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THE TEACHING OF FRACTURE IN UNIVERSITIES

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ABSTRACT

It is argued that the teaching of fracture as an undergraduate engineering subject is especially important because of the potentially disastrous consequences of the failure of materials in engineering structures. Some contemporary approaches to teaching fracture are discussed on the basis of results from a questionnaire survey of delegates to ICF4, and the pedagogical implications of different teaching methods are examined. It is concluded that fracture is now, in 1977, a "discipline" and that a reappraisal of its place in engineering education is required.

1. INTRODUCTION

Fracture is a phenomenon so ubiquitous that it is a daily concern of such diverse specialists as engineers, physicians and kinesiologists as well as the public at large. Although the topic of fracture is relevant to most branches of engineering, it sometimes occupies a less important place in the engineering curriculum than seems desirable - especially when it is considered that a major concern of engineers is building and designing useful products and that such products often fail by one or more fracture processes. One reason to argue that fracture should be a central component in engineering education derives from the fact that the technical and social consequences of some types of fracture are immense. This presents considerable challenges to those experts in fracture who are involved in education.

A good example, among the many that might be cited, is the explosion at Flixborough described by Kennett [1]. Twenty-nine people died and more than 100 were injured when a pipe in a petrochemical plant leaked and caused an explosion that devastated the plant and was heard more than 30 miles away. The basic cause of the failure, according to Cottrell [2], was the rapid development of intergranular cavities in the steel pipe that was operating in the creep range of temperature. Failure was thus due to creep cavitation fracture. The explosion brought into question the wisdom of building large-scale factories or other massive engineering structures, and the disaster eliminated the only source in Britain of an essential raw material for the production of nylon. In the Open University course on Materials Failure a radio interview was held with Sir Alan Cottrell, a leader of the official Flixborough enquiry, and the tape recording of the interview was used as a teaching aid. This tape, as well as other real life examples of failures and their political and social consequences, is also used at the University of Waterloo to provide an added realism to the teaching of fracture analysis.

Society faces the possibility - however remote - of even more catastrophic environmental disasters than Flixborough, for example in nuclear reactors

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and in operations of the petrochemical industry such as offshore oil-rigs. These examples are especially politically sensitive. Month by month significant material failures cause major problems, and headlines such as "Jet Engine Fails due to Metal Fatigue", "Cracks in Prestressed Concrete Skyscraper cause Evacuation" are not uncommon around the world. It thus seems imperative that engineers be thoroughly educated to deal with such problems.

But not only is it necessary that scientists and engineers be educated to recognize, prevent and rectify fracture problems, they must also be able to do this within the wider political and social context of contemporary society. For it is to these experts that the public and the political decision-makers must turn to advise upon and to resolve, such crucial issues [3]. Thus it is important that engineering students have a practical understanding of the political and decision-making processes in society. Just as, for example, students of sociology, humanities and law need some understanding of basic technology, the converse is equally important. Furthermore, society as a whole must also be educated to understand some of the important technical consequences of large-scale fracture, so that laymen may respond intelligently when called upon to make political decisions that have far-reaching consequences for the use of technology in society. The aim of this paper is to provide a preliminary examination of how the subject of fracture is presently handled in universities, focussing particularly on innovative approaches, in order to determine how fracture may be taught in a way that is most relevant to the changing needs of society at large.

2. THE PLACE OF FRACTURE IN THE UNIVERSITY CURRICULUM

In an attempt to discover something of the present status of fracture in the university curriculum, in April 1977 a short questionnaire was sent to each of the registered delegates to ICF4. Of over 400 questionnaires distributed, 80 were returned, from 60 different institutions in 17 different countries. The complete returns by country were: United States, 25; United Kingdom, 14; Japan, 9; Canada, 7; Finland, 3; France, 5; Germany, 3: India, 2; Netherlands, 2; South Africa, 2; Sweden 2, Argentina, 1; Denmark, 1; Italy, 1; Israel, 1; Switzerland, 1; Yugoslavia, 1.

Only 10 respondents did not teach at a post secondary institution, and the great majority were affiliated with a university or its equivalent. The highest degree offered by such institutions was almost invariably the Doctorate (6), usually the Ph.D., but occasionally a D.Eng., D.Sc., or D.Tech. In 3 further cases the institution concerned offered only a Master's degree. The departments represented were Materials Science/Metallurgy - 28; Mechanical Engineering - 23; Engineering (in general) - 9; Aerospace Science/Aeronautical/Naval Engineering - 4; Solid Mechanics - 3; Mining - 2; Physics - 2; Chemical Engineering - 1. Most of these departments themselves gave the Doctorate (55), with 4 departments giving only a Master's degree in their subject.

Graduate Courses on Fracture

Respondents were asked whether graduate courses specifically on fracture or failure analysis were offered in their department or another department they knew of. Responses indicated considerable differences between European institutions and those in North America. In the case of the United States and Canada, no fewer than 30 separate graduate level courses were mentioned by respondents, offered primarily in departments of metal-

lurgy, mechanical engineering, or materials science (the courses concerned invariably included the word "fracture" in the title); 1 institution reported that fracture was covered as part of another graduate level class; and 2 respondents reported that a course on fracture was offered on an irregular basis or at the inclination of a particular lecturer. For the European universities represented, only 7 graduate courses in fracture or failure analysis were reported; though in the case of 2 institutions such courses were sometimes given; in 3 other cases fracture was covered as part of another course (for example, the mechanical behaviour of materials).

Undergraduate Courses on Fracture

Respondents were asked whether the subject of fracture was an officially designated part of the undergraduate curriculum - for example was there a course entitled Fracture or was fracture a specified part of another course? Analysis of responses here did not reveal the differences between countries apparent in the case of graduate level courses. In fact only 12 fully fledged courses on fracture or failure analysis were reported in total - 4 in Europe, 3 in the U.S.A., 2 in Britain, 2 in Canada, and 1 in Japan. In the case of 33 other institutions, fracture was covered as part of a course or courses, generally in materials science or mechanical metallurgy.

Fracture as a Compulsory Part of the Curriculum

Respondents were asked if the subject of fracture was part of the core (mandatory) curriculum of the undergraduate engineering program. Only 1 department replied affirmatively, with another 1 department reporting that the subject of fracture was compulsory for some students, depending on the option they took. A further 17 reported that the topic of fracture was mandatory in the sense that it was part of a wider course or area that itself was part of the core curriculum (typically a course on materials): 4 institutions in England, 3 in Canada, 2 in Finland, 2 in South Africa, 2 in the United States, 1 in France, 1 in Japan, 1 in Sweden, and 1 in Switzerland. This contrasts with a total of 36 institutions which indicated that fracture was definitely not a mandatory part of their degree requirements at the undergraduate level - except as a rather small part of a general materials course.

Novel Approaches to Teaching Fracture

Respondents were asked if the topic of fracture was taught in their institution in any special or unusual way - for example by means of a "case study" approach, through the use of extensive project work and so on. In all, 20 affirmative responses were received, including 5 from universities in the U.S.A. and 4 from British institutions. The majority of respondents mentioned project work or case studies, occasionally done in a real life industrial setting. The following comments were made by individual respondents,

- "The topic is the subject of a full year's research for the final year student in some laboratories in our department." (Yokohama National University, Department of Mechanical Engineering)
- Fracture is taught by the case study approach. (University of Southampton, Department of Mechanical Engineering)

"Apart from standard lecture units on various aspects of Fracture in courses such as 'Mechanical Properties of Solids', we use one less usual type of 'case study' approach. I introduced this method when I joined the staff ... and it is still proving useful. Students are each given a different article (i.e. a metallic component) which has failed in service. These components can vary from bearings for large rolling mills to rocker-arms from motor engines. The student is given a period of laboratory time to determine the cause of failure, prepare a detailed report (in a form comparable to a report from a consultant) and then face an oral examination for about an hour with a member of staff. This approach not only gives them practice at report preparation and orally supporting their work, but provides an excellent check on their understanding of metallography, fracture modes, etc., and forces them to become familiar with 'material specifications' and 'codes of practice', etc. It certainly brings home to them the gulf between academic lectures and the realities of service failure examination." (University College of Swansea, Department of Metallurgy and Materials Technology)

- "A small service failure analysis project is attempted." (University College, London, Department of Mechanical Engineering)

- "One of the undergraduate laboratory courses has an experiment on fracture using compliance methods." (University of Rochester, Department of Mechanical and Aerospace Science)

- Fracture is integrated with the research work of some staff, and an attempt is made to relate fracture to fundamental deformation mechanisms. (University of Cincinnati, Department of Materials Science and Metallurgical Engineering)

- "Yes, in the failure analysis course fracture is taught as both a 'case study' subject and as a real case experience, with students working with four industrial concerns on problems selected by them." (University of Michigan, Department of Mechanical Engineering)

- "We frequently use case studies dealing with fatigue and/or fracture from the Stanford/ASEE case library." (Wichita State University, Department of Mechanical Engineering)

- "We often use outside lecturers for specific expertise." (Carnegie-Mellon University, Department of Mechanical Engineering)

- The case study approach is used. (McMaster University, Department of Mechanical Engineering)

- Fracture is taught by a combination of lecture, laboratory, and research project. (Carleton University, Department of Engineering)

- Fracture is taught as a research project as part of the study of reactor materials. (Technical Research Centre of Finland)

- "Sometimes we are able to co-operate with industry when they ask us to investigate damage or similar problems." (Technical University of Aachen, Faculty of Mining and Metallurgy)

- "Not yet, however the Department of Mechanical Engineering is going to start a 'case study' approach by way of an experiment." (University of Witwatersrand)

- "We are developing a method of analysis for nuclear structures taking into account fatigue, failure and plasticity for a tri-dimensional case." (Ecole Polytechnique of Paris, Department of Solid Mechanics)

- Fracture occasionally appears in final year project work, often done on an industrial problem. (Chalmers Technical University of Sweden, Department of Physics)

The Place of Fracture in the Undergraduate Curriculum

No fewer than 46 respondents replied to a question which asked them what place courses on fracture should have in the undergraduate curricula for engineers. A majority felt that it indeed should occupy a fairly prominent place, though most of these stopped short of saying that fracture merited treatment in a special course at the undergraduate level. A further 5 respondents had considerable reservations about (or were completely against) the teaching of fracture to undergraduate engineers.

The following comments are selected from those made by individual respondents.

- "Fracture should be taught as a topic (general approach) in the course on Materials Science."

- "There should be a mandatory one-semester course for all engineers; it is advisable to have a part of this course based on 'case histories'."

- "Contributions to fracture mechanics by metallurgists are very much needed. Unfortunately, however, the status of the subject 'Fracture' in metallurgical engineering is of secondary importance, at least in this institution. It appears that fracture is more important to users than to producers. I think that the theory of fracture should be developed more systematically from the point of view of physical metallurgy: then fracture will attain the status of an independent subject within the field of metallurgical engineering."

- "Fracture is too sophisticated for undergraduate students to understand completely; so it may be enough at the moment to give some basic concepts."

- "In a general engineering course fracture could occupy 5% of the curriculum, or about 27 lectures (say 1 lecture a week for a year; in mechanical and electrical engineering up to 10% of the curriculum could be devoted to fracture (in the case of electrical engineering that concentrates on nuclear applications, turbines, etc.); in civil engineering internal fracture and structures should occupy about 10%; materials engineering also needs about 10%; aeronautical engineering needs at least 10% on fracture in relationship to structure, and somewhat less than 5% on fracture in relation to engines; in the case of electronic and management engineering fracture deserves less than 5% of the curriculum."

- "Fracture is an essential part of all undergraduate curricula in engineering, at least as part of a course on materials."
- "A permanent place, but at present fracture should be dealt with within materials and mechanics courses rather than separately; fracture should be part of courses on mechanical behaviour of materials and design."
- "It is essential that design for structures containing defects be included in all courses in mechanical engineering to an extent which recognizes that most engineering failures are of this type and not failures of the traditional 'stress analysis' method which occupy so much of present courses."
- "Fracture should be taught in the core courses of materials science as well as in the sequence of machine design courses; in particular, the importance of fracture control in design should be emphasized."
- Fracture should be taught as part of a mechanical metallurgy course - more time should be spent on fracture ("a problem of general interest") and less on rolling etc.
- Fracture should be an elective course, but encouraged for metallurgy, mechanical engineering, chemical engineering and civil engineering, and should be taught at an advanced undergraduate or graduate level.
- "Fracture should be introduced early in the curriculum for most engineers and should have at least as much time devoted to it as the traditional mechanics type courses such as strength of materials, in which fracture is barely touched upon."
- "Fracture should not be taught as an exercise in mechanics - this needs a proper base in materials and plasticity. Rather, fracture should be presented as a culmination of response to loads, and related to service environments and structures."
- "Fracture is one mode of failure, which should be covered in some undergraduate curricula - I do not believe undergraduates really comprehend fracture or can learn about it in the period of time I can devote to it (about two weeks). Fracture should be introduced and some idea given of the importance of the topic; however there is no time to treat the topic in depth in the undergraduate curriculum."
- "I believe fracture topics should be integrated into courses in mechanics and in materials."
- "There should not be a full course (i.e. a semester-long course) on fracture, but it should be covered as a part of a course sequence in materials and mechanics."
- "Fracture should be a specifically designated part of the core curriculum for engineers."
- "Fracture as a mechanism should be taught both under 'strength calculus' and 'materials' courses."
- "In Finland we should have more fundamental and mandatory courses in fracture."

- "In our system these courses should be given at the graduate level."
- "Fracture should be part of a course on 'mechanical properties of materials'; I do not consider that fracture can be separated from other mechanical properties."
- "Fracture should be taught at a later stage, following courses in strength of materials, elasticity and basic materials science."
- "The topic of fracture should be briefly outlined as part of the mandatory curriculum; it should be dealt with in more detail as an elective and/or graduate course."
- "There should be more interdisciplinary co-operation in the teaching of fracture. Very often the development of fracture is prohibited by the sharp limit between mathematicians and materials scientists, i.e. the two groups have large difficulties learning from each other and work in isolation. Furthermore, I think there has been a stagnation in the field since the major developments between 1957 and 1970."
- "In my opinion fracture should not be treated separately from other mechanical properties. In the case of steel we have always to look for the strength *and* fracture properties. Therefore we always try to find correlations between the structure and fracture appearance. That is the reason for treating fracture as a part of physical metallurgy of steel in our courses."
- "In our teaching course *'Fractology'*, the first special way is to understand the fundamentals and the methodologies of fracture by an interdisciplinary approach, the second by the development of the comparative science of fracture."

3. TEACHING FRACTURE AS A FORENSIC SKILL

Although the evidence for successful innovation, based upon the results of this survey, is somewhat sparse, distinguished experts in the field of fracture have not fought shy of calling for radical changes in the way the topic is treated in university education. Cottrell [3] calls for a "science of materials in service", with a stress on applied aspects of materials and materials failure. He points out that universities presently tend to emphasize unduly the training of research workers, and argues that a more applied approach is needed with more integration of university and industrial research. This indeed is a basic thrust of the University of Waterloo in its co-operative approach to education, and it has been actively pursued, (if, perhaps, less successfully) in Britain.

For Cottrell, this hiatus is indicative of what is wrong with the way fracture is often taught in universities, and he argues that the subject should not be taught as pure science, with the aim of producing a "good research man", but that what is needed is a qualitative, illustrative and applied approach. A similar point has been made with regard to the teaching of science and technology to non-science majors. It is felt by some critics that stressing theoretical and technical detail (analysis) only serves to confuse the student with unnecessary, complicated information; what is needed is an emphasis on the more qualitative general issues, with provision of concrete examples and exploration of the various implications of modern science and technology.

Reid *et al.* [4] argue in a similar vein when they comment on the tendency of the traditional university teacher to tell his students what he knows, regardless of its relevance to their (and society's) needs. Cottrell regards engineering as essentially a profession for the "generalist". One implication of this is that engineering education must train its students to know when they are out of their depth with a particular problem and when to call in a specialist. This implies familiarity with learning in very practical situations, and in the case of fracture Cottrell recommends the examination of real or simulated failures, and practice at diagnosing them. This is very similar to the "forensic" or trouble-shooting approach that Reid *et al.* report as being used at the Open University. The technique typically involves what is generally called a "case study approach", in which students are set an empirical task for which there is not necessarily any single "right answer". (This is in contrast to the situation to be found in more traditional laboratory work, where there is often an undue emphasis on producing "the correct results" rather than on the process of learning and discovery leading to the conclusions.) To help them with their task or problem students are typically provided with certain factual data which may be more or less relevant to the problem's solution. This material may come in a number of forms, ranging from written documents to physical specimens, and the possibilities for using audio-visual aids are considerable, as is exemplified in the approach adopted by the Open University, which has made use of written reports, photographs, recorded interviews with experts, and even a home experiment kit.

The use of case studies in this way has the advantage of presenting the student with a problem that is very close to real life - indeed, genuine examples taken from industrial settings may be selected, and a student's manner of arriving at a solution may be compared to those of established experts in the field. Where co-operative programs exist there is the possibility of carrying out such projects in an authentic setting, perhaps with the student acting as a member of a team rather than an individual.

The case study approach has some severe limitations - in providing a collage of cameos, for example - but it does appear to be extremely valuable in exposing students to reality-based contingencies where practical remedies are called for. The pedagogical advantages of this type of learning are that the student acquires knowledge and skills by direct (as opposed to second-hand) experience, and hence, it is believed, is better able to transfer the skills he has learnt to the work situation.

The case study approach has a close relationship with the "heuristic" technique pioneered by Armstrong in the late nineteenth century [5]. This approach eventually developed into the Nuffield Science Teaching Project for schools [6],[7]. Indeed university science and engineering professors have much to learn from the science educationalists who focus on teaching in high schools (14-18 yr olds): an example would be the work of Jenkins and Whitfield [8].

Heuristics derives from the Greek *heurisko* meaning "I discover". Van Praagh [5] first developed the technique in full for the teaching of "Chemistry by Discovery" in England and later went to lead the Nuffield Chemistry Team developing and spreading the basic method. Reynolds [4] was an exponent of this technique for studies of materials failures and provided much of the original "heuristic" thrust for the Open

University course. Martin [9] has also done a great deal to bring the study of materials, strong solids and fracture into the secondary school curriculum.

4. ENGINEERING EDUCATION AT THE UNIVERSITY OF WATERLOO

The University of Waterloo is *de facto* and by deliberate design a technological university with considerable emphasis on professional programs in Engineering, Mathematics and Science. It grew quickly to a place of international prominence in these areas and it has a particularly high reputation within the engineering community in Solid Mechanics and Fracture. Indeed there are some 40 researchers, including over 20 faculty members, working in the field of fracture. Much of this research is of a directly applicable "mission-oriented" nature and it is reflected in the teaching on the Faculty of Engineering. An important tenet of Engineering education at Waterloo is that Engineering education has an important responsibility to train students who will be able to use their knowledge in a practical way to solve very practical problems. One way to expose students to the industrial environment they are likely to encounter in their later careers involves the notion of co-operative education, and this co-operative approach was a major element in the founding of the University of Waterloo 20 years ago. It had the aim of providing an educational system that would formally integrate a student's academic study with suitable work experience, or as Wright [10] noted, to produce an engineer who could function in the modern role of "manager technologist". The advantages for students were thought to be considerable: not only would they achieve some level of financial solvency, but they would benefit academically, experimentally, and in terms of eventual career opportunities. Presently at the University of Waterloo there are over 5,800 co-op students (and 900 employers) throughout all six faculties of the institution - with some 2,700 students in Engineering and over 1,700 in Mathematics. This makes Waterloo's co-operative program the largest in Canada and the second largest in North America (the largest being at North Eastern University, Boston); in fact *just under half* the total undergraduate enrolment is engaged in co-operative programs.

The mechanics of the scheme now run exceedingly smoothly. The Department of Co-ordination and Placement, staffed by over 30 co-ordinators (all with academic *and* practical backgrounds in their particular programs) arranges student placements in carefully selected positions after interviews with employers and with each individual student. The co-ordinators also visit students on the job and help with the general assessment on an ongoing basis. A co-operative student typically requires 6 work terms and 8 academic terms to graduate with an honours degree. Work reports (a professional level paper or research report on a topic of interest to the student and his employer) are required, and these are graded by the employer or by a faculty member; in addition, the employer must complete an evaluation of the student each work term. Cohesion among students is partly achieved by a system of streaming, whereby the same group of students proceeds through its academic career together, being enrolled in the same classes for the same academic terms. This is a fairly uncommon procedure nowadays in North American universities, and it would be interesting to determine empirically whether or not the plausible benefits in terms of morale do indeed exist in comparison with students who have no sense of class identity. There is a feeling that co-operative structures lead to rather less friendly and humane places than traditionally structured courses, perhaps due to the complex and changing work schedules involved.

Additional features of the co-operative scheme as it operates at Waterloo include adjunct appointments from industry and government, a student advisory council, and feedback sessions with students at the start of each academic term. There also exists an Industrial Advisory Council of 24 engineers and scientists from Canadian industry and government agencies that meets twice a year on campus with the Department of Co-ordination and Placement and faculties of Engineering and Science to provide input and advice on directions that scientific and technical education at the University of Waterloo should be taking.

As can be inferred from the above information, the University of Waterloo is extremely anxious to continually monitor the success of its co-operative program. To achieve this, an annual questionnaire survey of all co-operative students is carried out, supplemented from time to time by surveys of former graduates of the program. Results show that students overwhelmingly (over 94%) feel that co-operative education is a valuable experience, although surveys of past graduates reveal considerable criticisms of the relevance of the undergraduate curriculum to the jobs they eventually occupy. In terms of some other criteria co-operative education appears to have been markedly successful for Waterloo: those departments that offer co-operative programs have seen a considerable rise in enrolment, and an increase in the calibre of students applying. There is also some evidence that such students are preferred by employers compared with graduates of other equally prestigious, but non-co-operative schools. Certainly if the remarks made above about the pedagogical value of practical experience for the engineer have any validity, then it might be expected that students educated in co-operative programs would be in a better position to transfer what they learn in the classroom to the tasks they eventually face as professional engineers or scientists.

5. PEDAGOGICAL IMPLICATIONS

One theme that can be seen to run throughout the above discussion - but which has not been identified specifically - is the psychological concept of "transfer of training" [11]. This refers to the idea that what is learnt in one situation will be in some sense transferable and applicable to other situations. Transfer is an implicit assumption underlying university education - and indeed, all education. Assuming general agreement that it is desirable to teach for such transfer, the question remains as to how best to do this. For example, is it preferable to go from the general and the theoretical to the particular and applied, as in the traditional notion of discipline-oriented university teaching, or is the reverse precept a better strategy, as is claimed by those who favour a case study or problem oriented approach? Most people would agree that the closer the learning experience to the practical ("real life") situation, the easier it is for transfer to take place, and on this basis it might be expected that co-operative education would be particularly effective. However, this would clearly only be the case if students are given work experiences relevant to experiences they will encounter in their later careers, and if the program of academic training is closely geared to the practical situations they encounter in their work terms.

This points up the necessity - in co-operative programs as elsewhere in education - to specify precisely the objectives for learning [12],

at the level of the individual course as well as the entire program. (In passing, it is interesting to note that the stress upon writing objectives and then testing to see whether they have been attained, which is now ubiquitous among educationalists, originally derives from systems engineering.) Unfortunately it is often more difficult to specify precise learning objectives than it sounds in principle, especially where less tangible skills are required. However, as work at the Open University has demonstrated so effectively, learning that is based on solutions to specific practical problems lends itself particularly well to the "objectives approach", and it is often possible to see quite clearly the degree to which students are able to achieve the desired behaviour and in what ways they failed to do so [13].

One other pedagogical advantage of the integrated case study approach that is claimed by its advocates is its stress on the process of synthesis as opposed to the analysis that is often the major concern in more traditional, discipline-oriented approaches to learning [14]. Common sense would suggest that this is the case, but to guide students through the sophisticated process of synthesizing solutions to a problem is extremely demanding on faculty time and departmental resources. Not only do suitable problems have to be delineated (and the same problems cannot necessarily be used from one year to the next), but experience at the University of Waterloo has shown that the teacher often needs to be available to small groups of students seeking advice on a daily basis: demand on faculty time is not only great but unpredictable. Furthermore, not all university teachers are able to respond very well in this type of learning situation, which demands very different skills from the didactic approach normally taken in a lecture. One solution to this problem that has been used at the Open University is team teaching (both to prepare the course materials as well as to teach them) and the division of responsibilities amongst teachers according to particular skills in style of *teaching* as well as *topic*.

The reference above to the need for careful selection of problems is oversimplified. It is now well recognized that to be a successful engineer involves much more than solving problems within technological constraints. There may be financial, moral, social and political influences and restrictions on decision-making. Wright [10] noted that the rapid advance of technology means that the old "empirical" solutions to problems are no longer adequate. He felt, writing over a decade ago, that rigorous analytical procedures had perhaps been overdeveloped at the expense of skills involving synthesis as well as analysis. One consequence of this was the development of a separate and very successful Department of Systems Engineering at the University of Waterloo. Wright - the first Dean of Engineering at Waterloo - saw the task of the future engineer to be one of "managing and planning an industrialized society in which economic and social factors are no less significant than technical factors". Ironically, co-operative education at the University of Waterloo may make it somewhat harder for the motivated student to obtain exposure to classes outside the faculties of science and engineering because of the limited range of electives offered during the summer periods when he is frequently on campus for his academic work. It is encouraging, however, that the surveys of co-operative students show many are aware of the need for knowledge about the social, psychological and political aspects of technological decision-making. In fact what is probably needed is integrated courses for engineers on "Fracture and Society", for example, rather than an odd course in politics or sociology.

Just as the idea of university education has changed considerably in the last 30 years - due to changes in the subject matter, new challenges from the outside world, and a different range of student entrants - so the concept of the engineer/technologist is also changing [16]. For example, one compelling need in contemporary society is for an engineer who can communicate what he knows to those without technical training. Another is for the engineer/scientist of the future to be able to straddle disciplines - and nowhere is this brought home more clearly than in the case of fracture, which is not only a discipline but also a phenomenon that, to understand it, requires skills from a variety of traditional disciplines. It is already being recognized that the range of skills in such problem-solving has to go beyond traditional scientific fields and encompass information and insights derived from social science. Soon it will be necessary to go even further afield into questions of philosophy and aesthetics. Inclusion of such topics may cause the academic engineer to balk at curriculum planning but guidance exists in the literature e.g. [16,17].

But if pedagogical guidelines in this area have yet to be worked out, there is one educational axiom that remains true, and it is one that takes us back to the concept of transfer of training, mentioned repeatedly in the paragraphs above. This is that the knowledge and skills taught to university students will quite certainly change even more rapidly over the careers of the present generation of students than they did during the past three decades. This means that it will no longer be adequate for university educators to rely on subject matter expertise and traditional teaching methods that view students as passive receivers of transmitted information. Rather, students will need to be taught that most fundamental skill - the skill of learning how to learn [15].

The engineering educationalists who debated the issue at ICF4 have provided considerable data that may now be explored further to produce some integration which may lead to useful curricular changes. Some may see Professor Rice as a purist and traditionalist and Reid and his colleagues [4] as practical and radical. Yet these two approaches are certainly not as diametrically opposed as might appear at first sight.

The purpose of the present discussion has been simply to raise some questions, with the object of enhancing the quality of education in the area of fracture. However, in 1977 it can be fairly claimed that Fracture is a *discipline* in its own right in the sense, for example, that the relevant subject matter is "available knowledge organized in such a way that it is suitable for learning." As Whitfield [8] put it:

> "A discipline is thus the flexible conceptual structure, a community of concepts, which contains the raw knowledge and experience of particular fields of enquiry. Disciplines are concerned with particular domains of experience; they have a history and a heritage of literature; they have developed their own distinctive public criteria, conceptual frameworks and modes of investigation... They generate a communicating community of men who have been initiated into the domain of experience and they all embody some expression of the human imagination."

In 1977 *Fracture* surely fulfills this definition and requires a full reappraisal of its place in the core and elective engineering curricula of educational institutions, and in particular with regard to new integrated courses under the title *Fracture and Society*.

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APPENDIX - Questionnaire Sent to all ICF4 Delegates

Two panel discussions have been organized at ICF4 under the general heading *Fracture and Society*. The first of these is scheduled for Wednesday 22 June, 1977 and is designed to provide a basis for the development of clear educational objectives with respect to *Fracture* as an Engineering subject. It is expected that the discussion will be very lively and several speakers have been lined up. If you wish to contribute to discussion on this topic, please so indicate below. It would also be valuable if all participants would complete and return the remainder of this short questionnaire.

1. Do you wish to contribute to or participate in the discussion on Fracture Education and Society? Contribute Yes____ No____
   Participate Yes____ No____
2. Do you teach at a post-secondary institution (university, technical institute, etc.? If so please give the name of the institutions, and the highest level of qualifications offered (e.g. Ph.D.).______
3. Please give the name of the department or academic unit in which you work, and the highest qualification it is possible to obtain in your own department.______
4. Are graduate courses on Fracture or Failure Analysis specifically offered in your department or another department? Please give details.______
5. Is the subject of fracture an officially designated part of your undergraduate curriculum (e.g., do you have a course entitled fracture, or is fracture a specified part of another course)? If so, please give details______
6. Is the subject of fracture part of the core (i.e. mandatory) curriculum of the undergraduate engineering programme (if you have one)? Yes ____ No ____
   Please give details.______
7. Is the topic of fracture taught in your institution in any special or unusual way - e.g. by means of a "case study" approach, through the use of project work, etc.? If so, please give details.______
8. What place should courses on fracture have in undergraduate curricula for Engineers? ______
9. Please add any other comments on this topic - overleaf.

Return to Professor D.M.R. Taplin, Department of Mechanical Engineering, University of Waterloo, Waterloo, Ontario, Canada, N2L 3G1.