Comments by the author of the introductory report: optimization concepts & techniques in structural design

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Comments by the Author of the Introductory Report

Remarques de l'auteur du rapport introductif

Bemerkungen des Verfassers des Einführungsberichtes

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Optimization Concepts & Techniques in Structural Design

In preparing the Introductory Report for Theme II, 'Progress in Structural Optimization' the three reporters each took a specific aspect of the theme. My objective was to provide an introduction to Structural Optimization; to describe its philosophical goals and to outline in brief and simple terms some of the mathematical techniques which are most frequently used to solve structural optimization problems. It was intended to be a 'beginner's guide' to the topic which would be expanded in more detail by the other Reporters and by the authors of papers in the Preliminary Report.

I will not dwell on an introduction to structural optimization but will assume that you are familiar with it from the Introductory Report. Towards the end of the Report I have remarked that by 1970 most of the simple problems of structural optimization had been solved, only the difficult ones being left. I think this point is demonstrated very well by the six papers in the Preliminary Report under Theme IIa. None of them deals with simple, straightforward problems; they all are concerned with difficult aspects of the topic and they all give a very fair indication of the present-day complexities of structural optimization.

I would like to consider first the papers by Anraku and by Balasubramonian and Iyer since they represent the forefront of technologically difficult problems. Anraku is concerned with designing steel frames to withstand dynamic earthquake loadings. Balasubramonian and Iyer are concerned with random variable variable loadings. It is significant that throughout my Introductory Report I have not mentionedloadings such as these. Much of the research done in structural optimization over the last twenty years has considered only deterministic static loads. Only in the last few years have researchers begun to look at optimum design for dynamic or non-deterministic loads. The reason for this is that the complexity of the problems increases dramatically as one moves away from deterministic static loads and this is an area of work which still requires much research. It is also an essential area for future research. Structural design methods and codes of practice are now moving towards a greater recognition of the probabilistic nature of loadings. Limit state concepts in which safety factors against many different possible occurrences are assessed are also becoming widely accepted. If structural optimization is to retain any relevance for the practising engineer it is essential that it too should be able to handle dynamic loads, probabilistic loads and limit state concepts.

The papers by Anraku and by Balasubramonian and Iyer are therefore welcomed because they are pointing in the right direction for the future of practical structural optimization. However, Balasubramonian and Iyer's paper dealing with structural optimization under random loading effects is entirely theoretical. One of the main reasons why structural optimization methods are not now used more widely in practical design is that there has too often been a large gap between what is correct in theory and what works in practice. This is particularly so when using applied probabilistics. There is a world of difference between defining in theoretical terms the probability of failure of a structure and actually evaluating it accurately for a real-world structure. Nevertheless Balasubramonian and Iyer have made a start in rationalising the effects of random loadings.

Anraku's paper deals with optimum design of frames for earthquake loading - once again a technologically complex form of loading. Some codes of practice incorporate requirements for designing against earthquakes and Anraku is to be complimented on attempting to extend structural optimization into this difficult area of work. As an optimization method Anraku has used sequential linear programming. This method is often used when no other method is available or when the problem is very complicated. Unfortunately it is on these highly nonlinear problems that its performance is worst and it is evident from Anraku's paper that he has experienced difficulties with this method. He comments that an accurate analysis of the dynamic loading is essential if the method is to converge and it appears from his Figure 6 that his optimized design violates some design restrictions by as much as 20%. Both these effects are inherent in the sequential linear programming method. Any linearisation of a highly nonlinear model is bound to be both sensitive to error and inaccurate.

The paper by Brozzetti *et al* is a complete contrast to the preceding papers. It is concerned with a very practical, pragmatic approach to using a commercially available computer package program for designing steel structures. In particular they consider the minimum weight design of practical steel frames so as to satisfy a large number of limit state criteria. The paper highlights the philosophical point that structural optimization is not a mathematical discipline but is, and will always continue to be, an engineering discipline. The objective of structural optimization is to produce the best possible engineering structure. Sometimes precise mathematical methods will allow this to be done mathematically but usually the practical limitations of codes of practice, methods of construction and aesthetics.make a completely mathematical formulation of the design problem impossible. Here the expertise of the engineer is essential. Sometimes those researching new structural optimization methods ignore practical considerations or make dubious assumptions in order to force a practical problem into a mathematically amenable form. While this may be possible for research purposes it is not possible for practical design purposes. Practical structural optimization very often has to be an inexact process relying sometimes upon rigorous mathematics, sometimes upon heuristics and always relying upon engineering experience. Brozzetti *et al* do not describe their optimization technique in detail - it seems to be sequential linear programming but coupled with a lot of engineering knowledge in order to produce real-world structural designs. In their paper they demonstrate that in order to produce really economical designs it is necessary to include the nonlinear interactions of axial forces and bending moments in steel framed structures. Very often these interactions are ignored by researchers when studying these structures since they introduce awkward mathematical nonlinearities.

The remaining three papers all deal with almost classical topics in structural optimization. Structural optimization has always been concerned with two basic questions - one practical, the other more theoretical. The practical question is - 'How can I design the most efficient structure to perform a specific task?' The more theoretical question is - 'What are the funadmental laws which govern structural efficiency?' It is important to distinguish between these two questions and theoretical work which attempts to answer the second question should not be criticised because it seems irrelevant to practical design. Work in theoretical structural optimization is important and essential because it adds to our fundamental knowledge of structural behaviour. An increased awareness of why some structures are more efficient than others will eventually benefit practical design engineers but the immediate practical relevance of such work may not be apparent.

Nakamura and Nagase consider the optimum rigid-plastic design of multi-storey plane frames for multiple load cases. In my Introductory Report I mention in Section 4.4 that optimum rigid plastic design can be represented as a linear programming problem. Nakamura and Nagase have done this and have then considered some of the more advanced aspects of linear programming theory using duality theory in order to reduce the size of the problem and solve it rapidly. This area of work, optimum rigid-plastic design is much researched and it can truthfully be said that our knowledge of the mechanics of structures in the plastic régime has been greatly advanced by such work. Nakamura and Nagase have made an important contribution to this topic by considering multiple loading cases and their paper is well worth further study. They do not claim to be able to produce an optimum practical design but their method can be used for rapidly producing an efficient and economical initial design which can then be analysed and modified in minor ways to satisfy engineering criteria. I commend their treatment and uses of duality and I believe their work could be developed to form the basis of really efficient design programs for practical structural design.

The two final papers, one by myself and one by Lipp and Thierauf both deal with the same classical problem. How can one design truss-type structures for minimum weight in the presence of restrictions upon member stresses, nodal displacements, member size limits? The optimum design of trusses has always been a subject of much research for several reasons. First of all trusses are practical engineering structures and so it is a relevant area of work. Secondly, the problem is a nonlinear one of a most interesting mathematical form and thirdly the methods which can be used to design trusses can also, with minimal modifications, be used to optimally design certain classes of more complex finite element plate structures. Perhaps the major difficulty which any optimum truss design method has to face is that of problem size. For each truss member there is usually one variable (the cross-sectional area) for which an optimal value is to be found. Trusses of several hundred members are not uncommon so for these structures the optimum design problem expressed mathematically is nonlinear, has several hundred variables and even more constraints.

A straightforward numerical search for an optimum of such a large problem is not possible as it is wasteful of time and computer resources. Recently engineers have looked more deeply at this problem and have found that by examining the theory of optimality more carefully new, more rapid design methods for trusses can be developed. My own paper explores this topic further and describes how duality principles can be used to develop new design methods. The paper by Lipp and Thierauf is concerned with the same approach - indeed the mathematics of the two papers is remarkably similar. I do not have time in this summary to talk about the differences and similarities in these papers in detail but I would like to add a final comment. In my Introductory Report I mention that duality might prove to be a mathematical concept of great value to those interested in the optimum design of large structures. My own paper reflects this of course but it should be noted that the Lipp-Thierauf paper is also concerned with duality via the Lagrange multiplier technique thus strengthening my earlier opinion.