FESI

UK FORUM FOR ENGINEERING STRUCTURAL INTEGRITY

THE FESI INTERNATIONAL BULLETIN ON STRUCTURAL INTEGRITY

The important role of Structural Integrity in the construction industry - Micheal Burdekin FREng, FRS

Contents

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Aims

This new journal is aimed at studies at the interfaces between industry, public utilities, insurance and legal bodies, and academe.

The major objective of the journal is to bring together under one cover, reports and investigations relating to the safety, reliability, durability, integrity and life-time evaluations of and improvements to engineering products.

All countries suffer a slow but continuous deterioration of their engineering plant and the possibility of serious accidents, all of which cause grave concern to society. Railways, automobiles, aircraft, roads and bridges, chemical plant, shipping, off-shore structures, computer software, energy production and transmission systems etc, all require continuous surveillance and constant improvements. Frequently such problems lead to unnecessary expensive legal actions in national and international courts. No engineering discipline is immune when considering plant failures and yet modem facilities, together with a wide knowledge base, plus a desire to constantly improve the design, manufacture, and usage of engineering products are readily available in depth but need to be integrated for the benefit of all concerned.

Articles in the journal will cover all engineering disciplines and products involving their design, manufacture, monitoring systems, and lifetime assessment evaluations. Review articles, ethical problems, synopses of important technical issues in court cases, case histories, requirements for modifications to, and explanations of, complex issues in Standards and Codes of Practice, and finally, the development of engineering techniques to improve the safety and integrity of plant, will be recurring themes of the Journal. It follows that the Journal will promote the engineering knowledge base, the modelling of plant, and risk assessment procedures, rather than present results of pure science studies. All sectors of the industrial world and leading engineering research centres, will be involved in the writing of articles for the benefit of all engineers in technologically advanced countries.

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Who is FESI?

Over the past 10 years, a UK group of interested industry parties has organised a successful series of biennial international conferences, held on the subject of ESI, which has sought to examine the status of the technology and its effectiveness in application. More recently an associated programme of teaching seminars has developed, using senior expert academic staff, to propagate good practice and awareness in areas such as risk based tools and methods, and the quantification of failure. This collective experience has been brought together under the UK Forum for Engineering Structural Integrity (**FESI**).

The aim of FESI is to provide opportunity to facilitate the effective development and implementation of ESI technology across industry sectors. We believe that this will be achieved through the following means:

- The organisation of teaching seminars on developments in ESI technology and its application.
- The organisation of one day topical discussion seminars on interdisciplinary and/or cross industry sector issues in ESI.
- The organisation of specific industry Discussions/meetings/seminars on ESI, on request.
- The organisation, as appropriate, of international Conferences in the UK on Engineering Structural Integrity Assessment concerned with the dissemination of ESI technology and its application across industry sectors. Liaison with other bodies involved in significant ESI R&D and applications programmes (e.g. EPSRC, European Structural Integrity Society (ESIS), EU/JRC Networks, International Institute of Welding).
- The organisation, jointly with collaborators, of similar national conferences/seminars in the UK and other countries.

Through these activities, the Forum seeks to encourage technology transfer across industry sectors and the development of technologies which will support the safe and cost-effective design and operation of major engineering plant, structures and components. Its activities will cover a range of industries including aerospace, petrochemical, oil and gas, power generation, automotive, transport and construction. Technology integration includes inspection, monitoring, diagnosis, analysis, materials, IT and assessment methods.

Who's who in FESI

John Edwards MBE is a consultant with many years experience in testing technology, and is a lead assessor National Accreditation, Measurement and Sampling (NAMAS) in mechanical testing.

Professor Peter Flewitt is Consultant Professor within BNFL British Nuclear Group. He has worked on a range of structural integrity topics in the power generation industry .

Dr Brian Tomkins is AEA Technology's Senior Technical Advisor and is an expert in engineering plant integrity and safety

Philip Heyes is Head of the Engineering Control Group at the Health and Safety Laboratory

Professor John Knott OBE is the Feeney Professor of Metallurgy and Materials at the University of Birmingham with a particular interest in fracture and crack arrest

Ken Morton is a consultant engineer, specifically in the areas of fracture, fatigue and structural integrity

John Schofield is a principal engineer with Rolls Royce

Professor Rod Smith is Head of the Mechanical Engineering Department at Imperial College. He is an authority on fracture and fatigue particularly in the Rail industry

Dr Alan Turnbull is a Senior Consulting Engineer at the National Physical Laboratory, specialising in corrosion and fatigue

Dr Christoph Wiesner is Director of Research and Technology at TWI Ltd

Professor Gordon Williams is a Senior Research Investigator in the Department of Mechanical Engineering at Imperial College. He is a world expert on polymers

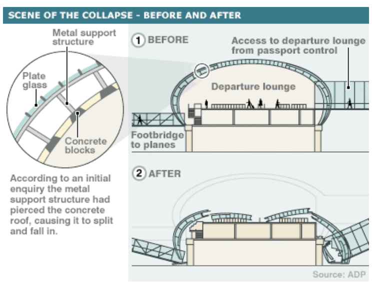
STRUCTURAL INTEGRITY OF CIVIL ENGINEERING STRUCTURES

By Michael Burdekin

Major Civil Engineering structures are often very large individual structures, designed for a specific purpose. Their appearance is a challenge for architects to make them look attractive and blend with their environment. Their function often involves use by the general public, sometimes in large numbers and safety is paramount in their design and construction. Building structures essentially provide accommodation of one sort or another for people, living, working or in transit. In addition they have to provide a weather tight envelope and withstand the full range of environmental loadings due to wind, temperature and earthquake. These structures are invariably designed to Codes which are based on a combination of research results and the experience of the profession. Limit state design codes are widely used in Europe and National Codes are being superseded by the whole suite of Eurocodes. The Eurocodes seek to provide a given target reliability; for Eurocode 3 for example, this is set at about 3×10^{-3} events per year. It is often not realised that the costs of building structures are typically of the order of one third for the structure, one third for the cladding and one third for the fitting out and services. The common materials used in Civil Engineering structures are steel and concrete for the main load bearing parts with a wide range of materials used for cladding. Glass is extensively used for cladding of buildings to provide light and solar gain.

Failure of Civil Engineering structures is a rare event. However, on the rare occasions that failures do occur, they can be both tragic and spectacular. Such a failure occurred on May 23rd this year when a section of part of the new Terminal E at Charles de Gaulle airport, Paris, collapsed killing four people and injuring three others. The building had been opened in June 2003 and cost 750m euros (£500m) to build. It provided a floor space of 104,000 sq m and a capacity of six million passengers a year. It was made from reinforced concrete with 36,000 sq m of glass cladding and provided parking gates for ten planes. The building consisted of a series of part oval concrete ribs supported on piers as shown in Figure 1 (before). These ribs supported metal struts perpendicular to the ribs which in turn supported the glass envelope.

Figure 1. Schematic indication of collapse of Paris Airport Terminal E



A preliminary government report on the collapse released in July by a panel of investigators appointed by Transport Minister stated that the concrete appeared to have been pierced by the steel struts supporting the glass envelope as shown in the inset picture in Figure 1. The resulting fractures of the concrete ribs and form of the collapse are shown in the lower part of Figure 1 (after). The investigation found that ''The perforation by the steel ribs led to its breakage by bending", and it appeared to have "folded like a wallet" at three positions collapsing on to the floor area of the departure lounge below. The investigators are also quoted as suggesting that the exact reasons were not known but the findings point to a gradual deterioration of the concrete in the 30-metre section of the building's 700 metre long arched roof. The collapsed structure is shown in Figure 2.

According to press reports in the International Herald Tribune, Jean Berthier, a professor at the Ecole Nationale des Ponts et Chaussées in Paris, and president of the inquiry commission studying the collapse, declined to offer a reason that would explain why the steel ribs would have pierced the concrete, saying that further tests would be needed. He suggested however, that the weakness of the concrete might have been due to the effect of temperature differences between the inside and the outside of the structure causing the shape of the building to change slightly, especially during hot summer months when the inside was air-conditioned.

Figure 2. Collapsed terminal at Paris airport from access walkway side.

The terminal's latticed roof was designed by Paul Andreu, the former chief architect for Aéroports de Paris, the airport's state-owned operator. In addition to the Transport Ministry's inquiry into the collapse, a French court is pursuing a criminal investigation into the case. A public prosecutor is carrying out a separate inquiry into the collapse, which could establish who is to blame.

Standard procedures for structural integrity failure investigations

In any failure investigation there are a number of standard procedures which must be followed. Clearly if there have been any injuries, both the police and the appropriate branch of the Health and Safety Executive must be informed.

Photographs should be taken of the position of any collapsed or broken elements. Engineers with expertise in failure investigation should be involved at the earliest possible opportunity. Failures inherently fall into a number of potential categories as follows:

(a) Overload above design capacity.

(b) Material properties which are inadequate for the intended purpose.

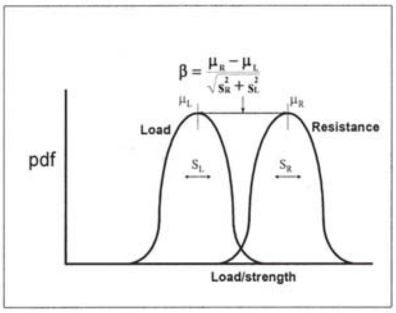
(c) Deterioration of the component or structure in service.

In reliability analysis terms, failure occurs when load effects (L) are greater than resistance effects (R), i.e.:

$$L > R$$

In practice there are uncertainties in both the load effects and resistance effects and these have to be represented by distributions as shown in Figure 3. The probability of failure depends on the overlap between the two distributions, and for simple cases this can be determined by use of the reliability index, , as defined in Figure 3. Here $_R$ and s_R are the mean and standard deviation for resistance effects and $_L$ and s_L are the corresponding values for the load effects. The reliability index is directly related to the probability of failure and a value of 3.8 corresponds to typical Eurocode targets.

Figure 3 Structural Reliability Index



For load effects, the first requirement is to understand what loading was actually present at the time of the failure. Clearly, extreme overloads can occur under earthquake, typhoon or impact collision conditions but there are no reports that such conditions are relevant to the Paris airport collapse.

Sometimes, there may be errors in the design, either in estimating the types and levels of loading that may occur or in determining the levels of load effects correctly. Finite element analysis is now commonly used to determine the load effects within the structural components (shear forces and bending moments etc., leading to calculation of stresses). Reference has been made in the comments attributed to Professor Berthier on the Paris airport failure about the possibility of differential expansion due to temperature changes being a factor. It is noticeable that the glass Envelope is held in place on the outside of the concrete ribs by metal struts which are essentially perpendicular to the rib surface, but there are no diagonal bracing members between these struts.Expansion and contraction of the outer glass envelope with respect to the concrete ribs is likely to cause the struts to rock on their supporting pads and to subject them to fluctuating tension and compression. It would appear from the reports that the investigators are considering whether repeated expansion/contraction effects can have caused weakening deterioration in the concrete. However, they will also have to consider whether the design catered adequately for the punching shear effects on the concrete produced by expansion and contraction of the glass envelope relative to the concrete ribs and to the effects of wind loading on the structure.

For the resistance effects, a significant factor is to determine what are the material properties actually present. Thus standard tests for material properties should invariably be carried out. This should include chemical analysis and mechanical property tests (tensile, compression, hardness, fracture as appropriate to the material and failure). Such tests are essential both in helping to determine the cause of failure and to check whether the materials comply with the specification requirements and whether any deterioration has occurred. The properties of concrete do change with time, particularly in the early stages of life whilst curing is occurring, until the concrete attains its specified strength. Some concretes can reach a peak in strength and then lose some of their strength by various mechanisms so that the investigators of the Paris airport collapse will be checking to see if there is any evidence of this happening. However, the structure was only of the order of one year old and loss of strength due to aging would not be expected to occur in this period in well made concrete.

Deterioration of concrete can occur by mechanisms such as carbonation and by alkali-aggregate reactions. Deterioration of metallic structures can occur by corrosion or perhaps by crack growth by fatigue or stress corrosion. In reinforced concrete, corrosion of the reinforcement can occur if there is inadequate cover, particularly in the presence of chloride environments. Any evidence of deterioration of these types should be obvious to experienced investigators, with the aid of some relatively simple laboratory tests.

Concluding Remarks

In any Structural Integrity failure investigation, it is important to follow a number of standard procedures to establish why the load effects have exceeded the resistance effects. This will involve a team of expert investigators to consider design, materials and specialist failure mechanisms. Sometimes the cause of failure may be obvious, but it is still necessary to follow the standard procedures as in addition to determination of the cause, sufficient evidence must be recorded to be produced at any enquiry or possible litigation.

ESIA7 "Integrity For Life"- Conference Review- John Edwards Conference Chairman

FESI held the seventh conference in the series on Engineering Structural Integrity Assessment, **"Integrity For Life"** at the Manchester Conference Centre, University of Manchester,. on the 20 21 October 2004. Continuing the theme of the previous conference, the first day was devoted to **NEEDS** and the second day to **PROVISIONS**.

The Manchester Conference Centre provides excellent facilities for presentations, with several lecture theatres enabling parallel sessions to be held easily and with en-suite accommodation on site keeps the delegates together for social activities. Despite the current uncertainty in the world 67 delegates from 10 countries attended and heard 45 presentations from leading experts in the field.

The conference opened with a keynote presentation from Phil Heyes of the Health and Safety Executive entitled "Structural Integrity Working Together and Getting It Right". A second keynote paper was given by Iain Le May of Metallurgical Consulting Services entitled "The Human Factor in Engineering Structural Integrity". The final keynote paper on the day on the topic of NEEDS was given by Professor Ted Smith of Kinectrics entitled "Development of a Canadian Standard for In-service Evaluation of Zirconium Alloy Pressure Tubes in Candu Reactors". The first day concluded with the conference dinner and a humorous after-dinner speech give by Professor Rod Smith of Imperial College.

Day two opened with a keynote presentation given by Peter Scott of Framatome entitled " Modelling of Stress Corrosion Cracking in PWRs". The second keynote was due to be delivered by Professor John Knott of Birmingham University entitled "Two Steps from Disaster" Unfortunately John was unable to attend so the paper was summarised by Professor Peter Flewitt followed by a panel question and answer session which provoked lively discussion.

Before closing the conference the chairman, John Edwards, presented the prize for the best student paper to Miss Loujaine Mehrez of Southampton University for her paper entitled "Reliability Analysis: A New Approach to Assess the Performance of a Cemented Total Hip Replacement".

A most enjoyable and technically stimulating conference. It so appealed to Dr Hongyun Luo from Beijing University, PR of China, that she asked if the next one could be held in Beijing.

See you all there.

CALL FOR PAPERS

ESIA8 "Throughlife Management of Structures and Component"

the Eighth International Conference on Engineering Structural Integrity
Manchester - 24 to 25 October 2006

This eighth Conference, to be held over two days, will be based around **Throughlife Management of Structures and Component**s. The overall conference theme will be cradle-to-grave management of the integrity of structures and components relating to economic, safety and sustainability benefits.

For a copy of the First Announcement and Call for Papers, contact Poul Gosney at FESI Ltd at fesi@aeat.co.uk

THE PROFESSIONAL RESPONSIBILITY OF ENGINEERS

Dr B Tomkins FREng Chief Technical Advisor, AEA Technology plc
&
Prof I Howard, Department of Mechanical Engineering, University of Sheffield

Introduction

In many regards this paper is a follow-up to an earlier paper by the authors which explored the ethical principles which dictate the behaviour of the Professional Engineer in today's world [1]. The paper explored the wider range of demands upon the professional engineer as a result of society's wish for greater awareness of both benefits and risks in an engineering enterprise, and the care which must be taken to achieve this without threatening the engineer's ethical basis of virtue and trust; a key factor in both safe engineering and ongoing innovation. Figure 1, taken from that paper, shows the professional engineer's links to the variety of stakeholder interests in his/her activity. The spine of the relationships represented by these interests is that

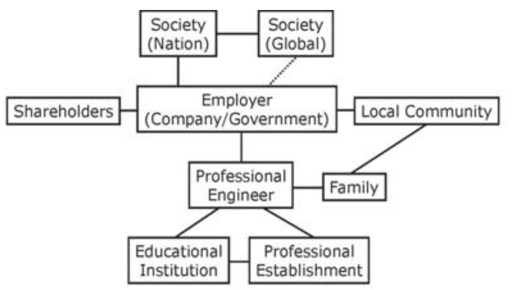


Figure 1 - Stakeholder interests in the Professional Engineer

which connects the professional engineer to the society which he/she serves. Service to the community/society is the raison d'etre of any professional, but in the case of the engineer the link to society invariably passes through an intermediary, the "engineer's customer" represented by the company he/she works for or

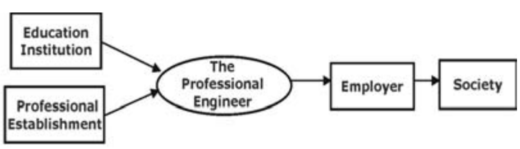


Figure 2 - Key players in the engineering enterprise

the project on which he/she is engaged. Society looks to the company or project to deliver the required product or service, who in turn looks to the professional engineer to deploy his/her skills responsibly and with high integrity. Trust between all three parties, based on trustworthy relationships and communications is essential for satisfactory delivery. In this context, It is important that the Professional's "virtue ethic" in carrying out his/her specific role is carried through the higher levels of company/project structures so that what is delivered to society is acceptable. Figure 2 shows the spine of this structure with the addition of the engineer's technical and experiential support from teaching and professional institutions. This is a key input to enable the engineer to make appropriate judgements which influence ultimate benefit/risk of a product, based on best usage of both knowledge and experience.

This paper explores the interaction of this structure of relationships with the overall professional and societal context in which the engineer now works. It explores both the internal context of projects and relationships as well as the external interactions with representatives of society. As this is a conference concerned with engineering structural integrity, three examples have been chosen to illustrate the relevance and importance of internal and external factors to a successful engineering venture in this arena. Structural failure, particularly where it leads to loss of life, threatens the trust placed by society in the engineering enterprise and in the competence and responsibility exercised by the profession. The examples illustrate how that trust can be demonstrated in the light of real or perceived threats.

The Context of the Professional Engineer Today

Professional engineers, as professionals in other disciplines, are under greater public scrutiny today than in the past, particularly when significant engineering failures occur. This requires a greater awareness by the engineer of his/her place in the specific engineering enterprise, and of the complexity of the various professional interactions in the enterprise itself. Hierarchical professional structures are weaker and the professional engineer's own responsibility must be more visible, and be integrated in to multi-professional teams. Closely related to multi-professional working is the introduction of new science based technology in to both established industry sectors, and new technology based sectors. The professional engineer is key to the introduction of new technology, requiring sound knowledge of the technology providers (e.g. universities, technology services companies) and the feasibility of its introduction in terms of economic viability, industry/public acceptability, timing, and compatibility with overall engineering context (e.g. plant operation and performance). The demise of in-house research and development activities within established industry sectors makes this process more difficult.

Increasingly, major engineering assets are seen as an integrated entity, not just in terms of engineering performance but also lifetime management. This requires professional engineers to work comfortably across engineering and scientific discipline barriers particularly in the area of structural integrity and reliability. Finally, society's increased interest in the risks as well as benefits of the engineering enterprise has resulted in the need for the professional engineers to interact with society's guardians; the regulatory authorities (e.g. for safety and environmental impact) and in some cases the media.

Multi-Professional Working

Professional engineers invariably work as part of a team; even when acting as independent consultants they relate to a team activity. Successful delivery of any engineering project depends on such team working under a competent project manager whose job it is to deliver the product, however large or small, on time and within budget. The aspect of multi-professional working which is increasing, however, involves professionals from different engineering disciplines working together to produce new products and services. Many consumer devices from cars to cameras involve a combination of disciplines linking electrical/electronic and mechanical engineering with sensors, data collection and control equipment being all pervasive. The assurance of engineering integrity and reliability for all types of engineering plant now involves integration of condition evaluation, analysis, materials engineering, often combined with a risk assessment, which involves detailed knowledge of both design and operation. In addition, techno-economic procedures are increasingly used to provide optimisation of design and operation in economic terms whilst remaining at all times in a safe and reliable condition. The new engineering graduate is therefore required to be much more of a polymath with good interpersonal skills, than has been the case in the past.

Whilst integration of engineering skills and technologies is of benefit in ensuring that products and services can effectively move across technical boundaries, fragmentation of large companies and public service providers can increase the difficulties of integrating necessary professional engineering expertise. Again, business partnerships and contractorisation are not new in the engineering arena. However, it is necessary that professionals working for a given project or providing a service are sufficiently informed of the context to exercise an adequate level of commitment and delivery. Both good cross boundary management structures and communications are essential for success. In the engineering integrity area, it is now recognised that successful proactive management of plant to prevent failure depends on the ability to integrate engineers working in design, construction/manufacture, operations, and technical support (This will be discussed further in section 2.3).

Engineering Technical Advances

We are all aware of the continuing incorporation of new technology in established industry sectors. This is in response to a combination of driving forces; economic, safety, environmental impact and consumer demand. In the transport and infrastructure sectors safety has been a major driver along with economics (e.g. reduction in fuel consumption). In the oil and gas sector it has been economics which has enabled oil and gas to be produced from deep offshore sources. In most cases new technology has been acceptable on grounds of increased benefit or reduced risk. The introduction of new technology poses a significant challenge for the professional engineer. The engineer, who must implement the technology, has a responsibility to be fully conversant with the technology itself, interacting with scientists/technologists involved, as well as having responsibility to adapt the technology in an appropriate way for use in the particular industry. In addition the engineer has some responsibility for advising on both the risks and the benefits to the industry or company involved as new technology is often found not to live up to expectations, particularly when first introduced. It should be noted that most technical advances in established industries are readily accepted by society

However, when new technology leads to a new engineering sector, such ground rules have not been established, and risks and benefits are more difficult to evaluate. Recent contrasting examples are mobile communications and bioengineering. With mobile communications, the consumer benefits have been perceived to be so strong that longer term risks e.g. From electromagnetic radiation, are deemed acceptable. In the case of bioengineering, society is much more sensitive to possible risks. The problem with new science based technologies is that scientific knowledge alone can rarely give an accurate assessment of long term risk and if the benefits are not clear or strong enough, the more informed society of today is unwilling to support ongoing development. This inhibits the traditional development route for any technology where practical experience is a significant factor in evaluating actual risk. Engineers working in new technology areas have a responsibility to deal with risk by a combination of knowledge and experience, even if direct experience is limited and judgements need to be made often by analogy with other associated areas. The development of a sound engineering dimension in all science based new technologies is important if real benefits are to be realised in a timely.

Any comments on the relevance of advanced technology to engineering must take note of the pervasive influence of computational analysis. Engineering software is now widely used across all industry sectors, old and new, in both design and operation. The reliability of such software which often includes contributions from both knowledge and experience, is of prime importance and in terms of engineering responsibility involves both the software producers and users.

Integrated Asset Management

Two questions are asked of any engineered product: will it work? (i.e. will it do the job for which it was designed), and will it continue to work satisfactorily for the full extent of its design life? A positive answer to the first question is the responsibility of the design engineer and the engineers who manufacture of construct the product. A positive answer to the second question involves operational and maintenance engineers as

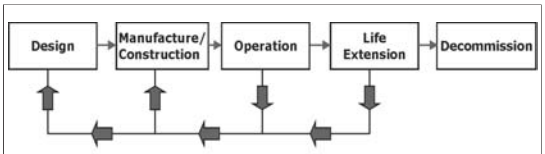


Figure 3 - "The Asset Management Life Cycle"

well as designers and fabricators. Figure 3. shows schematically the life cycle of an engineered plant/system or component. For high investment plant (e.g. in power generation, petrochemicals, infrastructure) such a life cycle may last several decades and changes which occur during the longest, operational part of the cycle, due to increased demand on the plant or regulatory changes, may require re-assessment of the design intent. In addition, long life operation of a plant taking it beyond the knowledge and experience base available at the design stage, often involves quite complex monitoring and evaluation if a positive answer can continue to be given to the second question. In particular, experience has shown that in many industries long life components and structures, materials ageing processes, which were not understood or appreciated at the outset, can have a significant debilitating effect. In addition, it may also be desirable from an economic point of view to extend the life of a plant or structure beyond the original design intent, requiring a significant design review. Along with options for repair and replacement in service, such considerations have led to the development of integrated management of major assets in many industries. Integrated Asset Management is a proactive process being a significant extension to, whilst integration with, the maintenance programme set out at the beginning of life. A considerable driving force for such proactive asset management has been the demand for assurance of ongoing safety alongside the demand for operational reliability, crucial to economic viability. As noted earlier, this process requires a combination of engineers expert in different areas of the life cycle, combined with engineers Integrated Asset Management is a proactive process being a significant extension to, whilst integration with, the maintenance programme set out at the beginning of life.

A considerable driving force for such proactive asset the beginning of life. A considerable driving force for such proactive asset management has been the demand for assurance of ongoing safety alongside the demand for operational reliability, crucial to economic viability. As noted earlier, this process requires a combination of engineers expert in different areas of the life cycle, combined with engineers who provide up-to-date supporting technical services. The latter are particularly important in relation to current assessment of the integrity of systems, components and structures. Such structural integrity engineers may come from a variety of engineering disciplines. Integrated asset management has developed strongly in recent years in relation to older high investment plant and structures. However, lessons learned concerning inspectability and alleviation of ageing, e.g. through materials selection or improved control of plant operation, are now being applied to new plant design. The importance of this is shown in Figure 3. as a feedback loop.

External Interactions of the Professional Engineer

As noted earlier, unlike other professionals who deal directly with the public, the direct interactions with society of professional engineers are very limited. However, the engineer does deal directly with society's representatives in the form of the regulators. Both the safety and environmental regulators are largely made up of professionals, including many professional engineers, who engage in detailed technical discussions concerning safety cases and environmental impact assessments. Being responsible to government, the regulator fulfils the traditional role of government inspection safeguarding society's interests. Safety cases and environmental impact assessments now provide a vehicle for detailed consideration of all aspects of design and operation of engineered systems, structures and components. They involve up-to-date detailed knowledge and experience, reflected in engineering judgement relating to a societally acceptable level of risk. They also represent helpful vehicles for the utilisation of best practice across different industry sectors as well as transfer of appropriate technology. These interactions between project/company engineers and regulator represent a proactive approach to societal concerns and now include consideration of risk perception as well as more specific risk evaluation [2].

Another body which plays an increasing role in representing society's interest and concerns in engineering and technological enterprise is the media. The proliferation of communication routes, not just nationally but internationally, along with society's increasing sensitivity to benefit and risk has encouraged more direct contact by the media with companies, projects, and professional engineers. The engineer is rightly seen as the source of knowledge and expertise in relation to a given plant or system and is ultimately the source of confidence on how it will perform.

It is important that professional responsibility in this regard is carried through to the highest levels in engineering projects and companies so that these aspects can be adequately represented in the public arena. Traditionally this has been the role of the Director of Engineering or Chief Engineer but today it is important that knowledge and opinion is shared more widely. The "virtue ethic" of individual engineers must be carried throughout the teams, projects, and companies in which engineers reside and this should be ensured by an adequate independent internal and, where appropriate, external peer review process. The engineer has some responsibility to ensure that in some way such processes are in operation. They provide a means, through company or regulator, of communication between the engineering activity

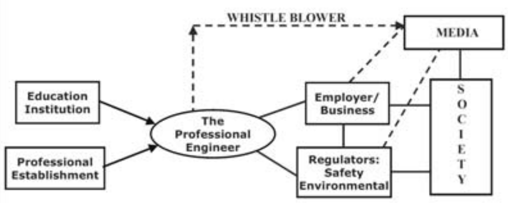


Figure 4 - Interactions between the professional engineer and society

and the media. Figure 4. shows the connections in relation to both regulator and media regarding society's interests and concerns. Also included in this Figure is a possible direct connection between the individual engineer and the media; the "whistle blower" route. Any good project or engineering venture should have an internal whistle blowing route, by which the engineer may express any individual ethical concerns, because direct whistle blowing to the media should be justified only in extreme circumstances.

Examples of Engineering Professional Responsibility

The paper has made clear that today's professional engineer is required to exercise his/her responsibility more widely than has been the case in the past. Three examples have been chosen to illustrate how this is working in practice. The first example concerns a new creative engineering project, the Millennium Bridge in London, and the technical problems which arose when it became operational. Such a high profile project ensured that these problems were exposed and resolved within the public gaze. The second example concerns Ball Mill Explosions in a very traditional, low tech, ceramics industry. Resolution of this problem, involving responsible cross discipline teamwork, ensured that a new collective working practice in the industry was established. The third example, from the oil & gas industry, involves responsible technical brokering by engineers with the major oil company owner and safety and environmental regulators, to justify continued operation of an ageing main oil line in the North Sea. It is hoped that these three examples will encourage engineers, who continue to be in the forefront of providing society with both innovative and necessary products and services, whilst satisfactorily dealing with matters of benefit and risk.

The Millennium Bridge

The elegant and technically innovative Millennium Pedestrian Bridge [3, 4] in London opened in June 2000 in the glare of media interest and publicity. The opening attracted large crowds of visitors who soon experienced considerable lateral bridge motion. Although the bridge remained safe throughout, the motion amplitude was quite unacceptable, and the bridge was closed after two days. Ove Årup, the engineers responsible, conducted a thorough investigation. This involved the time of a team of Ove Årup staff and included a range of engineering consultancies, including several university engineering departments. Ove Årup discovered that the cause was a natural frequency mode [5] that was excited only if large enough numbers of pedestrians were on the bridge. In this, they also found that several other bridges world-wide had also suffered from the same problem, some of them many years in the past. This important knowledge had never entered the general engineering profession until Ove Årup made their researches public. This is probably because each incident was seen by the engineers responsible as a "one-off", caused by a very much larger mass of moving people than the bridge would normally support. Ove Årup initiated modifications based upon their investigations [5]. Whilst all this was going on, they ensured that the media was kept up to date as the work proceeded. There are two benefits that come from this, at least. One is the gradual alleviation of the public mistrust induced by the original problem and exacerbated by reports in some of the media. Full public trust of the integrity of a structure like this benefits members of the public, the engineering profession, and those components of the media that provide responsible investigative reporting of such important public issues. The second is less obvious, but probably more important. Engineers know that there is always a risk in any new product or design that it might not fulfil its expected duty. They strive to minimise this risk during design and development, an essential duty of any responsible member of the profession. Even so, the risk of any new engineering product not working according to expectations is finite, and the risk inevitably increases with the level of innovation. However, this cuts across the contemporary expectations of many members of the public who desire "safe" products and services. For them, "safe" often means risk free. This fantasy is both supported and amplified by irresponsible media reporting, and by further contemporary trends associated with a blame and compensation culture. Dealing in public with the problems that occur is a highly effective way of helping the ordinary citizen to understand these truths, and to see how engineers deal responsibly with their own fallibility. In an apparent paradox, real public trust in the profession needs a public understanding of the fallibility of engineering and engineering judgement. The trust comes from citizens recognising that responsible engineers have both personal and cultural techniques of minimising this fallibility. For the London Millennium Bridge, the solution, involving fluid viscous and tuned mass dampers, has recently proved fully successful, and the re-design has not degraded the original graceful structural form. Transparency was rewarded by unhindered problem resolution.

Structural Integrity of Ceramics Industry Ball Mills

Raw materials for the production of ceramic products are often ground up in batch ball mills (BBMs). These are closed and sealed containers that are filled with the raw materials/ grinding media and water. They are typically cylindrical in form, and rotate about a horizontal axis with power supplied from a motor geared into the teeth of a ring attached to one end plate of the mill.

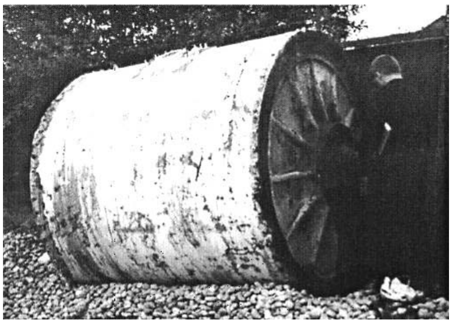


Figure 5(a)

Figure 5(a) illustrates the arrangement. Ceramics industry mills typically run between 2 and 40 hours. As a result of a mill exploding in the spring of 2000, a Working Group came together, composed of technical representatives from several ceramics companies, members of the UK Health and Safety Executive, and academic technical consultants with structural integrity knowledge. A rough, initial set of calculations suggested that the safety problems revealed by the explosion could be alleviated by an agreed set of working procedures, to be based upon a detailed investigation of the failed mill. Since this was quite typical of many mills in the industry, the group believed that its investigation would be helpful in setting future safety standards.

A recent survey [6] of 19 companies in the Potteries area of the UK identified 243 ball mills ranging in age between 60 years and nine months. At least one half of these were the same or similar types to that which had failed. There was no knowledge of the history of almost one half of the mills surveyed, and there was a significant proportion that had been bought second hand. Figure 5(b) is a view of the exploded mill, showing the remains of the end that was almost fully blown out in the explosion. The ends are cast iron, 7-foot in diameter, and the wrapper is steel. The date of manufacture of this mill, and others in the industry, appear to be unknown, except for the fact that many mills have been in use "for a long time", and could easily be more than 50 years old. Two other ball mills stored in the yard had cracks in their end plates (see Figures 5(a),(c)). These

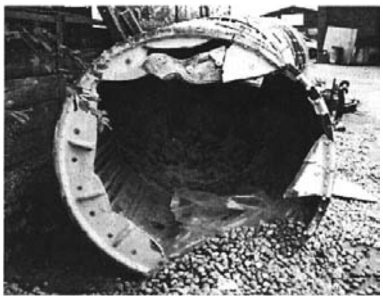


Figure 5(b)

cracks were both longer than 50mm. The heat generated by grinding raises the internal pressure in the mill, partly due to expansion of the trapped air, but mainly due to the rapid increase with temperature of the vapour pressure of water.

Figure 5(c)

Since ball mills of this type were not originally designed as pressure vessels, they are exempt from pressure component standards so long as the internal pressure is less than 0.5 bar. This threshold pressure is reached when the internal temperature is approximately 70ºC. The particular grind during which the mill exploded was unusually long lasting. Hence the temperature and pressure in this unit at the time of the explosion were significantly larger that those normally experienced.

The task facing the Working Group was to find ways of reducing the risk of such an accident in the industry to an acceptably low level. It brought together the interests, and potential conflicts, of industry engineers and managers, safety professionals, and technical consultants. The technical consultants provided a structural integrity analysis [7] showing that, even with the very poor quality of the cast iron of the failed mill, it could operate safely with cracks of modest size. This depended upon the internal pressure being kept below the necessary bar limit. Health and Safety engineers undertook to steer the work of the group, and to publicise the recommendations. The Industry agreed to investigate affordable ways of real-time automatic monitoring of the mills; the aim being to ensure that every mill is operated below the limit of 0.5 bar internal pressure. A simple and inexpensive system for temperature monitoring has been successfully investigated [8], and finally, the industry accepted the need for regular inspection, and the training of all personnel in the necessary practice. The group recommends a set of actions, base upon the technical data provided by the technical consultants which set temperature and crack size limits.

End Of Life For A Main North Sea Oil Transmission Line

A main sub sea oil transmission line from one of the older North sea oilfields was shown in 1996 from the internal inspection runs (PIG) to be sufficiently corroded to raise concern about its continuing fitness for purpose, according to the established pipeline assessment code, ANSI/ASME B31G. This code was recognised to be overly conservative in its assessment of the residual strength of corroded pipelines [9]. The oilfield serviced by the pipeline was in decline and did not possess sufficient resources to justify line replacement, but immediate shutdown of the line would result in lost production of ~$7.5M per annum for the several years left before field exhaustion. This situation arose at a time when, in many countries, the regulations governing pipelines were undergoing revision, with a move away from prescriptively based rules to a goal setting, risk based approach. This latter approach allows fuller use of ongoing inspection data, particularly where uncertainties can be quantified statistically. In principle, PIG run data is well suited to this approach. Following discussions between the pipeline owner and the two interested regulators (Safety and Environmental), it was agreed to produce a risk based case for continued operation. Technical consultants were employed to produce the quantified case, by estimating the failure probability of the corroded line.

Determination of failure probability required the following:

- a realistic failure criteria based on detailed analysis of the worst defect in terms of pit depth
- a statistical model of the degradation rate of the pipeline using data from successive inspection runs
- a statistical model of the current condition of the pipeline based on inspection data, with allowance for pipeline lengths not covered. This involved the use of extreme value statistics. [The methodology used in the assessment is given in Reference 10].

The results of the first assessment (1996) indicated a failure probability of 10^{-6} per annum. An acceptable increase in failure probability based on conservative assumptions was judged by the regulators to allow operation until 2000. For operation beyond 2000, additional assurance was required in the form of a hydrotest. The test pressure was also chosen on the basis of assessed failure probability based on the PIG data. The hydrotest was carried out successfully leading to further operation beyond 2000. The savings per annum were assessed at $30M up to 2000 [10] with further savings by the deferment of decommissioning.

Summary

It is clear that overall, professional engineers have continued to exercise their responsibility through the changing demands made upon them. However, vigilance is required if trust is to be maintained and new demands met. The paper has explored some of the key areas of challenge from education through to interactions with the public, and noted the need for wider awareness and integration of disciplines.

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Authors

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Upcoming FESI Events

Impact of Environment on Structural Integrity - London - 18 October 2005
This seminar/workshop will reveal the considerable developments that have been made towards the procedures for structural integrity assessment in corrosive environments

Professional Responsibilities in Engineering - London - May 2006
How engineers discharge their professional responsibility today is not clear, with the potential for confusion of rôle and marginalisation.

ESIA8 - Manchester - October 2006
8th International Conference on Engineering Structural Integrity Assessment. The theme is "Throughlife Management of Structures and Components"

International Conference - Beijing - 2007
Technology and tools for Engineering Fatigue assessments

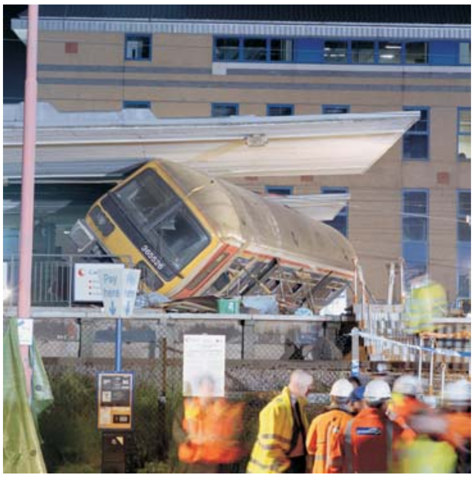
More details of each of these events will be appearing on our website at:
www.fesi.co.uk

Lessons Can Be Learnt - Phil Heyes

This extract has been taken from the introduction to the presentation given by Phil Heyes at ESIA7 in October 2004. The Editor believes that the very valid message Phil made should reach a much wider audience. This will be the start of a series of short articles of how lessons can be learnt.

There are approximately 250 workplace deaths in the UK every year and 150,000 serious injuries causing over three days' absence from work. Approximately seven million working days are lost each year as a result of workplace injury. Hence, in addition to daily personal tragedies, the cost of workplace accidents to the UK economy is considerable.

Due to the manner in which accident statistics are collected, we can only speculate about the proportion of this cost that is due to loss of structural integrity. However, some indication can be gleaned from the work of the Health & Safety Laboratory (HSL) which, amongst other things, carries out investigations of workplace accidents on behalf of the Health & Safety Executive. Only the most high profile and contentious accidents are referred to HSL but, of these, approximately 30% could be said to be due to a loss of integrity in an individual component or structure. We should be in no doubttherefore that both the initial integrity and the continued fitness for purpose of components and structures are very important for both safety and economic reasons.



In the UK, it is often said that essential safety engineering lessons are learned only after a catastrophe has occurred and it is tempting to take this approach in this paper, as shown in the example below. therefore that both the initial integrity and the continued fitness for purpose of components and structures are very important for both safety and economic reasons.

In the UK, it is often said that essential safety engineering lessons are learned only after a catastrophe has occurred and it is tempting to take this approach in this paper, as shown in the example below.

However, rather than use such a negative approach, I have chosen to concentrate on proactive measures that have been employed to prevent failures in the first place. In particular, I want to stress the importance of collaboration between some of the many organizations involved in ensuring safety in UK industrial sectors: designers, manufacturers, operators, insurance companies and regulators, and their contribution to ensuring the integrity of structures.

Phil Heyes is Head of Engineering Control Group Health & Safety Laboratory, Buxton, Derbyshire

Assessment Tools for Structural Integrity

Dr I Le May, Metallurgical Consulting Services Ltd, Saskatoon, Canada
&
Dr R Seshadri, Memorial University, Newfoundland, Canada

Introduction

Engineering structural integrity has become a topic of vital interest and importance to the engineering community and to the public at large. There is increased concern about the safety of structures, vehicles, power plants, bridges and other structures, and concern over other industrial accidents both offshore and on land, but there is little formal training provided for engineering students and professionals. The problem is compounded because evaluations of engineering structural integrity normally include a number of disciplines and also involve thinking "out of the box", which few professionals who have been practicing for many years in narrow disciplines find easy to do. In addition, there are very few university faculty members who have experience to guide students in this approach, particularly as so few have real experience of practical industrial problems or of design of real engineering components and structures.

One of the most effective methods of improving the engineering product has been to refine the design to the point that the limits of safe design are reached. In other words we learn by our mistakes when we push a little to far and go beyond the envelope of safety. Indeed, Robert Stephenson said in 1856 (Whyte [1]):

"...nothing was so instructive to the younger Members of the Profession, as records of accidents in large works, and the means employed in repairing the damage. A faithful account of these accidents, and of the means by which the consequences were met, was really more valuable than a description of the most successful works. The older Engineers derived their most useful store of experience from the observations of casualties which had occurred to their own and to other works, and it was most important that they should be faithfully recorded in the archives of the Institution."

We still need to learn from experience of failures today, and we need to have a good dissemination of such information despite the
Problems imposed by litigation that so often follows a major (or even a minor, in some cases and some jurisdictions) failure. However we need to be pro-active in avoiding failures while improving the design and integrity of engineering structures.

Some of the methods that are appropriate and are being applied to reduce the risk of structural failure are:

- Development of codes of practice for the assessment of fitness for service of operating (and ageing) plant and equipment.
- Risk-based inspection methodologies and the planning that goes in hand with this.
- Development of simplified and robust methods of analysis.
- Strict verification of computer codes for structural assessment.
- Improved nondestructive evaluation (NDE) and quality assurance procedures and improvements in the qualification of NDE inspectors.

Codes of practice

While emphasis will be placed on developments taking place in North and South America, similar developments are taking place in Europe and in Asia.

Much of the effort to develop new codes for operating equipment in North America is being undertaken by the American Society of Mechanical Engineers (ASME) and the American Petroleum Institute (API). Two areas of particular relevance are:

a) Risk based inspection, covered by the draft document "Risk-Based Inspection" (API Recommended Practice 580) and a corresponding draft ASME document "Guideline for Inspection Planning Using Risk Based Methods. The API document is intended to provide guidance on developing a risk based inspection programme for fixed equipment and piping in the hydrocarbon and chemical process industries petroleum, whereas the ASME document is being developed for applications involving fixed pressure-containing equipment and components that are not covered by ASME Section XI, "Rules for Inservice Inspection of Nuclear Power Plant Components": it is intended to provide guidelines to owners, operators and designers of pressure-containing equipment for developing and implementing an inspection programme. The spectrum of complementary risk assessment approaches (qualitative through fully quantitative) will be included as part of the planning process in the ASME document.

Both documents will have a similar coverage that includes:

i) An introduction to the concepts and principles of risk based inspection; and

ii) Individual sections that describe the steps inapplying these principles within the framework of the RBI process:

- Planning the Risk Assessment
- Data and Information Collection
- Identifying Potential Deterioration mechanisms and Failure Modes
- Assessing Probability of Failure
- Assessing Consequence of Failure
- Risk Determination, Assessment and management
- Risk Management with Inspection Activities
- Other Risk Mitigation Activities
- Reassessment and Updating
- Roles, responsibilities, Training and Qualifications
- Documentation and Record Keeping.

(b) Fitness for service, which is defined as the ability to demonstrate the structural integrity of an in-service component containing a flaw or damage. It is applicable to pressurized equipment in terms of the mandate of the ASME and API committees, although the principles may be applied to other equipment. In the API document (API Recommended Practice 579, Fitness-for-Service" the first edition of which was published in January 2000, albeit in an incomplete form as the section dealing with high temperature assessment in the creep range was not available) the coverage is intended to meet the needs of the refinery and chemical industry with respect to pressurized equipment.

ASME had established a separate sub-committee dealing with flaw assessment which would have paralleled the API activities, but in the context of pressurized equipment for industry in general and including the power industry (again with the exception of equipment and components covered by ASME Section XI, "Rules for Inservice Inspection of Nuclear Power Plant Components"). In 2002, agreement was reached between ASME and API to establish a Joint committee on Fitness for Service and to work on a common document based on API 579 to meet the needs of industry as a whole.

API 579

It is appropriate at this point to describe the coverage of API 579. The sections are as follows:

- Section 1 Introduction
- Section 2 Fitness-For-Service Engineering Assessment Procedures
- Section 3 Assessment of Equipment for Brittle Fracture
- Section 4 Assessment of General Metal Loss
- Section 5 Assessment of Local Metal Loss
- Section 6 Assessment of Pitting Corrosion
- Section 7 Assessment of Blisters and Laminations
- Section 8 Assessment of Weld Misalignment and Shell Distortions
- Section 9 Assessment of Crack-Like Flaws
- Section 10 Assessment of Components Operating in the Creep Range
- Section 11 Assessment of Fire Damage
- Appendices

Three levels of assessment are provided in each section of API 579 for which fitness for service procedures are outlined:

Level 1: assessment procedures provide conservative screening criteria that can be used with minimum quantity inspection data or information about the component.

Level 2: assessment procedures provide a more precise and detailed evaluation. The inspection and data information requirements are similar to those for Level 1 but more detailed calculations are required.

Level 3: assessments require detailed inspection data and information about the component. Detailed calculations are also required commonly using numerical methods.

Although rule-based methods of approach for the assessment of flaws are generally used in API 579, risk-based considerations can be included and have been included in some of the analyses such as those governing locally thin areas in order to match these with the rules in construction codes. Consideration of the variability in material properties and of uncertainties in analytical methods can be taken into account, but taking the minimum values of fracture toughness, for example, that might be encountered in the absence of materials data together with the maximum size of a crack whose geometry and size cannot be well defined, and the maximum value of stress that may be present may produce unrealistic rejection of components. A statistical approach may be required with the allowable risk level or probability of failure being chosen on the basis of the potential serious of the consequences. This is also a case where monitoring in service might be called for, or relatively short inspection intervals recommended.

ASME Repair and Testing Activity

As part of the ASME activity on Post Construction Standards, ASME has initiated activities in preparing procedures for repair and testing of in-service pressure system components. These are being prepared as individual procedures to be publisher on a case-by-case basis, and are roughly similar to Boiler and Pressure Vessel Code Cases. They will not, however, be Code items, merely providing examples for guidance to repairs showing analyses taking into account relevant engineering considerations to ensure structural integrity.

A partial listing of items being prepared or studied includes:

- General repair considerations
- Valve repairs
- Pipe and tube crimping
- Cured in place inserted liners
- Compressed seal at joints
- Repair of stripped threads in tapped holes
- Hydrogen blisters
- Hot tapping
- Alternative to post weld heat treating

⊗

Developments In Latin America

It is appropriate to review the development of structural integrity assessment awareness and implementation of such methodology in Latin America. Following upon efforts of the Canadian International Development Research Centre (IDRC) to promote technological development a collaborative Canada-Brazil research project was established in 1984 to examine the development of high temperature damage in structural steel for power station and petrochemical plants. Subsequently, several Recommended Practices on integrity evaluation were developed and published by the Associação Brasiliera de Ciencias Mecanicas (ABCM the Brazilian Society of Mechanical Engineers) (da Silveira [2]).

A series of conferences were held dealing with integrity evaluation and plant life extension: these were held initially in Brazil, but with a number of attendees from other South American countries. As a consequence, at a conference dealing with structural integrity and life extension held in Uruguay in 1992, a multinational organization (PROMAI "Proyeto Multinational de Análysis de Integridad y Extension de Vida de Equipos Industriales") was set up to foster such activities. Since that time PROMAI has organized a number of courses, sponsored joint projects between universities and industries, and organized a number of conferences and workshops to raise awareness of structural integrity concerns, and has published documents covering basic definitions and procedures for integrity evaluation and life extension (Stuckenbruck [3]).

Power production in Brazil has been increased greatly in the area of hydroelectric generation in recent years. This has resulted in many thermal stations that were formerly used for base load generation now being operated at peak load times only, causing accelerated aging and degradation. Thermal power stations are aging as in most other countries, as of 1999 approximately 63% having been in operation for more than 25 years. The intention is to extend the useful life of thermal power plants by from 25 to 30 years, to produce a total useful life of from 50 to 60 years or more. All boilers are subject to the Federal law with respect to pressure vessels, the relevant standard, NR13 (Associação Brasileira de Normas Técnicas [4]), requiring regular inspections to be made. However, because the major part of the power generation in Brazil has been and continues to be hydroelectric in nature, there had been relatively little effort to apply the techniques for damage assessment and life extension of thermal plants by most companies responsible for electricity generation.

In view of the fact that CEPEL (Centro de Pesquisas de Energia Elétrica), the main research and technology centre for Eletrobras, which is the Brazilian company that has been the holding company for many of the Brazilian power producing companies, had been conducting inspections and assessments of many of the thermal power stations in Brazil, a project was initiated through which CEPEL would develop a set of guidelines for the assessment of thermal power plants. The manual was completed in 1999 (Furtado et al. [5]).

The manual, "Guia de Avaliação de Integridade em Usinas Térmicas", contains the following main sections:

1. Introduction
2. Terminology
3. Planning for Integrity Evaluation
4. Methodology Proposed for Integrity Evaluation
5. Criteria for Selection and Execution of Tests
6. Criteria for the Evaluation of Test Results
7. Costs and Benefits
8. Conclusion of the Integrity Evaluation
9. Extension of Useful Life
10. Appendices
11. References

Under the heading "Planning", prioritizing of components for inspection is discussed in terms of history, their original design, the time for replacement during service in case of a failure, and their thermal and mechanical loading. Several approaches to this may be followed.

They may be prioritized in terms of their being critical or non-critical. A critical component is considered to have the following characteristics:

- A failure would cause shutdown for a considerable time.
- A failure implies risks to employees of the plant
- Substitution or repair implies high costs and long delay in operation.
- A non-critical component would have the following characteristics:
- A failure could result in a significant reduction in capacity, but would not lead to a forced shutdown.
- A failure would not cause concern for the safety of personnel nor lead to secondary damage.

An alternative method of classification of components is based on whether they can be replaced or not. Components that can be replaced may also require an analysis of remaining life and are subdivided into the following categories:

- Components relating to safety: these include ones that have the potential to cause injury to plant personnel in the case of failure
- Limited availability of components.
- Long delay in obtaining a replacement.
- Components whose failure would lead to a shutdown of the plant.
- Components that have the potential for early failure.
- Components with poor reliability: those in which there have been many failures causing shutdowns.
-
- Components in which serious loss of performance is observed, causing deterioration in plant performance.

Section 6 of the Manual, titled "Criteria for the Evaluation of Test Results", covers the problems of general loss of thickness, local thinning, pitting corrosion, crack-like defects and high temperature creep damage. Here, the outline of the assessment procedures for creep damage will be detailed.

A Level I approach calls for the following steps:

1. Obtain the design data and operating records for the various components. If there are records of significant failures, move to a Level II assessment.

2. If any condition of temperature or pressure exceeds the design conditions, move to a Level II assessment.

3. Determine the minimum thickness for each component according to the design code, using the tabulated properties for the particular material.

4. Determine the minimum measured thickness for each component from inspection records. Simplified stress analysis using mean diameter is appropriate.

5. If there are calculated minimum thickness values that are less than the minimum permissible, taking the corrosion allowance into account, the component does not meet Level I assessment requirements and must be evaluated by Level II methods.

6. Prior inspection data for cracks, particularly at structural discontinuities, need to be evaluated. If there are any significant cracks, they must either be repaired and eliminated or evaluated using a Level III approach.

7. The operational history must be reviewed. The life fraction used from cumulative damage by creep is estimated on the basis of the design conditions for temperature and pressure, using a cumulative damage relation. Stresses are based on mean diameter and the estimated cumulative damage (or life used up) is compared with the minimum rupture life for the material from the data bank for the code at the design temperature and pressure. If the value estimated for the fraction of life expended is greater than 0.6, a more detailed analysis of creep damage is required using metallographic techniques and hardness measurements.

8. The creep damage can be evaluated using metallographic methods, hardness measurements, or both. If apparent voids are detected after repeated polish-etch procedures, if the microstructure displays severe degradation in terms of carbide spheroidization, or if the Hardness are lower than the minimum specified for the particular material, the component needs to be evaluated by a Level II approach.

9. If any significant change in dimension is encountered, the evaluation must be made using Level II procedures.

10. If the component satisfies Steps 1 to 9, a Level I approach is adequate and it can continue in operation until the next inspection period, as defined by the projected rate of damage accumulation.

A Level II evaluation is required when components of a steam generator operating under pressure in situations where the creep damage is not able to satisfy the conditions required for evaluation using Level I. It consists of the following steps:

1. Inspection is required to ensure that there are no cracks present. If cracks are detected, they must either be eliminated or an evaluation using Level III criteria is required.

2. Estimate stresses on the basis of the operating conditions and determine the cumulative life expended on the basis of the minimum properties of the material under operating conditions. hence, determine the remaining life. If the remaining life is less than the planned inspection interval, a Level III evaluation is required. The stress analysis can be made using stress analysis equations.

3. The damage by creep can be checked from metallography and hardness. These tests should be made on a number of areas to ensure they are representative. For example, in the case of a header, the tests should be made towards the ends and in the centre, close to welds. In the case of severe carbide spheroidization, microcracks or apparent voids on grain boundaries being detected, or where the hardness is much less than the minimum specified for the material concerned, a more detailed analysis is required using a Level III approach.

4. In the case of the detection of distortions, ovalization or significant deformation, an analysis of the creep deformation must be made. The stress distribution resulting from changes in geometry can be used to recalculate the cumulative life expended and the minimum remaining life. The stress analysis can be made using simplified applied mechanics methods. If the safe minimum life is less than the interval to the next planned inspection, the component must be changed or evaluated using Level III criteria.

Level III analysis required if the steam generator does not meet the required criteria of Level I or Level II. It is also required to evaluate the growth of cracks that have been detected and which may grow in service. The required steps are as follows:

1. All cracks need to be dimensioned precisely and characterized according to their growth mechanism.

2. The cracks need to be evaluated using fracture mechanics methods, including their growth by creep and from creep-fatigue interaction. Recognized proprietary programs, such as R5 and R6 (Nuclear Electric [6]) and PCPIPE (Saxena [7]), may be used.

3. Stress analysis may be made using numerical methods to obtain more precise results. Such analysis may require that the effects of stress relaxation be considered as these may be significant during elevated temperature service. Multiaxial stresses and complex geometries as at nozzle connections may be evaluated and a more precise analysis of the effect of pipe bends and of supports may be made than was done previously.

4. Better estimates of the creep damage can be made. these can be made using estimates of metal temperature based on hardness or measurements of the oxide thickness on the steam side of tubes and headers in order to estimate more accurately the cumulative life expended. If this is less than the projected interval to the next inspection, the component may be replaced, re-dimensioned or re-evaluated using Level III methods. Alternatively, creep rupture tests of the material can be made to estimate the remaining life more accurately. This can be compared to the to the time to the next planned inspection. If remaining life is less than this value, the next inspection interval can be reduced or the component replaced. Approximations of damage accumulation using continuum damage mechanics may also be used in the evaluation (Penny [8]).

5. In the case of distortion, ovalization or local deformation, these may be evaluated using numerical methods to determine the extent of creep deformation and stress redistribution. The analysis needs to ensure that the projected safe life as estimated on the basis of actual stresses, the precise values of thickness and geometry and the current properties of the material, is more than the planned inspection interval.

6. In the case of a component that does not satisfy a Level III evaluation, it must be replaced.

Simplied and Robust Methods of Analysis

Structural integrity assessment is clearly a multidisciplinary and a multi-industry effort. While new engineering facilities are built according to applicable codes and standards, these facilities undergo degradation and ageing when operational. These codes and standards for new facilities are well-developed; however, there is a general lack of guidance with respect to the integrity assessment of ageing facilities, especially in the oil and gas and petroleum sectors, although the situation is improving as discussed above.

The "design-by-analysis (DBA)" approach of the ASME Codes, for instance, is based on a framework of failure avoidance for identified modes of failure. The grouping of potential modes of failure falls into two categories, namely:

- failures that can occur without warning on a one time application of loads, and
- failures due to repeated action, as during startup-shutdown sequence or severe thermal transients.

Three classes of stresses are identified that have different degrees of significance and are therefore assigned different stress limits on the basis of failure risks posed, namely primary, secondary and peak stresses. Primary stresses arise from ensuring equilibrium with external loads and stringent limits are placed in order to prevent failure due to one-time static loading. Secondary stresses arise from requiring compatible deformations at discontinuities of pressure components. In order to prevent the occurrence of incremental collapse due to repeated loading, stress limits that are less stringent than for primary stresses are assigned. Peak stresses arise at notches or sharp geometric transitions, and are limited in order to prevent low-cycle fatigue failures during cyclic operation.

While appropriate for new designs, the ASME-DBA procedures are somewhat awkward for integrity assessment of ageing facilities. On the other hand, a robust simplified assessment framework would be attractive for assessments in a plant environment, assuming that it can fully capture the technical and design intent and basis of the codes. In this context, robust methods are ones that provide reasonable results for a wide range of component geometries on the basis of readily available material data, conceptual insight, and economy of computational effort and time. Robust methods are especially useful for:

- Initial scoping and feasibility assessments,
- screening of critical areas in complex systems,
- independent verification of inelastic analysis of complex problems, and
- fitness-for-service evaluations.

The integrity assessment framework developed in the United Kingdom by Nuclear Electric's procedures R5 and R6 [6] is promising for evaluations in an operating plant environment. The evaluations are based on two parameters that are specific to a structure, i.e., the local constraint parameter (Z) and the limit load based reference stress (σ_{ref}). While the reference stress deals with modes of failure that occur without warning associated with the one-time application of load, the local constraint factor addresses failure modes that arise from cyclic loading, as occurs in a repeated startupshutdown sequence (Mackenzie et al. [9], Seshadri [10]).

The R5, R6 framework essentially addresses the various modes of failure identified in the ASME Codes for the design of new pressure vessels, and would be a viable approach for structural integrity assessment of new as well as ageing components and structures.

Concluding Remarks

The foregoing has been a brief overview of developments in the evaluation of engineering structural integrity. Five methods were outlined at the outset, namely development of codes for fitness for service assessment; risk-based inspection methodologies and inspection planning; robust methods of analysis; computer code verification; and improved NDE. The first three have been covered in this overview, however little has been said about the last two topics. However, it was noted in discussing simplified and robust analytical methods that these are valuable in providing verification of complex analyses.

With regard to improvements in NDE, two points will be made here. The first is that every NDE method has limitations in the detection of flaws, and that such uncertainties must be recognized; also that inspectors need to be qualified from time to time. The second point is that structures must be designed to be inspectable. All too often it is impossible to obtain access to critical areas because inspection in service was not considered at the design stage. If something cannot be inspected and its failure could be critical, then the risk of an accident may be greatly increased and the integrity of a structure may not be able to be established with a sufficient degree of confidence.

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