberkonstruktion unter der Annahme einer beschränkten Exzentrizität und einer durch Versuche festzulegende Anprallkraft eines Perronfahrzeuges zu bemessen.
- Die Abfangkonstruktion soll neben den üblichen Lasten auf den Fall bemessen werden, dass eine ganze Stützenreihe ausfällt. Für diesen Fall ist eine reduzierte Last aus den abzufangenden Hochbauten einzusetzen und gewisse Schäden an der Abfangkonstruktion zuzulassen. Diese Schäden sollen so beschränkt werden, dass in den Hochbauten keine Menschenleben bedroht und Rettungsaktionen auf den Perrons nicht behindert werden. Ferner soll die Abfangkonstruktion ohne Totalabbruch wieder hergestellt werden können.

Anweisungen für die Ueberwachung während der Bauausführung

- Neben den üblichen Kontrollen während der Bauausführung sind insbesondere die Massgenauigkeit der Stützen und der Krafteinleitung an den Stützenenden zu überprüfen, sodass die ungewollten Exzentrizitäten auf ein bestimmtes Mass beschränkt bleiben.

Anweisung für die Ueberwachung der Nutzung

- Die Geleiseanlagen sowie die automatische Zugsicherung müssen einer strengen, periodischen Prüfung unterzogen werden.
- Die Nutzung der Hochbauten muss periodisch auf ihre Konformität mit der Nutzungsvorschrift überprüft werden.

Vereinbarungen über spezielle Risiken

- Die in den Anweisungen für die Bemessung vorausgesetzten, zulässigen Schäden im Falle der Zerstörung von Stützen sind allen Benützern der Abfangkonstruktion vertraglich bekannt zu geben.

3. ZUSAMMENFASSUNG

Die Begriffe "Gefährdungsbilder" und "Sicherheitsplan" stellen zwei praktisch anwendbare Mittel zum Erreichen gewisser Sicherheitsziele dar. Die Gefährdungsbilder bieten nicht nur bei der Beschreibung von zusammen wirkenden Lasten, Gefahren und aussergewöhnlichen Einflüssen Vorteile, sondern auch darin, dass sie den praktisch tätigen Ingenieur auf das ursprüngliche, ingenieurmässige Denken beim Bemessen und Konstruieren für alle möglichen Situationen zurückführen. Die Vorteile bestehen auch darin, dass der Projektierende auf die Gesamtheit der Gefahren aufmerksam wird, die nicht nur aus Lasten und Einflüssen, sondern auch aus Gefahren infolge menschlicher Unzulänglichkeiten besteht.

1. Sicherheit und Gebrauchsfähigkeit von Tragwerken, Weisung des SIA an seine Kommissionen für die Koordination des Normenwerkes, Mai 1980.

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Safety Concepts for Fire Protection

Concepts de sécurité pour la protection contre l'incendie

Sicherheitskonzepte für den Brandschutz

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SUMMARY
A safety concept for fire protection is outlined focussing on measures eligible for a limited exchange with respect to the effort employed. Special consideration is given to the interaction between measures influencing the occurrence of fires and structural measures, such as member design and the arrangement of fire compartments. In regard of this interaction the allocation of effort can be adjusted according to national circumstances, types of buildings considered, and individual circumstances.

RESUME
Un concept de sécurité pour la protection contre l'incendie est présenté, soulignant en particulier les mesures essentielles. L'attention est attirée sur l'interaction entre des mesures agissant sur l'apparition des incendies et des mesures structurelles, tels que le dimensionnement des éléments de construction et l'arrangement des parties-coupe-feu. Cette interaction permet de déterminer l'effort principal en fonction des circonstances nationales, des types des bâtiments et de leur utilisation, et selon les circonstances individuelles.

ZUSAMMENFASSUNG
Ein Sicherheitskonzept für den Brandschutz wird vorgestellt, wobei jene Massnahmen im Vordergrund stehen, bei denen eine gewisse Ausgleichsmöglichkeit im Hinblick auf den jeweiligen Aufwand besteht. Insbesondere wird die Wechselwirkung zwischen Massnahmen, die das Auftreten von Bränden bestimmen und baulichen Massnahmen, wie die Bemessung von Bauteilen und die Bildung von Brandabschnitten, verfolgt. In Anbetracht dieser Wechselwirkung kann die Verteilung des Aufwandes auf die jeweiligen Massnahmen je nach nationalen Gegebenheiten, Art und Nutzung der Gebäude und nach den Gegebenheiten im Einzelfall erfolgen.

1. INTRODUCTION

Various measures are employed to protect human lives, buildings, and contents of buildings against hazards arising from fire. Within a specified set of measures providing an agreeable level of fire safety individual conditions should be accounted for by allowing a limited exchange of effort with respect to various measures. The conditions governing a reasonable - or optimal - effort may vary considerably as in the case of industrial buildings. However, an exchange of effort must be confined to measures with strong interaction averting the same cause or consequences of hazards.

This safety concept - presented in a slightly extended form in this contribution-provides the background for the model code draft "Structural Fire Protection"/1/ which introduces a design concept making allowance for a limited exchange between structural measures and measures influencing the occurrence of fires.

2. OCCURRENCE OF FIRES

In the first place measures concentrate on the prevention of fires. The expected number of fires $E(N_o)$ per year in a specified population of buildings of the same type, use, and floor area A_o will obviously depend on the effort invested in preventive measures. Generally, the probability of occurrence of at least one fire per year within the area A_o can be estimated from

$$p_o \cong E(N_o) \tag{1a}$$

assuming the occurrence of fires in time to follow a poisson distribution /1/. According to studies on office buildings /2/ the number of fires is approximately proportional to the floor area confirming a poisson modelling for the spacial occurrence as well /3/, /4/. Hence, the probability of occurrence of fires per year within an area $A = k\ A_o$ may be assessed by:

$$p_k \cong k\ p_o \tag{1b}$$

Given the occurrence of fire, merely a limitation of spread - or losses - remains subject to influence.

3. FIRE FIGHTING MEASURES

Considering buildings of the same general arrangement and spacial distribution of the potential fire load the fire process is governed primarily by the fire fighting measures applied. Uncontrolled fires processes within this population will vary only with respect to unavoidable deviations from the same target conditions and the random location of the fire origin.

Let the random fire process be represented by a single appropriate characteristic X (e.g. maximum gas temperature during the process or total area seized by fire) which in the individual case takes the value max x_o for an uncontrolled process and otherwise some value $x < \max x$, depending on the success of fire fighting measures. $s = x/\max x$ is referred to as the individual "fire extent" allocating a realization of the random extent S to every fire event.

The distribution function of the extent S reflects the effort invested in fire fighting measures (e.g. public fire brigades, private fire brigades, sprinkler-systems) or more precisely, their efficacy which is frequently limited by insufficient water supply. In case of general dispense of all measures every initial fire would grow out of control yielding the maximum extent (s=1) as the almost sure event (see fig. 1, $F_o(s)$). If, on the other hand, the effort in fighting fires would tend to infinity the extent of initial fires would rarely be exceeded. Eventually, according to the measures employed, the distribution $F_m(s)$ for a specified effort will be located between these limiting distributions (see fig. 1). As the distribution $F_m(s)$ describes the probability for an initial fire to develop up to a certain extent, the reverse distribution $\bar{F}_m(s)=1-F_m(s)$ may be regarded as the probability that fire fighting measures fail to a certain extent in limiting fire spread.

The probability for complete failure of measures $\bar{F}_m(1) = p(\bigcap_i \{\text{failure of measure } i\})$ entailing an uncontrolled fire process in the wake of a flash-over may be approximately calculated from /1/, /5/:

$$\bar{F}_m(1) = p_{f_m} = \prod_i p_{f_{mi}} \tag{2}$$

wherein $p_{f_{mi}}$ denotes the probability that control is not established by public fires brigades ($p_{f_{m1}}$), nor by private brigades ($p_{f_{m2}}$), nor by sprinkler-systems ($p_{f_{m3}}$), etc. Possible dependency between these events as in the case of insufficient water supply may be accounted for by introducing a lower bound for p_{f_m}.

Considering the probability of occurrence of (initial) fires p_o or p_k according to equ.(1), the probability of occurrence of fires per year with an extent exceeding s amounts to

$$p_s = k\, p_o\, \bar{F}_m(s) \tag{3}$$

provided that the efficacy of the fire fighting measures is independent of the size $A = k\, A_o$ of the floor area. This independency may hold for one-storied-(industrial) buildings, for multiple-storied-buildings, however, the efficacy may decrease. According to /1/, /5/ a decrease by $k = A / A_o$ (with A_o the average floor or compartment area in types of multiple-storied-buildings considered) may be assumed when assessing fires following complete failure of measures yielding the following probabilities for uncontrolled fires:

$$\begin{aligned} p_{s,1} &= k\, p_o\, \bar{F}_m(1) && \text{for one-storied-buildings} \\ p_{s,1} &= k^2 p_o\, \bar{F}_m(1) && \text{for multiple-storied-buildings} \end{aligned} \tag{4}$$

4. STRUCTURAL MEASURES

The general arrangement of a building with respect to possible operations of the fire brigades, spread of fire, etc. - which, however, was supposed to remain unchanged within the population considered - may significantly influence the extent of fire in terms of $F_m(s)$.

Furthermore, structural measures comprise arrangement of the structural system and design of members such as to provide sufficient structural integrity, i.e. to sustain exposure to fire with adequate reliability. This adequate reliability may be derived from the acceptable failure probability for structural members in non-accidental situations considering the probability of occurrence of fires (accidental situation). As structural members are mainly affected by fires of a great extent it generally suffices to consider fires yielding the maximum extent, i.e. uncontrolled fires. Thus, the conditional failure probability

$$p_{fb} = \frac{p_f}{p_{s,1}} = \frac{p_f}{k^{(2)} p_o\, p_{f_m}} \qquad \text{for } p_f < p_{s,1} \tag{5}$$

is decisive for the design encountering this accidental situation. The design procedure then involves assessment of either the complete uncontrolled fire process as a stochastic process /5/, /6/, or in simplification, assessment of a single random characteristic max X_o representing the uncontrolled fire process, e.g. the equivalent fire duration /5/, /7/.

Obviously, member design becomes superfluous as the probability of occurrence of fires approaches the acceptable failure probability p_f ($p_{fb} \rightarrow 1$). This result eventually reflects common sense - if great effort is employed to avoid a hazardous situation further effort applying to the situation should diminish.

Another structural measure is the partitioning of buildings into fire compartments size A_i ($A = \sum_n A_i = k\ A_o$). Guidelines for acceptable sizes A_i for one-storied-(industrial)buildings may be derived from fire fighting criteria, taking the available water supply into account /8/. Additional criteria can be introduced by loss considerations as follows.

If the characteristic X, representing a fire process, is chosen to describe losses in case of a fire instead of a physical quantity, then s would attribute the relative losses - as compared to the maximum losses possible - to the individual fire event. For simplicity only losses from contents of buildings are accounted for supposing an equal distribution of monetary value throughout the floor area A.

The expected relative losses in buildings without partitioning would amount to

$$E\ (S) = \int_o^1 k\ p_o\ f_m\ (s)\ s\ ds = k\ p_o\ \overline{S} \qquad (6a)$$

with $p_k = k\ p_o$ the probability of occurrence according to equ. (1b), $f_m(s)$ the density function of relative losses and $\overline{S}$ the expected losses in case of a fire (conditioned by the occurrence of fires).

Fire effective partitioning into n compartments - neglecting the probability that members separating compartments fail to fulfill their function - reduces the maximum losses possible by 1/n. Thus, the expected relative losses in buildings with a total floor area A divided into n equal-sized compartments decrease to

$$E\ (S_n) = \int_o^{1/n} k\ p_o\ f_m\ (s)\ s\ ds\ /\ F\ (1/n) = k\ p_o\ \overline{S}_n \qquad (6b)$$

with $\overline{S}$ the expected loss in case of fires; however, considering only relative losses up to 1/n.

In case of fire fighting effort tending to infinity partitioning remains without effect with respect to the expected losses since the losses approach zero regardless of size of floor area. If fire fighting measures were generally omitted the expected relative losses would decrease from ($k\ p_o$) to approximately

$$E_o\ (S_n) = k\ p_o\ /\ n \qquad (6c)$$

These boundary considerations allow the following conclusions: Are fire fighting measures so efficient that without partitioning the expected losses in case of fire are much smaller than maximum losses possible within a compartment ($\overline{S} \ll 1/n$), then partitioning does not contribute considerably to a decrease of losses. If, however, the expected losses without partitioning exceed the maximum losses possible within a compartment ($\overline{S} > 1/n$), then partitioning, surely, is an effective measure for limiting losses. Eventually, this measure deserves even more attention if conditions governing losses (monetary values, probability of occurrence p_o, etc.) vary considerably within a building.

It should also be noted that, in case of effective partitioning, member design does not have to account for the probability of occurrence within the whole floor area A but only within the compartment size A_i. This increases the conditional failure probability according to equ.(5) by n when introducing the probability for uncontrolled fires as $p_{s,1} = k\ p_o\ p_{f_m} / n$. Hence, with respect to member design, partitioning may also be regarded as a measure directed at reduction of the probability for uncontrolled fires, as members are only affected by fires occurring in the respective compartment area. When assessing structural members or elements separating fire compartments, consequently, both adjacent areas have to be considered.

5. CONCLUSIONS

Measures directed at preventing fires and fighting fires, as well as member design, and partitioning of building into fire compartments form a subset of measures eligible for an exchange of effort employed. Individual optimization, however, may be restricted by public safety requirements. It should be acceptable, e.g. to refrain from severe requirements applying to the fire resistance of structural members in case of extensive fire fighting measures or preventive precautions. On the other hand, structural measures may not replace a minimum standard in fire fighting, e.g. substituting a missing water supply. Nevertheless, with a safety concept of this kind sufficient degrees of freedom are available for establishing subsets of measures adjusted to prevailing individual conditions.

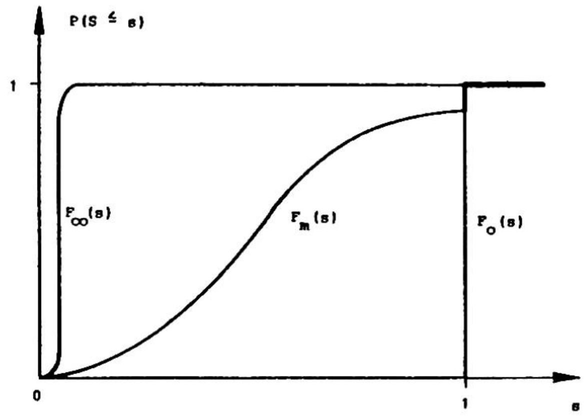

Fig. 1

Possible distribution functions of the random fire extent S for different effort employed in fire fighting measures

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Quality Assurance of Bridges in England

Assurance de la qualité des ponts en Angleterre

Die Qualitätssicherung von Brücken in England

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SUMMARY
Quality Assurance of structures does not consist merely of their design in accordance with published codes. Control is required from the very beginning, right through to the end of the service life of the structure. Procedures as applied to Highway Bridges in England are described.

RESUME
L'assurance de la qualité des constructions ne consiste pas qu'uniquement en leur conception conforme avec des normes publiées. Le contrôle est nécessaire dès le début et jusqu'à la fin de l'utilisation de la construction. Les procédés appliqués aux ponts routiers en Angleterre sont décrits.

ZUSAMMENFASSUNG
Die Qualitätssicherung von Tragwerken besteht nicht nur darin, dass sie nach geltenden Normen geplant werden. Von Anbeginn bis zum Ende der Nutzung der Tragwerke sind Kontrollen erforderlich. Die in England bei Strassenbrücken angewendeten Verfahren werden beschrieben.

1. INTRODUCTION

It is the standard practice in England for bridges to be fully designed and tenders invited for the construction only. The designs are carried out in accordance with national codes, supplemented by Design Standards issued by the Department of Transport (DTp). This takes care of the anticipated behaviour of the structure making due allowance, with a sufficient margin of safety, for variation of loads and strengths of materials from their expected values. However this is only one aspect of quality assurance which in its wider sense also covers the quality control of the design and construction processes together with the control in use and the systematic inspection and maintenance of the structure. This paper describes these processes as applied to highway bridges in England.

2. QUALITY CONTROL IN DESIGN

2.1 Faulty design due to human error may result from misunderstanding of broad philosophical principles, poor judgment consciously applied, ignorance or indifference, arithmetical errors and other errors resulting from the increasing complexity of modern analytical methods. The Department of Transport's Technical Approval procedures which were introduced in 1973 were framed with these factors in mind, to ensure that the possibility of human error occurring in bridge design is reduced to a minimum.

2.2 All DTp bridge designs of any significance have to be formally approved in principle by a Technical Approval Authority (TAA), which may be the DTp's Bridge Engineering Division in London or one of its Regional Offices called Road Construction Units (RCU). At Approval in Principle the TAA and the designer agree the parameters and criteria to be used in the design of a particular structure - the type of structure, geometry, loading, standards to be used selected from a general schedule of standards (TAS), any known departures from these standards, any known aspects not covered by the standards, design methods and any computer programs to be used.

2.3 Approval in Principle is formally given by the TAA signing a form TA1 which sets out the parameters and criteria agreed. It is at this stage that the category of the structure for checking purposes is agreed. This dictates the type of independent check which a structure is to be given (see para. 2.6 below).

2.4 On completion of the Approval in Principle detailed design proceeds and although the TAA do not check calculations they are frequently involved at this stage because it is unlikely that the design and check will be completed without

- The need for specific interpretation of particular requirements within the published list of standards.

- The need to use material or methods which lie outside the practice defined by the list.

- The need to settle disagreement between checker and checked.

Each case has to be referred to the TAA which will thereby fulfil its role of arbiter and interpreter. As practice and experience are good teachers a store of solutions to problems will be built up in the TAA. The process is, therefore, one by which problems select themselves and the important by-product is that the issue of new technical memoranda, the initiation of new standards and codes of practice, and the commission of new work in the DTp's research and development programmes reflect current problems and their priorities, preventing practice from racing ahead of its support technology.

2.5 In accordance with the philosophy described, the degree of check needs to vary with the economic consequences at risk. However, the check cannot be continuously variable and broad categories have to be chosen. Three broad categories have now been established as follows

- Category I: Certificate required stating that the design has conformed to the TA list and TAA instructions; has been accurately translated into contract drawings and that all these have been checked.

- Category II: Two certificates are required: one stating that the design has conformed to the TA list and so on, and a second stating that the design has been checked by an independent team in the design office.

- Category III: As for category II but the independent team must be from a different design organisation.

2.6 The TAA's selection of a category for a bridge is flexible, thus enabling the TAA to make judgments which cannot be written down in concrete terms and acknowledge the risks inherent in design complexity.

2.7 On completion of the design and check the designer provides the TAA with certificates that the structure has been designed in accordance with and checked for compliance with the Approval in Principle as set out on the TA1 form.

2.8 These procedures give the best assurance possible against human error and, of course, the procedure is allied with the selection and monitoring of the design agencies involved. The Department's staff are particularly briefed to ensure that innovation is encouraged but responsibly undertaken.

3. QUALITY CONTROL IN CONSTRUCTION

3.1 In the design of the structure it is assumed that the materials used and the workmanship will be to a certain quality and standard. These are specified in the DTp's Specification for Road and Bridge Works. It has long been our practice for the Contractor's work to be supervised by a Resident Engineer assisted by adequate numbers and quality of staff at different levels to ensure that the work is done to specification. Specialist Inspectors are appointed to supervise fabrication off the site and to carry out non-destructive testing where necessary. In our experience, this kind of close supervision has proved useful in ensuring that the work is done to specification. While we have not found the need for a general review of our arrangements in this respect, we are nevertheless continuing to look for an optimum deployment of resources to obtain best value for money.

3.2 There have however been failures of falsework resulting, sometimes, in loss of life. According to our Conditions of Contract, the temporary works are the responsibility of the Contractor although the Engineer will check them to ensure the safety of the permanent works. Since 1974, we have introduced an additional clause in the Conditions of Contract which requires the Contractor, in certain cases, to submit a certificate from an independent person that his proposals for erection and temporary works are satisfactory. This amounts to an independent check which is paid for by the employer within the Contract without changing in any way the responsibilities of the various parties. We have considered that the money spent in these special cases is worth the extra assurance that we are buying.

4. INSPECTION AND MAINTENANCE

4.1 According to our Conditions of Contract the Contractor is responsible for maintaining the works for a period of one year after completion. After this maintenance period is over, bridges are maintained for the Department by County Councils acting as the Agents of the Department.

4.2 During the construction period, the Resident Engineer's Staff will complete the "As-built" drawings. These, together with calculations and maintenance schedules for major structures, will be handed over to the Agents. About three months before the end of the maintenance period, a joint inspection is carried out by the RE's Staff, the Agents and the Contractor, to ensure that the structure is fully serviceable. Any faults found are made good by the Contractor.

4.3 The following inspections are carried out during the service life of the bridge

- Superficial inspection, not necessarily made regularly. Absence of defects are not recorded but the purpose is to report fairly obvious defects which if unattended could lead to traffic accidents or high maintenance costs.

- General inspection, carried out at intervals not exceeding 2 years by Engineering Staff who record the visual condition of the bridge against a check list.

- Principal inspection carried out by Engineering Staff at intervals not exceeding 6 years. This requires close examination of all parts of the structure and a written report on its condition.

- Special inspection after a special event, eg flooding, extraction of coal, passage of an exceptionally heavy load or to examine a special condition or other similar reason.

4.4 It is essential that these inspections are carried out diligently and the necessary maintenance carried out if the structures are to be used with assurance. It is possible that a feature which gives rise to a fault discovered on one bridge could be built in to other bridges of similar design. These need to be identified quickly and monitored or remedied. To facilitate this a data bank is being built up of all bridges on trunk roads with the maximum amount of technical information as possible. This will enable quick retrieval of the necessary information.

5. PROJECT MANAGEMENT

5.1 In addition to applying quality control measures during preliminary design, final design, construction through to handing over the structure to the maintaining authority, it is also necessary to ensure that these are properly linked together with effective co-ordination of these activities. In my Department this function is carried out by a Project Manager and for large bridges, the task would be carried out by one person through all the stages. All the tasks that he has to perform, together with the stages at which these have to be executed are written in the Department's Highways Manual and these include both Administrative and Technical functions.

6. CONTROL OF VEHICULAR LOADING

6.1 Bridges in UK are designed to carry Standard Loading which simulates trains of normal vehicular loading of up to 32 tons and also for controlled movement of Abnormal Loading of up to 180 tons.

6.2 The gross weight, axle weight and axle spacings of normal vehicles are controlled by law. The Department of Transport takes the lead in any changes to these regulations and the Bridge Office is consulted to ensure that changes will not produce greater load effects on existing bridges.

6.3 It is also the law in the UK that vehicles of gross weight between 32 tons and 150 tons should give notice of their movement. This will enable Highway Authorities to check that the Bridges on the routes will not be overstressed.

6.4 Vehicles of gross weight over 150 tons need a Special Order. Authorisation is given only if a safe route is available. The Special Order includes a mandatory route and these journeys are normally made under police escort.

7. CONCLUSION

During the last ten years, new procedures have been introduced in England for the Quality Control of Design and also for control of erection. These have certainly resulted in greater assurance and we believe that now the optimum amount of effort is applied at each stage to ensure overall quality assurance.

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A System Approach to the Study of Structural Failures

Méthode pour l'étude systématique des sinistres des constructions

Ein systematischer Ansatz zur Untersuchung von Schadenfällen an Tragwerken

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SUMMARY
The British building control system is described and some weaknesses discussed on the basis of detailed analysis of building failures and observations made on construction sites. Building control systems of various countries are studied and common principles identified for the development of a System Model. A simple table is proposed to describe the System Model and the relations between failure data and systems are discussed for Britain, France and the Federal Republic of Germany.

RESUME
On présente le système utilisé en Angleterre pour le contrôle des constructions. Sur la base d'une étude détaillée de quelques sinistres ainsi que sur celle d'observations faites sur les chantiers, on montre les faiblesses du système. Les systèmes de contrôle de différents pays sont comparés. On a résumé les propriétés communes aux systèmes qui pourraient servir de base à un système modèle. Enfin, on propose un tableau simple, qui permet d'établir rapidement les relations entre les dommages et le système de contrôle. La discussion du tableau a été faite pour l'Angleterre, la France et la République Fédérale d'Allemagne.

ZUSAMMENFASSUNG
Das britische System der Baukontrolle wird beschrieben. Aufgrund einer eingehenden Untersuchung von Schadenfällen im Bauwesen und Beobachtungen auf Baustellen werden einige Schwachstellen dieses Systems aufgezeigt. Kontrollsysteme verschiedener Länder werden verglichen und gemeinsame Merkmale für die Entwicklung eines Modells zusammengestellt. Schliesslich wird eine einfache Tabelle vorgeschlagen und die Beziehungen zwischen Schaden-Kenndaten und Kontrollsystem für England, Frankreich und die Bundesrepublik Deutschland werden diskutiert.

In preparing this paper the authors were well aware that the seminar would be attended by engineers from nearly 20 countries experienced in structural safety. Advantage is therefore taken of this opportunity to discuss two topics : Comparison of existing methods of quality assurance (QA) in various countries and evaluation of QA, as illustrated by the British model.

Evaluation of the British system of building control

There are no acceptable methods for the evaluation of QA systems but identifying what went wrong is a valuable starting point. Study on building failures (collapse and unserviceability) has indicated what went wrong that led to failure but could not uncover faults that did not matter at the time because of over-design or another fault. Hence it is important to study in parallel the processes of design and construction to identify what went wrong and in particular how much was not put right in the completed building. Since the construction phase is more critical in the sense that design faults can be revealed and there is considerable pressure to meet deadline, a study on site observation is presented here.

Figures 1 and 2 show the weaknesses in the system and team (organization of human activities) respectively and Figure 4 shows the various stages and processes in the building process together with the British system of control. The remedial measures are suggested in Figure 3. These diagrams are based on the results of a recent detailed study by BRE on 120 building failures in the UK.

A separate study was recently undertaken by BRE to observe problems arising during construction which were considered to affect the standard of quality. The study covered 27 sites involving contracts ranging in value from £100,000 to £12M and about 500 incidents were recorded where the relevant personnel had to pause in their work to consider the rightness of what was being built.

Figure 5 shows the causes of these incidents (also called quality-related events) and the extent to which the related problems were solved successfully. Figures 6 and 7 compare the extent of consultation among personnel between two sites (site with lowest and highest standards of construction).

Some conclusions are similar in nature to those of the failure study. Thus, the standard of construction depended very much on the quality of project information from the designer and workmanship problems were caused predominantly by lack of care on the part of tradesmen rather than by lack of skill or knowledge. One observation made here but could not be made in the failure study is that a number of serious quality problems were identified but not solved, mainly because of the lack of authority of the client's quality controller (clerk of works). Furthermore, quality standards were found not to rely significantly on formal checking and acceptance or rejection of completed work.

Comparison of Quality Assurance Systems

The formal application of quality assurance to engineering construction is relatively new and work in this field on an international level was undertaken only in recent years. The primary objective of the work (by JCSS and CEB) was to promote structural safety but it is increasingly clear that the work has played two further roles. Firstly it has stimulated a closer examination of a wide range of activities in the overall building process. Secondly its output is expected to provide a basic framework of reference for harmonization of international construction. So far harmonization has concentrated on products and standards which have the least interrelation with other elements in the building process. Having now reached a saturated point, harmonization could not go much further until quality assurance procedures are at least better understood.

In the course of its work on quality assurance, CEB (Commission I) has identified a priority area : a comparison of the status quo of QA methods actually used in various countries. It has been suggested that a simplified table be prepared and tentative entries made for iterative corrections by the relevant experts. Figures 4 and 8 are the result of this suggestion and it is hoped that improvements will be discussed in this seminar.

FIGURE 1 : **WEAKNESS IN SYSTEM**

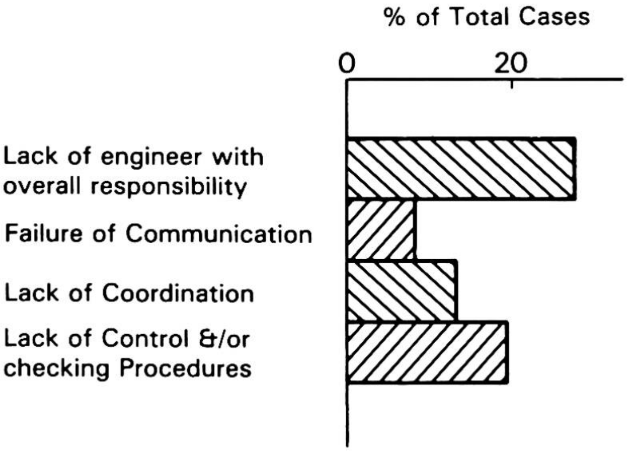

FIGURE 2 : **WEAKNESS IN TEAM**

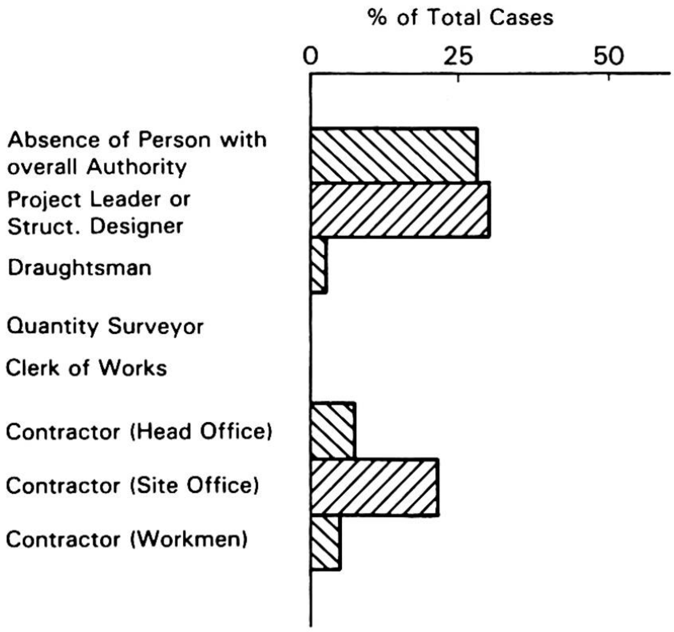

FIGURE 3 : **MEASURES TO MINIMIZE RECURRENCE**

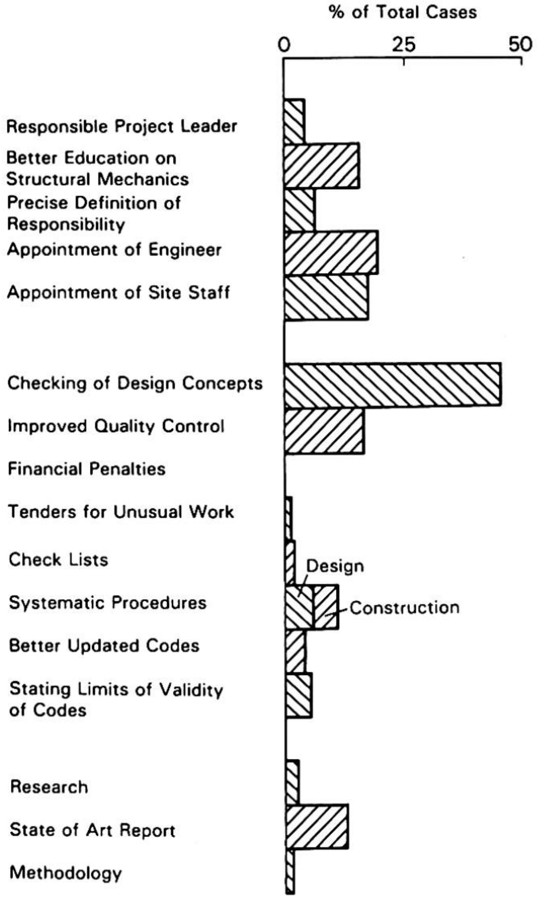

FIGURE 4

COMPARISON OF BUILDING CONTROL SYSTEM

Stages & Processes	Control Methods	Controlling Authority: England & Wales	Controlling Authority: Germany	Controlling Authority: France
Briefing				
Design				
Idealization				
Calculation	Building Regulations & Acts	Central Government & Parliament	Land Ministry & Parliament	Central Government (Decrees & Orders), Laws (Parliament)
	Codes & Standards	Standards Organization (BSI)	Standards Organization (DNA) & Engineering Association (VDI)	Mixed Committees
	Checking	Local Authority	Building Authority	Insurance Companies
Project Information				
Selection Materials Components Techniques	Standards Product Approval	BSI	DNA, VDI Building Institute	Mixed Committees CSTB
New Products	Agrément or General Approval	Agrément Board	Building Institute	CSTB
Construction	Codes & Standards Quality Control	BSI Industry	DNA, VDI Industry & Official Testing Stations	Mixed Committees Insurance Companies
	Inspection	Local Authority	Building Authority	Insurance Companies
Completion	Final Inspection	Local Authority	Building Authority	Insurance Companies
Use & Maintenance				

Stages & Processes	Control Methods	Controlling Authority: Scandinavia	Controlling Authority: Netherlands
Briefing			
Design			
Idealization Calculation	Building Regulations & Acts	Central Government Parliament	Local Authorities (Bylaws) & Parliament
	Codes & Standards	Engineering Associations	Association of Engineers
	Checking	Local Government	Local Authority
Project Information			
Selection Materials Components Techniques	Standards Product Approval	Engineering Associations Standards Organizations	Standards Organization (NNI) Official Approval Authority (KOMO)
New Products	Agrément or General Approval	Central Government	KOMO
Construction	Codes & Standards	Engineering Associations	Association of Engineers
	Quality Control	Industry	KOMO
	Inspection	Local Government	Local Authority
Completion	Final Inspection	Local Government	Local Authority
Use & Maintenance			

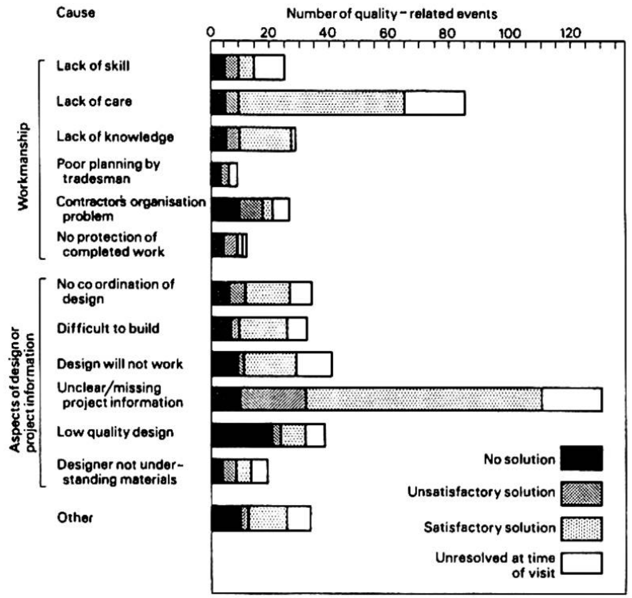

FIGURE 5 : Causes of all 501 quality-related events, and success with which they were resolved

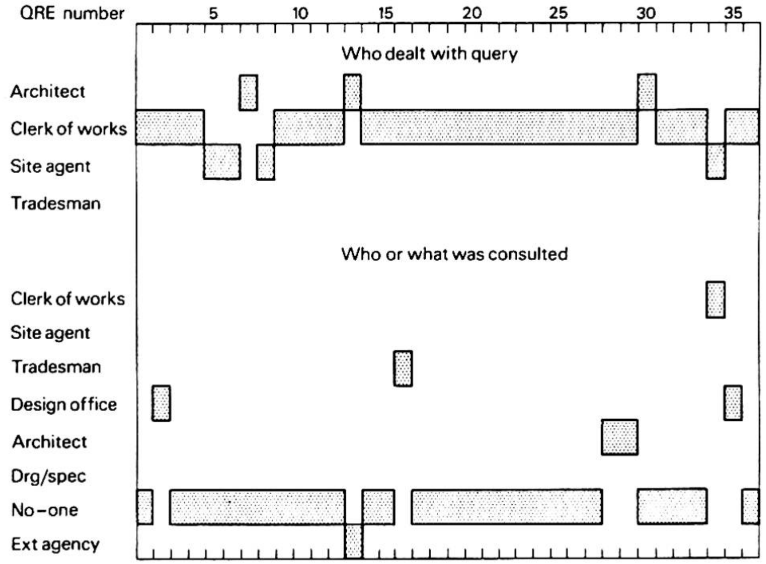

FIGURE 6 : Personnel involved with the quality related events (QREs) observed on a 'non-consultative' site. Quality standards were generally poor on this site

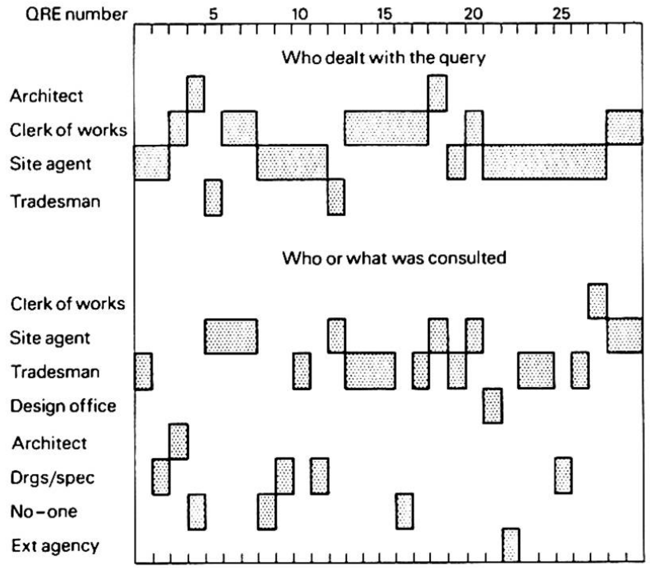

FIGURE 7 : Personnel involved with the quality related events (QREs) observed on a 'consultative' site. Quality standards were very satisfactory on this site

FIGURE 8

CODES OF PRACTICE – Simplified Table of Differences among some EEC Countries

	UK	Germany	Denmark	France	Netherlands	Italy
(A) Who issue Regulations & Codes	Secretary of State Dept of Finance (Northern Ireland) BSI	DIN Ministers of Federal Laender. Additional rules by Ministry of Transport	Ministry of Housing DIF (Danish Society of Engineers)	Public Contracts – Ministry of Equipment French Standards Assn (AFNOR) Private Contracts – Standards Technical Documents Grp or above	NNI (Netherlands Standards Institute)	Ministry of Public Works CNR, UNI (Italian Standards Institute)
(B) Are they Mandatory?	(1), (2) and (3) Mandatory (1) Building Regulations (2) Loading Codes (3) Standards & Technical Memoranda for Highway bridges (4) British Standards – deemed to satisfy	Yes (de facto) Approval may be given for departure in special cases	Laws and Circulars – Yes Codes – deemed to satisfy	Public Contracts – Yes Private contracts – Builders subject to 10-yr guarantee by law. Hence Insurance companies become approval bodies	Yes if client and contractor agree	Laws, Decrees, Circulars – Yes
(C) Do they define roles of parties to building works?	Building Regulations do not specify roles	Yes	Yes	Not generally	No	Yes, two "Directors":– Resident Engineer (design/construction) Site Agent (Workmanship)
(D) Is there a Master Code (Principles for various Material Codes)?	No	Yes, since 1977 Revised version near completion (not mandatory)	Yes, 1978 (NKB document)	Yes, since 1971	Yes, since 1972	Yes (1979)
(E) Future Codes based on Limit States?	BSI Committees agreed	Yes	Yes, since 1965	Yes, gradually	Yes, gradually	Yes, gradually
(F) Enthusiasms in Reliability Theory (0 = very low)	0	2	3	1	1	2

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Models for Human Error and Control in Structural Reliability

Modèles de l'erreur humaine et contrôle de la fiabilité des structures

Modelle für menschliche Fehler und Kontrollen in der Bauwerkszuverlässigkeit

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SUMMARY
Some elementary models for human errors occuring throughout the cogitative and decision network of planning, design and execution of structures are reviewed. The effect of errors of various type on structural reliability is formulated. A model for error detection is presented. It is concluded that the problem of human error is primarily a problem of control, in particular of allocating the control efforts with due consideration of the prior error probabilities of given tasks.

RESUME
On présente quelques modèles simples pour les erreurs et les oublis humains apparaissant pendant les phases de l'analyse et de la décision ou lors de la conception, du projet et de la réalisation d'ouvrages de génie civil. On décrit l'effet d'erreurs de différents types sur la fiabilité des ouvrages. On présente aussi un modèle pour la détection d'erreurs. On en conclut que le problème de l'erreur humaine est avant tout un problème de contrôle; en particulier un problème de la répartition de l'effort de contrôle en tenant compte a priori des probabilités de répartition des erreurs pour des tâches données.

ZUSAMMENFASSUNG
Einige einfache Modelle für das Auftreten von menschlichen Fehlern und Irrtümern während der Erkennens- und Entscheidungsprozesse bei Planung, Bemessung und Ausführung von Bauwerken werden diskutiert. Die Wirkung von Fehlern verschiedener Art auf die Bauwerkszuverlässigkeit wird beschrieben. Ein Modell für die Fehlerentdeckung wird vorgestellt. Es wird gefolgert, dass das Problem menschlicher Fehler in erster Linie ein Kontrollproblem ist; insbesondere ein Problem der Verteilung des Kontrollaufwandes unter Berücksichtigung der a priori Wahrscheinlichkeiten für Fehler bei bestimmten Aufgaben.

1. INTRODUCTION

The analysis of structural reliability has made considerable progress in the very past. If the mechanistic problem can be formulated and the physical uncertainties can be modelled realistically, then there can be at least an approximate reliability solution. Successful applications to structural design codes or to the design of complex structures are available, and more are still to come. Some results exist for the analysis of robustness and redundancy of structural systems. However, results are almost inexistent for the main cause of structural failures which is human error, omission or negligence. As a consequence, the theory of structural reliability practically has failed so far to produce concepts and measures with which the effect of protective actions could be quantified and, thus, enable the optimization of such protective actions. Clearly,the object of engineering rules including design codes, construction rules, compliance criteria, requirements on professional qualification and, last not least, principles for the organizational structure of building activities and their legal and economical implicationsis to guide the realization of structures which are optimal in a socio-economic sense. Then, human error is, in fact, an important subject of an overall theory of structural reliability.

Those protective measures are essentially of three types. Firstly, one can reduce the probability of an error occuring, e.g. by professional training or by the creation of an appropriate physical and psychological working environment. Similarly, appropriate detection strategies for human errors, e.g. by multiple control, use of check lists, etc., may reduce the error content of planning and design or the execution and, finally, one can design for errors and has to do so by introducing structural redundancies at least for those errors which escape a necessarily imperfect control. This last alternative is not necessarily the most effective one since genuine "standby" systems with stochastically independent components, which are the only really efficient systems, are rarely possible in practice. Usually, structural systems show a strong dependency among failure of components and in different modes so that effective redundancies require rather high cost. This alternative will not be discussed herein.

In the following, an attempt is made to summarize some probabilistic models for error occurence, outline the formal treatment of errors and develop a model for error detection.

2. BASIC MODELS FOR HUMAN ERRORS

By their very nature, human errors are discrete events which can occur everywhere in the cogitative and decision network accompaning the realization of a structure. Errors are "marked" events. Thus, an occurrence model must be supplemented by a magnitude model; moreover, by a model describing the effect on some physical quantities. For example, let $\underline{X} = (X_1,\ldots,X_n)^T$ be the random vector of basic uncertainty variables such as strength of materials, geometric properties or actions upon the structure and let $g(\underline{x}|\underline{\pi}) > 0$ describe the domain in which the structure is said to be safe. Therein, $\underline{\pi}$ is the vector of design parameters, e.g. a dimension of a structural element, a material grade, a set of partial safety factors or the amount of reinforcement. An omission takes place if one or several actions are not considered or important failure modes are ignored. Denote the relevant "false" failure condition by $g_k(\underline{x}|\underline{\pi}) < 0$ with k indexing the type of omission and k = t being the case of no omission. A special case is when not all components of $\underline{X}$ or $\underline{\pi}$ are taken into account (negligence of some loads or load cases). Further, an error in structural analysis occurs if the structural system is not properly identified so that the failure domain $g_j(\underline{x}|\underline{\pi}) < 0$ is drastically different from the realistic one indexed by j = s. An error in the vector $\underline{\pi}_i$ occurs if, e.g. the wrong shape or size of a rolled steel beam is chosen. Clearly, many other examples can be given. It appears, however, that mathematically the spectrum of errors can sufficiently will be represented by these models. Also, though not necessarily, one may assume that an error manifests itself in one or the other type but not simultaneously in a combination of error types.

If the errors are assumed to occur independently, the total failure probability becomes

$$P_f = \sum_{i=1}^{r} \sum_{j=1}^{s} \sum_{k=1}^{t} p_{ijk} \quad P[g_{jk}(\underline{x}|\underline{\pi}_i) < 0] \tag{1}$$

with $p_{ijk} = p_i \cdot p_j \cdot p_k$. In many cases, one may conservatively set $P[g_{jk}(\underline{x}|\underline{\pi}) < 0] = 1$ for any $i \neq r$, $j \neq s$ and $k \neq t$, which simply means that an error implies failure. For the same activity it appears also reasonable to neglect the joint occurrence of errors of different types.
The probabilities p may be given as

$$p = q \cdot \bar{d} \tag{2}$$

where q is the occurrence probability and $\bar{d}$ the probability of not detecting it. If there are n independent, consecutive checks one may write

$$\bar{d} = \prod_{\nu=1}^{n} (1-d_\nu) \tag{3}$$

An optimal structure is a structure where the generalized expected cost are minimized, i.e.

$$\{C = C(\text{efforts}) + H \cdot P_f(\text{efforts})\} \rightarrow \min \tag{4}$$

where H is the damage cost in case of failure.

A model essentially as outlined before has been used by a number of authors [1,2,3,4,5]. The first conclusion from these studies is that for a large range of practical cases the optimization of cost with respect to control efforts can essentially be carried out independently of that with respect to design parameters which determine the error-free failure probability. The second important conclusion is that for the likely range of occurrence and detection probabilities for errors as well as for the cost of protective actions, the optimal number of control checks is one or two.

Some further insight can be gained from the study of the optimum total control effort as measured by the number of checks. Let the detection probability d be equal in consecutive, independent checks. Also, let the error occurrence probability be $q = 10^{-3}$ per task. For the cost per check being 1 % of the total building cost, Figure 1 demonstrates the optimum number of checks versus control efficiency as a function of the ratio n_H of damage to building cost. As expected this optimum number increases with increasing ratio n_H. It also increases with decreasing control efficiency d up to a certain value beyond which there is simply too little control efficiency to make control a reasonable means to increase safety. As shown in Figure 1 the critical value depends strongly on the ratio n_H. For realistic values of n_H = 5 to 50, the critical value is of the order 0.7 to 0.9. In other words, if there is control then it ought to be rather efficient; otherwise, it is not worth the effort.

A similar calculation can be made for certain assumptions concerning the dependence structure of error detection in consecutive control steps. Let detection

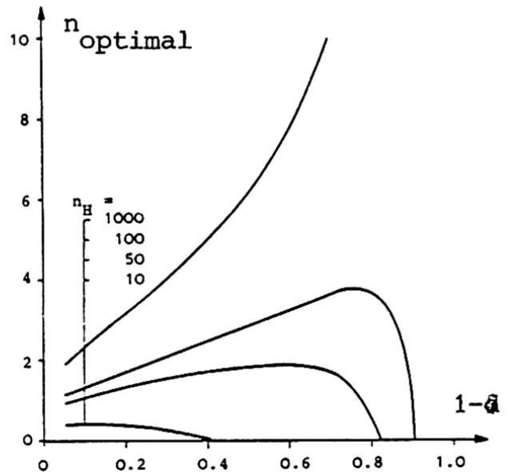

Figure 1: Optimal number of control checks versus control efficiency

and non-detection form a simple Markov chain. It is easily shown that the total control efficiency significantly falls off even for slight dependencies of the detection operations. Since such dependencies exist in practice the optimal number of checks is essentially one. Moreover, design and construction should be made independent as far as possible from the respective controlling bodies; whatever the ways how independenc can be achieved, e.g. by distinct organisational and financial partition of the activities, by the selection of representatives of two different schools of thought in the two functions, or by providing different data bases if possible.

However, the lack of precise knowledge about occurrence or detection probabilities and the various types of stochastic dependencies makes more quantitative conclusions which may be drawn from the model underlying eqs.(1) to (4) questionable.

3. THE RATE OF ERROR OCCURRENCES

For a small number of simple tasks, such as meter reading, pushing buttons, positioning objects detailed statistics exist [6,7]. Correct speaking or writing has reliability of .9995 to .9999 while higher mental processes, such as recognition or decision making, have values of .9 to .999 depending on the subjective difficulty and overall complexity of the task. Human reliabilities increase with the time available to perform a task and decrease drastically under stress. Starting from a Poisson error occurrence model but allowing for an uncertain (gamma distributed) occurrrence rate reflecting the variations between tasks and persons or groups the error content of a facility is known to follow a negative binomial distribution.

$$P[K=k] = \binom{k+v-1}{k} p^k (1-p)^v \tag{5}$$

where k the number of errors, $v = V^{-1/2}$ and $p = (1 + (E/v)^{1/2})^{-1}$ with V the coefficient of variation and E the mean of the mean error rate per facility. Thus, if n is the number of tasks to be performed per facility and $\bar{\lambda}$ the mean rate per task then $n \cdot \bar{\lambda}$ would correspond to E. Note the change of the parameters of eq. (5) with the size of the facility.

Although this model has been found to agree well with statistical observations in a number of areas, e.g. for accidents in plants or military actions, its application to civil engineering works appears doubtful at least as long as no specific data are at hand and as long as a "task" in engineering is not properly defined so that it can be distinguished from another. Although much research is needed in this field it appears more profitable to concentrate in the development of control plans and, thus, tacitly to assume that errors exist in the facility.

4. DETECTION PROBABILITIES

Intuitevely, the detection probability increases with time spent for the search of an error. In the theory of search [8,9] it has been shown that this probability can asymptotically be described by an exponential distribution of effort (checking time) t

$$d_\nu(t) = 1 - \exp[-\alpha_\nu \cdot t] \tag{6}$$

where α_ν is a constant being inverse proportional to the size of the task investigated and proportional to the extent with which each detail is examined. If the executing actions are not independent from the controlling actions the right hand side of eq.(6) might be multiplied by a factor $A \leqq 1$ which approximately takes account of dependencies introduced by common education, inadequate organizational separation of the two functions or even common codes of practice. The parameter α_ν may vary from controller to controller. The exponential increase of the detection probability is due to the fact that the controller in turn introduces redundancy into his cheking procedure with time increasing. Therefore, it seems natural to invest only a limited effort into the first check and then continue the search with a second independent controller. The same theory then states that there exists an uniformly optimal search plan. In other words, if there are uniform prior probabilities for erros in each task, a systematic checking of all tasks is optimal. Only after the first overall check is completed, a second check may be undertaken. On the other hand, if there are non-uniform prior probabilities, one should start the search at the task with the highest prior probability. The control effort dedicated to that particular task at the first check should then be limited to the amount where the *a posteriory* probability (= probability of an error after the check has been terminated) equals the next highest error probability in an other task. This search strategy might further be improved by wheighing different tasks according to their importance on eq.(1). In practice, higher *a priori* probabilities have been observed for a number of specific tasks, e.g. in the mathematical idealization of the real structure, the initial choice of design situations (hazard scenarios), the choice of materials, the design of joints and supports, the detailing of three-dimensional curved structures, the choice of construction processes including the design of all auxiliary structures but also in siting and site exploration. It is not possible here to give explicit numbers. They are, nevertheless, urgently needed. More details on established results on such prior probabilities as well as on the concepts of optimal search for target whose location is unknown in the particular case can be found in the literature [8 - 10].

5. CONCLUSIONS

There exist a few models for human error occurrence and detection which clearly have the potential of being still considerably refined. However, great difficulties arise when defining "tasks" as well as in assessing their error probabilities. The rareness of error occurrences and the known difficulties to obtain reliable data on those events suggest that a theory of structural reliability which includes human errors may only provide some qualitative insight. Therefore, it appears that much can be achieved in the optimal allocation and structuring of control efforts where some theoretical tools have already been developed in other fields. This also includes the systematic investigation of the prior error probabiliteis in the various task. The problem of human error in structural reliability may, in fact, find suitable solutions if the control effort allocation problem finds a solution.

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X

Systematisches Vorgehen gegen Fehlhandlungen als ein Element eines umfassenden Sicherheitskonzepts

A System of Strategies against Human Errors as an Element of an Overall Safety Concept

Procédé systématique contre des erreurs humaines en tant qu'élément d'un concept général de sécurité

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ZUSAMMENFASSUNG
Fehler lassen sich verhindern oder rechtzeitig entdecken. Auf diesem Prinzip ist ein systematisches Vorgehen gegen Fehlhandlungen aufgebaut. Den Fehlhandlungen wird an den drei wichtigsten Fehlerquellen begegnet: Im Ablauf des Bauprozesses, im organisatorischen Bereich und im Bereich des menschlichen Verhaltens. Einzelne Strategien werden in Form von Beispielen näher erläutert.

SUMMARY
Errors can be avoided or detected in time. On this principle a system of strategies against human errors is based. Human errors may be countered at the three most important sources of errors: in the course of the building process, within the management of activities and within the range of human behavior. Some of these strategies are further explained by samples.

RESUME
Les erreurs peuvent être évitées ou détectées à temps; c'est selon ce principe qu'un procédé systématique contre les erreurs humaines a été développé. La plupart des erreurs humaines se rencontrent à plusieurs sources dont les trois principales sont celle de la planification, du dimensionnement, de l'exécution et de l'utilisation; celle de l'organisation des activités en général et enfin celle du comportement humain. A l'aide d'exemples, on présente en détail certaines de ces stratégies.

1. EINLEITUNG

Die Ergebnisse der früher durchgeführten Arbeiten (3), insbesondere der Schadenanalyse, bestätigen die in den Einführungsberichten (1) (2) beschriebene Tatsache: Die Schäden sind entweder auf das einkalkulierte, bewusst akzeptierte Risiko oder auf das Restrisiko infolge von Fehlhandlungen zurückzuführen. So ergab sich z.B. nach (3): 25 % der Schadenfälle und 10 % der Schadensumme sind auf das akzeptierte Risiko und 75 % bzw. 90 % auf Fehlhandlungen zurückzuführen. Aufgrund dieser Tatsache ist es unerlässlich, den Menschen mit seinen Aktivitäten und seinem Verhalten als ein Element des Sicherheitskonzepts zu betrachten (4) (5) (6) (7). Sicher wurde und wird menschlichen Fehlhandlungen begegnet, wie z.B. durch Ausbildung, Weiterbildung, Kontrollen, etc. Wie jedoch die Schäden zeigen, reicht das heutige, oft unsystematische Vorgehen gegen Fehler nicht aus. Ein systematisches Vorgehen ist erforderlich. Dieses gibt an, wie und wo den auf den Menschen zurückzuführenden Fehlern zu begegnen ist.

Grundsätzlich lässt sich Fehlern durch ein zweckmässiges Vorgehen, durch sog. Strategien, auf zwei Arten begegnen:
- Verhindern
- Entdecken und korrigieren.

Die Anwendung dieser Strategien muss der gesamten Fehlerstruktur angepasst sein. Aufgrund einer solcher Fehlerstruktur (3) lässt sich den Fehlern in den folgenden drei Bereichen begegnen:
- im technischen Ablauf des Bauprozesses
- im organisatorischen Bereich
- im Bereich des menschlichen Verhaltens

In den folgenden Abschnitten wird auf den Aufbau der Strategien in den einzelnen Bereichen sowie auf einige Beispiele kurz eingegangen.

2. STRATEGIEN IM TECHNISCHEN ABLAUF DES BAUPROZESSES

2.1 Uebersicht

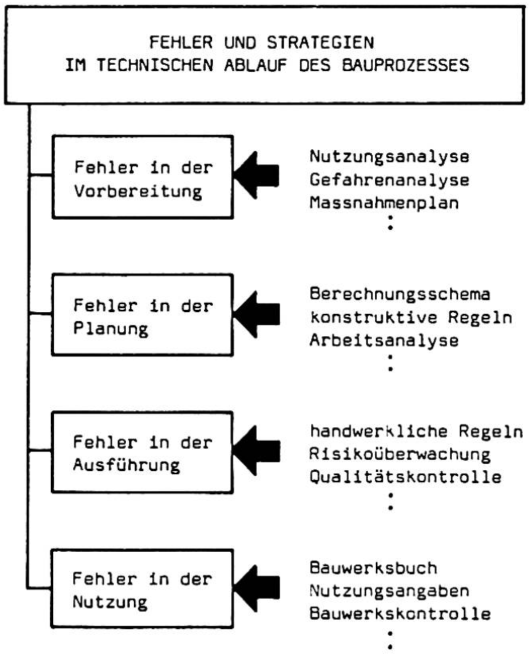
Diese Strategien beziehen sich nur auf den technischen Ablauf und Zusammenhang der einzelnen Teilvorgänge des Bauprozesses, ohne auf die Aktivitäten der am Bau Beteiligten und deren Verhalten einzugehen. Die Strategien sorgen für eine klare Linie in Vorbereitungs-, Planungs, Ausführungs- und Nutzungsphasen. Was beabsichtigt ist, soll auch geplant,ausgeführt und benutzt werden. In den einzelnen Phasen können jedoch Fehler entstehen, die in fehlenden, falschen oder ungenügenden Unterlagen bzw. Sachverhalten bestehen. Solche Fehler sind durch Strategien zu verhindern, bzw. rechtzeitig zu entdecken.

In der *Vorbereitungsphase* müssen Ziele klar formuliert, die Ausgangssituation eindeutig beschrieben, die Wahl der Bauweise begründet, die Gefahren analysiert und schliesslich die Massnahmenplanung dokumentiert werden. Zu den Strategien gehören z.B. Nutzungsanalyse, Anforderungskatalog, Gefahrenanalyse, Massnahmenplan, Dokumentation des akzeptierten Risikos, Kontrollisten, etc.

In der *Planungsphase* müssen die zu behandelnden Sachverhalte klar abgegrenzt, die Projektierungsarbeit eindeutig gegliedert, die konstruktive Durchbildung gewährleistet, die Sachverhalte in Zeichnungen eindeutig dargestellt und schliesslich die Ausführung der Bauarbeiten vorbereitet werden. Zu den Strategien gehören z.B. Berechnungsprinzipien, Berechnungsschema, Fragenkatalog, Kontrolllisten, Arbeitsanalysen, etc.

In der *Ausführungsphase* müssen die erforderlichen Unterlagen vorhanden sein und die Ausführung der einzelnen Arbeiten eindeutig beschrieben werden. Zu den Strategien gehören z.B. Ausführungsprinzipien, Unterlagenkatalog, Arbeitsanweisungen, Ueberwachungsplan, Kontrollplan, etc.

In der *Nutzungsphase* müssen die vorgesehene Nutzung sowie der Unterhalt gewährleistet werden. Zu den Strategien gehören z.B. Nutzungsanweisungen, Bauwerksbuch, Nutzungsangaben im Bauwerk, Risikoüberwachung, Wartungspläne, etc.



2.2 Beispiele

2.2.1 Massnahmenplan

Im Massnahmenplan wird festgelegt, wie den einzelnen Gefahren bei den einzelnen Bauwerkskomponenten (Tragwerk, Ausbau, Installationen, etc.) begegnet werden soll. Der Begriff "Massnahme" ist dabei sehr weit zu verstehen und nicht nur auf die Bemessung des Tragwerks zu begrenzen. Der Massnahmenplan geht von den in der Gefahrenanalyse beschriebenen Gefährdungszuständen der einzelnen Bauwerkskomponenten aus. Für die Gefahren des jeweiligen Gefährdungszustands sind folgende Abwehrmassnahmen möglich:

- *Umgehen* der Gefahren durch Aenderung der Bauabsicht bzw. des Baukonzepts
- *Eliminieren* der Gefahren an der Gefahrenquelle
- *Minderung* der Gefahrenwirkung (z.B. Druckventil)
- *Aufnehmen* der Gefahrenwirkung (z.B. Tragwiderstand)
- *Bewältigung* der Gefahren durch Kontrollen und Ueberwachung
- *Akzeptieren* der Gefahren als Risiko.

Bei der Planung und Festlegung von Massnahmen werden meist die einzelnen Möglichkeiten der Gefahrenabwehr kombiniert. In einfachen Fällen reichen die Angaben im Massnahmenplan aus. In anderen Fällen werden die Angaben in Bemessungsplänen, Dokumentation des akzeptierten Risikos und in Kontroll- und Ueberwachungsplänen, Unterhaltsplänen, Nutzungsreglement, etc. detailliert festgelegt.

2.2.2 Arbeitsanalysen in der Arbeitsvorbereitung

Die Arbeitsanalyse analysiert die einzelnen Arbeitsabläufe nach erforderlichen Mitteln und möglichen Gefährdungen. Sie geht grundsätzlich von den fünf, für jeden Arbeitsablauf erforderlichen Komponenten *Mensch*, *Methode*, *Arbeitsmittel*, *Material und Umwelt* aus. Der Bedarf an diesen Komponenten wird festgelegt und untersucht, durch welche Gefahren diese bedroht sind, und wie sich diesen Gefahren begegnen lässt. Die Schritte der Analyse lassen sich mit den folgenden Fragen beschreiben: 1. Was will man? 2. Wie soll die Arbeit ablaufen? 3. Was könnte die Arbeit behindern? 4. Welche Massnahmen sind anzuwenden? 5. Welche Risiken sind zu übernehmen? Die Durchführung der Arbeitsanalyse lässt sich durch vorgedruckte Formulare erleichtern.

2.2.3 Risikoüberwachung im Bauvorgang

Die im Bauvorgang eingegangenen Risiken müssen überwacht werden. Die Risikoüberwachung beschränkt sich auf einige, für das unerwünschte Ereignis massgebende, Indikatoren (z.B. Wasserstand, Wasseraustritt, Bodenbewegung, Schneehöhe,etc.). Die entsprechenden Ueberwachungsmassnahmen werden in einem Kontrollplan detailliert festgelegt. Neben den bewusst eingegangenen Risiken sind immer Restrisiken vorhanden, die aus unvorhergesehenen, schädigenden Einflüssen entstehen. Solche Risiken lassen sich oft erkennen, indem im Rahmen der Risikoüberwachung alle auf ein schädigendes Ereignis hinweisenden Vorkommnisse beobachtet und gemeldet werden.

2.2.4 Bauwerksbuch

Das Bauwerksbuch ist ein Hilfsmittel, um Fehler infolge unklarer bzw. unvollständiger Nutzungsunterlagen, unklarer Nutzungsregln, etc. zu verhindern. Das Bauwerksbuch gliedert sich in verschiedene Teile:

Ein *Nutzungsreglement* gibt an, wie das Bauwerk benutzt werden muss, und klärt Zuständigkeiten und Verantwortung der an der Nutzung Beteiligten.

Die *Risikodokumentation* beschreibt die eingegangenen Risiken und klärt deren Ueberwachung.

Die *Ueberwachungs- und Unterhaltspläne* legen fest, was in welchen Zeitintervallen zu überwachen und zu unterhalten ist. Die durchgeführten Kontrollen sowie Unterhaltsarbeiten sind zu protokollieren.

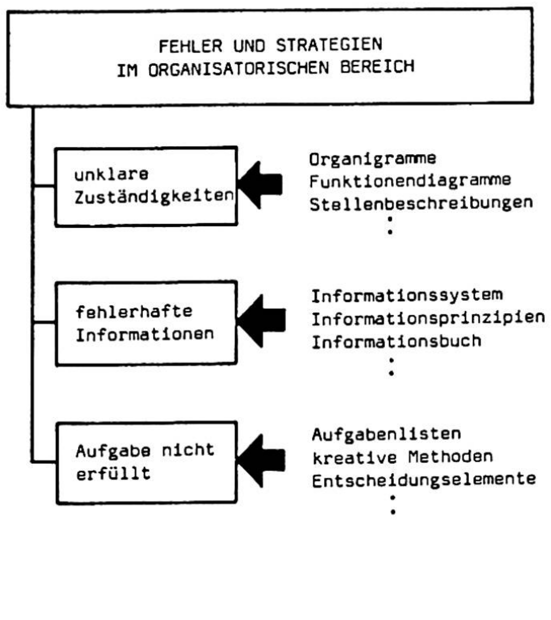
Die *Aenderungsprotokolle* dienen zur Dokumentation aller Aenderungen am Bauwerk sowie der Nutzung.

Die *Liste der wichtigen Bauakten* enthält alle zur Abklärung des Bauwerkverhaltens erforderlichen Akten, wie Pläne, Berechnungen, und gibt an, wo diese aufbewahrt sind.

3. STRATEGIEN IM ORGANISATORISCHEN BEREICH

3.1 Uebersicht

Die technischen Teilvorgänge des Bauprozesses werden durch die Aktivitäten der am Bau Beteiligten ausgeführt. Bei den Aktivitäten handelt es sich um die Aktivitäten der Information (Informationen mitteilen, aufnehmen, speichern, abrufen) und um die Aktivitäten der Aufgabenerfüllung. Die Ausführung der Aktivitäten setzt voraus, dass die Beteiligten mit diesen Aktivitäten eindeutig beauftragt werden. Unklare Abgrenzung der Aktivitäten, unklare Kompetenzen und Verantwortung, ungenügende Informationen sowie unklare Aufgabenerfüllung führen trotz geplanten Ablaufs zu Fehlern. Diese Fehler lassen sich durch Strategien verhindern oder rechtzeitig entdecken. Zu diesen Strategien gehören z.B. Organigramme, Funktionendiagramme, Mitteilungsnotizen, Informationsbuch, etc.



3.2 Beispiele

3.2.1 Funktionendiagramm

Funktionendiagramme stellen übersichtlich dar, durch welche Aktivitäten sich die einzelnen am Bau Beteiligten an den einzelnen Aufgaben beteiligen. Das Funktionendiagramm stellt in zwei Dimensionen die einzelnen Aufgaben den einzelnen Beteiligten gegenüber. Bei jeder Aufgabe wird angegeben, für welche Aktivität welcher Beteiligte zuständig und veranwortlich ist. Im jeweiligen Schnittpunkt lassen sich die Aktivitäten mehr oder weniger detailliert angeben, wie z.B. Ausführen, Kontrollieren, Koordinieren, Entscheiden, Informationen weiterleiten, Informationen aufnehmen, usw.

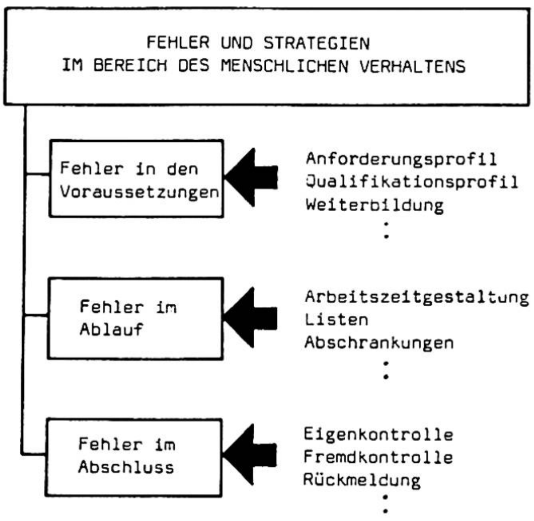
3.2.2 Informationsbuch

Das Informationsbuch dient zum Festhalten wichtiger Informationen. Nicht jede mitgeteilte bzw. aufgenommene Information wird von den am Bau Beteiligten in Briefen, Aktennotizen, etc. festgehalten. Diese Informationen gehen in der Regel verloren. Ein solcher Fehler lässt sich verhindern, indem jeder Beteiligte (Zeichner, Statiker, Bauführer,etc.) seine Informationen in seinem Informationsbuch festhält. Bei jeder Eintragung wird angegeben: Zeitpunkt, Informationsinhalt, daraus erforderliche Aktivität sowie der für die Aktivität Verantwortliche. Ist die Aktivität beendet, wird diese im Informationsbuch als erledigt quittiert. Durch dieses Vorgehen werden nicht nur Informationen gespeichert, sondern auch die daraus folgenden Aktivitäten überwacht.

4. STRATEGIEN IM BEREICH DES MENSCHLICHEN VERHALTENS

4.1 Uebersicht

Der Mensch mit seinem möglichen Fehlverhalten wird als die letzte Fehlerursache angesehen. Die einzelnen nach ihrer Wirkung gegliederten Strategien sind die folgenden:



Voraussetzungsstrategien sorgen für die erforderliche Leistungsfähigkeit und Leistungsbereitschaft. Typische Beispiele sind: Anforderungsprofil, Qualifikationsprofil, zweckmässige Wahl der Mitarbeiter, Weiterbildung, Training, Motivation.

Die *Ablaufstrategien* wirken gegen störende Einflüsse und gegen unbewusste und bewusste Fehlhandlungen. Typische Beispiele sind: ergonomische Anpassung des Arbeitsplatzes, Arbeitszeitgestaltung, Listen, Checklisten, Abschrankungen, Blockierungssysteme,etc.

Die *Kontroll- und Korrekturstrategien* sorgen für die Entdeckung und Korrektur trotzdem entstandener Fehler. Zu diesen Strategien gehören z.B. Eigenkontrolle, Fremdkontrolle, Quittier-Verfahren, Rückmeldungen, Korrekturvorgehen,etc.

4.2 Beispiele

4.2.1 Anforderungsprofil

Das Anforderungsprofil dient zur Festlegung der durch eine bestimmte Arbeit gestellten Anforderungen an die ausführenden Personen. Das Anforderungsprofil besteht aus den einzelnen Fähigkeiten und aus einer Bewertung der gestellten Anforderungen. Die Fähigkeiten im Anforderungsprofil lassen sich nach den einzelnen Bereichen gliedern,wie Wissensbereich, physischer Bereich (Kraft, Ausdauer), psychischer Bereich (geistige Fähigkeiten, Wahrnehmungsfähigkeiten), sozialer Bereich (Anpassungsfähigkeiten, Führungsfähigkeiten), Emotions- und Motivationsbereich (Freude, Initiative). Die Aufstellung des Anforderungsprofils setzt eine Untersuchung der Aktivitäten voraus, z.B. nach Ort, Zeitpunkt, Art der Aktivität, Umwelt, usw. Aufgrund des Anforderungsprofils werden diejenigen Personen gesucht, deren Qualifikationsprofil sich mit dem Anforderungsprofil möglichst gut überdeckt, nach dem Motto "auf jeden Platz den richtigen Mann".

4.2.2 Qualifikationsprofil

Das Qualifikationsprofil dient zur Beurteilung der Qualifikation einer Person. Wie das Anforderungsprofil, besteht es aus einzelnen Fähigkeiten und deren Bewertung. Die Bewertung lässt sich durch Selbstbeurteilung, durch Tests, durch Sachverständige, etc. durchführen.

5. AUSBLICK

Sicherheitskonzepte des Bauwesens dürfen sich nicht nur auf die Bemessung von Bauwerken beschränken, sondern müssen auch den Menschen mit seinen Fehlhandlungen berücksichtigen. Den Fehlhandlungen muss durch, hier nur kurz angedeutete, Strategien begegnet werden. Diese müssen für alle Fehlerbereiche vollständig entwickelt und anschliessend im Bauprozess eingesetzt werden.

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X

Formal Failure Probability and Observed Failure Rate

Probabilité formelle de ruine et fréquence observée des défaillances

Formale Versagenswahrscheinlichkeit und beobachtete Versagenshäufigkeit

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SUMMARY
Formal probabilistic reliability theory is an indispensable basis for choosing structural dimensions whatever be its ability to predict real failure rates. Most failures are caused by gross errors. It is argued that a measure of proneness to tailure due to gross errors can play only a secondary role for this choice. However, it is essential for choosing the structural lay-out.

RESUME
La théorie formelle des probabilités est une base indispensable au choix des dimensions structurales, quelle que soit son aptitude à prédire des défaillances réelles. La plupart des défaillances sont dues à des fautes graves. Il est démontré qu'une évaluation de la tendance à commettre des fautes graves joue un rôle secondaire dans ce choix. Cette évaluation est cependant essentielle au choix de la conception des structures.

ZUSAMMENFASSUNG
Die formale Zuverlässigkeitstheorie ist eine unentbehrliche Grundlage für die Festlegung von Tragwerksabmessungen auch wenn sie nur begrenzt geeignet ist, die wirkliche Versagenshäufigkeit vorauszusagen. Die meisten Versagensfälle gehen auf grobe Fehler zurück. Es wird gezeigt, dass ein Mass für die Versagensempfindlichkeit von Tragwerken aufgrund grober Fehler im Hinblick auf diese Festlegung nur eine zweitrangige Rolle spielen kann. Für die Wahl des Tragwerkkonzepts ist dieses Mass jedoch wesentlich.

Discussions among professionals about safety with respect to structural failure are often revealing great confusion about the concept of theoretical reliability. It is a fact that the failure rate of several important types of real structures is orders of magnitude higher than the rate predicted by probabilistic reliability theory, [2]. Thus it is quite natural that the value of this theory is questioned by engineers who have been taught to judge theories by their ability to predict the real world's behavior. A typical reaction is that of H. Rüsch *), [7]:

> "Damit könnte man sich zufrieden geben, wenn diese operative Wahrscheinlichkeit zu der unter wirklichkeitsnahen Annahmen berechneten in einem bekannten und konstanten Verhältnis stünde. Dies ist aber wenig wahrscheinlich. Die Frage wurde auch nie untersucht. So ist es verständlich, dass man als Prüfstein für die von der neuen probabilistischen Sicherheitstheorie abgeleiten Bemessungsverfahren nue die Frage wählen konnte, ob sich die Ergebnisse mit jenen den bisherigen deterministischen Verfahren annähernd decken oder nicht. Viele werden mit Recht fragen, wozu der ganze Aufwand, wenn letzten Endes für die Praxis nur neue, aber kaum bequemere Krücken angeboten werden.
>
> Der Verfasser hat schon seit Jahren die Sicherheitstheoretiker gebeten, sich mit der Abgrenzung des Gebiets der groben Fahrlässigkeit zu beschäftigen. Er hat auch Lösungsmöglichkeiten aufgezeigt, die als Instrument die subjektive Statistik benutzen, welche sich auf dem Gebiet der Meinungsforschung bewährt hat.
>
> Diese Vorschläge stiessen aber auf kein Interesse. Das Hauptargument der Ablehnung war, man dürfe eine strenge Sicherheitstheorie nur auf statistischen Verteilungen aufbauen, die auf objektiv messbaren Sachverhalten beruhen. Dem entsprechen z.B. Festigkeitswerte, Lasten oder Toleranzen. Nur subjektiv belegbare Werte zu verwenden, wurde als unwissenschaftlich angesehen".

The engineer's primary job is, however, to make <u>decisions</u> rather than to make <u>predictions</u>. This fact is in contrast to the contents of most traditional engineering educations in which methods of rational decision making are parenthetic in comparison with the weight given to theories of physical behavior of materials and structures.

Probabilistic reliability theory is an indispensable decision element in the process of making rational design rules that utilize available empirical evidence on material strengths and environmental actions in combination with models that predict structural behavior. The result of using these rules is a set of drawings and a set of specifications containing a linguistic description of the structure including both general and specific quality requirements. Theoretical reliability is attached to this ideal description of the structure and not to the realized structure. The key point is that probabilistic reliability theory is a formalism which is sufficiently rich of concepts and variables to be well suited for combining information on uncertain quantities that may be of importance for the safety of the real structure. Several widely different sources may contribute to this information. This is in contrast to the naive de-

*) The pessimism of late professor Rüsch with respect to getting the reliability theorists to accept applications of subjective probabilities was, perhaps, a little exaggerated. Engineering judgement elements are, in fact, essential in several recommendation documents based on the concept of "operative Wahrscheinlichkeit", see [4,5].

terministic formalism of safety factors as handled without any reference to a formal probabilistic framework of reasoning. The deterministic formalism simply has no rules for using essential elements of information of direct consequence for the structural safety.

On the other hand, application of probabilistic reliability theory requires that it is possible to formulate a mathematical model of the structural behavior with well defined variables that may be interpreted as random variables, random vectors, or even random processes in time and space. Clearly any such model will be highly idealized relative to the real structure even though the model may be supplemented with variables that are substitutes for the idealization errors to an extent where these may be modeled as if they were drawn from a homogeneous statistical population. Such idealization errors are of several categories. One is due to non-controlable deviations of real dimensions and shapes from specified dimensions and shapes because perfect workmanship is not obtainable and, for economical reasons, perhaps, not even desirable. A completely different categori is the type of idealization error which results from adopting a well defined mathematical model of the structural system. The profession has throughout its history developed a set of generally accepted modeling elements and principles for application in the analysis of usual structures. Provided the combination of these standard modeling elements into a structural model is based on competent engineering inspection of the lay-out of the real structure and its loads the acceptance follows from the fact that experience reveals no catastrophic deviations between predicted behavior and real behavior. Deviations are believed to be within control in a sense equivalent to drawing from a well-defined statistical population. The modeling of such a population may be based on statistical evidence from laboratory experiments or it may be based on comparative studies between different models that describe the same phenomenon. It may even be strongly influenced by subjectivistic factors stemming from the general experience and insight of the engineer (or the profession) about the nature of the matter.

The absense of consistency and rationality behind the old deterministic methods make their use a more or less trial and error procedure for example to decrease material consumption of structural elements down to such limits that the rate of failure due to simple uncontrollable statistical deviations of relevant parameters to the unsafe side is still within acceptable limits. Use of tools based on probabilistic reliability theory is in contrast to this "blind man's slow walk" an apprehensible and expedient method of analysis and decision. Perhaps the intellectual rationality of reliability analysis may best be appreciated by the fact that a calculated failure probability always can be taken as a prediction of the relative frequency of the event called failure in a consistently programmed Monte Carlo simulation on a computer. It should be emphasized, however, that this simulated relative frequency rarely, if ever, can be taken as a prediction of the physical failure rate in the corresponding population of real structures. There are three main reasons for this. The first reason is that probabilistic reliability theory explicitly works with a more general probability interpretation than just the narrow relative frequency interpretation. To be useful reliability theory must work with subjective probabilities (or credibilities), that is, degrees of professional belief about the values of parameters of interest. The second main reason is that the real structure may be supplemented with several secondary elements (e.g. window frames) which in the safety analysis are neglected as contributors to the carrying capacity but which in reality may contribute significantly. This is in particular so in cases where gross errors in the structural principle either inherent in the design or occurring in the building process of the structure cause significant forces to be transmitted to these secondary elements. This is in spite of the primary design principle of protecting these elements against loads that may cause damage to them. If the secondary elements are able to sustain the loads the result is, obviously, an increased carrying capacity of the structure. Secondary elements may often be allowed to carry loads but their effect is considered difficult to take into account in the structural analysis model or the effect is considered insufficiently reliable to be taken into account. This attitude is in particular characteristic for the old deterministic safety reasoning. In principle the effect of secondary elements can very well be taken into account in probabilistic reliability analysis under due consideration of the model uncertainty and the uncertainty of knowledge attached to the evaluation of the effect. The third main reason that the failure rate of real structures is different from that resulting from a reliability analysis is the occurrence of human gross errors in all stages of the realization and use of a structure including structural lay-out, mathematical model formulation, evaluation of environmental factors, communication (e.g., drawings, descriptions, verbal instructions), building process, material delivery etc.

Some types of gross errors may in principle be described in parameter form and considered statistical. Such errors can be consistently included in the reliability analysis model. Typically they are of "on-off" type like "upside-down" errors. The failure probability given the error may be calculated and knowing the probability of occurrence of the error the product of the two probabilities may be calculated giving an additive contribution to the total failure probability. Clearly, if the error is reasonably rare, the failure probability given the error may be allowed to be considerably larger than the total failure probability before its contribution becomes a dominating part of the total failure probability. By active control procedures or "fail-safe" design the probability of occurrence of such an error may be kept below reasonable limits.

Left over beyond systematic mathematical description and, perhaps, imagination there are all kinds of arbitrary gross errors due to mistakes, gross negligence, criminal acts, bad human performance as results of economical or political pressures, haste, lack of "think before you leap"-attitude, haphazard behaviour etc. Imprudent application of new materials, new structural types, significantly changed dimensions relative to traditional dimensions, new erection principles on building site etc. may involve danger of overlooking new significant modes of mechanical behaviour or it may even expose effects outside the knowledge and experience of the profession. A famous case of this is the Tacoma bridge failure.

In view of the existence of non-parametrizable gross errors it may seem hopeless to try to formulate a mathematical rationale which is able to predict the failure rate in the population of a given type of real structures. Something can be done, however. Clearly it is important to be able to identify the circumstances that have potential for producing gross errors and to judge their gravity.

For a complicated project several such circumstances may be present and thus it is important to be able to evaluate their common effect with respect to proneness to damage or failure. Such insight may be the basis for wise decisions about design changes, changes of production, contractors, or use of the structure.

It is important to make clear that an increase of the safety factor level, that is, an increase of the theoretical reliability, has generally very small or no effect at all with respect to decreasing the proneness to failure due to most types of gross errors. The effect is only to increase member dimensions. For example, an upside-down error in placing a prefabricated reinforced concrete beam is not made harmless by any substantial increase of the intended down-side reinforcement. What helps is to identify the possibility of the upside-down error and then change the design to eliminate the possibility of the error, that is, to make the design fail-safe in this respect.

Commonly it is argued that the design value of the theoretical failure probability for a given structural lay-out should be fixed at the value which minimizes the total expected costs (where "costs" may be taken in a more general sense than just direct monetary costs), that is, the expected value of the establishing costs plus the operation and maintenance costs plus the costs of damage or failure. The question raises whether such an optimization is reasonable in consideration of the gap between real and theoretical failure rate. Fortunately the answer is confirmative in most cases. To see this let p_{th} be the theoretical probability of failure and let p_{gr} be some measure of proneness to failure due to gross errors. The point is that for a given lay-out of the structure (including the entire plan for the building process) the proneness to failure p_{gr} is in most cases almost unaffected by variations of p_{th}, these variations only causing variation of the material consumption. Therefore the value of p_{th} which minimizes the expected cost of the given lay-out is almost unaffected by the expected cost of failure due to gross errors (provided the costs associated with a failure are only slightly dependent on variations of the material consumption). Thus it is rational for each lay-out to choose as design value that value of p_{th} which minimizes the expected cost of the given lay-out. The validity of this argumentation seems to be the only salvation of probabilistic reliability theory from being just a plaything for university teachers. However, when the question is about choosing between different lay-outs the expected cost of failure due to gross errors must be added, that is, a cost which depends on p_{gr} must be added. While the widely accepted modern decision theory defines the failure cost as a function of p_{th} simply as the expected cost with respect to the given probabilistic model there is as yet no generally accepted definition of p_{gr}. Even with such a definition available it is by no means obvious how to define the expected failure cost as a function of p_{gr} except, perhaps, that it should be an increasing function of p_{gr}.

To the author's knowledge the terminology "proneness to failure" together with an attempt to define a numerical measure of it was first suggested by Pugsley, [6]. Blockley, [1], has published a useful checklist for grading the quality of a project with respect to proneness to gross errors in all its stages from design to use. He applies this checklist in a grading of 23 major projects that all turned into disasters. The problem is to cook down all these gradings to a single appreciable measure of proneness to failure. He applies the fuzzy set concept which was introduced by Zadeh in 1965, [8], with the purpose of giving a precise mathematical interpretation of imprecise linguistic statements and a modeling of relations between such statements. However, in the light of the above discussion, Blockley's attempt in [1] (see also [2]) to "fuzzify" the theoretical failure probability p_{th} seems inappropriate.

An extension of this paper, [4], analyses the fuzzy set tool with respect to the possibility of establishing a measure of proneness to failure due to gross errors.

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X

Safety Requirements and Structural Design Process

Critères de sécurité et dimensionnement des structures

Sicherheitsanforderungen und Tragwerksbemessung

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SUMMARY
This contribution presents a brief discussion on the requirements to meet for a level 1 design process capable of translating in simple rational code rules the actual reliability demand. The weight of the random uncertainty on load values and load combinations on structures is in particular emphasized and a policy, that has been recently proposed for calibrating the load safety factor values, is discussed.

RESUME
L'article traite des exigences à remplir par un projet de structures, au niveau 1, afin de pouvoir traduire en règles simples les critères de fiabilité. Le rôle joué par les charges aléatoires et leurs combinaisons sur la sécurité des constructions est en particulier considéré. Une méthode récemment proposée est analysée pour calibrer les valeurs des facteurs de sécurité à appliquer aux charges.

ZUSAMMENFASSUNG
Dieser Beitrag behandelt kurz die Anforderungen, die ein Bemessungsverfahren der ersten Stufe (Level 1) erfüllen muss, um die Fragen der Tragwerkszuverlässigkeit in einfache Normregeln überführen zu können. Auf die Wichtigkeit der zufallsbedingten Unsicherheiten von Lasten und Lastkombinationen bei Tragwerken wird besonders eingegangen. Schliesslich wird eine Methode vorgestellt, welche kürzlich für die Festlegung von Lastfaktoren vorgeschlagen wurde.

1. SAFETY REQUIREMENTS

The document "Common Unified Rules for Different Types of Constructions and Materials" |1|, that was proposed by the Joint Committee on Structural Safety and assumed as a basis for both concrete |2| and steel |3| european recommendations, states that the "aim of design is the achievement of accettable probabilities that the structure being designed will not become unfit for the use for which it is required during some reference period and having regard to its intended life". Thence each structure or structural element should be designed and constructed such that, with an appropriate degree of reliability, they:

a) perform adequately in normal use and sustain actions liable to occur during their life;
b) maintain sufficient structural integrity during exceptional events as fire, explosions, strong earthquakes;
c) have adequate durability against biological and chemical influences.

This contribution to the discussion on Theme X (Safety Concepts), planned for the 11th IABSE Congress, presents a brief survey of the requirements to meet for a level 1 design process capable of translating in practice the expected reliability demand.
A first aspect to emphasize concerns the appropriate degree of reliability. In fact it is very difficult to state a quantitative unambiguous definition of such a degree and only qualitative considerations are generally introduced in a code (f.i.: such a degree has to be correlated to the risk of consequences to human lifes or to social conveniences).
However this aspect is beyond the structural engineering role and hence, in the next point, attention is only devoted to the analysis of the possibilities of providing safety during the performance of the single design steps. Further, points 3, 4 and 5 are related to some aspects of item a) whose requirements are the basis of current design procedures.

2. ACTUAL DESIGN CRITERIA

Analysing items from a) to c), stated at the previous point, the following considerations may be pointed out.

- At present the durability of the structure against chemical and biological influences (item c) may be guaranteed by means of rules of good practice for design, construction, control, inspection and maintenance. The problem is not yet stated with the support of mathematical model because the relevant variables are not yet well known.

- It is not easy to provide design criteria in order to mantain integrity during exceptional events (item b). In fact the knowledge of the ultimate behaviour of structures, expecially in dynamic range, is not accurate enough. At present the design can only be based on global parameters as, for example, ductility factors.

- It is possible to state in a mathematical way the design for providing a good performance to the structure during normal use (item a). This leads to the three design levels presented in |1|. However only level 1 (semi-probabilistic method) appears to be fully applicable in common engineering practice.

3. CODE REQUIREMENTS

In order to perform a level 1 verification such as:

$$\gamma_{f3} S(\gamma_{F_i}, \psi_{o,i}, F_i) \leq R(f/\gamma_m) \qquad (1)$$

a code have to point out:

(i) the design methods for evaluating loading effect (S);

(ii) the input to design (i.e. loads F_i and resistance R that is generally a function of the properties f of the material);

(iii) the partial safety factors γ_F, $\psi_{o,i}$, γ_m, γ_{f3}.

Some considerations on these requirements are performed for the purpose of underlining lacks and open questions.

- Design methods have to be different depending on the type of limit state considered. Linear methods are sufficient for serviceability limit states: they are well known and improved by automatic techniques. For ultimate limit states non linear methods are necessary but they are not yet general enough to cover design needs. For this reason sometimes it is useful to state conventional ultimate limit states |3| in order to allow the designer to use linear methods in structural analysis.

- Resistance and stability of structural elements and ultimate behaviour of connections are widely explored. Many results still need but the most is already available. Permanent and live loads are not well known from a statistical view point but a good estimation may be done in many cases. Snow loads are not yet known everywhere. Wind speed is often stated with sufficient precision but interaction between gusts and ultimate behaviour of structures is not known. It follows that if the wind speed characteristic value is given as the 95% fractile of the maximum value during the structural lifetime most of existing steel constructions are...unsafe if analysed by a very recent code |4|. On the contrary the 98% fractile of the yearly maximum does not fulfill probability requirements.

- Safety factors depend on the probability level and on the type of structure or structural element considered. At present they are assumed so that the level 1 design is not very different from the one based on the past common practice. In other words the factors γ_{f3}, γ_m and γ_F may be stated on the basis of the old safety factor ν used in the allowable stress design and confirmed by fifty years of common practice. But such a correspondance between γ_{f3}, γ_m, γ_F and ν is not a one-to-one correspondence and hence the results is not unique.
  In order to obtain a better advantage from the degrees of freedom offered by level 1 approaches, a more rational choice of the safety factor values is necessary. In particular the loads require an accurate estimation of the safety factors as they are the structural parameters with greater random uncertainty. Finally, the combination factors $\psi_{o,i}$ cannot be worked out by ancient practice and so they have necessarily to be decided on the basis of a more rational approach.

4. EVALUATION OF THE LOAD COMBINATION FACTORS

A general policy for calibration of the load combination factors (i.e. of the load enhancement factors $\gamma_i = \gamma_{F_i} \psi_{o,i}$) may be summarized in the following steps:

a) choose the criteria for evaluation of the load enhancement factors;

b) define a procedure independent of the actual nature of the considered structure (i.e. of the type of material and construction and of the considered limit state).

Let $\underline{x}$ denote the set of parameters that define a design situation (i.e. loads, resistance and their variability) and D the definition field of the quantities $\underline{x}$ corresponding to the group of structures for which the partial safety factors are to apply. For every design situation $\underline{x}$, different reliability degrees can be obtained by level 1 design procedures making use of different values of the enhancement factors γ_i. In order to optimize these values, in a previous paper |5| suitable "safety" and "economy" requirements have been assumed.

The actual probability of failure p_f associated with this final level 1 design is always required to be lower than a given target level $\bar{p}_f$: $(\bar{p}_f - p_f) \geq 0$ for each $\underline{x}$ (safety requirement) and the sum over D of the deviations $(\bar{p}_f - p_f)$ must be the minimum (economy requirement). In such a way a mathematical programming problem is obtained:

$$\begin{aligned} &\min \sum_j (\bar{p}_f - p_f(\gamma_i))_j &&\text{(economy requirement)} && \text{a)} \\ &(\bar{p}_f - p_f(\gamma_i))_j \geq 0 &&\text{(safety requirement)} && \text{b)} \end{aligned} \qquad 2)$$

where Eq. (2b) is written for each $\underline{x}$ and also for each of the considered safety domain shapes on which $p_f(\gamma_i)$ depends. Then the solution of the problem (2) may only be applied to the design situations accounted by the constraints (2b). Hence general results would require the solution of a problem with a number of constraints whose computational effort might not be sustained.

In order to formulate an operative procedure, the actual structural properties must be idealized by one conservative safety domain shape that model any structural behaviour. In this way, in fact, constraints (2b) must only be written with reference to different values of the parameters that describe the randomness of the considered actions and of the idealized safety domain (characteristic values, coefficients of variation, type of probability law). Therefore the obtained load enhancement factors hold for the wide group of structures whose parameters belong to the investigated definition field. Obviously a such approach involves a design altogether less economical.
For this purpose it is worth noting that if one considers a family of safety domains each of them may be expressed by one parameter r (i.e. a conventional resistance), the constraints (2b) become:

$$r(\bar{p}) - r(\gamma) \leq 0 \qquad (3)$$

The simplest safety domain for which Eq.(3) holds, is the "hypersphere" in the load space. Furthermore this hypersphere must be considered inscribed in the actual safety domain of the single structure so that a conservative approximation is obtained. Ref. |5| and |6| made use of such a conservative approximation to investigate one of the two tasks that are generally demanded to the enhancement load factors by a level 1 design procedure. It consists in ensuring that, in the load space, the boundary of the safety domain relevant to the limit state of interest is safe enough in the neighbourhood of the meaningful load combinations. The second task, that concerns the definition of the load combinations significant for design purposes, will be discussed in the next point 5. The analysis of the results determined under the hypersphere assumption has emphasized the following remarks (among others):

(i) the structural resistance against permanent loads must be estimated allowing for enhancement load factors associated with the selfweight and the imposed load that must have the same value. However in the case that different codes for steel and concrete structures are required, the factor of the selfweight is prevalent for concrete structures, while the steel structures are characterized by an higher value of the permanent load factor;

(ii) the safety factor corresponding to the environmental actions is much greater than the one of the permanent loads for both the greater value of the relevant coefficients of variation and the shape of the functions describing their probability law;

(iii) by a stochastic analysis of simultaneous action of two environmental forces, it is possible to point out that the importance of this combination in the design process was underestimated until now.

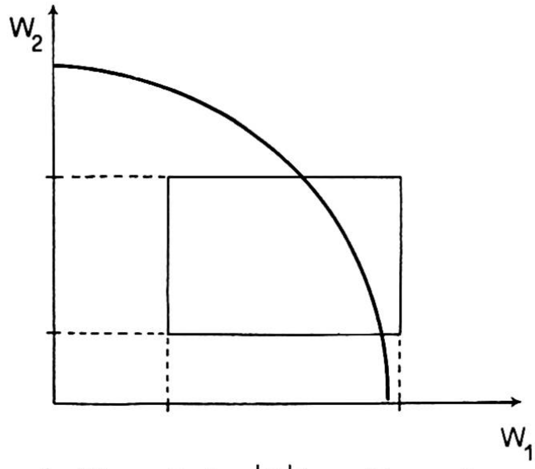

Fig. 1 (from Ref. |7|) - Circumference having as radius the characteristic value of the resistance and definition of two random actions.

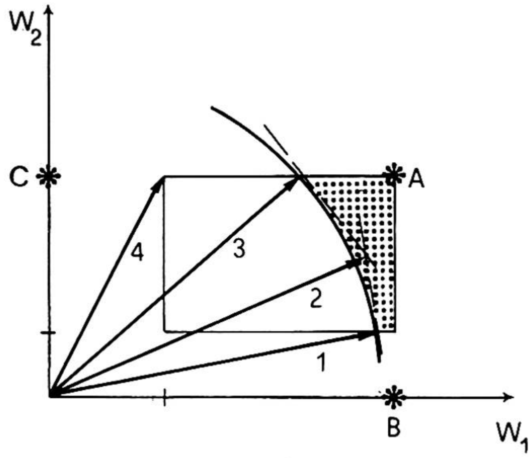

Fig. 2 (from Ref. |7|) - Load combinations meaningful for a level 1 design procedure (case of two loads).

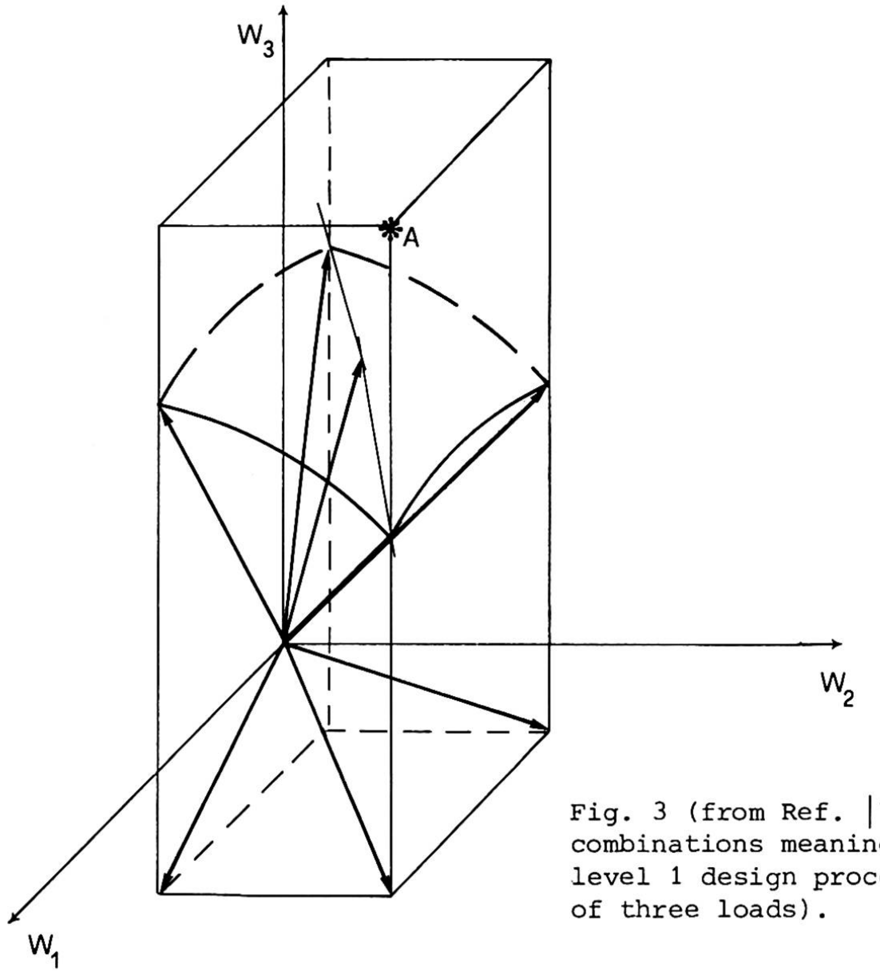

Fig. 3 (from Ref. |7|) - Load combinations meaningful for a level 1 design procedure (case of three loads).

Table 1 - Selfweight W_2 and permanent load W_1: values of γ_i's required to provide the reliability value $(1 - 10^{-5})$

Verification		1		2		3		4		4'	
μ_{W1}	μ_{W2}	γ_{W1}	γ_{W2}	γ_{W1}	γ_{W2}	γ_{W1}	γ_{W2}	γ_{W1}	γ_{W2}	γ_{W1}	γ_{W2}
1	0.2	1.22	0.44	1.22	0.86	1.20	1.29	0.44	1.29	-	-
1	1	1.29	1.20	1.20	1.20	1.20	1.29	0.44	1.29	1.29	0.44
1	4	1.29	1.19	0.86	1.22	0.43	1.23	-	-	0.44	1.29

5. SIGNIFICANT LOAD COMBINATIONS

It is worth noting that a level 1 code format making use of the results obtained by the above approach, would have to prescribe that the safety domain of the final design must be outside the hypersphere whose radius has components $\gamma_{Fi}\ \psi_{o,i}$ F_i. Such a requirement may appear to be extremely conservative for same real cases. However the coefficients of variation of loads, generally, are not so large that all the load space has to be considered. For each load, one can generally introduce a definition range so that the probability that a value of the relevant load is out of this range is much lower than the target level $\bar{p}_f$ (f.i.: 10^{-7}, if $\bar{p}_f = 10^{-5}$). Thus the subset of the hypersphere safety domain of actual interest is the one shown in Figure 1 for a two-load case. Note that the radius of the drawn circonference is the characteristic value of the resistance.
The previous remark is the basis of a research that is in progress |7|. Some of the results obtained in this research are summarized in the following.

(i) Let W_1 and W_2 be the random loads that act upon a structure; further let their values be constant in time. The present level 1 formats require that the load combinations denoted by stars (points A, B, C) in Fig. 2 are checked. However, by introducing the circumference obtained in Ref. |5|, the dotted zone of Fig. 2 must not necessarily belong to the safety domain to provide the "appropriate" design reliability to the design. Nevertheless the advantage of neglecting the dotted zone is only obtained if the number of load combinations that have to be checked (Fig. 2) is increased. For instance, if W_1 and W_2 are normally distributed with coefficient of variation 10% and mean values μ_{W1} and μ_{W2} respectively, the verifications summarized in Table 1 are required in order to provide $\bar{p}_f = 10^{-5}$;

(ii) The previous approach may appear to be few advantageous for permanent loads, but it becomes very suitable when one must take into account "enviromental" actions that are characterized by large coefficients of variation and extreme type probability distribution functions. Let W_3 be an enviromental force: in the space W_1, W_2, W_3 the point A (see Fig. 3) involves $\gamma_{W3} = 2.17 \div 2.41$ if a coefficient of variation $c_{W3} = 0.186$ is considered. But, by using the approach proposed in Ref. |7|, γ_{W3} is obtained lower than 1.90 when $\bar{p}_f = 10^{-5}$, $\mu_{W1} = 1$, $\mu_{W2} = 4$, $\mu_{W3} = 5$ and the resistance coefficient of variation is 5%.

(iii) It is worth noting finally that, if $\bar{p}_f = 10^{-5}$ is required in the W_1, W_2, W_3 space (Fig. 3), a greater reliability degree in the plane W_1, W_2 must be achieved |7|. It follows that the values of γ_{W1} and γ_{W2} obtained from the case of Fig. 2 are not conservative in the case of Fig. 3 and so on. Perhaps a solution for such a problem is to consider very high reliability level in estimating the enhancement factors of the permanent loads, so that their values can be maintained as the number of acting loads increases.

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X

Approximate Analysis and Safety of Structures

Méthodes de calcul approchées et sécurité des structures

Näherungsberechnungen und Tragwerksicherheit

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SUMMARY
The influence of errors involved by approximations in structural design is discussed in the context of the probabilistic approach to structural safety philosophy. A definition of the ,,design load'' is proposed, and distinction between ,,design'' and ,,service'' loads is related to error estimates. The ,,reliability error''is also defined, and a practical example is dealt with for a comparison of the upper bound to the actual value of the reliability error.

RESUME
L'influence des erreurs induites par les approximations de calcul est discutée dans le contexte de la philosophie probabiliste de la sécurité structurelle. On propose une définition de ,,charges de projet'' et on introduit la distinction entre charges de projet et charges d'exploitation, en relation avec l'évaluation des erreurs. L',,erreur en sécurité'' est également définie; un exemple numérique permet d'en déterminer la valeur supérieure.

ZUSAMMENFASSUNG
Der Einfluss von auf Näherungsberechnungen beruhenden Fehlern wird im Zusammenhang mit dem wahrscheinlichkeitstheoretischen Ansatz der Tragwerksicherheit diskutiert. Eine Definition der ,,Bemessungslast'' wird vorgeschlagen, wobei der Unterschied zur eigentlichen ,,Nutzlast'' auf Fehlerschätzungen beruht. Der sog. ,,Zuverlässigkeitsfehler'' wird ebenfalls definiert und in einem praktischen Beispiel sein oberer Grenzwert abgeschätzt.

1) INTRODUCTION

The probabilistic approach to structural safety, while originating many questions concerning research of suitable techniques to deal with random variables and/or random functions in the area of structural analysis (for a review of such problems, see for instance Ref. [1]), also enhances the role of interactions between the solution of mathematical problems involved by structural design and the use that can be made of the results of computations. Really, the main difference between the engineering approach to continuum mechanics problems and the analogous treatment by mathematical physics, should be found in the circumstance that mathematical results are not employed directly, but are always filtered, and often neglected in the details, by the engineer's judgement that enters into the rationale (i.e.: the set of rules) of structural design and analysis as a decisive factor, often conditioning even the output of seeming pure mathematical procedures.

As a matter of fact, behind the visible ease by which the "analysis pattern" is usually set up in regard to design loads, admissible stresses, structure geometry, etc., a somewhat more complex reality can be found, that most times could only be modeled by a multiplicity of situations, rather than by a single pattern.

In front of the above considerations, it is quite spontaneous to believe that exact mathematical results may be a too severe requirement, inadequate in view of the fading connections between the real structure and the analysis pattern, that can only be viewed at as a "conventional" description of the expected situation. Nevertheless, errors in analysis may be decisive to cause structural malfunctions, and the control of allowable approximations should be required and founded on well defined rational criteria.

A possible approach to the question is provided by the probabilistic theory of structural safety: since the safety certification is the main objective of the (civil) engineer, the influence of approximations on the safety indices can be investigated after having recognised the conventional character of the mathematical model.

In the treatment presented in the paper, the problem is simplified by assuming that the only source of uncertainty is the service load, often not predictable in detail, that is conventionally replaced by the design load in the analysis pattern.

The latter is supposed to be quite adherent to the real structure except, precisely, as for the loading condition, and a possible philosophy to evaluate the additional safety coefficient to be applied in consequence of approximation is explained.

2) BASIC ASSUMPTIONS

Assume that the service loads on the structure are constant in time and are applied once at the beginning of the structure's lifetime. Consider the structure to have (or to have been reduced to) a finite number of degrees of freedom, say n, and let F be the set of n-dimensional load vectors possibly acting on the structure. Let $\underline{f}$ be any possible load vector, $\underline{u}$ the structure response vector (for instance the displacements) and $\underline{A}$ the characteristic operator of the structure, so that the response equation is established as follows

$$\underline{A}\,\underline{u} = \underline{f} \tag{2.1}$$

and assume that such equation has one and only one solution for any $\underline{f} \in F$. Let $\bar{\underline{u}}(f)$ be an approximate solution of (2.1), and put

$$\bar{\underline{f}} = \underline{A}\,\bar{\underline{u}}(f) = \underline{D}\,\underline{f} \tag{2.2}$$

$\bar{\underline{f}}$ is named the emerging load associated to $\underline{f}$. It is assumed that an approximate solution $\bar{\underline{u}}(f)$ can be found for every $\underline{f} \in F$, and that the set of emerging loads $\bar{\underline{f}}$ covers the whole F, when $\underline{f}$ varies in F.

Consider then that the degree of safety of the structure is expressed by the safety index β, substantially as proposed by Hasofer and Lind [2] with a slight modification in order to neutralize the dimension effect.

Let $\underline{f}$ be the generic load vector, $\underline{f}_m$ the expected load vector, and S' the boundary of the strength domain of the structure in F, $\underline{C}_f$ the covariance matrix of the load vector, and put

$$\underline{\sigma}_f = \sqrt{\underline{C}_f} \tag{2.3}$$

Consider then the n-dimensional vector space X of reduced load vectors

$$\underline{x} = \underline{\sigma}_f^{-1}\,(\underline{f} - \underline{f}_m) \tag{2.4}$$

and define the biased (by the dimension effect) and the unbiased safety indices β_n and β respectively, putting

$$\beta_n = \min_{\underline{x} \in S'_x} |\underline{x}|\,; \quad \beta = \sqrt{\chi_1^{-1}\{\,\chi_n(\beta_n^2)\}} \tag{2.5}$$

S'_x being the boundary of the strength domain S_x in the space of reduced variables, and χ_n the chi-square distribution.

Now, the conventional character of the design load $\underline{f}_d$ should be explicitly stated. It is assumed that coupling exact structural analysis with correct design and building rules, if the structure resists $\underline{f}_D$ it will also resist any possible service load, except possibly a sufficiently small number, whose probability of occurrence is low enough.

In symbols

$$(\underline{f}_D \in S) \Rightarrow (\,\beta \geq \beta_p) \tag{2.6}$$

otherwise, $\underline{f}_D$ cannot be taken as the design load. Note that in the present treatment the circumstance is neglected that design requires sometimes the action of two or more design loads.

3) PRELIMINARY REMARKS

Let S be the actual safe domain (Fig.1.a). It is obvious that if the structure cannot be solved exactly, this domain remains unknown. Approximate analysis being possible, a different domain $\bar{S}$, the approximate safe domain, can be investigated. The same applies in the space of reduced variables (Fig.1.b), where the domains are named respectively S_x and $\bar{S}_x$. It is obvious then that only the seeming safety indices $\bar{\beta}$ can be controlled

$$\begin{aligned} \bar{\beta}_n &= \min_{\underline{x} \in \bar{S}'_x} \underline{x} \\ \bar{\beta} &= \sqrt{\chi_1^{-1}\{\chi_n(\bar{\beta}_n^2)\}} \end{aligned} \tag{3.1}$$

the actual safety index remaining unknown. Note however that, as proved in [3]

$\bar{\underline{f}} \in S' \Leftrightarrow \underline{f} \in \bar{S}'$

remembering that S' denotes the boundary of S. If the definition of emerging load $\bar{\underline{x}}$ associated to $\underline{x}$ is extended to reduced variables by the position

$$\bar{\underline{x}} = \underline{\sigma}_f^{-1} (\bar{\underline{f}} - f_m) \qquad (3.2)$$

the same applies to domains S_x, $\bar{S}_x$

$$\bar{\underline{x}} \in S'_x \Leftrightarrow \underline{x} \in \bar{S}'_x \qquad (3.3)$$

Hence, everywhen the structure is analyzed by the approximate procedure under any load $\underline{f}$, and it is found that $\underline{f} \in S$ (i.e. the structure resists $\underline{f}$), really $\underline{f} \in \bar{S}$, and it is the emerging load that actually falls in S. Then, the difference between $\underline{f}$ and $\bar{\underline{f}}$, the vector $\Delta\underline{f} = \underline{f} - \bar{\underline{f}}$ provides the difference between S and $\bar{S}$. Accordingly, the difference $\Delta\underline{x} = \underline{x} - \bar{\underline{x}}$ provides the difference between S_x and $\bar{S}_x$.

Define now the numerical error ε as follows

$$|\underline{f} - \bar{\underline{f}}| \leqslant \varepsilon |\underline{f}| \quad \forall \underline{f} \in F \qquad (3.4)$$

and note that for most approximate techniques of solving structural models, ε can be actually calculated. It can be conceived that availability of bounds on $\Delta\underline{f}$ can be used to get similar bounds on $\Delta\underline{x}$, and that such bound can be used in turn to get a bound on β_n. In a previous paper [4], the Writer has obtained the following lower bound for the actual biased index

$$\beta_n \geq (1 - r\varepsilon)\bar{\beta}_n - \frac{\varepsilon r}{V_f} \qquad (3.5)$$

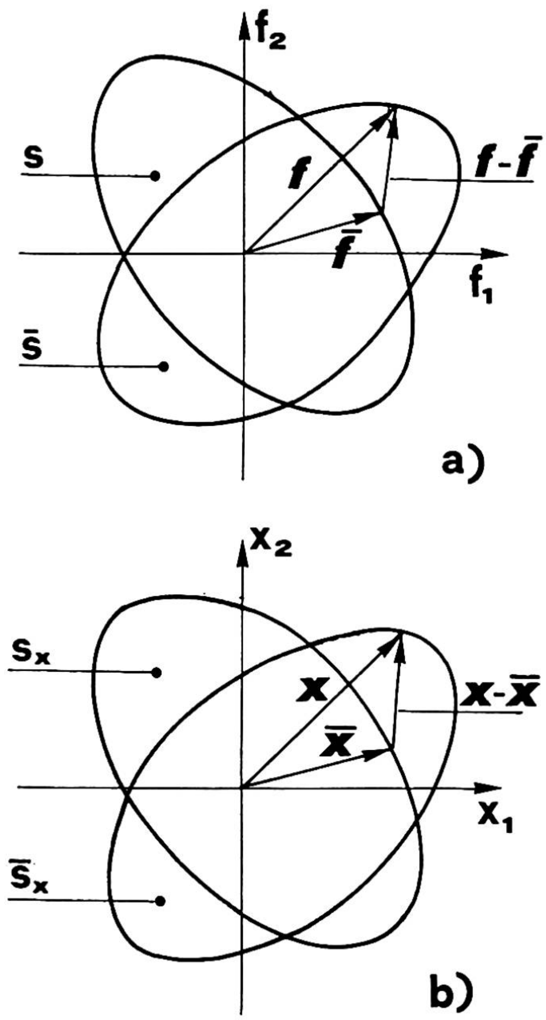


Fig. 1

where r is the condition number of the matrix $\underline{\sigma}_f$, and $V_f = |\underline{\sigma}_f^{-1} \underline{f}_m|^{-1}$ is a parameter that essentially specifies the coefficient of variation of loads. From eq. (3.5), the unbiased index β can also be bounded in an obvious way, and a condition for $\bar{u}$ to be considered an approximation of the true response is established in the form $r\varepsilon \leq 1$.

4) THE RELIABILITY ERROR

It is now necessary to specify a parameter allowing to evaluate the significant error introduced by approximations, in accord with the considerations presented in the Introduction.

Let γ^* be the coefficient to be applied to the design load $\underline{f}_D$ in order to neutralize errors in the solution procedure as regards the safety index, i.e. such that

$$\gamma^* \underline{f}_D \in \bar{S} \Rightarrow \beta \geq \beta_p \qquad (4.1)$$

$\bar{S}$ being the erroneous strength domain that could be calculated by approximate methods.

The <u>reliability error</u> ε^* is defined by the position

$$\varepsilon^* = \gamma^* - 1 \tag{4.2}$$

In Ref. [4] , it is proved that, if β_p is the prescribed value of the safety index, the following upper bound ε^*_u can be established for ε^*

$$\varepsilon^*_u = \frac{\varepsilon}{1-\varepsilon} \quad \frac{1+\beta_{pn} V_f}{\beta_{pn} V_f} \tag{4.3}$$

This upper bound enhances some valuable features that can be attributed to the reliability error; namely, confusing ε^* with ε^*_u:

i) The (upper bound on the) reliability error <u>does not depend on the error in load effects</u>, but only on the error in applied and emerging loads, as defined in [3,4] .

ii) ε^* is a decreasing function of the product $\beta_{pn} V_f$, i.e. it is smaller when applied loads are affected by increasing uncertainty (larger V_f) and it is smaller when high reliability is required for the structure (larger β_{pn}), a result that agrees with the well known circumstance that the diagram of the failure probability versus the load factor becomes steeper and steeper as the failure probability decreases.

iii) ε^* is proportional to the numerical error , a result in agreement with numerical experiments.

iv) if $\beta_{pn} V_f = 0$, ε^* has a finite value only if the numerical error $\varepsilon = 0$. In other words, approximations would not be allowed if no margin of safety was guaranteed ($\beta_{pn} = 0$), <u>or</u> if the design philosophy rested on exact, deterministic, prediction of applied loads ($V_f = 0$).

This is probably due to the upper-bounding procedure used to obtain ε^* independently from analysis of load effects; in such case, analysis of the propagation of the error on load effects cannot be avoided.

5) NUMERICAL PERFORMANCE OF THE UPPER BOUND

In order to have an idea of the difference of the upper bound (4.3) to the true reliability error, the results obtained by the Author in Ref. [5] are considered, where the frame in Fig. 2 under stochastic loading (25 independent load components) was analyzed and designed in the elastic range, and exact solution of the classical equilibrium equations written by the displacement method was compared with the iterative solution of the same system, obtaining different levels of approximation by stopping the procedure after 1,2.., n iterations. The actual numerical error ε , and the reliability error were calculated by a Montecarlo procedure, for V_f = 5%, 10%, 15%, 20%. Here, the calculated ε^* is compared with the corresponding ε^*_u obtained by eq. (4.3), and the results are presented for V_f = 10% in Fig. 3, where h denotes the number of

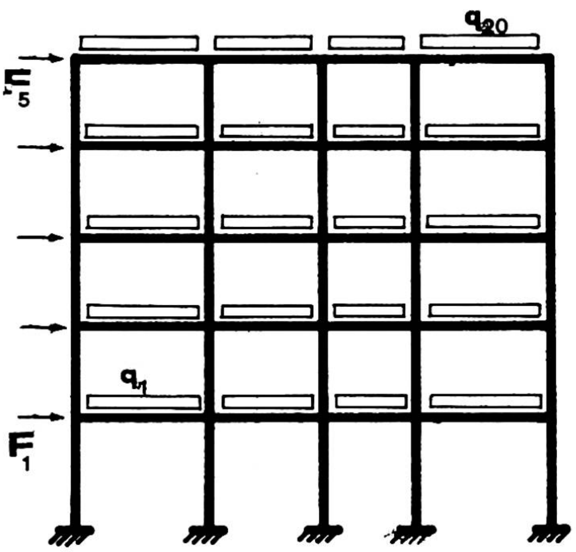
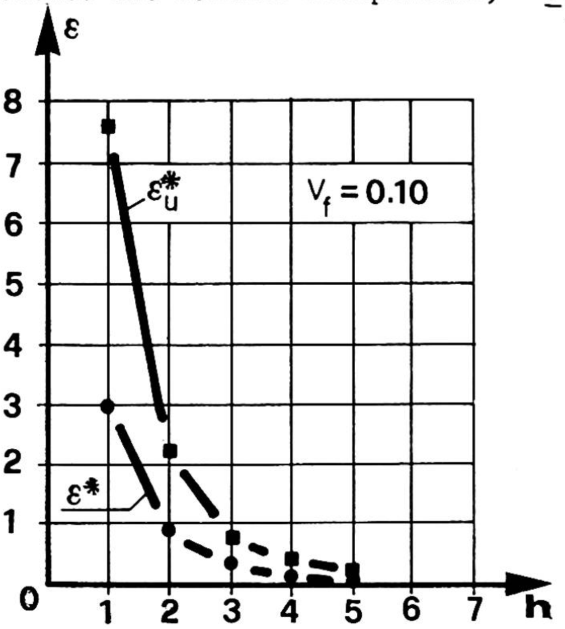


fig. 2

iterations. Note that, since the load components are assumed independent, $\underline{\sigma}_f$ is a diagonal matrix, and its condition number is equal to unity, and that β_{pn} is calibrated on the calculated collapse probabilities corresponding to different values of V_f in Ref. [5] .It should also be evidentiated that, in the case considered and for all values of V_f that have been investigated, the ratio $\varepsilon^*/\varepsilon^*_u$ is not much different from 2.



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X

Structural Design for Serviceability

Dimensionnement des structures pour le domaine d'utilisation

Tragwerksbemessung im Hinblick auf Gebrauchstüchtigkeit

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SUMMARY
In this paper design for serviceability is considered from a fundamental point of view. The differences between design for safety or ultimate limit states and design for service conditions are emphasized. A methodology for the evaluation of alternative design constraints is presented together with a preliminary numerical application.

RESUME
Dans cet exposé, l'utilité des constructions est calculée d'un point de vue fondamental. On insiste sur les différences entre les calculs visant à la sécurité ou aux limites de rupture et les calculs visant aux conditions d'utilisation. Une méthodologie permettant d'évaluer d'autres limites est proposée, accompagnée d'une application numérique préliminaire.

ZUSAMMENFASSUNG
In diesem Beitrag wird die Bemessung im Hinblick auf die Gebrauchstüchtigkeit von Tragwerken von einem grundsätzlichen Standpunkt aus betrachtet. Die Unterschiede zwischen der Bemessung gegen Tragwerkversagen und der Bemessung auf Gebrauchstüchtigkeit werden dargestellt. Eine Methodik für die Bewertung weiterer Randbedingungen für die Bemessung wird — zusammen mit einem praktischen Zahlenbeispiel — vorgestellt.

1. INTRODUCTION

The essential criteria for structural engineering were stated succinctly in the nineteenth century by Henry Wotton - "*In Architecture as in all other Operative Arts, the end must direct the operation. The end is to build well. Well building has three conditions - Commodity, Firmness, and Delight.*" Basic problems associated with assuring "firmness", or safety against structural failures are the major concern of the theme paper for the session on Safety Concepts. The purpose of this contribution is to examine closely related problems associated with "commodity" or assuring that structures can perform their intended functions.

Within the context of at least North American practice, it seems evident that inadequate building performance rather than structural collapse is the major source of professional liability at the present time. Current practices which limit professional supervision and inhibit development of adequate control in the building process must be critically evaluated and substantially revised in the future.

The role of a structural engineer relative to serviceability is very similar to his role relative to safety. As mentioned in the theme paper, there are two general strategies in current practice: (1) formal design constraints, and (2) checking and supervision procedures. However, design for serviceability is fundamentally different from design for safety in several important respects.

2. TYPES OF SERVICEABILITY CONTROLS

A design approach to the control of serviceability conditions normally involves a set of simple rules limiting, for example, deflections, drift, slab or beam depths as a function of span, crack formation or crack width. Coupled with these is a family of general rules of practice such as minimum reinforcement for shrinkage and crack control, or the maximum number of storeys of brick facing without supporting steel angles.

Throughout design and construction, serviceability control can be exercised by means of performance specifications, performance recommendations and a system of supervision. Inadequate controls during design permit design oversights, inadequate analysis, and the use of inappropriate design serviceability constraints. Design oversights and inadequate analysis can lead to isolated cases of very serious unserviceability, while inappropriate design serviceability levels can lead to the development of systematic serviceability problems.

Control during construction normally involves checks on material properties coupled with on-site inspection to ensure compliance with specified design requirements. Failure of control during the construction phase can lead to economically disastrous serviceability failures, in the extreme resulting in total abandonment of a building.

3. MAJOR SERVICEABILITY PROBLEMS

Although service failures are undoubtedly of major importance, research on the subject is relatively limited. A survey of the literature relative to deflection problems has been made by Galambos et al [1]. In the realm of concrete buildings, significant results have been provided by, for example, Mayer and Rusch [2] and the error survey of the American Concrete Institute [3].

In an effort to clarify the nature of serviceability problems and identify critical areas for detailed study, a survey of structural engineers was undertaken [4]. For each of steel, concrete, timber and masonry structures, a comprehensive list of building elements was given with subsidiary lists of potential limit states, their manifestations and their likely causes. Correspondents were asked to rank all states and their causes in terms of relative importance.

While individual responses within the 17 replies received varied a good deal, a consensus was quite clear. The most significant current concerns are:
- transverse deflections of concrete slabs and beams, steel and timber beams, and masonry walls
- durability of all types of construction
- axial deflections of concrete columns
- sway deflections of concrete and steel structures
- transverse vibrations of concrete slabs and steel beams
- sway vibration of steel frames
- cracking of concrete slabs

Material variation with time, creep deflection, ponding, material incompatabilities, and dynamic actions were identified as primary causal factors.

While the results of this survey are limited several conclusions may be drawn. Firstly, time dependent phenomena are of much greater significance than generally assumed in practice. Furthermore, more sophisticated analysis of behaviour and material interactions may be required in future designs. Except perhaps for problems of durability, however, it does not seem that major new sources of uncertainty are involved.

4. DESIGN FOR SERVICEABILITY

Although design for serviceability involves relatively well known physical phenomena, major philosophical problems arise. On a very fundamental level, it is not obvious that design codes should define serviceability constraints with the degree of authority normally used for safety constraints. While there is a consensus that building owners must not be permitted to subject the population to undue risks of injury or death, there is much less moral justification for imposing uniform building quality standards. If an owner wishes to reduce initial investments at the cost of inferior building performance and shorter expected useful life, the right of a state or professional body to prevent such a compromise is not evident. In the extreme it can be argued that the general legal regulation of construction should be limited to questions of public safety.

A second fundamental problem of design for serviceability is the absence of limit states. In structural safety analysis there exists an algebraic relationship between variables which, at least conceptually, uniquely separates the space of building response into safe and unsafe regions. Safety analysis is thus a binary problem in which response can be evaluated as an either-or situation.

In design for serviceability there is no clear boundary between acceptable and unacceptable behaviour. Instead, there are degrees of undesireability related to a spectrum of possible building responses.

Formulation of serviceability design in terms of specific boundaries thus involves an artificial set of criteria imposed on the true situation.

4.1 Serviceability Measures

Unfortunately,the measurement of serviceability involves value judgments which can only be expressed on a subjective scale of relative loss or benefit. Such a "utility" scale can be mapped onto a monetary scale to allow an objective economic assessment of situations involving subjective evaluations.

Assessment of the utility of a structure may require several behaviour parameters. Some parameters such as maximum crack widths and inelastic deformations involve "absorbing" failure states caused by the occurrence of a single maximal event during the service life of a structure. More commonly, serviceability involves the parameters of "recurrent" failure states such as vibration and elastic deflection. For some recurrent conditions, such as non-structural storm damage, the mean rate of occurrence of an event may be relevant, while for others, such as human response to vibrations, the stationary probabilities of events may be important. In every case, the definition of efficient serviceability parameters requires careful consideration.

Given the definition of efficient behaviour parameters, the degree of structural serviceability or alternatively of nonserviceability or "aversion", can be expressed as a function of these parameters. Such functions may take many forms, but the following general characteristics are evident.
- The function has finite bounds of complete serviceability and complete unserviceability.
- Realistic functions are continuously differentiable; i.e., there are no "limit states" at which discontinuities occur.
- The function is monotonic.

As mentioned previously, serviceability is not a binary function (e.g., satisfactory/unsatisfactory) with a discrete "limit state" such as is generally assumed. It is thus impossible to calculate probabilities of serviceability "failures" and a generalized measure of structural utility is required.

4.2 Generalized Utility Measures

A generalized measure of structural utility is total expected utility, $E(U)$, defined as

$$E(U) = \int_{-\infty}^{\infty} u(x)\ f_X(x)\ dx = \int_{-\infty}^{\infty} v_X(x)\ dx$$

where x is some serviceability parameter (a function of time)
$u(x)$ is utility as a function of x
$f_X(x)$ is the probability density function of x
and $v_X(x)$ is the density function of expected utility

Note that the classical reliability, R, is a measure associated with a binary $(0,1)$ utility function, discontinuous at a failure point or limit state, x_L, so that

$$E[U] = \int_{\infty}^{\infty} u(x)\ f_X(x) dx = \int_{-\infty}^{x_L} f_X(x) dx = R$$

The usefulness of expected utility lies in its applicability to non-binary utility functions. In general, one must define utility in terms of a suitable state variable, determine the probability distribution function of the selected state variable with reference to appropriate load and structural response models and relevant design constraints, and finally integrate the derived density function of expected utility to obtain total expected utility as a basis for decision.

4.3 An Example of Expected Utility Evaluation

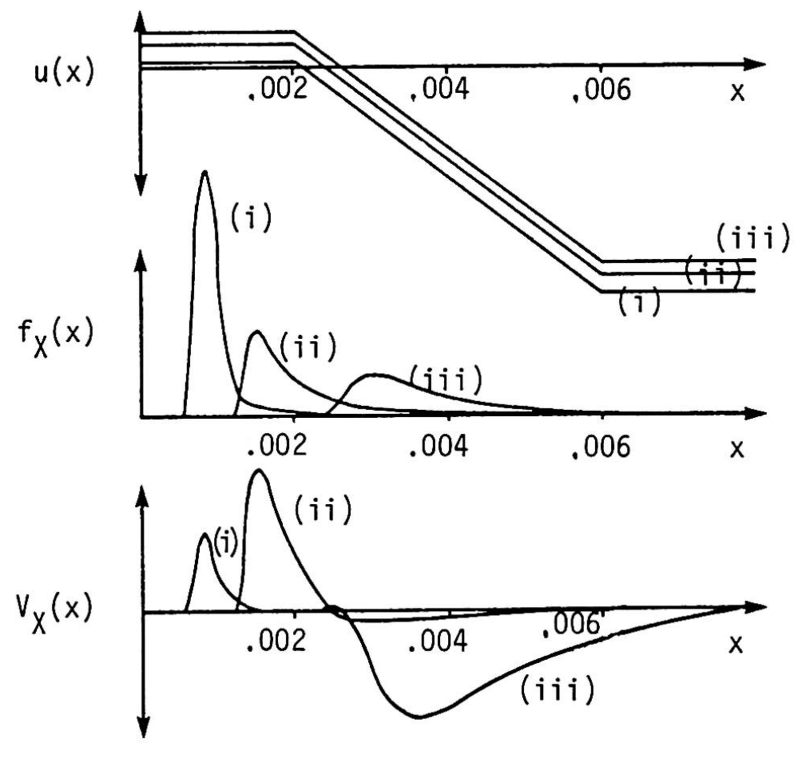
As an example of the application of utility concepts, consider a serviceability condition associated with the maximum elastic mid-span live-load deflection of a simply supported office floor beam during one office tenancy. The simplified live-load model of McGuire and Cornell [5] can be adopted and load response can be assumed given by the elastic response of a simply supported beam providing a simple support for a one-way floor system.

Conventional design in this case involves two basic criteria:
- a design load with a specified probability, q, of exceedance during an occupancy, and,
- a maximum permissible calculated midspan deflection to span ratio, Δ/L, under the design load.

By means of deterministic influence coefficients for midspan deflections, and appropriate statistics for the distributions of random sustained and extraordinary live loads, the probability distribution function of maximum midspan deflection during one occupancy can be derived.

To proceed further, a number of assumptions concerning the relative values of benefits derived from the use of a structure, construction costs, and penalties associated with serviceability characteristics must be made. For purposes of demonstration, the cost penalty associated with response was assumed to be zero for deflection to span ratios δ/ℓ up to 0.002 (full serviceability) and then to decrease linearly up to a complete loss of the investment in construction plus demolition costs for δ/ℓ of 0.006 or greater.

Figure 1 illustrates the elements of an evaluation of expected utilities associated with various design deflection ratios, Δ/L, for a design load of 2.4 kPa over a tributary area of 18.6 m^2, which corresponds to a design load fractile of .95.



(i) $q = .05$, $\Delta/L = 1/720$, $E[U] = .16$

(ii) $q = .05$, $\Delta/L = 1/360$, $E[U] = .59$

(iii) $q = .05$, $\Delta/L = 1/180$, $E[U] = -2.3$

Fig. 1. Expected Utility Evaluation of Alternative Design Criteria

5. CONCLUSIONS

This brief overview of design for serviceability suggests a number of general conclusions. Firstly, serviceability design involves relatively well known physical phenomena. However, serviceability does not involve a set of discrete limit states which uniquely define acceptable and unacceptable behaviour. As a corollary to this observation, conventional safety index, or β, analysis is not valid.

One feasible approach to establishment of design constraints is based on concepts of utility. A measure of the degree of aversion or undesireability of behaviour over the whole range of structural response is required together with a realistic set of load and structural response models. By means of probabilistic analysis the total expected utility associated with alternative design proposals can be estimated and an optimal approach adopted. It should be noted that any analysis involving economic considerations adds another level of uncertainty to those already existing in conventional structural design.

Adequate mechanisms of control during design and construction are of great importance. Many errors in construction details lead to serious service problems which do not involve public safety. Implicitly or explicitly an owner tends to receive what he pays for - cost compromises in, for example, materials or site supervision will lead to inferior structural performance.

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Summary of Concluding Remarks

Closing Address

C. BØE
Dr. Eng.
Det Norske Veritas
Oslo, Norway

This session has brought forward several interesting and important papers on safety concepts. It is not fair I think to single out any particular papers. I shall therefore put forward two comments of general nature to the papers.

Firstly, several of the presentations have focused on the task of optimizing safety within economic constraints - or was it vice versa? Anyhow, I have noticed that economy has entered the equations as a kind of "total cost" concept. Furthermore, it has been treated as an investment proposition in a long term perspective. This puzzles me, because so many decisions regarding economy - also in relation to safety - are taken on the basis of cash-flow considerations. To me it is then a question of how realistic the equations for "minimizing total cost" really are, and subsequently how realistic are the models which have been presented in this context?

If the models and the basic reasoning do not match the daily life of the decision-maker or the businessman, we are on the wrong track.

Secondly, I have the impression that every contribution more or less touched on the subject of safety versus economy, treating the two as equal parameters. In my opinion this is not always true as I have already stated in my introductory general survey.

I think we have to fully recognize the fact that in the individual trade-off between safety and economy: safety comes last. It is a common business attitude - found also in public authorities - that safety is considered a limitation to business opportunities. Perhaps equally important is that safety is considered as a limitation to human initiative and freedom. To accept this fact of life, is very important in my opinion. Because if we don't, we shall not gain further ground in our quest for greater insight into the handling, analysis and acceptance of risks.

Having made these two points, I shall only refer to the many excellent papers you have heard today which certainly have given plenty of major topics to discuss.

Concluding Remarks

FRANZ KNOLL
Dr. Eng.
Roger Nicolet & Associates
Montréal, Canada

PURSUING HUMAN ERRORS

It appears that the problem of human errors and their effects is finally coming to life after having been pushed off for a long while as the research community was looking at other, seemingly more rewarding tasks.

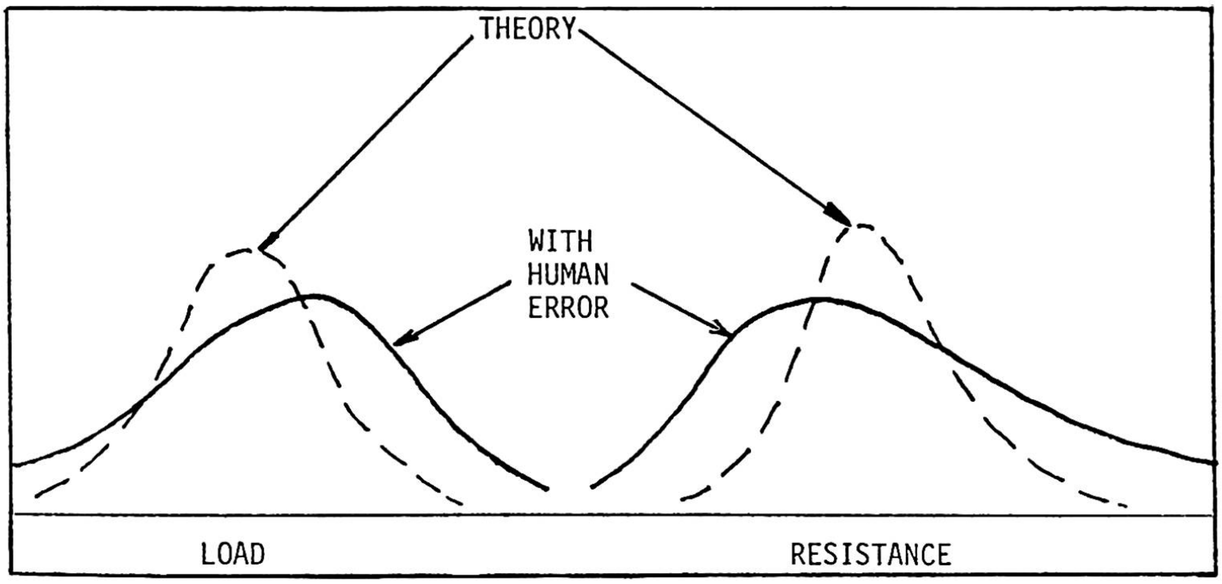
In the meantime methods of structural analysis were brought to all but perfection, making programmes and tools available, taylored to just about every conceivable type of structure. Also the analysis of statistics and probabilistics in the field of structures has been pushed perhaps to the limit of what can sensibly be used in today's construction industry, its application being limited only by the hypothesis that in construction everything is going the way it should go "weil nicht sein kann was nicht sein darf" (because that which must not be, cannot be).

Voices have been heard rarely until recent years who tried to focus attention to the fact that things do go wrong in spite of statistics and probabilistics, giving the lie to those disciplines when it comes to close the gap between reality as it happens every day and the perception of such in theory.

The fact of that discrepancy has now been widely recognized and a number of attempts can be listed that were undertaken in the last few years to clarify the reasons and conditions for the gap to exist. The general name of "human error" or "gross error", was found to suggest concisely the source of the discrepancy and two roads of attack to deal with the problem can be discerned so far, as documented by today's papers and many other recent contributions. Let us consider for a little while what these two lines of attack really are and perhaps the prospects of success may become foreseeable.

1. The a priori model :

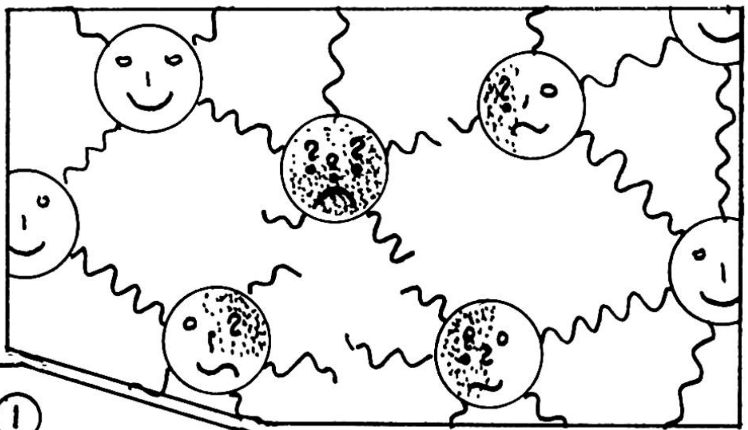
Human error has been perceived by some researches as just another source of variation of building parameters such as for example the so called stochastic variation of climatic phenomena. Distributions have been proposed for this particular source of deviation and, for a number of trivial cases, the algebra has been worked out including it, and with the purpose of fitting it in with the previously found probabilistic models of the building parameters. Results of this have been quite predictable, shifting and flattening the humps of loading and resistance distribution.

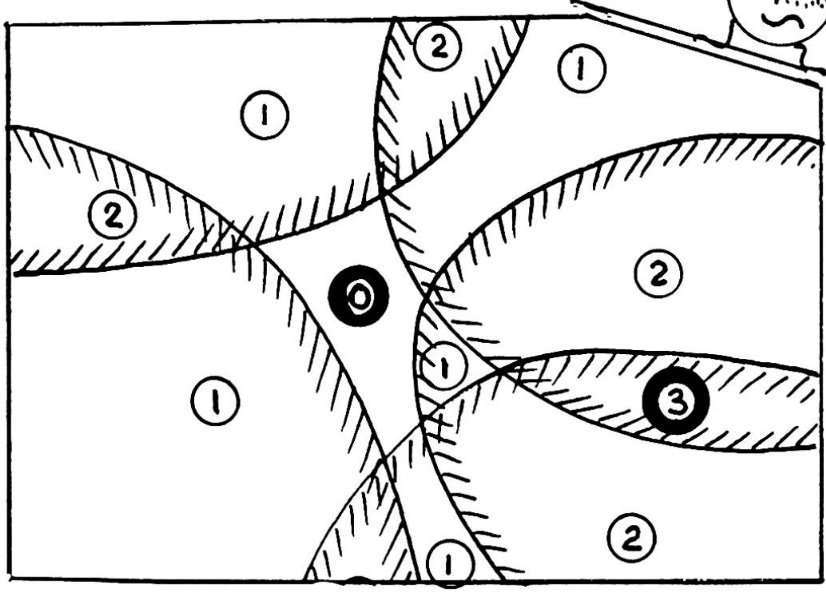


Nobody though, to this author's knowledge, has been able to prove sofar to any degree of certainty that such distributions really apply or even, whether or not this is an appropriate way to treat the problem.

When one diverts for a moment from the civilized although trivial model cases and looks at reality, one cannot but notice that its complexity is so great that to this date, it has defied any rational analysis of its parameters. It is quite easy to enumerate fifty or so factors that relevantly influence the creation and well-being of a structure, some of which are of a character which makes them altogether inaccessible to the classic statistical approach. Let us just recite a few of the more difficult ones, such as :

The information flow among the participants of a project whose interruption or malfunction can be traced as a cause of many mishaps.





The mapping of responsibility. Gaps exists where things fall between chairs, nobody feeling responsible for them; or the contrary where too many people or bodies do share in the responsibility for one particular portion and therefore spend their time and effort stepping on each other's toes.

The disposition of incentives, positive or negative. Often people can be found in a position having to make important decisions concerning events that are not related at all to any of their interests, financial or legal, or whose weight is out of all proportion to what the person can perceive as an incentive for himself. Or : Who causes the problem,

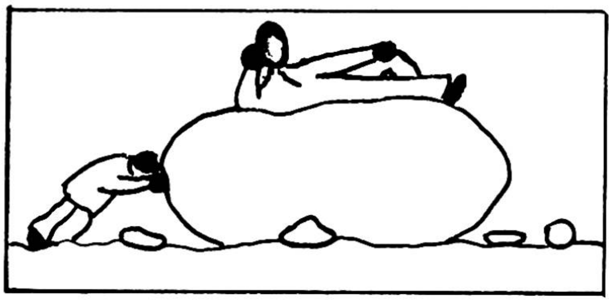
Is it the highly paid and pampered big boss

or

the poorly rewarded underling who will goof?

The qualifications and abilities of people assigned to a task :

Is it the little guy who is given a task beyond his abilities or the highly qualified who gets bored and goes to sleep because his work is not enough of a challenge to him ?
Who will cause the blunder ?

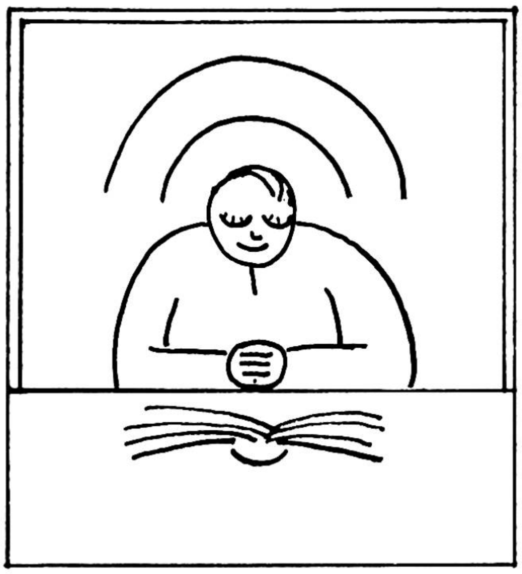


The general working condition of participants :

Is it better to keep people in key position under high stress

or

should they be shielded from anything that might be upsetting their peace of mind ?



Among many other things it is questions like this that need an answer, before we can start building theories about the probabilistics of human error and its effects. Of course, everything can eventually be expressed in terms of resistance or load, stirring it in with the all encompassing stochastic model we always apply unto events we are not able to analyse or understand. But is this ever going to teach us anything of value on the human errors that cause all the grief of structural failure ?

2. The common sense approach :

What then are all the engineers doing who build our reality while the researchers debate on the pros and cons of this or that model ? It is nothing more than the application of the best of their knowledge and the best of their experience, in other words, common sense.

Human errors do occur and means do exist to curb their frequency and effects. The uses of checking, verification, supervision and control were recognized since man began to build structures, and normally, resources are made available to perform it. We have today heard a number of contributions dealing with this common sense type of approach, and a number of others have been published in recent years. What they all have in common is that they try to formalize, on the basis of the logistics of the building process as perceived by the author or authority in charge, a system of verification and control of the building process in its phases. Some of these mechanisms have also been institutionalized, even for quite some time like the German "Prufingenieur", the French "bureau de contrôle", or more recently, in Great Britain. Only, in different countries different systems are applied and nobody has been able to prove one of them to be the best or merely superior to another. Not even the comparison with countries that do not have institutionalized procedures at all, has been made so far. This indicates two things :

- The common sense is entirely subjective and directly reflects the perception of circumstances by whoever applies it.

- There is no uniquely best or even better formalization of common sense measures against human errors, since every application works in its particular environment.

One can see immediately the limitation of this second approach to human errors. It is the bounds of what can be perceived at any one time and by any one person or perhaps group of persons in charge. It is therefore congruent to the limits of the human mind which we shall not probably change very much in the near future.

Serious impediments then exist for progress along both these lines of approach, the theoretical as well as the practical.

3. Data collecting :

Similar limitations have also become apparent in yet another area relating to the problem of gross errors: The collection of data. In several countries of Europe and North America, serious efforts have been started, and what has been recognized among many promising results is that we are not really certain what the relevant parameters of the problem are.

Looking back into my few illustrations as well as the questionaires I have been finding on my desk in recent years enquiring about past scenarios of structural failure, one thing is quite apparent : We do not know how and what to ask.

It is fine to find out that 60% or so of all failures occur during construction. But that is not really new since every experienced engineer will essentially know the same thing from his personal or indirect experience. And : This does not really tell us why the failure occurred. Perhaps we can pinpoint a person in a particular case but why was it that person and how can we go about preventing the same from happening again. Do we replace him with someone higher qualified, and in which respect, or do we increase the salary of his equivalent next time around ? Obviously, the trivial solution of the problem is to replace everybody who fails or is likely to fail with someone better qualified, and everything will be alright.

The only drawback is of course : Supermen do not occur in sufficient numbers to staff all vacant positions. We shall thus have to make do with whoever is available, i.e. ourselves, including the short-comings we may have been finding in each other. Therefore : Human short-comings do exist and will always lead to things being less than what they are supposed to be. All we can do is try and prevent them from taking effect. Either by eliminating conditions that are recognized to favor the generation of gross errors or by catching them in time. But how ? How do we set a building project up to make it less error prone, within the limitations imposed by the day. How do we assign resources available to the various possibilities of checking / verification / supervision / control in order to obtain the best possible results ? These are the real questions behind the problem of structural safety which we are facing today.

With this in mind we can now, I believe, conclude on the most promising approach we should take to deal with the problem of gross errors. It is not, at first, a direct approach with statistical methods but will have to consist of something one might call a parameter study, or a system analysis : We shall have to study the gross error at its source, namely the human individual, and along its history until it takes effect. Then and only then can we hope to be able to do something rational about it that will improve today's situation, by either reducing the results of human gross errors, or by reducing construction expenditure while maintaining the same level of safety (frequency of mishaps); only on the basis of an analysis of the genealogy of the human error shall we be able to conceive rational mechanisms for its prevention.

4. Modelling the building process :

Human error can be seen as something resembling a parasitic growth on the organism of a building process. It will, like any parasite worth its name, attack in particular the portions of the organism that are already weak or sick and there it will thrive. In order to keep the organism sound, one therefore has to find out where those weak and sick places are located, so that they can be healed, repaired or otherwise made good for. This kind of reasoning has recently been discussed rather extensively among a group of Canadian engineers, and I think I am in a position to submit some preliminary suggestions that I hope will fall on fertile ground and grow into something more concrete.

The building process seen in its totality is a very complex organism, being composed of many elements and aspects of great diversity. As we previously found, it can be perceived as a communication network, with human individuals forming stations linked together and information flow forming the currency. It can also be seen as a field of responsibility which one can map and determine, plan and change. Other aspects, or better projections as I should like to call them would be the field of incentives influencing the human elements;

positive incentives like financial reward or professional acknowledgement, or negative ones like getting fired, or the threat of legal consequences. Other properties of the building process include such features as the hierarchical organization, the selection of individuals in terms of their apparent qualifications, the general climate of personal relationship : Are we all in one boat or do we have the lawyers at the ready to be at each other's throat every minute. And last but not least, and obviously, control and checking mechanisms, regulations and institutions will constitute a major ingredient.

To put order into this cluster of parameters, elements and relationships, will require a major research effort of a rather interdisciplinary nature. The most promising approach appears to be the creation of a computer simulation or model of the building process which will then serve as a tool to do studies of various aspects and/or the problem in its totality.

The model will have to act as a receptacle for data gathered and yet to be collected : Let us not forget that the documentation on mishaps which we have begun to acquire, must be greatly expanded if ever we should hope to determine significant results in the statistical sense. If we have collected more or less complete data on perhaps 1000 cases or so, this must be measured against the number and complexity of the parameters it takes to describe a building process in all its relevant features. Mishaps on the other hand, are by no means the only source of data; what may prove to become an equal or even richer source could be the near-misses, i.e. records of cases where gross errors were caught in time and could be corrected. Fortunately in building the successes outnumber the failures by several orders of magnitude and although the latter can teach us much, we may eventually learn even more from the former. Data collecting may also be less difficult since people prefer to talk about things that went right rather than wrong.

The model will also, eventually, serve as a tool to study projected building processes, or in particular strategies for the prevention of the effects of gross errors. Once sufficient data has been absorbed and the model can itself apply formalized experience, we may be able to rationalize on how to assign resources into the places where they are having their best effect.

Or, in a wider frame, we may be able to adjust the set-up of the entire building process in order to make it function as a sounder organism.

5. Serviceability :

One aspect similar to the safety problem has been clearly recognized in the recent past : It is the serviceability criterion.

It is not always outright collapse that constitutes the most important concern but the failure of structures in general to fulfill the requirements they were designed for. States of unserviceability can generally be considered in the same fashion as the failure state itself, although some distinct differences exist. Mainly these are with the definition of the limit of serviceability which has to respond to conditions occurring together individually for each single case : The same degree of deflection or cracking may be acceptable in one case, but not in another.

One of the more difficult cases of unserviceability in terms of logic is for instance the lack of sufficient safety against failure. The question arises there: How is a structure to be classified that did not fail but is not in conformity with whatever safety rules apply ?

Research on serviceability criteria has been relatively rare and only recently the basic principles are being studied. This is perhaps a consequence of a different legal and social situation, when compared to the question of safety against failure. In the latter case it is of course mainly the public whose interests lie with the achievement of safe structures whereas in the case of serviceability, it is mostly the owner who in general, and in western countries, is a different entity.

This would be of practical advantage because where no correlation exists, the two problems can be treated separately. Unfortunately, a number of cases exist where both criteria are not orthogonal such as the abovementioned nonformity with safety criteria against failure, or like all cases of deterioration through accumulating damage through corrosion, cracking, settlement etc.

Let us also keep in mind that the cost of correcting all cases of unserviceability may well exceed the cost of making good for manifest failures.

And lastly, or course, human and gross errors have their influence on serviceability of structures as much as on the failure criteria.

Free Discussion – Second Part

In the free discussion to the preceding 9 contributions and the two concluding remarks the following persons (listed in alphabetical order) participated:

Prof. G. Ballio, Pavia, Italy
Dr. C. Bøe, Oslo, Norway
Prof. O. Ditlevsen, Copenhagen, Denmark
J. Ferry Borges, Lisbon, Portugal
Prof. H. Iemura, Kyoto, Japan
M. Kersken-Bradley, Berlin, German Federal Republic
Dr. F. Knoll, Montreal, Canada
Prof. G. König, Darmstadt, German Federal Republic
Prof. H. Kupfer, Munich, German Federal Republic
N.O. Larsson, Stockholm, Sweden
J.A.P. Laurie, Pretoria, South Africa
M. Matousek, Zurich, Switzerland
Dr. R. Rackwitz, Munich, German Federal Republic
Prof. J. Schneider, Zurich, Switzerland
K. Sriskandan, London, Great Britain
Prof. C. Turkstra, Montreal, Canada
Dr. L.P.C. Yam, London, Great Britain

Their statements are given below in chronological order:

Ferry Borges: I am most interested in the presentation of Dr. Knoll. However, it was not clear to me what is the position of Dr. Knoll concerning the implementation of his ideas. Is he optimistic or pessimistic about the practical application of the concepts presented?

Knoll: My reply is simple: I came to the session actually looking for help for the undertaking of our research. I have been able to obtain a number of useful suggestions. The task seems quite formidable to me but we have hope to come up with a suitable arrangement to set-up a research group.

Kersken-Bradley: A question to Mr. Bøe: In your concluding remarks you referred to safety as a "limitation of business opportunities". I do not quite agree. Within a framework of clearly defined responsibilities and liabilities - including appropriate sanctions and legal prosecution - business decisions based on the consideration of possible consequences of the decisions should yield a level of safety not differing very much from a prescribed level. Thus, business and safety requirements should not be contradictory; if they are contradictory, then either the framework, mentioned above, or the safety requirements are not adequately balanced and need to be rechecked.

Bøe: To make it clear, I said it is the attitude that most demands for safety are considered as limits to business opportunities. I don't think there is a constant conflict between safety and economy. It is more like a constant trade-off situation where economy always comes first and forces safety into the background. This is why codes are so important because they represent limits to risk which are not negotiable, i.e. not dependent on individual trade-off between safety and economy.

Yam: While agreeing with Dr. Bøe that safety and cost are somehow related, I am uncertain about the degree of this relation. The recent British study on failures has indicated that increases in resources would not have significant effects on failures. Perhaps only investment at a national level could have helped. Let us take another look at this relation from practical observations. One tends to assume that building is a business in which construction quality is in conflict with profit. But when we examined failure incidents in some Eastern European countries, in which the element of profit did not predominate, we found the same familiar patterns and causes of failure. For example, human errors occurred to a similar extent, some due to pressure to meet deadlines though financial pressures were absent. Let us turn to industries with relatively abundant resources, such as offshore, nuclear and construction for defence. They are highly safety conscious but, in spite of vast investment on quality assurance, have to admit that money alone cannot buy safety. We need to do more work to understand human nature.

Matousek: I have a question to Professors Kupfer, Ditlevsen and Baratta: What is the definition of "gross error" you introduced into your papers?

Kupfer: To answer the question of Mr. Matousek about the difference between deviations from target values due to natural variations and due to human error, I would like to point out that large deviations caused by natural variations generally occur with extreme low probabilities. On the contrary, the same deviations if they are caused by human error have much higher exceedance probabilities, e.g. 10^{-2} or 10^{-3}.

Of course, there is also a philosophical aspect because it is not easy to distinguish whether a large deviation was caused by natural variations or human error. In particular, it is necessary to look at the process generating the quantity under consideration. E.g. in concrete production extreme low strength values can not totally be excluded even if the relevant codes of practice have been observed. However, a large deviation of the location of the reinforcement in concrete members from its intended position can hardly be viewed as the result of random influences since the men at the job reexamine the result of their work. Also, the functioning of the distance pieces can be controlled before concreting. In this case one might consider to define a deviation being the result of an error if it exceeds a certain value.

Schneider: Could we hear the definition Mr. Matousek would like to have in this context?

Matousek: I think the notion "tolerances" should be used in this context. All human activities or results beyond stated tolerances would then be defined as gross errors.

Rackwitz: From a modelling point of view it appears useful to define errors independent of their size or their effect on structural safety as marked events belonging to a certain error generating point process. This implies that jurisdicial definitions do not apply in the strict sense. An error is present if a faulty action or omission takes place which is in conflict of what should have been done according to given professional rules, codes, regulations, etc. valid for the activity under consideration. Thus, an error which increases structural safety also is an error as this is the case if it has no effect on structural safety at all. Natural variations can then be taken within their entire physical or geometrical domain of definition. This definition of errors necessarily excludes faulty actions due to general professional ignorance for which no rational remedy appears possible.

Ditlevsen: Mr. Matousek directed his question to me also. As it can be seen from my paper, theoretical reliability is related to a mathematical model which may, according to the engineer's own choice, contain errors described in probabilistic terms. Some of these errors may, in fact, be denoted as gross errors which are parametrizable and therefore accessible to statistical analysis, and, consequently, accessible to rational control. In this view it is, perhaps, not very important or even useful to set up a general definition of what is a gross error. However, relative to a specific structural design including its mathematical model it may be useful to consider as a gross error any gross deviation of the realized structure and its environment from what was intended in the mathematical design model, and this whether or not the deviation has damaging consequences. This concept includes gross deviations caused by nature itself due to unsuitable choice of mathematical model. That claim in this case is to be put on the engineer and not on nature is not essential. The term "gross deviation" is imprecise and is to my opinion, as paradoxial as it seems, only practically operational as such. For the design process and the construction process a "fuzzy" perception of what are gross errors suffices. Quite another question is the legal one of claiming somebody in the court if damage has occurred.

Turkstra: Technically one can define a gross error as any condition in which design parameters are chosen from populations not envisaged in the design process. Personally, I do not like the term because it is too gross.

Errors in construction are of many kinds, may be made by various actors in the process, and can be prevented in different ways. They should not be lumped into a single category.

Nor do I believe that we should model errors and accept them in design. This penalizes the careful and responsible engineer and removes the incentive to improve practice. It is our responsibility to see that human errors are avoided.

Laurie: Figure 3 of Yam's paper indicates that in nearly 50 % of failures, checking of design concepts would have minimized recurrence of this type of failure. This appears to contradict his comment that responses to the survey questions had disclosed that increased budgets (more money) would not have avoided the failures - surely checking costs money?

This in turn suggests that engineers instinctively think in terms of investing more money in the structure or perhaps in more refined analyses when searching for improved safety rather than in the procedural or organisational aspect of design and construction (such as checking) which have been shown to be more critical when it comes to failures.

Yam: Mr. Laurie is quite right in pointing out that some remedial measures in Figure 3 involve spending money. Of course, money has to be spent on implementation and is in this respect related to safety. When I said money alone can't buy safety, I was warning against over-simplifying the relation. The simple relation holds up to a point. For example, improvement at a project level is quite impossible in many instances and has to be considered on a national scale.

König: I want to point out and underline that the amount of money spent on a structure can indirectly influence safety to a great extent.

The Civil Engineer is forced by competition to build new structural systems, use new construction methods, new materials and in the extreme to reduce the dimensions of structures from those used in previous structures. If the designer works far beyond the limits of general experience it is possible that he may not fully understand the overall behaviour of the structure, or he may not realize that there could be some new aspects of behaviour which were not known before. In such cases there is a greater likelihood of structural accidents.

Errors in estimating the price of a structure may also influence safety to a great extent. In such a case the contractor, in an effort to keep within his price, is forced to design and to build a weaker structure. Even with a high effort of control it is very difficult to avoid failures under these conditions.

The above statement is similar to that made in Prof. Kupfer's presentation and I would like to add the following to his list of causes of failure:

a. Bad estimating by the contractor especially in design and build contracts.

b. The engineering climate, e.g. time pressures on engineers to complete schemes quickly.

Also Sriskandan must have found that the higher effort of control reduces the failure rate of bridges in UK.

Skriskandan: I would like first to add to what Dr. Yam has said in answer to Mr. Laurie's question. In the UK we have been following procedures for quality control of design since 1973. Prior to that there were no formal procedures and there were errors which cost money to put right. However, since 1973, there has been only one known case of an error that slipped through the checking system.

The cost of the checking has varied from 5%-20% of the cost of design with an overall average of about 10%. We consider that we are getting good value for this money.

Professor König has suggested that there might be a difference in risks between structures that are fully designed before inviting tenders and those that are submitted in competition to design and build. I think that even in the latter case it would be possible to prescribe the safety requirements and independently check the design before it is constructed. However, what is more difficult to prescribe are the requirements for durability and adequate inspection and maintenance.

In my view, this is where competitive designs may prove to be troublesome. The client should try and prescribe these requirements very fully or be prepared to pay extra for modifications to improve these aspects of the design.

Ferry Borges: I call the attention of Prof. Turkstra to the need of considering duration when dealing with several types of serviceability limit states.

Schneider: I don't like the notion "serviceability limit state" at all. In my opinion serviceability basically is defined by an agreement between the client of the structure to be erected and the designer. Safety requirements, on the contrary, are to be stated in obligatory terms in codes. For serviceability, a limit state does not exist, as I see it.

Turkstra: Mr. Ferry Borges is quite right in his statement that our definition of serviceability is not quite right. We simplified the problem in order to make the general points.

In reality, unserviceability is associated with several types of load characteristics - some are reversible up-crossing problems, some are holding time problems and some are first passage problems. We consider these types of problems in our detailed studies which will be published later.

Kersken-Bradley: The following presentation I should like to make, is not to be regarded as a sincere contribution to the discussion on what is the appropriate objective in optimization techniques accompanying engineering decisions. You may take it as an absurd provocation:

For some structures losses in case of failure may be very large:

$$L \rightarrow \infty$$

(some people refer to e.g. nuclear power plants in this way).

Question: By which measures can expected losses be reduced to an acceptable level ?

Provocative answer: The probability of failure can never be reduced to precisely zero. Therefore, measures have to be employed, ensuring total destruction; i.e. total destruction of our globe.

Then, no human beings survive
no possibility to suffer from losses
thus, no losses at all (as nobody can suffer)

$$\rightarrow E(L) = 0$$

Obviously, something is wrong with this answer, but what ?

Schneider: One of possible contradictions could be that human instinct - at least in sudden incidents - forces the individual to adequately behave in order to avoid being killed.

Ditlevsen: This provocative example is not consistent with proper application of decision theory. The falacy is that costs should be assigned also to the act that carries out the decision (in this example, costs which ethics, or human instinct, would dictate to be infinite) and not just to the state following after the act. In short, utility should be assigned prior to the act and not posterior to the act.

Kupfer: Referring to Mrs. Kersken-Bradley's provocative exposition, I sincerely question whether the sufferings of those who remain are of any concern. Instead, human life should principally be protected as far as possible. This ought to be achieved via an overall optimization. In such an optimization, the total available working power corresponding to the state of technology and human way of life would have to be taken as a given quantity. Also the optimization process might be affected by the availability of resources. Excessively safe and thus uneconomical construction leads equally to losses of lives which then are caused by the lack of various other needs, e.g. nutrition, clothing, buildings.

Such global optimization studies are, nevertheless, as the initiating question very theoretical since with the obvious irrationality of humanity which primarily demonstrates this in the misuse of technology, presently optimization can only be done in very narrow fields.

Iemura: Acceptable risk depends on people and circumstances. For example, if people are told that a big earthquake which has a return period of 100 years may occur tomorrow, they suddenly decrease the "acceptable" risk to earthquakes.

Rackwitz: I feel that there is some kind of religion or ethic imperative in a number of the arguments just put forward. There is certainly not a unique number of an acceptable risk which unequivocally comprises those intangibles, it cannot be determined by looking at statistical failure rates and if it would exist, there are heavy technical difficulties in the use of such a number. At present, an acceptable risk to human life and limb cannot be defined without explicit reference to the overall probabilistic uncertainty model used for the calculation. Thus, structural failure probabilities should not be compared with failure rates in areas of human activities where statistics are available nor should two designs be compared on this basis unless the uncertainty model is the same. The acceptable risk rather is a conditional by-product in the process of minimizing the generalized cost of a structure. The concept of probability should only be viewed as a meaningful intellectual tool in a decision theoretic context. The structure finally is described by a very real set of dimensions, material grades, etc. and these are the natural descriptors of the state of a facility. Explicit optimization of utilities immediately reveals that the "acceptable" risk should be identical to the optimum risk under each particular circumstance. It depends on many factors which differ from structure to structure, material to material, one type of loading to the other, etc. Thus, in principle, there may be neither an acceptable nor an uniform risk .

Turkstra: I am glad that we have reached the "fun" part of the program. The answer to Kersken-Bradley's dilemma may be as follows: Utility involves the product of failure probability and costs of failure. If failure costs are infinite, utility losses need not be infinite so long as failure probabilities approach zero in the limit faster than failure costs go to infinity.

Failure probabilites become "effectively" zero relatively quickly as I tried to show in an ASCE paper in 1967. Who, for example, can tell the difference between probabilities of 10^{-10}, 10^{-20} or zero.

Larsson: The result of our design procedures should be studied and failures analyzed so that we can adjust our safety factors. As an example, we have no experience of some new structures. A prestressed ground-anchor could have been correctly designed in the limit state, but could have its corrosion protection destroyed after one single moderate overloading, causing collapse within a few years.

Closing Remarks

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If this session had been held, for example, five years ago the main part of it would probably have concerned the choice of appropriate safety factors or safety index and similar questions. Today, we have got almost all possible points of view on safety problems. Thus, the concept of safety has been enlarged considerably during the last years. When we speak about safety today, we do only think of safety factors in the calculations but also of optimization, performance criteria and quality assurance, the risk of accidental events and gross errors, the effect of control and similar questions. Many of these questions are fairly new and involve a large number of problems which ought to be dealt with in future research.

Sitzungs-Bericht des Koordinators

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Grundlage der Diskussionen waren die Einführungsberichte "Sicherheit als sozio-ökonomisches Optimierungsproblem" von Th. Schneider (Schweiz), "Risk Management - The Realization of Safety" von C. Bøe (Norwegen) und "Safety, Building Codes and Human Reality" von F. Knoll (Canada). Schon die Titel dieser drei Einführungsberichte zeigen, dass es nicht darum gehen sollte, den Begriff Sicherheit, Sicherheitsziele und Sicherheitsmassnahmen im engen Sinne zu diskutieren. Vielmehr war beabsichtigt, die Bemühungen des statisch-konstruktiv tätigen Bauingenieurs um ausreichende Tragwerksicherheit in einen grösseren Zusammenhang zu stellen und, wo möglich, mit anderen Bereichen der Technik zu verbinden.

24 Beiträge von Fachleuten aus 10 Ländern wurden eingereicht. Obwohl von grossem wissenschaftlichen Wert, mussten hiervon 8 Beiträge ausgeschieden werden, um den Zeitplan nicht zu überlasten und den durch das Thema gesteckten Rahmen auch wirklich voll auszunützen. In Wien wurden schliesslich an einem ganztägigen Seminar in einer Gruppe von etwa 80 Teilnehmern aus aller Welt 14 sehr wertvolle Beiträge vorgetragen und in freier Diskussion ausgiebig besprochen.

Die Diskussion zeigte, dass wir auch heute noch weit von einem allgemein akzeptierten Mass für sicherheitsrelevante Ingenieurentscheidungen entfernt sind. Offensichtlich ist jedoch die zentrale Bedeutung, die fast alle Teilnehmer den sog. groben Fehlern zumessen. Bemühungen um die Voraussage rechnerischer Versagenswahrscheinlichkeiten unter Ausschluss solcher Fehler treten heute eher in den Hintergrund. Menschliche Fehlhandlungen dominieren das Schadengeschehen in der Technik im allgemeinen und damit auch im Bauwesen. Die Bemühungen der Fachleute konzentrieren sich heute einerseits auf die Entwicklung geeigneter Massnahmen, um solche Fehlhandlungen weniger wahrscheinlich zu machen, und andererseits auf die Bereitstellung von Kontroll- und Ueberwachungssystemen, um Fehler rechtzeitig zu entdecken und auszumerzen. Das Seminar "Sicherheits-Konzepte" des 11. Kongresses der IVBH in Wien hat hierzu zweifellos wertvolle Anregungen gebracht.