Int. J. Engng Ed. Vol. 20, No. 1, pp. 96–102, 2004
Printed in Great Britain.

0949-149X/91 $3.00+0.00

Fostering Creativity in Students in the Teaching of Structural Analysis*

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The need to design structures for ever harsher environments, to greater heights and spans, with greater controllability and durability, and of greater economy and safety, calls for creative solutions by today's structural engineers. This paper examines the issue of fostering structural engineering creativity in students, which does not appear to have been discussed in the open literature. The paper begins with a brief discussion of creativity followed by an analysis of the design process as a creative process. This analysis identifies the deficiencies in the current approach of teaching structural analysis which emphasises the mastery of skills for quantitative analysis but neglects the development of structural insight and an ability for divergent thinking. A number of measures which may be able to rectify these deficiencies are then discussed. These include the imparting of qualitative-analysis skills in students, the use of structural paradoxes to develop problem-solving skills, and a stronger emphasis in teaching on links between structural forms and functional attributes and between different structural forms.

INTRODUCTION

THE HISTORY of structural engineering is one of innovations. While new structural forms, new structural materials, and new theories for analysis and design are obvious examples of innovations, innovative approaches to structural engineering problems are also found in the day-to-day work of many structural engineers. The need to design structures for ever harsher environments, to greater heights and spans, with greater controllability and durability, and of greater economy and safety calls for ever greater creativity in today's structural engineers.

Structural engineers today are armed with powerful computers and analysis/design software. They are thus largely liberated from extensive hand calculations and drawings, and the restrictions of analytical power to obtain accurate quantitative answers. As a result, they have more freedom for innovative designs than their predecessors. While full advantage must be taken of computer-based tools in design, these tools alone cannot produce creative solutions, at least not in the foreseeable future. The key to innovative designs lies in the creativity of structural engineers. This paper thus examines the issue of fostering structural engineering creativity in students, which does not appear to have been discussed in the open literature. It should be noted that the paper is explicitly concerned only with creativity in the production of innovative designs by structural engineers, but, with some modification, the conclusions drawn should also be applicable to other activities undertaken by structural engineers.

* Accepted 28 March 2003.

DEFINITION OF CREATIVITY

There have been many definitions of creativity. According to Couger [1], over 100 definitions of creativity have been published. The two important aspects of creativity are 'newness or uniqueness' and 'value or utility'' [1]. In structural engineering, creativity can thus be defined as the production of a design which is both novel and of practical value. As structural designs are carried out with structural and functional requirements as the constraints, the value/utility aspect is intrinsic in any accepted design. The emphasis of this paper is therefore on the novelty aspect of creativity.

THE CREATIVE PROCESS

A commonly accepted model of the creative process is that formulated by Wallas [2]. This model divides the creative processes into four stages:

- preparation
- incubation
- illumination
- verification.

Santamarina and Akhoundi [3] suggested to replace the stage of illumination by the stage of

Table 1. Torroja's design method as a creative process [3]

Creative process	Preparation stage	Incubation stage	Idea generation stage	Elaboration stage	Implementation and evaluation stage
Torroja's design method	Familiarise with the project	List requirements	Sketch ideas: new, adaptation, combination	Solve conflicts, find alternatives	Evaluation, select solution

idea generation, and separate the verification stage into two stages for engineering activities. They then considered the design process employed by Torroja [4, 5], who is known for the creative nature of his design, and matched it to the creative process as shown in Table 1.

The above matching of Torroja's design process to the creative process is probably not entirely appropriate. For example, the incubation stage is generally considered to be the stage when one has reduced the focus on a particular problem on which a great deal of time has been spent, while listing ideas as given in Table 1 implies continued concentration of attention on the problem. Furthermore, the stage of illumination, often associated with a rush of excitement [6], has been replaced by the stage of idea generation. Table 2 shows an alternative matching proposed by the present authors of Wallas' four-stage creative process [2] to a typical design task which requires a creative solution.

KNOWLEDGE BASE FOR CREATIVITY IN STRUCTURAL ENGINEERING

The level of creativity depends on the breadth and depth of an individual's knowledge base, and the ability for unrestricted (divergent, lateral) thinking [3]. Having examined the design process as a creative process, it is now possible to identify how these two ingredients are made use of in a creative design process, and what constitutes the knowledge base for a creative structural engineer.

The first three stages of the creative process (Table 2) all require a sound structural insight (i.e. a sound understanding of structural behaviour). That is, the creative structural engineer must be able to anticipate how a structure responds to applied loads and other external influences, and in turn is able to visualise structural forms which are appropriate for given conditions. This knowledge is generally qualitative rather quantitative and numerically precise answers are not required. The final stage, the verification stage, requires technical competence in the numerical analysis of structural systems which may be very complex and the dimensioning of structural elements. In today's computer-intensive design environment, these tasks require mainly (a) a strong background in computer analysis techniques and (b) a good understanding of structural behaviour so that correct structural models are built and the results are properly interpreted.

The above analysis demonstrates that quantitative numerical analysis skills are required only in the last stage of a creative design process, while a sound structural insight is required in all four stages. In addition, an ability for divergent thinking is crucial in the exploration of alternatives in the preparation stage, and in the incubation stage, although here how the mind works is out of conscious control and defies a clear explicit explanation.

DEFICIENCIES IN THE PRESENT TEACHING METHOD AND REMEDIES

The conventional teaching method emphasises the mastery of quantitative analytical skills rather than the development of structural insight and a divergent thinking ability, and this is still prevalent. The lack of structural insight as a result of the current teaching method has been noted in a number of papers [7–10] and by the Institution of Structural Engineers [11]. One may question why there has been so much recent concern about the conventional teaching method if it has served our profession well in the past. This, according to

Table 2. A typical design process as a creative thinking process

Creative process	Structural design activities
Preparation stage	Understand the requirements and constraints of the problem, gather information and consider various alternative approaches. In this stage, a solution has not yet been reached, but many ideas are explored.
Incubation stage	The mind processes all possible alternatives during a stage when the concentration of attention on the problem is at a reduced level compared to the preparation stage. This may be years, months or days, or just a few minutes or even seconds in more trivial cases.
Illumination stage	A solution comes to the mind of the designer as being the appropriate one, and this being one that has not been thought of in the preparation stage.
Verification stage	Quantitative analyses, generally using computers nowadays, are undertaken to see if the solution found is indeed appropriate.

Brohn [9], is due to a new paradigm in structural engineering: the dominance of computers in structural engineering practice.

The challenge of the new paradigm to the teaching of structural analysis has been discussed by others, for example in [9] and may be briefly summarised as follows. On one hand, a higher level of structural insight is demanded of new graduates and young inexperienced engineers than their predecessors as they, being the most computer literate, are often asked to analyse complex structures. On the other hand, they have reduced opportunities to develop such insights as computer methods are given more and more emphasis at the expense of hand methods in both teaching and practice. Calladine [10] described the present teaching method as being inadequate in promoting the powers of the mind, the most important objective of a university education.

In addition to the deficiency in teaching structural insight, there is generally little consideration given to the development of a divergent thinking ability or creative problem solving skills in the present teaching method. Changes to the current approach of teaching are therefore desirable for the fostering of creativity in students.

Although it is difficult to show that creative people like Einstein can arise from training alone, it is widely accepted that there are ways to enhance one's creativity through a number of means [6]. For example, Hayes [12] suggested that creativity can be enhanced by: (a) developing a knowledge base; (b) creating the right environment; and (c) searching for analogies. Clearly, both the knowledge base and the ability for divergent thinking need to be enhanced in the fostering of creativity.

DEVELOPMENT OF A SOUND STRUCTURAL INSIGHT

As discussed earlier, the deficiency in the current teaching method is the insufficient emphasis given to the development of structural insight which is a very important part of the knowledge base for creative structural engineering. A number of studies have examined the teaching of structural behaviour [9, 10, 13, 14]. Four approaches for the development of structural insight are discussed below: (a) qualitative analysis; (b) qualitative experiments; (c) computer simulation and (d) structural games.

Qualitative analysis

Qualitative analysis has been strongly promoted in recent years as an effective approach for learning structural behaviour [7–9, 11, 13]. Typically, this involves the sketching of bending moment and shear force diagrams and deflected shapes based on physical reasoning. Qualitative analysis skills can be perfected through repeated practice, much like the development of quantitative analysis skills.

Qualitative experiments

Laboratory experiments form an important part of the learning experience of an undergraduate student by providing an effective link between the theory and actual behaviour of structures. The emphasis of these experiments is on quantitative results, with their role being mainly the confirmation of theory [15]. By analogy to qualitative analysis as described above, qualitative rather than quantitative experiments should be used more to illustrate deep concepts and clarify complex behaviour. Furthermore, such experiments can be conducted in classrooms rather than in the laboratory as the model can be made small and no measurements are normally taken. Such classroom experiments are not new: many lecturers have used small physical models in teaching. Classroom experiments provide immediate physical clarifications of theoretical issues, so they can support lecturing more effectively then laboratory experiments. They are also cost-effective as no laboratory space and manpower are required.

Computer simulation

Classroom experiments are generally limited to simple cases. For more complex structures and more complex phenomena, computer simulation is ideal. Brohn [9] has discussed such computer simulation. There is now a strong interest in universities in the use of computer and multimedia packages in teaching, and the eventual aim, in terms of the learning of structural behaviour, should be the development of a virtual structural laboratory to which students have constant access.

At The Hong Kong Polytechnic University, a web-based package for Computer-Aided Learning of Structural Behaviour, the CALSB package (URL: http://www.cse.polyu.edu.hk/~cejgt/calsb) [16], has recently been developed to assist civil engineering students in developing a sound insight into the linear elastic structural behaviour of plane skeletal structures. In this package, all data are linked to a single graphical display wherever possible, which also responds dynamically to any change in the data. For example, as a load is moved along the beam by the cursor, the continuous changes in the distribution of the chosen quantity such as the bending moment or the deflection can be seen on the screen. Figure 1 shows the computer-generated responses of a continuous beam to a load acting at two different positions. A connected sequence of such responses, changing continuously and dynamically with the load position, provides the students with a vivid picture of how the structure responds to the load as the load moves across the beam. The CALSB program provides many other interactive functions to assist students' learning of structural behaviour. For example, students can add or remove a support, insert a pin in a member and modify a span. In all such cases, instant responses of the structure are provided on the screen.

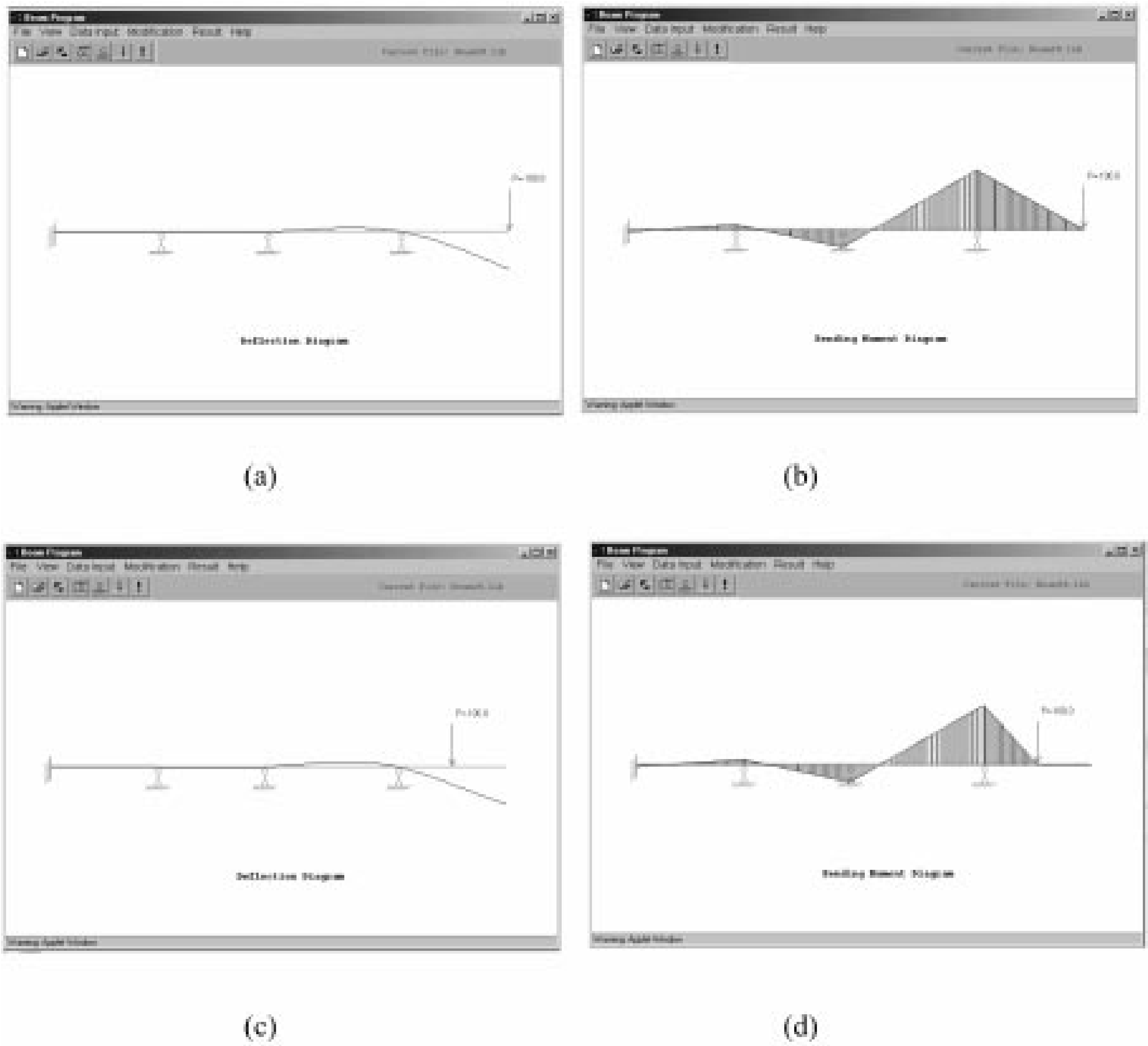

Fig. 1. Response of a continuous beam to a moving load.

Computer-based interactive simulation of structural behaviour such as that provided by CALSB enables the students to 'test' different structures on their computer screen rather than in the traditional laboratory that is both time-consuming and costly. This is a very effective approach to teach students structural behaviour [9, 13].

Structural games

The normal learning process with many exercises is seen by many as drudgery. To reduce boredom in learning, computer games involving structural concepts and behaviour are believed to be a useful learning tool, if appropriate games can be devised. Games have the single distinguishing feature that the player derives joy and excitement from playing them, and this feature must not be compromised in structural games. Structural games must however be developed with an emphasis on the learning function so that the player derives new knowledge about structural behaviour from playing the game. An element of challenge or adventure should also be included in such games to provoke deep-thinking processes in the player. With these features, players of structural games have an opportunity to apply, reinforce and enhance his knowledge in an exciting and joyful environment.

As an example, a structural game developed at The Hong Kong Polytechnic University is introduced here, which has been implemented in the CALSB package [16]. This game is to help students reinforce their knowledge about geometric stability and static determinacy of two-dimensional skeletal structures. In this game, a variety of predefined statically indeterminate structures are available and students can choose any of these structures for their game. They can also design their own truss for practice. The player is asked to remove a member, a constraint or to cut the member at a time using the cursor to obtain a structure which is both geometrically stable and statically determinate. If a member or constraint essential for

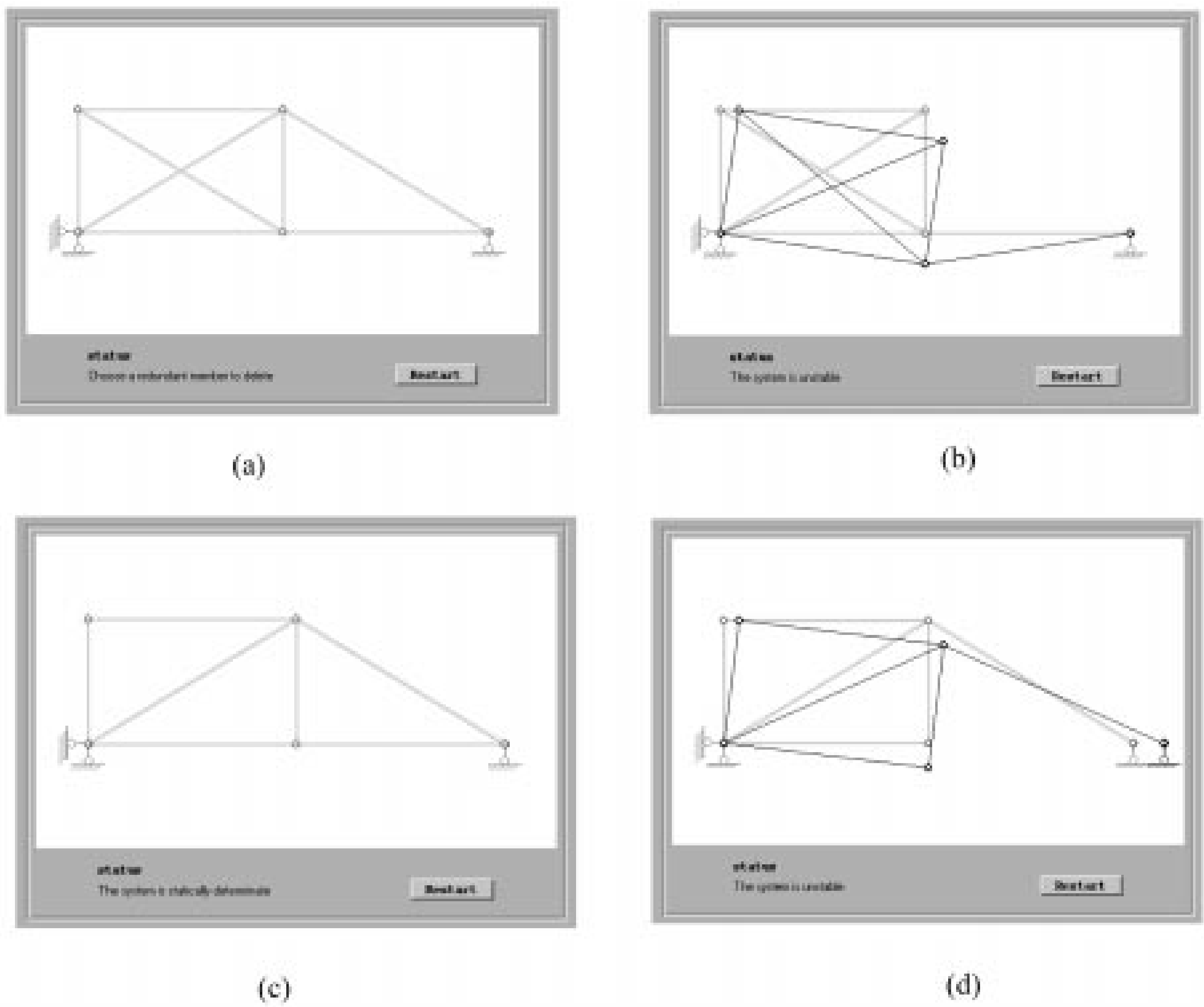

Fig. 2. Example stability and determinacy game.

geometric stability is deleted by mistake, an error message will appear with the sound of an alarm bell. The mechanism of the unstable structure will also be shown at the same time. The player can re-examine the structure by choosing the restart option. By playing this game, students can acquire a solid knowledge of the geometric stability and static determinacy of structures.

Figure 2a shows an example truss for such a game whose degree of indeterminacy is 1. The player is asked to remove members one by one to find a geometrically stable and statically determinate structure. If the player removes the inclined member on the right, the resulting mechanism of the structure (Fig. 2b) will be shown. If the player removes one of the inclined members on the left, then the player will be told by a statement below the diagram that the structure is now statically determinate (Fig. 2c). If the player proceeds to remove another member, the structure will again become unstable and one of the possible mechanisms such as that shown in Fig. 2d will appear on the screen. More elaborate cases are available within the CALSB package and can also be designed by the player.

DEVELOPMENT OF A DIVERGENT THINKING ABILITY

The development of a strong ability for divergent thinking is a difficult task, although there are books such as [1] which intend to teach techniques for divergent thinking. Perhaps university students should be taught these techniques, but this is best done outside the structural engineering curriculum. Structural design projects would provide a good environment for practising such techniques, provided that they are made as open-ended as possible. What then can be done in the teaching of structural analysis? Creativity may be viewed as problem solving [1], the production of a novel solution to a challenging problem. By exploiting this notion, it may be anticipated that the creative thinking ability of students can be enhanced through the solution of structural problems which do not seem solvable by following a simple straightforward logic based on their prior knowledge. These problems may be referred to as structural paradoxes, whose solution process may involve all four stages of a typical creative process. Solving these paradoxes leads to the development

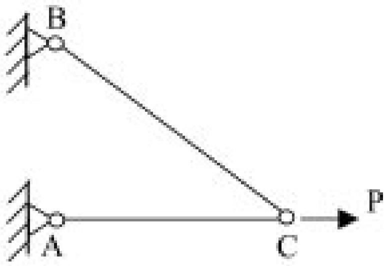

Fig. 3. Two-bar truss.

of problem solving skills and the development of a sound structural insight at the same time.

The paradoxical experiments described by Calladine [15] represents such an approach. While laboratory experiments are usually conducted to confirm a theory that has been taught, Calladine's paradoxical experiments on beams [15] were designed to demonstrate the consequences if assumptions made in the engineer's beam theory are violated, providing much food for thought for the students. Of course, paradoxical experiments can also be conducted in classrooms.

Structural paradoxes can also be analysis problems. Figure 3 shows such a problem which has been used in tutorial sessions at The Hong Kong Polytechnic University. Students are asked to determine if there is any vertical displacement at C of the two-bar truss by simple physical reasoning. They are likely to be unable to answer the question quickly and may never come up with the right approach. After some time, many students can see that there is no force in member BC but at the same time think that there should be no vertical displacement as the load is horizontal. They then come to a paradox: member BC cannot elongate as it is not stressed but elongation seems necessary if point C is to move horizontally. The key to the solution is to realise that BC can rotate as a rigid body. Once the students have reached or have been led to the right answer, they are also asked to work out the magnitude of the vertical displacement, given a value for the horizontal displacement. While one may debate whether the solution of this problem requires any divergent thinking skills, students are generally intrigued by the problem, and the solution certainly requires something which is different from the ability to find the answer by the logical steps of the virtual work method.

REORGANISATION OF SYLLABUS TO MAXIMISE ANALOGICAL PROBLEM SOLVING

Searching for analogies is suggested as an effective means for enhancing creativity by Hayes [12]. For example, through analogies, structural systems for tall buildings and tall bridge pylons may be mutually exploited or combined to produce innovative designs. It is therefore useful to examine if the current way of teaching structural analysis leads to a knowledge base that is organised to maximise such analogies. Structural design begins with specified functional attributes such as spans, heights and load resistance capabilities, and the solution process involves the use of appropriate structural forms to achieve these attributes. To enhance creativity in design by analogies, the relationship between a structural form and its functional attributes, and between different structural forms should be clearly established in the knowledge base.

Currently, the teaching of structural analysis is organised to cover analytical techniques one by one, with little explicit information on these relational aspects. In addition, the emphasis is generally on skeletal structures. This deters the innovative use of other forms in structures, and inhibits a creative combination of different structural forms in a single structure. It is thus suggested that in addition to the teaching of analytical techniques, attributes of a variety of structural systems, how these are achieved and how different structural systems may interact with each other to achieve certain attributes should form an integral part of the syllabus of structural analysis.

CONCLUSIONS

It is well accepted that creativity depends on the knowledge base and the ability for unrestricted thinking. The current method of teaching structural analysis emphasises quantitative analytical skills, which only form part of the required knowledge base for innovative designs. Insufficient attention is given to the development of structural insight in students. In addition, there is generally little consideration given to the development of a divergent thinking ability or creative problem solving skills. A number of measures, which may be able to correct these deficiencies, have been discussed. These include the imparting of qualitative-analysis skills in students, the use of structural paradoxes to develop problem solving skills, and a stronger emphasis in teaching on links between structural forms and functional attributes and between different structural forms.

Acknowledgements—The authors wish to thank Professor C. R. Calladine of Cambridge University and Dr. J. F. Chen of Nottingham University for their kind help with the gathering of some of the references.

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