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Lessons from the Past for Engineering Students

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SUMMARY The educational objectives and some of the more recent experiences which final year mechanical and industrial engineering students at the University of Melbourne have gained from field work in the history of technology are discussed.

1 INTRODUCTION

Engineering is the application of scientific and other knowledge which requires both skill and experience for its successful accomplishment. It has long been recognized (e.g. Rankine, 1875; IEA, 1971) that the study of both the underlying scientific principles and their application is necessary in any course of professional engineering education. The need to include engineering applications material has usually been satisfied by introducing students to engineering design: commencing with the design of simple machine elements and progressing on to the design of engineering systems with an emphasis upon design rules, design methodologies and techniques for engineering problem solving (e.g. Lewis, 1977; Samuel, 1984; Milner, 1984.3). This supposes that students already have an adequate understanding of engineering hardware, that the transition from science to its application can be readily achieved and that what students experience in design courses is sufficiently representative of engineering practice. But there is now some evidence to suggest that what may have been a satisfactory arrangement is so no longer. Firstly, in the sciences attention is being more and more devoted to the inner representation of phenomena. There has been a shift in emphasis from the study of engineering systems to the corresponding processes; from engines, turbines and boilers to processes of heat and mass transfer; from fluid machinery to boundary layers and from rotating and other machinery to the various configurations of stress and flow. As the result students often display an erroneous, superficial, or overly-narrow understanding of engineering hardware (Milner, 1977). They have difficulty describing how things work (Samuel, 1984), they display neither confidence nor ability in applying theory to practice, they fail to grasp the technical possibilities of scientific principles and they cannot always be blamed for this. Furthermore, engineering problem solving tends to be a rather restricted conceptual exercise. It is restricted because problems are presented in isolation and devoid of information on the social, economic, political and even technical environment in which they would otherwise appear. This may have been stripped away in the interests of assessment, because such data are not readily available or, if included, would make the whole exercise more artificial than it presently is. At the same time practical limitations, time and material resources and perhaps nowhere more so than now (IEA, 1983), usually do not permit students to construct practical operating engineering systems, as distinct from mechanical toys, and to test them under realistic service conditions. So they do not perceive some of the difficulties associated with the construction, operation and maintenance of their designed systems in the real world.

In 1977, in response to the changes then perceived in the structure and content of its engineering courses, and to the difficulties being experienced by students (Milner, 1974; Milner/Pengilley, 1976), the Department of Mechanical and Industrial Engineering at the University of Melbourne began to offer a final year option subject in the history of technology for students in engineering and other faculties. This has entailed some 60 hours of formal contact divided more or less equally between lectures and field/assignment work. The rationale, style, content and scope of this subject has already been discussed elsewhere (Milner, 1982.2, 1983.1-3) as well as the methodology especially developed for field work (Milner, 1980.2, 1981.2, 1982.3, 1984.1). A major feature of the subject has been its field work; in which students have gone out and recorded significant industrial sites (Allen et al, 1983; Anderson et al, 1984.1-2; Brown et al, 1982.1-2; Chen et al, 1982; Clark et al, 1984; Dransfield et al, 1984; Fullinfaw/Stone, 1980; Jarrett et al, 1983; Wearne, 1982), have subsequently studied the history of particular types of machinery (Dalley, 1977; Dawson/Hinz, 1979; Grant/Mercer/Pretty, 1984; Kent, 1983; Morley, 1983; Saflekos, 1981) or of particular engineering firms/industrial organizations (Clark, 1984; Fitzpatrick, 1977; Hayes, 1978; Lench/O'Brien, 1981.1-2; Robinson, 1978; Sanders/Steel, 1981; Silverson, 1980; Weir/Thomson, 1981) and analyzed specific engineering artefacts/machine elements (Allen/Hannaford, 1983; Anderson/Burns, 1984; Dransfield, 1984; Houghton/James, 1983; Hunter, 1982; Jarrett/Kee, 1983; Kaleski, 1984; McFarlane, 1984; Morley/Wearne, 1983, Salden, 1982). This has resulted in the preparation of an increasing number of classification reports for the National Trust (Milner, 1982.4-7; 1983.5, 1984.5-6,8) and of several submissions to government calling for the preservation of significant elements of the State's engineering heritage (Milner, 1981.1, 1982.8, 1983.4,7, 1984.7; Milner/Pengilley, 1979). But whilst participation in conservation activities provides many students with a personal motivation for doing the subject, the cultivation of this response is by no means the most important educational objective to be achieved. These are, in rough order of importance:

1. to gain some perspective on the engineering pro-

fession,

2. to temper theory with practice,
3. to gain some familiarity with full-scale machinery,
4. to study realistic examples of engineering problem solving, and
5. to develop skills associated with the recording and analysis of engineering artefacts.

It is proposed to discuss here how some of these objectives have been achieved and the response of students to some of the related assignment work.

2 COMPARATIVE TECHNOLOGY

The design of even the simplest of machine elements, usually set as introductory exercises in engineering design courses, presents students with a number of decisions for which there can be no appeal to some scientific theory: the determination, for instance, of a factor of safety, or the selection of a suitable material and surface finish. Some of these considerations can be ignored in the first instance although this does not usually apply to factors of safety. In the Level 1 design course at the University of Melbourne students are provided with a rational but not entirely satisfactory means for calculating factors of safety (Lewis, 1977, 5-6):

$$F_d = F_0 l_1 l_2 l_3 s_1 s_2 s_3 s_4 s_5$$

where

F_d = factor of safety

F_0 = factor depending upon the consequence of failure

l_1 = factor depending upon uncertainty in the magnitude of the applied load

l_2 = factor depending upon uncertainty in the rate of application of the load

l_3 = factor depending upon uncertainty in the sharing of the load between members

s_1 = factor depending upon variations in material properties

s_2 = factor depending upon the introduction of defects during manufacturing

s_3 = factor depending upon the effects of the physical environment

s_4 = factor depending upon the effects of stress concentration

s_5 = factor depending upon the reliability of the mathematical model employed

Of these factors, s_4 and, to a certain extent depending upon circumstances, other factors can be given a quantitative value based on experiments, although it is usual to regard them as subjective for which these guidelines may apply:

1.4 (very serious) $\leq F_0 \leq 1.0$ (not serious)

1.6 (poor) $\leq l_1, l_3, s_1, s_2, s_3, s_5 \leq 1.1$ (very good)

1.2 (light shock) $\leq l_2 \leq 3.0$ (heavy shock)

Without taking the stress concentration factor into account this gives a possible range for F_d of:

$70.46 \leq F_d \leq 2.13$

so it is not surprising, even given the usual amount of collaboration evident in a design tutorial class that students will compute factors of safety varying for a given situation from 2.5 to 6.0. Whilst this is considerably less than what is possible, the disparity is sufficient, in a practical situation, to make one design quite uneconomic relative to another. The primary cause is undoubtedly uncertainty resulting from a lack of experience in judging the appropriate value of the factor to be employed. Students can be told what is a more acceptable final result and may even be shown how such a result is obtained. But this is a much less satisfactory way for students to learn than by finding out for themselves. This suggests, perhaps, that, as a preliminary exercise, students should analyze some already existing machine element and determine the factors of safety involved. But quite apart from the fact that this can so easily become yet another exercise on paper, so that students are unable to visualize the consequences of their design decisions and gain no sense of right proportions, there is a failure to recognize that many of these design parameters change with time. The situation is not a static, but a dynamic, one and just as it is important to know what is currently the right value an indication of the present trend is equally so.

What has become evident from the data collected during field work is that machinery designed and installed many years ago was often more generously proportioned than the modern counterparts. This may be due to any number of different reasons: greater perceived uncertainties in the design situation resulting in larger factors of safety, lower working stresses, more conservative design rules and different economic relativities in manufacturing processes. This suggests that students may gain a useful perspective on these and other aspects of the engineering profession if, having recorded some artefact in the field, they were to design some relatively simple part of it according to the rules for design relevant to the period of its construction, to design it according to current design rules and then to try and explain the differences both in the magnitudes of the various design variables, working stresses and factors of safety and in the two sets of design rules themselves. For a number of years now students have been given the opportunity to do an assignment of this kind and in that time analyses have been made of:

1. a turbine shaft extension installed in 1877 at the Barwon paper mill (Anderson/Burns, 1984),
2. a bevel gear pair installed at the same time and in the same mill (Kaleski, 1984),
3. a spur gear pair installed at a battery on Morning Star Creek between 1875 and 1880 (McFarlane, 1984),
4. an intermediate shaft on a stamp battery designed in 1888 (Dransfield, 1984), and
5. an unfired pressure vessel installed at a mine in 1907 (Jarrett/Kee, 1983).

McFarlane, for instance, discovered:

1. that factors of safety are now lower than they were a hundred years ago (2.3 versus 6.7),
2. that working stresses are now higher,
3. that there is now greater insistence upon surface finish,
4. that gear design has become more complicated: it now involves 15 more design variables, 11 more design equations and it has resulted in a tighter specification not only for the gear teeth but for the gear blank as well, and
5. that design rules for gears have been practically unchanged for considerable periods of time. But between about 1930 and 1940 there were rapid changes to allow for: design for wear as peripheral velocities increased, the effects of temperature on material properties, higher working stresses and the differing areas of contact between meshing teeth.

Students, generally, have been surprised by the lack of standards and codes of practice at the beginning of the period they have been investigating, by how long it has taken for matters which are now commonplace to be introduced, by how much had been left to the discretion of the individual designer, and by factors of safety based on ultimate strength; forgetting that a hundred years ago the most common constructional materials were cast iron and timber. As the result of this there has been a greater appreciation of the discretionary element in existing design rules and of where changes may be made in the future.

3 THE STATE AS A LABORATORY 1. THEORY AND PRACTICE

Familiarity with engineering systems, representative of what the student might expect to find in practice, is now a minor and almost incidental objective to be achieved by time spent in engineering laboratories. Increasingly, therefore, students enter the later years of their courses unable to identify the basic components of some of the engineering systems on which they may have earlier performed experiments (e.g. an internal combustion engine) and even less ready to describe, in appropriate scientific terminology, their operation. This also applies to even simpler engineering components with which they may have a greater, though usually superficial, familiarity (e.g. a tap or valve). Too much theory and not enough "science in practice" is damaging for both. For either theory will be learned in isolation and forgotten where it cannot be applied, or outworn rules and explanations will persist in practice because they are not subjected to proper scrutiny. So inefficiencies continue and opportunities for improvement are lost. Design, for instance, remains anchored in the sureties of the past and that, as students can now discover for themselves, results in waste on the one hand and failure on the other.

If the traditional components of an engineering course are unable to remedy this then some alternative bridge has to be established between theory and practice. In a developed economy this can be achieved by regarding what is outside the educational institution as a vast laboratory requiring little more than the cost of transport to bring it into use. Visits to operational engineering systems rarely give students the opportunity to gain anything other than a superficial understanding; whilst vacational employment often comes too late, is limited in scope and only rarely, and usually incidentally, satisfies educational objectives. An alternative is to examine engineering systems which are no longer operational on the understanding that whilst the form may have changed the underlying engineering principles will be the same. These systems may be components of our engineering heritage or they may become so as the result of attention directed to them. Usually these components/systems are simpler or less complicated in construction; they may be found stripped down to essentials or completely dismantled and therefore awaiting inspection. There are, for instance, any number of Cornish boilers around the State which it is possible to crawl inside to see how water circulation and heat transfer have been achieved, and to examine the problems of sludging and corrosion. A wide variety of engines: hot air engines, steam engines, and various kinds of internal combustion engines, all in various stages of disassembly, makes it possible to show how the several heat engine cycles are realized in practice, the types of ignition systems which have been developed, and the details of machine element construction: bearings, shafts, cams, keys and couplings, for instance. There are also Pelton wheels and water turbines, air compressors, fans, centrifugal and reciprocating pumps, heat exchangers, agricultural and electrical machinery, and various kinds of ingenious mechanisms such as toggles, quick-return mechanisms and double four bar chains as may be found on concentrating tables, all of which may become the subject of detailed study based upon field recording (e.g. Grant/Mercer/Pretty, 1984; Houghton/James, 1983; Kent, 1983; Salden, 1982). At the same time the opportunity can be taken to extend the range of machinery and machine elements normally considered within the course as, for example, in the analysis of a Pelton wheel driven single drum winch which incorporates some epicyclic gearing (Allen/Hannaford, 1983; Morley/Wearne, 1983).

4 THE STATE AS A LABORATORY 2. ENGINEERING PROBLEM SOLVING

Students often develop a very simplistic attitude to engineering problem solving chiefly because of the nature of the problems they are asked to solve and the environment in which they are required to do this. Overwhelmingly, these problems are to develop an understanding of the relevant scientific principles rather than their application in practical circumstances (Milner/Pengilley, 1972, A6/1). They are old problems with known solutions rather than novel problems; problems with tidy, closed-form solutions rather than open-ended ones with only approximate, multiple, or temporary solutions. They are well formulated problems that have been abstracted out of their original socio-economic circumstances (Milner, 1978; 1984.3) and therefore lacking the complexity and unexpectedness of real problems. Simplified problems are obviously essential to give students confidence for tackling more complicated, more demanding and, hopefully, more realistic problems later in their courses. This is assuming greater importance now that The Institution expects the inclusion of professional responsibility material related to the social effects of engineering decisions (IEA, 1971); for this requires a discussion of social, economic, political and other factors not only in the implementation of solutions to engineering problems but in their formulation as well.

The case study approach to engineering design has been employed for a number of years (e.g. Krick, 1969; Fuchs/Steidel, 1973), although the emphasis has usually been upon modern operational engineering systems where the elements/stages of the design process can be illustrated without the introduction of too much "extraneous" material. But there may be advantages in extending the time frame backwards to consider also historic/non-operational engineering systems. The myths that explain and maintain a currently operational system can be stripped away so that the system and the myths can be studied independently and more objectively. In several instances where systems have fallen into disuse, have been dismantled or demolished, so that there may be very few material remains, quite substantial records survive from which case studies may be constructed. For instance,

1. the log books for the Melbourne and Metropolitan Board of Works pumping station have survived even though the plant was decommissioned in 1965. These books, particularly the earliest ones, provide an almost minute by minute account of the troubled operation of the four Thompson pumping engines installed there in 1897 and withdrawn in two stages, in 1922 and 1937/8 respectively,
2. at the Barwon paper mill, where paper was made between 1878 and 1922, the buildings have survived although the machinery has long since been

scrapped. Yet over 40 architectural and engineering drawings have survived. One dates from 1876 and shows the general arrangement of the machine room as designed for the mill owners. There are over 100 old photographs, several of which were taken in 1880. There are also newspaper accounts, labour contracts, samples of paper, and illustrations of machinery which all make it possible to investigate the problems faced by the mill's first engineer, Andrew Millar (Milner, 1982.1), and

3. in 1895 the United Brothers Gold Mining Company erected a model quartz treatment plant at Sunnyside, Victoria. It operated in a disappointing fashion for a number of years before being sold and removed so that the site is now no more than a series of overgrown terraces cut in a hillside. For this installation mining records, correspondence, an engineering drawing of the battery buildings, newspaper accounts, photographs and illustrations have survived.

In this last case the analysis of these records throws an interesting light on the nature of compromise. Had the company installed the battery alongside the entrance to their main working level the distance over which the stone had to be hauled would have been very short. But here there was not enough water for the size of plant contemplated. Down in the main creek below the mine there was plenty of water but the stone would have had to be hauled over a very considerable distance. So they did what any engineer might have done when faced with conflicting requirements. They compromised; placing the battery half-way down the slope on the banks of a tributary of the main creek and getting the worst of both positions. For in summer when stone could easily be hauled along the tramway the battery ran short of water, whereas in winter, when there was plenty of water, the battery had to stop for lack of stone as the tramway was blocked by ice and snow. Consequently, the company only paid regular dividends when they shut the battery down completely and began cyaniding their extensive tailings dumps.

Compromise is so integral a part of engineering design (Lewis, 1977; Samuel, 1984) that students need to have this method of dealing with conflict critically examined. In this case, it seems that rather than seeking a compromise, the company would have been better rewarded had they reviewed the many decisions already made in connection with the potential ore reserves, the grade of stone and the proposed method of working the mine. In this they would have had the experience of several other companies with batteries in the area to guide them had they so chosen.

Not all historic engineering installations are likely to provide suitable case material, despite the wealth of documentary and other evidence that may exist about them. Nevertheless, because the essential nature of engineering problems has hardly changed, even though the form of their solution may have changed quite dramatically, the use of historical material in this way appears to offer students a way of understanding the social, economic and political setting within which all engineering problems must be solved; and certainly it appears to be a more cost-effective way than some recent case studies which have involved observation of the process of solving some particular engineering problem.

5 CONCLUSIONS AND RECOMMENDATIONS

The study of our engineering heritage in an analytical fashion can be an economical and effective way for engineering students to gain some perspective on their chosen profession, to see how scientific theory can be applied in practice, to gain some familiarity with the types of engineering systems they may later have to design and manage, and to study the cultural environment of engineering problem solving. The experience gained within the Department suggests that all engineering courses, but chiefly those in mechanical and probably civil engineering, would benefit from a proper study of suitably selected components of our engineering heritage, either as a separate subject or as a substantial component of another in one or other of the later years. For as is well known, those who ignore the lessons of history are prone to repeat its mistakes.

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