The 1987 Hopkins Lecture

This Year

Dr A.R. Flint

Talks About

"Structural Reliability and the Community"

Dr A.R. Flint of Flint and Neill, Consulting Engineers of London. He has specialised in the field of design and supervision, appraisals and special investigations for bridge works, towers and masts, offshore structures and buildings.

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THE 1987 HOPKINS LECTURE

SCHOOL OF ENGINEERING, CANTERBURY UNIVERSITY, N.Z.

STRUCTURAL RELIABILITY, SAFETY AND THE COMMUNITY

by

A.R. Flint

1. Introduction

This lecture was instituted by the School of Engineering and I.P.E.N.Z. in recognition of the great contributions made by Professor Harry Hopkins to our profession and the University. Its purpose is to encourage discussion of engineering issues within the civil engineering profession and to encourage public understanding of such issues. The topic of matching structural reliability to the needs and behaviour of the community which I intend to discuss is one which deserves continuing debate and which I believe would have appealed to Professor Hopkins. It is a subject which needs to be addressed by the profession if we are to continue to make progress with economy in use of resources and yet with innovation. It is also one seldom rationally considered by society as a whole and fraught with misconceptions and woolly thinking.

At the onset we must be very clear what is understood by 'safety' and 'reliability'. To many safety is thought of as an absolute term - safe means to them the absence of risk of harm. It embraces one of George Washington's tenets of liberty -

freedom from fear. In the context of structures there is a common belief that complete safety can be provided. That this is seen to be so is the expression 'safe as houses!' Despite the experience of the normal hazards of every day life and of uncertainties in nature and in human performance there is the flattering misconception that engineers can, with enough care and diligence, create artefacts free from risk. This view has, until recent times, been held by many within the profession. As an undergraduate I was led to believe that it was feasible to accurately predict stresses which would occur in a structure and I can recall no mention in my tutoring of the nature and extent of uncertainties. Only a few years ago the then Chief Highways Engineer of the Department of Transport expressed his requirement that bridges in the U.K. must be absolutely safe - the counsel of perfection.

In fact there is nothing in creation which is certain except death and this applies to structural performance as well as anything else. Not only are structures made of materials having variable properties and are designed and built by humans and so subject to human error, but they are also subject to loadings of magnitudes and in combinations which cannot be surely predicted. Loading due to natural phenomena (such as wind, wave and earthquake) is often beyond man's control. No matter what margins of safety are adopted in design there is always some risk that a structure will collapse or become unserviceable at some time. Risk, the antithesis of safety, is a relative term. In the terminology of statistics it can be defined as the chance (or probability) of an adverse event occurring during prescribed sequences or intervals. It is the probability of failure to perform in the case of structures. The converse, structural reliability, is simply probability that they will perform.

Despite a common belief in the feasibility of absolute safety, there is perception by society of most of the risks which beset us. I understand that there has been some difficulty in New Zealand in convincing people of the potential risks of earthquake and of accepting the need for more stringent design criteria. Edgecumbe may have changed perception, however. Recent investigations, admirably summarised at a Royal Society Discussion meeting in 1980 on the assessment, and perception of risk have shown wide disparities between objective and subjective views of hazards. This is part of the dilemma we face in so-called rationalisation of safety factors for design and in the provision of the appropriate funds and resources for construction.

2. Why is structural reliability of increasing interest?

There are a number of factors which are bringing about radical changes in the engineering approach to safety and which justify debate within and outside the profession.

The earliest shelters used by man, such as caves, were naturally occurring. Primitive huts or other shelters were not durable nor capable of withstanding extreme conditions. As in nature, they were (and still are) regenerated frequently.

The evolution of masonry led by an empirical process of trial and error to the construction of massive and durable buildings. It was common for collapse to occur during construction. However once completed the large structures, such as domes and arches, were usually reliable except under exceptional conditions. Most reason for this is that their primary loading was self weight. Most uncertain components of loading, such as wind, were trivial by comparison. The stresses which they sustained were a small fraction of the strengths of the materials. Only in the case of earthquake was their weight of disadvantage.

The development of the domestic dwelling has also until recently been largely evolutionary. Structural arrangements and sizes have been usually dictated by considerations other than those of strength (such as the need to be weatherproof or fire resistant) for buildings a few storeys high and have been optimised by means of experience gained with large numbers of similar structures.

Hazards encountered such as pestilence, war or famine have gradually diminished. Fatalism and acceptance of Acts of God have become outmoded. Life expectancy has increased and self reliance has decreased. Society has tended to seek more protection by others against the risks of life, leading to legislation affecting engineering. All this has led to a decreasing acceptance of structural failure as a normal but minor risk.

In parallel with these trends in society has been a rapid growth in world population with consequent demands for more houses for more people for less cost and increasing drain on natural resources of power and materials. This has encouraged frugality in structural design for greater efficiency (the minimisation of materials and resources used in building). Development of the structural art and of building technology have provided the means of achieving this. Intrinsic reserves of strength, present in 'traditional' buildings, have diminished in new forms of construction. Design against the ultimate 'limit state' of collapse, instead of for working conditions with limitation of permissible stresses, tends to reduce reserves of strength. Self weight no longer predominates as structures have become relatively lighter. As a result uncertainties in 'live' load increasingly influence the risk of failure or of unserviceability.

Innovation frequently carries increased risk of failure due to unforeseen structural behaviour. We are building increasing numbers of structures which are 'one off' to serve specific social and industrial purposes. For these the engineer does not have the benefit of knowledge of past performance which is available from gradual evolution nor can he test prototypes to destruction.

We are also building structures for which weight limitation is of paramount importance. An aircraft for example either cannot fly or, if it does, can only carry inadequate payload unless it is light. Very long span bridges have become feasible only by tight control of weight. These constraints imply the use of stresses in the structural material of a far higher fraction of its strength than a century ago, with a consequent reduction in safety margins.

3. Factors influencing acceptable levels of risk

Social factors

It was Professor Hopkins who wrote in his book "A Span of Bridges":- "The whole of the history of civil engineering cannot be dissociated from the hopes and aspirations of the people..."

The levels of risk which society accepts or tolerates are influenced by many and complex factors including: 1. The degree to which the risk is imposed or voluntary

2. The nature of the consequences
3. Personal or social benefits for which the risk is suffered
4. Difficulties of controlling the risk .
5. Historical background of the risk

The risk of death per hour of exposure of a mountaineer is about 1000 times greater than that due to an accident at home and 1 million times greater than that of being killed by a structural failure.[1]

In a study undertaken for the Construction Industry Research and Information Association ten years ago, which I coordinated, a proposal was made for selecting target reliability levels for structural design related to various attitudes of the community. The starting point taken was the basic risk level, experienced and tolerated in the U.K., of death by accident (about 1 in 10,000 in any one year). Fatalities in the category of basic risk might be deemed to be inescapable and unaffected by aversion.

To allow for aversion to catastrophe, related to numbers killed at one time, the probability of failure needs to be in inverse proportion to the number of people who would be at risk in the event of failure.[2]

A, perhaps surprising, fact learned from analysis of failures is that a large proportion of them have occurred without loss of life as a result of discontinuous usage and good fortune. For example a large roof of unusual construction covering a sports stadium at Hartford, Connecticut, fell under snow and ice loading in 1978 without loss of life. The 1250 ft high television guyed tubular mast at Emley Moor vibrated to failure in 1969 in thick fog with heavily iced stays. It fell across an unoccupied chapel and all round the occupied transmitter building without causing injury.[3] It is therefore logical in estimating the number at risk to allow for the average within the duration of the risk. When there is full correlation between the level of risk and the number at risk, the number at risk should be taken as independent of diversity since the extreme loadings correspond to the maximum hazard. There was positive correlation when, in 1981, two suspended walkways above a dance hall in Kansas City collapsed under the weight of people, killing 113 and injuring a further 186.[4] When there is a negative correlation (as for extreme wind conditions on an exposed bridge on which it would be impractical to drive) the number at risk tends to zero and the acceptable failure probability would not be governed by risk of a fatality.

Numbers potentially at risk are also related to the warning of structural distress prior to collapse. The visibility and the characteristic behaviour of a structure are relevant. The roof of a school swimming pool at Stepney fell in 1974 as a result of conversion of its high alumina cement and started a major scare in the U.K. The spalling and cracking of the precast beams was noticed and the building was evacuated before collapse occurred.[5] A visible and ductile structure having alternative load paths should be designed to a lower factor of safety than a brittle concealed one. (The Kansas walkways had no capacity for redistribution of load and collapsed due to failure of the suspension bars without prior sign of distress)[6] There is also greater risk of loss of life if the build up of extreme loads is rapid (as in a store at the start of the annual sale) than when they increase gradually (as for snow or wind loading) or when, as at Edgecumbe, there is some advance warning. However gradual increase in load by itself is no safeguard. In December 1974 I was sitting in an aircraft on the apron at Teheran airport in heavy snow awaiting take off having just spent two hours in the departure hall when the roof of that hall collapsed.[7] Failure was attributed to poor connections in the roof trusses, the accretion of layers of roofing material over a period time (the airport authority having ignored the design criteria) and, as a final coup de grace, a foot of snow. I noticed no sign of distress, nor warning of impending disaster, nor apparently did others. Although more than 30 died, the number would have been far greater had flights not been cancelled due to the snow. There were normally at least five relatives or friends to every passenger arriving or departing and the hall would otherwise have been packed. (A further example of negative correlation)

Neither the ice on the stays of the Emley Moor mast, nor the severe vibrations were visible due to the fog and hence the local staff had no warning of danger. Failure resulted from weld fractures on a leg flange joint in which welds were concealed from inspection.[27]

The principle of selection of a target reliability for design related to potential numbers at risk has been followed in the drafting of two recent British Standards, BS.8100 for lattice towers and BS.5502 for agricultural buildings. Both give guidance on choice of safety factor to provide consistent safety to society. A transmission line tower in open country may be designed with a smaller factor than a television tower in a city centre. A hay barn can have a lower factor than a milking parlour. The same principle has been adopted in a rather general unquantified way in the New Zealand earthquake loading Code by relating design accelerations to the nature of a building and similarly in the Wind Loading Code. (11)

It has also been suggested that the target design reliability should relate to hazards associated with the activities undertaken in or on a structure. For example there could be lower safety margins when risk of death by structural failure is small compared to that due to other causes associated with usage (such as motoring on bridges or diving from offshore platforms) Conversely domestic or hospital structures should have low design risk commensurate with human need for sanctuary.

It is only by accepting this approach that many of the innovative and economical structures have been built. Failures during erection, particularly of large bridges have killed or injured many workmen. The collapse of an approach span of the Westgate bridge in Melbourne during its completion after lifting, for example, caused the loss of 35 lives. (12) However the rate of serious accident in the construction industry due to other causes (about 1 in 500 per annum in the U.K) is such that the risks related to structural collapse are very small by comparison. Control of such risks is improved by independent assessments of erection schemes and design of temporary works rather than by requiring increased safety margins.

The CIRIA report suggested that taking all these factors into account a rational total risk of failure during a design life of N_d years might be expressed by the simple relationship

$$P_{ft} = \frac{10^{-4}}{N_r} K_s N_d$$

where N_r is the average number at risk in the event of failure and K_s is a social criterion factor to to be taken as:

0.005	for places of public assembly, dams
0.05	for domestic, office or trade and industry buildings
0.5	for bridges
5	for towers, masts and offshore structures

This approach would aim for consistent annual probabilities of failure. It is contrary to the policy adopted in some design rules of reducing the design loading for structures to be used for only a short while, which implies increased risk in any year or day.

There may be other social consequences of structural failure. For example the collapse in 1975 of three spans of the Tasman bridge due to collision of a bulk ore carrier not only killed seven of the vessel's crew and the occupants of three cars, but also caused serious disruption to the lives of the population of the district of Clarence, which had expanded rapidly when the bridge was built. There was no other link to Hobart within 20 km. For a period of ten months, during which ferry links were re-established and a temporary bridge was built, the business and social life of 40,000 people was severely impaired. Such potential effects need to be considered both when planning new developments and when designing structures of vital importance to them. A socio-economic approach to choice of safety levels is probably the most appropriate in such instances.

Another consequence is loss of confidence by the community which can increase the political and economic burdens of engineering. After the collapse during erection of two spans of the Milford Haven bridge over the top of a road and some houses, I had my only experience of addressing a congregation from a pulpit in a Welsh chapel. (14) It was my task to allay fears that a strengthened reconstructed bridge would suffer a similar fate and avert local resistance to rebuilding. It was not easy to convince the majority that the work would in future be free from risk, particularly knowing that to be impossible.

The bridge was successfully completed, (15) in part due to the efforts of a young engineer who was working with us on the erection engineering, Dr. David Hopkins.

The economics of safety

I have so far discussed structural safety in relation to the emotive wants and demands of society. These are usually urged without the important ingredient of assessment of the desirable economic balance between the expenditure of materials and resources on control of a risk and that on other needs. Within limits structural reliability can be increased by spending more on design, on design checking, on quality assurance and quality control and on higher safety margins, on load control and on inspection and maintenance. The question "how much is the right amount to spend" has not been adequately debated in the field of Civil Engineering. It is a question which I know to be topical in earthquake engineering.

For such debate to be unfettered it needs to be clearly understood by the community, who will eventually pay the cost of safety, that in a society with limited resources excessive expenditure on construction to reduce risk of failure must imply a reduction in expenditure on other needs such as medical care and accident prevention. There is a pervading belief commonly promoted by some politicians that someone else will pay the costs of providing security - structural or otherwise. In the U.K, and I expect in New Zealand, many measures have been and are being implemented to improve the safety of structures without any prior cost benefit analysis. Most of such measures are beneficial, but not all. For example, there is evidence that quality assurance procedures frequently deflect inspectors away from the work front towards form filling to the detriment of quality control. Such analysis may justify either increase or decrease of expenditure compared to prejudged amounts for a project.

For structures the collapse of which would be unlikely to cause bodily harm the choice of safety margins can rationally reflect the economic optimum balance between first cost of construction and the consequential costs of failure multiplied by the statistical probability of failure. Reliability theory can be used to produce relationships between combined annual costs of construction plus failure costs and the target failure probability which, for a given type of structure to be built in a particular environment for a particular use, provides a basis for the choice. This approach has been used in the codified rules for the selection of design factors for lattice towers in BS.8100. The designer can adjust the factors on the basis of an estimate of the ratio between cost due to failure and initial cost and adopt the higher of a factor so chosen and a factor appropriate to the risk of loss of life. Although, as with all structural applications of reliability theory, such an approach may be criticized as reliant on inadequate data for statistical modelling and on assumptions as to the quantitative relations between safety factor and failure probability, it offers the best available basis for judgement.

The projected consequential costs of failure during construction, can inter alia, include allowances for delay in completion of the project and in the provision of the amenity and thereby the safety factors can reflect the importance of the structures to society. (17)

One important assumption required relates to the influence of safety factor on the risk of failure due to error, unforeseen events and other causes than the magnitude of a type of loading considered in design exceeding the resistance of the structure. Although evidence is sparse, it has been estimated that typically the risk due to blunders is an order of magnitude greater than that due to overload. In most cases in which collapse has been found to be due to blunder the incident would not have been avoided had the design safety factor been higher, although there have been opinions expressed that a reduction in such factors from present levels would increase error dominated failures. I prefer to consider the control of errors as best effected by means of quality assurance rather than by safety factors.

The question of the appropriate national expenditure on accident prevention has been considered in various fields. Present levels of expenditure per life saved vary widely. It has been suggested that a per capita sum of n_r million dollars might be appropriate in the U.S.A., where n_r is the number likely to be killed in one accident. It has similarly been proposed that preventative expenditure on nuclear reactors should be related to the number at risk in the event of accidental release of fission products. Typically the target probability levels for reactors are of the order of 1% of those justifiable on the grounds of economic consequences including compensation. The increase in security and associated cost is justified on the grounds of aversion by the community and of the possible economic repercussions following a serious incident. The same disparity between optimum reliability on economic and social grounds exists for most inhabited structures.

The approach to choice of safety factors using economic optimisation may be adopted to allow for aversion provided that the amount which society is prepared to spend to prevent loss of life due to a collapse is formulated. Consumer preference methods have been used, for example in assessing the worth of highway improvements. However they lead to sums considerably less than those expended by the community out of public funds on like for like accident prevention. The majority of the populace are unaware of this disparity.

Curiously the apparent subjective and collective choice by the community to demand greater expenditure on prevention of death by accident than can be economically justified is not reflected in public accounting related to design and construction. It has been the practice for years to select contractors on the basis of the lowest tenders and similar practice with regard to appointment of designers and supervisors is becoming commonplace worldwide. It was an astronaut who stated after the recent space shuttle disaster that his main worry prior to blast-off was that he was sitting among the results of thousands of lowest tenders! This approach is extraordinarily illogical for a variety of reasons related to safety. Quality assurance in both design and construction is expensive and one of the first targets for pruning in competitive bidding. On average the cost of doing the work properly will be more than the lowest tender and it follows that both designers and contractors must be constantly trying to minimise their input to the detriment of standards. As a result greater surveillance by independent checking of designs or by inspection of construction, becomes essential if reliability is to be maintained. It is not normal practice to choose a doctor or surgeon on the basis of their lowest fixed price tenders or the time for their task, nor to provide a team of supervisors to oversee a surgeon undertaking an operation. Both doctor and surgeon are expected to do what is necessary for your health or safety and are recompensed for the time and resources deployed in doing it. It can only be concluded that since the risk of death due to structural collapse is currently two orders of magnitude less than the risk of death due to 'natural' causes society is prepared to accept cut price building.

What is often not appreciated is that the same levels of reliability (if not greater) can be achieved at less cost by reducing safety factors and improving the quality of design and construction. For example the annual probability of failure of a typical structure due to the loading exceeding its strength in a condition for which it was designed is of the order of 10^{-6} per annum with current U.K. safety factors. A reduction in the global margin of safety of 10% is calculated to increase that risk by 10 times to about 10^{-5} . The risk of collapse due to error or unforeseen hazards has been estimated to be of the order of 10 times that due to safety factors being inadequate for design conditions. It follows that improvement in error control and reduction in design safety margins is likely to be cost beneficial. A 10% reduction in safety factors could be expected to reduce costs of structures by about 3%. Costs of independent design checks are of the order of 1% and of supervision of construction about 2% of structural cost.

Economic pressure for rapid construction in times of high interest rates to achieve the earliest return on an investment is also hazardous and needs to be resisted for safety.

4. The influences of human demands and behaviour

The security of structures in service can be radically affected by change in their pattern of use unforeseeable at the design stage. A classic recent example of this has been the rapid growth in potential extreme loading due to vehicular traffic in the UK in the past decade. The advent of the container lorry of all up weight 35 (and now 38) tonnes with a weight/unit length much greater than previously followed pressure from road hauliers and, later, a broader group of society - the European Economic Community. It has led to radical growth in the loading intensity from a long traffic jam as the percentage of heavy articulated lorries in goods traffic has increased. As is so often the case, action by the community preceded engineering and this led to the introduction of traffic controls on Severn bridge. The potential loading is linked to human behaviour, the propensity to overload vehicles and to drive close up to the vehicle ahead in a jam.

The growth of number of goods vehicles (or the number of axles) has also increased the rate of fatigue damage to both bridge decks and road surfacings, leading to increased need of inspection and maintenance and hindrance to the road users who cause the damage. Recent experience on the Auckland Harbour bridge, which is similar to that on Severn bridge, has followed a pattern expected to be followed for other bridges designed before the upsurge in goods traffic. 'No highway', the title of Neville Schute's book which made the public aware of the phenomenon of metal fatigue, could not have better expressed its consequences!

In the bridge field there are other man made influences. Citizens band radio has facilitated the habit of commercial drivers to meet at a roadside cafe and to thereafter travel in convoy, increasing the risk of a train of heavily loaded vehicles without dilution by cars. The U.K. miners strike in 1984 led to the emergency road haulage of coal to serve power stations previously supplied by rail and the sudden appearance of heavy convoys on routes previously lightly trafficked.

At least two bridges to my knowledge were loaded in excess of their design live load on the day on which they were opened. The opening of the Bosporus bridge providing the first link north to south at Istanbul generated such public fervour that once the official ceremony had taken place crowds from both ends surged through the police cordons and converged on mid span, tightly packed in the footways and carriageways and creating loading greater than the full vehicular design load.[20,21] A similar situation occurred more recently at the opening of the Jindo cable stayed bridge in South Korea. Although there were a number of injuries in the course of these events there was fortunately no structural failure. Luckily there was no wind. However these are examples of occurrences of human behaviour not catered for in conventional design rules and in which the risk of failure was correlated with the number of lives at risk.

Such events lead to the conclusion that the profession needs to be cautious in relying solely on statistical diversity when considering design loading combinations. Crowd loading at an opening does not form part of the statistical population of loadings to be expected on a bridge in service. The rare or freak unexpected event has often been a prime cause of collapse such as that of the bridge at Tangiwai which was washed away by flood in 1953 after the sudden release from the Crater Lake on Mount Ruapehu through an outlet cave with the loss of 150 lives of passengers in a passing train.

Innovation or building to a scale or in any environment of which there is no previous experience can lead to encounters with unexpected phenomena. The engineer is frequently required to design beyond the bounds of knowledge to meet the changing requirements of the community. Offshore fixed or tethered structures are designed for increasingly deep and hostile waters. Bridges span further. Buildings grow taller.

The classic example of the effect of these factors was the collapse in 1968 of part of the high rise block of flats known as Ronan Point in east London. To assist slum clearance the london Borough councils changed their policy regarding population density in the mid 1950's. In the early 1960's shortage of skilled labour encouraged development of industrialised 'system' building and these two factors led to the construction of residential blocks unusually tall for that time and prefabricated. A gas explosion occurred on the 18th floor of one of them soon after it had been inhabited, leading to progressive collapse of one corner of the building and four deaths. The failure resulted from the lack of robustness of the new form of structure to resist or survive local accidental damage. Neither the U.K Building Regulations nor the Codes of Practice to which they referred addressed the matter of design against progressive collapse. Owing to changing practices aimed at serving the needs of the community a new and unexpected design criterion became apparent.

The repercussions of the incident were extensive and expensive. (the aftermath cost more than £80 million) The large stock of system built dwellings existing at the time of the collapse were appraised and most of them were strengthened to withstand the effects of a nominal internal pressure due to explosion. Many families were displaced while the work was undertaken and public confidence was severely diminished.

My firm designed the strengthening for one group of buildings which no sooner was installed and the building reoccupied than the high alumina cement concrete scare broke and the buildings were again evacuated having floors containing that material. The Council responsible for the flats was unable to encourage most tenants to return after they had been proclaimed safe and the buildings were demolished. Since then the sister buildings to Ronan Point and many others like them have also been replaced by low rise housing in which inhabitants feel secure. It so happened that this reaction to a structural incident coincided with a rebellion against the post war architectural idealism of developing skywards. The Ronan Point affair has encouraged a reversion to a more human approach to housing.

On the recommendations of the Ronan Point Tribunal of Inquiry, the U.K. Building Regulations were rapidly amended to include a requirement that designs should either cater for a prescribed internal pressure, or provide for alternative load paths in the event of failure of a member. This approach has been found to be inflexible and inappropriate for many classes of building and is now under review. However the affair has led to a greater awareness by engineers of the influence of redundancy and robustness on the reliability of structures.

Other influences of the community on structural engінering issues

Politics

In his excellent analysis of influences on structural safety, Sir Alfred Pugsley referred to the climatology of safety of which political climate was one of the influences. He discussed the risks which can result from pressure by politicans on engineers to complete a project to meet a political deadline and cited the infamous example of the airship R101.

The airship crashed on her maiden flight in 1930 following undue government pressure for hurried completion to enable the Air Minister to travel in her to the Imperial Conference in Delhi. Added to the technical difficulties of the project and rivalry with the R100, the resulting atmosphere led to disaster.

The design and construction of the first St. Lawrence river bridge, Quebec, were beset by both political and financial constraints. Design and build tenders were received in 1900 following which there was a delay of three years until the government intimated that it desired the bridge to be ready for the Tercentenary in 1908, leading to a hurried programme and collapse during construction in 1907 with the loss of 85 men. (25, 26)

Such political interference in the processes of designing and building is commonplace. I have encountered it in a number of major projects in recent years and been aware of the dangers which it creates.

The law

It has long been recognised in law that some risk is unavoidable and so not blameworthy. According to Lord Reith, "In the crowded conditions of modern life, even the most careful person cannot avoid creating some risks and accepting others. What a man must not do, and what a careful man tries not to do, is to create a risk which is substantial."

In the majority of instances in which the required level of reliability is not laid down by statute, the restraints imposed by law are determined by all the factors in a given situation. The standards required of engineering design and construction are those which a 'reasonable engineer' would adopt. The duty of an engineer to the public is not to guarantee safety, but to take reasonable care to avoid undue risk to them. He is required to balance the risk, with consideration of the numbers affected and the seriousness of its consequences, against the cost of controlling it.

Unfortunately at present there are no generally recognised rules for achieving this balance and recourse is made to relying on past practices which have proved satisfactory. Adherence to codes of practice normally safeguards their users from liability but may frustrate the commonsense of the law by undue use of resources to avoid risk.

There is evidence of increasingly onerous expectations by the community expressed in law, of the extent of care by engineers. In recent times it has been deemed their responsibility in certain cases to inform past clients of changes in knowledge which may affect the safety of structures designed earlier. The high alumina cement scare, mentioned earlier, led to a requirement of designers to review their previous use of such materials and inform owners when their buildings contained them. There has been a recent case in which designers of a tunnel were held to be liable in Tort for not informing a client of potential risk of ingress of methane even though it was accepted that there were no reasons for anticipating such an event at the time of the design. It was held that subsequent knowledge should have made the designers aware of a risk and that they should then have taken action.

There have been recent trends towards increased litigation over structural matters which suggest that the community expects engineers to carry the liability for almost any mishap. It is now common practice in the U.K to join all the parties engaged in design and construction in an action for damages irrespective of the likelihood of their individual liability. As a result the costs of litigation have escalated to an extent that they are frequently of the same order as the damages suffered. Significant engineering resources are diverted to the processes of the law. The costs of insurance, both professional and contractors, have soared. It is now unusual for any defendants to emerge from a case concerning a structural failure without some attached blame, although there is no evidence that engineers are becoming lax.

Paradoxically litigation has the effect of stultifying the dissimination of experience within the profession and thereby maintaining certain risk. Engineers are unwilling to publicise problems met in projects for fear of encouraging claims and are unable to discuss them if they are sub-judice. The U.S. Congressional Inquiry which followed the Kansas City hotel walkway collapse suggested that any major accident should be investigated and fully reported by a technically qualified body, quite independently of any law suits and without aiming to allocate blame.

The demand for increasing legal protection has also led to unreasonable modifications to the law on limitation. In the past liability lasted in Tort for six years from the time of an act which led to a damaging event. Now a three year period also runs from the time when a harmful defect is observed or could have been observed within an overall limit of fifteen years. The change considerably increases the burden of liability placed by society on designers and builders and results in increased insurance premiums, the cost of which must ultimately be passed on to the community.

The media

Perception of structural risk by the populace and opinion as to culpability for failures are considerably influenced by the press and broadcasting. Because of the overwhelming preponderance of bad news disseminated there is generated a misconception that there is a relatively great incidence of structural mishaps. The impression is usually given that failures could and should have been avoided. Due to the pressure to publish 'hot' news, precipitate and ill-informed diagnosis of causes of collapse is commonplace. Experience shows that there is usually need for prolonged investigation before such causes are established. Since prudent engineers will not express premature opinions, instant commentary on failures is often conjectural and misleading. I have generally found reporting on engineering events to be factually incorrect, even in engineering magazines. Emotive treatment of failures by the media, as in politics, encourages hasty actions, usually to shut the door after the horse has bolted, without cost benefit analysis.

There are, however, signs of an awakening of awareness by the media of the need to view failures in perspective. For example one recent BBC documentary attempted to explain the uncertainties with which structural engineers have to contend and the economic equations which they have to solve.

Protection against consequences of extreme events

One approach to providing an acceptable high level of security to people while achieving economic optimisation in a design is to arrange for evacuation of the occupants of a structure when extreme events occur or are predicted. It is for example usual to provide means of escape in the event of fire in a building and to limit the amount of fire protection of the structure to that needed to ensure that it will not collapse before being completely evacuated. Oil platforms in the hurricane infested Gulf of Mexico are not designed to withstand the most severe conditions imaginable but are evacuated when extreme storms are predicted by weather forecasts.

A similar approach was adopted to safeguard the staff operating the television broadcasting station at Winter Hill in Lancashire. Following the collapse of the mast at Emley Moor there was concern that the sister mast at Winter Hill might suffer a similar fate. The staff at Winter Hill were considered to be at risk in adverse weather conditions. Instruments were therefore installed on the mast to record dynamic strains, deformation from verticality and wind speeds. They were linked to a system of alarms which were triggered when safe levels of the chosen parameters were exceeded, enabling the station to be evacuated while the adverse conditions prevailed. The mast was subsequently strengthened and vibration dampers were installed to provide a normal level of reliability.

In these examples society is protected against circumstances beyond its control In other instances security has been provided against man made risks. The Severn crossing is at present subject to controls aimed to avoid the risk of overloading of critical parts by traffic jams of excessive weight. In the early morning when heavy goods vehicles up to 60% of the traffic flows the bridge is operated with one lane only open in each direction. A bridge watch patrol operates during the day to give early warning of the formation of a jam or of an incident which could cause one. They communicate by radio with the westbound toll booth and the westbound carriageway is closed whenever there is an incident in either carriageway. By these means the structure and the public are being protected until the bridges have been strengthened to cater for the curent design loading.

Experience with motorists has shown that voluntary control by means of signs and signals is not effective. Despite warnings drivers will always endeavour to proceed until physically stopped. The optimism of the human has caused the collapse of numerous cranes which, although fitted with overload alarms, have been operated, with the bell ringing, beyond their safe working limits. I am told that there have been many of such collapses in the past two years in New Zealand causing concerng at the levels of training and supervision. Safe load limit notices on the Hammersmith chain suspension bridge over the Thames failed to prevent the transit of an excess weight vehicle one night last year which caused one of the tower saddles to move sufficiently for its rollers to pass beyond the end of the bearing and the deck to drop 6 inches, fortunately without catastrophic results.

Many other structures are designed to operate safely only within certain operational limits. For example aircraft frames are designed for forces constrained by limits to payload and accelerations in flight under the control of pilots. Furthermore their reliability commonly depends on regular inspection for fatigue damage and repair at safe intervals. Similarly mobile offshore platforms are subject to regular weight audits, operational limits to drilling in heavy seas and to inspection routines. The loss of the semi-submersible accommodation rig, the Alexander Keilland, in 1980 resulted at least in part from its operation for most of its short life in the most adverse orientation in relation to the prevailing wind, and from failure to carry out inspections at sufficiently frequent intervals. Fatigue failure of a bracing member caused one leg of the rig to fail, and the platform tipped into the sea. Although designed to remain afloat in such conditions, it capsized owing to watertight doors being left open. There had been no safety drill for the crew before the event and as a result 123 out of the crew of 212 perished. A sad saga of human follies.

The lesson to be learnt from such events is that, despite improvements in education, society is not to be trusted to behave sensibly at all times. It perceives the safety of structures as absolute or, when accepting there to be a risk, assumes that it "does not apply to me."

The future

The consumption of natural resources in civil engineering has grown to an extent such that it is rapidly depleting reserves in many parts of the world. In the structural field the material content is directly related to design safety factors. Reduction in margins of safety would be of benefit in saving the rare minerals used in steelmaking and the fuels used in manufacturing steel, cement and bricks, in excavating rock, crushing aggregates and transporting materials. It would contribute to limitation of atmospheric pollution and of the volume of road traffic and to protection of the environment.

It should be feasible in many instances to significantly reduce material content even without accepting higher risk of failure or unserviceability. The growth of population with unemployment should, with appropriate education, enable more human resource to be deployed on design, quality assurance and maintenance. Electronic aids may also be expected to reduce design uncertainties and improve the capability of design optimisation and inspection during construction and in service. These would enable the present high levels of reliability to be maintained or increased.

Universities can play a major part in educating the community in general and engineers in particular in rational approaches to structural safety. They can contribute to the philosophical and statistical arguments concerning the objectives of design and construction. They can increase awareness and understanding of engineering uncertainties and teach how to deal with them by safety margins and controls. Structural research engineers should measure and record values of all parameters which contribute to variability of performance of structures or their components which they investigate. There should be data banks to sift and store such information. The development of reliability and risk analysis is at present severely handicapped by shortage of quantitative material.

There should be improved procedures to enable the nature and causes of failures and unserviceability to be established and widely reported without prejudice to legal and insurance interests.

The trend to relate design safety factors to social and economic consequences of failure will undoubtedly continue, although there is need for a firmer basis.

I believe that engineers must continue to take the initiative in interpreting the needs and requirements of the community with regard to structural safety. They should promote discussion within the professions of the desirable balance in resource expenditure. There is an urgent need to analyse the cost benefit of safety measures. Just as in medicine the provision of extremely expensive resources and equipment to prolong the lives of the elderly may deplete resources to maintain the health of the remainder so also may excessive expenditure on building safety deprive the community of funds for other artefacts or facilities. There are many well intentioned innovations in our field the cost and worth of which have not been established. There is need to examine the optimum fractions of total construction cost to spend in design, on quality assurance including independent checking of design and erection schemes, on quality control, on safety measures during construction and on maintenance. The debate on this subject is particularly relevant to design against earthquake in New Zealand and was evidently lively after Mr. Ingrams Hopkins Lecture in 1983.

In design the introduction of the partial safety factor format of rules is resulting in greater uniformity of reliability among structures of a like kind. There is need for concerted calibration of Codes against established satisfactory past practice worldwide in order to gain the greatest advantage of experience. The following steps to further rationalize safety margins are as yet uncertain. There is need for an accepted methodology for reducing factors when design uncertainties are reduced by means of research, advances in computational techniques or improved quality control. We are not benefitting as we ought from progress in technology. I see the application of reliability theory as essential to the process.

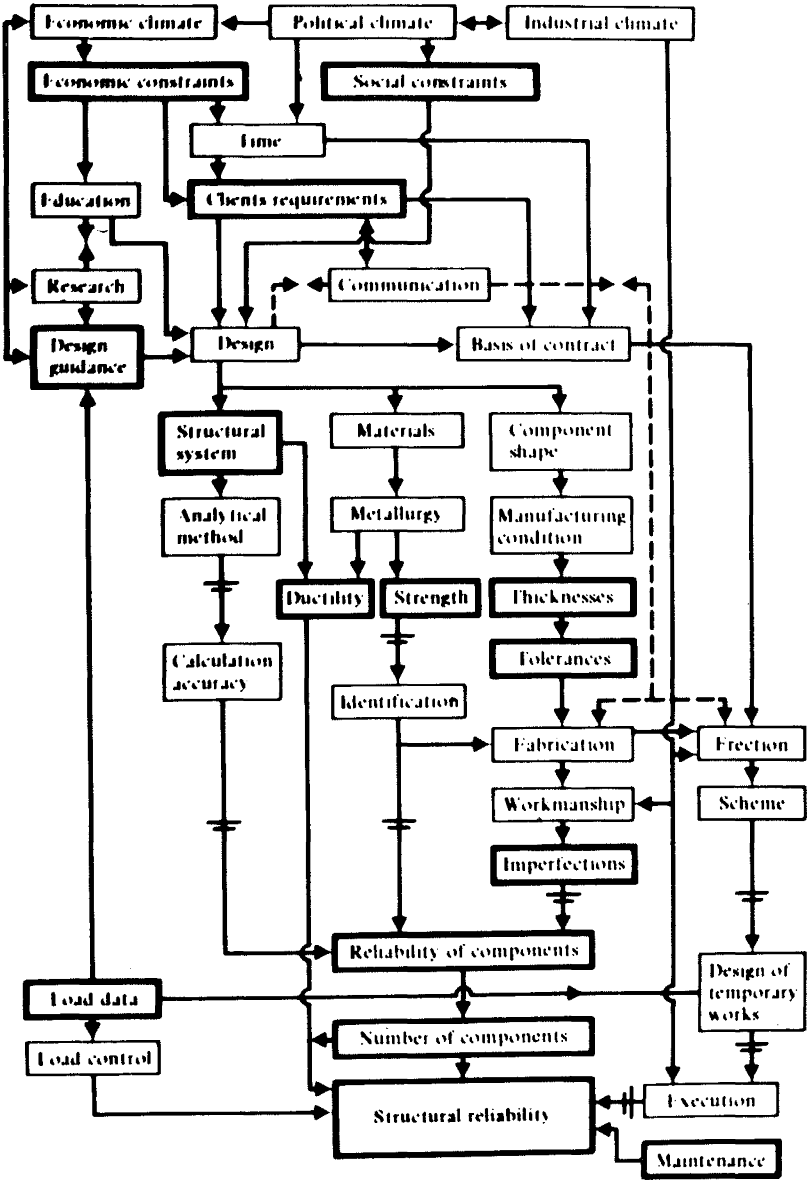
There is need to monitor changes in use of structures. For example we have instituted a regular audit of potential vehicular loading on the Severn crossing employing statistical analysis of traffic frequency and loading data.

As with freedom, the price of safety is eternal vigilance. The community relies on us as the watchdogs for its security of use of engineered artefacts. It needs to be confident in them. (28)

Since I have referred to a number of mishaps to illustrate various points, I must emphasize that these have been extreme rarities and that the standards of safety achieved in engineered structures are outstandingly high. The profession serves the community with great success and the community should learn to appreciate this.

The Hopkins lecture has provided me, and I hope you, with the opportunity to stand back from the daily round and to briefly consider how our work relates to the needs of society. This, I am sure, was what Professor Hopkins would have wanted. He would have hoped that the lecture would act as a catalyst for continuing discussion and positive actions. He would have expected the University of Canterbury to play a leading part in developing and promulgating ideas and methods for the benefit of the community during its second century.

Influences on structural reliability



Heavily framed boxes indicate matters related to safety factors

Indicates control points