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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 implications is 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

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

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

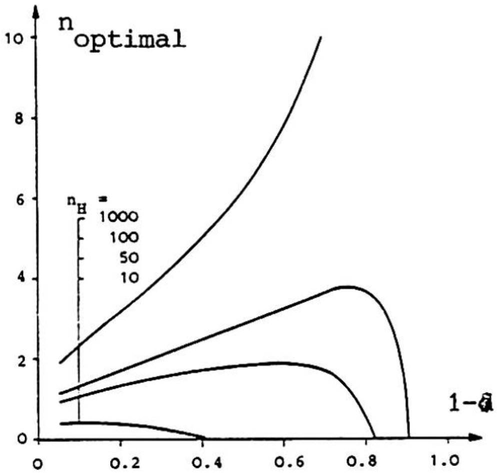

Figure 1: Optimal number of control checks versus control efficiency

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.

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

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 $A \leq 1$ 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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