Achievement of safety and economy in design and construction

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Achievement of Safety and Economy in Design and Construction

Des exigences de la sécurité et du souci de l'économie dans l'étude et la construction

Sicherheits- und Wirtschaftlichkeits-Aspekte im Entwurf und in der Ausführung

D. DICKE
Professor
Technische Hogeschool Delft
Delft, Netherlands

Introduction

Over the years much literature has appeared on the subject of "Structural Safety". A first tangible result of this was the presentation of the semi-probabilistic concept of safety which has been adopted by the CEB, the FIP, the CECM and the ISO.

The primary advantage of this semi-probabilistic concept of safety was its appeal to structural engineers and designers; it opened their eyes to the non-deterministic character of safety. They were accustomed to thinking in absolute terms: allowable stresses, code load requirements and factors of safety based on allowable stresses. Nevertheless most of the literature on safety remained a closed book to them. This literature was usually too mathematical and theoretical for the practicing engineer. The Model Code of the CEB opened up the prospect of a statistical approach to safety to them, it widened their horizon. Most building structures are designed by these practicing engineers with their rather conventional approach. Since the results of scientific research during preceding years has been incorporated in each new edition of Guides of Practice and Building Codes, these documents provide this large category of engineers with the strongest stimulus for selfstudy and development. The most obvious result of this semi-probabilistic concept of safety is in the practice of testing of materials, especially concrete, where quality is not defined as a mean value anymore, but as a characteristic value.

This is about as far as we have come with Guides of Practice. Finally the margin between characteristic strength and characteristic load is established as the product of some factors, but the relation with the probability of failure, let alone with economy, is not only unclear, this relation hardly exists. There are many problems here.

The symposia of the IABSE, the joint committee on structural safety CEB-CECM-CIB-FIP-IABSE, the joint committee on Tall Buildings, all the work done by several CEB-committees and research at various universities supply more and more material and show interesting developments. But all of this does not reach the great majority of the practicing engineers. The rapid development of scientific research causes a wide gap between researcher and practicianer.

The author of this Introductory Report belongs to the second category: for 20 years he was a structural engineer before he accepted a teaching position at the Delft University of Technology where he is trying to give architectural students some insight into the relation load-resistance-economy of building structures.
In that position you have to philisophize about the unsafeness of the world we live in with its tremendous "natural" catastrophes at the one hand and at the other those calamities we bring upon each other and ourselves, senseless destruction in the "solving" of controversies, unsafety due to crime, to traffic, to evergrowing pollution which so often accompanies prosperity in many countries.

How much can and will a community spend to give its members the feeling that their built environment is a safe place to live, work, recreate, etc.?
The line where safety is considered to become excessive is partly determined by the economy but also by politics.
Can we make this line clear?

The subject of this Session is: "Achievement of <u>safety and economy</u> in design and construction".
Our investigation of this subject should eventually lead to guides of practice and building codes. Safety cannot be tied to a number, in the way allowable stresses, factors of safety or loadfactors can. Only a probabilistic approach can give some real insight. But even then only a relative insight, in a way that "this is safer than that". If we can link safety to economy this might enable us to talk about safety in absolute terms. Is not the price of a structure partly determined by its measure of safety, but also — in the opposite direction — by the insurance premium?

The normal built environment

Now I propose that at this Session we concentrate on the safety and economy of "normal" structures. We shall not concern ourselves with prestige objects — economy and status contradict each other. Nor with the economy of special objects such as large bridges, tunnels, off-shore constructions, pipelines, etc. These projects are big enough to let specialists advise on the safety and economy of each individual object; a general code hardly applies here.

We shall concern ourselves with the economy of that category of structures — by far the biggest in volume — that constitutes the normal built environment of man, i.e. houses, schools, office-buildings, factories, nursing-homes, simple civil engineering constructions, etc.

Can we formulate rules that guarantee an optimum combination of safety and economy in these normal structures?
Before answering this question I should like to submit the following general observations:

1. Safety — probability of failure

Safety has to do with the probability of the occurrance of an event. This can be the probability of unacceptable cracks or deformations, of a fire of certain intensity, of excessive loads, of corrosion, etc. Here we confine ourselves to a concept of safety that is based on the probability of failure of an element of a structure and the consequences of this failure.

2. Loads

For the design of structures a lot of information on loads must be gathered.

a. Dead loads and other sustained loads

If we have already chosen the materials and made a preliminary calculation and also have decided on non-structural elements and finishes, then these loads are fairly accurately defined.
When making the final calculations all of these data must be checked for possible changes and controlled till the day of delivery.
What happens after this day? Where does the resposibility of the designer end: at the delivery of the building when he must tell the owner that after this day nothing should be changed anymore without the designer's consent? Or should he not trust the owner too far in this respect and allow for these possible changes in his calculations?

b. Live loads

Through field surveys we can obtain statistical data about a number of live loads, especially for those often occuring spaces like in houses, office-buildings, etc. Our surveys always show what is, not what may be.
Can we project our observations of the present into the future? How popular will waterbeds become? Or should we decorate the walls of each space with the data on which our calculations of its structure are based and leave the responsibility to the user? In this way we could give each distribution function a clear upper bound.

How much do we know of possible future changes in the use of spaces? If we can set clear limits to those loads over which the user has control and leave the consequences of overstepping these limits to him, then we can make considerable gains in this respect. Is this realistic and if not entirely so then perhaps to a certain extent?

As long as we confine ourselves to normal building structures we have reasonably accurate data at our disposal about the climatic loads wind and snow. What however do we know about "loads" like fire and gasexplosions and how do we project this knowledge into the future? How careful are we in the use of new materials (calamity on the Isle of Man in 1973)? The installation if fire-resisting materials is a statistical-economic problem.

For the CUR-committee "Safety"[x] the IBBC-TNO-Institute in Delft has done some research on a concrete floorslab with a span of 4.25 m and a thickness of 141 mm. In accordance with the Code Requirements the amount of reinforcing steel was found in a deterministic way. By considering all data of the slab itself and of the load as stochastic quantities a theoretical value of 1.4×10^{-14} for the probability of failure was found. By repeating the process, but now including the possibility of fire, the theoretical value increased to 3.6×10^{-4}. If we keep the amount of reinforcement and the thickness of the slab the same but increase the cover, the probability of failure due to overloading will grow, but due to fire will diminish. For this concrete slab the optimum was found for a cover of 33 mm, the probability of failure being 1.5×10^{-7}.

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[x] Members of the CUR-Committee A16 "Safety": D.Dicke, H.v. Koten, J. Kuipers, F.K. Ligtenberg, J. Strating, A.W.G. Thijsse.

The big increase in the use of natural gas makes the occurance of gasexplosions much more likely and can therefore influence the probability of failure.
This unfluence can be considerably reduced by appropriate measures Summing up we can say that some of the types of live loads — as they are now — are fairly accurately known. Projection of data into the future is difficult but not impossible; these data cannot be defined as clear distribution functions. "Loads" like fire and explosions have a measurable influence on the probability of failure and must be taken into account. If we do not want to do this then we must take measures to eliminate or greatly reduce their influence on failure. These measures cost money: it is a question of economy.

c. Simultaneous loads

Information on this possibility must also be gathered. In applying deterministic methods we are often required to examine combinations of different loads or a different disposition of loads.
From a probabilistic point of view the combination that causes the highest stresses or failure does not necessarily have to be the most dangerous combination: it is conceivable that the chance of this combination occurring is particularly small.

d. Forced deformations

These deformations, caused by differences in temperature or by shrinkage and creep usually hardly influence the probability of failure, but can cause cracking and deformations which may lead to damage.

3. The shape of the structure

The engineer must develop the overall shape of the structure in close collaboration with the designer of the building. This shape itself has a bearing on the safety and economy of the structure. Are there members of the structure that may cause extensive damage when they fail? Is there a chance of progressive collapse? Can we work towards an optimum combination of safety and economy in the design stage? Yes, that is possible with the help of the probabilistic concept of safety.

4. Materials

The materials selected for the structure must be closely related to its overall design. Here quality control plays an important role. Close inspection upon delivery may allow us to reckon with a lower bound in the quality distribution function. In the case of concrete poured in situ, quality depends largely on the builder and the supervisor. Very often, especially in cases where bending is predominant, the strength of reinforced concrete depends entirely on the quality of the steel. Here stringent (and expensive) requirements regarding the quality of the concrete do not make sense, unless they are necessary for other reasons.

5. Elements

Out of the selected materials the elements of the structure must be manifactured.

The care given to this process, the expertise of the people involved and the effectiveness of the inspection determine the strength of these elements to a large extent. A weak element will remain a weak element during the whole lifespan of the structure.

6. Joints

The elements of the structure must be joined together. The character of these joints, monolithic or not, can not only influence the safety of the elements themselves, but also the safety of larger portions of the structure. In case of monolithic joints the detailing of the reinforcement in the joint may play a role.

7. Calculations

The actual dimensions of the elements of a structure must be determined by calculations. To this end we reduce the real structure to a "model" which allows us to apply the principles of Mechanics to it. In this way we find the forces working in these elements, their resistance against these forces and their deformations. In these models we also schematize the loads and the properties of the building materials.
These models are rather primitive and we often find big differences between calculated and measured values for the deformations and the distribution of forces which is derived from them. As the conditions for equilibrium are usually fulfilled, the use of computers in attempts at making these models more true to reality does not influence the calculated probability of failure very much. Constructions and elements under compression and bending (like columns) however become very sensitive to errors in "schematisation" of the properties of the material and of their boundary conditions when the load approaches its critical value. If we deal with large series of the same type of buildings then Computer Aided Design might offer an extra possibility to find an optimum combination of safety and economy. Refinements in calculation, intended to produce safer structures, may make the calculation and also the working drawings more laborious: 10% higher costs here mean a costincrease of 2‰ for the whole building. Lowering the factors of safety in the present Codes by 5% would mean a cost-decrease of 2‰ for the whole building.

One more observation: a calculation is made only once, but its discrepancies with reality last the building's lifetime.

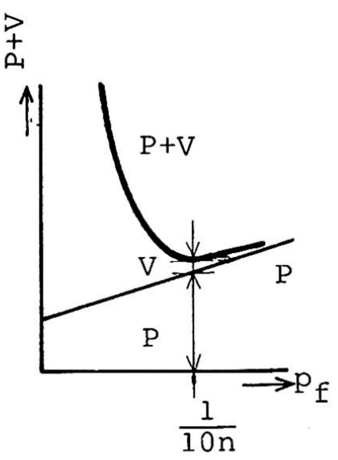
8. Use

After the delivery of the building, people live and work in it. This not only affects the loads (cf.2a and b) but also the preservation of the building. How well will the owner take care of his building? Does he maintain it well, does he immediately notice extreme deformations, cracking, corrosion, ageing? Vreedenburgh once remarked that - had steel braces been put around the Campanile in Venice one hour before its collapse in 1902 - the tower would still stand as it was.

Optimum combination of safety and economy

The information gathered in items 1 through 6, with projections into the future, combined in the calculation (item 7) should enable us to determine the probability of failure.

Assuming that we should succeed, then we can certainly expect the question: "Is this safe enough?" Ligtenberg[x] has pointed out a possible criterion which establishes a direct relation between safety and economy.



If we call n the ratio of the total damage caused by the collapse of one element and the price P of that element, then the sum of the price P and the fictitious insurance premium V shows a minimum for approximately $p_f \cdot n = \frac{1}{10}$ (p_f is the probability of failure). The difficulty of this otherwise simple and clear criterion is not establishing the material damage but translating human grief into an amount of money.
How do we "price" those who are killed, who are crippled for life, the wounded; the exasperation, loss of irreplaceable goods, loss of reputation, emotional and political consequences? As we confine ourselves to the great mass of relatively simple structures, this should not pose an insurmountable problem for a great many elements.

Let us take floors of houses as an example. We assume floors to be designed in such a way that collapse without warning is out of the question. Then the human aspect is reduced to some annoyance and inconvenience. Here failure takes on the meaning: inability to serve its purpose due to large deformations.
Let us suppose that the cost (including inflation) of replacing such a floor by a new one would be ten times the original cost (n = 10), then according to Ligtenberg we should design this floor with a value $p_f = \frac{1}{100}$. This is the probability of failure, no matter if this is caused by excessive loading, fire or explosions. The probability of fire in a house during its lifespan also equals about $\frac{1}{100}$. If we know the coefficient of variation of the load and of the resistance and also the influence of fire on failure, then we can establish a value for γ_k (i.e. the ratio of the characteristic values of resistance and load). In this case the value would be 1.2 at the most. At such a low value for γ_k it is not unthinkable that other requirements prevail. One might base the design on acoustical requirements for instance, and check deformations, cracking (in the case of concrete), stresses and economy afterwards.
Fire hardly influences the probability of failure in this case.
Starting from the simple rule of Ligtenberg $p_f \cdot n = \frac{1}{10}$ we can arrice via a probabilistic concept of safety, at deterministic calculations. The question is: is it possible to classify the most common elements (as we have just done in a somewhat simplistic manner), to formulate a number of boundary conditions and to establish a value for γ_k?

This could be a first step on the way to put the probabilistic philosophy of safety into full practice.

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[x] ir.F.K. Ligtenberg: Discussion Summary, Vol.D.S. Planning and Design of Tall Buildings, page.437

Making the practicing engineer aware of the backgrounds of this methods together with much research can pave the way for a more differentiated computer-programmed use of this method.
Systematic investigation and registration of all cases of serious damage would provide the facts and the insight to extend the application of this method to a wider range of elements.

I have not discussed loads brought on by tornados, earthquakes, floods and violence. Normal rules do not apply here. Elements exposed to these loads must be dealt with in a separate discussion.
The relation we used between the probability of failure p_f and the ratio n = total damage / price is an optimum relation which can only be influenced by the appraisal of damage that is hard to put in terms of money — the human aspect.

Probablistic approach and public relations

A general belief in the absolute safety of our buildings still prevails. The probability of failure is not yet accepted. Whenever a building structure collapses it is a foregone conclusion for many people that this was either caused by the engineer's or contractor's negligence or blunder, or by an act of God. If we want to bridge the gap between scientific research and daily practice, we must explain the philosophy of safety to the practicing engineer. A probabilistic approach must be accepted. The author of this Report found this out when the notes of his student lectures on Safety were published as CUR-Rapport 63[x]. There was an obvious need for a simple approach to new concepts of safety. This may form a basis for further study necessary for acceptance and application of these concepts.

SUMMARY

The idea behind this Introductory Report is this: it must be possible to gather sufficient data about the most common types of building structures to enable us to derive a design method from the probabilistic concept of safety. This method, using optimum economy as its criterion, will be deterministic in appearance, but will have a highly variable factor of safety. Possible causes of failure, other than overloading, should also be taken into consideration.

Moreover this Report appeals for making the probabilistic concept of safety more accessable to the practicing engineer.

RESUME

L'idée à la base de ce rapport introductif est la suivante: il doit être possible de réunir suffisamment d'informations sur les types les plus courants de structures, en vue d'en tirer une méthode de calcul basée sur un concept probabiliste de la sécurité. Cette méthode utilisant le critère d'une économie optimale, sera déterministe en apparence, mais offrira un facteur de sécurité extrêmement variable. Des causes possibles d'effondrement autres qu'une surcharge, devraient également être prises en considération.

En outre, ce rapport souhaite qu'un concept probabiliste de la sécurité soit rendu plus accessible à l'ingénieur praticien.

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[x] Those interested in this Report can order a copy in English from: Secretariaat CUR, Postbus 61, Zoetermeer, The Netherlands.

ZUSAMMENFASSUNG

Folgende Idee liegt diesem Bericht zugrunde: Es muss möglich sein, genügend viele Daten der gebräuchlichsten Typen von Bauwerken zu sammeln, um daraus eine Methode abzuleiten, die auf dem probabilistischen Sicherheitskonzept beruht. Diese Methode, deren Kriterium die optimale Wirtschaftlichkeit ist, wird, äusserlich besehen, deterministisch sein, weist jedoch einen ungewöhnlich stark variablen Sicherheitsfaktor auf. Neben der Ueberlastung, sollten auch andere Versagensursachen in Betracht gezogen werden.

Zudem will dieser Bericht dem in der Praxis stehenden Ingenieur das probabilistische Sicherheitskonzept zugänglicher machen.