Structural Safety
2000-01

Thirteenth Report of SCOSS
The Standing Committee on Structural Safety

May 2001

SCOSS
11 Upper Belgrave Street
London SW1X 8BH

CLASSIFICATION

Availability:	Unrestricted
Content:	Review
Status:	Committee-guided
User:	Civil and structural engineering professionals and organisations

ISBN 0 901297 16 X

Published by The Institution of Structural Engineers

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Foreword

The Committee, commonly known as SCOSS, is charged primarily with giving warnings to relevant bodies where unacceptable risk is believed to exist. To that end the Committee aims to identify, in advance, trends in the construction industry that may have an adverse effect on structural safety. It is in the nature of the Committee's work that available evidence on the precise nature of a suspected unacceptable risk is often limited. Devising an appropriate response or solution will usually require much more information. The Committee does not have the facilities to carry out the additional investigations often necessary but, by drawing the attention of relevant bodies to its concerns, the Committee seeks to prompt in-depth and strategically focused investigations by those best placed to carry them out.

The Committee is concerned primarily with experience in the United Kingdom. It seeks information on structural safety on a worldwide basis however, and its conclusions may be relevant to other parts of the world. I believe its great strengths are the wide collective experience of its members and its independence to express views on matters of structural safety. We owe this position to the farsightedness of those who established the Committee twenty-five years ago and to the Committee's sponsors who continue to provide resources whilst respecting the Committee's independence to express concerns on structural safety.

Over the past two years the Committee has reviewed its methods of providing warnings in discussion with its sponsors, the Institutions of Civil Engineers and of Structural Engineers and the Health and Safety Executive. As a consequence this Thirteenth Report is more in the nature of a benchmark report and discusses themes that have frequently emerged in the Committee’s deliberations. The Committee believes that this form of report will better transmit the conclusions of its recent work to the intended readership, ie primarily senior engineers and others in government, industry, academia and the engineering professions who will read it on behalf of their organisations. The Committee would welcome comments on this Thirteenth Report from readers.

The Lord Lewis of Newnham
Chairman

SUMMARY

Trends and changes in society and industry are often perceived to be pervasive and occurring at an ever-increasing rate. Certainly the construction industry has been subject to substantial changes, particularly over the last ten years or so, as a result of pressures for greater efficiency, productivity and safety. Most changes, even changes intended to improve safety, can have some detrimental effects on safety. The Committee seeks to identify trends and changes in the construction industry that may have an adverse effect on structural safety and to provide warnings where it is believed an unacceptable risk may exist.

The Committee is constantly reminded in its work that the achievement of safety is generally a question of balance. The possible detrimental effects of changes on structural safety need to be effectively countered or compensated for. In particular, pressures on time and cost can have adverse effects on structural safety that need to be countered. Keeping risks to structural safety (and safety more generally) acceptably low requires a learning culture throughout the industry. The release of information from experience, particularly of failures, is therefore important. However, the possibility of claims, litigation, arbitration or criminal proceedings often involves the allocation of blame and can thereby inhibit such release and the spread of learning. Thus a dilemma exists arising from events that could lead to disputes or enforcement action. Appropriate answers to these conflicts and dilemmas depend, it is suggested, on developing a proper sense of balance.

In contrast to previous SCOSS reports, this Report is presented in a thematic form. It discusses themes that have frequently emerged in the Committee's deliberations over the past two years. Issues of balance are found throughout. The Committee recognises that some of the conclusions are general and may have a wider relevance than solely to the particular theme discussed or to structural safety generally. It is thought that the possible wider relevance should not prevent their presentation here.

In drawing the conclusions listed below, the Committee has sought to identify the key factors and requirements for assuring structural safety in the future so that the industry, the professions and government may consider them in developing suitable systems. The Committee believe this Report may also assist individual engineers, including those in training, to develop greater awareness of structural safety issues.

The control of risks to structural safety

(1) Structural safety can be placed at risk by active errors by designers, site personnel and the like and by latent errors introduced through inadequate procurement procedures, codes, standards and regulations.

(2) Codes and standards provide a core means of controlling risks to structural safety. Identified shortcomings should be addressed with urgency. It must be recognised that there may be gaps in codes and they may not cover recent innovation.

(3) The control of risks to structural safety depends primarily on the competence and integrity of individuals and organisations. The possibility that individuals or organisations might not be competent, or that their competence might be affected by commercial or other pressures is a risk to structural safety and needs to be controlled.

(4) Supervision and management systems used to control risks to structural safety should include appropriately independent arrangements for checking safety-critical elements. There is doubt as to whether systems conforming with ISO 9000 are adequate for this purpose.

(5) The certification of structural safety-related work should be entrusted only to appropriately qualified and experienced engineers.

(6) **Certification by the work originator of the design and construction of structures whose failure would not have high consequences can give adequate assurance of structural safety provided there are appropriate systems in place for ensuring competence.**

(7) **For safety-critical aspects of design and construction of structures whose failure would have high consequences, third party independent certification is needed to give adequate assurance of structural safety.**

(8) **For structures whose failure would have high consequences and for structures that are innovative or unfamiliar in relation to the experience of the project team, an explicit process of risk management should be used. The process should include the systematic identification of hazards and assessment of risks to structural safety, followed by the selection of critical situations for design.**

Dynamic response of structures

(9) **Specifically targeted research is needed to evaluate the uncertainties in the structural design of cantilever seating decks for dynamic effects and to assist the IStructE/DETR/DCMS Working Group.**

(10) **There may be many bridges that have only experienced moderate pedestrian traffic and have performed well but which, if subject to greater pedestrian density, could suffer strong lateral vibrations.**

(11) **Where previously unknown structural behaviour is observed, whether failure has occurred or not, it is incumbent upon professional engineers to report the observations in the technical literature, if possible, so that others are alerted to potential risks to safety.**

(12) **The identification of dynamically sensitive structures and the visualisation and understanding of structural behaviour at the design stage may not be sufficiently well covered in the education and formation of civil and structural engineers.**

Naturally-occurring environmental hazards to structures, including climate change

(13) **The consequences for structural safety of climate change should be regarded as a national and international issue. Consequences should be assessed taking account of the uncertainties existing in the predictions of climate change. Changes should be quantified by continuous monitoring and analysis of the climate.**

(14) **A prudent minimum approach for maintaining structural safety as climate change occurs would be to update design and assessment criteria as change is confirmed. Anticipating climate change in design and assessment may be justified in some cases, particularly if evidence is found that a significant change is taking place over a short time scale relative to the life of structures, say 50-200 years.**

(15) **Research is needed into the sensitivity of structures to climate change to determine thresholds at which the updating of design values and the strengthening of existing structures may be necessary to maintain acceptable structural safety.**

Duties to warn and heed warnings

(16) Giving and heeding warnings are essential parts of ensuring structural safety. In difficult situations, the Royal Academy of Engineering Draft Guidelines for Warnings of Preventable Disasters are commended to engineers.

(17) Views would be welcomed by the Committee on whether the establishment of a system for confidential reporting on matters affecting structural safety, or safety in construction generally, is needed and would be used.

1 INTRODUCTION

1.1 General

The principles of prevention, stated in the EU Framework Directive, indicate a philosophy that, for safety, risks should preferably be avoided. Structural engineers seek to avoid risks, for example, restricting the height of buildings or bridge pylons on aircraft take-off and approach paths near an airport, to minimise the risk of an aircraft strike (as well as preventing interference with guidance systems). As the Concorde disaster in Paris reminds us, however, even with such steps, the risks are not eliminated. The general philosophy of structural engineering is not about turning away from risks, but rather looking for and facing up to risks and minimising and dealing with them safely, adopting a balanced and informed response. One would not expect an engineer to advise that a tall building or long bridge should not be built because there was the risk of, for example, typhoons, earthquakes or fire.

Over the years engineers have found an accommodation with the risks of nature, men and machines through the accumulation and sharing of knowledge, and the development of practices which minimise the likelihood of shoddy work, mistakes or bad judgement being perpetrated and overlooked. However, there is no complete 'map' of how the knowledge is accumulated or shared, nor of the checks and balances inherent in the practices which have a bearing on structural safety. Rather processes have evolved, in the face of changing circumstances, as the various component entities in the construction industry have striven for viability. Governments have supported and intervened to a greater or lesser extent. Individuals, professional institutions, trade associations, research bodies and academia have made their various contributions, subject to limitations on ability, resources, funding and influence.

The history of engineering shows consistent application of two approaches to assist in this work, namely simplification and codification. Simplification, or approximation, is an essential tool in engineering, enabling problems to be dealt with within the limits of analytical and computing power and human understanding. For example, the assumption that steel frames could be analysed as pin-jointed structures with members represented by their centre lines, was the standard basis of structural design for many years. The simplification in that case generally erred on the side of safety. However, oversimplification can lead to problems, for example when second order effects become significant. Equally, failure to simplify, perhaps because the computing power is available, can cause problems by not assisting or enabling adequate human understanding or appreciation. It is, again, a question of balance.

Codification has been an essential tool in passing on lessons learnt from experience efficiently for the benefit of safety. Codification therefore provides benefits, but it also brings a risk of a blinkered approach. Codification can conceal or distract from the wider picture. A sound approach to codification again requires a sense of balance.

An example of the problems of both oversimplification and excessive reliance on codification concerns the increasing trend towards formalised risk assessment. While this should ensure that people address risks, it may actually lead them to address risks with a narrow mind. The HSE Report on the Heathrow tunnel collapse[(1)] highlights the danger with its observation, "The pro forma approach [to risk assessment] kept the focus on routine worker safety. It did not encourage the strategic identification of high-level engineering and management issues essential to the success of NATM, such as the major hazard events and their prevention."

These considerations suggest a more general principle, that all steps, even those intended to improve safety, may have some potentially detrimental effects on safety. The effects may not be immediately apparent, sometimes because the inherent assumptions or unintended benefits of existing methods may be overlooked. We therefore need to be alert to change and the potential adverse impacts of change. We need to be aware of the possibility that the solution to one problem may create another problem, that an evolutionary trend might destroy the balance, that the weakening or removal of a check giving assurance of safety in one part of the system may not be countered adequately, or even at all, by measures elsewhere. This is not to suggest that changes should be abandoned and their beneficial effects lost, but that care must be taken to overcome or compensate for the adverse effects.

The role of SCOSS is, of course, to look out for emerging trends of change and warn of possible dangers for structural safety. Many of the trends observed in this Report, as in previous Reports, concern trends in materials, methods, loading or structure types. However, we also observe significant trends of change in design and procurement processes, in reluctance to release technical information, and in increases in penalties and costs imposed by courts in health and safety prosecutions (where an intention of the latter is to deter others from jeopardising safety).

In design and procurement, the cumulative effects of competition, client demands, and commercial and time pressures generally may result in

- Less time spent in reflection on design
- Loss of traditional systems of checking
- Inhibition of individuals from giving or heeding warnings
- Introduction of innovations without the support of adequate research or development.

There is a trend of increasing reluctance to release technical information from experience in construction into the public domain. Such information is an important source for learning across the industry. Release of information is inhibited when litigation or arbitration proceedings are anticipated or have been commenced. The parties often maintain or impose confidentiality restrictions which remain in place after the dispute has been resolved. In addition, there have been examples of construction projects where information was not released by regulatory authorities pending potential enforcement action although some improvements in this area have been noted over the past two years, for example on bridge access gantries[2]. There appears also to be a trend towards the imposition by the courts of harsher penalties and cost orders for health and safety offences, which could result in more reluctance generally to put the results of investigations of safety shortcomings into the public domain[3].

We need to be alert to ensure that the evolutionary trends do not undermine either the accumulation and sharing of knowledge, or the checks and balances, which are together the foundation for securing structural safety. We must ensure that engineering problems receive engineering solutions. We must instil awareness that political, legal or commercial interventions provide partial solutions, but they cannot alone suffice.

The Committee believes that it is right to draw attention to these trends, whilst accepting that they are not all universal and some may be considered controversial. The trends mentioned above are not claimed to be exhaustive. They do, however, suggest that the checks and balances in parts of the construction system relating to structural safety are being weakened. Such effects should be countered, not only by direct attention, but also by the education, training and updating of all parties involved in procurement, design and construction.

In summary, most changes, even initiatives intended to improve safety, can have some detrimental effects. It is important to be alert to the possibility of such detrimental effects, and provide effective counter or compensatory measures. In particular, pressures on time and cost can have adverse effects on structural safety that need to be countered. Keeping risks to structural safety (and safety more generally) acceptably low requires a learning culture throughout the industry. The release of information from experience, particularly of failures, is therefore important. However, the possibility of claims, litigation, arbitration or criminal proceedings often involves the allocation of blame and can thereby inhibit such release and the spread of learning. Thus a dilemma exists arising from events that could lead to disputes or enforcement actions. Appropriate answers to these conflicts and dilemmas depend, it is suggested, on developing a proper sense of balance.

Some areas where the Committee has particular concern about achieving balance are discussed in the later sections of this Report.

1.2 References

(1) *The collapse of NATM tunnels at Heathrow Airport.* Health and Safety Executive. HMSO, London, 2000.

(2) *The use of temporary bridge access gantries in the UK.* Discussion Paper. Health and Safety Executive, 2001.

(3) Barber, J. 'Defending safety and environment prosecutions: some positive thoughts'. (2001) 17 *Construction Law Journal.*

2 THE CONTROL OF RISKS TO STRUCTURAL SAFETY

2.1 Introduction

Design of new structures and structural assessment of existing ones have always been about the identification, assessment and control of risks. In particular, these tasks have involved consideration of risks in the loading to be experienced by the structure during its intended future lifetime (including loads due to accident, misuse or malicious action), risks in the behaviour and reliability of materials and in workmanship, and risks of errors being made in design and construction processes.

Engineers have, through research and experience, accumulated data and found safe ways of dealing with the risks to structures, and have translated that research and experience into practical guidance in the form of codes and standards (which will be referred to below jointly as 'codes'). These avoid the need to repeat a full risk assessment exercise afresh for each project for common situations and common risks. Providing codes are adequate and are kept up to date with the state of knowledge and any changes in conditions, their use achieves both consistency and economy of effort. There could, however, be risks to safety if codes are inadequate or are not kept up to date.

Codes have always been intended for use by individuals who are competent, particularly to appreciate the limitations of the guidance. They have not been intended to be interpreted as quasi-legal documents to find the least onerous solution. There can be risks to safety if the application of codes is entrusted to individuals who are not competent, or if the codes are interpreted in a deliberately narrow or literal way.

Although these risks ought to be combated at source as far as possible, structural engineering also has a tradition of independent checking, as a secondary protection to pick up errors and omissions in design and defects in materials and workmanship.

Recent trends and developments in the construction industry exert influences, which may be positive, negative or neutral. One trend, which would be expected to have a positive influence, has been the effort to ensure organisational competence through formal management systems. A second is the introduction of explicit legal requirements under health and safety legislation, the Management of Health and Safety at Work Regulations 1992/1999 (MHSWR) and the Construction (Design and Management) Regulations 1994 (CDM), to carry out formal risk assessments, to ensure that risks are comprehensively addressed.

Conversely, the strong commercial pressures presently experienced in construction work, relating to time and money, might be expected to have some negative impacts. It is also a cause for concern that the number of high quality graduates entering the construction engineering professions over the past 10 years has been limited, with many of the best graduates being immediately lured away to jobs outside of engineering. This is a particular concern for the medium to long term.

Other trends, which might have either positive or negative effects, include the trend to privatisation or public-private partnerships; the growing use of certification by the work originator (commonly termed 'self-certification); and the increasingly prevalent use of computer-aided design and drafting.

In reviewing all these trends, the question is raised how formal risk assessment should best be applied, so as to complement what already exists in codes, to support design and checking processes, and to ensure that risks not covered by codes are identified and controlled.

2.2 The human contribution to structural failures

There is a general awareness of the possibility that individuals or organisations may introduce errors in design and construction through lack of competence or simply through a mistake or dishonesty.

Understanding of the human contribution to accidents in complex technological systems has grown substantially through studies of major accidents in recent times[(1)]. A distinction is made between two kinds of error: active errors, whose effects are felt almost immediately, and latent errors whose adverse consequences may lie dormant within the system for a long time, only becoming evident when they combine with other factors to breach the system's defences. In general, active errors are associated with the performance of the 'front-line' operators of a complex system: pilots, control room crews and the like. Latent errors, on the other hand, are most likely to be spawned by those whose activities are removed in both time and space from the direct control interface, for example, managers and those responsible for industry standards and control.

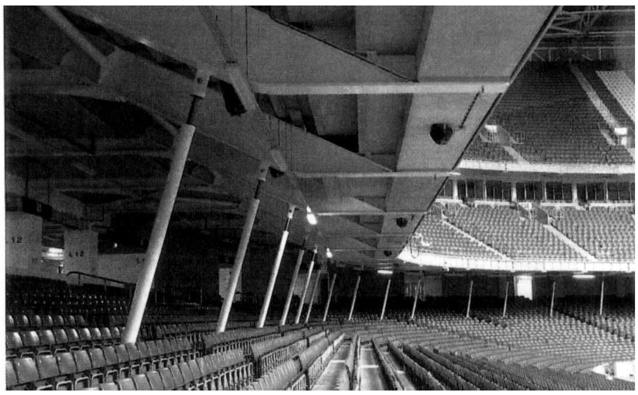

Figure 1: Cardiff Millennium Stadium - Photograph showing temporary props used to control vibration risk during 'pop' concerts

Case study analyses of six major accidents, i.e. Three Mile Island, Bhopal, Challenger, Chernobyl, Zeebrugge and the Kings Cross Underground fire, have shown that latent rather than active errors now pose the greatest threat to the safety of high-technology systems[(1)]. Other disasters such Flixborough, Summerland, Heysel Stadium, the Bradford and Piper Alpha fires, the Clapham Junction and Purley rail crashes and the Hillsborough Stadium catastrophe are also reported to support this view.

The Committee sees strong parallels between the systems discussed above and the systems within the construction industry for the execution of construction projects. The industry should work in the interests of structural safety (and safety more generally) recognising the need to minimise the risks of active errors by designers, site personnel and the like and, equally importantly, to prevent latent errors arising through, for example, inadequate procurement procedures, regulations, codes and standards.

2.3 Codes and standards

The use of codes of practice

Safety of structures has commonly been achieved in design, since the advent of structural testing and analysis in engineering, through consideration of the assembly of structural elements and the use of safety factors. The total structural concept and the form of the assembly has been decided largely intuitively from overall considerations with the aid of analyses using simplified mathematical models. Risks in loading, materials and workmanship have then been covered by the application of load factors and safety factors in the design of elements. The prototypical nature of most structures militates against the regular use of other methods, such as full-scale testing.

This approach has been embodied in codes of practice, originally prepared by the professional Institutions directly, but now mainly prepared under the aegis of, and issued by the British Standards Institution. British Standard (BS) codes of practice for structural design are developed through consensus amongst industry and government representatives and define generally established good practice.

Risks during conversion to Eurocodes

Since the 1980s preparation has been underway of a new set of codes of practice, known as Eurocodes, intended for use throughout Europe. The Eurocodes have already been issued by the Committee for Standardisation (CEN) as ENV documents for voluntary use and a programme of work is now in hand to convert them to EN documents over the next few years. They cover the design of most building and civil engineering structures. Once issued as EN documents, they will replace existing, but not all, BS Codes of Practice for structural design. The requirements of the Public Procurement Directive may require engineers involved in public funded projects to use Eurocodes as soon as they are issued in BS EN format regardless of any coexisting British Standards.

The Committee expressed concerns in the Twelfth SCOSS Report about inadequacies, inconsistencies and confusions between BS Codes and Eurocodes, which could provide a seedbed for the germination of latent errors in design and construction and constitute a background hazard to safety.

The introduction of the Eurocodes, replacing the existing BS Codes, will inevitably be a complex process. A clear policy is needed for convergence by the construction industry, especially by clients, construction service providers, the professions and academia, to the use of the Eurocodes and the withdrawal from use of current BS codes. Careful management of the change alongside initiatives for the education and training of engineers in the use of the Eurocodes is required to keep risks of errors leading to unsafe structures acceptably low. The recent issue of Eurocode versions of the IStructE/ICE design guides for steel and concrete structures are useful initiatives in this direction[(2,3)].

These issues were examined by the Study Group on Structural Design Codes in Construction during 2000[(4)]. The Committee hopes that consideration of the Group's recommendations by government, industry and the professions will lead to action that will help to reduce risks of latent errors being embedded in structural design and assessment and in construction.

Risks not covered by codes and standards

Almost by definition, codes of practice may not cover the most recent technical innovations and developments, or changes in conditions. It is therefore important for designers to recognise that current codes may not cover all matters of design that can affect structural safety. Experience has highlighted a number of such risks:

- Changes in the loading regime due to subtle changes of use.
- Susceptibility of structures to aspects of loading not normally recognised or considered significant.
- Lack of knowledge at the time of design.
- Lack of information at the time of design.
- Lack of adequate maintenance and/or inspection.

Changes in loading

Risks arising from loading may be naturally-occurring or man-made. Whilst the extremes of naturally-occurring loads may change very slowly over time as climate changes, see Section 4, the risks associated with man-made hazards may change relatively rapidly over time because the magnitude or nature of the hazard changes. For example, traffic loads on bridges have increased in magnitude and intensity, and crowd behaviour at sports stadia has become more boisterous and difficult to control, and is sometimes influenced by the introduction of rhythmic music. Such changes should be researched in a continuing way so that design and assessment standards for loading can be revised as necessary. The risks from these hazards may also change because the form of particular types of structure may evolve or be ‘stretched’ in response to client requirements, technical innovation and/or economic pressures. As a result the behaviour of new structures under load can be different from that experienced previously. Such new structures may then be unexpectedly vulnerable to loss of structural safety.

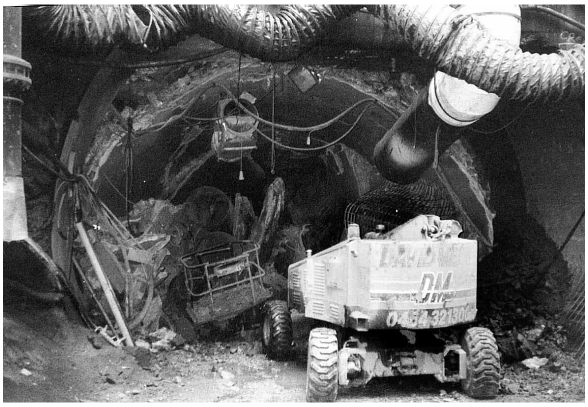

Figure 2: The concourse tunnel eye after the collapse of NATM tunnels at Heathrow Airport. The Report on the collapse by the Health & Safety Executive [22] found, amongst other causes, that "self-certification systems did not deliver the quality required".
Photo: Health & Safety Executive

Particular susceptibility of structures to aspects of loading not normally recognised or considered significant

The unexpected response of the Millennium Bridge to pedestrian traffic illustrates such a risk, see Section 3. This may be considered as a particular example of a lack of knowledge of a risk.

Lack of knowledge at the time of design

Other examples where lack of knowledge led to risks not being adequately controlled by design are the inadequacies in shear strength of reinforced concrete beams designed before about 1969[5] and the possibility of methane accumulating in tunnels and other confined spaces from remote sources, as at Abbeystead[6,7]. The professions, industry and academia generally have a reasonable record of responding to events and disseminating such knowledge for future design work, but see also Section 3. There are, however, limited mechanisms or statutory requirements to ensure the re-evaluation of existing structures, which may be at risk.

Lack of information at the time of design

A lack of information about ground conditions or the condition of existing structures can lead to cases of inadequate design, e.g. quay wall movement, Southampton[8]. However, this is a problem at individual project level. Codes can only indicate what information should be obtained. Legislation has moved towards requiring clients to obtain and provide such information to designers and contractors, rather than merely transferring the risks by contract. Greater efforts are needed to get this message through to clients.

The risk of lack of adequate maintenance and/or inspection

A lack of adequate maintenance and/or inspection was a major factor in the collapse of the Pipers Row multi-storey car park[9] Codes generally presume that adequate maintenance and inspection will be carried out, but as noted in the Twelfth SCOSS Report, the legislation does not create clear, appropriate duties in this area for all potentially vulnerable structures. There is also confusion over statutory enforcement responsibilities.

Examples of failures due to code inadequacies

The traditional approach based on the use of codes by competent engineers has been generally successful in recent times. Structural collapses in the UK were rare during the twentieth century. There were however a few major failures, in particular during the late 1960s and early 1970s that caused considerable concern. Whilst these failures may be considered 'just mistakes', they arose largely because new hazards were introduced but not recognised and adequately controlled. The failures generally occurred amongst non-traditional structures that incorporated technical innovations and developments made in response to national demand for growth in construction output, or they occurred where the span or size of the structure was extrapolated beyond the range previously built. In general the codes current at the time did not adequately cover the structure that collapsed.

The failure incidents, e.g. Milford Haven bridge[10], Aldershot Officers Mess[11], Ronan Point[12], Camden School Assembly Hall[13], Stepney swimming pool roof[14], Birkenhead sports hall collapse[15], led to modified codes of practice and Building Regulations. They did not, however, lead to a questioning of the overall approach to structural design. Rather there was focus, with the benefit of hindsight, on getting the technical shortcomings right within the same overall approach.

However, for bridges, in contrast to buildings, a hierarchy of controls on procedure and on the independence of checking was introduced after 1970 to prevent a recurrence of the shortcomings in design and construction processes found following the collapse of the Milford Haven bridge and similar bridges abroad. These procedures, which depend on the size and importance of the structure and whether it is a well-tried or innovative and unusual form of construction, have generally been successful.

Interpretation of codes

There appears to be a trend to treat codes as quasi-legal documents, to be interpreted by semantic and syntactical analysis to find the least onerous solution. It should be readily appreciated that this is seriously misguided and liable to create risks to safety.

The effectiveness of codes in assisting the provision of safe structures can be adversely affected by the way design is procured. Design and build arrangements can lead to excessive time pressures on designers quickly to interpret codes in the most advantageous way in relation to cost. The risks of active errors may then be high.

2.4 Competence and integrity

The Committee believes that the control of risks to structural safety depends not only on the competence and integrity of the individuals using the codes but also on the content of the codes themselves.

Design, assessment, construction, maintenance and repair work should be undertaken and supervised by appropriately qualified and experienced people. This requirement for competence provides the main line of defence against errors being made that may jeopardise safety or indeed other aspects of the work, especially costs and programme. Qualification, experience and engineering common sense should enable competent engineers to identify the relevant risks (including naturally-occurring and man-made risks and the risks associated with design, assessment, construction and maintenance processes), decide on the structural concept and design the structural system as a whole so that the structure would be safe over its specified design life.

Although many, if not most decisions on structures are taken by individual engineers and the competence of the individual engineer is the primary focus, most engineers are working as part of an organization and reliability also depends on the competence of the organization.

Individual competence and integrity

Competence is usually understood to mean 'sufficient ability'. This is principally the ability to deal with relevant problems, but an essential complementary requirement is the ability to recognise that there is a problem to be dealt with and appreciate that the apparent answer to one problem may actually create or exacerbate another problem. The sufficiency of competence is to be judged relative to the particular structure or the particular task. Individuals may require broad or narrow competence according to their position.

Relevant recent definitions of a competent person may be found, for example:

> "A person shall be regarded as competent where they have sufficient training and experience to take responsibility for an identified task. It is important that they have a detailed knowledge of the type of structure, and particularly of those matters which are essential for its structural reliability. A competent person will have an awareness of the limitations of their own experience and knowledge".[16]

> "A person shall be regarded as competent where he or she has sufficient training and experience to take responsibility for an identified task. A competent person will have an awareness of the limitations of his or her own experience and knowledge".[17]

Competence involves natural ability combined with knowledge, experience, education and training. Knowledge is derived from a mixture of systematic knowledge obtained from formal education, knowledge gained from experience, and knowledge gained from continued study and participation in professional activities. Knowledge may of course be acquired for a specific task, but the recognition that there may be relevant knowledge and of the need to acquire it depends on embedded knowledge. The ability to acquire knowledge depends both on education and available resources. The competence requirement may thus be affected by the availability of resources. Education, experience and training also provide skills and awareness.

High-level competence involves judgement, a proper sense of balance, and the ability to visualise. Discontinuities in the chain of competence in an organisation can lead to risks to structural safety. A more senior person, assumed competent because of seniority, may not appreciate the significance of good advice from a competent, and perhaps specialist, person lower down the chain. The competence of senior people to recognise and act properly on sound advice when they receive it is important.

In addition, structural safety depends on the integrity of those involved. Recent cases in Hong Kong have demonstrated the damaging effects of failure by individuals to do their work with integrity, to the extent of being positively dishonest. It is necessary to recognise the possibility during construction projects that one or more individuals involved may not have performed their tasks diligently, faithfully or honestly and, indeed that they may have taken steps to conceal dishonesty. Guidance on ethical behaviour should help the control of this risk[18].

Assessment of individual competence

The competence required for any particular task is not easy to determine. The criteria for assessing competence usually include relevant education and training, and previous experience of undertaking similar work. In deciding on the suitability of any individual to undertake specific work, it is important to be clear about what their professional or other qualification covers. Reliance is often placed, in determining competence requirements, on the common sense and judgement of those at more senior level who are accepted as competent by virtue of their experience. The integrity and professionalism of the person judging competence is crucial. For the construction industry this person is not necessarily an engineer.

The qualification and experience of a person to an appropriate level is an essential first step in judging competence, but it does not necessarily mean that a person will practice with commensurate competence. It is what people do that matters and not simply what they should have the competency to do. Where qualification and knowledge of experience is limited, as may be the case for foremen, supervisors and site operatives, judgement of competence is particularly difficult.

Competence of organisations

The competence of organisations, both locally and more widely in the construction industry, can enable or adversely affect the ability of competent individuals to control risks to structural safety.

Whilst the organisation does not generally take decisions on structural design, assessment or construction as corporate decisions, it usually:

- Selects and appoints the individuals
- Provides training for individuals
- Provides resources for individuals, including assistance and equipment
- Provides supervision and/or checking
- Provides research and standards
- Provides communication systems
- Provides procedures and management systems
- Carries out audits
- Appoints sub-contractors and sub-consultants

Organisational systems, for example involving supervision, certification, and quality management processes, are there, inter alia, to reduce the possibility of mistakes by competent individuals that may result in errors in design and construction processes. The systems should therefore provide support to competent individuals in avoiding mistakes in their work, but they cannot replace the role of competent individuals. No clear definition of such organisational systems exists that would enable a system for a particular project to be determined commensurate with the need to ensure that structural safety (and other) risks are as low as practicable.

Pressures affecting the exercise of competence and judgement

Judgements can be put under pressure by financial considerations, especially where self-judgement is required, e.g. in lump sum bidding for consultancy services, or in certification of one's own or colleagues' work. If such pressures were to influence the judgements of engineers generally, it can be envisaged that some form of external control could become essential to maintain structural safety.

Examples of risks due to lack of competence

Whilst the need for competence is well understood, it can easily be forgotten. For example, organisational pressures for speed or economy, or changes in responsibilities or procurement methods can result in inadequate expertise and experience being applied to particular engineering activities. An accident may then be the outcome with a lack of expertise in engineering or management identified as contributing to the tragedy.

Examples of such accidents are the Royal Canberra Hospital demolition by a planned implosion, the HMAS Westralia ship fire, and the Esso Longford explosion[(19)]. In all three accidents, a lack of technical expertise and competence was identified as a contributing factor. The expertise was either lacking in the contract managers and contractors, or unavailable when required.

Another characteristic of these accidents was that they could not be attributed totally to one individual or group. Instead the failures involved many people and other factors. The existence of a management system is clearly insufficient to prevent failures and does not compensate or cover for a lack of competence in the individuals or organisations to which specific tasks have been entrusted.

Similar characteristics and issues of competency may be identified in recent structural accidents in the UK, e.g. Ramsgate Walkway collapse on 4 September 1994[(20,21)] and the collapse of NATM tunnels at Heathrow on 20-21 October 1994[(22)].

The investigation of the Walkway collapse revealed a number of errors, mostly in the design[(20,21)]. Erroneous assumptions were made about the vertical reactions on the supports and about the transfer of forces through the support bearings. The result was inadequate design for the forces in the articulating structure which led to fatigue failure of the support bearings. Almost the same conceptual errors were made by the independent checkers of the design. This tragic incident emphasises the importance of competence of individuals in understanding the load carrying behaviour of the structure and in correctly establishing the critical load situations for design.

The collapse of the NATM tunnels at Heathrow was reported to be an 'organisational accident'[(22)]. A multiplicity of causes led to the position where the systems variously used by the client, designers and contractors failed. A cultural mind-set focussed on the need for production rather than the risks to safety. This focus might be viewed as resulting from a conflict of interest. Risks were not controlled during construction by the preventative management systems in place. These systems failed. They did not deal adequately with hazard identification, risk avoidance and reduction, and the control of remaining residual risks. Errors and omissions of individuals were not identified and corrected through the management systems. A number of salutary lessons were identified from this incident including:

- The potential for major accidents in construction projects must be addressed by all parties through the effective use of hazard identification, consequence analysis and risk reduction techniques.
- New and unfamiliar technologies require rigorous understanding and assessment before they are adopted.
- It is essential to take into account organisational and human factors when devising management systems to secure health and safety.

Overall, these experiences emphasise that there are broadly two sources of errors and mistakes in construction that may jeopardise structural safety. Individual errors and omissions may arise through lack of competence and/or integrity. Mistakes and errors may also emerge from social interactions in complex organisational and management systems where no one seems culpable.

2.5 Supervision and management systems

It is essential to take into account organisational and human factors when devising management systems to secure health and safety. In particular there appears to be no clear consensus on avoiding conflicts of interest in checking processes that arise when the checker is not financially independent of the work originator.

Errors may be introduced in design jeopardising the quality of the work and safety. This is the reason for supervision as a line of defence against design and construction errors. The concept is that a more experienced person oversees the less experienced, guiding, controlling and directing their work. The supervisor's task is to make sure the required work is done and that errors due to shortfalls in the competences of the less experienced are identified and corrected. In modern-day construction, the task may, however, be undermined by time and cost pressures, lack of diligence and the like, as already discussed.

More broadly, internal management systems are used to assist the achievement of sound design and construction. Essentially, internal systems should record work done, supervisory actions taken and may include also certification and internal or external audit. The aim of these systems is to ensure that the work is done to the required standard. They are part of modern structural engineering. Their effectiveness is variable. They are necessary essentially because modern engineering projects are almost always complex, involving many people and organisations and supply chains. It is not possible for individuals to progress their work satisfactorily without the help of management systems to keep track of progress and plan and initiate forward actions. A high reliability is essential for such systems from the structural safety point of view. However, given the great extent to which IT systems are now used for information storage, analysis and transfer, there clearly may be risks that critical safety information is not processed or seen by appropriately responsible and competent people. An overall concern is that organisational systems for design and construction may have gaps or weak points between them where continuity is lost in the transfer of knowledge of the design to its interpretation and implementation in the construction.

The creation of organisational systems appropriate to a construction project is key to ensuring success, including structural safety during the construction phase and subsequently. This task is generally done individually for major projects by the client and project team. They use their knowledge and experience to decide on appropriate arrangements for checking, especially of safety-critical elements. This process has been generally successful in recent times. There have been a few cases where the arrangements have not prevented structural failure, e.g. the collapse of the Ramsgate Walkway(20,21). For small projects, organisational systems are generally decided by the project team only. Model organisational arrangements are difficult to define because of the great variety of circumstances found in practice. There is therefore a question as to whether greater formalisation is practical or even desirable.

Some organisations in the construction industry have come to rely on ISO9000 quality management systems to control the risk of design and construction errors becoming latent errors in the as-built structure. Whilst ISO9000 systems work well in manufacturing industries, it is not clear that they bring overall benefit to the largely prototypical design and construction processes in the construction industry.

The philosophy behind ISO9000, and quality management systems generally, is that if the processes of design, production and supply are correctly defined and implemented, then it is highly likely that a product of the specified quality will be delivered. The concept is that this is a more efficient route to quality products (including their safety) than supplying products and then inspecting them and rejecting those found to be below standard. There is clearly a degree of risk in relying entirely on process definition and control as a guarantee of quality. There is a body of opinion in the construction industry that ISO9000 systems are not robust enough and do not control quality effectively but rather only 'generate paper'(23). There is concern that the exercise may degenerate to only the filling in of forms and ticking of boxes and may therefore be ineffective. The experience of failure of quality control procedures at British Nuclear Fuels' Demonstration Facility in 1999 is salutary(24). It is an illustration that the mere existence of a quality assurance scheme does not absolve the organisation and individuals from administering it correctly and from having sufficient competence to undertake that task.

There is the additional problem in the construction industry that the designers are not necessarily from the same organisation as the builders. An ISO9000 design system can produce a 'product' in the form of drawings and specification. This is not the ultimate product, which is only delivered to the client after construction where the designers may have limited or no control or supervision over the construction process.

A system complying with ISO9000 should minimise the risk of poor quality being delivered. It should, at least in theory, reduce the amount or extent of independent checking and testing needed but, of course, it does not eliminate the risk entirely. A quality management system conforming to ISO9000 series means only that a system is in place to provide some reasonable assurance that the product will consistently meet specification. It implies, of course, that the product specification itself is correct for the intended use.

In view of the risk of relying entirely on process definition and control, some degree of inspection or validation is almost always included in any quality assurance system. For safety-critical products the degree of risk that can be accepted is a matter of great importance. There is, of course, a degree of risk in relying entirely on either self or even on independent checking, if it is only on a 'sample' basis.

2.6 Checking and certification

Certification, accreditation and audit

Certification of design or other structural engineering work is a formal step included in many engineering projects to provide additional assurance that defined requirements are met. Certification may be by the project engineer within the design organisation, commonly termed self-certification, as part of the organisation's quality management system. It may also be by a separate group employed by the organisation originating the work. This is also sometimes referred to as self-certification. Alternatively an independent third party certifier may be employed by the client. Arguably the latter provides the greater assurance. The closer the organisational link of the certifying function is to the work originator, the greater the risk that commercial and other pressures will influence the certification process, weakening the assurance provided.

Proposals for the self-certification of work in the construction industry appear to be increasing. Two such areas of work have been discussed by the Committee, the self-certification of work under the Building Regulations and the testing and checking of materials and components carried out by the producer/contractor. The question considered was whether the checks and balances in self-certification arrangements are sufficient to ensure the safety of the completed structure.

The Committee believes adequate assurance can be provided through self-certification only if self-certification is entrusted to:

- appropriately qualified and experienced persons and they are certified as competent by an independent accredited body that also audits their work.
- individuals and not to enterprises or groups of unidentified people.

It may be argued that, given these requirements, it would be more beneficial to adopt third party certification in the first place.

Independent certification of organisations to certify their own work is usually undertaken by specialist companies that are accredited independently to give certification. Accreditation bodies must be recognised widely as having the capability to certify persons and organisations. It would be wrong however, to assume that such bodies are somehow perfect. Certification is generally assigned to an organisation to undertake defined design, manufacturing or construction processes with specific tasks in the processes restricted to named individuals who are accepted by virtue of experience, training and/or demonstration as competent to undertake particular tasks. The management systems to ensure the correct procedures are followed, with the tasks undertaken by those named as competent, need to be tight. For this purpose independent auditing by an accredited body is essential.

Given that these requirements are met, the assurance obtained is, even so, considered by the Committee to be insufficient for safety-critical aspects of design and construction of many structures, i.e. those whose failure would have high consequences. Safety-critical aspects are considered to include design concept, design and construction of critical structural elements, and erection and temporary works. For these situations direct third party, independent, checking is needed to give the assurance required.

Self-certification of design under the Building Regulations

In October 1997, the Department of the Environment, Transport and the Regions (DETR) issued proposals for reducing the administration burden of the Building Regulations by means of self-certification. The response to the principle of self-certification was reported to be largely favourable. Following on from these proposals, in October 1999 the DETR Building Regulations Division issued a Consultation Paper[25]. The Institutions of Civil and of Structural Engineers have prepared a joint response to this document. The Consultation Paper also generated correspondence in the *Verulam* column of *The Structural Engineer* and comment elsewhere in the press. Some comments expressed concerns that self-certification can have adverse effects on safety. The essence of the concerns was that commercial pressures on consultants and contractors would force them to 'put profits before safety'. The value from a structural safety point of view of a truly independent third-party check was mentioned in several comments.

An open letter issued by the Wessex Area Local Government Structural Engineers in February 2000[26] highlighted concerns that, due to pressure for Building Control to be self-financing, public safety is being compromised. The letter stated that:

"an independent third-party check is believed to be essential on issues relating to safety. Structural proposals often receive insufficient attention due to the ubiquitous pressure to keep costs down. Smaller Building Regulations Applications are frequently submitted with minimal information with structural elements having safety factors lower than required by British Standards and, in some cases, having potential for structural failure".

This letter raises concern about the competence of those making Applications for small building projects. It should be noted however that a self-certification scheme has been successfully used in building construction for some years in Scotland where the project engineer, who is required to be a chartered civil or structural engineer, signs for the work. The scheme minimises the risks of such engineers working beyond their competence or being unduly influenced by commercial pressures since they are bound by professional codes of conduct.

The DETR Consultation Paper was concerned primarily with inviting expressions of interest from organisations that wish to certify competent enterprises, i.e. competent to self-certify that their own work meets the requirements of the Building Regulations. The focus was on two possible types of competent enterprise, specialist contractors who primarily undertake one type of work and contractors or clients who have the necessary expertise to certify the whole work or scheme. The DETR aim in the first stage of its initiative was to implement a scheme in which approved bodies authorise persons to self-certify their own work.

The proposals in the DETR Paper were silent on the scope of work that individuals (or organisations in a later stage of the DETR self-certification initiative) would be approved to self-certify. Risks to structural safety are generally higher, the greater the scale of the structure and the more innovative or unusual it is in concept or detail. Individuals who certify their own work relating to Part A of the Building Regulations would clearly need to restrict themselves to structures within their limits of competence. As structural projects increase in size and complexity, a matching set of checking options is needed. The design and construction of complex structures whose failure would have high consequences, e.g. grandstands, should require independent third party certification of safety-critical work.

Definition of the limits of scope of structural engineering work that individuals can self-certify is necessary. Whilst the definition of scope may be difficult to determine, it is important since work beyond the scope may invalidate any indemnifying insurance. A reasonable approach would be to base the limits of scope on the competence of the individual as demonstrated by experience and track record with an overriding requirement for defined structures that are innovative or whose failure would have high consequences to be checked independently. Some form of independent certification of engineers, as envisaged in the DETR paper, will be needed to control certification of individual's competence.

There appears to be a general acceptance that truly independent third-party checking is the surest form of checking that structural design is sound. Accepting this view as valid, it remains necessary to determine in what circumstances independent third-party checking is necessary or essential. An approach to answering this question might be developed on the basis of the risk (probability and consequences) should a fatal error in design go undetected. The greater the risk, the greater should be the independence and thoroughness of checking.

This principle has been used successfully for many years by the Highways Agency in approval procedures for highways structures[27]. Structures are classified into four categories depending on cost and complexity. A hierarchy of approval and checking levels is specified, the more stringent levels being required, the more costly and complex the structure. For the lowest category, design may be checked by another engineer within the design team. At the other extreme, the design of complex structures has to be checked by an independent separate organisation. Independent checking of erection proposals and temporary works details is also required for major highway structures on trunk roads and motorways[28]. The requirements apply also to any innovatory or special temporary works or falsework. These requirements recognise experience indicating that risks to the safety and stability of highway structures are generally greatest during erection.

Self-certification of construction materials and components during construction

The second area of Committee discussion on self-certification concerns the testing and checking of materials and components during the construction process. Similar concerns and arguments apply. Two aspects may be distinguished, non-proprietary products and their incorporation into the construction, and proprietary components and products.

Non-proprietary materials and components

The trend away from independent testing and checking appears to be due mainly to the adoption of design-and-build contracts and of ISO9000 quality assurance systems. As a result, testing and checking of non-proprietary materials and products and their incorporation into the construction may be carried out by employees of the producer/contractor. The concern is that they cannot be relied on with confidence. They may not have the resources, ability, experience, willingness or status to carry out sufficient checking, spot problems and ensure that inadequacies are dealt with. When testing and checking is not undertaken independently, it is difficult to ensure that management supervision and personnel are free from internal and external commercial and financial pressures and other influences that may adversely affect the quality of their work. Confidence in self-testing and certification can be enhanced by the client engaging an independent organisation to undertake quality audits on the contractor. The organisation employed must be independent and experienced in both construction and quality assurance. In cases where the consequences of below-standard work by the contractor are not safety-critical, such audits may be acceptable as a substitute for independent third party certification and testing.

A lower risk of below-standard materials and components being used in construction is likely where the testing and checking is undertaken by a financially independent organisation not subject to the risks of commercial pressure. Complete independence may not be present in the testing and checking of materials where the work is undertaken by a UKAS approved laboratory commissioned by the contractor. Greater independence arises where the commission is by the client. A UKAS approved laboratory is required to "have arrangements to ensure that its management and personnel are free from any undue internal or external commercial, financial and other pressures and influences that may adversely affect the quality of their work". This requirement may be difficult for a contractor to uphold when he is testing on his own contract. Although 'ring fences' can be put around the testing work, they are vulnerable to being undermined by conflict of interest. Most commonly, inadequate testing and checking leads to shortfalls in the long-term serviceability of the construction, but in some cases structural safety may also be prejudiced.

Proprietary materials and components

For proprietary components and manufactured products, certification through independent third party assessment bodies, such as the British Board of Agrément, provides assurance that components and products meet the requirements of the appropriate specification. The soundness of their installation into the construction may rely on checks made by the contractor's employees. Clearly a product known to be fit for its intended use either by way of having statements of conformity to a standard and/or certification through an independent assessment body, although an excellent product, may not be installed as it should be. More assurance in this case may be obtained by installation made under approved installer schemes. Such schemes have to take regard of not only the products themselves but also their consistency of production and their correct installation.

The way forward

In modern procurement environments, the principle of "the greater the risk, the more independent and thorough should be the checking" should be applied based on risk assessments. Whilst this suggestion may appear daunting to some, it is effectively what most project managers do implicitly at present. The question is perhaps whether safety would be better served if the process were more formalised. A possible framework for this purpose is described below.

For inspection and testing during construction for example, a hierarchy of categories and requirements, analogous to that used by the Highways Agency for highway structures, can be envisaged along the following lines:

(A) For areas of works where a low risk assessment is found, use self-certification by the supplier with the results made available to both contractor and client.

(B) For areas of works where medium risk is found, use self-certification based on independent inspection and testing by a body that is not necessarily commercially independent from the supplier, e.g. a related company specialising in inspection and testing.

(C) For areas of work where medium to high risk is found, use certification based on inspection and testing by a separate body employed by the supplier. Alternatively the inspection and testing team could comprise resources drawn on a 50-50 basis from the supplier and from an independent testing and inspection body appointed by the client.

(D) For areas of work where a high risk to structural safety is present, use inspection and testing by an independent body appointed by the client.

Assessment of whether risk is low, medium or high might be based on factors along the following lines. Low risk would relate to situations where non-compliance is easily identified and rectified and the consequences for the completed works are low. Medium risk would relate to those situations not assessed as low or high risk. High risk would relate to those situations where non-compliance would result in high consequences, i.e. losses of human life, high financial or operational consequences, serious impact on public confidence, a much extended timescale before the non-compliance can be corrected, or low feasibility of correcting the failure. A non-compliance jeopardising structural safety would be classified as a high risk.

In addition, audit inspection and testing can be introduced by the client to check that the system (A), (B), (C) or (D) is functioning correctly. Three levels of audit may be envisaged - client receives results of inspection and testing for part or all of the works, client witnesses part or all of the inspection and testing, and client inspects and tests part or all of the works. The last option would be appropriate for high risk situations.

The auditing of contractor's work is a part of quality assurance It may be in-house (i.e. self-auditing as part of a quality management system), third party commissioned by the in-house organisation, or independent third party in the form of an accreditation body or other independent body. Auditing is generally perceived to give greatest assurance when it is carried out by a financially independent third party. Since it is done at intervals, it does not give continuous reassurance, nor the assurance gained through fully independent checking of all stages of work in a construction process.

2.7 Application of risk assessment methods

Evolution from prescriptive codes-based approaches towards a more systematic and rigorous approach to preventing failures in engineering systems began following experience and inquiries into catastrophic failures in the nuclear, chemical process, offshore oil and railway industries and the increasing understanding of the human contribution to accidents. The emphasis in these industries has turned more to a 'goal-setting' approach in which hazards are identified and assessed and then measures determined to control the risks arising. Use of a 'goal-setting' approach has been encouraged by legislation, e.g. Health and Safety at Work etc Act 1974, and associated regulations. The legislation deals with initial and ongoing health and safety for occupational purposes. Such regulations include the Workplace (Health, Safety and Welfare) Regulations 1992 which are due for review and are scheduled to be augmented to include a specific requirement for ‘solidity and stability’ of buildings(29).

Structural engineering generally appears not yet to have adapted to use the more explicit and rigorous ‘goal-setting’ approaches to manage risk. Whilst these procedures are incorporated within the licensing processes for nuclear and offshore structures for example, they are not recognised in some codes of practice for structural design. Part A of The Building Regulations(30) and Approved Document A(31), dealing with structure and currently under review, do not encourage a systematic identification of likely hazards and assessment of the risks at the outset of the design process. Nor is there guidance that relevant critical situations for design should then be selected reflecting the conditions that can reasonably be foreseen during future use. Additionally in practice there is frequently a shortcoming in the provision of a maintenance regime or manual such that the client is made to realise that maintenance must be carried out to preserve structural adequacy.

Approved Document A either refers directly to Codes of Practice for the structural design (but also includes a prescriptive approach for reducing the sensitivity of a building to disproportionate collapse) or it gives prescriptive solutions. The latter relate to small buildings and dwellings where experience has shown that, by adopting particular forms, materials and dimensions, safe structures result. The use of prescriptive solutions in this way is entirely reasonable. There is no need when designing such small 'traditional' structures to go to the lengths of determining critical situations for design from consideration of likely hazards and risks, and then making a structural analysis and detailed design. Essentially the prescribed solutions encapsulate experience and thus take structural risks into account.

It is only for structures whose failure would have high consequences or for innovative structures where the service environment and structural requirement is likely to be less predictable, that a more fundamental approach is desirable to achieve safety. Existing Codes of Practice for structural design leave the assessment of hazards and risk and the determination of overall structural concept largely to the skill and experience of the designer. They focus primarily on defining methods for verifying the design of individual structural elements. For structures whose failure would have high consequences or for innovative structures, there is little guidance in codes of practice on the early stages of the design process leading to decisions on the structural concept. These stages should require an explicit process of risk management, including the identification of hazards and assessment of the risks followed by the selection of critical situations for design. Risk management, however, cannot be fully acceptable unless it is framed against the background of the public perception of risk. Whilst there may be a general acceptance that living is essentially hazardous, the public acceptance of risk depends on many factors. Hazards cannot be eliminated in general, although there appears to be public pressure for the total removal of involuntary risk(32).

The identification of hazards and assessment of risks for large or innovative structures is likely to be most effective where several experienced engineers consider together what hazards might arise in the life of the structure. Such considerations naturally should include the stability and critical conditions that apply during the construction, when partly completed elements may be prone to instability, wind or other temporary effects, e.g. erection of composite steel bridges.

It is important to recognise that a type of structure which is outside the experience of the project team may be considered innovative to them although it may not be innovative in worldwide terms. They may not therefore recognise the risks. This shortcoming should be offset by study and systematic identification of hazards by a group of experienced engineers. It is no easy task for a project team to identify and take benefit from experience of a proposed innovation that may exist elsewhere in the world. However, the Committee considers that such studies considerably reduce, although not eliminate entirely, the risk that relevant experience elsewhere in the world is overlooked.

2.8 Conclusions

(1) Structural safety can be placed at risk by active errors by designers, site personnel and the like and by latent errors introduced through inadequate procurement procedures, codes, standards and regulations.

(2) Codes and standards provide the core means of controlling risks to structural safety. Identified shortcomings should be addressed with urgency. It must be recognised that there may be gaps in codes and they may not cover recent innovation.

(3) The control of risks to structural safety depends primarily on the competence and integrity of individuals and organisations. The possibility that

individuals or organisations might not be competent, or that their competence might be affected by commercial or other pressures is a risk to structural safety and needs to be controlled.

(4) Supervision and management systems used to control risks to structural safety should include appropriately independent arrangements for checking safety-critical elements. There is doubt as to whether systems conforming with ISO 9000 are adequate for this purpose.

(5) The certification of structural safety-related work should be entrusted only to appropriately qualified and experienced engineers.

(6) Certification by the work originator of the design and construction of structures whose failure would not have high consequences can give adequate assurance of structural safety provided there are appropriate systems in place for ensuring competence.

(7) For safety-critical aspects of design and construction of structures whose failure would have high consequences, third party independent certification is needed to give adequate assurance of structural safety.

(8) For structures whose failure would have high consequences and for structures that are innovative or unfamiliar in relation to the experience of the project team, an explicit process of risk management should be used. The process should include the systematic identification of hazards and assessment of risks to structural safety, followed by the selection of critical situations for design.

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3 DYNAMIC RESPONSE OF STRUCTURES

3.1 Introduction

The loads that most buildings and many other structures are designed to resist are generally represented as static and stationary although many of them are not. For design, live loads are often represented by equivalent static values of uniformly distributed loads that give the same overall load effect as peak values of the actual loads of short duration. The self-weight of a structure is usually the only load that does not vary significantly. Naturally-occurring environmental loads, e.g. wind, and most man-made loads, e.g. traffic, vary substantially over both time and space.

The use of static design loads makes for ease of design, although it does not, by definition, examine dynamic response from variable or rhythmic loading. It produces structurally-safe designs for most structures because they are sufficiently stiff such that dynamic responses or vibrations are inhibited. In these situations there may nevertheless be a need to take account of the variations in loading in the design.

Impact or rapidly applied loading, such as when vehicles cross a bridge, increases the loading effect. This increase is generally allowed for in design codes by use of an impact factor. It is used to give an equivalent static load or enhanced load effect for design. There may also be other impact hazards arising from accidents, e.g. accidental vehicle impact on bridge supports, that need to be designed for. Additional capacity in the structure is therefore required to ensure safety. This is usually provided by specifying additional design forces which represent the accidental effect. For example, bridge supports located within 4.5m of railway tracks are required to resist an assumed horizontal force of 2000kN. Similarly, bridge supports and the soffits of bridges over highways are designed for particular forces depending upon their proximity to the roadway so as to reduce the risk of collapse of the structure if it is struck accidentally.

The hazard of fatigue failure is generally associated with fluctuations of load on structures rather than the dynamic response but it can be a mode of failure of dynamically responsive structures in some circumstances. The phenomenon of fatigue arises where repetitive loading occurs over a period of time, e.g. on bridges due to traffic or on offshore structures due to current and wave actions. It occurs in metal structures, but also to some extent in concrete, and is manifest by the growth of cracks at critical details of the structure, which can lead to eventual failure or to maintenance needs. Where there is a significant risk of fatigue failure, design against it is usually made separately, alongside a static design, using analysis and criteria based on an assumed spectrum of the loads that the structure will experience in its design life.

Vibration may also be a significant feature of the response of some structures to dynamic loads. Some structures or parts of structures may have natural frequencies that are equal to or multiples of the frequency of an imposed dynamic load. Such coincidence, or near coincidence, of frequencies can give rise to a resonant response of the structure in which the amplitude of structural vibrations and stresses may both increase rapidly over time. These increases in vibration amplitude and stress are countered by damping inherent in the structure or by damping added artificially to limit the amplifying effects. The response may be unacceptable in terms of acceleration and/or amplitude causing discomfort or alarm to users or loss of operation of processes housed by the structure. In the extreme, resonance can lead to damage or collapse of the structure itself.

Structures that may be subject to the hazard of resonance are generally those that have low stiffness and relatively high mass in relation to the applied loads. Examples of structures where this hazard can be significant are tall buildings, masts and chimneys and slender flexible bridges (subjected to wind loading or pedestrian loading), railway bridges on high speed routes, and cantilevered seating decks of grandstands subjected to crowd movement involving rhythmic jumping. In these cases a ‘static’ design is not always adequate to ensure that the risks from the hazard are acceptable. A ‘dynamic’ design is required in which the feasibility of controlling the loading is considered and the response of the structure is examined. The static design is then adjusted where necessary, for example by modifying the natural frequencies of vibration such that they do not coincide with the high risk loading frequencies. An example of structures where the risk is reduced through modification or control of the loading is the use of helical strakes on tall circular chimneys where the strakes break up the phenomenon of vortex shedding which can induce excessive vibrations transverse to the wind direction. Another example is the prohibition of the use of musical stimulation of crowds on grandstands.

The risk of an unacceptable dynamic response of potentially susceptible structures cannot generally be controlled with sufficient assurance solely by modifying the loading. In addition, it is necessary to design the structure to minimise susceptibility, where possible.

Recent experience of structures where unacceptable dynamic response has arisen is reviewed briefly below.

3.2 Cantilevered seating decks at sports grounds

The safety of grandstand structures at sports grounds has been discussed in recent SCOSS Reports(1). Over the past two years the attention of the Committee has again been drawn to the trend to build cantilevered seating decks with increasingly large seating capacity.

A considerable number of sports stadia have been built in the UK during the last decade(2). Modern cantilevered grandstands are major, often spectacular, structures, eg Cardiff Millennium Stadium(3), built to challenging timescales and other requirements. The consequences of a structural collapse or disturbing movement causing panic amongst an occupying crowd could be very high given the large numbers of people that might be involved. An additional factor in considering such risks has been the knowledge that cantilevered structures can have a high susceptibility to collapse if local structural damage or failure occurs.

Some relatively modern structures in the United Kingdom are known to be prone to respond dynamically to rhythmic crowd movement, particularly where stimulated by rhythmic music. In some cases the structure has had to be modified or its use curtailed to limit the risk of unacceptable dynamic response.

There are a number of uncertainties concerning the behaviour of crowds at modern sports events. Synchronisation of rhythmic movement of a crowd is usually necessary for a dynamic response of a cantilevered seating deck to be generated. Rhythmic music with a strong beat assists synchronisation but the extent that may be achieved in any particular circumstance is not quantifiable. It appears also that a significant degree of synchronisation can be achieved without the aid of music and particularly if elements of a crowd behave in a wilful way.

There are also uncertainties relating to the analysis of the structure to determine the action effects for detailed design. Cantilevered seating decks are usually designed first on a 'static' load basis, generally seeking to achieve the longest cantilever possible, thus giving the largest seating capacity. A check may then be made of the fundamental natural frequency to determine whether it is above that associated with rhythmic crowd movement[4,5]. For this purpose methods based on a full three-dimensional representation of the structure to determine natural frequencies and establish significant modes of vibration are believed to be accurate generally. Short-cut approaches using, for example, two-dimensional analysis or the static deflection profile to estimate natural frequency, can lead to inaccurate approximations.

The uncertainties in the design of cantilevered grandstands for dynamic effects may be reduced gradually by specifically targeted research. However, in the meantime owners and operators will require existing grandstands to continue safely in use and they are likely to seek the design of 'bigger and better' grandstands. Such requirements can be met provided the uncertainties are adequately offset through the design and construction processes and control of the use of the structure.

A Working Group convened by the Institution of Structural Engineers (IStructE), the Department of Environment, Transport and the Regions (DETR), and the Department of Culture, Media and Sport (DCMS) was set up on 1999 to review current design approaches, analytical methods and test data and to propose design recommendations. It is expected to issue Interim Guidance during 2001.

3.3 Dynamic behaviour of bridges under pedestrian loading

The dynamic behaviour of the Millennium Bridge over the River Thames in London, completed in 2000, resulting from pedestrian traffic surprised many people. Although the basic concept is that of a suspension bridge, the conventional proportions were extended to create a very shallow bridge profile and the suspension cables were inclined and curved in plan. The resulting tension ribbon bridge obtains almost all its stiffness in both vertical and lateral directions from the geometric stiffness of the cables. Such a structure would be expected to vibrate to some extent under pedestrian use or wind loading, and indeed, lateral and torsional response to eccentrically applied loads was assessed during the design process. However the observed lateral vibration of the footbridge under pedestrian traffic was a resonant response with the resonant lateral motions caused almost entirely by dynamic forces exerted horizontally by pedestrians [6].

An apparently similar swaying phenomenon of the new Pont Solferino in Paris, whilst pedestrians were crossing it during the opening ceremony, was reported to have led to its immediate closure in 1999. Other instances of bridges suffering excessive lateral vibration under crowd loading have come to light during the investigations of the Millennium Bridge. The investigations have indicated that this vibration phenomenon can arise on a bridge of any structural form. The only requirements for susceptibility to synchronous lateral excitation are a lateral mode of low frequency, i.e. below about 1.3 Hz, and traffic by a sufficiently large number of pedestrians[6]. The implication for existing bridges with low lateral frequency is that, unless a particular bridge has experienced its critical number of pedestrians, there will not have been any evidence that there may be a potential problem. There may be many bridges that have only experienced moderate pedestrian traffic and have performed well, but which, if subjected to perhaps only a slightly greater pedestrian density, could suffer strong lateral vibrations.

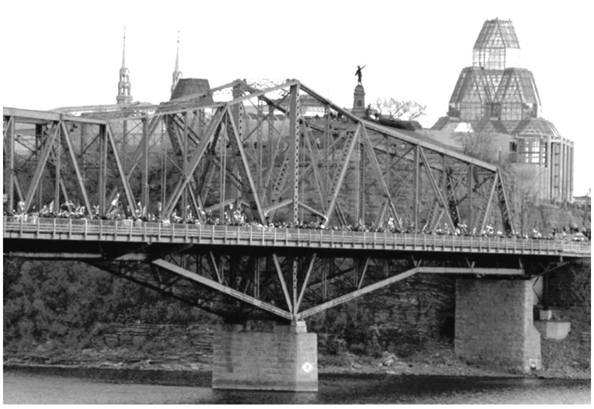
Current bridge design codes cover the effects of vibration due to pedestrian and wind loading on conventional bridges, but do not deal with the form of horizontal vibrations which was experienced on the Millennium bridge. The intensive studies that have now been carried out on this potentially critical loading effect have increased understanding of the phenomenon. Technical notes have now been published, providing a valuable sharing of knowledge and alerting designers to the phenomenon[6,7]. They helpfully. identify research needed to develop design rules. This research would be beneficial in providing engineers with a fuller basis for design to avoid or control the phenomenon in future bridges and for assessment of the risk in existing bridges.

The Committee draws attention also to a second implication of the experience of the Millennium Bridge. Scant references were found in the literature to the lateral vibration phenomenon[8] even though it has been observed on several bridges. Where observed behaviour is previously unknown, whether failure occurs or not, it is incumbent upon professional engineers to report the observations in the technical literature, if possible, so that others are alerted to potential risks to safety, see Section 6

3.4 The education of engineers

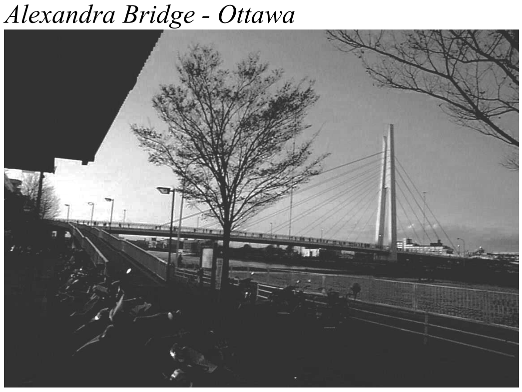
There appears to be a trend in structural engineering towards the use of more slender and larger structures. The trend is a result of society seeking more elegant and exciting solutions and clients seeking greater economy in meeting increasingly onerous structural performance requirements. Today structural engineers are therefore much more likely to be required to

London's Millennium Bridge
Photo: K Stansfield



Alexandra Bridge - Ottawa

NEC Bridge - Birmingham



T-Bridge - Tokyo

Queen's Park Chester

Figure 3: Examples of bridges on which synchronous lateral excitation has been observed

design dynamically responsive structures than in earlier decades. The ability to identify dynamically sensitive structures has therefore become a necessary part of a structural engineer's skills. Often the emphasis in engineer's education is however on 'static' design based on computer analysis.

The design of dynamically responsive structures for safety and to meet performance requirements for acceleration and frequency is a relatively complex subject. It is perhaps not sufficiently well covered as a matter of course in the education and formation of civil and structural engineers. Today these engineers should, it is suggested, learn the principles of the subject as undergraduates. There may also be a need for more post-graduate courses specialising in structural dynamics. In addition practising engineers should perhaps have more opportunity to develop their skills in identifying and designing dynamically responsive structures as part of their continuing professional development. In summary, there is doubt in the Committee as to whether the balance in the education and formation of civil and structural engineers gives sufficient emphasis to developing understanding and skills of visualising structural behaviour under dynamic loads.

3.5 Conclusions

(9) Specifically targeted research is needed to evaluate the uncertainties in the structural design of cantilever seating decks for dynamic effects and to assist the IStructE/DETR/DCMS Working Group.

(10) There may be many bridges that have only experienced moderate pedestrian traffic and have performed well but which, if subject to greater pedestrian density, could suffer strong lateral vibrations.

(11) Where previously unknown structural behaviour is observed, whether failure occurs or not, it is incumbent upon professional engineers to report the observations in the technical literature, if possible, so that others are alerted to potential risks to safety.

(12) The identification of dynamically sensitive structures and the visualisation and understanding of structural behaviour at the design stage may not be sufficiently well covered in the education and formation of civil and structural engineers

3.6 References

(1) *The Standing Committee on Structural Safety*, Reports: October 1992, October 1994, January 1997, February 1999.

(2) 'Sports stadia in the UK.' *Structural Engineering International*, Vol 9, No 3, August 1999, pp. 186-199.

(3) Otlet, M and McLaughlin, D. 'Design and Construction of the Millennium Stadium, Cardiff.' *The Structural Engineer*, Vol 78, No 20, 17 October 2000, pp 22-29.

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(5) British Standards Institution, BS6399 (1966), Part 1: *Loads for buildings.*

(6) 'The Millennium bridge, London: problems and solutions.' *The Structural Engineer*, Vol.79. No.8, 17 April 2001, pp 15-17.

(7) 'Pedestrian-induced vibration of footbridges.' *The Structural Engineer*, Vol 78, No 23/24, 5 December 2000, pp 13-15.

(8) Bachmann, H and Ammann, W. *Vibrations in structures induced by man and machines*. Structural Engineering Document 3e. International Association for Bridge and Structural Engineering, Zurich, 1987.

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4 NATURALLY-OCCURRING HAZARDS TO STRUCTURES, INCLUDING CLIMATE CHANGE

4.1 Introduction

The naturally occurring environmental hazards that threaten the structural safety of a building, bridge or other civil engineering structure arise primarily from the climate and sometimes from naturally occurring chemicals or earthquake phenomena at the location of the structure. The main climatic hazards are the effects of extreme wind, snow, rain, ice and temperature (including flooding, scour, settlement and instability of the ground). The risks associated with these hazards are usually controlled using predictions of extremes based on historical data of magnitude and frequency. In structural engineering, it is generally assumed that future risks will be the same as historical risks. This may not be the case if the climate changes.

4.2 The implications of climate change

Losses to the economy and insured losses worldwide due to damage caused by extreme climatic events are considerable and increasing. For example, losses from major windstorms have increased dramatically in the past thirty years. Of course only a part of the losses arise from structural collapses and damage. The increases have been due predominantly to factors such as increases in population density and living standards, the habitation of previously avoided 'risky' regions, and greater demand for insurance cover. The contribution of future changes in climate however could be significant if the changes predicted are realised.

The last decade (1990-99) was the warmest on record in Europe, both annually and for the winter season(1). Most scientists now agree that the climate is warming as a result of human activities(2,3). It is expected that global climate will continue to change throughout the present century, particularly if no additional action is taken to mitigate greenhouse gas emissions. Uncertainties remain however in the predictions of the extent of the changes that will occur(3). Generally with global warming more extreme and variable weather can be expected: more gales, more floods, more heat waves and more droughts.

4.3 Future changes in UK climate

National and international work on climate change gives a basis for examining the likely impacts on society and, more specifically, for examining how engineers may need to respond(4,5,6). The UK Climate Impacts Programme (UKCIP) has presented four scenarios (low, medium-low, medium-high and high) that span a range of possible future UK climates(5). For the UK warming rates are expected to be similar to global warming rates, i.e. from about 0.1^oC to 0.3^oC per decade. The south-east warms more rapidly than the north-west of the UK.

For many engineering purposes changes in the frequency of extreme events will be more important than changes in the average climate. Changes in frequency can be illustrated by looking at how often a very warm year like 1997 is predicted to occur in the future. 1997 was the third warmest year ever recorded in the UK. It was nearly 1.1^0C warmer than the average 1961-90 temperatures. By the 2080s nearly all years are predicted to exceed the warmth of 1997, except for the low scenario.

Increases in average sea level around the UK coast will be very similar to global increases, i.e. in the range 12-67 cms by the 2050s relative to the 1961-90 average. In addition it is important to take vertical land movements into account when assessing impacts on coastal environments. These rises or falls of the land are the result of tectonic adjustments from the last glaciation 15000 years ago. Much of the southern UK is sinking and much of the northern UK is rising. By the 2050s East Anglia is expected to sink by about 9cm and western Scotland to rise by about 11cm.

Most detail on the medium-high scenario has been given by UKCIP. For this scenario which is reported to be no more likely than the low and high scenarios:

(1) Winter temperatures become less variable while summer temperatures become more variable.
(2) Precipitation becomes less reliable from year to year despite the fact that it increases in winter/autumn and decreases in spring/summer.
(3) The probabilities of certain seasonal climate extremes change, e.g. hot 1997-type August and summer rainfall deficits become more frequent.
(4) Extreme wind events – high summer wind speeds will be more frequent in the northern UK. In winter, overall gale frequencies decline although very severe winter gales increase in number.
(5) The climate will change gradually and the change will often be masked by natural variability. Because of the natural variability, the establishment of record extremes, e.g. maximum temperatures or wind speeds, will be sporadic.

4.4 Implications of UK climate change for structural safety

Hazards to structural safety from the climate may arise from several variables, including:

(1) Extreme winds.
(2) Extreme precipitation, especially snow.
(3) Extreme precipitation leading to flooding and scour.
(4) Periods of drought and high temperatures leading to ground movements.

(5) Extreme depositions of ice on structures.
(6) Extreme diurnal temperature changes.
(7) More severe wave climate at sea.

The design and assessment of structures normally take these hazards into account using predictions of climate based on local meteorological historical information. At present, information on likely future climate change is not available at this level of detail. However, it is important to recognise that the consequence for structures may be magnified by the non-linearity of the effects.

There have been calls for action by engineers and others to counter the more damaging effects of global warming[6]. Actions suggested include:

(1) Whilst flooding cannot be stopped altogether, the worst effects of increased rainfall can be channelled.
(2) Stop building on flood plains or raise floors above flood level.
(3) Increase coastal defences where practicable to resist the impacts of sea level rises and the increased frequency of storm tide surges.
(4) Modify Building Regulations to recognise increased likelihood of high winds and more extreme temperatures.

Clearly increased flooding, greater extreme winds, temperatures and/or precipitation would increase the present low incidence of collapse and damage to structures. Levels of structural safety (and serviceability) would, in effect, be reduced. There may also be implications arising from changes in the planning of building development, e.g. more building on higher ground may lead to more slip failures of foundations.

At present, engineers in the UK are not generally considering the effects of climate change in their designs. Nor are committees that are preparing and updating codes of practice for structural design and assessment taking account of likely increases in wind speeds, temperatures, or rising sea levels.

Adverse trends on structural safety that may arise from a more severe and uncertain climate may be assessed and offset in a number of ways as discussed below.

Quantification of the implications relevant to structural safety

A recent BRE report[7] has considered the implications of climate change in the built environment and suggested adaptation strategies to minimise impacts on buildings. The strategies were given in relation to domestic and non-domestic buildings, existing buildings and new.

The BRE report was based largely on the UKCIP medium-high scenario and gives some quantitative indications of the impacts using assumed increases of climate severity, e.g. extreme wind speeds. The recommendations for adaptation cover predictions of climate change, planning, design, construction process, and the maintenance and replacement of buildings.

The BRE report suggests that the confidence levels in climate predictions should be improved and regulations, codes and standards kept in line with the predictions. Whilst this is an important option to consider, it is not straightforward to determine by how much design criteria should be made more onerous.

Extreme winds may be considered as an example of a climatic hazard that is particularly relevant to structural safety. Design wind loads are currently based on historical records of wind occurrence and an assumption that the wind climate will not change in the future. To base them on an assumption of a future more severe wind climate would maintain safety but increase construction costs, perhaps unnecessarily in view of the uncertainty in the prediction of a more severe climate. Such change would be difficult to justify unless increases of construction costs are small. The 'pre-strengthening' of new structures on the off-chance that the greater strength may be needed to maintain safety in the future is perhaps not a generally valid option. However, detailed study of this option would be worthwhile since additional structural strength can be provided at the design stage much more economically than through modification after construction is completed.

It has already been suggested that monitoring and analysis of the wind climate should be a continuing process aimed at detecting and quantifying increases in the severity of the wind climate. Criteria for determining wind loads for design and assessment could then be adjusted to reflect updated wind climate data. This approach appears to be a prudent minimum as a basis for the design of new structures. A similar approach should be taken for other relevant climatic variables, e.g. temperature, and for other hazards including rising sea level and vertical movements, up or down, of the land.

The sensitivity of structures to climate change

The BRE recommendations[7], relating to planning, design and construction of new buildings and the maintenance and renewal of existing buildings, are essentially for strategies that avoid the hazard or reduce the risk. Included amongst them are several recommendations to conform to current good practice or to enhance it in an ad hoc way. Such enhancements from a structural safety point of view, e.g. use x% stronger connections, may be appropriate depending on cost, especially for housing where design is generally prescriptive. However, research into the sensitivity of structures, both existing and new design, to more severe climatic effects would be worthwhile. Research on the major types of structure, i.e. bridges, buildings, towers, masts and marine structures, would provide a basis for determining tolerance to a more severe climate and at what point enhanced design or strengthening of existing structures may be necessary to maintain adequate safety margins.

Since it is not certain that the climate will become more severe, and there is even greater uncertainty about the extent of such changes, in some cases an appropriate option may be to introduce provision for retrofitting into the construction of new structures. The threshold for action to retrofit can be decided on the basis of the monitoring and analysis of climate change and the safety margins in such structures as discussed above. It must be borne in mind that these new structures will represent only a small proportion of a very large total population of existing structures. Substantial construction resources would be needed to strengthen this total population, where generally no provisions for retrofitting exist, should the climate become significantly more severe. For this structures population generally, the impact of climate change on safety margins should be monitored nationally and internationally. Research should be undertaken to determine thresholds above which strengthening work may need to be initiated to maintain acceptable safety of structures most at risk.

4.5 Conclusions

(13) The consequences for structural safety of climate change should be regarded as a national and international issue. Consequences should be assessed taking account of the uncertainties existing in the predictions of climate change. Changes should be quantified by continuous monitoring and analysis of the climate.

(14) A prudent minimum approach for maintaining structural safety as climate change occurs would be to update design and assessment criteria as change is confirmed. Anticipating climate change in design and assessment may be justified in some cases, particularly if evidence is found that a significant change is taking place over a short time scale relative to the life of structures, say 50-200 years.

(15) Research is needed into the sensitivity of structures to climate change to determine thresholds at which the updating of design values and the strengthening of existing structures may be necessary to maintain acceptable structural safety.

4.6 References

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(4) *Climate change and its impacts: a global perspective*. Department of the Environment, Transport and the Regions, December 1997.

(5) *Climate Change Scenarios for the United Kingdom*. UK Climate Impacts Programme. Technical Report No 1, October 1998. Summary Report, September 1998.

(6) *Climate Change - A Briefing Note*. The Royal Academy of Engineering, July 1997.

(7) *Potential implications of climate change in the built environment*. BRE Report. FB2, 2000.

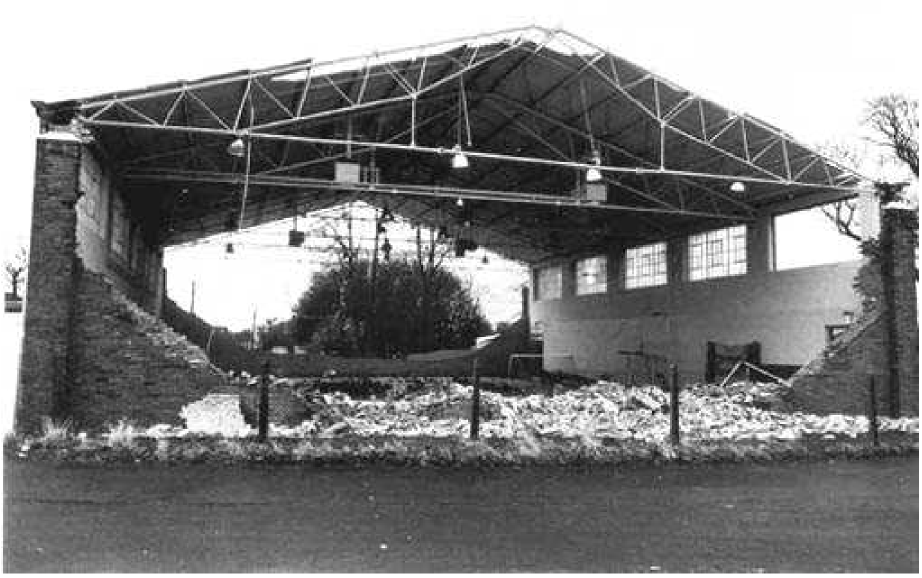

Figure 4: A wind-damaged building. If greater extreme winds due to climate change occur, more wind damage to structures can be expected
Photo: Building Research Establishment

5 DUTIES TO WARN AND HEED WARNINGS

5.1 General

Professional engineers can find themselves in situations where it might be appropriate or essential, in the interest of structural safety, to give a warning. Situations can be considered in three categories.

The easiest category is where the engineer is one amongst a group of professionals charged collectively to prepare advice and guidance for use by others relating to structural safety. In this situation, there is a duty to provide sound advice and to warn the group where the proposed guidance could lead to unsafe structures. An engineer who has received draft guidance for comment and has reason to believe that the guidance would lead to unsafe structures should, similarly, make the cause for concern known to the drafting group.

A second category of situations is where the engineer has a direct responsibility for the relevant work or structure, for example:

- An engineer checking or certifying design or construction work observes an error or situation that he reasonably believes to be unsafe or likely to lead to an unsafe structure.
- An engineer checking the quality of materials or fabrication of structural components, whether off-site or on-site, identifies quality below specification.
- An engineer monitoring the stability of a structure during construction observes movement indicating the approach of a potentially unstable condition.

In these situations, it is usually clear both that a warning should be given and to whom it should be given in the first place.

Greater difficulties arise in the third category, which are more complex situations such as:

- An engineer who has a direct responsibility for the relevant work or structure, has given a warning to the proper person, but finds that that person is ignoring the warning.
- An engineer employed in design or construction of a structure observes a situation that he reasonably believes will lead to an unsafe structure, but the control of the situation is outside his direct responsibility. Colleagues who are responsible pay little or no attention to his concerns.
- An engineer passing a structure as a member of the public identifies a structural condition or work that he reasonably believes to be unsafe.
- An engineer has observed an unsafe situation or novel structural behaviour, which has passed uneventfully, but considers that the situation could recur or arise in other similar circumstances.

In all these situations, the engineer has to deal with four questions:

- Whether to warn (or give further warning)
- When to warn
- Who to warn
- How to warn

The situations differ in the immediacy of the risk and also the extent to which the individual's concerns can be raised within the collective responsibility of a peer group. In some cases, the unacceptable risk does not yet exist but it may be created in the future.

Where observed structural behaviour is novel or failure occurs, the knowledge should be promulgated through the technical literature alerting others to potential unsafe practice and situations. For example, the dangers of overconfidence in computer analysis were reported following the investigation of the collapse of the roof of the Hartford Civic Centre Coliseum under a heavy snowfall(4). Similarly, the implications of the unexpected behaviour of the Millennium Bridge have been drawn to the attention of structural engineers generally, see Section 4.

Guidance on whether, when and how to warn was prepared by a Working Group chaired by the late Edmund Hambly and published in 1991 by the Royal Academy of Engineering (then the Fellowship of Engineering) as Draft Guidelines, and offered to the Professional Institutions for consideration(1). Although the Guidelines have yet to be formally adopted by the Institutions, the Committee commends them as very helpful guidance, particularly in dealing with the difficult questions of professional ethics that can arise. A copy is included as Appendix C to this Report for ease of reference.

The Committee would also stress the need for clarity in warnings. The wish to avoid the appearance of criticism can sometimes lead to obfuscation. A warning, which is not clear and direct, may completely miss its purpose. Complaints that warnings have not been heeded can often be explained by the lack of clarity of the warning.

The Committee itself issues warnings generally through its published reports, bulletins and web site and sometimes through technical journals. For example, see recent articles about ply-web timber beams(2) and stadia crush barriers(3).

There is a corresponding duty on persons to heed warnings. There is a duty to heed specific and immediate warnings. There is also a longer-term duty to note and digest warnings for the future. There may even be a duty to consider the significance of warnings in relation to work which has already been completed.

5.2 Confidential reporting systems

The Committee has been attracted by proposals for a confidential reporting system for the construction industry. There is increasing development and use of such systems in some other sectors of industry, particularly in transportation, e.g. air[5] and shipping[6]. There is a difference, however, in that those systems are generally concerned with learning from incidents which have passed. Civil and structural engineers may have concerns about ongoing, live problems. At present, the Committee itself welcomes warnings relating to long term dangers. Senior officers of the Institutions of Civil Engineers and of Structural Engineers respond to situations where reference is made to those Institutions. However, the Committee would welcome views on whether a more extensive confidential reporting system relating to structural safety, or safety in construction generally, is needed and would be used.

5.3 Conclusions

(16) Giving and heeding warnings are essential parts of ensuring structural safety. In difficult situations, the Royal Academy of Engineering Draft Guidelines for Warnings of Preventable Disasters are commended to engineers.

(17) Views would be welcomed by the Committee on whether the establishment of a system for confidential reporting on matters affecting structural safety, or safety in construction more generally, is needed and would be used.

5.4 References

(1) 'Draft Guidelines for Warnings of Preventable Disasters Offered to the Professional Institutions for Consideration.' *Conference: Warnings of Preventable Disasters*. Proceedings. Fellowship of Engineering, London 1991.

(2) *SCOSS Bulletin 4*, November 2000.

(3) 'Stadia crush barriers alert.' *The Structural Engineer*, 6 February, 2001.

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(5) Tait P. 'Confidential Reporting in the UK. Commercial Air Transport Industry.' *Seminar: Confidential Human Factors Incident and Near Miss Reporting Programmes*. Health and Safety Executive, 1998.

(6) Beedel, R. 'International Marine Accident Reporting Scheme: Lessons from MARS.' *Conference: Learning from Marine Incidents*, London, October 1999

Figure 5 : These 1970s ply-web roof beams collapsed recently as a result of inadequate gluing of joints during manufacture. The Committee drew attention to the possibility of other roofs of similar construction being defective in SCOSS Bulletin 4
Photo: Glyn H. Robinson Associates Ltd

6 CONCLUDING REMARKS

Trends in the construction industry that may have an adverse effect on structural safety have been described in this report. The human contribution to structural failures through active and latent errors was taken as the background in Section 2 for a discussion of the control of risks to structural safety. In Section 3, particular issues concerning the dynamic response of cantilevered seating decks at sports grounds and of bridges under pedestrian loading were outlined. The potential consequences for structural safety of climate change were discussed in Section 4. Duties to warn and to heed warnings were found in Section 5 to be essential parts of ensuring structural safety.

The Committee has aimed to draw conclusions on its concerns indicating principal or general directions for future action. It is hoped that the relevant bodies in the construction industry and government will undertake in-depth and focused investigations of the issues raised as a prelude to action better to control risks to structural safety.

Figure 6: Bulging and splitting of 'sealed' hollow tubular steel members due to ingress of water. The Committee drew this potential structural safety problem to the attention of engineers in 'The Structural Engineer', 6 February 2001
Photo: Shepherd Gilmour

Appendix A - SCOSS: Origin, role and terms of reference

In the 1960s and 1970s a few structural collapses occurred in the UK, eg Ronan Point, which caused widespread concern. As a result a CIRIA Study Committee on Structural Safety was set up under the chairmanship of Sir Alfred Pugsley to examine aspects of structural design. Its Report in 1971 suggested "the establishment of a professional committee on a permanent basis to keep under review questions of structural safety and make such recommendations for action as seem desirable". The Institutions of Civil, Structural and Municipal Engineers took up the suggestion and in 1976 the Standing Committee on Structural Safety (commonly known as SCOSS) had its first meeting under the chairmanship of Lord Penney.

Today the Institutions of Structural Engineers and of Civil Engineers and the Health and Safety Executive support the administration of the Committee. The Institution of Structural Engineers provides secretarial and office services. Members of the Committee, who serve for a period of three years, are appointed by the Presidents of the two Institutions in a personal capacity and are eminent members of their profession. The current Chairman of the Committee is The Lord Lewis of Newnham, Warden of Robinson College, University of Cambridge. The primary aim of the Committee continues to be to identify, in advance, trends in the construction industry that may have an adverse effect on structural safety and to give warnings to relevant bodies where unacceptable risk is believed to exist.

SCOSS reports directly to the Presidents of the Institutions and liaises with the Directors of Engineering of the two Institutions and the Health and Safety Executive. Its Reports are published biennially. The Reports are available from both Institutions and are sent to key representatives of organisations with responsibility to contribute to structural safety. Papers and bulletins are also published from time to time to draw attention to SCOSS's recommendations and to encourage the collection and dissemination of experiences likely to foster the avoidance of structural failures and a greater measure of structural reliability.

Whilst concentrating on matters relating to the United Kingdom, SCOSS maintains an awareness and contact with construction events worldwide. In so far as its resources enable it to do so, it seeks to obtain information from overseas experience by appropriate contacts with the International Association for Bridge and Structural Engineering and other international associations.

Topics for consideration by SCOSS arise from many sources, relying upon information derived mainly from the experience of others. SCOSS seeks information on how structures actually perform in practice. It identifies where risks are thought likely to be unacceptable and then seeks changes of practice, which will maintain safety. It is itself a feedback mechanism and encourages other, more comprehensive, modes. Feedback is received through the day-to-day interaction of SCOSS members with the professions, industry and government. Feedback on topics that are considered particularly relevant is actively sought by the Secretary and Technical Officer. SCOSS receives presentations on specific topics from relevant experts. More than a hundred topics have been closely studied at some time in the last 25 years. Many of these topics are, by their nature, fundamental and ongoing and of a general nature, see Appendix D. Others are relatively detailed and result from incidents reported to SCOSS as potential problems. Not all topics drawn to the attention of SCOSS are necessarily pursued. Once a topic has been addressed, SCOSS aims to leave the matter unless it decides that there are ongoing structural safety issues which are not being adequately addressed elsewhere.

Confidentiality is an essential feature of SCOSS's procedure. This helps to encourage those who have doubts, fears or experiences of potential problems to share them with SCOSS. It also means that ideas, materials or techniques under discussion are not seen to be unnecessarily blighted by suspicions.

Terms of reference:

- Consider both current practice and likely development from the standpoint of structural safety.
- Be aware of trends and innovations in design, construction and maintenance from the standpoint of safety.
- Consider whether unacceptable risk exists or might arise in the future and, if believed so, to give warning to relevant bodies.
- Consider whether further research and development appears desirable from the standpoint of structural safety.
- Disseminate the findings of the Committee by a biennial published report and by other appropriate means.
- Avoid duplicating the work of the Health & Safety Executive, of the Institution of Civil Engineers and of the Institution of Structural Engineers.
- Report to the Presidents of the Institutions of Civil and of Structural Engineers annually and from time to time on specific issues.

Appendix B - Membership of the Committee

Chairman
Lord Lewis of Newnham Kt. FRS FRCS, Robinson College, University of Cambridge. [from May 1998]

***Members*:**

J N Barber MA LLB CEng FICE MHKIE FCIArb. Consulting Engineer. [from November 1995]

Professor D I Blockley BEng PhD DSc FREng FIStructE FICE. Faculty of Engineering, University of Bristol. Vice President: Institution of Structural Engineers. [until March 2001]

T J Collins MSc CEng MICE MIStructE. Head: Highway Structures Branch , National Assembly for Wales. [from February 2001]

Professor P Das OBE PhD CEng FICE. Project Director, Bridge Management, The Highways Agency. Visiting Professor: University of Surrey. [from February 2001]

D Fowler BSc DPhil FIStructE FIMarE MICE CEng FIStructE Independent Consultant. [from February 2001]

A C G Hayward CEng FICE FIStructE MIHT. Senior Partner, Cass Hayward and Partners. [until March 2001]

R A McClelland CEng MICE MIHT. Senior Engineer, Alfred McAlpine Civil Engineering. [from May 1999]

G S Millington OBE BSc CEng FIEI Hon FICE FIStructE FIHT MASCE. Senior Partner, Kirk McClure Morton, Consulting Engineers. [from June 1997]

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Appendix C - Draft Guidelines for Warnings of Preventable Disasters Offered to the Professional Institutions for Consideration

SUGGESTED ACTIONS FOR PEOPLE MAKING OR RECEIVING WARNINGS OF DISASTER

1. Introduction

1.1 These Guidelines suggest courses of action to assist engineers to react in a responsible, prompt and disciplined manner when they are faced with potentially disastrous situations. Engineers, in the course of their work and at other times, can identify unforeseen risks of disaster to the public or the environment. Others managing public facilities and hazardous installations can be presented with unexpected warnings of potential disaster. Engineers are placed under a professional duty to uphold the safety of the public and the environment by the codes of conduct of their Institutions and organisations. A reciprocal responsibility is placed on the Institutions and organisations to assist any member who turns to them for help in furthering this duty under the code of conduct.

1.2 Well-managed organisations have safety cultures which encourage employees to be vigilant in the identification and elimination of hazardous situations. They encourage employees at all levels to report potentially dangerous situations, and commend the employees even when a warning later proves to have been unfounded. Many organisations have established procedures for making and responding to unexpected warnings; and engineers are expected to work within such procedures where they exist. The systematic reporting of warnings enables newly developing risks to be identified before disaster occurs. These Guidelines may help organisations and Institutions to review their existing lines of communication. However, the Guidelines have been prepared primarily for the non-routine circumstances which occur rarely and which do not fall within established procedures.

1.3 The underlying principle of these Guidelines is that any person needing to make a warning or receiving a warning should draw on his professional peers to verify the risk, decide upon appropriate action and remedy the situation. By sharing the problem the person improves his own credibility and improves the effectiveness of the course of action.

1.4 In the normal course of events a warning can be given, and avoiding actions taken, in an informal manner by the individuals and organisations directly involved. It is anticipated that the more formal procedures of this document will only be followed on very rare occasions.

1.5 This document examines what may be good professional practice in appropriate cases. The Guidelines do not displace or alter the statutory, contractual and civil law duties of the parties involved. The laws in some countries may impose greater duties on organisations and individuals than are implied here.

2. Actions Which Might be Taken by a Person Identifying a Possible Cause of Disaster

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2.1 Prepare a simple explanation of the potential disaster situation which can be understood by a layman.

2.2 Obtain a second opinion on an advisable course of action from someone competent to understand the failure risk.

2.3 Review your motives for making the warning. Ensure that you could make a declaration that the warning is not influenced by financial or personal considerations.

2.4 Make the warning with explanation to someone in the responsible organisation who is in a position to take action to avoid the possible disaster.

2.5 Enclose a copy of this document with the warning and indicate your availability to discuss the problem.

2.6 Maintain confidentiality.

3. Actions Which Might be Taken by a Person Receiving an Unsolicited Warning of Disaster

3.1 Draw the warning to the attention of those ultimately responsible for resolving the situation and obtain a response.

3.2 If the risk of disaster, or the necessity for avoiding action, is not clear cut, obtain a second opinion from a competent person who is truly independent. Guidance may be sought through the Secretary of the appropriate Chartered Engineering Institution.

3.3 Consider your position and, if appropriate, obtain advice on legal liability and implications for insurance cover in the light of the warning received.

3.4 It is desirable that all parties concerned discuss the matter and come to an agreement. If this is not done, advise the person making the warning that action is being taken, or that a second opinion is being obtained.

4. Notes

4.1 In this document the 'warner' is the person making the warning, while the 'warnee' is the person receiving the warning, and the 'hazard' is the possible disaster situation. 'He' and 'his' should be interpreted as 'she' and 'hers' where appropriate.

4.2 This document is not intended to be exhaustive or restrictive. The course of action in each situation, and the need for detailed calculations and checking, must be decided by the warner and the persons consulted for guidance. Simpler courses of action than those listed may be suitable when the risk or cost of remedy is small, or if effective lines of communication already exist.

4.3 The warner would normally be expected to turn for advice in the first instance to his colleagues or managers. He should continue to obtain guidance from his advisers during subsequent developments. Colleagues and management are likely to understand the repercussions of the problem better than people less familiar with the warner or hazard. The warner may not be able to identify all the factors involved or all the repercussions of a warning. He should take particular care if his concern is not shared by the people he turns to for advice: if he cannot convince friends he is unlikely to persuade others.

4.4 If the warner is an employee, or consultant, of the organisation responsible for resolving the situation, and if he does not resolve the matter quickly with his immediate manager, he should pursue the matter to senior management (preferably with a private meeting). Reference should be made to this document and to the professional duties of his Institution's Code of Conduct.

4.5 It is essential that the warner should retain an attitude of cooperation with the warnee and that he should follow established procedures and lines of communication as far as practicable.

4.6 The warner should make clear whether he is basing his warning on professional knowledge or is acting simply as a non-expert member of the public. If he has professional knowledge relating to the hazard he adds weight to the warning and takes on a greater degree of responsibility, as discussed in this document. If he does not have relevant expertise he should take care not to give the impression that he has.

4.7 Many failures and disasters have resulted from unpredicted oversights or human errors. Moreover, a disaster seldom results from a single cause but rather from a chain of events, the elimination of any one of which may be sufficient to prevent tragedy. Prior to failure the risk can seldom be predicted precisely and, to a certain extent, its assessment is subjective and a matter of opinion. It is therefore important that any second opinion is as objective and independent as possible, and takes account of all the factors considered likely to lead to disaster.

4.8 An engineer may seek advice through the Secretary of the appropriate Engineering Institution on how to proceed and on his professional duties and obligations. He should take care not to disclose the names of other parties or confidential information, unless such disclosure is agreed by the other parties. It is possible that others may wish to turn to the Institution in confidence on the matter.

4.9 Disclosure of confidential information may infringe conditions of employment, which could have serious repercussions for the employment or advancement of the warner. A warner who is concerned about the consequences of a warning on his employment should discuss the matter with his Engineering Institution.

4.10 If an informal warning is not heeded, and the warner and his advisers remain convinced of the seriousness of the hazard, then he should issue a formal written statement to the warnee setting out the reasons why he believes the public or environment is at risk, and indicating how he has followed these Guidelines.

4.11 The warner's obligation to his Institution's Code of Conduct should be discharged by issuing the written statement, except where the warner has in some way contributed to the risk. The warner should seek guidance from the Institution about how much further it is right to take the matter. An employee has no authority to direct his employer, therefore he cannot be held responsible for his employer's conduct. If the employer's action should prove to be detrimental to public health and safety then this would be a matter for adjudication by the Courts.

4.12 If the warner is uncertain as to whom to make the warning within the responsible organisation, he should make the warning to the head of the organisation; e.g. Chairman of the company, Minister of Government Department.

4.13 If the hazard could relate to several organisations and situations that the warner and Engineering Institution may not be able to identify, it may be appropriate to approach a national body, such as the Health and Safety Executive, or Government Department. Under some circumstances the Engineering Institution might consider it appropriate to organise a meeting for discussion which is open to the public. In the case of a generic hazard the Engineering Institution might issue a public warning.

4.14 The warner and the warnee are likely to incur expense which is not recoverable. The warnee, or his advisers, could suffer substantial loss as a consequence of a warning even if they are supported by a second opinion. The warner must take care not to be negligent or careless in communicating the warning. The need for legal advice should be included in the matters discussed with the Engineering Institution.

4.15 The Chartered Engineering Institutions or The Fellowship of Engineering will endeavor to supply names of appropriate persons and organisations who can provide a second opinion or can undertake an independent safety audit.

4.16 If the disaster does occur the warnee should seek legal advice immediately and the warner should consult his Engineering Institution.

4.17 If this document is used by members of the public The Fellowship of Engineering will endeavour to advise them on the appropriate organisation to approach for guidance.

4.18 This document is published by The Fellowship of Engineering solely to assist professional engineers by giving guidance to such engineers about the way they discharge their professional duties in the circumstances described above. The Fellowship of Engineering hereby expressly disclaims any duty of care, or any other special relationship to any third party and specifically states that it assumes no responsibility or risk at law, however arising, for any use (including the ignoring of any warning) made by any party of these Guidelines and/or any warnings issued because of the existence of these Guidelines.

29 January 1991

Appendix D - Topics discussed by the Committee during 2000-2001

The Committee has monitored and discussed developments relating to earlier recommendations in its published Reports and recent trends and changes that potentially may give rise to a concern for structural safety. The topics discussed during 2000-2001 included:

1. Bridges under pedestrian loading
2. Cast iron columns
3. Change of use and higher loadings
4. Competence and integrity
5. Confidential Reporting on Structural Safety (CROSS)
6. ISO9001 definition of a 'product' of a design consultancy
7. Education of engineers
8. Effects of climate change
9. External tubular structures – damage due to ingress of water
10. Glass balustrades
11. Government Proposals on Reforming the Law on Involuntary Manslaughter
12. HSE discussion document: Reducing Risks Protecting People
13. Inspection of structures
14. Management of structural reliability
15. Micro-biological attack on concrete
16. Micro-biological attack on steel
17. NATM tunnels collapse, Heathrow Airport
18. Overhead non-structural glazing
19. Ply-web beams supporting flat roofs
20. Regular inspection of buildings
21. Report of the Study Group on Structural Codes in Construction
22. Rising ground water
23. Risk assessment
24. Self-certification and independent checking
25. Stability of terraced housing
26. Sports stadia – Dynamic excitation of cantilever structures
27. Supervision and checking
28. Sustainable development
29. Temporary conditions of bridges
30. Timber balconies
31. Timber trussed rafter roofs in fire
32. Tunnel linings and fires
33. Underpinning
34. Unplanned collapses during demolition
35. Walkway collapse. Ramsgate
36. Warnings

Appendix E – Cumulative index to topics featured in SCOSS Reports since 1976

The Ninth, Tenth, Eleventh, Twelfth and Thirteenth SCOSS Reports can be purchased from the Institution of Structural Engineers, 11 Upper Belgrave Street, London SW1X 8BH. Photocopies of earlier Reports may be obtained from the SCOSS Secretariat, at the same address.

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