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Editorial – Assessing structural risk

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There has been an explosion in the number of papers in the field of 'risk' in recent years and various methodologies for quantifying the probability and/or consequences of structural failure have been proposed. In risk analysis one predicts the probability or consequences of failure but it is somewhat less clear how one should interpret the statement that the probability of failure is 10^{-5}.

Prior to the 1986 Challenger disaster NASA's management reported the probability of shuttle failure to be 1 in 10^5. Prior to the recent Columbia disaster this figure had fallen to 1 in 250. After the Columbia tragedy the probability of failure, based on the historical record, now stands at 2 in 113 i.e. $1{\cdot}8 \times 10^{-2}$. Why the discrepancy? As with any modelling exercise, the reliability of the output is only as good as the model itself and the input data used. And it is here that researchers and practitioners in the field of concrete structures must be wary and ensure they are familiar with the assumptions underlying these methods.

Conceptually and philosophically the probabilistic approach to risk evaluation is both attractive and convincing. Of course there is variability and uncertainty in all the parameters that engineers must deal with in structural design and assessment, so intuitively it seems that some form of stochastic analysis should be adopted to account for these uncertainties. Indeed there is a strong lobby in the structural engineering profession promoting the use of structural reliability analysis, arguing that it is the most rational method for quantifying safety.

However, there are also significant limitations with this approach. Reliability analysis methods still rely on the same structural analysis techniques, e.g. grillage or FE, to predict the distribution of stress resultants within a structure, and the same simplified models for concrete behaviour, e.g. flexure or shear, that are used in deterministic design and assessment. The difference is that some of the input parameters are now assigned statistical properties such as mean, standard deviation and distribution type to account for possible variability. The likelihood or probability of failure, which is usually defined as exceedance of one of the ultimate or serviceability limit states, can then be estimated *for the particular failure criteria and input variables assumed.* The increasing sophistication of these probabilistic methods can at times shroud the limitations of the fundamental structural model being employed to predict the mechanism of failure and give an unwarranted sense of confidence in the probabilities derived. In such cases no amount of probabilistic refinement can make up for an inadequate model of failure.

Paradoxically we conventionally define failure at the ultimate limit state as global collapse of a structure and yet we employ linear elastic analysis methods, applied to individual elements and sections, to determine the load carrying capacity of the structure as a whole. Our decisions are heavily reliant on the accuracy of the resulting stresses that are calculated using the many elastic structural analysis programs around today. The difficulty is that the answers obtained are only as valid as the assumptions made for parameters such as the dimensions, Young's modulus and the degree of restraint. In practice, construction tolerances, indeterminancy and the true boundary conditions may result in various degrees of local or global self-stress that are difficult to include in the analysis. Fortunately, being a lower bound approach, the engineer can be confident that the ensuing design or assessment will be based on a safe prediction of capacity, even if in practical terms it may be very conservative indeed, since plasticity theory allows us to ignore the initial state of stress in such structures provided sufficient ductility is present to validate the theory used. In addition, failure of any single element is unlikely to lead to overall collapse in most practical, well designed structures.

More importantly from the perspective of safety, the reliance on elastic analysis methods can potentially result in engineers losing sight of the reasons for the often large discrepancy between computed element capacities and the actual load at which a structure would collapse. Thus the ability to visualise possible modes of failure and understand the likely progression to collapse as load is increased beyond the elastic range is perhaps one of the most important skills an engineer requires when considering structural safety.

It can thus be argued that if engineers genuinely wish to predict the likelihood of structural collapse much greater attention should firstly be focussed on adopting improved failure analysis methods, such as non-linear finite element analysis or plastic methods (e.g. yield-line analysis), rather than the elastic methods currently employed. Only then shall we be in a better position to determine more realistically the margin of safety available in our structures.

Secondly, the reliability analysis results are highly sensitive to the statistical models used to represent the variability in the load and strength parameters. Since most structures designed using modern codes of practice are inherently extremely safe, the mathematical determination of the likelihood of failure relies upon finding combinations of parameters in the extreme tail regions of the probability density functions for the key parameters governing structural behaviour. These tails are rarely defined by reference to actual measurement or accumulated data, but by the selection of a probability distribution which is found to model the region around the mean where data are likely to be available. But do these tails actually exist? In practice there may well be physical limits which would effectively truncate some distributions and significantly alter the estimated probability of failure.

Thirdly, the historical record shows that structural failure is more often than not the result of gross errors or omissions in design or construction, or unforeseen loading events that are not the result of a predictable stochastic variation in the applied loading or the material strengths. Attempts have been made at modelling human error; however it is extremely difficult to assign meaningful quantitative measures to such events. It is thus important for engineers to recognise that only a limited number of potential modes of failure are normally considered in structural reliability analysis and gross errors and 'acts of God' are not usually included when deriving estimates of the probability of failure.

Perhaps the greatest difficulty faced when interpreting failure probabilities is selecting an acceptable *target* level of safety, particularly when one takes into account the consequences of failure as well. Unlike mass-produced mechanical or electrical components for which failure rates can be observed, structures tend to be unique and collapse is exceedingly rare. As a result determining an appropriate probability of failure, which can be applied consistently across the wide spectrum of structural forms, becomes problematic.

In reality the safety index or β-index, used to quantify risk in a probabilistic analysis, is not a true measure of structural safety. Although promoted as a comparative measure of safety it could perhaps be better defined as a *sensitivity index* which measures *the* ***susceptibility*** *of the structure to the* ***variability*** *in the key parameters which govern its behaviour.*

It can provide the engineer with a better understanding of how sensitive a structure is to changes in the key parameters of loading or strength, but provides little information on the actual probability of failure.

Neither conventional elastic analysis nor reliability analysis addresses those features of a structural design which, arguably, contribute most to a structure's robustness i.e. its ability to withstand extreme loading events without suffering damage disproportionate to the original cause. For example, it could be argued that the catastrophic consequences of the Oklahoma bombing were a direct result of the building's lack of robustness.

It is suggested that a more rational approach to managing and reducing the risk of structural failure would be achieved by greater attention to the following three attributes

(*a*) Redundancy – structural forms which can sustain local damage or individual element failure and still provide alternative load paths for carrying extreme overloading.
(*b*) Connectivity/continuity – details which literally tie elements together to allow the transfer of extreme loads.
(*c*) Ductility – materials and sections detailed so that they can yield, deform and redistribute loading while retaining their strength.

All of these concepts are fundamental to the safe performance of structures and yet there is relatively little formal guidance available for engineers on how to include provision for these features in their designs and hence how to quantify their effect on the measures of safety used in practice today.

It is very difficult to quantify safety in a consistent, invariant and meaningful way. However the lesson from history is that the engineering profession has an enviable track record of building safe, robust and durable structures. It is thus important that the wider attributes of structural behaviour that have contributed to this success are not forgotten in the rapid changes of recent years and in the current trend towards adopting probabilistic reliability analysis methods to define adequate levels of safety.