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FAMOUS FAILURES
and
STRUCTURAL SAFETY

Inaugural Lecture
delivered at the
University College of Swansea
on December 4, 1973

by

PROFESSOR J. D. DAVIES
M.Sc., Ph.D., D.Sc., C.Eng., F.I.C.E., F.I.Struct.E.
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FAMOUS FAILURES AND STRUCTURAL SAFETY

At first sight, the title of my lecture may appear to indicate a rather negative and pessimistic attitude to the work of the engineer. Let me assure you at once that this is not the case. First of all we must accept that failure is a part of life and I am sure that we are all aware of major failures not only in technological activity but also in the political, economic, social, medical and legal affairs of mankind. Provided we can benefit from our mistakes then a study of failures can lead to positive progress in all professional fields. In a sense, the standing of the Civil Engineer in society is particularly vulnerable because his mistakes are generally on open display and usually accompanied by a large degree of publicity. Therefore, part of my task tonight is to try and set the record straight from the engineer's point of view. To this end, part of the lecture will be devoted to some case studies of famous civil engineering failures to highlight the problems confronting the engineer.

Naturally, closely linked with the problem of failures is the concept of structural safety. The very name ' safety ' is an emotive one and therefore another part of my lecture will be devoted to an objective attempt to define and measure safety in a technical sense. Of course, the civil engineer is concerned with many diverse problems such as water supply, public health, traffic and transportation. However, I shall concentrate my attention on my own subject which is the study of engineering structures. If you bear in mind that the construction industry in the U.K. provides about 10% of the gross domestic product and produces about 50% of the country's fixed capital formation, I hope you will appreciate the importance of the subject matter of this lecture.

Before starting on the main topics, let me attempt to show how the work of the Civil Engineer differs from that of other engineering specialists. One of the first definitions of Civil Engineering was given by Thomas Tredgold who described it as the ' art of diverting the sources of power in nature for the use and convenience of man '. This description, made over a century ago, may be an accurate statement of the purpose of all engineering activity. However, with the rapid technological advance of the past fifty years the modern engineer is educated and trained to work in a more specific field. Broadly speaking, whereas the mechanical engineer may be concerned with production of a large number of identical products (for example the motor car), the electrical engineer with the design of devices for accurate measurement or the chemical engineer with the control of systematic processes, the civil engineer is usually confronted with what may be described as "one-off" type situations where every problem is unique and a solution has to be produced based on uncertain data.

Therefore, the civil engineer has to adopt a flexible attitude to produce a workable solution and make adequate allowances for subtle and ill-defined variations. For example, if an engineer is concerned with the production of one million cars of a particular type, he can indulge in a process of continuous development and improvement—and as we all know, things can still go wrong. On the other hand, a huge project such as the Severn Bridge must be right first time. When one is aware of all the complications in a vast constructional process the impressive aspect of civil engineering activity is not that we get an occasional failure but that we achieve such a large proportion of successes.

I am now going to commit an act of academic sacrilege by saying that there are relatively few "fundamentals" in civil engineering practice that have stood the test of time. Experience has shown that detail is just as important as principle in the real world of construction. It has been demonstrated in many ways that some of the original unshakeable basic precepts can develop, after harsh lessons, into no more than a set of myths. Thus, the successful engineer has to understand his own special kind of relativity theory so that he can operate from a variable datum and adjust his aims accordingly. Paradoxically, this situation poses both a frustrating prospect and a stimulating challenge. In brief, the modern civil engineer has to learn to compromise his scientific training to allow for the imponderable non-scientific aspects of his work.

Types of Failure

Before considering some famous failures, let us consider some simple categories of failure as shown in Table One.

Table 1 SIMPLE CATEGORIES OF FAILURE

- Frightening failures
- Frustrating failures
- Fantastic failures
- Funny failures
- Future failures

An example of a frightening failure resulting in high loss of life would be the Mara Bridge in Melbourne which collapsed during construction.

A frustrating failure is one leading to public inconvenience as the result of the loss of an amenity.

An example of a fantastic failure is provided by the Leaning Tower of Pisa which must be one of the most successful failures of all time as far as the Italian tourist industry is concerned.

Some failures are not without their touches of humour, such as the failure of a railway bridge and despite the collapse of the main span the carriage neatly spans the gap.

A future failure could be in the form of the Centre Point building in London. I describe this as a future failure because it may well cost more to pull it down than it did to put it up originally. This indicates that when engineers erect large structures in city centres they should give some thought in the design to the eventual demolition of the building.

Some Variables in the Design and Construction Processes of Structures

To set the background to the main topics I will refer briefly to some of the variables that the engineer has to consider in the design and construction of structures.

Table Two shows some of the variables from the design point of view.

Table 2 THE DESIGN PROCESS

- Primary function of structure
- Knowledge of loads
- Knowledge of materials
- Knowledge of workmanship
- Available analytical tools—theoretical analysis
  - numerical analysis
  - model analysis
  - empirical analysis
- Compliance with codes and specifications
- Cost and time of design
- Continuity of staff
- Quality of staff

Table Three shows some of the variables from the construction point of view.

Table 3 THE CONSTRUCTION PROGRESS

PLACE — climate, geo-physical conditions
MEN — availability, quality, amenities, Trade Unions
MATERIALS — availability, quality, consistency, testing facilities
PLANT — availability, maintenance
SUPERVISION — experience, judgement
COST CONTROL
SECURITY
COMMUNICATION
LIAISON

From the strictly technical point of view, Table 4 shows the steps to be taken in assessing the safety of a structure.

Table 4
SEVEN 'S' STEPS SATISFYING SYSTEMATIC STRUCTURAL SYNTHESIS

1. Site
2. Shape
3. Section
4. Strength
5. Stability
6. Stiffness
7. Servicability

These are interdependent upon the quality of :

DESIGN
MATERIALS
WORKAMNSHIP

FAMOUS FAILURES—SOME CASE STUDIES

I will now refer to some structural failures that have caught the headlines over the past 100 years because they demonstrate how certain disasters can contribute to our knowledge of the behaviour of engineering structures.

The Tay Bridge Disaster

The first Tay Railway Bridge crossing the Firth just south of Dundee was opened on the 1st June 1878. At that time it was the longest bridge of its type in the world and the engineer responsible for the design, Thomas Bouch, was knighted in recognition of his work. Eighteen months later, on the night of 28th December 1879, thirteen of the spans collapsed. Unfortunately the mail train was on the structure when the disaster occurred and 75 lives were lost when the locomotive and carriages plunged into the water.

Prior to the collapse, knowledge of the intensity and distribution of wind loads on bridge girders was meagre and a paper presented to a meeting of the Royal Society suggested design values ranging from 6 lb/ft^2 for high winds to 12 lb/ft^2 for a storm or tempest.

At the subsequent enquiry it was estimated that a wind pressure of 40 lb/ft^2 would have been necessary to initiate the collapse. These wide variations in loading data pinpointed the necessity of obtaining more reliable information on the effects of wind on exposed structures and for the Forth railway bridge a wind loading of 56 lb/ft^2 was specified. Also, a detailed examination of the cast iron support columns salvaged from the debris showed a number of flaws. Another ancillary cause of the disaster was attributed to inadequate provision for uplift forces at the bearing supports.

The Tacoma Narrows Bridge Disaster

The suspension bridge is one of the most elegant of man-made structures. The beauty of the profile seems to typify the best combination of graceful shape and structural efficiency. One of the really spectacular failures of comparatively modern structures was that of the bridge over the Tacoma Narrows near Seattle in the U.S.A.

A few months after the structure was opened to traffic in 1940 the deck started a series of severe oscillations in a cross-wind of 40 m.p.h. In less than an hour the superstructure had collapsed leaving only the main suspension cables between the piers on each side of the crossing.

A report on the disaster, published in 1941, suggested that the excessive vertical and torsional oscillations were made possible by the extraordinary degree of flexibility of the structure and its relatively small capacity to absorb dynamic forces. The authors of the report also recommended a series of experiments and analytical studies of suspension bridges. An intensive research programme was started and the model tests carried out were able to accurately reproduce the collapse behaviour of the full-scale prototype structure. These studies led to a deeper understanding of the aerodynamic response of civil engineering structures under wind loading.

Fortunately, extensive movie pictures were made at the time of the collapse and I would now like to show a small excerpt from one of these films which are now part of the invaluable archives of civil engineering history.

The Comet Aeroplanes Disasters

I would now like to refer to a different type of failure concerned with aeroplanes. Although they are not civil engineering structures, a study of the failure of aircraft structures is relevant because of the common techniques of analysis used by aeronautical and structural designers. A series of disasters that befell a number of the Comet jet aircraft in the 1950's led to a realisation of the need to examine the effects of repeated loads on the long term behaviour of structural components and the importance of the need for proper design of details.

The Comet aircraft was introduced for BOAC passenger services in May 1952 and was the forerunner of the giant jets now used on all international services. A year later,

in May 1953, the first disaster occurred when one of the fleet of Comets crashed in a storm near Calcutta. An inquiry instituted by the Indian Authorities concluded that the accident was caused by a failure of the airframe. The prevailing weather conditions were so severe that no immediate action was taken to modify the airframe design of the other aircraft in service at this time. In January 1954, in clear weather, another Comet crashed into the sea shortly after leaving Rome airport. BOAC then grounded all similar aircraft pending an examination of the aircraft salvaged from the Mediterranean. Some small modifications were introduced to the fleet in March 1954. In April 1954, yet another Comet crashed near Naples. There were no survivors from the three crashes and the Comet service was stopped.

As a result of the findings of the British inquiry into the disasters there was instigated one of the most intensive testing programmes in aviation history. After a full size test of the fuselage in a pressurised tank at the RAE, Farnborough, it was shown that failure had occurred due to fatigue in the stressed skin structure around the cabin following a large number of pressure variations. The design was changed and the aircraft now has an excellent safety record.

The Malpasset and Vajoint Dam Disasters

Returning to the subject of true civil engineering structures, I now want to describe two major catastrophes that occurred at dam sites, one in France and the other in Italy, where the toll in terms of loss of life was particularly horrific.

The first disaster befell the Malpasset Dam which was located across a gorge in the mountains north of the Mediterranean resort of Frejus on the French Riviera. The structure was curved in plan and constructed of mass concrete. Building work was completed in 1954 and the impounding area behind the dam was allowed to fill slowly. Extensive measurements were taken on the structure and the behaviour of the dam and its foundations appeared to be satisfactory. The failure occurred about 5 years after the completion of the main dam structure.

On the 2nd December 1959, after some exceptionally heavy rainfall, the level of the water in the reservoir reached a point about 6 ft. below the crest of the dam and at 6 p.m. that evening a discharge valve was opened to lower the water level. At 9 p.m. the site watchman heard successive crackings, a violent blast opened the doors and windows of his home, a brilliant flash appeared and the electricity supply was cut as the dam failed within a few seconds. The rapid discharge of the huge mass of water led to high loss of life and extensive damage to property in the zone below the dam site.

The French Ministry of Agriculture appointed a commission to investigate the causes of the disaster. Because a number of similar types of dam structure had been built in many parts of the world the findings of the commission were of relevance on an international scale. The detailed investigation was thorough and comprehensive, but of a purely technical character, and made no attempt to establish responsibility for the disaster.

Numerous theories were put forward in the press and by individuals and the Commission considered all relevant evidence. Listed amongst the possible causes leading to the disaster were (1) seismic phenomenon, such as earthquakes, (2) partial or complete sabotage, (3) meteorites and other causes. These causes were listed under external effects. Other possible causes were listed under the water control system and, of course, the condition of the construction itself.

The Report concluded that the design of the structure was correct and the quality of the materials and workmanship excellent. The most probable cause of the disaster was attributed to the presence of a slip plane in the adjacent ground leading to high deformability in the foundations. The Commission commented that the disaster was particular to the site conditions and should not diminish confidence in the safety of arch dams

supported on foundations capable of permanently carrying the loads transmitted by such structures.

A few years later another disaster, of comparable catastrophic proportions, occurred in northern Italy at the site of the Vajoint Dam. However, in this case, the holocaust was caused not by the failure of the structure or its foundations but by the discharge of a huge mass of water over the crest of the dam when the complete side of the valley upstream of the site fell into the impounding reservoir. This highlighted the need to consider the consequences of large construction works on the stability of natural valleys used to impound water for water supply, hydro-power or irrigation purposes.

The Ferrybridge Cooling Towers Disaster

Some of the largest one-piece concrete structures in the world are the shells of the cooling towers which are a common feature dominating the landscape around the inland power stations in this country. Although these structures are 400 ft. high with a maximum diameter of about 300 ft., and contain a concrete surface area of some 5 acres, their thickness is generally of the order of only 5 ins. Thus, their thickness to maximum dimension ratio of about 1 to 900 is considerably smaller than that of an egg for example. Arising from the massive building programme for new power stations during the 1960's, British contractors acquired a considerable experience of the construction of such structures.

A distinctive feature of this type of work is that contractors are required to provide competitive tenders for both the design as well as the construction of the towers. This contrasts with the more normal procedure whereby the design is undertaken by independent consulting engineers on behalf of the client and the contractor is responsible only for the construction of the works. Most modern power stations require eight towers to cope with the huge quantity of water that has to be cooled as part of the energy conversion cycle.

In November 1965, during a 75 m.p.h. wind, there was a spectacular collapse of some of the towers at the Ferrybridge coal-fixed power station in Yorkshire. At this time 6 of the towers had been substantially completed and three collapsed in virtually identical shape and form and extensive cracking developed in the other three towers. The three collapsed towers were on the leeward side of the power station.

The inevitable Committee of Inquiry was set up to try and establish the cause of the failures and to make recommendations for reconstruction of these particular structures and for the design and construction of similar towers. There was also considerable press publicity following these events and the traditional quality of British engineering was brought into question.

Some initial reactions to the cause of the collapse speculated that the grouping of the towers was a key factor due to the funnelling effects leading to increased effective wind pressure. However, counter-arguments were put forward to discount this effect because one of the group of four towers did not collapse. The Committee of Inquiry did not attempt to apportion blame for the failure but compiled all the facts and drew attention to the lessons to be learned. Buckling, vibration and foundation failures were eliminated as the prime causes. It was considered that the wind loads had been underestimated by 25% and that the duration of any gusting effects was of prime importance. For example, the forces due to wind over a 10 second gusting period could be substantially higher than the average effects over the 60 second period assumed in the design specification. Also, the philosophy of the method of designing the steel reinforcement to cope with the indeterminate effects of the wind loading was criticized. It was also considered inadvisable to place the responsibility for design and construction in one contract. All future towers were required to have a minimum thickness of 7 in. and a double layer of reinforcement.

It is sad to relate that another similar cooling tower, on an industrial site in the North of England, collapsed in a gale in September this year.

The Ronan Point Disaster

The disasters I have described so far have been related to the failure of some spectacular structures. It is pertinent to ask that if such elegant constructions can go wrong what are the chances of failure in more mundane structures such as the homes we live in. Fortunately, the term "safe as houses" still has relevance in this age of rapidly advancing technology. However, there occurred in 1968 a calamity which sapped the confidence of people in those modern city dwellings called high rise buildings. I refer of course to the disaster at the Ronan Point 22 storey block of flats in Canning Town, London, when a number of people were killed when an internal gas explosion on the 18th floor led to the collapse of all the flats on one corner of the building. This structure was one of many using prefabricated components in what was called an industrialized building project instead of the traditional method of constructing the parts in-situ.

The social as well as the technical and economic effects of the disaster ricocheted around the modern urban communities of the world. The design and checking of such structures is now strictly controlled and has led to significant changes in the building regulations of this country. Naturally, the psychological effects of structural failures of this type on the peace of mind of people living in tall buildings is a matter of national concern.

Apart from the tragedy of this particular disaster, thousands of families were put to considerable inconvenience because of the strengthening operations carried out on similar structures to Ronan Point. On the economic side, the GLC spent £3 million on checking alone and it was estimated that £30 million would have to be spent on remedial works for the homes of 25,000 families.

The more recent collapse of the roof of a school at Camden, fortunately empty at the time, has led to further public disquiet regarding the safety of structures occupied by people.

The Box Girder Bridge Disasters

I would now like to refer to a series of recent bridge disasters which have had wide repercussions on the convenience of motorway travellers and have led to a considerable increase in the costs of new, and many existing, bridges constructed on the steel box girder principle. Failures have occurred during the erection of four major bridges, one over the River Cleddau at Milford Haven, one at Melbourne, Australia, and two in continental Europe. The recommendations of a government appointed committee, under the chairmanship of Dr. Merrison, Vice-Chancellor of Bristol University, are now being implemented. All new box girder bridges will have to comply with the Merrison Rules and many existing bridges are being strengthened to conform to the new standards. Many motorists will have experienced the frustration with delays caused by partial traffic lane closures on bridges which have been in operation, apparently without any ill-effects, for many years. You may recall the strict control imposed on the use of the Severn Bridge complex during checking and strengthening operations.

One positive benefit arising from these disasters has been the encouraging move in international co-operation on matters of common interest. At a recent meeting in London to discuss the Merrison proposals some 500 delegates attended and 21 countries were represented.

The report of the enquiry into the Melbourne bridge collapse was, in true Australian fashion, refreshingly forthright in its conclusions and pin-pointed several non-technical factors that contributed to the disaster. These included industrial, organizational and communication difficulties between all the parties concerned with the project.

STRUCTURAL SAFETY

I now come to the second part of this lecture where I would like to discuss some trends in structural safety in terms of its definition and measurement. One of the leading international authorities in this field is a distinguished British engineer Sir Alfred Pugsley, FRS, formerly Professor of Civil Engineering at Bristol. He has combined his knowledge of aeronautical and structural engineering to formulate a unified approach to the study of failure that is being accepted by engineers on a world wide basis.

Most people think of safety in a purely relative or qualitative way and we frequently hear such expressions as very safe, acceptably safe, etc. Such descriptions are alien to the scientific training of engineers who are accustomed to applying specific numbers to describe the importance of particular variables in a problem. It would be helpful if safety could be defined in some numerate way but its precise appraisal is complicated by the subtle variation of the data to be considered in the technical sense and in the inherent variability of human beings as designers, builders and users of structures.

One of the most difficult decisions facing those authorities concerned with the specification of structural safety is related to the balance to be drawn between degrees of safety and the costs of structures. In general terms, the safer a structure has to be the more will be the expense of building it—an exception arises when there is the danger of a structure collapsing under its own weight. The engineer has the virtually impossible task of deciding what is acceptable to society as an adequate degree of safety at reasonable cost. It will be appreciated that ethical as well as technical and economic considerations may be involved in arriving at a firm decision.

Definition of Structural Safety

A simple dictionary definition of safety is "freedom from danger or risks". Unfortunately, the absolute safety of structures cannot be guaranteed to comply with this modest requirement. All we can hope to ensure is that the probability of failure is kept to an acceptably low figure. We then have to decide what is an acceptably low figure.

The traditional method of assessing the safety of a structure is to consider its behaviour under load and then try and measure the degree of safety in terms of factors of safety or load factors. Therefore, in simple terms, we consider the safety of a structure in terms of the loads it can support. The definition of a load factor is the ratio of some load required to cause some critical condition in the structure to the load that the structure would normally be required to sustain during its life, that is,

$$\text{Load Factor} = \frac{\text{Limiting Load}}{\text{Working Load}}$$

In other words, if the load factors for a structure exceed unity it is deemed to be safe and should perform satisfactorily the function for which it was designed to the satisfaction of the users. Note that I used the plural "load factors" for there may be more than one load factor to allow for different critical conditions such as strength, stability, vibration, etc. Thus, the problem is not to achieve perfect safety but to determine the degree of safety in terms of the variables influencing the behaviour of a structure.

In 1951 the Institution of Structural Engineers set up a Committee with the following terms of reference :

(*a*) to review structural safety problems, including modes of specifying margins of safety for design purposes,

(*b*) to prepare a report for discussion and publication.

This report was finished in 1955 and many of its proposals are now being incorporated, in various forms, into several international codes of practice concerned with the specification of structural safety. The long gap of almost 20 years between proposal and implementation is not exceptional : this inertia is largely due to the complex technical, communication and legal procedures to be followed before radical new ideas can be converted into the official legislation of the land.

The Report suggested three basic needs for any structure :

(1) that the structure shall retain, throughout its life, the characteristics for fulfilling its purpose, without abnormal maintenance cost ;

(2) that the structure shall retain throughout its life an appearance not disquieting to the user and general public, and shall neither have nor develop characteristics leading to concern as to its structural safety ;

(3) that the structure shall be so designed that adequate warning of danger is given by visible signs ; and that none of these signs shall be evident under design working loads.

One of the important items in this statement of basic objectives is the reference to the "life" of the structure and Pugsley has suggested some typical values as shown in Figure 5.

Figure 5 *"Life" of some Typical Structures*

Motor cars	100,000 miles or 10 years
Aeroplanes	30,000 flying hours or 10 years
Ships	40 years
Houses	100 "
Blocks of flats	100 "
Office blocks	50 "
Large factories	40 "
Warehouses	80 "
Road bridges	100 "
Railway bridges	80 "
Harbour works	200 "
Churches	500 "
Cathedrals	1000 "

How do these estimates compare with the life of some structures in the Swansea area ? One of the first reinforced concrete buildings erected in the country was the Spiller's Mill built early this century. This is now awaiting demolition. Many of you will remember the old Plaza cinema which was knocked down to make way for the new Top Rank Suite in the Kingsway. I have mentioned previously that it probably costs more to dismantle some old buildings than it cost to erect them in the first place—it must be something to do with the floating Pound !

Of course we have one or two anomalies on our own doorstep. We still have in active use on the campus the "temporary" buildings put up in the early thirties pending the provision of more permanent accommodation. Also, the estimated life for the motor car does not apply to student vehicles—looking at some of the exhibits in the car park you might think they are in competition with the cathedrals for longevity of purpose.

Measurement of structural safety

Let us now examine some of the methods used to establish the numerical values of load factors of safety. The committee of the Institution of Structural Engineers suggested the following approach in an attempt to determine the load factors against collapse of a structure.

The variables are considered under two groupings.

GROUP X *Factors influencing the probability of collapse*

(A) WORKMANSHIP : having regard to inspection, maintenance and materials

(B) LOADING : having regard to control of use

(C) ACCURACY OF ANALYSIS : having regard to type of structure

TABLE OF 'X' FACTORS

Ratings Very good (vg) Good (g)
Fair (f) Poor (p)

Characteristic		B=			
		vg	g	f	p
A=vg	C= vg	1.1	1.3	1.5	1.7
	g	1.2	1.4	1.7	1.9
	f	1.3	1.6	1.9	2.2
	p	1.4	1.7	21.	2.4
A=g	C= vg	1.3	1.5	1.8	2.0
	g	1.4	1.7	2.0	2.3
	f	1.6	1.9	2.3	2.6
	p	1.7	2.1	2.5	2.9
A=f	C= vg	1.5	1.8	2.1	2.4
	g	1.7	2.0	2.4	2.7
	f	1.9	2.3	2.7	3.1
	p	2.1	2.5	3.0	2.4
A=p	C= vg	1.7	2.1	2.4	2.7
	g	1.9	2.3	2.7	3.1
	f	2.2	2.6	3.1	3.5
	p	2.4	2.9	3.4	4.0

GROUP Y *Factors influencing the seriousness of the results of collapse*

(D) Danger to personnel

(E) Economic considerations

TABLE OF ‘Y’ FACTORS

Characteristic	D=		
	Not serious	Serious	Very serious
E= Not serious	1.0	1.2	1.4
E= Serious	1.1	1.3	1.5
E= Very serious	1.2	1.4	1.6

Final load factor $= X \times Y$

Thus, instead of specifying one global load factor for all categories of structure this approach attempts to make a realistic assessment of the various characteristics for a particular structure in determining an appropriate value for the load factor.

In general, the factor X is based on the technical assessment of the structure and the factor Y is based on social and economic considerations. I would like to single out one characteristic for special comment and that is the loading aspect, particularly the reference to the control of use of the structure. As an example, let us consider the loading assessment for this lecture theatre. It was probably designed for an assumed working load of about 50 lb/ft^2 to allow for the weight of the audience. Such a loading is perfectly reasonable when the building is used for a relatively mild lecture such as mine. However, suppose that the next public lecture were to be delivered by a pop star and the admission tickets were free. You can imagine that the floor loading could become a little excessive unless entry were controlled.

Also, referring back to the extremes suggested by the tables of X and Y factors it will be seen that these are very wide ranging from 1.1 if A, B and C are all ‘very good’ and D and E ‘not serious’ to 6.4 if A, B and C are all ‘poor’ and D and E ‘serious’. Because of this wide variation in the values of load factors, and the somewhat subjective interpretation of some of the characteristics, this particular method has not been completely adopted for current procedures in the design of structures.

However, many of the basic ideas have been incorporated into a new international code of practice which is founded on a new philosophy of design called the “limit state” approach. In essence, this new approach entails the determination of several load factors for a given structure in respect of certain critical limiting states such as strength, stability, stiffness and serviceability. In particular, great emphasis is placed on the statistical evidence of our knowledge of loads and materials. Using probability concepts, the new code defines characteristic loads and characteristic material properties to arrive at factors of safety that are based on hard and cumulative evidence that can be modified and up-dated as our knowledge of the complete structural system is increased. All we now need to complete the cycle is the definition of the characteristic engineer. Of course, engineers are just as fallible as the rest of mankind and structural failures will continue despite all our efforts. I do feel however, that we are now beginning to see a new awareness of the total problem and I feel confident that the safety record will improve in the future. Before I finish I would like to refer to two other topics that are of particular interest to university teachers of engineering.

The Computer

The past decade has seen a radical change in the analytical techniques used by the engineer : this is largely due to the wide availability of the digital computer. What role does the computer have to play in the context of structural safety ? Undoubtedly a most significant one. However, the use of this new and powerful design aid is not without its own particular potential sources of danger. Indeed, the very fact that it can relieve the engineer of much of the tedium involved with the old and cumbersome methods of computation demands a new degree of alertness and responsibility to ensure that gross errors do not arise. Because the computer now enables us to analyse the most complex situations with relative ease the sheer size of some computational problems means that, statistically, the chances must increase of some mistake in the preparation of input data or the interpretation of output data. There is the possibility that the engineer may lose his intuitive understanding of the basic behaviour of a structure because of his failure to cope with the mass of extra information provided by the computer. Fortunately, this saturation of numerical information can now be more clearly and succinctly presented in a geometric form on a plotting facility. In other words, the computer can be programmed to replace many hundreds of thousands of tables of numbers with a few drawings—the engineer's traditional and well established method of communication.

Another important aspect of the computer is that the engineer can now choose the degree of accuracy of his analysis. For example, for the design of a small bridge it may cost £1000 of computing time for an accuracy of ± 1% ; or £100 for an accuracy of ± 10%. Of course, someone in a hurry may opt for an accuracy of ± 100% on a 30 bob slide rule !

The Universities

These modern trends in the concept and specification of structural safety should, naturally, be included in the education of young potential engineers during their university training. Surprisingly, a study of the curricula offered by many departments of civil engineering shows that relatively little or no time is given to this important

subject except in an indirect way. This omission may be due to two factors :

(*a*) It may be considered advisable to delay a detailed study of structural safety until the young engineer has gained sufficient practical experience so that he can better appreciate the probabilistic and statistical aspects of loads and material properties.

(*b*) The subtle and partly nonscientific aspects of the safety of structures does not fit easily into an undergraduate scheme of study steeped in rigorous academic methods in which each problem is perfectly defined and for which there is a single unique solution.

However, now that the practising engineers are beginning to appreciate the logic and purpose of the new design philosophy, based on a realistic assessment of structural safety, there is a feed-back from the profession to the educational establishments and it is likely that within the next year or so the study of failures and structural safety will be part of the staple diet of the undergraduate's training.

On the research side, a pleasing aspect of working in the safety field is the awareness of the unity of purpose and common approach of research workers in an international context.

CONCLUSIONS

I mentioned at the beginning of this lecture that it was my purpose to discuss failure and safety of structures from the engineer's point of view. Of necessity, my treatment has been superficial but I hope I have given sufficient detail to provide you with an appreciation of the general difficulties to be faced in designing and building structures that will be adequately safe for a reasonable cost. Obviously, no engineer wants to be responsible for a structure that is inherently unsound nor, on the other hand, does he want to be excessively conservative by designing structures that are too strong for their particular purpose. It would be helpful if there existed some consultative procedure so that the engineer could be made aware of the views of the public at large on the correct balance to be drawn between levels of safety and cost. The burden of choosing appropriate load factors is a heavy one and in the final analysis we get the structures we deserve. There is no doubt that safety costs money and Society must decide the price it is prepared to pay. Generally speaking, the engineer is as competent as any other specialist when working in his own particular field : occasionally he may mis-interpret the requirements of his fellow men. At least his mistakes are on display and open to public scrutiny.

One final thought on the general prevailing attitude to problems and their solution. We have to get away from the old adage that it does not matter if the answer is wrong provided the method is right. In engineering, the answer should be right even if the method is wrong. If you consistently get method and answer right—fine. If you consistently get method and answer wrong there is only one safe job left—you become a professor !