Models in Engineering Science and Structural Engineering Design

Modélisation dans la science des ingénieurs et la conception des structures

Modellbildung in Ingenieurwissenschaften und Tragwerksentwurf

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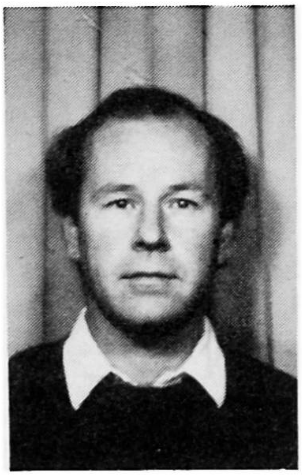

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SUMMARY
The paper considers the uses of mathematical and physical models by engineering scientists and engineering designers. The different uses are characterised by the different goals of these two professions. The criteria for choosing models appropriate to these goals are discussed, and suggestions are made for research into the effectiveness of different models in providing adequate justification of designs of structures.

RÉSUMÉ
Cet exposé traite de l'utilisation des modèles mathématiques et physiques par ceux qui s'engagent dans la science des ingénieurs et dans la conception et le calcul des structures. Les utilisations différentes s'expliquent par les buts différents des deux professions. On discute les critères pour le choix des modèles les plus appropriés. On propose quelques nouvelles voies de recherche pour évaluer l'efficacité des différents modèles dans l'étude de la conception des structures.

ZUSAMMENFASSUNG
Dieser Aufsatz behandelt die Anwendungen von mathematischen und physikalischen Darstellungen in der Arbeit der Ingenieurwissenschaftler und Tragwerks-Entwerfer. Die verschiedenen Anwendungen sind entsprechend den verschiedenartigen Zielen dieser zwei Berufe charakterisiert. Die Kriterien, nach denen Darstellungen gewählt werden, die den verschiedenen Zielen entsprechen, werden ebenfalls behandelt. Auch wird die Wirksamkeit der verschiedenen Darstellungen zur Rechtfertigung der Strukturentwürfe diskutiert und einige neue Forschungsthemen werden vorgeschlagen.

1. THE USE OF MODELS IN STRUCTURAL ENGINEERING

The use of models, both physical and mathematical, to represent the behaviour of a "real" structure has been well established in the field of structural engineering for at least 150 years.

During this period, however, relatively little has been written upon the aim or function of using models in engineering, in general, and in design, in particular. Their use has come to be rather taken for granted, not, of course, without justification, for they are indeed very useful.

In consequence, there has arisen a degree of confusion about the use and purpose of models. This confusion is typified by the developement, within a University research program, of sophisticated mathematical models relating to the behaviour of, say, a steel-framed building, which are not taken up by professional designers of such buildings. A gap is thus perceived between academics and practising structural engineers which is found to be difficult to bridge, despite many Government studies to seek more effective ways of putting the research work of Universities into practice in industry.

While there are no doubt many reasons for this state of affairs, perhaps the most significant is a fundamental misunderstanding about the activities of academics and designers. They are each engaged in different work with different aims - the one with engineering science, the other with engineering design; and this distinction seems to be more appropriate here than the more common distinction between theory and practice [1].

2. ENGINEERING SCIENCE

2.1 The Nature of Engineering Science

Engineering scientists are engaged in a branch of experimental or theoretical science with the same methodology and aims as other scientists, such as physicists. Their aim is to seek a deeper understanding of the world about them and to be able to explain the phenomena which they observe in it.

2.2 Models in Engineering Science

Engineering scientists use models in conjunction with theories or hypotheses as part of the process of explaining certain phenomena. They are also likely to be used in conjunction with an experiment designed in some way to test a hypothesis. This whole process constitutes the "scientific method" and has been thoroughly discussed by, for instance, Popper [2] and Kuhn [3]. Models in engineering science are almost invariably tested under laboratory conditions where the environment can be carefully controlled. Because of the complexity of the real world, both physical and mathematical models are usually much simplified and idealized to avoid the influence of many phenomena which might possibly interfere with the particular phenomena under scrutiny.

2.3 Criteria for Choosing between Models in Engineering Science

In a sense, the scientist's primary goal is to invent better and better models of the world in order to improve our understanding of it. The judgement as to just what constitutes a better model is influenced by a number of criteria of excellence, and by the relative importance ascribed to the different criteria [3], [4].

Examples of some criteria typically used by an engineering scientist might be:

- accuracy
- simplicity
- generality
- elegance
- ability to account for and explain past phenomena
- ability to predict the outcome of experiments

The result of these various circumstances is a rather protected environment in which certain highly specialized fields are investigated at a level which is simplified and idealized enough to be effective, using methods which are well understood. Nevertheless, despite being thus simplified, the work is often highly sophisticated, rigorous and complex - as reference to any of the many technical papers to which this type of work leads, will confirm.

3. ENGINEERING DESIGN

3.1 The Nature of Structural Design

The structural designer is faced with two distinct tasks:

- to conceive and describe a solution to a structural problem (the "specification" of a solution)
- to prove to the satisfaction of various persons, including the designer him/herself, that the solution is viable (the "justification" of a solution)

For both the specification and the justification, the designer may draw upon many types of knowledge and data, including intuitive knowledge of structural behaviour, precedent, empirical design rules and proof tests, as well as the use of mathematical and physical models of the structure or its parts. These different elements are taken into account and combined by means of a "design procedure", nowadays closely related to the Codes of Practice for the design of structures.

3.2 Models in Engineering Design

The role of models in structural engineering design is different from their role in engineering science by virtue of the different goals of the two activities. Designers do not have the luxury of being able to simplify and restrict their field of inquiry in quite the way that scientists can. They have to meet the challenge of a proposed building design by whatever means they can lay their hands on.

3.2.1 The use of mathematical models

Mathematical models form the basis of all the various techniques of structural analysis and need not be discussed here. The important point is that, according to the degree of simplification, and the way the designer conceives of the way in which the structure is behaving, so different models may be chosen. This possibility of choice will be discussed below.

3.2.2 The Use of Physical Models

Designers only resort to the use of physical models when they perceive a need to do so. This is likely to result from a direct knowledge or, sometimes, only a more subtle "gut feeling", that the use of design procedures based wholly upon mathematical models will be inadequate and not provide the required justification of the proposed design. This is typically the case for unusual structures, such as the Sydney Opera House, and for structures, such as suspension bridges, subject to complex and dynamic loading.

In these cases the model is designed with an intent very different to that of the engineering scientist. Rather than be as simple as possible to reduce the interferance of extraneous factors, it has to model the structure in the way most appropriate to providing the required justification of the proposed design. This has to be a compromise, somewhere between a totally accurate model, which would be a replica of the structure, and one that would be too simple to be convincing in its ability represent the relevant behaviour of the structure.

3.3 The Designer's Choice between Models

Within this wider context of a design procedure, the choices facing a designer about the use of mathematical or physical models are different from those which face the engineering scientist.

Designers are invariably faced with a structure which is much too complicated to model fully and in every detail. Even to attempt to do so would usually be inappropriately complex, and far too time consuming and expensive.

Designers consequently choose very simple models of the structure they are designing. For example, it is still common to design steel-framed buildings as a grid of columns to support vertical loads and a series of simply supported or partially restrained beams spanning between the columns; even in cases where the rigidity of joints is fully taken into account, it is common to ignore the extra strength and stiffness added by the system of enclosure used (e.g. cladding).

The use of such simple and "out of date" methods is wide open to the criticism of engineering scientists who are generally accustomed to using much more sophisticated mathematical models. And yet the structural design profession is notably reluctant to adopt the latest and most sophisticated techniques of structural analysis and design. One example is the almost total rejection of the results of the Steel Structures Research Committee recommending the adoption of more rational elastic design procedures [5]. Other examples are the continuing rejection by some designers of plastic and load factor design methods for steel structures [6] and of the recent more complex Codes of Practice for the design of concrete structures [7].

Such rejection of new methods is often with good reason, since the use of well-established methods has a strong attraction; but it belies an important underlying issue, namely the nature of the factors which influence a designer's choice of design procedure. A new model or new use of an old model will only be adopted by designers if some benefits of doing so are perceived.

3.4 Criteria for the Designer's Choice between Models

In the cases of both mathematical and physical models, designers are forced to make choices which engineering scientists do not have to make - choices about which model and which level of sophistication would be appropriate. Furthermore, these choices might be made according to criteria very different from the criteria used by engineering scientists when choosing between models in the pursuit of their goals. Or, while the criteria might be similar, the weight and importance they are given might be very different.

Thus, the criteria applied by designers to their choice of model might include:

- simplicity
- rationality
- speed
- cost-effectiveness
- accuracy
- reliability
- level of sophistication
- the power to justify a proposed design

The most significant difference between this list and the one given above, of the criteria applied by engineering scientists, is that it is more open to subjective opinion. At a particular time and place in history, the opinions, by and large, will lie within a narrow band of concensus which reflects the appropriate "engineering climatology" (as Pugsley calls it [8]).

4 THE CRITICAL APPRAISAL OF DESIGN PROCEDURES

The subjectivity of some of the opinions about the relative merits of the different models and their use in design procedures, ought somehow to lead to frequent and open debate on the subject: yet, in general, it does not. Three exceptions to this norm have interesting conclusions.

In the 1930s the Steel Structures Research Council was set up to review the current elastic design methods for steel framed buildings. It concluded that "the method of design of steel-framed buildings in common use had no firm rational basis" [4]: and yet the more rational methods proposed were strongly rejected by the structural design profession because they were more complex and did not yield significantly better, safer or cheaper structures.

Some 20 years later a different type of survey was contained in the Report of the Conference on the Correlation between Calculated and Observed Stresses and Displacements in Structures [9]. This conference aimed to present the results of tests on structures, some real, some part-structures and some models, in the hope of providing designers with better methods of designing structures. The results were, however, extremely confused, presenting neither the current state-of-the-art of engineering science, nor of engineering design procedures. This confusion was largely because the criteria for assessing the different types of results by the two different professions (scientists and designers) were neither stated nor discussed. The conference left the designers with no clear advice as to how to design better, safer or cheaper structures, and the engineering scientists appeared entirely happy that their duties had been adequately discharged in performing highly specialised research of little direct interest to the designers.

The final example comes from a paper in which a contributer noted that a reinforced concrete slab designed to the very latest procedure was not obviously safer or better and yet cost some 13% more than if it had been designed according to the out-of-date Code of Practice [10].

5. CONCLUSIONS

This paper has sought to draw attention to the need to look carefully at the different actities and goals of engineering scientists and designers. These differences are particularly important when considering the use of both mathematical and physical models and the criteria for choosing between different models which could be used.

The main conclusion of the paper is that there is an important area of research to be pursued - the critical appraisal of models and the criteria for choosing between them, particularly in the field of structural engineering design. For design procedures, the relative merits of, for instance, simplicity and accuracy, or cost-effectiveness and sophistication, need to be evaluated.

Perhaps most importantly, the role of models in engineering design needs to be more fully investigated and understood. Many structural designers are able to design entire structures on the sole basis of their experience and without any recourse to the use of models and structural analysis. They are then required to justify these designs by means of models. The processes of justification could be made more acceptable and reliable if there was a clearer understanding of the powers of justification of the various means outlined above - precedent, the use of mathematical models of different complexity and sophistication, and the testing of physical models.

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