Some thoughts on optimization in civil engineering

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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 parameter 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

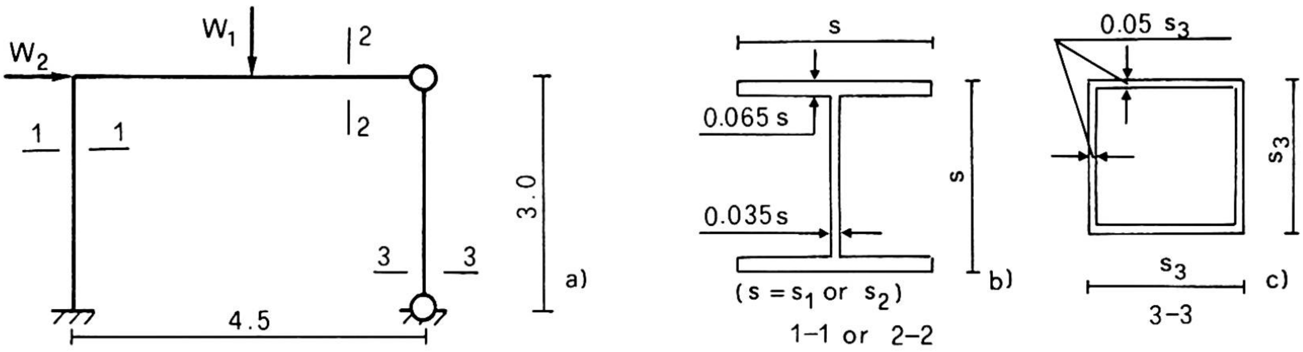

FIGURE 1 (from Ref. |2|) - Example design problem (lengths is meters). Economical parameters: total benefit in case of full success $B^{\circ}=3000$; loss for total failure $H_f=750$ or 1500; loss of excessive deformation $H_d=3$ or 15; interest rate $\gamma=5\%$ or 15%. Monetary unit: 1 kg of steel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

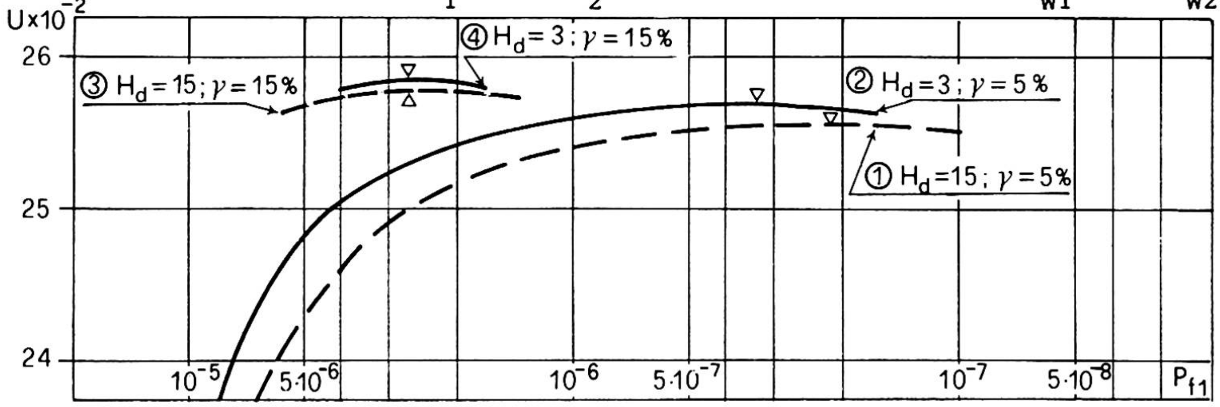

FIGURE 2 - Expected utility U vs. prob. of failure rate P_{f1} per year ($H_f=1500$)

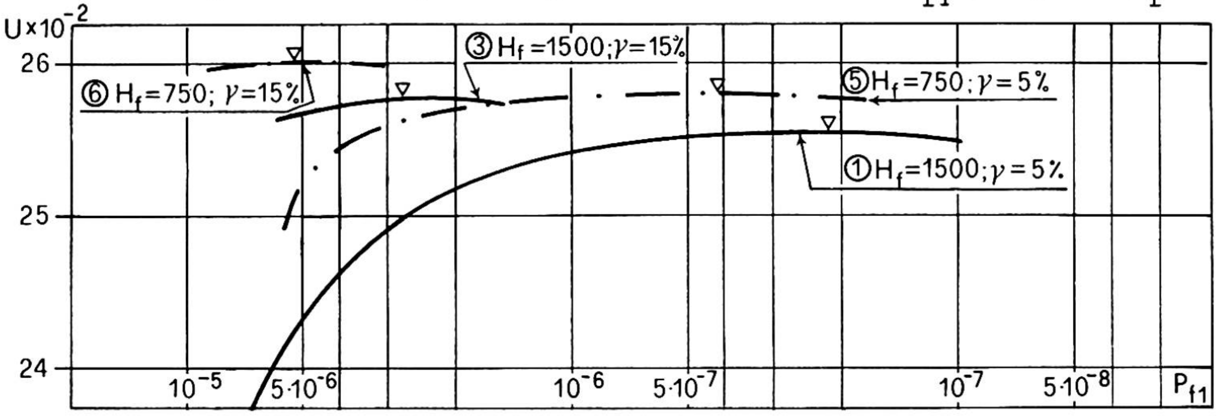

FIGURE 3 - Expected utility U vs. prob. of failure rate P_{f1} per year ($H_d=15$).

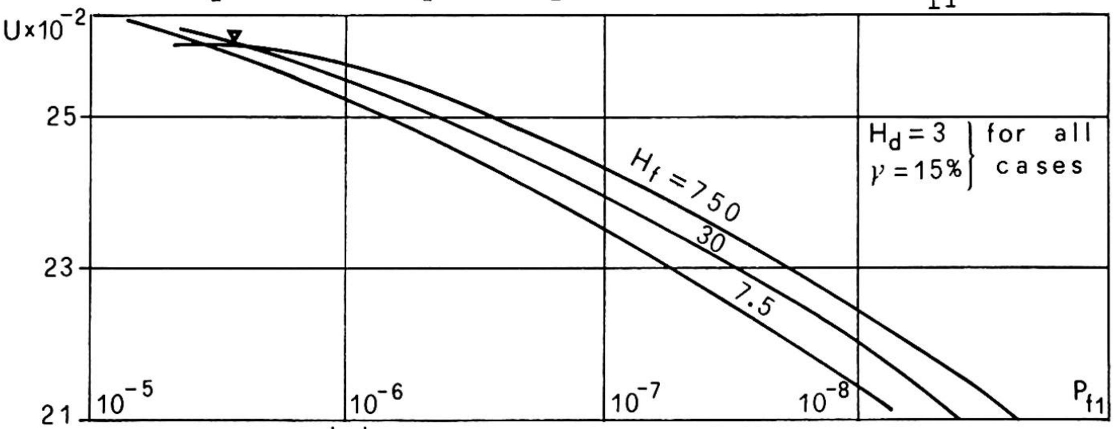

FIGURE 4 (from Ref. |8|) - Expected utility U vs. prob. of failure rate P_{f1} per year; the curves are obtained by following the slowest descent path.

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.

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REFERENCES

1. AUGUSTI,G. and CASCIATI,F.: Multiple Modes of Structural Failure: Probabilities and Expected Utilities,Proc. 2nd ICOSSAR,1977(Werner-Verlag,pp. 39-57)
2. AUGUSTI,G. and CASCIATI,F.: Further Studies on Structural Design for Maximum Expected Utility, Proc. 3rd ICASP, Sydney 1979, Vol. II, pp. 686-700
3. BAUMOL,W.J.: Economic and Operation Analysis, Prentice Hall Inc., 1971
4. THOMPSON,J.M.T. and HUNT,G.W.: A General Theory of Elastic Stability (Chap.13: "Structural Optimization"), J. Wiley & Sons, London, 1973
5. GRANDORI,G.: Earthquake Risk, Proceedings of the Seminar on Earthquakes, Soils and Structures, Saint Rémy lès Chevreuse,November 1979
6. ROSENBLUETH,E.: Optimum Design to Resist Earthquakes, Proc. ASCE,105,EMI,1979 pp. 159-176
7. AUGUSTI,G.: Some Considerations on the Assessment of Structural Reliability, Nuclear Engrg. and Design, to be published in Vol. 59, 1980
8. AUGUSTI,G., BORRI,A. and CASCIATI,F.: Structural Design under Random Uncertainties,and "Intangible" Quantities, in preparation for 3rd ICOSSAR(i.e.3rd Int. Conf. on Struct. Safety and Reliability),Trondheim, June 23-25, 1981