# HOW TO TEACH FRACTURE MECHANICS?

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*During the past 20 years the whole world of engineering has been subjected to fundamental changes with totally new developments and concepts in science, technology, industry, administration, business, marketing and education. This continuous sequence of changes has fundamentally revolutionised society where an ever-increasing pressure towards productivity and improved quality, engineering design for profit while keeping safety at a highest possible level pushes the engineer into a difficult position. The transformation of the world of engineering with a trend towards highly sophisticated structures and structural components which have become prone to unwanted damage and failure also has promoted research in fracture and fatigue to the stage where the practising engineer can immediately put fracture to work to meet the requirements of society and modern engineering. Optimal education and training in fracture mechancis and fatigue are the key for success and, therefore, should be a mandatory prerequisite for every engineer. This contribution deals with methods and techniques of teaching and learning in the field of fracture and fatigue and highlights some of the pertinent issues on education in fracture mechanics.*

## INTRODUCTION

Basic training and education in the discipline of fracture and fatigue (F&F) of materials and structures have become a major issue recently. While the importance of research in the field of fracture and fatigue is recogniced and the application of the results to practical problems is increasingly felt to be a crucial necessity in many fields of engineering, contemporary teaching and the dissemination of fracture mechanics ideas often prove to be insufficient and do not meet the goals required. Unlike teaching in classical fields such as mechanics or electrical engineering where abundant experience accumulated over decades has been converted into most effective textbooks and handbooks for the beginner as well as for the expert and practitioner, counterparts in fracture and fatigue are still missing except for a few noteworthy examples.

In calling for special sessions concerned with issues on education and training in the field of fracture and fatigue on the occasion of the ICF-6 in New Delhi ([1]) and ICF-7 in Houston ([2]) the importance of optimally conveying information on solving actual and academic problems in fracture and fatigue has been clearly

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expressed. In addition to plenary lectures and workshop paper presentations panel discussions have been organized for review and assessment of the *state of the art* in education in fracture and fatigue.

Efforts concerning previous round-table discussions based on the pioneering Burdekin Report ([3]) culminated in the proposition and publication of a set of guidelines which address *facilities* as well as course contents suggested for teaching fracture on the undergraduate and graduate levels at universities. Most attendees confirmed that education in fracture and fatigue was primarily accomplished at universities not in the form of separate courses offered but most often as part of classical courses on conventional strength of materials. In addition, fracture mechanics rarely seems to be applied to practical problems, part of the reasons being that practical problems in general appear to be too complex and application of fracture mechanics often is too difficult for the students([4]). Emphasis was put on the fact that in many countries particular importance is attached to studies of brittle fracture of structural components and structures such as weldments in pipelines carrying natural gas, agricultural machinery, bridge failure etc.

Assessing the image of fracture education at ICF-6, diverging opinions and viewpoints could be noticed with respect to this topic. The most obvious discrepancies concern:

- the two schools of thought in teaching of fracture – teaching by case study as opposed to classical development of the principles of fracture and,
- the fact that the views of all panelists on fracture were restricted and focussed on *fracture as an unwanted phenomenon*,

thus completely discarding and neglecting the possibly much wider field of *wanted fractures*, so important and useful in areas such as mining, metal working, etc.

The following contribution will focus on teaching of and education in fracture and fatigue on a wider scope of application and will highlight some of the pertinent features of teaching programmes.

## THE SUBJECT OF FRACTURE AND FATIGUE

Depending on who uses it the term *fracture mechanics* is associated with a variety of different viewpoints. Theoreticians, structural engineers and mechanical engineers will cultivate an attitude toward *fracture mechanics* that is different from that of metallurgists, material science engineers etc. and so will those who apply fracture mechanics to practical problems on a daily routine basis. A definition of *fracture mechanics* in the strict sense of the meaning of the compound encompassing only the mechanical aspects of fracture appears to be too narrow. It is agreed on that the technical term *fracture mechanics* does indeed include the mechanical, physical, metallurgical, numerical etc. aspects of the processes of fracture and fatigue. It is, however, important to realize that fracture mechanics has also become a popular term in boundary areas such as quality control, failure assessment for damage indemnification etc.

Scanning the literature on fracture research one easily gets the impression of fracture being synonymous with **prevention of an unwanted physical process.** Obviously, in normal life, fracture always implies something broken, something apart from the normal, malfunction etc. and very seldom is the word fracture associated with fragments and pieces in a positive manner. However, fracture prevention only constitutes one side of the coin with fracture enhancement representing the other side and fracture control forming the base. Fracture control is called for both, prevention of extensive fracturing and fatigue where aspects of life time and safety against failure are so important, as well as in blasting in tunnelling where unwanted damage to the surrounding rock mass should be avoided. These different viewpoints on fracture and the various attitudes towards fracture have a bearing on the particular selection of the teaching material and are ultimately reflected in the diversity of the curricula for teaching fracture and fatigue.

## TEACHING AND TRAINING

Teaching and training in the field of fracture and fatigue is an essential means for worldwide promotion of cooperations among material scientists and engineers. The general conclusion of an investigation in teaching of fracture and fatigue implies that present fracture teaching is very inadequate when compared to the recommended curriculum.

A traditional separate course on fracture or at least the way fracture most often is incorporated into existing courses is strongly influenced by the overall training and/or background of the teacher. Comparison of sets of course notes compiled and prepared for course teaching from several countries over the past 15 years basically reveals four approaches to fracture and fatigue:

- theoretical-analytical approach
- numerical approach
- materials science approach
- applied approach.

These four approaches follow different strategies for their own modelling of the real world (fracture, fatigue, etc.) by means of suitable models (theoretical-analytical, numerical, etc.) and finding explanations and solutions to practical and/or theoretical problems in the field of fracture.

Textbooks as well as proceedings reflect this tendency and one finds it sometimes difficult to bridge the gap between material science and mechanics. Apart from this classification a more rigorous division into academia and practice can be found. When concerned with applied fracture mechanics academic research and industrial research have different objectives ranging from the solution of purely hypothetical fracture problems (e.g. Yoffee-problem) to the consideration of fracture as a general purpose tool ready for uncritical application to practical problems of all sorts. The discrepancy will become even more apparent whenever theoretical solutions of idealized fracture problems, e.g. the semi-elliptical surface flaw (Figure 1a) offered by theoreticians find their way through handbooks to the workbench of practitioners who face the real world problem of clustered surface damage as shown in Figure 1b which may approximately be modelled as a semi-elliptical surface flaw.

Teaching and education for academia and industry not only requires a different attitude towards fracture and fatigue but also requires a different curriculum. University undergraduate and graduate courses on fracture and fatigue will be tought by methods different from those of industrial short courses which in general are custom-tailored courses fit to satisfy the specific needs of particular branches of industry or single companies. The individual characteristic features of university and industrial fracture courses will be discussed in the following sections.

## TEACHING PHILOSOPHIES AND METHODOLOGIES

Previous sessions and panel discussions on education and training in fracture and fatigue have revealed that in the industrialized nations university undergraduates receive about 20 hours of lectures of teaching and training on Linear Elastic Fracture Mechanics (LEFM) and Fatigue Crack Growth (FCG) including environmental and frequency effects whereas on the graduate level the total number of hours dedicated to fracture ranging from 6 to 25 will depend on the general course pattern and the particular research projects and topics. There seems to be general disagreement on the issue of whether or not the subject of fracture does merit a special course on the undergraduate level. Special courses comprising or exclusively devoted to Elasto-Plastic Fracture Mechanics (EPFM), composites, dynamic fracture and advanced testing etc. are commonly offered at universities and academic institutions only where there is a strong research attitude in these particular areas. It is also noted that fracture teaching branches off into different fields of engineering depending on the importance of fracture and fatigue in those areas. Education and training of fracture and fatigue on a broad university level in the developing countries rank from *just started* to *practically nonexistent.* Only very briefly will concepts of fracture and fracture prevention enter the undergraduate students curriculum or be discussed in greater detail and connex with applications. In many of the less developed countries the age of teaching fracture has only recently begun.

With respect to teaching fracture and fatigue at universities essentially two very different educational strategies have been adopted and followed. The pedagogical value of each method is difficult to assess towards favorisation of one of the two methods.

## A) Traditional sequential subject teaching and learning (TSS)

This approach follows along the lines of traditional subject teaching where the subject is being developed sequentially starting from the very basic issues in engineering important to fracture such as elasticity theory, dislocation mechanics, plasticity.

A recommended basic curriculum [1] for undergraduate teaching for students in engineering will comprise the following core topics:

**Fast Fracture:** modes of failure, material resistances, basic metallurgical aspects of fracture, fractography, temperature effects on toughness, materials selection with respect to failure prevention, basic fracture testing, etc.

**Fatigue Cracking:** basics of FCG, fracture surface topography, S-N curves, stress concentration, high cycle versus low cycle fatigue, welded joint fatigue behaviour, fatigue life assessment and improvement, cumulative damage, shear loads, fretting, wear, codes, etc.

**Basic Fracture Mechanics:** modes of fracture, Griffith theory, strain energy release rate, near field solutions, fundamental crack problems, fracture toughness, fracture criteria, small scale yielding, scaling and size effects, weld effects, residual stresses, basics of EPFM, crack opening displacement, J-contour integeral, ASME-rules, CEGB-R6 approach, practical fracture toughness testing, numerical fracture mechanics etc.

**Application of FM to Fatigue:** Paris law, integration of crack growth law, relation between S-N curves and crack propagation law, examples of crack growth curves, thresholds, overload effects, significance of weld defects, etc.

**Environmentally Assisted Crack Growth:** cracking due to combined effects, stress corrosion cracking, hydrogen embrittlement, creep behaviour, heat treatment, creep tests, etc.

Optional additional material for selected disciplines could encompass advanced analyses, investigation and modelling of

- fast fracture
- fatigue
- environmentally assisted crack growth
- stress analysis of cracked bodies and K-determination
- fracture mechanics of concrete and rock
- numerical fracture mechanics
- probabilistic fracture mechanics, etc.

Postgraduate teaching of fracture and fatigue will concentrate on more advanced aspects of the topics mentioned.

Whereas main emphasis in examinations in fracture courses will be put on the understanding of the basic physical and mechanical phenomena associated with a certain working skill with regard to application of the concepts, methods and techniques to practical problems of simple and intermediate level of complexity, the goal for post graduate fracture teaching is considered to be the students comprehensive ability in reflecting on the applicability and limits of fracture mechanics and fatigue and acquisition of a high level of skill in solving more advanced and challenging practical problems for the benefit of society and in order to meet the needs of industry.

This systematic way of teaching fracture not only has been very popular but is also assisted by the overwhelming majority of text books available. The advantage of systematically learning the subject by a recipe-type step-by-step method is balanced by an increasing loss of innovative cooperation and a certain obscurity of the applicability of the individual topics to practical problems on the part of the students.

## B) Teaching fracture by the case method

An alternative to classical teaching is given by teaching fracture by the case method. This mode of teaching and study has been adopted and further developed by the Faculty of Technology of the Open University in the United Kingdom as a means for *distance learning* for home study, usually part-time. The teaching philosophy addresses the students' interest in solving practical problems and by doing so a selection of well structured example case studies covering a broad range of engineering serves as the starting point for subject development. On the basis of individual case problems different sections of the field of fracture mechanics will be presented and discussed. Each case study is presented to the student as a problem for an engineer to solve where either a diagnosis of a failure that has occurred and a remedy is required or a structure or structural component needs to be designed within the framework of a fail-safe design methodology. In the course offered by the Open University each case study (part A of a course unit) is accompanied by a didactic text (part B) which includes the necessary background learning material. The Open University's version of teaching fracture and fatigue by the case study heavily draws on written texts and audiovisual elements, i.e. it is a multimedia course.

The case study approach to fracture is also employed at traditional universities with special emphasis on practical work such as identification and assessment of failure cases and associated study of the theoretical basis of fracture research. As a particular example of the fracture educational program of the Open University the unit on failure of an artificial hip joint is highlighted. The key failure mechanism to be discussed in this unit is wear and the artefact employed to illustrate the theory is an artificial hip joint. Contemporary modern designs based on titanium-polyethylene joint are contrasted with earlier designs and failures are discussed. Particular topics associated with the study of the problem, such as adhesive wear, abrasive wear, interface cracking, fatigue-initiated rupture, environmental effects and laboratory testing complete the course unit.

Feedback from students has revealed that they find the case study approach a particularly interesting one with the advantage of their being exposed to practical engineering problems and the application of scientific principles. A high degree of motivation is associated with this approach of learning and the question *why am I studying this?* loses sense. This is, however, balanced by the ever present danger of the teacher's detouring into dealing with incidental details of the case thus obscuring the general principles intended to be conveyed to the student. Teaching the case study approach aims at learning lessons from one particular case and subsequently apply them to other problems. It therefore can truly be classified as a technique which promotes development of skilled engineers which can readily put their knowledge to work.

The intrinsic differences between these two types of approach in teaching fracture are revealed in Figure 2a and 2b. The classical method of teaching follows a systematic flow pattern starting with the most basic material and building up for the investigation of more complex topics and problems. The case study approach in Figure 2b resembles more a coarse clustered pattern of individual problem studies.

### C) Combined approach

Contemporary educational programs at Austrian universities are structured as shown in Figure 2c. Undergraduate programs follow the traditional approach of sequential learning in the form of individual courses which most often concentrate on teaching of theoretical background lacking potential applicability to practical problems. Students training on the graduate level starts with so-called *Proseminars,* a form of small scale case study teaching which focusses on solving practical problems within a framework where requirements generally do not meet higher standards. They are meant as a preacademic exercise and training ground, where the effort is directed towards the acquisition of research skills on the part of the student rather than the academic output. *Seminars* could be classified as pure *case study learning* with a strong tendency towards mastering the theoretical knowledge for carrying out individual research and solving practical problems. This type of educational approach is represented by the pattern depicted in Figure 2c.

As regards education and training in fracture and fatigue the approach shown in Figure 2d is favored by the author. This approach combines the essential advantages of both, the sequential learning method and the case study method. Systematic development and transfer of basic theoretical knowledge is heavily interspersed with demonstrative practical applications the solution of which require knowledge and skills for combining different fields of learning. Requirements on the part of the teacher are higher in this method than otherwise. Several advantages characterize this method of teaching fracture mechancs. During the development of the basic material simple non-academic cases can be employed to illustrate the applicability and the way how to apply this new information effectively in particular situations. Continuous interest is guaranteed if this blend of theoretical course work and attaching practical problems is done to perfection. The pedagogical requirement to go from the special to the general is satisfied and although working on his own the student is permanently guided by the educator. There is however a disadvantage to this method: the teacher has to take much care over the presentation of the course and the teaching aids.

## WAYS TO TEACH AND TEACHING AIDS

Classical teaching of fracture and fatigue is conventional classroom teaching where simple use can be made of various teaching aids. This is contrasted by the tele-teaching method where the student's interaction with the teacher occurs in an impersonal way mostly via acoustic or visual media or printed matter. This lack of personal contact between student and teacher may not stimulate and motivate to the degree wanted. The tele-teaching method however makes it possible for those students to enroll in a fracture and fatigue learning program who would otherwise refrain from physically attending class for various reasons, such as long distance between work place and study place, handicapped persons, part time study etc. The Open University's educational and training program in fracture and fatigue has been highlighted and critically discussed in [1].

## Text books

In class room teaching almost all lecturers rely on some (one ore more) textbook(s) for the preparation of the course. Since none of the existing textbooks on fracture mechanics and fatigue satisfies the *general requirements* derived from practical needs of academia and industry a recommended basic curriculum has been developed (see previous sections). Almost all textbooks on fracture and fatigue to a higher or lower degree reflect the particular interest and the field of research of the teacher. Not only would the idea of publishing a textbook on fracture and fatigue suffer from the relatively low number of students who would buy such a special book, but also from totally non-scientific aspects and decisions on the part of the publishers such as marketability, profitableness, etc.

All this leads to a wide variety of books on fracture and fatigue for undergraduates and graduates with drastically differing objectives and goals. A survey on selected textbooks on fracture and fatigue has revealed the interesting pattern of characteristic features presented in Table I.

## Audio-visual teaching aid

The contents of a normal full semester graduate course on the concepts of fracture mechanics is also marketed in the form of a video tape. Renowned experts in the field of fracture present all the concepts and fundamentals as well as recent advances in fracture mechanics in a 10 hour video course intended for individual group study. The course comprises advanced fracture mechanics and presents an interesting approach to fracture which in the author's opinion can be fully appreciated by those who already had some training in fracture and fatigue. The one-way transfer of information paired with the complete loss of interaction with the teacher and impossibility of feedback, especially important to the student, are considerable drawbacks of an otherwise excellent, although fairly costly idea.

## Teaching kit

Over the years the author had the chance to study the course notes of a large number of teachers in fracture from several countries. Most of the course notes were custom-tailored notes which would serve the needs of the particular person, institution or country. What is really missing and what there could be a market for is a teaching kit for education and training in fracture mechanics and fatigue based on existing experience with audio-visual techniques and conventional teaching. Here, the recommended basic curriculum as designed by the ICF working group on education in fracture could serve as a starting point.

## Fracture mechanics and fatigue software

Over the years textbook authors have to a more or less remarkable extent and success increasingly attempted to accompany their textbooks on fracture and fatigue with educational software programs. The usefulness, instructiveness and demonstrative power of teaching software is beyond any doubts, however, care has to be taken in not obscuring fundamental physical relationships by more computational issues intriguing to the numerical analyst but irrelevant for an understanding of the basic physical, mechanical, metallurgical processes that take place during fracture and fatigue. Educational software can very effectively assist and facilitate teaching and comprehension of fracture and fatigue. Simple and clear-cut programs can easily be developed by the student as a part of the case study and there seems to be very little need of purchasing all-purpose fracture and fatigue software program packages which very often are cumbersome to work with and expensive in cost. It is remarkable that – to the author's knowledge – extremely few of the commercially available textbooks on fracture and fatigue are equipped with reasonable (or at all with) software programs.

## Workshop training and failure analysis

All teaching and learning in fracture and fatigue is dry as bones as long as the student is not taken to the actual failure site, workshop or laboratory, i.e. to the scene of action where a failure has occured or is being investigated and where he can lay actually hand on broken pieces. At the University of Technology of Vienna a course on failure analysis by *case study* is offered even to undergraduates where the student is thoroughly exposed to fracture and fatigue by means of a program comprising the entire field of failure treatment from failure identification, failure assessment, failure analysis and proposing remedies or methods for either failure prevention or failure control. This type of course, however, does require the formation of an educational pool, where several experts exhibiting excellent knowledge in their own field of research and teaching and demonstrating a strong inclination for the associated disciplines pool their pedagogical skills for the benefit of the student's education and training.

## TEACHING, INDUSTRY AND SOCIAL ACCEPTANCE

With the ever increasing trend towards optimisation and tighter budgets funding of educational programs becomes highly dependent on profit return. With the appearance of publications on the economic effects and costs of fracture in the US as well as in Europe ([5],[6],[7]), fracture research and teaching has entered the stage of national interest and has become a sensitive issue to industry. It is to be expected that the fracture cost problem will at least also interest the conscious tax payer. Industry supporting a multitude of research projects in fracture and fatigue will increasingly exert a controlling and directing influence on education and training in fracture. The rise of the importance and acknowledgement of environmental issues can already be felt in connection with fracture and fatigue. Fracture prevention associated with environmentally sensitive large scale technical structures (e.g. failure of oil and gas-carrying supertankers or pipelines, vibration-reduced blasting in quarrysites or civil engineering construction sites in close proximity to urban settlements) is now receiving full attention by decision making institutions, agencies and governmental bodies of legislature. A new form of economic and technological awareness has emerged with great promise of enhanced acceptability of the importance of education and training in the field of fracture and fatigue. Despite the fact that figures on student enrollment in courses on fracture and fatigue are still low in most countries the growing awareness for compulsory education in fracture is a most promising feature. In assessing *cost of fracture* against *cost of education and training* even the most confirmed and sturdiest capitalist and materialist would without any fuss put some life into the promotion of education on fracture and fatigue.

## CONCLUSIONS

This survey on *how to teach fracture?* presents different methodologies of teaching and training undergraduate and graduate students at universities in the subject of fracture and fatigue. In addition, teaching strategies for industrial short courses within the framework of postgraduate continuing education of practising engineers are presented. The treatment of subject is by no means exhaustive and only some of the major aspects of teaching fracture and fatigue have been addressed. It is found, that a general prepossession for and acceptance of the issues of fracture mechanics can be sensed and its further development and enhancement strongly depends on the capability of the teacher to turn his students' attention and long-time interest to the subject. Different teaching methodologies are fit for purpose and should thoroughly be exploited for the full benefit of society. In this brief essay on education and training of fracture and fatigue some of the most important features have been highlighted but many problems have not even be entouched upon. This situation calls for further intensive work on education and training in the field of fracture and fatigue in future.

**Table I:** Comparison of content of selected textbooks on fracture and fatigue

| [8] | [9] | [10] | [11] | [12] | [13] | [14] | [15] | [16] | [17] | [18] | [19] | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | * | | | * | | | | * | | | | History of Fr. Mech. |
| * | * | | * | * | * | | * | * | * | * | * | Fract. Mech. Appl. |
| * | * | | * | * | | | | | * | * | * | Origins of fracture |
| | | * | * | | | | * | | | | * | Solid Mechanics |
| * | * | * | * | * | * | * | * | * | * | * | * | LEFM |
| * | | * | | | | | | * | * | | * | Dyn. Fracture |
| * | * | * | | | * | * | | * | * | * | * | EPFM |
| | | * | | | | * | | | * | | * | Composites |
| | | | | | | | | | * | | * | Creep |
| * | * | * | * | * | * | * | * | * | * | * | * | Fatigue Crack Growth |
| | | | * | | * | | | | | * | * | Information |
| * | * | * | * | * | * | | | * | * | * | * | Testing |
| * | * | * | | * | * | | | | * | | | Applications |
| | | | | | | | | | | | | Probabilistic FM |
| | * | * | | * | * | * | | | * | * | | Notch analysis |
| * | * | | * | * | | | | | | | | Case studies |
| * | * | * | * | * | | | | * | * | | | SIF-Tables |
| * | * | * | * | * | * | | | | * | * | | Material-data |
| | * | | * | * | * | | | | | * | | Data interpretation |
| | | | | * | | | | | | * | | Statistics |
| * | * | | * | * | | | | | | * | | Fracture control |
| * | * | | * | * | * | * | | | * | * | | Flaw assessment |
| * | * | | * | * | * | * | | | | * | | Failure analysis |
| | * | | | * | | * | * | | * | * | | Exercises |
| | * | | | * | | * | * | | * | | | Worked out exercises |
| | | | | * | | | | | | | | Numerical programs |
| | | * | | | | | | | | | | Rock fracture |
| | | | | | | | | | | | | Concrete fracture |
| * | | * | | | | | | | * | | | Mode-II cracking |
| * | * | * | * | * | | | | * | * | | | Micromech. of fracture |
| * | | * | * | | | | | | * | | | Craze/polymer fracture |
| * | * | * | * | * | * | | | * | * | | | Metallurgical aspects |
| | | * | | | | | | | * | | | Compression fracture |
| * | * | * | * | * | * | | | | * | * | | Residual stress |
| | | * | | | | | | | * | | * | Interface cracking |
| * | * | * | * | * | * | * | | | * | * | * | Environm. A. Fr. |
| * | * | | | * | | | * | * | * | * | * | Design against fracture |
| | | | | | | * | | | | | | Numerical techniques |

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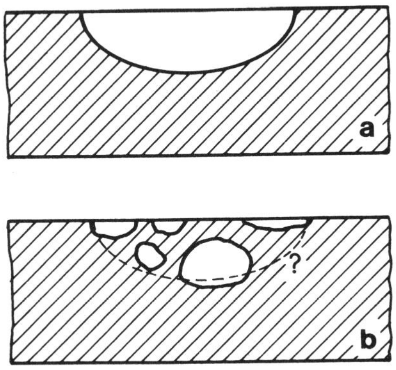


Figure 1: Comparison of idealized and real fracture
a) semi-elliptical surface flaw
b) clustered surface damage

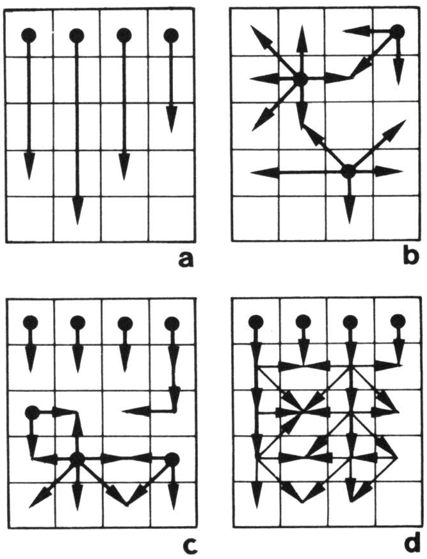


Figure 2: Types of approaches for teaching fracture