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Life Expectancy Studies of Reinforced Concrete Using Microcomputer

Étude de la durée de vie du béton armé par simulation

Studie zur Lebenserwartung von Stahlbeton mit Hilfe von Simulationen

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SUMMARY

The paper describes how a systematic stochastic life-expectancy and financial analysis can be performed by exploiting the combination of microcomputers and Monte Carlo simulation. The use of the program "Venturer" developed by the author, is illustrated with an example of a footbridge.

RÉSUMÉ

L'article décrit comment les analyses systématiques et aléatoires, de durée de vie et de risque financier, peuvent s'effectuer à l'aide de micro-ordinateurs en utilisant la simulation de Monte Carlo. L'utilisation du programme "Venturer", qui a été développé par l'auteur, est illustrée par un exemple de passerelle.

ZUSAMMENFASSUNG

Der Beitrag beschreibt wie eine systematische stochastische Lebenserwartungsberechnung unter Einbezug der Kosten mit Hilfe einer Monte Carlo Simulation auf Mikrocomputern durchgeführt werden kann. Die Anwendung des vom Autor entwickelten Programmes "Venturer" wird am Beispiel einer Fussgängerbrücke erläutert.

1. INTRODUCTION

A designer usually has a target life, referred to as a design life, for which s/he will attempt to design the structure. The actual service life, however, will be shorter or longer than the design life. It is, therefore, necessary to examine the uncertainties that influence the service life if rational decisions for economical design are to be made. The economic analysis should not only acknowledge the engineering uncertainties (i.e. physical, statistical and model) but must also take into account the financial risks caused by the uncertainties in the economic environment. The life-cycle costing exercise must include estimates of construction cost, salvage value (if any), design life as well as maintenance/repair costs over the life of the structure. Deterministic life-cycle (i.e. single point) estimates produced to compare and evaluate alternative designs can lead to bad decisions. These estimates, at best, aspire to produce likely values of life and cost. Figure 1 shows that if only likely values of the objective function (e.g. life) of the alternative designs A and B (on scale OS) are available to a designer then B will be chosen. On the other hand availability of the full probability distribution not only provides insight into the nature of the designs but also throws a very different light on their relative merits, and may lead to the alternative A being chosen as a safer or a low risk design. There is a rapidly growing awareness in the professions of the need for taking a view that reflects the stochastic nature of the problems that the designers are called upon to model and analyse.

2. DESIRABLE FEATURES OF LIFE EXPECTANCY STUDIES

All quantitative studies have two important features. Firstly, there must be a mathematical model which expresses the relationship between the objective (e.g. life, cost) and the various variables that are recognised to be the controlling factors. For a model to be successful it should be reasonable, complete and adaptable. A reasonable model does not violate the basic logic of the process being modelled and provides plausible results. A 'complete' model contains all the important influencing factors (termed uncertainties) and their interrelationship. Generally a real-life system will have innumerable factors influencing the objective. Inclusion of all these will cause loss of manipulative flexibility. Unimportant factors have to be identified and neglected. An adaptable model can be easily enriched in light of new knowledge and insight that ensues from its use as well as in light of continuing research in materials and structures. The studies should reflect this and allow the designer to assess the effect of choice of a model on the objective. Secondly, a reliable probability distribution of the objective can result only from a set of carefully estimated probability distributions of the variables (termed uncertainty profiles). When these are based on empirical studies or historical data it is important to be aware of the changing circumstances and environment. Due weight should be given to expert opinion and motivational and cognitive biases should be avoided by using Delphi technique. An important point that needs to be emphasised is that the uncertainty profiles of the various variables do not all conform to some convenient shape but can range, for example, from a near normal for one variable to near exponential shape for another within a model.

3. ANALYTICAL TYPE OF STUDY

This type gives stylised probability distribution of the objective function. It is obtained analytically from the uncertainty profiles of the controlling factors which have to be expressed in stylised forms. The mean and standard deviation of the objective are obtained from those of the variables and from the coefficients of correlation between them. This involves the use of simplifying assumptions about the variables and their correlation coefficients [1,2]. With many design problems of even modest complexity this approach may not even be possible [3] unless the model is simplified so much that it is no longer reliable; in that case the analyst gets a (so called) precise answer to a wrong question. Surely even an approximate answer to the right question is vastly superior. The author's "experiments" with senior engineers, postgraduates and undergraduates, have shown that they are ill-at-ease with this method and experience difficulties even with very simple problems.

4. MONTE CARLO SIMULATION TYPE OF STUDY

Unlike a field or a laboratory experiment, simulation can be conducted entirely on a computer by expressing the interactions and the dependencies among the various controlling factors in the form of a mathematical relationship. It has been used in a host of situations [4,5,6]. In Monte Carlo Simulation, we "construct" a large number of structures with our model to reflect the characteristics of our design. From these large number of results, the probability distribution (termed venture profile) of the objective is obtained. The input information does not have to be forced into some idealised mathematical shape, and full probability distribution of the objective is obtained. There is virtually no constraint as far as the complexity of the model is concerned. Thought processes associated with analysis and synthesis in this approach are positively more attractive to engineers. Sensitivities of the objective to the various factors as well as to the various mathematical models can be easily studied. This helps to identify the factors which contribute most to the phenomenon under study and to assess the effects of errors in the estimation of the data and in development of the models. Efforts to improve the estimates and the design procedures can then be made in proportion to their relative importance. Additionally the results of these analyses are very valuable for drawing attention and allocating effort towards improving the construction, maintenance and use of structures.

5. MICROCOMPUTER SIMULATION

It is most relevant to note that in the coming decade, microcomputer power is expected to quadruple, at least. Memory size alone is likely to quadruple every three years for a constant price. Bell [7] predicts that "the power of todays Cray X-MP (four processors delivering a peak power of one billion floating point operations per second... and a main memory of one million 64-bit words) will be available in a workstation". This is roughly 60,000 times the power of a personal computer. Even today, one of the criticisms levelled against simulation is that it is computationally expensive. This view is out of date by a number of years. These costs will be very trivial in the near future. Other reservations that are often expressed are the time and the cost of programming. This is valid if every problem needs to be programmed separately. To overcome this and to encourage greater use of probabilistic modelling techniques a package has been developed [1] which is designed to (a) provide an aid to learning modelling and simulation techniques and (b) provide an applications program for general use in a host of situations. It has been used for synthesising and analysing a number of problems, such as cost risk analysis of a hydroelectric project, stability of dams, project appraisal and atomic bomb detonation effects [4]. The application program allows direct entries of the mathematical model and data interactively without any need to access the codes. These entries can be "enriched" and revised as and when necessary. Other features included are resimulation, filing and hard copy facilities. Facility for sensitivity analysis is of particular value. Perhaps the most important argument for using Monte Carlo Simulation is the fact that the exponents of the analytical approach resort to using this method to check the validity and the reliability of their analytical methods.

6. ILLUSTRATION

Figure 2 shows a section of the foot-bridge used as the example. For this illustration we shall consider the service life in terms of the deck (slab) only. In order to determine the service life of a structure it is necessary to identify the influencing factors, their actual effects and the respective failure mechanisms. This is called "Failure Mode and Effect Analysis" (FMEA). A check list of the factors, mechanisms and their effects for structures can be obtained from various studies [8]. Corrosion of reinforcement as a result of carbonation of concrete is considered to be the most significant failure mode. Here we shall consider failure mechanisms mainly due to this factor. The effects of the other factors are implicitly included in variables that define the climatic conditions.

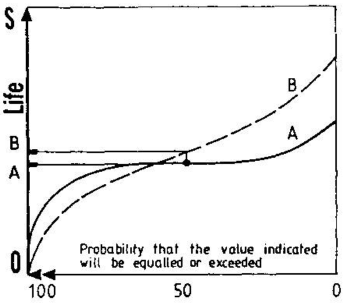

Fig.1 Comparison of Venture Profiles

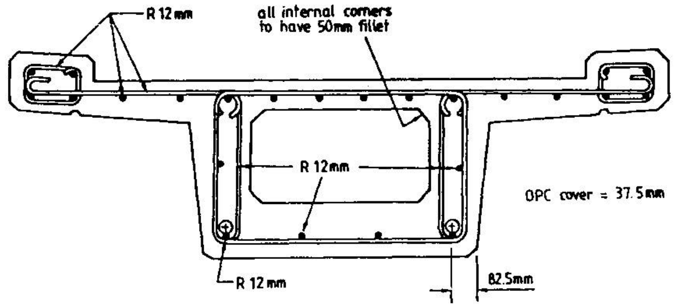

Fig.2 Foot-bridge: X-section

6.1 Model for Life

The question as to which model should be used is an area of wide controversy. The author does not intend to enter into this argument, and for his illustration he will employ a model provided by Siemes et al [8]. In their model the service life (L) is the sum of three elements; the time for carbonation, the time gap until the visibility of corrosion and the prolongation of the service life due to coating, i.e.

$$L = t_{cb} + t_{cr} + t_{ct}$$

Enrichment of this equation yields the following model:

$$L = \left[\frac{(c-d)}{R\,k} \times \frac{2.7}{46w-17.6} \right]^2 + \frac{0.08c}{d_i\,V_c} + \left[\frac{(c-d)S}{180f_o} \times \frac{(T/T_c)\ln f_o}{1-e^{\wedge}-[(T/T_c)\ln f_o} \right]$$

where t_{cb} = carbonation time; t_{cr} = time to visible corrosion
t_{ct} = time extension due to coating; w = water/cement ratio
R = cement type factor; k = climate type factor
c = concrete cover; d = carbonated depth (mm)
d_i = bar diameter (mm); V_c = rusting rate (mm/year)
T = maintenance period; T_c = coating durability parameter
f_o = damage of coating (mm/year) S = coating thickness (mm)

For economy of space the last term is discarded with the assumption that coating will not be employed. Our model now has seven variables. The diameter of bars d_i is considered to be deterministic (12 mm). The uncertainty profiles of the other six are shown in Figure 3. Venture profile of the service life is shown in Figure 4. The sensitivity profile shows the relative importance of the factors. The lengths of the darker bars are scaled to give the variations in the average value of the objective as influenced by changes in the respective uncertainty profiles. The lighter bars give the ratio of the total change in the average value of the objectives to the total change made in the average value of the variable.

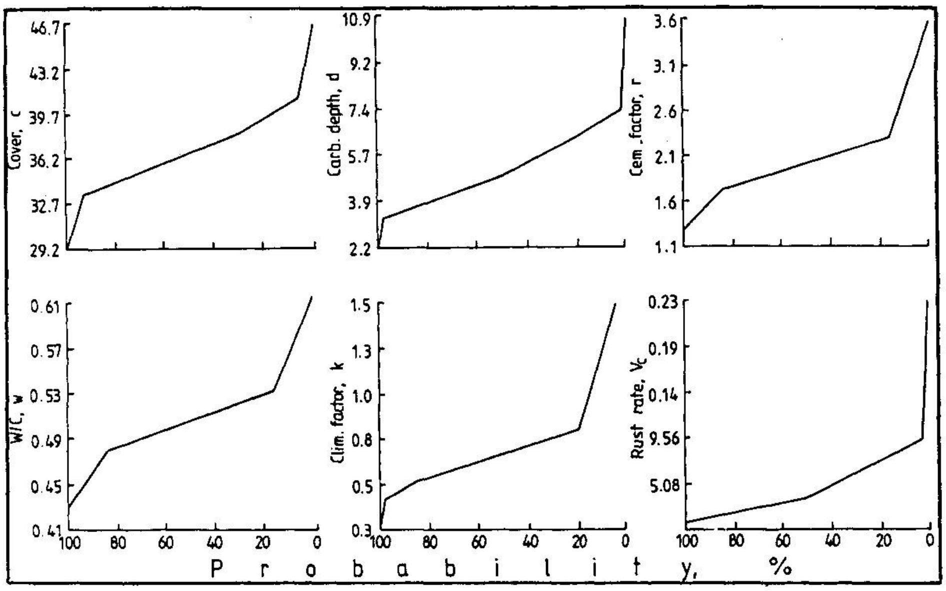

Fig.3 Uncertainty Profiles of variables in Life model

6.2 Model for Cost

There are, again, various ways in which the total cost of a structure can be modelled. For illustration let us use the following for estimating the Net Present Value (NPV) of the bridge.

NPV = Present worth factor x salvage value + present worth factor x (annual income - annual maintenance cost) - initial construction cost.

Enrichment of the model leads to the following; written in the form which can be entered directly through the keyboard (with the help of inbuilt logical checks and editing facilities provided in the Venturer) with meaningful variable names.

```
NPV = (1/(1 + (discourate/100))^life) * salvage)
    + ([(1 + (discourate/100)) ^life-1]/[(discourate/100)
    * ((1 + (discourate/100)) ^life)] * (anincome - anmaint))
      - constrcost
```

Venture profile for life (L) obtained earlier can now be entered as an uncertainty profile. Figure 5 shows the results with the assumption that the ranges of the other five variables are, in order in which they appear above, 7 to 12%; 14 to 147 years; £70,000 to 130,000; £100,000 to 220,000; £50,000 to 90,000 and £1,000,000 to 1,400,000. The results are obviously very valuable in design and economic studies such as evaluation of alternatives or establishing optimum maintenance policies. The sensitivity profile puts the relative importance of the engineering and economic factors in proper perspective.

7. CONCLUSIONS

Monte Carlo technique as implemented in the form of VENTURER, an interactive and tolerant educational and applications package, helps to overcome effectively the serious limitations of the analytical approaches to life-cycle studies. It encourages healthy scepticism towards assumptions in modelling and towards quantification of the influencing factors. It encourages and facilitates sensitivity analyses at the modelling and parameteric stages.

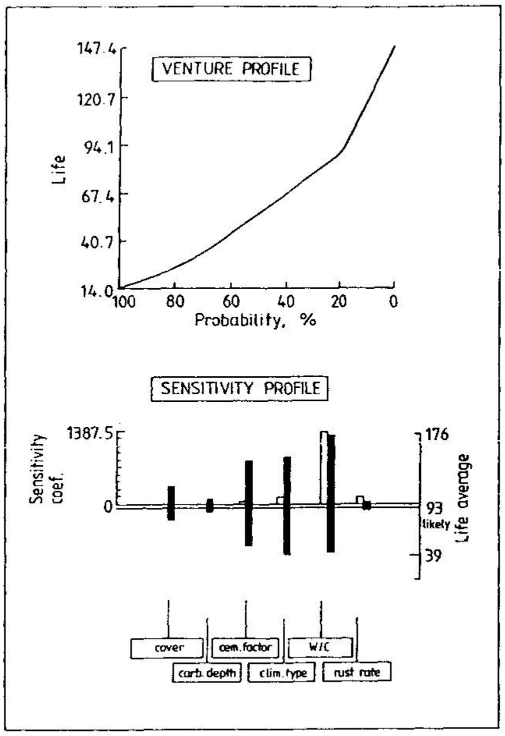

Fig.4 Life results

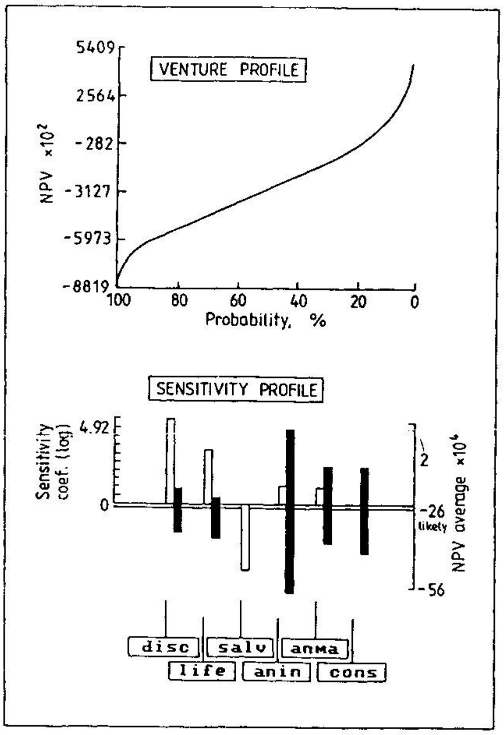

Fig.5 Cost results

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