Editorial comment

by A. W. Beeby

Empiricism versus understanding, in the successful use of materials in a changing world

THE NOBEL PRIZE winning physicist Richard Feynman served as a member of the committee investigating the failure on the space shuttle Challenger. He wrote an appendix to the congression report (Appendix F) where, among other matters, he examined the management attitudes which led to the failure of the seals between the elements of the booster rockets, the cause of the explosion. He said that there was no way in which the behaviour of these could have been properly predicted without full understanding. He then wrote 'Nevertheless, officials fooled themselves into thinking they had such understanding . . . by using a mathematical model of behaviour . . . based not on physical understanding but on empirical curve fitting'. Here we have a major disaster which set back the US space programme by some years, as well as costing seven lives, blamed on a confusion in the minds of engineers on the difference between empirical knowledge and understanding.

Very much of the knowledge used in the construction industry is empirical rather than based on any true understanding. We call it 'experience' and, within the industry generally, tend to rate it much more highly than 'theory', which is an attempt at understanding. Are we putting ourselves at risk by our traditional approach? Should we pay more attention to theory?

Engineering is very different from science in critical ways. Basically, science aims to increase understanding of the physical world while engineering aims to solve practical problems. In solving these practical problems the engineer will use the findings of science but, because of the complexity of real problems, the understanding provided by science is never sufficient. It has to be supplemented by information from wherever it can be found. Information may be of many types and qualities; for example, it may be

- theoretical, based on agreed assumptions
- empirical from experiment—quantitative
- experience—qualitative
- rules of thumb
- anecdotal information

The engineer would be failing in his duty if he did not take account of *any* information which might assist him in arriving at a solution to his problem. He could not, however, use this information uncritically; he must make judgements about the relevance and quality of each piece.

It is this question of judgement which really sets the engineer apart from the scientist. The engineer must arrive at a practical solution to his problem. Complete understanding will not be available to him, and he must make judgements and back these judgements. Many lives may depend on the reasonableness of these judgements. They cannot, however, be unnecessarily conservative, as the engineer must tread a tightrope between safety and economy. Civil and structural engineers carry particularly heavy responsibilities because they rarely have the opportunity to construct and test prototypes which would allow them to correct and refine their designs; they must be adequate first time.

The engineer, then, must use all sources of information open to him and must make judgements in arriving at a safe, practical, economic solution to this problem. He must be willing to employ empiricism *and* theory, and indeed any other source of information that may be relevant.

Where does this leave Professor Feynman's point? The point, in my opinion, is not that an engineer should not use empirical information but that he should understand the *limitations* of the various sources of information he is using and make appropriate judgements about its quality. A fault which is

common to UK engineers seems to be to over-value experience, empirical knowledge and rules of thumb and to underate theory. It is possible that Continental engineers tend to the opposite fault.

What are the weaknesses inherent in the use of experience and empiricism and what are the strengths of theory? In the following, experience, empirical approaches and theoretical approaches are all considered in their 'pure' form. In reality most solutions to problems derive from a mixture of the three.

Let us deal first with experience. Experience works where you can be certain that what you are trying to do is the same as what has been done successfully before, and that all the conditions are comparable. Basically, it is like walking backwards and steering by looking where you have come from. The system will work provided the road is straight and there are no obstacles in your path; otherwise disaster strikes. Most major engineering disasters have arisen from the uncritical application of experience.

In the research field, empiricism is characterized by taking a body of data which we hope is relevant to the problem we wish to solve and using curve fitting procedures to develop an equation. This is done without serious consideration of why the resulting curves have the form they do. This process, or something approaching it, is used extensively. Often, one really has little choice but to adopt this approach. The weakness is that, without some understanding of why the relationships have the form they do, it is very difficult to be certain that the conditions in real life problems are really the same as they were in the tests, and hence whether the result is applicable. Also, one needs to be aware of Professor Feynman's point: equations give a false sense of understanding which can have disastrous consequences.

A theory is an attempt to explain and hence predict behaviour at one level in terms of behaviour at a more basic level. For example, theories of section behaviour in reinforced concrete aim to explain section behaviour in terms of the behaviour of the constituent materials: reinforcement and concrete. An alternative way of looking at it is that the development of a theory is the construction of a model of behaviour based on stated assumptions about behaviour at a more basic level. A fundamental difference between theoretical and empirical approaches is that the assumptions made are stated and their adequacy can be tested or discussed. An empirical relation contains implicit assumptions about behaviour; what these assumptions are is not known and therefore they cannot be

critically examined. This ability to trace back a theory to its basic assumptions, and then be able to examine these for relevance to the particular problem being considered, makes theoretical approaches in principle more reliable than empirical approaches. Theoretical approaches are therefore to be preferred where they are available.

Seen from a reliability or quality assurance point of view, it is possible to list the three sources of information in order of increasing inherent reliability, as follows

rules of thumb experience	} specific background untraceable
empirical relationships	traceable to a specific set of data
theories	traceable back to a testable set of basic assumptions; predictions of theory testable against the same data set as an empirical relation

If the significance of reliability is to be fully understood we need to be clear about one of the principal functions of research. I believe that research enables industry to manage and react to change. Managing change is making change work for you by developing new products or methods. Reacting to change is ensuring that changes in conditions imposed from outside can be handled. The classic statement 'we've always done it this way and it has always worked' is a recipe for disaster if circumstances have changed. A particular weakness which leads to these disasters is that 'experience' is unable to spot that circumstances have changed until the changes cause problems. Empirical methods suffer to a lesser degree from the same problem, since coping with change requires extrapolation from current conditions. Empirical methods are reliable where one is interpolating within the range of the existing data but are unreliable for extrapolation. The pressure on researchers only to test 'realistic' specimens, which usually means specimens which conform to current practice and conditions, aggravates this weakness by ensuring that the data pool is not broad enough to cover the changed conditions.

Only the fundamental understanding of a problem offered by a properly constructed theoretical approach can offer a sound basis for moving forward into changed circumstances with any real confidence.