Experience, Research and the Construction Industry

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1. INTRODUCTION

In the construction industry, the primary concern of civil and structural engineers is the provision of economic and functioning structures as well as the design method used to achieve this. However, there seems to be a communication gap between those involved in research and those involved in design and construction practice with regard to the role of 'research' in this respect. Understandably, people involved in research would always think that research is important in providing theory for practice. However, those who belong to the practising group might argue that the industry does not need as much research as other industries like electronics or pharmaceutical would. Instead, many place great emphasis on 'experience' as the appropriate source of inspiration for design methods. This seems reasonable as great buildings of the world such as mosques, temples, monuments, palaces, etc, which are still standing today were designed entirely by the application of experience. But what can research and theory offer that cannot be provided by experience? What is the justification for the investment in university departments and research establishments in the construction field?

The aim of this paper is to discuss some of the issues related to the role of research in the construction industry, in particular attempting to answer the following questions:

- What are the limitations of experience as a source of design methods?
- Why do we need research and theory?
- What is the nature of engineering research?
- Why is scientific research important to the industry?

2. EXPERIENCE AND RESEARCH AS COMPLEMENTARY SOURCES ON DESIGN METHODS

Beeby [1] argued that the value of research lies in the assistance it can give in coping with change. The general consensus is that the design life for buildings should be of the order of 50 years. When change is very little within such timescale, then experience is a very powerful tool in developing design methods. This is because the engineer would safely and adequately extrapolate his/her experience to the new but similar situations. However, when change is substantial, then experience is less reliable as the designer is now faced with a totally different situation, which has little or no resemblance to what was experienced before.

Over the last 50 years or so, the industry has seen substantial changes with respect to the material properties, philosophies and loading types used in design of reinforced concrete structures. For example, the maximum design stresses for mild steel reinforcing bars under service loads have increased from 100 N/mm^2 in 1950 to an estimated 280 N/mm^2 in 1980 [1]. Over the same period, significant changes have also taken place in permissible concrete stresses. Concrete stress level has increased roughly from 20 N/mm^2 in the 1950's to over 80 N/mm^2 in 2000 [2]. The changes that have taken place in the permissible stresses of both materials are brought about by increases in the materials' strength and decreases in the design safety factors, resulting in the use of lesser materials and hence more economic designs. Apart from the material properties, concrete workability has also increased from as low as 50mm in 1950 to more than 150mm in 1980 with the advent of plasticisers [2].

With regard to the design approach used, there has been a fundamental change within the last 50 years or so. 1972 saw the introduction of the Ultimate Limit State (ULS) design concept through the CP110 Code of Practice [3] in place of the elastic, "permissible stress" approach of its CP114 predecessor [4]. The ULS approach allows uncertainties in material behaviour and loadings to be accounted for, by assigning partial safety factors to each material and load type, and considers load combinations for the worst-case scenario. This philosophy has been maintained in the subsequent BS 8110 code [5] and in the more recent European EC2 code [6]. However, in the new EC2 code, which is to be enforced in the UK this year, some important changes have been made to the current practice to allow designers to gain benefit from recent advances in concrete technology. For example, the code includes a provision for the use of high workability and high strength concretes, where strengths are now based on "cylinder" rather than "cube" strengths.

As far as local practice is concerned, loading types considered for design have also changed recently. For example, the design of multi-storey buildings shall now take into account the buildings' resistance against the effects of earthquakes and other natural disasters.

The above examples are sufficient to show that change has been substantial and continuous over the last 50 years or so. As explained before, this seriously limits the usefulness of experience as a source for developing design methods. Furthermore, it would take as long as the full 50-year design life period of the structure to see and judge the effectiveness of the design method used. Even for a highly "unhealthy" practice such as the abuse of Calcium Chloride or the use of High Alumina Cement in the UK would need a period of at least 15-20 years for the adverse effects to be identified and reported. In this case, experience may provide information about the adequacy of design methods up to the 15-20 years as they were applied. Thereafter, practices and materials may change and the relevance of this experience to current conditions is doubtful. This shows that experience alone would not be able to form a sufficient basis for the development of design methods for present or future conditions. A further essential ingredient is therefore an understanding of the behaviour of structures and materials. This is developed from theoretical and experimental work of research and this seems to be the only means by which designers can anticipate the consequences of change.

3. SCIENTIFIC VS. ENGINEERING RESEARCH

There has been some confusion even among research engineers as to what constitutes "Scientific Research" and what constitutes "Engineering Research".

According to Popper [7], the 'Scientific' method of research involves the following steps:

(i) identification of the problem
(ii) making observations
(iii) construction of a hypothesis
(iv) testing the hypothesis
(v) when the hypothesis fails a test, it is discarded and the process is repeated.

For the purposes of this paper, this will be described as 'Scientific Research'. "Hypothesis" above may be defined as a tentative assumption or answer regarding a particular phenomenon or behaviour, usually in the form of a relationship between variables concerned. A network of hypotheses makes up a "theory" which is more generalised and which can be used to explain or predict a phenomenon or behaviour. In a scientific method, the hypothesis or theory can be tested by conducting experiments to see whether it can predict or explain the phenomenon or behaviour correctly.

Engineers employ theory and experiment rather differently; they use theories as approximate models of reality. This can be illustrated by considering two basic theories used by engineers in treating structures: the theories of elasticity and plasticity. Both are highly mathematical theories used constantly in structural design despite the fact that the materials may violate the basic assumptions on which both theories are founded. Elasticity is the most commonly used theory even though it has been well known from the beginning that neither concrete nor reinforced concrete is elastic. Plastic theory is a relatively more recent development and is used in section design and also in methods such as yield line analysis though we know that concrete is not plastic. Philosophically, the situation becomes even more confusing when we employ elastic methods for structural analysis and effectively plastic methods for the design of critical sections.

It is also important to understand that engineers are not primarily concerned with accurate prediction of behaviour; their objective is the provision of economic structures which will adequately serve their specified purpose. For this, engineers develop approximate models which are accepted as having adequate reliability within defined limits. Models can be defined as "simplified conceptual or physical representation of a real-life system built to study the system". These models are calibrated and adjusted and their limitations defined by experiment. Theory forms the skeleton or framework for these models and also provides an insight into the mechanisms involved. This process, which for convenience will be called 'Engineering Research' may be explored further by considering a very simple and well-known example; theory for the ultimate strength of singly reinforced sections subjected to pure flexure as illustrated in Figure 1. The theoretical framework may be summarised as follows:

a) Plane sections remain plane under the action of flexure.
b) Moment is resisted by a tensile force in the reinforcement and a compressive force carried by the concrete.
c) The tensile and compressive forces are equal in magnitude and the moment of resistance is equal to either of these forces multiplied by the distance between the centroid of the two forces (the lever arm).

If the stress-strain curves of the materials are known, this provides sufficient information to define a relationship between applied moment and deformation. This would permit a maximum moment to be obtained.

Stress-strain curves for steel and concrete can be obtained experimentally. For steel, this is relatively straightforward but for concrete there are complications since the result is influenced by the shape of the specimen, the method of loading and the rate of loading.

Experimental work has therefore concentrated on testing compression

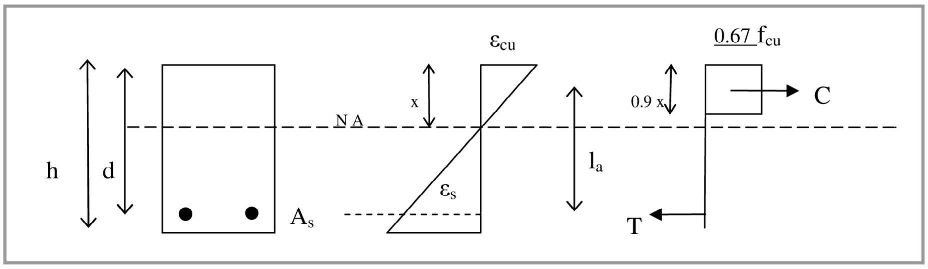

Figure 1: Simplified rectangular stress block for singly reinforced section

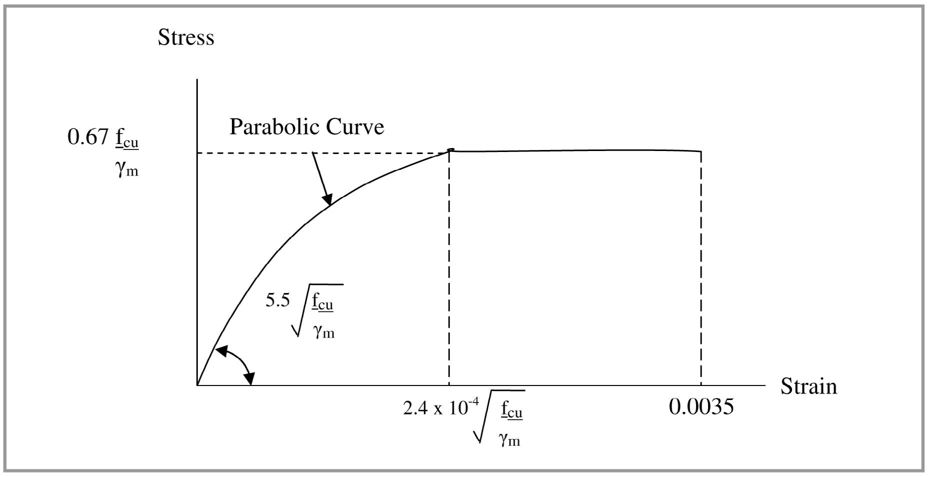

Figure 2: Short term design stress-strain curve for normal weight concrete

zones and defining for these maximum average stress developed and the corresponding position of the centre of compression and maximum strain. The experiments show that concrete fails at a maximum strain of around 0.0035, independent of strength. Simplified stress-strain curves can be proposed which give the correct average stress and centroid positions at failure. The BS 8110:1985 parabolic-rectangular and rectangular diagrams (Figure 2 and Figure 3) below are such simplified curves. It must be noted that these diagrams are purely empirical and owe little or nothing to theory.

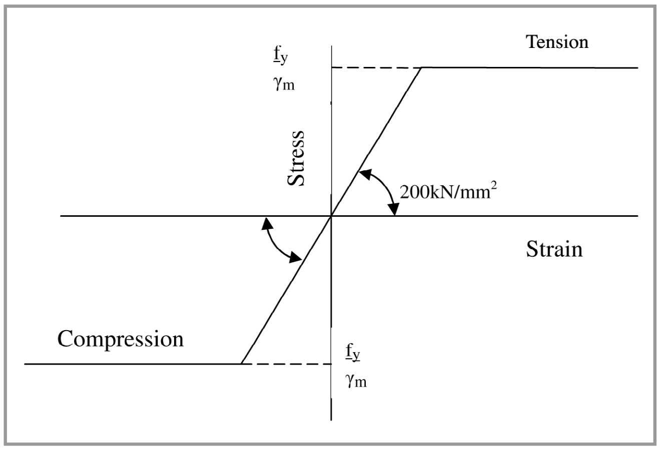

Figure 3: Short term design stress-strain curve for reinforcement

The above example illustrates well the interaction between theory and experiment in Engineering Research. The theory has provided the insight into the mechanisms involved and has defined the information required from experimental work. The experimental work has been formulated to provide this information and hence design equations could be developed. This relationship is totally different from that envisaged in 'Scientific Research'. Theory in Scientific Research is used to explain phenomenon or behaviour, and it helps us to understand more of the behaviour. It also helps us to make a reasonable prediction by extrapolating from a known behaviour. The theory outlined for a singly reinforced section in flexure described before is one such example. Using this theory, for example, we are able to assess the flexural strength of say, a circular section, even though all the experimental work had been carried out on rectangular sections. We recognise that the method will not be as accurate but our understanding of the theory suggests that any errors will be acceptable. Of course, such theory has to be tested first (by conducting experiments) to discover whether it can show the correct general picture of behaviour.

4. INDUSTRY EXPECTATIONS AND REACTIONS

The industry and funding organisations, both local and overseas, constantly pressure their research organisations to do 'Practical Research'. By this they seem to mean 'Engineering Research', where testing is limited to specimens within the scope of current practice. It must be emphasised here that this would only limit the range of applicability of any resulting design method, while adding little to our understanding of material behaviours.

A point which should be understood first about the relationship between research and design is that in construction, the nature of this relationship has traditionally been very different from that in some other industries. It will help to distinguish between the two types of relationship as follows:

a) Research leading. Here, it is research which leads to changes. This is typical of IT, electronics or other high-tech industries, where "next year's product results from this year's R & D".
b) Research reacting. In this case, research is a reaction to change imposed from outside. This is almost always the case in the construction industry. For example, the change in steel and concrete discussed in the previous section were not dominantly brought about by those within the industry but by material manufacturers and suppliers. As far as designers were concerned, their problem was to react to these changes; they did not cause them. This is clearly true in the case of the use of chlorides in rapid-hardening cements.

There are obvious weaknesses in using research in the 'reacting' manner. Designers have an exaggerated regard for experience and tend to extrapolate this to new situations unjustifiably. Research is only encouraged when this extrapolation has produced problems. The result can be very expensive in repair costs and in loss of confidence in the abilities of the industry. Research is then started urgently with solutions to the problem being required in far too short a timescale for these solutions to be adequately tested. Our reaction towards slope failures and other geotechnical problems, and more recently earthquake loadings are classic examples of this process in action.

5. CONCLUSION

Concrete design and construction is in an era of continuous change. As a consequence, experience is only of limited value in developing adequate design methods, even though it is subsequent experience which, in the end, provides the final judgment as to whether a method is satisfactory or not. Theories and experiments in research provide a means of reacting to change and of generalising experience to handle a wider range of problems. Two basic types of research have been recognised and the difference clarified. 'Scientific Research is concerned with development of theories that explain behaviour and testing of these theories by experiment. 'Engineering Research' is concerned with the development of reliable design methods. In this research, theory and experiment are complementary; the former providing a framework while the latter providing the numerical values.

In order to avoid troubles resulting from changes in practice, sufficient understanding of behaviour is therefore needed to foresee the consequences of change. Such understanding is developed from 'scientific' rather than 'engineering' research. Work done to increase understanding is of permanent value whereas work done to develop formulae using 'practical' tests is short-lived and has to be repeated and adjusted every few years as conditions change. It is therefore the author's opinion that research aimed at increasing understanding is currently under-valued and in short supply and should therefore be increased. The long-term durability behaviour of concrete may be one such research. It is also hoped that research should not be viewed by the industry as a 'trouble shooting' activity in which research is initiated following the identification of a problem. Rather, it should be used in a more leading and pro-active role for the sake of the industry's future. ■

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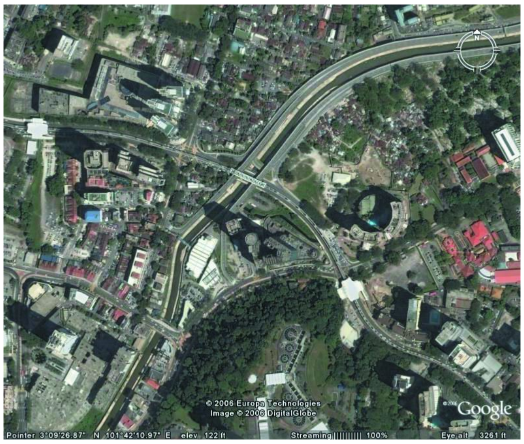

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