**Zeitschrift:** IABSE congress report = Rapport du congrès AIPC = IVBH Kongressbericht

**Band:** 8 (1968)

**Artikel:** Optimisation of structures

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**DOI:** https://doi.org/10.5169/seals-8694

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## Optimisation of Structures

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In our opinion, the optimisation of a structure consists of designing and constructing that structure at the lowest cost, with the object of fulfilling a well defined purpose. In particular, the safety factor of the structure must be specified. This point already raises many difficulties when a comparison is made of different projects for the same structure using materials with markedly different properties. In estimating the cost, consideration must, of course, be given to the service life of the structure, its maintenance, and the possibility of its adaptation to meet any foreseeable changes in the service required. These changes result, for example, from an increase in the weight and speed of the live loads for bridges, an increase in the weight of aircraft for runways, and a rise in the tonnage of ships in the case of harbour works.

The cost of the structure depends on a very large number of parameters. Some of these are known and constitute data imposed on the engineer. Others are variable and must be chosen so as to reduce the cost of the structure to a minimum.

Among the data that are imposed, a distinction may be drawn between:

A. *General data.* These are:

A 1. The qualities and prices of the materials available at the time of construction of the structure.

A 2. The state of knowledge regarding the mechanical and physical behaviour of these materials, which finds expression in criteria of safety and mathematical models enabling a calculation to be made a priori of the structures.

B. The data relating *particularly* to the structure being studied. They are:

B 1. The geometrical data, more especially the dimensions laid down for the structure. Such are, for example, the headway and waterway to be left under a bridge, both during its construction and in its final state.

B 2. The stresses, both mechanical and other than mechanical (for example, temperature). A distinction must be drawn between the stresses brought about by a system of given external forces not equivalent to zero, and the stresses which lead to a state of coercion.

B 3. The geographical data involving, in particular, the cost of transport and labour, and the quality of the foundation soil.

B 4. The time limit for the completion of the construction. If this is not respected, allowance must be made for the intercalary interests and an estimate made of the damage caused by the delay in putting the structure into service.

B 5. Possibly, the aesthetics of the structure.

The variable parameters left to the choice of the engineer are mainly:

C 1. The choice of materials: stone, wood, steel, concrete, reinforced concrete, prestressed concrete, etc.

C 2. The choice of the structure.

C 3. The mode of carrying out the structure, including the fundamental problem of the assemblies and the methods of construction.

In the case of a bridge, the problem of the choice of the materials and of the structure is relatively simple, because the experience gained from a large number of structures enables the engineer to ascertain rapidly which are the variants, and they are few in number, that it is advisable to consider.

On the other hand, in the case of industrial structures which have recourse to the collaboration of several techniques, the problem is far more difficult. Let us take, for example, the case of the shield of a nuclear reactor. If this shield is constructed of prestressed concrete, it is necessary to insulate and cool the concrete in order to reduce the stresses brought about by the temperature gradient. Optimisation then results from a balance-sheet comprising the costs of the structure, the insulation and the cooling circuit, and these costs are variable and depend upon the temperature gradient that is allowed to remain.

Another example of the collaboration of techniques which is again taken from the field of nuclear reactors. A reduction in the space occupied by the heat exchangers has made it possible to locate them inside the shield, and this has resulted in considerable simplifications and economies.

In the general case, therefore, it is always a question of overall optimisation. Each technique must place its problem before the others and tell them: "this is what I would prefer, have you a solution, or else: what additional cost will this entail for you, and we will add up the total amount".

The problem of optimisation as we have propounded it is extremely general; its solution is the business of the engineer, whose ability is measured by the quality of the solution adopted.

It should be observed that the cost of a structure is always a discontinuous function of the parameters of Class C. It is only after these parameters have been selected that the problem is reduced to the finding of the minimum value of a continuous function of one or more variables. Such are the conventional problems of beams and columns of equal strength, of finding structures of minimum weight or of minimum deformation energy.

We consider, however, that these particular problems are only of minor interest because, firstly, the economy achieved will always be slight, and, secondly, the structure obtained will very often be more expensive, or even impracticable, because it is too complicated. However, the plant and equipment often make it possible, when they are well designed, to build structures that are theoretically more satisfactory without any increase in unit cost. A balance has to be struck between an excessive simplification of the shapes and the additional expenditure entailed, in the case of concrete, for example, by more elaborate shuttering and more difficult operations. This remark is fully justified in all cases where a large number of identical components have to be produced.

It is essential to examine in greater detail the parameters which exert the greatest influence on the cost of the structure. They are the parameters A 1 and A 2 among the given data and the parameters C 2 and C 3 among the variables. Let us consider further these essential items:

### 1. Improvement in the Quality of the Materials and Search for New Materials

Two factors play a predominant part in the quality of the materials. They are, firstly, an increase in the mechanical properties (strength and elongation) and, secondly, a reduction in the dispersion of these characteristics. It is then possible, without reducing the safety, to adopt higher permissible stresses. The compressive strength of concretes has not ceased to increase, and it is probable that we shall have great progress to report in the coming years. For about ten years, mainly due to prestressing, the breaking strength of steel wires has increased by about twenty per cent, without their elongation capacity being thereby diminished; indeed the contrary is the case.

The importance of the search for new materials is illustrated by the stupendous development of prestressed concrete during the past thirty years. Prestressed concrete is, indeed, a new material enabling structures to be erected which exhibit mechanical behaviour different from that of the structures previously constructed. But this is not the only example. Light concretes which enable the actual weight to be reduced are being more and more extensively employed and we shall doubtless see, in the near future, concretes based on synthetic resins and possessing considerable compressive and tensile strengths.

## 2. Knowledge of Materials. Criteria of Safety and Methods of Calculation

For a long time all calculation of structures was based on Hooke's law (elastic model). The criterion of safety was given by limitation of stresses, without any particular care for the deformations.

The great progress made recently is due to the taking into consideration of the non-elastic deformations thanks to the theories of plasticity. Only these theories make it possible to take into account the adjustment of the stresses in the sections of a beam, and, in the case of hyperstatic structures, to demonstrate that the adjustment between sections gives a greater strength to these structures than the theory of elasticity would lead us to suppose.

The study of non-elastic deformations has made it possible to create new mathematical models for calculations such as rigid-plastic, elasto-plastic and visco-plastic models, etc., which give a better representation of the actual phenomena than do the elastic models. These models differ, of course, according to the material being considered. However, our knowledge regarding the non-elastic deformations of certain materials is still inadequate, particularly when these deformations are time-dependent. Laboratory researches into the relationships between the stresses and the deformations must be continued so that the engineer is better able to predict the actual behaviour of the structures he designs. An important problem which has not yet been properly solved is that of the development with time of the stresses in a hyperstatic structure made of reinforced concrete or prestressed concrete.

The calculation of the limiting loads on the structures is the simplest of the applications of the plastic theories. This calculation has the advantage of giving a better approximation of the safety factor than do calculations based on Hooke's law. Thus both engineers and regulations have recognized the necessity of verifying the safety against rupture of prestressed concrete beams. Why is this not done for concrete arches which are nevertheless in a closely similar position? By sheer force of habit, in remembrance of the days when the elastic theories were alone regarded as reliable.

Engineers, however, must never forget the conditions that are necessary in order that the calculation of the limiting loads should give correct results. In the first place, the deformations must remain small; for certain structures it is essential to impose limits on the deformations. In the second place, in the case of variable stresses, the calculation of the limiting loads often results in an over-estimation of the capacity for resistance of the structures. The general theorem of adaptation makes possible a correct calculation of hyperstatic structures subjected to variable loads. Let us recall the statement of this theorem which was established by means of the hypothesis of small deformations:

"If, for a given structure, the state of stress obtained by adding:

a) the elastic state of stress due to variable external forces
b) a fixed state of stress forming a state of coercion termed state of adaptation

belongs to the elastic range, the structure will remain stable and the residual stresses will tend towards adaptation stresses".

The adaptation may, moreover, be facilitated by a prior compensation obtained by pre-deformation.

An important problem for the optimisation of structures is as follows: How to make allowance, in criteria of safety, for the stresses of a state of coercion brought about, for example, by temperature, shrinkage or creep? Should they be merely added to the stresses due to the application of a system of external forces? We do not think so, but the criterion of safety has still to be found. We may mention, as examples, concrete arches in which shrinkage and temperature may result in high stresses, and, more particularly, the prestressed concrete shields for nuclear reactors in which the thermal stresses make it essential to increase the prestressing considerably. The most careful attention must, however, be given to the cyclic variations, because there is an enormous difference between a stationary state of coercion and the states of coercion resulting from alternating phenomena.

## 3. Search for New Structures

Contrary to what might be supposed, there are still many new structures to be found. An engineer who designs a project must give proof of imagination, and, above all, must be on his guard against the routine which consists of copying what has already been done without making any improvements. Thus, why are girders with Pratt triangulation still being constructed when a girder with Warren triangulation is more economical? How does it come about that it is only recently that bridges with guys have been constructed which are cheaper and more reliable than conventional suspension bridges with parabolic cables?

Very often the search for new structures proceeds from the improvement in the techniques of construction. Progress in welding has enabled three-dimensional steel structures to be constructed. The technique of construction by cantilevering out has made it possible to build new types of prestressed concrete bridges.

Thin shells appear to us to offer a vast field for research. The part played by experience in an increasingly emboldened attitude towards phenomena that are still not well understood, such as the buckling of shells, is predominant in this field. This experience is of two kinds: that of the constructor who, because he has built a structure and tested it, knows that he can go farther, and that of the laboratory, from tests on reduced-scale models, in spite of the difficulties of similitude.

## 4. Improvement in the Techniques of Construction

We shall draw a distinction between assemblies and actual methods of construction.

Numerous examples demonstrate that assemblies constitute one of the essential factors in the economy of a structure. Nowadays, timber-work, for example the centering for a large arch, requires only one-third of the timber that was necessary fifty years ago. This economy is due solely to the design of new methods of connection: nailed connections for transmitting the tensile stresses, concrete joints moulding the ends of the wood fibres for transmitting tensile stresses. Bonded laminated wooden frameworks have enabled wide-span roofs to be constructed economically. Prestressing is the only satisfactory process for connecting prefabricated concrete members. Very large bridges constructed recently by means of prefabricated voussoirs underline the advantage of this method of assembly from the point of view both of the rapidity and quality of the execution of the work, and of economy. In steel construction, the appearance of high strength bolts has enabled large structural members welded in the factory to be fastened together on the site both quickly and economically. It is owing to the progress made in welding that frameworks consisting of tubes, which are lightweight and cheap, have been developed.

It is not enough, however, to make projects; it is also necessary to construct. The methods of construction are of considerable importance in the economy of structures. We may mention, as examples, the development of prefabrication, the use of sliding forms, the construction of prestressed concrete bridges by cantilevering out, and the considerable progress achieved in the technique of foundations for structures. The engineer must therefore always bear in mind the manner in which the structure he is designing is to be built. He should endeavour to facilitate the construction by saving time and money and, in particular, avoid the niggardliness which, as often as not, takes a saving of materials as its pretext.

The foregoing developments demonstrate the extent and the diversity of the knowledge that should be possessed by an engineer responsible for designing the best project for a structure. In order to make a reliable judgement of the value of the solution adopted, it would be necessary to study fully, construct and utilise the various solutions submitted to comparison, or in other words, have recourse to experiments. This is feasible and it is the best solution of the problem of optimisation in the case of members constructed in a large number of copies, for example, prestressed concrete posts for electric power lines.

On the other hand, in the case of large structures, engineers are obliged to judge the chosen solution a priori. But with the exception of very simple structures or structures of which a thorough knowledge has been gained by long experience, engineers will come up against difficulties that they are unable to overcome by calculation, because calculation only converts the hypotheses, but is not creative. We do not underestimate the advantages of computers for the calculation of structures. Indeed, it is only thanks to them that it has been possible to make a thorough study of certain problems. Furthermore, they afford the advantage of relieving engineers of a wearisome task and of leaving them all the time they need for designing, making a critical examination of the hypotheses, and estimating the margin of safety.

If they are unable to solve their problems by calculation, engineers will be faced with the need for constructing and testing one or more reduced-scale models of the structures or parts of structures they are studying. This is not devoid of difficulty, because the material of the reduced-scale model must possess mechanical and physical properties similar to those of the material of the actual structure, since otherwise the tests on the model would only be, like photo-elasticity, an instrument of analogic computation. Reduced-scale models have already proved most useful in the study of arch dams, thin shells and the shields of nuclear reactors.

To sum up, the optimisation of structures must be based on experience and an accurate knowledge of the mechanical and physical properties of the materials. If it is desired to obtain, in the near future, substantial progress in the economy of structures, the number of test laboratories, of which there are far too few at present, must be increased. These laboratories would have a dual task; firstly, they should undertake fundamental research into the properties of materials, and secondly, they should conduct tests on scale models. The chief concern of engineers should be to afford proof of creative imagination, both in the design and in the construction of structures.

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