Creative design based on safety and economy

Autor(en): **Abeles, P.W. / Bobrowski, J. / Bardhan-Roy, B.K.**

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Creative Design based on Safety and Economy

Créativité et conception des structures, basée sur la sécurité et l'économie

Schöpferischer Bauentwurf gegründet auf Sicherheit und Wirtschaftlichkeit

P.W. ABELES
Consultant

J. BOBROWSKI
Senior Partner

B.K. BARDHAN-ROY
Partner

Jan Bobrowski and Partners
Consulting Engineers
Twickenham, England

1. Introduction

Pozzi[1] in his paper deals generally with planning of structures. The structure as an element of the building construction is only briefly covered as a particular problem. The present paper deals with the design of a structure considering the main title of Theme (I) "Design Philosophy and Decision Process for Structures" bearing in mind also Theme (II) "Progress in Structural Optimisation".

The three papers in Theme (II) attempt to show that optimum solutions can be arrived at by the computer; thus the main question of creative design versus computer design has to be discussed.

Dicke[2] deals with the optimum combination of safety and economy which is actually the most important point in connection with decision making in the creative design of a structure for which the criteria of safety and reliability are of the greatest importance. "Fire Effects" which comes under Theme (III) have also been briefly included to cover the overall aspect of safety.

The first writer already dealt with collapse load design as early as 1933 as a Consulting Engineer in Vienna in his capacity as advisor to a spun concrete works regarding the design of centrifugally moulded high strength concrete poles. These had to be designed for a definite load factor against collapse (based on the worst case of combined wind, snow and ice so far established), according to the design regulation of the Association of Electrical Engineers. Thus he had ample opportunities to deal with the problems of safety and ultimate load design before this subject became the topic of general discussion. In his further activity with British Railways Eastern Region he had the opportunity in 1948-1962 of introducing, in spite of great opposition, "partial prestressing" for bridges and structures on a safe and economical basis[3].

The second author, as Senior Partner of a firm of Consulting Engineers, has dealt with the question of creative design in some publications.[4,5,6]. The three authors have discussed the specific design problems of controlling the dynamic effect of wind on light cantilever roofs by external damping.[7]

In this paper the safety requirements are particularly emphasised, and the question of creative design is discussed on the basis of reference to some of the outstanding pioneers of reinforced and prestressed concrete design.

2. The Required Factor of Safety and Limit State Design

The first author had discussed this question in 1968[8]. Consider five simple principles from the book "Introduction to Prestressed Concrete".[9]

1) There is no progress without considered risk.
2) The proof of the pudding is in the eating.
3) We live and learn.
4) Do not generalise, rather qualify the specific circumstances.
5) It does not matter how cheap but how good a thing is.

With no progress we would still live, as our forebears did, in the Stone Age, Principles 1 and 2 can be combined, as preliminary tests may prove the suitability of new developments. "Considered risk" obviously does not mean gambling, as it must be based on preliminary studies according to principle 2. Nevertheless, it is possible that some properties of new structures or materials become known only at a later stage, which leads to principle 3. Obviously it is a question of economy to select a solution which is safe for definite conditions although not absolutely safe (which is impossible). However, it could be dangerous and false economy to select a solution which is cheap but not good enough (principle 5). The designer ought to be warned against optimisation for optimisation's sake, since the consequences of failure must always be borne in mind.

The question of the "desirable factor of safety" has been closely investigated by Freudenthal in many papers since 1945, as enumerated in [8] and also in the IABSE Congresses in New York (1968) and Amsterdam (1972). Already in the first paper in 1945 the importance of probabilistic methods and statistics of loading were stressed as an integral part of rational design. The concept of safety was developed as a problem of uncertain predictions of the performance of structural materials as well as of the magnitude of the load pattern. Also the need for serviceability was stressed; Freudenthal stated: "The safety factor is thus transformed into a parameter that is a function of the random variation of all design characteristics as well as of the non-random variations, essentially caused by the process of construction". To this, in the authors' opinion, should be added the parameter covering the consequences of failure and the practical implications of the non-random variations mentioned above, as discussed later.

Paez and Torroja[10] were the first to publish a book on this problem in 1950 and referred to the importance of economical considerations, indicating that the question of insurance premium and the cost of construction and probable indemnity for possible losses should be considered. This leads to the question of "calculated risk" which traditionally applied to a great extent to earthworks and foundation engineering, but which relates also to earthquakes, the effects of explosions and even to excessive high wind pressure and other accidental overloading. Casagrande[11] considers "two distinct steps" for the definition of "calculated risk": "(a) the use of imperfect knowledge, guided by judgement and experience, to estimate the probable ranges for all pertinent quantities that enter into the solution of a problem, and (b) the decision on an appropriate margin of safety, or degree of risk, taking into consideration economic factors and the magnitude of losses that would result from failure." This shows that the question of probability when extended to include unknown quantities becomes very involved.

The classical theory of probability, based solely on a statistical study of load and strength, would lead to the same safety factors for all elements of a structure regardless of their importance. The subjective or Bayesian theory is based on individual judgement. The decision making in this case is a part of the problem, including the admission of subjective probabilities. This has been partly embodied in the modern Codes by partial safety factors. However, many features still remain shrouded in the mysteries of engineering judgement. This question will be discussed more closely later. The problems of safety have been discussed for the last 10 years in Committee 348 "Structural Safety" of the American Concrete Institute, of which the first author is a member. One point where subjective considerations may apply is the selection of different factors of safety for specific structural members, e.g. a column carrying many storeys should have a greater margin in safety than a beam of minor importance. Although the probability of simultaneous overloading of all floors is very small, the cost of increased carrying capacity of a column is insignificant as compared with the entire cost of a building. Collapse of buildings has mostly been caused by an accumulation of mistakes in design and/or construction details, bad materials and unsatisfactory workmanship. Nevertheless, there always appears to be a dominant factor.

There is obviously no absolute safety of structures; e.g. an aircraft disaster may occur and an aeroplane may fall on houses causing destruction, or an atomic attack of unforeseen magnitude may occur. Obviously structures cannot be built to resist such possible, but improbable, events. However, it is suggested to design nuclear reactors strong enough to resist the dropping down of an aircraft, based on certain loads and impact.[12] The likelihood that earthquakes might occur is limited to districts where, based on experience, such catastrophies may occur and where the degree is classified by former events. Similarly, districts where special winds of high turbulence may occur (such as hurricanes and tornadoes) have to be dealt with separately. If these extraordinary conditions are excluded the following conditions ought to be taken into account:

a) Serviceability under working load, including fire resistance for a pre-determined time and the effect of maximum possible temperature changes due to environmental conditions.

b) Safety against collapse for ultimate limit conditions including fire resistance for a pre-determined time.

c) Capacity to absorb impact in the event of shock (such as an explosion).

d) Resistance to weathering including freezing if the structure is in the open for the expected life time.

In respect of working load, the effect of fatigue and vibration due to wind turbulence (particularly with light roofs) also needs to be taken into account. The importance of dealing with this problem has been discussed in the papers [7&13]. When excitation due to vortex oscillation applies, there are three basic possibilities: (i) continuous oscillation with varying amplitude which might cumulatively lead to fatigue failure; (ii) instability (flutter) both with high and low wind velocity; and (iii) resonance. The behaviour of each structure should therefore, where necessary, be aero-dynamically examined in a model test in a wind tunnel for various wind speeds and it may be desirable to provide external damping devices to reduce the amplitude of vibration, particularly of light roof structures. Davenport[14] stated in 1975 that the question of damping will be the most important problem to be investigated until the Fifth International Conference on Wind Effects.

3. The Fire Resistance of Reinforced and Prestressed Concrete

Kawagoe and Saito[15] state that "reinforced or prestressed concrete structures have explosively spalled in the early stage of fire". In the Report on "The Fire Resistance of Concrete Structures"[16] by a Committee of which the second author was Chairman, this question has been extensively dealt with. It depends greatly on the aggregates; calcareous materials are much less likely to spall than siliceaous aggregates such as flint gravel, granite and crushed stone. Three types of spalling are distinguished: (a) destructive spalling; (b) local spalling; and (c) sloughing off, which is a gradual progressive form of breakdown that may continue slowly through the later stages of heating. At many fire tests and actual fires spalling was not noticed, particularly with lightweight concrete made with sintered pulverised fuel ash aggregates. Obviously "explosive" spalling ought to be avoided by particular specification and selection of the aggregates, or detailing, or by a combination of both. Suitable detailing can take into account even considerable amounts of spalling without critically endangering the load carrying capacity[17].

Restraint of the member is of particular importance and a very favourable behaviour can be obtained as the authors have shown in the paper[18] where the deflection after 1½ hours fire was very small, although the temperature in the steel was very high. Based on the assumption that spalling can be minimised the construction can be designed to resist a required time and still remain serviceable and to avoid collapse for another required time, which would correspond to the conditions (a) and (b) described before.

Gustaferro[19] deals in his paper with a rational design for fire resistance. He appears to be of the opinion that spalling is not critical in the majority of cases, especially with well detailed constructions. The authors have in the second edition of "Prestressed Concrete Designer's Handbook"[20] shown that it is possible, and advisable, to design a member to resist fire for a definite time. This is again also a question of satisfactory detailing.

4. Elastic and Plastic Behaviour and its role in the Development of Reinforced and Prestressed Concrete

In the last quarter of the nineteenth century, the basic behaviour of the co-operation between concrete and steel was recognised. At the beginning of this century relatively highly-developed reinforced concrete structures were built by Hennebique, the creator of the T-beam, in France, Mensch in USA, Emperger in Austria, Maillart in Switzerland and Danusso in Italy.

These pioneers based their design computations directly on some large scale failure tests, without much reference to the actual distribution of stresses. Their method based on experience ensured already a definite load factor of safety against failure, combined with satisfactory behaviour under working load. An example of this kind of creation is Hennebique's famous bridge over the Tiber River in Rome, built in 1912, which is so slender and elegant that it would hardly be possible to replace it by a more slender solution today. Another outstanding example is the bridge at Liége in Belgium also designed by him.

The design of reinforced concrete was investigated by a French Commission in 1906 and their report (which was based on the elastic theory proposed by the German Professor Mörsch) recommended that the tensile strength of concrete be ignored, when considering resistance to bending. This "elastic" theory was accepted as the fundamental basis for reinforced concrete design until the more recent general acceptance of the ultimate load theory.

Olsszak presented at the New York IABSE Congress[21] an ingenious contribution to the question "elasticity" and "plasticity". He said "A reversible (or elastic) deformation, as you all know, is the response of a material in the first stage of loading process." "A plastic deformation is a kind of defence (self defence) of the material against overloading." and "A conscientious designer wants to know what really is going to happen to his structure in the course of its existence, let us say, in a year, or two, or five; or perhaps what is going to happen if the structure - by accident or purpose - is overloaded." Thus there is no contradiction, and of course no competition between "elastic" and "plastic" approaches.

Nervi[22] states that plasticity could be used to improve the re-distribution of stresses and makes special reference to the ingenious intuitive design of Hennebique's bridges as mentioned before. Nervi, himself a builder, combined the function of master builder and architect, and his designs were based on intuition and model tests. By the use of the very suitable micro-concrete he was able to minimise the use of materials and to employ reliable, first class craftsmen, thus ensuring the high quality of his structures combined with economy.

The creative design based on intuition, imagination and knowledge which became apparent in the work of the first pioneers of reinforced concrete and Nervi, as discussed above, will be dealt with in connection with describing the philosophy of Eduardo Torroja. The views of Freyssinet, the creator of the "elastic" design of prestressed concrete, should also be noted. Freyssinet stipulated that the structural member should be under "permanent" compression and as late as 1950 was of the opinion that any "half-way house" between reinforced and prestressed concrete was bad.[23] This is very surprising, bearing in mind his outstanding reputation as a designer of bridges and other structures based on his intuition. Thus, "permanent nominal compression" was a "must" for the prestressed concrete designer for some time. This claim is still considered essential by some authorities even today. However, within the FIP, discussion is proceeding with a view to the acceptance of limited cracking under service load, provided that there is no danger of corrosion. In fact, it has been suggested that reinforced concrete and fully prestressed concrete are the extreme conditions, with partially prestressed concrete as the general case. As in life, so in design, the middle of the road solution may be more satisfactory than the extremes, as the authors stated in the preface of [20].

5. Creative Design

Eduardo Torroja has dealt with this problem in a unique manner in his books [24] and [25]. He states: "The calculation of stresses can only serve to check and to correct the sizes of the structural members as conceived and proposed by the intuition of the designer." "For the sake of both stability and strength the first essential task is to determine accurately all possible loads and effects to which a structure is submitted." "The designer must obviously have full knowledge of the properties of materials and behaviour of structures, but when designing a structure of any kind, the ultimate purpose of the building has to be studied from every angle. This may be described by his design of the famous shell construction over the Madrid Racecourse in 1935. He came to the conclusion that it was essential as a safeguard against wind forces that the main support be rigidly fixed at the promenade level, the roof having a good stability by the general arrangement provided of having a massive column at the cantilever support and a vertical steel tie instead of a column at the other support. Several possible solutions were investigated, such as a conoid and hyperboloid. Torroja states in[25]: "Is the invention of a specially adapted form to solve a specific problem strictly an imaginative process, or is it the result of logical reasoning based on logical training. I do not think it is either of the two but rather both together. The imagination alone could not have produced such a design unaided by reason, nor could a process of deduction, advancing by successive cycles of refinement, have been so logical and determinate as to lead inevitably to it - whatever the reader of these lines may have inferred."

This is a perfect analysis of the problem of creative design. Obviously in addition to knowledge also technical experience must be available. In fact, knowledge is mainly obtained by what we have learned from our own shortcomings or from those of others. Another example of the works by Torroja may be mentioned; his design of the "Tempul Aqueduct" in 1925, at the age of 26 years. He was the first to apply prestressing high tensile cables in order to be able to omit two supports in difficult foundations in the river, and thus created the first prestressed suspended bridge. Also his process of obtaining prestressing shows the combination of simplicity and efficiency.

Torroja says in the preface that his "final aim has always been for the functional, structural and aesthetic aspect of a project to present an integrated whole both in essence and appearance". Unfortunately there are few, if any, designers able to follow Torroja's ingenuity, but it should be aimed at.

6. Safety-Optimisation

The question of economy leads often to investigations of optimsation in order to obtain the minimum of materials possible. This is quite often not the cheapest solution, as the general conditions of labour and transport have also to be considered. Nevertheless, the question of rationalisation needs to be discussed. Thompson and Hunt[26] have discussed the dangers which may occur by an increasing degree of optimisation "an increasingly unstable failure characteristic" may result, which ought to be well considered by civil and structural engineers, but need not perhaps be fully taken into account by a "weight conscious aircraft designer" who intends to "seek the highest possible optimisation allowing the best he can for the random manufacturing tolerances."

Thompson[27] deals in his paper with the new, so-called "catastrophe" theories (by R. Thom and Zeeman) which predict that "buckling strength can be dramatically eroded by small unavoidable manufacturing imperfections". Chilver[28] warns against the search for the lightest and therefore most efficient structural forms which may lead to potentially catastrophic engineering structures, although there are pressures put on the designer to converge on an optimal solution.

These considerations which mainly apply to buckling and stability problems ought to be applied generally when considering the partial safety factor for the material. Factory made precast concrete ought to be permitted lower values of partial safety factor for materials only when the designer is fully satisfied that these will be made under the supervision of a reliable, experienced and qualified engineer. Often this is not the case, even in factories, whereas in fact it can be achieved at a well organised building site.

Figure 1 lists the basic stages of supervision and explains the principles and the assumptions under which they are applied. By underlining certain parts of the explanatory notes the interdependence of the basic control method is stressed. Figure 2 gives a qualitative illustration of the interaction of production and independent supervision for various materials. While site standards of supervision give a relatively small drop along curve A, it results in a catastrophic drop along curve B.

In addition to the partial safety factor covering materials γ_m and another covering loads γ_f, it is desirable to introduce a third partial factor γ_c, covering the nature of the structure or member and the consequences of failure[29]. This latter factor can be considered in two stages (γ_{c1} and γ_{c2}). Firstly the nature of the structure and its behaviour, e.g. brittle or ductile, series or parallel assembly of members, is accounted for. Secondly, the seriousness of failure in human and economic terms is allowed for. Such criteria in fact renders explicit what has always been implicit in the thinking of the designer and permits us to clarify, indeed enumerate, an aspect of design hitherto hidden in the mysteries of engineering judgement.

7. Conclusions

The combination of a creative and economical design may be briefly outlined by statements of the second author, taken from his papers[4, 5 & 30]. He said that the ultimate achievement in creative design can only be truly measured by the closeness with which one approaches the unobtainable. Evolutionary processes in nature ensure that only the most rational forms pass the real test of survival.

The eagerness to calculate, rather than to think, coupled with a traditional 'Bill-of-Quantities' mentality is the main reason why many designs are unsatisfactory. Designers often are ignorant of production methods and often basic design decisions are taken by bodies independently of the designer. It is commonplace for the contractor, through inadequate pricing, to virtually subsidise bad designs, while good and progressive designs are often priced out of the market. "Design without imagination is a contradiction in itself. However, the designer with imagination but with insufficient knowledge of technology of the medium in which he designs, is not only wasteful, but indeed dangerous."[30]

In principle there are three types of control:

INITIAL TESTS

STATISTICAL ESTIMATION OF THE PROPERTIES OF THE MATERIAL TO BE APPLIED

CONTINUOUS PRODUCTION CONTROL

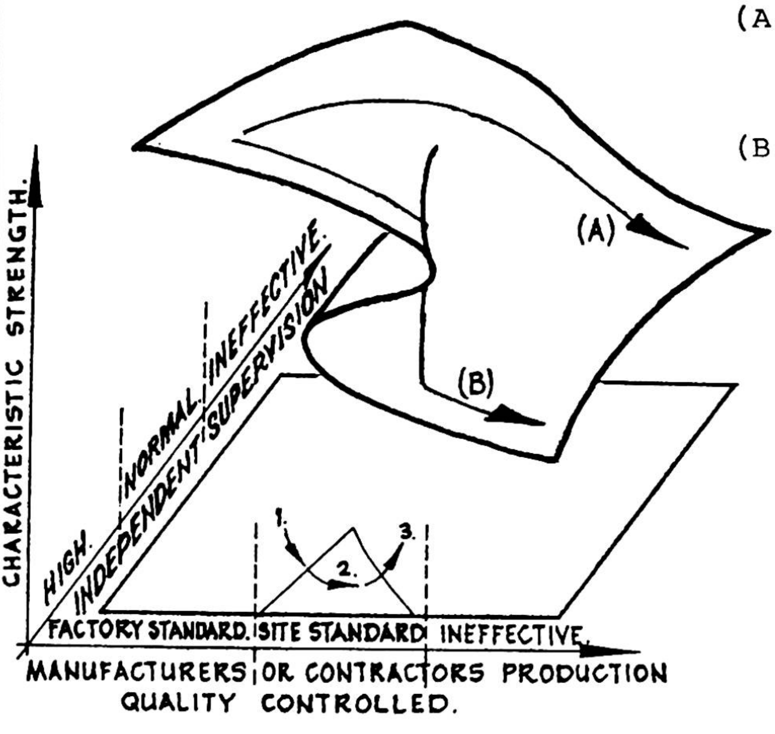
TO ENSURE STABILITY OF THE PRODUCTION PROCESS AND FOR THE CONTROL OF THE PRODUCTION (FACTORY CONTROL)

COMPLIANCE CONTROL

JUDGEMENT OF ACCEPTABILITY OF QUALITY

Although the three types of control are the responsibility of different persons involved in the process of the realisation of a structure, they serve, together with the design, in achieving the construction of economic and safe buildings. This achievement can, however, only be reached by a clear distribution of the responsibilities. As a rule, control systems have the greatest efficiency, if the producer accepts responsibility for the costs of control as well as the consequences of negative decisions.
It should be emphasised that the rules for the dimensioning, the type and extent of initial tests, the expense for the production control and the strictness of the compliance control interact with each other.

FIGURE 1 Extract from CEB Bulletin D'Information 111, October 1975



(A) Portland cement concrete (traditional way); mild steel.

(B) High strength concrete and concrete made with high alumina cement or with calcium chloride; high tensile steel; armoured glass; laminated timber; notch sensitive plastic; (all requiring care)

FIGURE 2 Qualitative illustration of the influence on characteristic strength of materials, of interaction of production control and independent supervision, using catastrophe presentation according to ref. 27.

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SUMMARY

Safety of structures for normal and abnormal loading (including fire) are discussed. "Calculated risk" is enumerated by three basic partial factors of safety: material ($\hat{\gamma}m$) Loading ($\hat{\gamma}f$) and mode of failure with consequences ($\hat{\gamma}c$). Creativity, a pre-requisite of conceptual design, balancing safety and economy, cannot be expected from the computer which serves only as a tool.

RESUME

La sécurité des structures est présentée pour des cas de charge normaux et anormaux (incendie inclus). Le "risque calculé" dépend des trois coefficients partiels de sécurité: Matériau ($\hat{\gamma}m$), charge ($\hat{\gamma}f$), genre de rupture et conséquences ($\hat{\gamma}c$). La créativité - condition essentielle d'une conception basée sur la sécurité et l'économie - ne peut pas provenir de l'ordinateur, qui n'est qu'un instrument de calcul.

ZUSAMMENFASSUNG

Die Sicherheit von Tragwerken für die gewöhnliche und aussergewöhnliche Belastung (inkl. Feuersicherheit) wird diskutiert. "Kalkuliertes Risiko" besteht aus drei elementaren Sicherheitsfaktoren: Material ($\hat{\gamma}m$), Belastung ($\hat{\gamma}f$) und Bruchart mit Folgen ($\hat{\gamma}c$). Kreativität, als Zusammenspiel eines zwischen Sicherheit und Wirtschaftlichkeit ausgewogenen Entwurfs kann vom Computer nicht erwartet werden. Dieser dient nur als Hilfsmittel.