Unclassified **NEA/CSNI/R(2002)13**

Organisation de Coopération et de Développement Economiques
Organisation for Economic Co-operation and Development

02-Jul-2002

English - Or. English

NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

FINITE ELEMENT ANALYSIS OF AGEING REINFORCED AND PRESTRESSED CONCRETE STRUCTURES IN NUCLEAR PLANT

AN INTERNATIONAL REVIEW OF CURRENT CAPABILITIES AND PRIORITIES FOR FUTURE DEVELOPMENTS

JT00129089

NEA/CSNI/R(2002)13
Unclassified

English - Or. English

ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

Pursuant to Article 1 of the Convention signed in Paris on 14th December 1960, and which came into force on 30th September 1961, the Organisation for Economic Co-operation and Development (OECD) shall promote policies designed:

- to achieve the highest sustainable economic growth and employment and a rising standard of living in Member countries, while maintaining financial stability, and thus to contribute to the development of the world economy;
- to contribute to sound economic expansion in Member as well as non-member countries in the process of economic development; and
- to contribute to the expansion of world trade on a multilateral, non-discriminatory basis in accordance with international obligations.

The original Member countries of the OECD are Austria, Belgium, Canada, Denmark, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The following countries became Members subsequently through accession at the dates indicated hereafter: Japan (28th April 1964), Finland (28th January 1969), Australia (7th June 1971), New Zealand (29th May 1973), Mexico (18th May 1994), the Czech Republic (21st December 1995), Hungary (7th May 1996), Poland (22nd November 1996), Korea (12th December 1996) and the Slovak Republic (14th December 2000). The Commission of the European Communities takes part in the work of the OECD (Article 13 of the OECD Convention).

NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1st February 1958 under the name of the OEEC European Nuclear Energy Agency. It received its present designation on 20th April 1972, when Japan became its first non-European full Member. NEA membership today consists of 27 OECD Member countries: Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, Norway, Portugal, Republic of Korea, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The Commission of the European Communities also takes part in the work of the Agency.

The mission of the NEA is:

- to assist its Member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes, as well as
- to provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

Specific areas of competence of the NEA include safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has a Co-operation Agreement, as well as with other international organisations in the nuclear field.

COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

The NEA Committee on the Safety of Nuclear Installations (CSNI) is an international committee made up of scientists and engineers. It was set up in 1973 to develop and co-ordinate the activities of the Nuclear Energy Agency concerning the technical aspects of the design, construction and operation of nuclear installations insofar as they affect the safety of such installations. The Committee's purpose is to foster international co-operation in nuclear safety amongst the OECD Member countries.

CSNI constitutes a forum for the exchange of technical information and for collaboration between organisations which can contribute, from their respective backgrounds in research, development, engineering or regulation, to these activities and to the definition of its programme of work. It also reviews the state of knowledge on selected topics of nuclear safety technology and safety assessment, including operating experience. It initiates and conducts programmes identified by these reviews and assessments in order to overcome discrepancies, develop improvements and reach international consensus in different projects and International Standard Problems, and assists in the feedback of the results to participating organisations. Full use is also made of traditional methods of co-operation, such as information exchanges, establishment of working groups and organisation of conferences and specialist meeting.

The greater part of CSNI's current programme of work is concerned with safety technology of water reactors. The principal areas covered are operating experience and the human factor, reactor coolant system behaviour, various aspects of reactor component integrity, the phenomenology of radioactive releases in reactor accidents and their confinement, containment performance, risk assessment and severe accidents. The Committee also studies the safety of the fuel cycle, conducts periodic surveys of reactor safety research programmes and operates an international mechanism for exchanging reports on nuclear power plant incidents.

In implementing its programme, CSNI establishes co-operative mechanisms with NEA's Committee on Nuclear Regulatory Activities (CNRA), responsible for the activities of the Agency concerning the regulation, licensing and inspection of nuclear installations with regard to safety. It also co-operates with NEA's Committee on Radiation Protection and Public Health and NEA's Radioactive Waste Management Committee on matters of common interest.

Foreword

IAGE WG deals with the integrity of structures and components, and has three sub-groups, dealing with the integrity of metal structures and components, ageing of concrete structures, and the seismic behaviour of structures.

A status report on the ageing of concrete nuclear power plant (NPP) structures [1] was prepared during 1995 by a task group to initiate activities in this field under IAGE WG. That report made recommendations regarding the issues that should be addressed and the relative priorities that should be attached to them. These were as follows:

First Priority

- Loss of prestressing force in tendons of post-tensioned concrete structures.
- In-service inspection techniques for reinforced concrete structures having thick sections and areas not directly accessible for inspection.

Second Priority

- Viability of development of a performance based database.
- Response of degraded structures (including finite element analysis techniques, possibly leading to an International Standard Problem).

Third Priority

- Instrumentation and monitoring.
- Repair methods.
- Criteria for condition assessment.

The two highest priority items have already been addressed through workshops and associated reports [2 and 3].

The first activity relating to the response of degraded structures through finite element analysis was a workshop held in October 1998 [4]. Further to this event, IAGE WG decided that there would be considerable benefit in producing this report on ‘An International Review Of Current Capabilities And Priorities For Future Developments in Finite Element Analysis of Ageing Reinforced and Prestressed Concrete Structures in Nuclear Plant.’

The complete list of CSNI reports, and the text of reports from 1993 on, is available on http://www.nea.fr/html/nsd/docs/

Acknowledgement

Gratitude is expressed to Dr Tony McNulty with NII (Nuclear Installations Inspectorate), HSE in the UK and to the contractor Wilde and Partners Ltd for carrying out this report.
Gratitude is also expressed to members of the IAGE Expert group which contributions helped in building an international review on the topic.

Abbreviations

ACI	American Concrete Institute
AGR	Advanced Gas Cooled Reactor
ASR	Alkali Silica Reaction
ASRANet	Advanced Structural Reliability and Analysis Network
BWR	Boiling Water Reactor
CCV	Concrete Containment Vessel
CEB	Comite Euro-International du Beton
CSNI	NEA Committee on the Safety of Nuclear Installations
FEA	Finite Element Analysis
FENET	Finite Element Network
IAGE WG	Integrity and Ageing Working Group
ILRT	Integrated Leak Rate Test
IMC	Industry Management Committee
ISP	International Standard Problem
LOCA	Loss of Coolant Accident
LWR	Light Water Reactor
NAFEMS	International Association for the Engineering Analysis Community
NEA	Nuclear Energy Agency
NPP	Nuclear Power Plant
OECD	Organisation for Economic Co-operation and Development
PCPV	Prestressed Concrete Pressure Vessel (e.g. UK AGR Magnox), referred to as ‘vessels’.
PCC	Prestressed Concrete Containment, referred to as ‘containments’.
PCCG	Pre-Conditioned Conjugate Gradient
PPT	Proof Pressure Test
PVCS	Pressure Vessel Cooling System

PWR	Pressurised Water Reactor
RC	Reinforced Concrete
RILEM	'Réunion Internationale des Laboratoires d'Essais et de recherche sur les Matériaux et les Constructions' or International Association for Building Materials and Structures
SPZ	Standpipe Zone (central area of top slab to PCPV, penetrated by an array of several hundred closely spaced tubes for control rod and fuel rod movements)
TNO	The Netherlands Organisation for Applied Scientific Research
ttc	Transient Thermal Creep

CONTENTS

PAGE

EXECUTIVE SUMMARY **13**

1.0 INTRODUCTION **15**
- 1.1 Background **15**
- 1.2 Objectives **16**
- 1.3 Scope **16**
- 1.4 Existing Finite Element Programs **16**
- 1.5 Report Structure **17**
- 1.6 Contributors to the Report **18**

2.0 NUCLEAR SAFETY RELATED CONCRETE STRUCTURES **19**
- 2.1 Common Structural Forms **19**
- 2.2 Loading Conditions **21**
- 2.3 Reasons For Using FEA **24**

3.0 REPRESENTATION OF GEOMETRIC FEATURES AND LOADING **27**
- 3.1 Summary of Topics Addressed **27**
- 3.2 Global Structural Representation **28**
- 3.3 Structural Discontinuities **32**
- 3.4 Representation of Steel **35**
- 3.5 Representation of Loading **40**

4.0 REPRESENTATION OF MATERIAL FEATURES **43**
- 4.1 Summary of Topics Addressed **44**
- 4.2 Concrete in Tension **45**
- 4.3 Concrete in Shear **54**
- 4.4 Concrete in Compression **56**
- 4.5 Representation of Steel **59**
- 4.6 Thermal Expansion of Concrete **62**
- 4.7 Creep **63**
- 4.8 Cyclic Loading **65**
- 4.9 Transient Thermal Creep **66**

5.0 REPRESENTATION OF AGEING EFFECTS **69**
- 5.1 Through Life Loading Sequences **69**
- 5.2 Summary of Topics Addressed **69**

6.0 NUMERICAL STABILITY **75**

7.0 VALIDATION OF ANALYSIS METHODS AND RESULTS **77**
7.1 Verification of a Finite Element Program and its Basic Formulation **77**
7.2 Validation of Material Models **77**
7.3 Validation of Analysis Results **78**

8.0 OVERVIEW OF RECENT RESEARCH DEVELOPMENTS **81**
8.1 Geometric Features **81**
8.2 Material Features **81**
8.3 Ageing Issues **85**
8.4 Stability of the FE Solution Algorithm **86**

9.0 PRIORITIES FOR FUTURE DEVELOPMENTS **87**

10.0 CONCLUSIONS **91**
10.1 Recommendations **91**

REFERENCES **93**

Figures **99**

APPENDICES

Appendix A Details of UK Stations **107**

Executive Summary

Nuclear plants contain a variety of concrete structures whose structural performance is essential to the safety of the plant. There is a requirement to demonstrate the robustness of these structures during normal operating and extreme accident conditions, throughout their life. During this time, the concrete may degrade due to the effects of ageing. This degradation must be accounted for during the assessment of their performance.

Finite Element Analysis (FEA) techniques have tremendous potential for providing valuable insight into the behaviour of these aged concrete structures under a range of different loading conditions.

Advanced FEA techniques currently enjoy widespread use within the nuclear industry for the non-linear analysis of concrete. Many practitioners within the nuclear industry are at the forefront of the industrial application of these methods. However, in some areas, the programs that are commercially available lag behind the best information available from research.

This report:

1. Summarises the needs for FEA of aged concrete nuclear structures.
2. Details the existing capabilities, not just in terms of what the software is capable of, but also in terms of the current practices employed by those in industry.
3. Looks at how engineers, within the nuclear industry, working in this field would like to see methods improved, and identifies the factors that are limiting current practice.
4. Summarises ongoing research that may provide beneficial technological advances.
5. Assigns priorities to the different development requests.
6. Selects those developments that are felt to be of greatest benefit to industry and provides a qualitative assessment of the relative costs involved in their implementation.

The primary factors that are currently placing limitations on the analyses performed are deemed to be:

- Issues of numerical stability.
- Long solution times, especially for 3D analyses.
- Limitations in methods to fully simulate ageing process.
- Lack of sufficient material data.
- Inability to simulate the link between cracking and leakage.
- Lack of collation of benchmark information for validation of techniques.

The background to the above limitations is tabulated at Section 9 of this Report. Resolution and progression of these limitations should be progressed through the following;

- Further collaboration with representatives of other industries that stand to benefit from the advanced analysis of concrete.
- Formal liaison with commercial software developers, to communicate effectively the prioritised needs of industry for this type of analysis.
- Cooperation with other bodies with an interest in this area of work (e.g. ASRANet, NAFEMS and FENET).
- Develop database of materials information.
- Develop database of benchmark information.
- A joint meeting with the participants in the latest Sandia test.
- Review progress in approximately 3 years.

1.0 INTRODUCTION

1.1 Background

Concrete containments and vessels are relied upon by nuclear power plants around the world. The integrity of these structures must be ensured at all times, during both normal operating conditions and all postulated accident conditions. Many of these structures are more than twenty years old, and some have a design life of forty years or more. It is essential to prove that they can withstand extreme loading conditions at any time during their design life, making due allowance for the effects of any age related degradation.

Many member states have, to varying degrees, turned to the use of non-linear finite element analysis to assist them in demonstrating the ongoing safety of their containment and vessel structures. For a variety of reasons, the techniques of non-linear finite element analysis of concrete, whilst they have been available and under development for some time, have only recently started to be adopted in a widespread fashion. There are developments available at a research level that have not yet been incorporated in the available programs. Equally not all the capabilities available in programs are being fully employed by all users.

Some of the first uses of the Finite Element Method (in the 1960s) to analyse the non-linear deformation of structures involved research investigations into the behaviour of prestressed concrete reactor vessels. The worldwide growth in the nuclear build programme, together with the acceleration in aerospace technology during the 1960’s, were perhaps the two primary driving forces behind most of the early improvements achieved in finite element structural analysis.

Since that time, a very wide range of scientific and engineering studies have been performed. The continual release of ever-faster computer processors, the reducing costs of core and high-speed backup memory and the availability of cheap high-specification graphics workstations have all contributed to the increasing use and availability of FEA techniques.

In many countries, the nuclear industry has been amongst the first to embrace the benefits of these techniques. Consequently, the nuclear industry possesses one of the most advanced sets of skills and experience of any industry.

The use of advanced finite element methods has already proved to be extremely successful. The insight about structural performance provided by these techniques is invaluable.

This document is an international review of current capabilities and priorities for future development relating to non-linear finite element analysis of reinforced and prestressed concrete in the nuclear industry in the various member states. Particular attention is paid to the analysis of degraded or ageing structures.

1.2 Objectives

There are a number of different objectives that this document is intended to fulfil:

- Gather together the various methods and procedures used in the non-linear analysis of concrete structures. Discussion is included about aspects where difficulties have been experienced, as well as the types of problem that can be routinely addressed with confidence.

- Provide an up to date understanding of both the strengths and the limitations of current non-linear analysis techniques for concrete. Since these techniques are still evolving and developing, there is a perceived need for such a review. In addition, a review should prove useful to those who are new to this field of analysis, by increasing their awareness of the existing capabilities.

- To identify which analysis features the nuclear industry would like to see developed further and to attach priorities to these features, based on their relative importance.

- To provide some assessment of the relative ease or difficulty with which it might be possible for the desired features to be implemented into the finite element programs currently being used by industry.

- To promote a better understanding of what is happening in the research arena and to assess how this might improve the capabilities that become available in the future. A significant proportion of the research work that has been carried out over the past decade or so has yet to appear in many of the finite element programs used by the industry. This report is intended to highlight research work that has already been carried out, or is currently underway, which can help to bridge any gaps between what is currently possible and what the software users would most like to be able to do. As such, it will hopefully provide a useful source of reference for software developers looking to prioritise their future development activities.

- To identify priorities for future research and development.

1.3 Scope

This document reports on the status of the non-linear analysis of reinforced and prestressed concrete that is being carried out by the nuclear industry. This report is prepared under the auspices of the ‘Ageing of Concrete Structures’ sub-group of IAGE WG. Emphasis within the report is therefore directed towards issues significant to ageing. This limits the scope such that short term dynamic loading (including seismic and aircraft impact) are not specifically addressed. Seismic loading is covered by a different sub-group of IAGE WG.

1.4 Existing Finite Element Programs

A wide variety of finite element programs are used by the nuclear industry around the world for the analysis of concrete structures. These may be broadly categorised as follows:

- General purpose commercial finite element programs. These have varying degrees of generic capabilities that can be applied to the specific requirements of concrete behaviour.

- Commercial finite element programs that focus particularly on concrete analysis.

- Programs developed specifically for use by the nuclear industry within a particular country.

- Programs developed by academic and research organisations.

Each of these types of programs has their own strengths, features and benefits. The purpose of this report, however, is not to present a discussion of the relative merits of each type of program compared to its rivals. Rather the report is intended to describe in more general terms the extent to which software which is currently available (and being used by the nuclear industry) is able to go towards providing the ideal representation of the true behaviour of concrete structures.

Much of the information that is gathered from a non-linear finite element analysis of a concrete structure would be difficult, if not impossible, to obtain by other means to a similar degree of accuracy. FEA has now become a proven and important tool for use in the assessment of nuclear safety related concrete structures. Provided that it is used properly and appropriately, the insight that it is able to provide into the behaviour of complex structures under a multitude of hypothetical loading conditions is invaluable.

Section 8 discusses past and present research work and describes many of the advances that have been made. It is inevitable that the development of commercial programs must, to some extent, lag behind the findings of the research community. It is noticeable, however, that in the area of concrete analysis, for most commercial programs, the extent of this gap is more significant than for other industries (for example the automotive and aerospace industries). The reasons for this are not totally clear, but probably stem from commercial pressures, and the lack of applicability of advanced analysis techniques to mainstream civil engineering design. This document highlights the areas where deficiencies in general purpose programs are preventing those working with concrete in the nuclear industry from performing the analyses that they would like to. Furthermore, references are provided to research work that might help to overcome some of these problems. It is hoped that this will provide some useful guidance for those software developers that wish to address the particular requirements of the advanced analysis of concrete structures in the nuclear industry.

In this report, it is assumed that the reader is familiar with the general concepts and terminology of traditional finite element analysis. Further background information can be obtained from traditional references [7, 8 and 9].

1.5 Report Structure

Tables have been used extensively in this report in order to provide a concise and readily accessible summary of all the information that has been gathered. These tables are supported by a number of descriptive text sections:

Section 2 provides a background to the typical structures that are being considered, the loads that they may be subjected to, and the information that is required from any analysis in order to make an informed assessment of their performance.

In Section 3, the geometric features of the concrete structures that should ideally be represented are identified together with a discussion on loading that applies. This section identifies the features of interest, the current capabilities of the software used, the current practice of the industry and areas of current research.

Section 4 identifies material features of interest and follows a similar format to Section 3, with Section 5 addressing the representation of ageing effects.

Section 6 includes a brief discussion on numerical stability within the finite element programs available, with Section 7 containing a brief summary of some of the more relevant validation tests that have been performed.

Section 8 looks at the topics raised in the earlier sections, from a research perspective.

The report concludes at Sections 9 and 10 with a summary of the priorities for future developments and recommendations for further research work.

Summary tables are included within the sections of the report to provide a list of:

- the features that it is desirable to represent
- how desirable each of these features are
- how effective current software is at capturing them
- how industry currently deals with them
- references to any pertinent research work being undertaken

1.6 Contributors to the Report

The report has been compiled by Wilde & Partners, a UK based firm of consulting engineers, in conjunction with the University of Sheffield, with guidance from Dr. Tony McNulty of the UK's Nuclear Installations Inspectorate. (Dr. McNulty is the UK representative on the IAGE WG task group on ageing of concrete.) Substantial information has been provided from the following organisations whose assistance is greatly appreciated:

UK	British Energy British Nuclear Fuels (BNFL) BNFL Magnox NNC NDA
USA	ANATECH Corporation
France	CEA

Valued comments on Draft issues of the report were received from:

Belgium	Tractebel
Sweden	Scansot Technology AB
Germany	Framatome
IAEA	

In addition, input provided by TNO in The Netherlands has proved to be extremely useful.

2.0 NUCLEAR SAFETY RELATED CONCRETE STRUCTURES

2.1 Common Structural Forms

This section provides a brief description of the common structural forms of the nuclear safety related concrete structures considered in the report. Areas of these structures that are of particular interest or relevance are discussed.

The attached Appendix A gives more detailed description and information relating to the UK plant to illustrate some areas of typical details.

A general description of the various forms of nuclear plant in operation around the world is contained in [6].

2.1.1 General

The report is primarily concerned with prestressed concrete containments (PCC) and prestressed concrete pressure vessels (PCPV) although reinforced concrete containments (RCC) and other forms of nuclear safety related concrete structures are included. Throughout this report PCC's are referred to as 'containments' and PCPV's are referred to as 'vessels.' Whilst the layout and function of the various structures described differs there are many areas of 'generic' similarity when considering FEA.

The materials of construction are similar; concrete is used as the main construction material with embedded reinforcement and/or prestressing tendons provided to achieve the required strength. Internal mild steel liners are used widely to achieve leak tightness. The concrete sections are substantial with significant levels of reinforcement and/or prestressing tendons. The forms of loading and the structural and safety related performance requirements are broadly similar. There are numerous penetrations through the walls and slabs of the structures.

2.1.2 Prestressed Concrete Containments

PCC's are used to house pressurised water reactors (PWR), some boiling water reactors (BWR) and heavy water reactors (PHWR).

Containments house the primary circuit and have a relatively passive function under normal operation. They normally experience a minimal negative pressure (-0.015 MPa) and ambient temperatures.

The significant design basis for containments follows a loss of coolant accident (LOCA) in the primary circuit, resulting in an internal pressure of typically 0.5 MPa and associated internal temperature of 40 to 50°C (and up to 160°C in some containments), with the possibility of localised significant pipe whip and jet impingement loads.

Containments also provide protection to the internal reactor from environmental effects (such as wind or rain) and external hazards (such as aircraft impact).

The design of containments is based on demonstrating integrity for all credible combinations of loading comprising normal loads, LOCA, environmental effects and extreme and hazard loading.

Various forms of containment are provided throughout the world, including:

i) single walled cylindrical/domed containments, usually of prestressed concrete construction (with some earlier containments of part reinforced/part prestressed construction).
ii) double walled cylindrical/domed containments with both walls formed from reinforced concrete.
iii) double walled cylindrical/domed containments with the inner wall being of prestressed concrete construction and the outer wall formed from reinforced concrete.
iv) spherical steel containments on a concrete base surrounded by a concrete shield structure.

Containments have several penetrations through their walls. Prestressing tendons can be either grouted or un-bonded.

Leak tightness is provided either by the concrete containment(s) alone or by an internal steel liner integral with the inner concrete structure.

Some operators are now considering other forms of internal liners based on polymer or composite materials (see for example[18]).

2.1.3 Prestressed Concrete Pressure Vessels

PCPV's are used for gas cooled reactors, and are lined with a gas tight steel membrane which is extended at the penetrations with sealed tubes to form the pressure boundary to the primary gas circuit under normal operational and fault conditions. Typical internal operational gas pressures and temperatures are 2 to 5 MPa and 630°C. The temperature of the liner and penetrations, and hence that of the concrete itself, is kept within operational limits (typically <50°C) by liner insulation and pressure vessel cooling water systems.

The normal operational requirements for vessels thus differ significantly from those for containments. Vessels experience sustained internal pressures and temperatures whilst containments only experience any significant internal pressures and temperatures under accident conditions.

There is a significant interaction between the vessel concrete and the internal steel liner. The steel liner provides the leak tight membrane and is integral with, anchored to and supported by the vessel concrete. The vessel in turn imposes a loading demand on the liner through strains at the anchorage points as the vessel responds to the various applied loads.

Vessels are generally cylindrical, have thick walls, bases and roofs (3 to 6m) with numerous penetrations for the various services associated with the internal reactor core.

2.1.4 Reinforced Concrete Containments

RCC's are used to house Advanced Boiling Water Reactors, where the containment structure is integrated with the structure of the reactor building. This means that the plant size can be reduced (when compared with PCC's).

2.1.5 'Other' Nuclear Safety Structures

This sub-section provides a summary of a wide range of nuclear safety related structures of concrete construction which do not fall into the categories of containments and vessels. The description is generic rather than specific and identifies typical forms of construction.

Structures within this category include:

- containment internal structures
- spent fuel core ponds
- external ice plants
- above ground fuel dry stores
- below ground long term spent fuel deposits
- process/research facilities

Such structures are generally of reinforced concrete construction with thick walls and slabs (provided for shielding purposes) although some older structures include prestressed concrete construction.

Shear wall type construction is used widely with structures typically arranged in a cellular layout with one or more stories. Floors/slabs are either of solid construction spanning to the walls or can be supported by an arrangement of beams and columns.

Pressure loading within the cells is generally minimal. Temperature loading can be significant in spent fuel stores. Seismic loading usually represents the dominant load case.

Liners are used where leak tight construction is required, typically for containment ponds.

Penetrations, temporary or permanent, are common through the walls and slabs of such structures.

2.2 Loading Conditions

This section contains a discussion of the typical forms of loading that act upon the structures described in Section 2.1. Such loading represents the demand acting on the structure with it being an explicit requirement that the FEA techniques employed be capable of predicting how the structures respond to this demand.

2.2.1 Dead and Imposed Loads

The self weight of the structure and major items of permanently fixed plant are considered as dead load with imposed loads including other plant and equipment together with items of moving plant (i.e. cranes). Such loading is acted on by gravity effects and externally applied inertial effects such as seismic loading. Imposed loads can act as distributed, line or point loads. The latter categories can include applied component restraint loads.

2.2.2 Environmental Loads

Externally exposed parts of containments and vessels can be subjected to environmental loads. These include wind, snow, ice, rain, temperature and humidity. The effects of such loading are generally small for the scale of structures considered in this report.

2.2.3 Prestressing Loads

The prestressing systems employed within vessels and containments represent a significant loading acting on the concrete of such structures. It is important to be able to accurately and fully model the distribution of the internal forces induced by the prestressing system as these act to resist the dominant applied loads. The manner and sequence in which the prestressing loads are applied needs to be considered in some cases. The effect of loss of prestress with time or along tendon length (due to frictional effects) is of particular interest when considering ageing.

2.2.4 Dynamic Loads

Dynamic loading effects can arise from a number of sources including seismic, aircraft impact, drop loads, pipe whip and explosion.

It is recognised that such loading is a significant issue for containments and vessels, especially seismic and aircraft impact. However the scope of this report is directed towards issues relevant to ageing. Short term dynamic loading is not considered to contribute to ageing, such that a detailed discussion on the manner in which such loading is represented is not included.

Seismic and aircraft impact are significant subjects in their own rights. The representation of seismic loading is covered in many other references, with this subject also being addressed by a different sub-group of IAGE WG.

The methods described in this report for representing geometric, material and ageing issues are generic to the analysis of concrete structures, with many of them being equally applicable when considering dynamic loading.

Load rate effects can be of particular interest with non-linear analysis techniques required to address many of the effects of dynamic loading.

2.2.5 Pressure Loads

Containments and vessels are designed to withstand significant internal pressures. FEA techniques must therefore be capable of accurately representing the effects of pressure loading.

Containments

Containments are designed to withstand their design internal pressures under accident conditions (LOCA) only, with sustained applied pressures under normal conditions being minimal and negative. Containments are subjected to periodic integrated leak rate tests where the internal pressure is raised to the design pressure.

At ultimate (LOCA) conditions there are two issues that need to be considered:

i The 'leakage' mode; a quantification of the size and distribution of any cracks through the wall that could lead to leakage through the containment wall.

ii The 'burst' mode; a demonstration that there are adequate margins against burst failure of the containment.

The first of these two issues influences containment design under LOCA (see Section 2.3.2 below).

Vessels

Vessels sustain their normal operational pressure and are also analysed for the effects of applied over pressure under proof test and fault conditions. Under ultimate conditions it is necessary to show that vessels can safely sustain a hypothetical over-pressure at a specified margin above the normal design pressure (typically by a factor of 2.5). The gas tight boundary is provided by the internal vessel and penetration liners. It is also necessary to show that vessels can sustain hypothetical 'gas in cracks' pressures that could arise if the liner was breached and the concrete backing the liner was cracked (this pressure is taken as 1.5 times the design pressure).

Localised high pressures can act on structures due to jet impingement (following pipe rupture).

2.2.6 Temperature Loads

Temperature loading arises from a number of sources with internal gas temperatures being by far the most significant. External faces of containments can experience temperature loading effects due to solar exposure.

Internal gas temperatures (at both operational and accident conditions) act on the lined faces of containments and vessels (with the vessel face being insulated and cooled to limit the temperature at the concrete surface). A temperature distribution is set up across the walls of such structures.

It is therefore necessary to be able to establish the effects of both the absolute temperature and the temperature distribution. These together can develop significant internal forces and moments and also affect the material properties for the vessel concrete influencing creep and relaxation, the prestressing tendons and reinforcement.

Separate transient thermal analyses may be required to establish the temperature values and distribution.

Under start up, shut down and some accident conditions it is also necessary to consider the variation of temperature and temperature distribution with time.

Local temperature loading (hot spots) can be developed at the internal faces of the structures due to local loss of insulation or jet impingement (following pipe rupture).

2.2.7 Through Life Loading Sequences

The through life operational history of vessels and containments contributes to ageing which can be regarded as a loading demand. This is particularly relevant when considering late life loading assessments. It is important to be able to represent this ageing process for such assessments. The through life loadings and effects that can contribute to ageing include:

i) the construction/build sequence.
ii) the application of prestressing loads.
iii) pre-operational pressure tests.
iv) operation (with sustained pressures and temperatures for vessels), including periodic shutdowns.
v) periodic pressure tests (Integrated Leak Rate Tests for containments).
vi) structural modifications.
vii) decommissioning.

The above loadings generally fall into one of the categories given in Sections 2.2.1 to 2.2.6.

2.2.8 Load Combinations and Frequency of Occurrence

The sections above describe the types of loading that need to be considered. It is necessary to be able to appropriately combine the effects of such loading to reflect the requirements of particular codes of practice, design guides or safety cases. The manner in which loads are combined and the associated load partial safety factors need to be reflected in FEA. The latter are selected to respect the frequency of occurrence of the loading being considered.

2.3 Reasons For Using FEA

FEA techniques are used to assist in the development of many aspects of the safety case for the facility being considered. Analyses are undertaken to both support the original design and Pre-Operation Safety Report and also to support through life considerations as part of Periodic Safety Reviews. The latter includes normal operation and fault credible conditions and is to reflect a number of issues including:

i) effects of ageing.
ii) evolution or addition of loads (i.e. assessing margins available for loadings that were not considered as part of the original design).
iii) new knowledge resulting from operational experience.
iv) effects of damage or changes made to the installation.
v) developments in codes, regulations and safety requirements.
vi) developments in analysis and assessment methods.
vii) developments in the understanding of material properties and degradation mechanisms.

There is an increasing need to consider post yield behaviour (under fault conditions) with non-linear analyses now undertaken as part of the through life safety justification of many structures.

It is however important to achieve an appropriate balance between the sophistication of any analyses undertaken and the accuracy of the loading predictions. A highly sophisticated analysis may not be warranted when there is significant uncertainty in relation to the derivation of the loading. However, this uncertainty can be offset to some extent through the use of parametric studies considering upper and lower bounds on the loading.

When undertaking complex analyses, it is important to recognise that there is likely to be only a few dominant load cases. Rationalisation of load cases can be used to limit the number of cases considered.

2.3.1 Representation of Ageing

The ageing process starts during or at the end of construction, and continues through the typical through life phases and loadings outlined at Section 2.2.7 above. FEA techniques are increasingly being called upon to capture the effects of the ageing process, such that continued operation of degraded facilities can be justified.

2.3.2 Compliance with Defined Acceptance Criteria

Acceptance criteria are defined in Standards or Codes of Practise. For example, in the UK containment design is based on meeting the requirements of ASME III Division 2 Boiler and Pressure Vessel Code [10] with vessel design based on BS 4975 [11], whereas in France the RCCG Code [12] is used.

Typical areas of interest within these documents where FEA techniques are used include:

i) Analysis for service load conditions: determination of stresses and deformations for appropriate combinations of mechanical and thermal loads to show that stresses and deformations remain within defined limits.
ii) Ultimate load analysis; assess the behaviour of the structure under a defined hypothetical over pressure condition to show that the required margin above design pressure can be achieved.

2.3.3 Demonstration of Integrity of Pressure/Leak Tight Boundary

The leak tight boundary is maintained either by the internal steel liner and its continuation across penetrations or by the concrete containment walls and domes (for unlined containments). It is necessary to show that this boundary can be maintained. For the lined case it is necessary to show that the internal liner can accommodate the strains developed at the concrete surface to which it is connected together with the effects of differential expansion between the steel and concrete. Analyses must therefore be focused or satisfying this requirement.

This is achieved by one of the methods outlined below:

i) include the liner in the model of the concrete structure, such that stresses and strains developed in the liner are produced directly.
ii) take the concrete inner surface strains as a set of boundary conditions to be applied to a separate model of the liner.

For the unlined case it is necessary to determine the likely distribution and size of wall/dome cracks and attempt to establish how these cracks affect the leak tightness of the containment. This is an area of uncertainty, with current research focused on producing reliable and robust methods for quantifying crack distribution and associated leakage rates. Current practice is to make very approximate estimates of any leakage rates.

Some containments without steel liners have some form of internal polymer or composite liners to provide leak tightness [18].

2.3.4 Confirmation of Containment/Vessel Behaviour

There are several areas of interest in relation to structural behaviour that can be addressed using FEA. These are associated with demonstrating that the behaviour of the structure is fully and confidently understood under all loading regimes:

i) Distribution of strains for comparison with installed strain gauges.
ii) Comparison of results with those obtained from scale models.
iii) Demonstration that failure mode is gradual and detectable to give adequate forewarning of failure.
iv) Consideration of structural integrity and establishment of possible level of damage to liner and concrete (at extreme accident/fault conditions).
v) Confirmation of behaviour under cycling effects through normal operation shutdown and start-up transients.

2.3.5 Retro-Analysis of Existing or Damaged Structures

Many of the nuclear facilities around the world were designed and built before FEA techniques were widely available and used and may not comply with contemporary safety requirements. Some such structures may have been damaged through normal operation. FEA techniques can be employed to consider the behaviour of these structures to establish whether the facilities can continue to be operated safely.

2.3.6 Input to Operation and Maintenance Schedules and Strategies

FEA techniques can be used to assist in determining suitable operation and maintenance schedules and strategies.

Through the life of a facility it is sometimes necessary to consider the consequence of changes to the loading regime or operational sequences. FEA techniques can be used to investigate the consequences of following various options to determine which is the most appropriate.

3.0 REPRESENTATION OF GEOEMETRIC FEATURES AND LOADING

Section 2.0 above contains a general description of the Nuclear Safety Related Concrete Structures addressed in this report. This section now considers in detail some of the geometric features and loadings applicable to these structures that need to be represented when considering FEA.

This section addresses the four topics listed in the table below, with summary tables provided for each of the topics. The summary tables include discussion against:

- The capability of the programs currently used by industry.
- The current practice of the nuclear industry.
- Areas of current research.
- Comments and limitations.

Each set of summary tables is preceded by descriptive text that expands on the first item. Section 8 provides a broad overview of Recent Research Developments.

3.1 Summary of Topics Addressed

TABLE	TOPIC
Global Structural Representation	
3.2.1	Three Dimensional Modelling
3.2.2	Automatic Mesh Generation
3.2.3	Supports and Boundary Conditions
3.2.4	Foundation Compliance
Structural Discontinuities	
3.3.1	Wall And Slab Penetrations
3.3.2	Standpipe Zone
3.3.3	Wall/Base Junction
3.3.4	Buttresses And Corbels
3.3.5	Construction Features
Representation of Steel	
3.4.1	Reinforcement Layout
3.4.2	Loading On Concrete From Prestressing Tendons
3.4.3	Combined Stiffness Of Steel And Concrete
3.4.4	Liner And Its Connection To The Concrete
3.4.5	Reinforcement Bond Slip
Representation of Loading	
3.5.1	Dead and Imposed Loads
3.5.2	Pressure Loads
3.5.3	Temperature Loads
3.5.4	Time Dependent Loads

3.2 Global Structural Representation

The basic aim of any non-linear analysis of a nuclear safety related concrete structure is to establish how the structure responds to a given set of loading conditions. The factors that are to be determined are discussed in Section 2.3 with Section 2.2 describing the loading conditions that might apply. To enable this aim to be realised it is necessary to create an adequate global structural representation of the structure.

The form and complexity required for this global structural representation is influenced by both the type of loading being considered and the factors that are to be determined from the analysis. At one extreme a fairly crude representation of the structure would be adequate: for example to capture fundamental dynamic characteristics. By contrast, at another extreme a very detailed representation would be required: for example to investigate how local features such as penetrations influence global behaviour.

The vessel and containment supports need to be allowed for in the finite element models developed. The manner in which they are included needs to take account of the anticipated degree of interaction between the structure and its underlying supports and foundation. For containments, it can also be necessary to include a representation of the internal structures to adequately capture the global foundation/structure response.

At one extreme, a representation of the structure (vessel or containment), the supporting sub-structure/base and the underlying founding strata might be required.

Alternatively (and especially for some vessels) it may be sufficient to only include the bearing pads that support the structure and assume that the underlying sub structure/foundation provides a rigid support to these pads.

3.2.1 Program Capabilities

Three Dimensional Modelling

Almost all of the packages currently in use have a wide range of available element types: spar, beam, plate, shell and solid elements. It is usually possible to use suitable combinations of these elements for both 2D (plane stress, plane strain, axisymmetric) and 3D analyses. These elements are frequently available with the options of linear or higher order formulations.

With linear elements, nodes are only positioned at end/corner points and the displacements between these nodes are assumed to vary in a linear fashion. With higher order elements, additional nodes are located along the element sides and/or in the element volume and a polynomial function is used to describe the variation of displacements between node points.

The availability of this wide range of element types theoretically allows all forms of structural geometries to be adequately represented. In practice, if the analysis needs to include many of the material non-linearities discussed in Section 4, the level of computational effort required can preclude the use of detailed full 3D analyses. The use of axisymmetric models for global behaviour, supplemented with detailed local models, is therefore widespread. The assumption of axisymmetry is reasonably valid for containments and vessels, although the effect of any local features (such as buttresses, penetrations and discrete corbels) is inevitably not taken into account. This can be significant, particularly if the ultimate failure load and mode of failure are of interest (see, for example, [14]).

3D models of sectors, with appropriate boundary conditions to represent cyclic symmetry, are a means of accounting for some of the 3D effects without generating an entire 3D model.

As substantially increased computing power continues to become readily available, the use of 3D simulations becomes more commonplace. Generally, the software is not an issue in the decision to perform a 2D or 3D analysis. The capabilities for 3D are well advanced, provided that sufficient computing power can be made available. Another issue, although less serious, is sometimes the difficulty of visualising and interpreting the data available from full 3D models.

Automatic Mesh Generation

Various techniques within most pre-processors are available for assisting with mesh generation. Automatic, or semi-automatic mesh generators can substantially reduce the effort required to achieve a desired mesh. However, there is as yet no automatic mesh generator that will reliably produce a satisfactory 3D mesh based on the preferred hexahedral elements.

Supports and Boundary Conditions

Standard finite element procedures can be used to represent boundary conditions. The analysis of concrete structures has no particularly special requirements in this regard. Boundary conditions might typically include:

- Nodal restraints
- Spring stiffnesses
- Interface elements connecting to ground or to another structure

The support offered to a structure by its foundation can be modelled in a number of ways, including:

- Nodal restraints – assuming a perfectly rigid foundation.
- Nodes with time dependent displacements, assuming, for instance, a certain settlement profile with time.
- Compliant springs – a series of springs at each node point with appropriate stiffnesses to represent the compliance of the foundation. Various empirical methods are available for deciding how the stiffness should be distributed between the springs in order to represent an adequate approximation of the load distribution across the footprint of the structure.
- Continuum elements to represent the soil, with the option of suitable interface elements between the soil and the structure. These interface elements can be used to prevent tensile forces being developed between the soil and the structure, and to limit the amount of frictional shear that is developed. The soil can be represented using an appropriate constitutive model. If necessary, “mixture” elements can be used to include the effects of the pore fluid within the soil allowing, for example, consolidation effects to be modelled.

3.2.1	Three Dimensional Modelling	Desirability (Low, Medium, High)
		H

Capability of Programs Currently Used By Industry
Geometric modelling capabilities of codes sufficiently developed to allow full 3D representation.

Current Practice of Nuclear Industry
Geometric modelling techniques employed include:

- full 3D models
- part sector 3D models
- 2D axisymmetric models

Technique adopted based on structural form, required output and available computing resource.

Current Research
Parallel FE codes used to exploit multi-processor architecture needed to perform large 3D analyses [59].

Comments and Limitations
Model run times and the time taken for pre- and post-processing are major issues. Full 3D modelling would be desirable but is often precluded.

3.2.2	Automatic Mesh Generation	Desirability (Low, Medium, High)
		M

Capability of Programs Currently Used By Industry
Many programs have fully automatic mesh generation algorithms integrated within them. When coupled to CAD systems, interface programs usually allow “defeaturing” to assist in the removal of small details which are not required in a finite element model and which would require a very fine mesh to represent realistically.
2D models can usually be fully meshed with quadrilateral elements.
Reliable automatic mesh generation of 3D meshes based solely on 6 sided “brick” elements not yet available.

Reasonable controls usually exist to allow user defined mesh densities in different areas.

Current Practice of Nuclear Industry
Most meshes still generated manually. The benefits in terms of time-saving in model generation are seen to be outweighed by the irregularity of some of the meshes that are created, by the enforced use of different element types (e.g. inability to produce pure “brick” meshes) and by the lack of complete control over mesh density.

The concrete mesh density is generally dictated by the structural discontinuities. The selection of mesh is problem specific. Walls can be modelled using layered shell elements to study global behaviour, while a solid continuum with many elements across the thickness would be required for the evaluation of leaks through evolving cracks.

Current Research
None.

Comments and Limitations
Preparation of steel mesh can be far more demanding and time-consuming than the concrete mesh. Special-purpose mesh generation software for the steel reinforcements and prestressing tendons has been developed, and is proving to be indispensable.
Other industries are now starting to make widespread use of tetrahedral meshes produced by fully automatic mesh generators.

3.2.3	Supports and Other Boundary Conditions	Desirability (Low, Medium, High) H
Capability of Programs Currently Used By Industry Available through a combination of rigid or flexible (spring) supports.		
Current Practice of Nuclear Industry Vessels (PCPV): bearings/pads modelled using spring elements. Containments (PCC): generally included via modelling foundation compliances.		
Current Research None.		
Comments and Limitations Techniques available are adequate to represent supports and boundary conditions.		

3.2.4	Foundation Compliance	Desirability (Low, Medium, High) H
Capability of Programs Currently Used By Industry Foundation compliance can be modelled using either discrete ‘spring’ elements or soil elements.		
Current Practice of Nuclear Industry Foundation compliance is included for containment structures where basemat/soil interaction has a significant influence on overall containment response.		
Current Research Use of infinite elements or methods based on Boundary Element [60] approaches used. Novel Scaled Boundary Finite Element method is still used only in research [61].		
Comments and Limitations Generally not an issue for vessels; founded on bearings/pads which in turn are supported on ‘rigid’ foundation sub-structure.		

3.3 Structural Discontinuities

There are several features of vessels and containments that can be classified as structural discontinuities that need to be considered when developing finite element models. These include the items listed below:

i) wall and slab penetrations
ii) vessel stand pipe zone
iii) wall/slab junctions
iv) cylinder/dome junctions
v) buttresses and corbels
vi) podded boiler recesses and associated gas ducts
vii) construction defects

It is not always necessary to include all of the above features, with the first six listed generally being of more significance than the seventh.

The behaviour of the SPZ (standpipe zone) is particularly complex, being a combination of the steel of the liner tubes and the interstitial concrete. Behaviour is markedly orthotropic.

The recent Sandia scale model analysis and testing programme [14] has shown the importance of modelling some of the above types of discontinuities, particularly when it is required to predict the actual performance of the structure, rather than demonstrating that it has sufficient capacity to withstand certain loading conditions.

3.3.1 Program Capabilities

Theoretically, current software allows all geometries and associated structural discontinuities to be included in a model. However, as mentioned previously, computer hardware restrictions can lead to the adoption of 2D models for global effects. These models are unable to accurately capture the detailed behaviour around discontinuities such as penetrations. Even where 3D global models are generated, practical limits on the number of elements prevent small details from being included in global models. In order to overcome these potential difficulties, many software packages offer facilities such as sub-modelling or substructuring. However, it should be noted that these techniques can be of limited applicability for problems with a significant degree of non-linearity.

When sub-modelling is not employed directly, local models can be used to study areas of particular interest, with the effects from the global model imposed as a set of boundary conditions to the local model.

One further area where caution sometimes needs to be adopted involves the use of shell elements. Shell elements are modelled based on centre-line geometry, with an assumed thickness either side of the centre-line. Unless care is taken, this can lead to junctions being overly stiff, due to the overlapping thicknesses that are represented (see Figure 2).

<table>
<tr><td rowspan="2">3.3.1</td><td rowspan="2">Wall and Slab Penetrations</td><td>Desirability
(Low, Medium, High)</td></tr>
<tr><td>H</td></tr>
<tr><td colspan="3">**Capability of Programs Currently Used By Industry**
3D Models
Penetrations can be modelled as voids in mesh.
2D (axisymmetric) Models
Penetrations not modelled explicitly. Can be allowed for by local adjustment of material properties if influence of penetrations is significant.</td></tr>
<tr><td colspan="3">**Current Practice of Nuclear Industry**
Penetrations included as voids in mesh in 3D global models.
Not included in 2D global models; argument developed that global influence of penetrations not significant.
Local models around penetrations (3D or 2D axisymmetric about penetration axis) undertaken if warranted, with global analysis effects superimposed.</td></tr>
<tr><td colspan="3">**Current Research**
None.</td></tr>
<tr><td colspan="3">**Comments and Limitations**
Use of 3D models in non-linear analyses generally precluded due to model run time constraints, although can be manageable with use of a coarse mesh for global models and a finer mesh for local models.</td></tr>
</table>

<table>
<tr><td rowspan="2">3.3.2</td><td rowspan="2">Standpipe Zone</td><td>Desirability
(Low, Medium, High)</td></tr>
<tr><td>**H**</td></tr>
<tr><td colspan="3">**Capability of Programs Currently Used By Industry**
Generally as Table 3.3.1 above, although influence of standpipe penetrations more significant in global terms due to increased density of penetrations (when compared with wall penetrations) resulting in markedly orthotropic behaviour.</td></tr>
<tr><td colspan="3">**Current Practice of Nuclear Industry**
Material properties adjusted to account for composite action between concrete (which creeps) and steel (which is less inclined to creep). Sensitivity studies undertaken to validate adopted properties.</td></tr>
<tr><td colspan="3">**Current Research**
None.</td></tr>
<tr><td colspan="3">**Comments and Limitations**
Significant for vessels, not for containments.</td></tr>
</table>

3.3.3	Wall/Base Junction	Desirability (Low, Medium, High) H
Capability of Programs Currently Used By Industry Capability available to model behaviour of the wall/base junction through local refinement of mesh and representation of tendons and/or liner.		
Current Practice of Nuclear Industry Wall/base junction modelled explicitly, with base fully represented. Modelling methods developed to suit extensive studies and available correlation between scale model tests and representative analyses.		
Current Research None.		
Comments and Limitations Can be included for both 2D and 3D analyses. More significant for containments than vessels. Cylinder/dome junction can be treated in a similar manner, although its influence is less significant than wall/base junction.		

3.3.4	Buttresses and Corbels	Desirability (Low, Medium, High) M
Capability of Programs Currently Used By Industry Can be included as 'additions' to global mesh. Linear corbels (crane supports) can be incorporated in 2D models. Discrete corbels and buttresses (anchorages for horizontal tendons) can be included in 3D modes.		
Current Practice of Nuclear Industry Vessels (PCPV): generally not included as influence not significant – behaviour governed by substantial thickness of vessel walls and slabs. Containments (PCC): (influence more significant due to thinner walls/dome) included in 3D models but generally not included in 2D models.		
Current Research None		
Comments and Limitations More significant for containments than vessels.		

3.3.5	Construction Defects	Desirability (Low, Medium, High) L
Capability of Programs Currently Used By Industry Can be modelled using combinations of elements as required.		
Current Practice of Nuclear Industry Can be important when considering leak tightness criteria and durability issues (penetration of chlorides).		
Current Research Work on modelling construction joints generally based on use of discrete crack approaches [57].		
Comments and Limitations Generally addressed at the local modelling level of liner details for predicting leakage failure mode (in containments).		

3.4 Representation of Steel

Reinforcement and Prestressing Tendons

Reinforcement and prestressing tendons are essential to the strength of vessels and containments. The influence of the prestressing tendons is usually by far the most significant, although there are some containments that are not prestressed where the contribution from reinforcement becomes more of interest.

Liner

The internal liner to containments and vessels has a fundamental role in ensuring leak tightness under all loading conditions although the structural contribution of the liner is generally small.

It is therefore not necessary to explicitly model the liner although in some instances this is done. The approach that is normally adopted is to undertake a separate liner analysis taking strain output from the primary structure analysis as input to the liner analysis.

Modelling of the liner may be considered when using FEA to predict the ultimate behaviour of containments and vessels where the contribution from the liner may become more significant or of interest. This is necessary where it is the liner and penetrations that actually form the pressure boundary. Concrete cracking may be tolerable, provided that this does not threaten the integrity of the pressure boundary components or the overall integrity of the structure.

The liner usually becomes a feature to be represented in a stand alone analysis, with this analysis also including a representation of the anchorage system employed to fasten the liner to the concrete of the primary structure. Such stand alone analyses might also need to consider local liner features at penetrations as this is an area where tests have shown that liner 'tears' actually occur.

3.4.1 Program Capabilities

Reinforcement

Different software vendors have made available different approaches to the modelling of reinforcement. These include:

i Embedded reinforcement.

With this approach, reinforcement is embedded in structural elements (known as the "mother" elements). This reinforcement does not have degrees of freedom of its own. By default, reinforcement strains are computed from the displacement field of the mother elements. This implies perfect bond. To allow for prestressing or post-tensioning of the reinforcement, this bond can be switched on and off at different stages of the analysis. The technique of embedding has the advantage that it allows the line of reinforcement to deviate from the lines of the mesh. However, it doesn't allow bond-slip behaviour to be represented. This embedded technique is only available in the more advanced programs aimed specifically at concrete analysis.

ii Discrete reinforcement merged to mesh.

Line or orthotropic shell elements are used to represent the reinforcement. These elements are fully merged to the continuum elements representing the concrete. All programs effectively have this capability. However, the meshes for the steel and the concrete must be compatible, making mesh generation more awkward. In addition, this method also doesn't allow any representation of bond-slip.

iii Discrete reinforcement coupled to mesh.

Line or orthotropic shell elements are again used to represent the reinforcement. However, instead of being fully merged to the concrete, they are coupled using multi-point constraint (MPC) equations. This partially removes the mesh compatibility requirement, but the input of the MPC relations can be cumbersome, and care needs to be taken to ensure that artificial restraints are not inadvertently incorporated into the model. Once again, bond-slip behaviour is excluded from the representation. Some programs allow the MPC relations to be generated automatically.

iv Layered elements.

With this approach, shell or solid elements that represent the concrete include a smeared layer (usually with orthotropic material properties) that models the reinforcement. These layered elements have been developed by software vendors primarily for use with multi-layered composite materials. The same technology can be used to approximate to the behaviour of reinforced concrete.

v Discrete reinforcement with interface elements.

Line, orthotropic shell or even solid elements are used to represent the steel. These elements are linked to the concrete continuum elements with interface elements, which allow a comprehensive material description of the bond between the steel and concrete, thereby allowing bond-slip behaviour to be modelled. As with some of the other methods, generating such a mesh can be very time-consuming. This method tends to be used for the detailed examination of local areas and joints, when the inclusion of bond-slip behaviour can have a significant influence on the overall load-displacement relationship.

If desired, the non-linear behaviour of the steel (yielding, hardening/softening, creep etc.) can be included for the reinforcement in most programs by the inclusion of appropriate material properties based on standard material laws.

Prestressing Tendons

The prestressing tendons, and the loads that they impart on the concrete, can be modelled using a variety of methods.

The degree of accuracy that is required for the modelling of prestressing depends to a large extent on whether the analysis is simply required to represent a pessimistic view of the structural performance, in which case simplistic conservative approximations can be adopted, or whether a prediction of the true response of the vessel to some loading condition is required.

In the simplest method, the tendons themselves are not physically included in the model, but the loads that they induce in the axial, radial and hoop directions are applied to the concrete as external loads and/or body forces. This method benefits from its simplicity, and is a reasonable approach in some situations for unbonded tendons, since the relative areas of steel and concrete makes the steel stiffness insignificant.

Alternatively, the tendons can be modelled as bonded or unbonded "reinforcement", using one of the methods described above. If the effects of friction between the tendons and steel are of interest, a detailed study using the method with interface elements may be carried out. Friction effects can also be catered for using ‘standard’ relations which allow the losses along the length of a tendon to be calculated and represented in the model.

An intermediate approach is to calculate the tendon stress, considering friction and steel relaxation but independent of the concrete behaviour, and then to apply these stresses to the complete model. Redistribution then occurs due to concrete deformation, which can be allowed for by a number of iterations on initial tendon stress to give the correct final value.

If required, accurate modelling of the prestressing can represent a major hurdle since, although the capabilities to model the effects are present, the time penalty in doing so can be significant.

Liner

The relative stiffness of the concrete compared to the liner means that it is usually valid to omit the liner when modelling the global behaviour. The liner can then be modelled separately at a local level, with the strains that are predicted to occur on the surface of the concrete being used as an input loading for the liner, applied at the base of the representation of the liner anchors. These liner models would then be detailed in the areas of greatest interest (for example in corners or around penetrations). These detailed liner models may also include a representation of the concrete local to the liner, with interface elements between the liner and the concrete. Practical limits on model size have, at least until recently, prevented this sort of exercise from being carried out at anything but a local level.

In some instances it can be appropriate to include the liner in the global model with steel plate elements connected to the inner concrete surface. The steel plate elements have their own elastic/plastic constitutive model. The connection is either modelled using interface elements or by coupling liner nodes to concrete nodes using spring elements to represent the anchorages.

The details of anchorage pull-out can be modelled at a local level. See for example [22].

3.4.1	Reinforcement Layout	Desirability (Low, Medium, High)
		H

Capability of Programs Currently Used By Industry

Different programs have different capabilities, including:
1) Bars or grids of bars embedded in concrete mother elements.
2) Bars tied to concrete mother elements by constraint equations.
3) Smeared layer of steel in composite elements.
4) Specific elements to represent steel with interface elements to connect to concrete.

Current Practice of Nuclear Industry

Containments (PCC): Reinforcement generally modelled by one of the available techniques.

Vessels (PCPV): For many analyses, it is known that the global effects of reinforcement are not significant. As a conservative approximation, the reinforcement is generally then not modelled explicitly. An exception to this is for ultimate load assessments, where the effects of reinforcement (strength and stiffness) may be significant and are therefore included.

When included, the reinforcing steel is usually considered to be linear but can be modelled as elastic-plastic. Bond slip effects are rarely considered.

Also, reinforcement may be taken into account in the assessment of post-cracking shear retention.

Current Research

Further work on automatic searching of elements where membranes pass through.

Comments and Limitations

Some smeared representations of reinforcement are constrained to be parallel to the element sides. Use of smeared reinforcement over entire element volume not considered appropriate. The more general arbitrary orientation capability is preferred.

3.4.2	Loading on Concrete from Prestressing Tendons	Desirability (Low, Medium, High)
		H

Capability of Programs Currently Used By Industry

If tendons are included in the model, some programs provide allowances for frictional losses along the length and anchorage effects.

Prediction of these effects in detail can be done with relatively complex models with appropriate elements to represent the steel, the concrete, and the interface between them.

Current Practice of Nuclear Industry

Tendons often not modelled explicitly, but prestressing loads (sometimes time dependent) applied to the concrete as external loads. Tendons may be modelled if this is desirable or is necessary from a modelling point of view. Frictional losses included if considered significant. The prestressing load is then applied as an equivalent thermal contraction.

Current Research

Split cracking under anchor blocks are difficult to control as shown by Japanese tests. More robust load transfer models are needed.

Comments and Limitations

Redistribution of load between the tendons and the concrete can be accounted for by using an iterative procedure to give the required tendon load.

Time and temperature dependent losses due to creep can be accounted for when the tendons are modelled explicitly.

3.4.3	Combined Stiffness of Concrete and Steel	Desirability (Low, Medium, High)
		M
Capability of Programs Currently Used By Industry Methods listed at Table 3.4.1 above can account for reinforcement stiffness. Tendons and liners can be modelled explicitly.		
Current Practice of Nuclear Industry Contribution of steel stiffness to global stiffness generally not included for global prestressed models.		
Current Research Some detailed research models account for dowel action in individual reinforcing bars.		
Comments and Limitations Global loss of bond not generally modelled in commercial codes.		

3.4.4	Liner and its Connection to the Concrete	Desirability (Low, Medium, High)
		M
Capability of Programs Currently Used By Industry The liner can be represented with appropriate steel elements. The interface to the concrete can be modelled with interface elements. The anchorage points can be modelled using coupled degrees of freedom or spring elements between the concrete and the steel.		
Current Practice of Nuclear Industry Liner not usually included in global models – liner strains assumed equal to concrete surface strains. Local models around penetrations etc. include the liner and interface elements between the liner and the concrete. In other situations the liner is included in the global model with its own elastic-plastic constitutive model.		
Current Research Extensive research on pull-out test simulations (local effects) have revealed need to include consistent strain-softening models for concrete [22]		
Comments and Limitations Relative geometric scales of the liner anchorage layout compared to the global structure prevents anchorage details from being included in any global model.		

3.4.5	Reinforcement Bond Slip	Desirability (Low, Medium, High)
		L
Capability of Programs Currently Used By Industry Available by representing reinforcement with explicit elements with interface elements to connect to the concrete.		
Current Practice of Nuclear Industry Effects very localised. Generally not included as model size and complexity required would make it impractical for all but the most detailed analyses.		
Current Research Some new work on use of meshless (element free Galerkin) approaches looks promising [31]. Treatment of this subject at the constitutive level is proving successful.		
Comments and Limitations Current capabilities require very detailed models, to the extent that it is not practical to represent reinforcement bond slip in large models unless the subject can be treated at the constitutive level.		

3.5 Representation of Loading

The loads that act on containments and vessels need to be represented within FEA. These loads are described in Section 2.2 and include:

i) Dead and imposed loads.
ii) Environmental loads.
iii) Prestressing loads.
iv) Dynamic loads.
v) Pressure loads.
vi) Temperature loads.
vii) Through life loading sequences.

Environmental loads are generally not significant for the scale of structures addressed within this report and are therefore not considered further.

Prestressing loads are covered in Section 3.4 above.

This report relates particularly to ageing issues. In the context of loadings, it is repeated or sustained loads that can contribute to ageing. Thus short term dynamic loads such as seismic, impact, shock and aircraft impact are not considered in detail.

3.5.1 Program Capabilities

Applied loads may be represented in a variety of manners, including:

- Displacements applied at nodes (which might vary with time)
- Temperatures at nodes (which may vary with time)
- Nodal forces (which might vary with time)
- Element pressures (which might vary with time)
- Gravity loads as accelerations
- Dynamic loads as spectral or time history inputs

<table>
<tr><td rowspan="2">3.5.1</td><td rowspan="2">Dead and Imposed Loads</td><td>Desirability
(Low, Medium, High)</td></tr>
<tr><td>H</td></tr>
<tr><td colspan="3">Capability of Programs Currently Used By Industry
Capability well developed; dead loads are included as a gravity vector. Imposed loads can be applied as discrete loads at node points (or pressure loads on element surfaces), distributed between adjacent nodes as required.</td></tr>
<tr><td colspan="3">Current Practice of Nuclear Industry
Use current capabilities of programs.</td></tr>
<tr><td colspan="3">Current Research
None.</td></tr>
<tr><td colspan="3">Comments and Limitations
None.</td></tr>
</table>

<table>
<tr><td rowspan="2">3.5.2</td><td rowspan="2">Pressure Loads</td><td>Desirability
(Low, Medium, High)</td></tr>
<tr><td>H</td></tr>
<tr><td colspan="3">Capability of Programs Currently Used By Industry
Capability well developed; included as pressure load acting perpendicular to exposed internal surfaces. Jet impingement acts as localised pressure loads and is treated in a similar manner.</td></tr>
<tr><td colspan="3">Current Practice of Nuclear Industry
Use current capabilities of programs.</td></tr>
<tr><td colspan="3">Current Research
IMC about to commission study into feasibility of developing numerical models to investigate the effects of pressurising crack surfaces with hot reactor coolant gas, which represents a complex, coupled, multi-physics problem.</td></tr>
<tr><td colspan="3">Comments and Limitations
General tractions should be able to be specified as being different at each node. Work consistent nodal forces should be used rather than simplified load distribution in higher order elements.</td></tr>
</table>

<table>
<tr><td rowspan="2">3.5.3</td><td rowspan="2">Temperature Loads</td><td>Desirability
(Low, Medium, High)</td></tr>
<tr><td>H</td></tr>
<tr><td colspan="3">Capability of Programs Currently Used By Industry
Apply as representation of defined temperature distributions at node points throughout model. Local hotspots can be treated in a similar manner with local temperature gradients.</td></tr>
<tr><td colspan="3">Current Practice of Nuclear Industry
Use current capabilities of programs.</td></tr>
<tr><td colspan="3">Current Research
Combined thermo-mechanical analyses performed coupling heat conduction with fracture propagation [51].
New work appearing in fire damaged concrete. Spalling and bursting coupled with high internal pore pressures [58].</td></tr>
<tr><td colspan="3">Comments and Limitations
Temperature distributions typically come from a previous thermal diffusion analysis. The trend may be to combine analyses, although the influence of mesh density may be different for thermal and mechanical loads.
Internal pore pressure limits operating temperatures to a fraction of boiling, but Code allows local hot spots; with hardly any analytical support.</td></tr>
</table>

<table>
<tr><td rowspan="2">3.5.4</td><td rowspan="2">Time Dependent Loads</td><td>Desirability
(<u>L</u>ow, <u>M</u>edium, <u>H</u>igh)</td></tr>
<tr><td>H</td></tr>
<tr><td colspan="3">**Capability of Programs Currently Used By Industry**
Transient pressures, temperatures, forces and displacements can be applied as a time dependent function.</td></tr>
<tr><td colspan="3">**Current Practice of Nuclear Industry**
Use current capabilities of programs.</td></tr>
<tr><td colspan="3">**Current Research**
None</td></tr>
<tr><td colspan="3">**Comments and Limitations**
None</td></tr>
</table>

4.0 REPRESENTATION OF MATERIAL FEATURES

This section is similar in format to Section 3.0, addressing the Representation of Material Features rather than Geometric Features. The eight topics listed in Section 4.1 are considered, with summary tables provided for each of the topics. The summary tables include discussion against:

- The capability of the programs currently used by industry.
- The current practice of the nuclear industry.
- Areas of current research.
- Comments and limitations.

Each set of summary tables is preceded by descriptive text that expands on the first item.

The representation of material properties varies from simple for linear analyses to fairly complex for non-linear analyses. In its simplest form reinforced concrete is modelled as a linear elastic material ignoring the contribution of the reinforcement with any prestressing modelled as applied loads. Such methods have sometimes been used to support the original design of a structure.

This report is concerned primarily with material modelling to support non-linear analyses where the representation of concrete, reinforcement and prestressing becomes considerably more complex.

Any numerical algorithm that is used to mathematically approximate the behaviour of a material (the constitutive model) needs to reflect the essential characteristics of that material. The various means that are commonly used by finite element packages to represent some of the main features of the behaviour of concrete are discussed in the following sections. It should be noted however that finding a wholly reliable mathematical means of capturing all aspects of the true behaviour of concrete continues to be an active area of research (see Section 8). A number of different methods have been developed and more continue to be proposed. The discussions below are intended to highlight the more common methodologies currently in use and to summarise some of the considerable progress that has been made towards finding an appropriate mathematical solution.

4.1 Summary of Topics Addressed

TABLE	TOPIC
Concrete In Tension	
4.2.1	Prediction Of Crack Initiation
4.2.2	Sensitivity To Mesh Density
4.2.3	Sensitivity To Mesh Orientation/Direction Of Element Boundaries
4.2.4	Numerical Stability
4.2.5	Effects Of Temperature On Stress At Which Cracks Initiate
4.2.6	Determination Of Crack Position And Direction
4.2.7	Representation Of Multiple Cracks
4.2.8	Calculation Of Crack Widths
4.2.9	Mode II/Mode III Effects
4.2.10	Visualisation Of Crack Position, Direction And Size
4.2.11	Rate Dependent Tensile Strength
4.2.12	Combination Of Cracking With Other Non-Linear Phenomena
4.2.13	Link Between Crack Strain And Permeability
4.2.14	Effects Of Pressure Within Cracks
Concrete In Shear	
4.3.1	Shear Stiffness
4.3.2	Ultimate Shear Strength
4.3.3	Representation Of Dowel Action Of Reinforcement Across Cracks
Concrete In Compression	
4.4.1	Characterisation of Strength Envelope
4.4.2	Inclusion Of Pre-Peak Elastic Non-linear Stress-Strain Behaviour
4.4.3	Inclusion Of Pre-Peak Inelastic Non-linear Stress-Strain Behaviour
4.4.4	Representation Of Post-Peak Behaviour
4.4.5	Dependency Of Strength On Level Of Multi-Axial Confinement
4.4.6	Inclusion Of Temperature Dependent Effects
4.4.7	Load Path Dependency
4.4.8	Effects Of Loading Rate
Representation Of Steel	
4.5.1	Modelling Of Non-Linear Plastic Behaviour Of Steel
4.5.2	Thermal Expansion Of Steel
4.5.3	Strain Rate Effects
4.5.4	Load Path Dependence
4.5.5	Representation Of Effects Of Fatigue
Thermal Expansion Of Concrete	
4.6.1	Representation Of Expansion Based On A Strain Of $\alpha\Delta T$.
4.6.2	Temperature Dependent Thermal Expansion
Creep	
4.7.1	Representation Of Creep And Relaxation Effects.
4.7.2	Temperature Dependent Effects
4.7.3	Maturity At Loading
4.7.4	Moisture Dependent Effects

Concrete Cyclic Loading Effects	
4.8.1	Modelling Irrecoverable Deformations During Unloading
4.8.2	Realistic Modelling Of Crack Opening/Closing, Unloading/Reloading
Transient Thermal Creep	
4.9.1	Determination Of Strain Due To Transient Thermal Creep

4.2 Concrete In Tension

The quasi-brittle behaviour of concrete in tension, combined with the comparatively low tensile strength, can lead to cracks which can potentially propagate through the body of the material. This is one of the key aspects of concrete behaviour, which can require simulation of the following features:

i) crack initiation: a representation of the stress state at which cracks are initiated.

ii) crack layout: the layout, distribution and direction of cracks.

iii) crack growth: how cracks grow and whether cracks merge or develop into secondary or tertiary cracks.

iv) crack width: the width of the developed cracks can be of interest, for example during comparison with defined acceptance criteria or scale model test results or for assessing leak rates. The width and distribution of cracks at the internal surface can be required for use in a separate assessment of the behaviour of the steel liner.

v) temperature dependency: the effect of elevated concrete temperatures on crack initiation thresholds.

vi) load rate dependency: stiffness and tensile strength (and hence crack initiation thresholds) can be load rate dependent.

vii) load path dependency: in particular arising from crack induced anisotropy.

4.2.1 Program Capabilities

Ever since the 1960’s a great deal of effort has been expounded in this area of analysis. A number of different approaches have been adopted by various software packages that have a concrete model. Some of the more widely used approaches are discussed below.

Currently there are two common ways of dealing with cracking: smeared cracking and discrete cracking.

Smeared Cracking

The smeared cracking approach treats cracking as a constitutive material behaviour (as opposed to a geometrical discontinuity in the case of discrete cracking). The concrete is represented with standard continuum elements and the material law for these elements allows cracking to occur. In this way, prior to the formation of any cracks, the concrete is considered to be an isotropic material.

At each loading increment, the stress state is checked to see if the tensile limit state has been reached. In its simplest and most common form, this limit is a check on the maximum trial principal stress at each stress point to see if it exceeds the tensile strength. If it does, the material associated with this stress point becomes orthotropic, with the crack normal forming a zero-strength (or reduced strength) axis.

There are two common variants of the smeared cracking approach: the fixed crack model and the rotating crack model.

In the fixed crack model, the crack direction and the material axes are defined by the principal stress direction at the onset of cracking. In further analysis, this direction remains fixed. If the stresses redistribute, trial tensile stresses in another direction may again exceed the tensile strength of the concrete. Some codes will then allow second (and further) cracks to form normal to this new direction, provided that the new crack direction differs from the original direction by more than a given threshold angle (see Figure 3).

In the rotating crack model, the crack direction always coincides with the principal stress direction. The cracks rotate to follow any redistribution that occurs i.e. the material in effect heals. This type of algorithm is best suited to loading conditions where the orientation of principal stresses only undergo small changes.

Using the smeared crack approach, the behaviour in tension is essentially defined by the uniaxial stress-strain law illustrated in Figure 4. Two things are of particular note here:

i) The post-peak behaviour. Although this can be defined as pure brittle behaviour, it is more usually defined by some form of “tension softening” diagram.
ii) The behaviour of the cracked concrete under conditions of unloading and/or reloading. Some of the more common ways of dealing with this are illustrated in Figure 5.

It should be noted that the determination of an appropriate stress-strain curve is not always a trivial matter, particularly since experiments inevitably measure stress as a function of displacement (i.e. crack opening) as opposed to strain.

The smeared cracking method has proved to be very popular and has been widely adopted by software developers. This is partly due to the comparative ease of implementation of the method. In particular, because cracking is considered as a constitutive material behaviour, the mesh topology does not need to account for the location or direction of cracks (information that may not be readily available prior to an analysis).

However, the implementation of smeared cracking is not without its problems, which include:

i) Numerical instability. The abrupt change in stiffness associated with the onset of cracking frequently makes it difficult to obtain a fully converged numerical solution.

ii) Crack strains. The output from a smeared crack analysis is crack strains, as opposed to the crack widths that are usually of primary interest. Prediction of crack widths then requires multiplication by an assumed crack spacing.

iii) Dependency on mesh density. In its purest form, the results predicted by a smeared crack analysis can be heavily dependent upon mesh density. There have been various attempts by researchers, some of which have been implemented in a number of finite element programs, to overcome this problem. In essence, these methods resolve the problem by adjusting the form of the tension softening diagram for each element, such that the work done in fully opening a crack is equivalent to the fracture energy of the concrete involved.

iv) Dependency on mesh layout. The direction of the element boundaries can influence the path which cracks propagate along. (The extent to which this influences the results can be checked by performing additional analyses with different orientations of mesh in the regions where cracking occurs).

Discrete Cracking

With the discrete cracking approach, interface elements are introduced into the mesh on the path which the crack might propagate along. These interface elements are given appropriate material characteristics, for example a limited tensile strength, a frictional shear capacity and an appropriate tensile stress-displacement relationship.

The advantages of the discrete method are:

- The well developed interface elements that are widely available allow a detailed material description of the behaviour of the crack.
- Crack widths are predicted rather than crack strains.
- The extent and effects of the cracks can be readily visualised.

However, a major drawback of this approach is that prior knowledge is required of the potential location of cracks and the direction in which they might grow. A common work-around for this is to perform an initial smeared cracking analysis before a discrete cracking analysis to obtain information about the likely location and direction of crack growth. Nevertheless, a discrete cracking analysis inevitably requires an additional amount of effort during model development.

The discrete cracking method is often a good technique to use for unreinforced or lightly reinforced concrete which tends to form a small number of comparatively large cracks. It is not so suitable for heavily reinforced concrete, which tends to experience a large number of smaller cracks.

4.2.1	Prediction of Crack Initiation	Desirability (Low, Medium, High) H
Capability of Programs Currently Used By Industry Multiple fixed smeared cracks based on cracks initialising when trial maximum principal stress exceeds tensile strength. Rotating smeared crack models. Discrete cracks based on stress normal to interface element direction exceeding tensile strength. Discrete cracks based on maximum principal strain (e.g. damage models)		
Current Practice of Nuclear Industry Generally use multiple fixed smeared crack approach.		
Current Research Experimental determination of multi-axial effects. Development of new constitutive models to account for multi-axial effects [62]. Stochastic FE being used to define material variability [63].		
Comments and Limitations Current approaches consider biaxial stress states (combined tension and compression). Whilst current commercial codes have algorithms for general 3D stress states, they can't always account fully for the multi-axial stress state.		

4.2.2	Sensitivity to Mesh Density	Desirability (Low, Medium, High) H

Capability of Programs Currently Used By Industry
All codes are mesh sensitive to some extent. Problem partially alleviated by some programs that have the capability to incorporate the concrete fracture energy into the crack opening algorithm.

Current Practice of Nuclear Industry
For unreinforced concrete, account for fracture energy by appropriate choice of tension softening diagram. For reinforced concrete, limiting tensile strain based on yield of steel.

Current Research
Development of new constitutive models.

Multi-axial stress states yet to be fully encompassed in the fracture energy approach, but work is underway [64].

Comments and Limitations
Most important for plain unreinforced concrete. Less significant for reinforced concrete.

4.2.3	Sensitivity To Mesh Orientation / Direction Of Element Boundaries	Desirability (Low, Medium, High) M

Capability of Programs Currently Used By Industry
No commercial codes fully overcome this problem. Sensitivity to mesh orientation can be checked by manually performing several analyses with different mesh orientations.

Current Practice of Nuclear Industry
Rarely considered

Current Research
Range of advanced regularisation techniques (including Cosserat continuum, gradient plasticity and non-local treatment) are currently being heavily investigated [65].

Comments and Limitations
Not felt to be a major issue.

Regularisation techniques should appear in next generation of commercial FE codes.

<table>
<tr><td rowspan="2">4.2.4</td><td rowspan="2">Numerical Stability</td><td>Desirability
(Low, Medium, High)</td></tr>
<tr><td>H</td></tr>
<tr><td colspan="3">Capability of Programs Currently Used By Industry
Some programs have algorithms which smooth off the sharp corners of yield / failure surfaces.
Consistent tangent modulus approach, available in some programs, helps make solutions more efficient.</td></tr>
<tr><td colspan="3">Current Practice of Nuclear Industry
Use best available advice of software vendors whenever possible. Full Newton-Raphson methods followed less frequently than initial stiffness approach.</td></tr>
<tr><td colspan="3">Current Research
Development of more stable constitutive models and numerical algorithms. Arc-length and line searching routines still under further development [66]. More work required in the area of stability / bifurcation analysis [26, 67].</td></tr>
<tr><td colspan="3">Comments and Limitations
Initial stiffness approach often employed to maintain symmetric global matrices (if unsymmetric solvers not available). Discontinuities in stress-strain envelope for crack initiation causes numerical difficulties.
Abrupt changes in stiffness and the associated unloading also cause problems in reaching convergence.</td></tr>
</table>

<table>
<tr><td rowspan="2">4.2.5</td><td rowspan="2">Effects Of Temperature On Stress At Which Cracks Initiate</td><td>Desirability
(Low, Medium, High)</td></tr>
<tr><td>H</td></tr>
<tr><td colspan="3">Capability of Programs Currently Used By Industry
Capability provided in some codes.</td></tr>
<tr><td colspan="3">Current Practice of Nuclear Industry
Use mean and lower bound value for tensile strength to err on side of conservatism.</td></tr>
<tr><td colspan="3">Current Research
Experimental determination of data, plus fully coupled thermo-mechanical models under development [68].</td></tr>
<tr><td colspan="3">Comments and Limitations
There is a lack of data in respect of residual tensile strength, fracture energy, the influence of the load path (loading/heating/cooling sequence) and multi-axial effects.
In PCPV’s, the residual strength is of particular interest. Typically, during fault conditions, the inner vessel surfaces heat up and this induces compression of the inner surfaces and tension on the outer cooler surfaces (which may lead to cracking). Due to the development of irrecoverable creep during the heating phase, residual tensile stresses and cracking may occur in the previously compressive inner surfaces of the PCPV during subsequent cooldown.</td></tr>
</table>

<table>
<tr><td rowspan="2">4.2.6</td><td rowspan="2">Determination Of Crack Position And Direction</td><td>Desirability
(Low, Medium, High)</td></tr>
<tr><td>H</td></tr>
<tr><td colspan="3">Capability of Programs Currently Used By Industry
Smeared crack model follows any direction, although it can be biased by mesh alignment (see Table 4.2.3). Discrete crack model requires prior knowledge, which can be achieved by performing an initial smeared crack analysis.</td></tr>
<tr><td colspan="3">Current Practice of Nuclear Industry
Generally use smeared cracking.</td></tr>
<tr><td colspan="3">Current Research
Combination of smeared and discrete cracking with adaptive re-meshing to modify mesh density and include appropriate interface elements as cracks propagate. Use of embedded discontinuities in advanced elements appearing in research codes [69].</td></tr>
<tr><td colspan="3">Comments and Limitations
Implementation of discrete crack model is more difficult and time-consuming, but the results obtained are generally more appropriate for lightly reinforced / unreinforced concrete.</td></tr>
</table>

<table>
<tr><td rowspan="2">4.2.7</td><td rowspan="2">Representation Of Multiple Cracks</td><td>Desirability
(Low, Medium, High)</td></tr>
<tr><td>M</td></tr>
<tr><td colspan="3">Capability of Programs Currently Used By Industry
Many programs have multiple fixed smeared crack capability, if redistributed stresses exceed crack criteria, but stress direction differs from crack direction by more than a threshold angle. Some programs limited to a single crack.</td></tr>
<tr><td colspan="3">Current Practice of Nuclear Industry
Use of multiple fixed crack approach with default threshold angle.</td></tr>
<tr><td colspan="3">Current Research
Further development of rotating crack type models. Work progressing on unilateral (anisotropic) models to account for rotation of principal stresses [70].</td></tr>
<tr><td colspan="3">Comments and Limitations
Post-crack stiffness not well represented – sometimes leads to over-estimates of strength. Also, crack development behaviour can sometimes be poorly represented.</td></tr>
</table>

<table>
<tr><td rowspan="2">4.2.8</td><td rowspan="2">Calculation Of Crack Widths</td><td>Desirability
(Low, Medium, High)</td></tr>
<tr><td>H</td></tr>
<tr><td colspan="3">Capability of Programs Currently Used By Industry
Smeared cracking predicts crack strains rather than widths.
Discrete cracking provides crack widths.</td></tr>
<tr><td colspan="3">Current Practice of Nuclear Industry
Mainly use smeared cracking in combination with an assumed / pessimistic crack spacing to determine crack widths.</td></tr>
<tr><td colspan="3">Current Research
New studies (experimental and theoretical) on material characteristic length coupled with size effect properly links crack strains to crack opening displacement [71].</td></tr>
<tr><td colspan="3">Comments and Limitations
Discrete cracking involves considerably more time to define the model and requires prior knowledge of crack locations and directions.</td></tr>
</table>

<table>
<tr><td rowspan="2">4.2.9</td><td rowspan="2">Mode II/ Mode III Effects</td><td>Desirability
(Low, Medium, High)</td></tr>
<tr><td>M</td></tr>
<tr><td colspan="3">Capability of Programs Currently Used By Industry
Mode II / III fracturing is not generally available in commercial FE codes.</td></tr>
<tr><td colspan="3">Current Practice of Nuclear Industry
Use of standard smeared/discrete cracking techniques as implemented in available commercial programs.</td></tr>
<tr><td colspan="3">Current Research
Experimental determination of fracture energy for these modes.</td></tr>
<tr><td colspan="3">Comments and Limitations
Improvements in this area would lead to greater confidence in analytical results.</td></tr>
</table>

4.2.10	Visualization Of Crack Position, Direction And Size.	Desirability (Low, Medium, High)
		M
Capability of Programs Currently Used By Industry Capability in some general purpose post-processors limited. In some post-processors, smeared cracks visualized as vectors at Gauss point locations. Vectors coloured according to level of crack strain. Contour plots also used. Some programs allow cracks to be visualised as discs. Gaps visible at interface locations for discrete crack method.		
Current Practice of Nuclear Industry Use of all available techniques.		
Current Research Very significant advances have taken place on computer based visualisation (e.g. recreational software, transparency effects etc.). These have yet to appear in general purpose FE codes.		
Comments and Limitations Current approaches are adequate for 2D analyses but further work may be beneficial for 3D problems.		

4.2.11	Rate Dependent Tensile Strength	Desirability (Low, Medium, High)
		L
Capability of Programs Currently Used By Industry Crack models in some programs have rate dependent term available in the cracking algorithm.		
Current Practice of Nuclear Industry Not accounted for unless undertaking dynamic/impact analysis.		
Current Research Large body of experimental data plus new findings from micro-mechanics studies.		
Comments and Limitations None.		

4.2.12	Combination Of Cracking With Other Non-linear Phenomena	Desirability (Low, Medium, High)
		H
Capability of Programs Currently Used By Industry Current capabilities somewhat limited, although usually possible provided that solution algorithms are based on incremental strain (as opposed to total strain) thereby allowing strain decomposition		
Current Practice of Nuclear Industry Combine cracking with other phenomena within the limits imposed by the program.		
Current Research Development of unified constitutive model combining all effects still remains an important objective for computational mechanics researchers. Work only just beginning in this area.		
Comments and Limitations Some significant limitations within current commercial programs.		

4.2.13	Link Between Crack Strain And Permeability (Leak Tightness)	Desirability (Low, Medium, High)
		L (LINED) H (UNLINED)
Capability of Programs Currently Used By Industry Moisture diffusion analyses possible in current FE codes but actual mechanisms are complex and not yet properly accounted for. Not possible to couple the effects of cracks on permeability with mainstream commercial codes.		
Current Practice of Nuclear Industry Not considered yet.		
Current Research Very latest research is just beginning to address these coupled multi-physics problems.		
Comments and Limitations Significant for unlined containments which are required to maintain leak tightness. Simulation of integrated leak rate tests is seen as being of major importance.		

4.2.14	Effects Of Pressure Within Cracks	Desirability (Low, Medium, High)
		M
Capability of Programs Currently Used By Industry Standard implementations of smeared and discrete cracking take no account of the effects of a pressurised fluid or gas entering a crack and helping it to grow. Some advanced discrete cracking implementations have limited (usually 2D) functionality.		
Current Practice of Nuclear Industry Not considered yet.		
Current Research IMC about to commission study into feasibility of developing numerical models to investigate the effects of pressurising crack surfaces with hot reactor coolant gas, which represents a complex, coupled, multi-physics problem.		
Comments and Limitations Can be important for PCPV’s, due to the potential for high pressure gases entering cracks. See also Table 3.5.2.		

4.3 Concrete In Shear

The development of cracks is associated with a reduction in shear strength and stiffness. It is therefore necessary to be able to model these reductions as cracks develop. As cracks widen the shear contribution from aggregate interlock under the action of external loads (e.g. prestress) and then reinforcement (if present) through dowel action can become of interest.

4.3.1 Program Capabilities

A truly accurate representation of the shear behaviour of concrete with cracks present remains difficult to achieve. In order to be realistic, an algorithm needs to account for a relatively high shear stiffness when the crack strains are very low, due to the rough nature of the cracks and aggregate interlocking. However, this stiffness reduces (ultimately to zero) as the cracks open up and the rough surfaces separate. Then, as the cracks become very large, the dowel action of any reinforcement that is present may be mobilised.

With the smeared cracking, fixed crack approach, many programs reduce the shear modulus in the crack normal-tangential direction to a given, user-defined percentage of its uncracked value. Some programs also offer a shear modulus that reduces in some exponential form with increasing crack strain (see Figure 6).

With the smeared cracking, rotating crack approach, a shear on the crack plane can never exist and so a shear model cannot and need not be employed.

With the discrete cracking method, the interface elements usually allow a user-defined shear stress versus shear strain relationship to be specified. A few of the more sophisticated elements will also allow the shear behaviour to be defined as a function of the crack opening.

Shear strength due to aggregate interlock can be modelled using discrete crack formulations based on empirical research findings which capture crack dilatancy [25].

<table>
<tr><td rowspan="2">4.3.1</td><td rowspan="2">Shear Stiffness</td><td>Desirability
(Low, Medium, High)</td></tr>
<tr><td>H</td></tr>
<tr><td colspan="3">**Capability of Programs Currently Used By Industry**
For smeared cracking, some programs offer shear retention factor which varies with crack strain, many do not.
For discrete cracking, some codes offer user defined function.</td></tr>
<tr><td colspan="3">**Current Practice of Nuclear Industry**
Constant shear retention factor used by some in conjunction with sensitivity studies on the value used.
Others use the variable shear retention method by default.</td></tr>
<tr><td colspan="3">**Current Research**
Crack interlock and frictional effects are complex but have been studied at a local level. Research ongoing in this area [72].</td></tr>
<tr><td colspan="3">**Comments and Limitations**
For smeared cracking, current algorithms can predict a response which is overly stiff.</td></tr>
</table>

<table>
<tr><td rowspan="2">4.3.2</td><td rowspan="2">Ultimate Shear Strength</td><td>Desirability
(Low, Medium, High)</td></tr>
<tr><td>M</td></tr>
<tr><td colspan="3">**Capability of Programs Currently Used By Industry**
This may be defined explicitly for discrete crack models based, for instance, on Coulomb friction.
For smeared crack models, the shear strength is indirectly given by the direct tensile strength.</td></tr>
<tr><td colspan="3">**Current Practice of Nuclear Industry**
A range of different approaches are used, including:
i) Account for indirectly through the failure criteria in traction and/or in compression.
ii) The introduction of shear shedding models to prevent over-estimation of shear strength.
iii) Use of crack dilatancy models to capture the effects of aggregate interlock/shear friction [25].</td></tr>
<tr><td colspan="3">**Current Research**
The large body of experimental work on final shear mechanisms have yet to be fully incorporated in FE codes.</td></tr>
<tr><td colspan="3">**Comments and Limitations**
Local effects are generally averaged.
Effects of high temperatures and load cycling not directly accounted for.</td></tr>
</table>

4.3.3	Representation Of Dowel Action Of Reinforcement Across Cracks	Desirability (Low, Medium, High)
		L (GENERAL) H (IMPACT STUDIES)
Capability of Programs Currently Used By Industry Detailed model representing each reinforcement with line or solid elements and interface elements to connect to the concrete – only practical for the most detailed local analyses.		
Current Practice of Nuclear Industry Only used in local analyses of pipe / aircraft impact studies when looking at final rupture state. Empirical methods and codified hand calculations often used.		
Current Research Some detailed research models account for dowel action in individual reinforcing bars. Dowel action in unreinforced concrete is not generally modelled well. More fundamental research required. Much code-based work was completed in the 70s [73].		
Comments and Limitations Only required in extreme conditions. Need very wide cracks to mobilise dowel action.		

4.4 Concrete in Compression

The behaviour of concrete in compression can be complex. The ideal situation would be to be able to represent all aspects of the three dimensional pre and post peak stress-strain behaviour of concrete. Figure 1 illustrates some of these aspects. The prime areas of interest from this behaviour are as below:

i) pre-peak stress strain behaviour: non-linear behaviour is found in both the elastic and inelastic (post yield) portions of the pre peak diagram. This non-linearity is of more significance post yield.

ii) multi-axial effects: multi-axial confinement leads to an apparent increase in the compressive strength of concrete. Multi-axial compression can also mitigate degradation of structural properties at elevated temperatures.

iii) load path dependency: this becomes of interest when considering the effects of load reversal or redistribution post yield and especially post peak. There can also be considerable load path dependency during high temperature loading conditions.

iv) temperature dependency: elevated concrete temperatures and the subsequent cooling can influence compressive behaviour.

v) load rate dependency: in particular, the compressive strength can be load rate dependent.

4.4.1 Program Capabilities

In a uniaxial sense, the methods available in most common programs allow a fair approximation of the behaviour of concrete in compression. Typically, these methods will include the ability to specify a linear elastic / plasticity relationship, combined with a user defined hardening / softening diagram. The onset of plasticity is defined by one of the common yield criteria such as Drucker-Prager. In some programs it is also possible to combine this with a non-linear relationship within the elastic regime. However, no programs are especially good at representing the effects of confinement, other than through pressure dependent strength envelopes such as Drucker-Prager or Mohr-Coulomb.

4.4.1	Characterisation of Strength Envelope	Desirability (Low, Medium, High)
		M

Capability of Programs Currently Used By Industry

Typically define failure surface using Drucker Prager or Mohr Coulomb yield criterion. Mohr Coulomb has sharp corners which can give rise to numerical problems. Some programs modify Mohr Coulomb by rounding off the corners. Drucker-Prager generally includes a tensile cut-off: this also introduces discontinuities.

Current Practice of Nuclear Industry

In some countries, the general approach is to use linear behaviour in compression. Stress levels are then checked to ensure that unsustainably high compressive stresses are not present. If investigating cases where high mechanical loads are involved, then plasticity is important and is normally included. Also, plasticity may still be important for cases involving prolonged exposure to elevated temperatures. In these cases, creep rupture may then become an issue. (In terms of a failure surface this may require the adoption of strain based failure criteria rather than strength based criteria.)

Other countries use non-linear behaviour, including the use of a constitutive model which has an expanding surface (with increasing stresses) and contracting surface in the post peak regime.

Current Research

Development of new unified constitutive models [37]. New Continuum Damage mechanics based models avoid the concept of a stress defined yield surface and are based on a rigorous thermodynamic framework.

Comments and Limitations

More work is required.

4.4.2	Include Pre-Peak Elastic Non-linear Stress-Strain Behaviour	Desirability (Low, Medium, High)
		L

Capability of Programs Currently Used By Industry

Some codes allow pre-plasticity non-linear behaviour to be defined. Sometimes there are restrictions on which other non-linear phenomena may also be included.

Current Practice of Nuclear Industry

Various approaches adopted, from the assumption of linear behaviour in compression, through to the use of continuous non-linear behaviour, with elastic behaviour defined at the origin only.

Current Research

See Table 4.4.3.

Comments and Limitations

Pre-peak elastic non-linear behaviour not of much interest except for alternate loadings.

<table>
<tr><td rowspan="2">4.4.3</td><td rowspan="2">Include Pre-Peak Inelastic Non-linear Stress-Strain Behaviour</td><td>Desirability
(Low, Medium, High)</td></tr>
<tr><td>H</td></tr>
<tr><td colspan="3">Capability of Programs Currently Used By Industry
Most codes allow plasticity based non-linear behaviour. Various failure criteria can be specified (e.g. Drucker Prager or Mohr Coulomb).</td></tr>
<tr><td colspan="3">Current Practice of Nuclear Industry
See comments in Table 4.4.1.</td></tr>
<tr><td colspan="3">Current Research
Over 200 constitutive models have been developed during the past 30 years. Extensive state of the art reviews exist [73]. Work continuing with development of a single unified theory for concrete.</td></tr>
<tr><td colspan="3">Comments and Limitations
Tensile behaviour tends to dominate, so compressive behaviour is deemed to be less important. More evidence required of the true role of non-linear compressive behaviour.</td></tr>
</table>

<table>
<tr><td rowspan="2">4.4.4</td><td rowspan="2">Representation Of Post-Peak Behaviour</td><td>Desirability
(Low, Medium, High)</td></tr>
<tr><td>L (GENERAL)
H (EXTREME LOADS)
H (Leaks)</td></tr>
<tr><td colspan="3">Capability of Programs Currently Used By Industry
Yield surface based on Drucker Prager or Mohr Coulomb, post peak behaviour by definition of a softening diagram.</td></tr>
<tr><td colspan="3">Current Practice of Nuclear Industry
Generally, plasticity approach not always used (see Table 4.4.1) but sometimes used when considering over-pressurization test cases.</td></tr>
<tr><td colspan="3">Current Research
See Table 4.4.3</td></tr>
<tr><td colspan="3">Comments and Limitations
See Table 4.4.3</td></tr>
</table>

<table>
<tr><td rowspan="2">4.4.5</td><td rowspan="2">Dependency Of Strength On Level Of Multi-Axial Confinement</td><td>Desirability
(Low, Medium, High)</td></tr>
<tr><td>H</td></tr>
<tr><td colspan="3">Capability of Programs Currently Used By Industry
Pressure dependent strength envelopes (e.g. Drucker Prager or Mohr Coulomb).</td></tr>
<tr><td colspan="3">Current Practice of Nuclear Industry
If necessary, use artificially high value of f_c in areas of high confinement.</td></tr>
<tr><td colspan="3">Current Research
Multi-axial testing at elevated temperature ongoing to gain new material data [4].</td></tr>
<tr><td colspan="3">Comments and Limitations
Of most interest local to bearings and anchorages. The basic shape of the multi-axial failure envelope under ambient conditions is known. However, few FE codes implement the advanced constitutive models which truly embrace these envelopes.</td></tr>
</table>

4.4.6	Inclusion of Temperature Dependent Effects	Desirability (Low, Medium, High)
		M
Capability of Programs Currently Used By Industry Can be included in some codes in a simplified manner.		
Current Practice of Nuclear Industry Sometimes used but there is a lack of sufficient material data.		
Current Research Obtaining new experimental data [4].		
Comments and Limitations Insufficient material data available.		

4.4.7	Load Path Dependency	Desirability (Low, Medium, High)
		H
Capability of Programs Currently Used By Industry All plasticity models include a degree of path dependency.		
Current Practice of Nuclear Industry Kinematic hardening with post-peak softening and cyclic dependence.		
Current Research Second order and fourth order tensor damage models appearing [55].		
Comments and Limitations These effects can be important in the final rupture stages when rotation of the principal axes can occur. Particularly important for the analysis of thermal transients.		

4.4.8	Effects Of Loading Rate	Desirability (Low, Medium, High)
		L
Capability of Programs Currently Used By Industry Viscoplastic model available.		
Current Practice of Nuclear Industry Some countries do not account for the effects of loading rate, others include rate dependence of strength, particularly for impact studies.		
Current Research Viscous-plasticity models now appearing to aid fracture regularisation [74].		
Comments and Limitations Difficult to calibrate.		

4.5 Representation of Steel

The features of interest in relation to steel behaviour are discussed below. In this context steel is taken to include reinforcement, prestressing tendons and the liner.

i) Non-linear plastic behaviour: The stress-strain behaviour of interest for steel is considerably simpler than that of concrete because the steel components used are generally one dimensional (tendons and reinforcement) or two dimensional (liner).

ii) Thermal expansion of steel: The thermal expansion of steel, as a function of the temperature rise and coefficient of thermal expansion is of interest. The thermal expansion coefficient can be a temperature dependent property.

iii) Strain rate dependency: The stress-strain behaviour of steel can be strain rate dependent.

iv) Load path dependency: This becomes of interest when considering the effects of load reversal or load redistribution post yield.

4.5.1 Program Capabilities

Non-linear plastic behaviour of steel is usually represented by a uniaxial stress-strain curve, based on von Mises or Tresca stress levels. Isotropic or kinematic hardening can be incorporated.

Several programs allow strain rate dependent stiffnesses to be incorporated into the material model for steel.

Load path dependency is accounted for by the use of a plasticity model.

Thermal expansion effects are usually well catered for, with temperature dependent coefficients of thermal expansion frequently being an available option.

<table>
<tr><td rowspan="2">4.5.1</td><td rowspan="2">Model Non-linear Plastic Behaviour Of Steel</td><td>Desirability
(<u>L</u>ow, <u>M</u>edium, <u>H</u>igh)</td></tr>
<tr><td>H</td></tr>
<tr><td colspan="3">Capability of Programs Currently Used By Industry
Capabilities well developed, usual methods available include definition of non-linear uniaxial stress-strain diagram, with von Mises or Tresca isotropic or kinematic work hardening.</td></tr>
<tr><td colspan="3">Current Practice of Nuclear Industry
Steel generally not included in global representations of prestressed structures. Elastic-plastic material properties generally included for local models.</td></tr>
<tr><td colspan="3">Current Research
Advanced (bounding surface) plasticity models developed for cyclic effects. [54]</td></tr>
<tr><td colspan="3">Comments and Limitations
Current capabilities appear reasonably satisfactory.</td></tr>
</table>

<table>
<tr><td rowspan="2">4.5.2</td><td rowspan="2">Thermal Expansion of Steel</td><td>Desirability
(<u>L</u>ow, <u>M</u>edium, <u>H</u>igh)</td></tr>
<tr><td>H</td></tr>
<tr><td colspan="3">Capability of Programs Currently Used By Industry
Represent expansion based on a strain of $\alpha\ \Delta T$ where α=coefficient of thermal expansion and ΔT is the temperature rise. α can be temperature dependent.</td></tr>
<tr><td colspan="3">Current Practice of Nuclear Industry
Included as appropriate as $\alpha\ \Delta T$</td></tr>
<tr><td colspan="3">Current Research
The authors are not aware of any significant current research that is directly relevant to the nuclear industry.</td></tr>
<tr><td colspan="3">Comments and Limitations
Capabilities well developed. However, other effects may be important. (e.g. transient thermal creep – discussed in Section 4.9).</td></tr>
</table>

<table>
<tr><td rowspan="2">4.5.3</td><td rowspan="2">Strain Rate Effects</td><td>Desirability
(<u>L</u>ow, <u>M</u>edium, <u>H</u>igh)</td></tr>
<tr><td>M</td></tr>
<tr><td colspan="3">Capability of Programs Currently Used By Industry
Capabilities well developed. However, other effects may be important. (e.g. transient thermal creep – discussed in Section 4.9).</td></tr>
<tr><td colspan="3">Current Practice of Nuclear Industry
Not accounted for.</td></tr>
<tr><td colspan="3">Current Research
Significant body of viscoplastic damage models developed to account for apparent stiffness and strength gain under rapid loading [55].</td></tr>
<tr><td colspan="3">Comments and Limitations
Creep effects discussed elsewhere.</td></tr>
</table>

<table>
<tr><td rowspan="2">4.5.4</td><td rowspan="2">Load Path Dependence</td><td>Desirability
(<u>L</u>ow, <u>M</u>edium, <u>H</u>igh)</td></tr>
<tr><td>L</td></tr>
<tr><td colspan="3">Capability of Programs Currently Used By Industry
Standard plasticity models exhibit a path dependency.</td></tr>
<tr><td colspan="3">Current Practice of Nuclear Industry
Accounted for in an indirect manner.</td></tr>
<tr><td colspan="3">Current Research
Extensive body of research on advanced constitutive models exhibiting various degrees of path dependency [56].</td></tr>
<tr><td colspan="3">Comments and Limitations
Not seen as a major issue in relation to the steel considered by this report.</td></tr>
</table>

4.5.5	Represent Fatigue Effects	Desirability (Low, Medium, High)
		L
Capability of Programs Currently Used By Industry Comparison of predicted stresses with S-N diagrams. specialist fatigue/fracture programs.		
Current Practice of Nuclear Industry Not considered as a significant effect.		
Current Research Most research for structural steelwork has been done in response to offshore platform response.		
Comments and Limitations Not seen as a major issue in relation to the steel considered by this report. Other industries (e.g. automotive) have developed a large body of specialist knowledge about this subject.		

4.6 Thermal Expansion Of Concrete

The thermal expansion of concrete, as a function of the temperature rise and coefficient of thermal expansion is of interest.

4.6.1 Program Capabilities

Thermal expansion of concrete can be adequately represented in most commercial codes by an expansive strain related to the temperature rise by the coefficient of thermal expansion, which may itself be a temperature dependent property

4.6.1	Representation Of Expansion Based On A Strain Of $\alpha \Delta T$	Desirability (Low, Medium, High)
		H
Capability of Programs Currently Used By Industry Fully available		
Current Practice of Nuclear Industry Regularly used		
Current Research None applicable		
Comments and Limitations None		

<table>
<tr><td rowspan="2">4.6.2</td><td rowspan="2">Temperature Dependent Thermal Expansion</td><td>Desirability
(Low, Medium, High)</td></tr>
<tr><td>H</td></tr>
<tr><td colspan="3">Capability of Programs Currently Used By Industry
Available in most codes</td></tr>
<tr><td colspan="3">Current Practice of Nuclear Industry
Regularly used by some for accident studies on containments and occasionally used in PCPV fault studies (thermal transients).</td></tr>
<tr><td colspan="3">Current Research
Further data is currently becoming available [4].</td></tr>
<tr><td colspan="3">Comments and Limitations
An issue for a PCPV if thermally induced degradation occurs under high temperature associated with loss of PVCS fault conditions.</td></tr>
</table>

4.7 Creep

Creep (or relaxation) occurs with concrete strains increasing with time under sustained stress (or stresses reducing with time under constant strain). This is of particular relevance for concrete under the action of prestress and other forms of long term loading such as mechanical and thermal loads induced via penetrations, internal reactor structures and reactor coolant gas. Such creep strains can develop to be of a similar magnitude to elastic strains. The degree to which such creep strains develop is influenced by the age and temperature of the concrete when the loading is applied.

4.7.1 Program Capabilities

The best capability that is frequently available for representing creep and relaxation effects in concrete is the use of viscoelastic material properties. These methods usually involve the use of the Kelvin chain (especially for creep) or the Maxwell chain (especially for relaxation). These material models can be physically interpreted by the analogy of a chain of springs and dampers in series or parallel (see Figure 7). By adjusting the physical characteristics of the springs and dashpots, it is possible to obtain a fit to a creep or relaxation curve. This curve fitting exercise is done automatically by some programs. This method of viscoelasticity is computationally efficient, and allows the material behaviour to effectively have a “memory” of the previous strain history and to allow this to have an effect on the current state of stresses.

<table>
<tr><td rowspan="2">4.7.1</td><td rowspan="2">Representation Of Creep And Relaxation Effects</td><td>Desirability
(Low, Medium, High)</td></tr>
<tr><td>H</td></tr>
<tr><td colspan="3">**Capability of Programs Currently Used By Industry**
Viscoelastic techniques based on Kelvin or Maxwell chains with some curve fitting algorithms allow reasonable representation of uniaxial data. Hereditary integrals with ageing are used in some programs for young concrete and mature concrete under high temperature.</td></tr>
<tr><td colspan="3">**Current Practice of Nuclear Industry**
Use design code models (e.g. ACI or CEB) or test data for long term creep.</td></tr>
<tr><td colspan="3">**Current Research**
Most work under uniaxial states and creep models have been developed on the basis of work done in 1960s and 1970s. Recent extensions consider multi-axial compliance, expressed in the form of a double power law [75].</td></tr>
<tr><td colspan="3">**Comments and Limitations**
Sometimes creep effects cannot be combined with other non-linear phenomena (e.g. plasticity) in existing FE codes. See Table 4.2.12.</td></tr>
</table>

<table>
<tr><td rowspan="2">4.7.2</td><td rowspan="2">Temperature Dependent Effects</td><td>Desirability
(Low, Medium, High)</td></tr>
<tr><td>H</td></tr>
<tr><td colspan="3">**Capability of Programs Currently Used By Industry**
Some general purpose FE codes have this capability.</td></tr>
<tr><td colspan="3">**Current Practice of Nuclear Industry**
This is important for PCPV's, where significant thermal gradients and hence differential creep strain rates may exist. It is also important for structures in which changes in temperature occur during normal operating conditions.</td></tr>
<tr><td colspan="3">**Current Research**
Little new research in this area, although it is recognised as important.</td></tr>
<tr><td colspan="3">**Comments and Limitations**
Some codes cannot adequately cater for this, and the creep calculation has to be based on a single defined temperature representative of the mean bulk temperature within the structure.</td></tr>
</table>

<table>
<tr><td rowspan="2">4.7.3</td><td rowspan="2">Maturity At Loading</td><td>Desirability
(Low, Medium, High)</td></tr>
<tr><td>H</td></tr>
<tr><td colspan="3">**Capability of Programs Currently Used By Industry**
Some programs allow the input of (a family of) age related Kelvin / Maxwell chains.</td></tr>
<tr><td colspan="3">**Current Practice of Nuclear Industry**
Cater for this by implementing standard design code models (e.g. CEB).</td></tr>
<tr><td colspan="3">**Current Research**
Work on solidification models to represent concrete hydration processes are emerging [49].</td></tr>
<tr><td colspan="3">**Comments and Limitations**
Creep effects particularly important when early age concrete is loaded.</td></tr>
</table>

4.7.4	Moisture Dependent Effects	Desirability (Low, Medium, High)
		M
Capability of Programs Currently Used By Industry Some codes will allow a moisture diffusion analysis to be performed. The resulting data is used in a “concentration dependent” creep model.		
Current Practice of Nuclear Industry Use ‘standard’ design code creep models, which take account for initial moisture content and age hardening. These do not cater, however, for moisture migration through thick sectioned, lined structures such as PCPV’s.		
Current Research This is a new area of research [58].		
Comments and Limitations Data not widely available but not considered to be a significant issue for analysis under normal operating conditions.		

4.8 Cyclic Loading

In the context of this report, cyclic loading refers to the small number of cycles of loading experienced during the normal operational lives of vessels and containments. Areas of interest include the ability to model irrecoverable deformations during unloading / reloading, the realistic representation of crack opening/closing and the degradation of material properties with cycling of loading.

For PCPV’s, cyclic loading (other than seismic analysis) is not a primary consideration. The only significant cyclic effect is experienced by the areas around the penetrations during shutdown and start-up. These would typically see 20 to 30 cycles (at most 100 cycles) of thermal loading and pressure loading. Most damage occurs during the first loading cycle.

Containment degradation due to the cyclic loading from integrated leak rate tests is addressed in Section 5.2.

4.8.1 Program Capabilities

The dominant considerations here are load path dependency, damage accumulation and possible fatigue effects. As noted above, the number of loading cycles likely to be experienced is relatively low, and fatigue effects are therefore generally not an issue.

Load path dependency and damage accumulation are accounted for to an extent by the standard plasticity representations, and also by the cracking models with their various unloading / reloading characteristics (see Section 4.2).

During the last decade many concrete models have been developed, which are capable of accounting for the unilateral effect corresponding to crack closure, and possible subsequent reopening. Hysteretic effects are sometimes accounted for. Inelastic strains are also often incorporated, in damage and plasticity models. Other degradation modes due to cycling are in general not available. Previous models are used to describe the different cycles, following a classical time-history approach.

4.8.1	Modelling Irrecoverable Deformations During Unloading	Desirability (Low, Medium, High) M
Capability of Programs Currently Used By Industry Plasticity models include irrecoverable strains, but no stiffness degradation (damage).		
Current Practice of Nuclear Industry Captured as part of the constitutive model.		
Current Research The authors have no knowledge of any significant research of direct relevance that is currently ongoing.		
Comments and Limitations None.		

4.8.2	Realistic Modelling Of Crack Opening / Closing, Unloading / Reloading	Desirability (Low, Medium, High) M
Capability of Programs Currently Used By Industry Variety of methods based on different algorithms, some of which perform quite poorly.		
Current Practice of Nuclear Industry Captured as part of the constitutive model.		
Current Research The authors have no knowledge of any significant research of direct relevance that is currently ongoing.		
Comments and Limitations None.		

4.9 Transient Thermal Creep

Transient thermal creep (ttc) strains develop when loaded or restrained concrete is heated to significant temperatures, typically above 100°C. This behaviour occurs only when the temperature of loaded concrete is increased beyond values that have previously been experienced. The resulting strains are not recoverable if the concrete subsequently cools.

4.9.1 Program Capabilities

Currently, few programs have a specific implementation of transient thermal creep effects. One commercial program has an option to include transient thermal creep strains which are equal to the product of a user defined constant, the stress level, and the incremental change in temperature.

In some programs it is also possible to include the effect by making use of User Supplied Subroutines.

4.9.1	Determination Of Strain Due To Transient Thermal Creep Phenomenon	Desirability (Low, Medium, High)
		H

Capability of Programs Currently Used By Industry

Some programs allow introduction of additional strain given by formula $\alpha k \sigma \, \Delta T/fc$ where α=coefficient of thermal expansion, k is the creep factor, σ is the stress, ΔT is the temperature rise and fc is the uniaxial compressive strength.

Can be implemented in other programs by User Supplied Subroutines, but the restrictions on what other non-linearities can be incorporated can be significant.

Current Practice of Nuclear Industry

For the analysis of PCPV's, substantial use is made of the best available commercial codes and material data. Numerous sensitivity studies by varying the creep factor.

Current Research

Obtaining further experimental data under multi-axial compression [4]. Development of new biaxial constitutive model [51].

Comments and Limitations

Becomes significant for any structure heated above 100^{0}C. Used for the analysis of PCPV accident conditions where temperatures reach 200-300^{o}C for several days and transient thermal creep can be an important issue. Generally not significant for CCV's as maximum design temperature is 50^{o}C. Can be relevant to internal CCV structures under LOCA.

Research restricted to biaxial work.

Further development of commercial codes would be beneficial to allow:

Strains to be irreversible on cooling [51].

Combination with viscoelastic creep.

Definition of the amount of thermal creep as a non-linear function of temperature.

Capture time dependent effects. It is still not totally clear whether transient thermal creep is a true new material phenomenon [76].

Moisture content to be accounted for.

5.0 REPRESENTATION OF AGEING EFFECTS

The ageing of structures starts immediately following construction and continues through their in service life. For nuclear structures, it is also necessary to consider the effects of ageing up to the end of any decommissioning process. Ageing is thus a through life issue.

To be able to model the ageing process, it is necessary to understand the forms of loading that can contribute to ageing and then to represent the geometric and material features of the structure such that the time dependent nature of the response to the loadings can be captured (e.g. creep).

A useful summary and discussion of ageing is provided in [13].

5.1.1 Through Life Loading Sequences

The through life loading sequences that can contribute to ageing are discussed in Section 2.2.7 and are summarised below for ease of reference:

i) the construction/build sequence, taking account of any built in residual stresses.
ii) the application of prestressing loads.
iii) pre-operational pressure tests.
iv) operation (with sustained pressures and temperatures for vessels), including periodic shutdowns.
v) periodic pressure tests (Integrated Leak Rate Tests for containments).
vi) structural modifications.
vii) decommissioning.

The manner in which these loadings can be represented, together with the representation of any time dependent effects is discussed in Section 3.5. When considering ageing, it is necessary to represent the time period over which the loads act and the sequence in which they are applied. Time dependent structural or material response can then also be captured. Time dependent material response due to effects such as creep and degradation due to cyclic loading is addressed in Sections 4.7, 4.8 and 4.9.

The above approach would theoretically allow a full numerical simulation of some parts of the ageing process. Further research and developments are necessary before this can be reliably achieved.

5.2 Summary of Topics Addressed

TABLE	**TOPIC**
5.2.1	Prestress Loss
5.2.2	Concrete Shrinkage
5.2.3	Corrosion
5.2.4	Alkali Silica Reaction
5.2.5	Carbonation
5.2.6	Chloride Diffusion
5.2.7	Irradiation
5.2.8	Integrated Leak Rate Test

i) Loss of Prestress; This can have a major effect due to tendon relaxation (or concrete creep) and can be modelled explicitly within a time domain analysis or be allowed for by re-analysing with reduced tendon loads. The variation in load along the tendon length (due to frictional effects) can become significant.

ii) Concrete Shrinkage; The effects of concrete shrinkage can be of interest when considering the long term behaviour of vessels and containments.

iii) Degradation Caused By Integrated Leak Rate Test; Cracking caused by the Integrated Leak Rate Test continues to be a significant ageing factor, and is of particular importance for unlined containments. The leak tightness of cracked containments is the subject of an active experimental programme (the MAEVA mock-up by EDF), where experimental results are compared with numerical predictions using FEA methods [20].

iv) Other Ageing Effects; There are several aspects of ageing that are generally addressed by a structured inspection and maintenance programme without the need to consider their effects explicitly within FEA. Where appropriate, effects can be covered by reasoned engineering argument (e.g. to show that adverse temperature or irradiation effects do not actually encroach on prestressing tendon zone).

Concrete:	chemical attack physical attack
Reinforcement:	corrosion temperature irradiation fatigue
Prestressing tendons:	corrosion temperature irradiation fatigue

5.2.1 Program Capabilities

Loss of Prestress

Prestress loss can be modelled with some degree of realism by allowing the tendons, if they are represented in the model, to creep by specifying appropriate creep parameters in the material model for the steel (either by visco-elasticity, or by using one of the more specific metal creep algorithms that are commonly available). If the tendons are not represented explicitly, then the load that they produce can be made to be time dependent.

Concrete Shrinkage

Some programs include algorithms that allow shrinkage strains to be introduced as a function of time and/or temperature. The tensile stresses that may develop due to constraining resistance to these strains can then lead to cracking, which can be represented by the methods presented in Section 4.2.

Corrosion

If the liner is modelled using shell elements (or line elements for a 2D analysis), this effect can readily be included by specifying the thickness of these elements to be time dependent.

Techniques are becoming available for accounting for the corrosion of tendons and reinforcement (see Section 8).

Degradation Caused By Integrated Leak Rate Test

Whilst any cracking caused by the Integrated Leak Rate Test can theoretically be captured using any of the methods described in Section 4.2, these methods are often not wholly appropriate for capturing local effects, and do not offer a valid solution for accurately determining the leak tightness.

Other Ageing Effects

Other ageing effects are more difficult to represent. In general, analytical tools do not yet have particularly well developed algorithms for representing these phenomena.

5.2.1	Prestress loss	Desirability (Low, Medium, High) H
Capability of Programs Currently Used By Industry Analytical capabilities well developed: Predicting prestress loss: The process of losing prestress can be represented by (temperature dependent) creep of tendons. Effect of prestress loss: The structural implications can be modelled by including tendons in the model and allowing them to creep. Time dependent loads can be specified.		
Current Practice of Nuclear Industry Analyse as creep of tendons. Assess effects by using time dependent loads. In practical terms, if prestress loss was significant, structures would be re-stressed or analysed with a lower prestress.		
Current Research None.		
Comments and Limitations See also Tables 4.7.1 and 4.7.2. See also [2 and 5], reports on a related workshop		

5.2.2	Concrete shrinkage	Desirability (Low, Medium, High) H

Capability of Programs Currently Used By Industry
Include algorithms to represent shrinkage strains.

Current Practice of Nuclear Industry
Sometimes include as an initial strain.
Sometimes model using a fictitious negative temperature in combination with a thermal expansion coefficient.
When performing transient creep analyses, include for shrinkage in choice of “k” factor.

Current Research
Testing to get further materials data.

Comments and Limitations
Materials data available generally restricted to information at ambient temperatures. Inclusion of shrinkage effects generally limited by availability of suitable materials data.

5.2.3	Corrosion of tendons, rebars and liner	Desirability (Low, Medium, High) L

Capability of Programs Currently Used By Industry
Can be modelled by specifying time dependent section sizes that reduce over time.

Current Practice of Nuclear Industry
Not modelled. Dismissed by desk studies or analysis completed with reduced section size. If water did get into a tendon duct, it would be detected and the tendon would be replaced.

Current Research
Nuclear industry sponsored studies ongoing to model the results of corrosion and the coupling between corrosion and cracking.

Comments and Limitations
No general, realistic treatment for corrosion (expansive forces, loss of bond) currently available.

5.2.4	Alkali silica reaction	Desirability (Low, Medium, High) L

Capability of Programs Currently Used By Industry
Can be included by the use of expansive strains. However, the value of this approach is somewhat limited as in practice the effect is known to be stress dependent.

Current Practice of Nuclear Industry
No analysis necessary where the materials used to construct nuclear plants are known to be not susceptible to this phenomenon.

Current Research
Some research work done in early 1990s relating to highway structures. More recent studies investigate the chemo-mechanics of the problem [77].

Comments and Limitations
This is a necessary area of study where materials susceptible to ASR are used in order to estimate the remaining life of structures affected.

5.2.5	Carbonation	Desirability (Low, Medium, High) L

Capability of Programs Currently Used By Industry
Extent of carbonation could be simulated by a diffusion analysis.
Changes to concrete material properties (stiffness and strength) could be modelled.

Current Practice of Nuclear Industry
Desk studies to demonstrate its insignificance.

Current Research
Research on 1D models.

Comments and Limitations
Near surface phenomenon. Changes to material properties usually fairly small. Problem is that if carbonation reaches reinforcement, corrosion can occur. However, this is not a problem in countries where vessels and containment are fully enclosed.

5.2.6	Chloride Diffusion	Desirability (Low, Medium, High) L

Capability of Programs Currently Used By Industry
Can be analysed in a simplified manner by a diffusion analysis.

Current Practice of Nuclear Industry
Desk studies to demonstrate its insignificance.

Current Research
Large body of research on chloride transport which is known to depend heavily on cement / admixture type [53].

Comments and Limitations
No change in material properties, but potential threat to reinforcement.

5.2.7	Irradiation	Desirability (Low, Medium, High) L

Capability of Programs Currently Used By Industry
No specific capabilities, other than manually changing material properties.
Difficult to include the expansive strains that are produced.

Current Practice of Nuclear Industry
For PCC, no high radiation other than primary shield wall. For PCPV, it is an end of life near surface effect and has been shown to be insignificant.
Some assessment was carried out in the UK of the embeddments close to irradiated surfaces (e.g. the bioshields at Magnox).
Some work has also been done using User Supplied Subroutines to take account of the change in E and ν.

Current Research
Some studies ongoing into the effects of irradiation on the material properties of reinforcement.

Comments and Limitations
Shortage of material data.
Main concern is the anchorage for the liner.
At design stage, effects were assumed to be negligible.

5.2.8	Represent effects of integrated leak rate test	Desirability (Low, Medium, High) H (UNLINED PCC) L (LINED PCC)

Capability of Programs Currently Used By Industry
Simulate cracking of concrete using one of the methods described in Tables 4.2.

Current Practice of Nuclear Industry
Plant ageing studies are conducted as a material properties effect (see Oak Ridge National Laboratories Publications).
Estimates of leak rates through cracks are currently based on approximated methods.

Current Research
The evaluation of permeability associated with cracking is a significant research issue. Currently there is no practical tool which can be used in industry. It is necessary to consider the transport of multi-phase (steam and air) fluids.

Comments and Limitations
Integrated leak rate tests frequently result in micro-cracking of containments.
See also Table 4.2.13.

6.0 NUMERICAL STABILITY

Several of the preceding sections have made reference to the potential for numerical instability when trying to obtain a solution for a representation of the complex non-linear behaviour which concrete can exhibit.

The types of program considered in this report are all implicit programs. (Although explicit programs are frequently used to study impact problems, that is not the main subject area of this report.) All these programs are based on incremental-iterative solution techniques. These techniques are discussed in [8].

(Implicit programs use a numerical procedure where the solution at step n+1 is obtained from the solution at step n and the conditions at step n+1. With an explicit program, the solution at step n+1 is obtained entirely from the solution and conditions imposed at step n.)

Usually, various options are available for incremental procedures. For example:

- Load and displacement control.
- Arc-length control.
- Adaptive loading.

Similarly, a number of different iterative schemes might typically be available:

- Newton-Raphson.
- Quasi-Newton.
- Linear stiffness.
- Constant stiffness.
- Line searching.
- BFGS (Broyden, Fletcher, Goldfarb and Shanno) secant type method.

The convergence criteria are usually defined by the user, based on some combination of force, displacement and energy norms.

Combinations of these various options provide the user with a “toolkit” of numerical techniques, the appropriate use of which can be something of an acquired art. Problems are still frequently experienced in obtaining a fully converged solution, particularly if the loading approaches or exceeds the ultimate loading of the structure.

6.1.1	Robust non-linear solver	Desirability (Low, Medium, High) H

Capability of Programs Currently Used By Industry
Newton-Raphson, modified Newton-Raphson and initial stiffness methods widely used. BFGS secant type approach also available.

Current Practice of Nuclear Industry
N-R and modified N-R used

Current Research
Little new research in this complex and important area

Comments and Limitations
Identification of an optimal non-linear solver is difficult. N-R still appears to provide the main method. Convergence dependent upon initial starting position. Further work required as lack of convergence is a common occurrence in NLFEA.

6.1.2	Efficient linear solver	Desirability (Low, Medium, High) M

Capability of Programs Currently Used By Industry
Direct (Gaussian elimination) and indirect (Pre-conditioned iterave e.g. PCCG) solvers available.

Current Practice of Nuclear Industry
Default solver adopted. PCCG becoming more common for large analyses.

Current Research
Work ongoing both with advanced frontal direct methods and GMRES stabilised iterative schemes [78].

Comments and Limitations
Runtime speed gains are always desirable.

6.1.3	Non-linear load incrementation schemes	Desirability (Low, Medium, High) M

Capability of Programs Currently Used By Industry
Cylindrical and spherical arc length procedures coupled with line searching algorithms.

Current Practice of Nuclear Industry
All available methods used to varying degrees. Linear stiffness approach popular due to its comparative stability.

Current Research
Studies ongoing linking local fracture induced snap-back and snap-through with bifurcation investigations.

Comments and Limitations
Little clear guidance given in most FE manuals. Users often left to experiment by trial and error.

6.1.4	Coupled transient multi-physics analysis	Desirability (Low, Medium, High) M

Capability of Programs Currently Used By Industry
Fully coupled, rigorous, thermo-chemo-mechanical analyses not yet possible

Current Practice of Nuclear Industry
Not yet used

Current Research
This is a key area for research in next ten years and is especially related to ageing and durability issues.

Comments and Limitations
It is anticipated that a full coupled analysis to simulate ageing effects in concrete will be possible by the end of the decade.

7.0 VALIDATION OF ANALYSIS METHODS AND RESULTS

The validity of any numerical technique needs to be proven by some independent means, in order that the results can be used with any degree of confidence. This is particularly true when the material behaviour is highly non-linear.

Individual analyses are usually supported by a series of sensitivity studies and bounding hand calculations. Nevertheless, the complexity of the situation means that these checks can rarely be more than very approximate checks on the predicted response.

There is clearly a need for a comprehensive validation of the underlying methods and results obtained. Work on this subject can generally be divided into three stages:

- Verification of a finite element program and its basic formulation.
- Validation of the material models.
- Validation of analysis results.

These three areas are discussed in the following sub-sections.

7.1 Verification of a Finite Element Program and its Basic Formulation

Software vendors usually provide a “Verification Report”, in the form of a series of relatively simple test analyses which are intended to verify that the program has been correctly coded and is performing in the way that is intended. These tests can generally be subdivided into three classes: consistency tests, patch tests and benchmark tests.

In consistency tests, simple element geometries are tested by rigid body motions and uniform strain fields. In general, the target values for the analysis results can be obtained from theory.

In patch tests the influence of the element shape on the analysis results is checked. Consistency tests and patch tests do not represent structures that could be found in engineering practice.

With benchmark tests, the geometry is more complex and target values cannot always be obtained from theory. Benchmark tests are an indispensable part of the verification of FE packages. For specific applications, benchmark tests can be developed. For general applications, benchmark tests are published in commonly available literature. A large number of benchmarks have been designed and published by NAFEMS, the *National Agency for Finite Element Methods & Standards* in the United Kingdom. The tests, including target values, are presented in a number of publications. To date, however, no benchmarks have been published by NAFEMS that are specific to the analysis of concrete. The benchmarks that are available are therefore limited to checking the general functionality of a particular package.

A series of benchmark tests specific to the analysis of concrete therefore remains a highly desirable development.

Similarly, there is no universally agreed procedure for validating finite element robustness.

7.2 Validation of Material Models

Across the different fields of engineering science, material models are generally validated by comparing the predictions of different constitutive models with results obtained from small scale tests. This is particularly well developed in the area of soil mechanics, where a range of different Round Robins exist.

There is no particular equivalent in concrete mechanics, and this part of the validation process usually happens piecemeal through various research programmes. Some benefits would result from collating this information into an international database.

7.3 Validation of Analysis Results

There are a number of methods available to validate the results obtained from complex analyses. These are discussed below. Complete validation can be by a combination of all or some of these methods.

7.3.1 Comparison of Results From Different Programs

Confidence in the validity of results can be increased by using different software packages to solve the same problem and then comparing the results obtained. For complex non-linear analyses, a direct comparison of results may not be readily obtainable, but trends in results and ranges of values can be used to give an indication of the validity of results obtained.

7.3.2 Comparison of Results with Bounding Hand Calculations

Simplified and bounding hand calculations, together with engineering judgement can be used to confirm the validity of results obtained.

7.3.3 Sensitivity/Parametric Studies

Confidence in results can be increased by performing extensive sensitivity and parametric studies to confirm that trends in results between the various analyses coincide with expectations.

7.3.4 Comparison with Physical Tests

There have been a number of physical tests performed on concrete structures where results from finite element analyses have been compared with the results obtained from tests. Some of these have been approached in the form of International Standard Problems, where analytical teams from different countries have predicted, prior to the test, what the anticipated performance will be. These, and other physical tests, have proven themselves to be a very useful means of testing the entire analysis process, including material parameter selection, modelling assumptions / approximations, constitutive models, finite element programs and results interpretation. Some relevant examples of these physical tests are listed below:

i Sandia Laboratories ¼ Scale Model of a PCC

> This test took place in the latter half of 2000, and involved pumping nitrogen gas into a 70 foot tall, 35 foot diameter replica of a Japanese PCC. The test, sponsored by the U.S. Nuclear Regulatory Commission (NRC) and Japan's Nuclear Power Engineering Corporation (NUPEC), involved increasing the gas pressure until failure. It was the largest nuclear reactor containment vessel model ever tested to failure, with the ultimate failure mode being leakage.
>
> The model was built with nearly 1500 sensors and fibre optic lines embedded in it, to enable data collection during the test. Prior to the test, all analysis results were reported [14].
>
> The test was terminated when the internal pressure was about 3.1 times the design pressure, at which time gas was leaking out faster than it could be pumped in.

ii Sandia Laboratories 1/6th Scale Model of a Reinforced Concrete Containment.

See [16 and 17].

iii 1/10th Scale Model of Sizewell ‘B’ Prestressed Concrete Containment.

See [19 and 21]

iv Testing of the 1/10th Scale Model of the Hinkley Point ‘B’ and Hunterston ‘B’ Prestressed Concrete Pressure Vessels.

See [15]

v Rilem Tests

See, for example [22 and 23]

8.0 OVERVIEW OF RECENT RESEARCH DEVELOPMENTS

Ever-more advanced FE codes, specialising on the response of concrete structures continue to be developed within universities and research institutes throughout the world. As is common in other areas of software development, the commercial codes remain some way behind the leading research edge. Further joint research and development projects between industry and academia could go some way towards remedying this situation. This section examines a selection of some of the more recent advances, which are not found in existing commercial codes; yet which may have an important impact on improving the realism of modelling reinforced and prestressed concrete nuclear power plant structures.

The breakdown within this section follows that of the rest of the report, by addressing geometric, material, ageing and numerical stability effects.

8.1 Geometric Features

Most of the basic, small deformation, continuum finite elements required to analyse three-dimensional structures were developed by the mid 1970s. The extensions that have taken place since that time have largely been associated with

i searching for more efficient numerical integration schemes,
ii developing more realistic interface elements (with automatic contact/loss-of-contact detection),
iii preventing spurious deformation modes (including locking and hour-glassing) and handling the incompressibility condition,
iv advancing thin and thick shell formulations and establishing a library of elements suitable for finite deformation analyses. Zienkiewicz and Taylor, Crisfield, Bathe and Belytschko, Liu and Moran [29] give detailed descriptions of many of these developments.

Considerable research effort has been expended on creating hybrid FE techniques (coupled with automatic mesh generation schemes) to cater for large deformation problems where boundaries move. Promising methods include Arbitrary Lagrangian-Eulerian formulations [30] and the more recent element-free-Galerkin (or meshless) methods. The former methods now appear in some codes. The latter techniques have the distinct advantage when tracing cracks, as the domain of interest need not be discretised into finite elements, eliminating all the attendant topology calculations [31]. Use of these adaptive methods relies upon the availability of a suitable error measure to drive the re-meshing processes. Much research has been conducted which can provide useful indications of the quality of the mesh [32].

8.2.1 Material Features

8.2.1 Concrete

The area where most work is still concentrated in the modelling of RC structures is in tensile crack simulation and multi-axial constitutive model development.

This sub-section starts with a brief review of concrete deformation behaviour under quasi-static loading. It is important to recognise that it is inappropriate to simply label concrete as a brittle material. Rather, the macro-scopic post-peak response (be it brittle, associated with discrete fracture, or ductile, associated with distributed fracture) should be related to the level of compressive confinement operating on the material. Only with this perspective can a meaningful interpretation of the behaviour be gained. Under compressive stress confinement states, concrete can exhibit very significant strength gain, high non-linearity in the stress-strain response and increased ductility when compared to the unconfined uniaxial behaviour. Under purely hydrostatic compression (or under a uniaxial compressive strain path) the material will never reach a peak stress (that is, its strength is unbounded). Stiffness degradation and hysteretic damping are observed under all states during repeated loading, particularly so under higher levels of strain. Under tensile states concrete shows little pre-peak non-linearity, a low strength and an abrupt loss of load carrying capacity once straining continues beyond the peak stress. It should be noted that the amount of confinement in containment structures, prestressed or reinforced is rather small and a Druker-Prager type model may be satisfactory, provided it is appropriately developed to treat cyclic loading.

During the 1970s much effort was expended on understanding and developing constitutive models for concrete under multi-axial stress states. This early work was largely restricted to continuum-based approaches similar to those used in soil and rock mechanics. At that time, many researchers treated the compressive behaviour within a different model framework to that used for the tensile response. For concrete loaded to its peak nominal stress in compression, the general features include inelastic compaction under hydrostatic loading, shear enhanced compaction, dilation, strain hardening and strain softening. Despite the large body of models developed for the compressive behaviour of concrete, the vast majority of early non-linear elasticity-based formulations represent little more than phenomenological curve fits to experimental data, with little attention paid to the evolution of irrecoverable strains, strain softening or stiffness degradation (as observed upon unloading).

Many of the early models employed 10 or more material constants which had no physically meaningful link to the internal fabric. Those that claimed fewer constants had generally been calibrated against a single mix and thus include hidden (fixed) material constants. In certain cases, the model development phase unsatisfactorily ended once triaxial test data had been simulated, and not when the model had been incorporated in a numerical scheme and real boundary value problems had been solved.

In the 1980s, this trend continued, however the concepts of engineering fracture mechanics (the notion of a Specific Fracture Energy, Modes I, II and III and the size effect) were gradually introduced. Thus attention switched to understanding and capturing the tensile behaviour. The 1990s saw a growing recognition of the difficulties associated with employing a strain softening formulation within a classical continuum model. In recent years, a wider range of physical and chemical phenomena have been addressed and included in FE analyses. The search for a unified, stable and accurate constitutive model for concrete remains ongoing.

The latest research is finally beginning to link micro-mechanical theoretical considerations to macro-scopic representations. For example, Ortiz’s formulation [33] explicitly introduces the different mechanical roles of the two dominant phases (aggregate and mortar) into the governing equations. The model includes a simple dependence of the elastic compliances on the extent of microcracking in the mortar. Penny shaped cracks, randomly oriented in the mortar are modelled in an average sense although no crack interaction effects are considered.

Many recent constitutive models [for example, 34] have taken to combining hardening/softening plasticity formulations with a continuum damage (CD) approach to model the highly non-linear behaviour. An alternative approach has been to consider the additive decomposition of slip on multiple planes. The microplane model [35] adopts this technique, providing it with the capability to partially capture the evolving anisotropy quite naturally. Just as in non-associated plasticity models, non-symmetry of the microplane constitutive matrix emerges as slip develops on different planes. Advanced plasticity-CD and microplane models have been under development for over 15 years [36], yet they do not appear in mainstream FE software (although some researchers have introduced them into general purpose codes via a user material model subroutine). Only a few of the more advanced plasticity models have rigorous stress return algorithms ([37], see Section 7.1).

Concrete Cracking

The two established techniques (smeared and discrete) for modelling cracking in concrete have undergone a number of modifications since their original development in the late 1960s [38].

Smeared Cracking

In a smeared crack approach the behaviour of the fractured concrete is described in terms of a continuum representation. Fracture formation is handled by the strain-softening constitutive relationships. Cracking is assumed to be spatially distributed over the volume represented by the element, or possibly the volume attached to one integration point. When first introduced, this method quickly became popular as it appeared to imply that no change in mesh topology was necessary; thereby suggesting a very efficient computational process [39]. However, during the last decade it has been shown that attempts to model discontinuum processes within a continuum framework inevitably leads to a change in the fundamental characteristics of the governing partial differential equations [40]. This results in finite element solutions being dependent on the mesh density and alignment of the element boundaries.

Unlike linear analysis, refinement of a mesh exhibiting continuum strain softening will not produce convergence to the unique, correct solution unless some form of material length scale [41] is introduced into the formulation and/or careful adaptive meshing is carried out.

Several regularisation procedures that introduce such an internal length are currently under study world-wide. These include simple crack-band methods (that adjust the equivalent material parameters with respect to the element size [42]) and techniques are based on non-local approaches [43], gradient plasticity [44] viscoplastic regularisation and micropolar continua. An alternative strategy is to embed a discontinuity field within continuum finite elements [45]. The relative merits of each of these have not yet been fully resolved, however both the gradient plasticity and non-local techniques appear to offer considerable promise [46].

A further challenge facing fracture investigators at present is the need to establish appropriate criteria for secondary crack formation. Within the family of conventional smeared crack models, two classes exist

i a fixed crack approach [47]
ii a rotating crack formulation which follows the major principal stress direction [48].

Plane stress comparisons between an *extended* fixed crack model and a rotating crack model, have highlighted the over-stiff behaviour of the former when compared with the latter.

In cases where significant stress reversals (in addition to rotation of the principal stress directions) can occur, the model should be capable of simulating not only the directional preferences introduced in the material structure but also the de-activation of fractures. For example, consider the situation where a tensile stress state has reached the fracture threshold whereupon (after strain-softening) the stress sense is reversed and compression is now applied to the crack surface. Under these circumstances the crack will close and a large proportion of the undamaged compressive stress may be carried across the crack. This feature cannot be modelled by an isotropically softening plasticity model but has been included in a number of multi-directional non-linear elastic crack models. At present, there is a concerted research effort to attempt to unify crack modelling treatments to provide a logical transition between equivalent continuum modelling and discrete fracture propagation. However, it may be ten years before a near complete, reliable and efficient anisotropic crack model emerges from the research community.

All aspects associated with developing and using advanced constitutive models for concrete suffer from a real lack of reliable, fundamental test data under three independent principal stresses. This also is partly to blame for the unavailability of any multi-axial constitutive models that offers a systematic calibration procedure to determine the material constants.

For massive prestressed reactor vessels, and thick walled containment structures, the concrete will be subjected to multi-axial confinement within the walls. More experimental research work is therefore required to capture the evolving form of the time dependent yield and damage surfaces in concrete under confinement levels consistent with those experienced in the walls. For example, to-date, there is no entirely conclusive evidence supporting the use of an associated flow rule, yet this option is often used in basic plasticity models with grossly over-simplified yield surfaces.

Of further interest to the UK nuclear industry (when considering the integrity of vessels) is the need to determine the effects on the residual strength, fracture energy and stiffness of concrete under sealed and unsealed conditions following alternative heat-then-load or load-then-heat cycles, with the latter being of particular interest. The further development of 3D thermo-mechanical constitutive models incorporating transient thermal creep effects [49] is reliant upon this new data that are just beginning to emerge.

Discrete Cracking

In the case of the discrete crack approach, the intact portion of the concrete structure is generally treated as behaving elastically, while crack propagation is simulated by changing the topology of the finite element mesh. It is the stress singularity at the crack tip that drives crack propagation, but fracturing can only be understood through considerations of energy expenditure. In the fictitious crack model, a fracture process zone is said to exist ahead of the crack tip. In this region, a reduced tensile load is carried. Crack opening displacement is related to the normal stress by a linear softening model, controlled by a fixed Fracture Energy Density. Separation of the material either side of the crack may be accomplished in a finite element context by introducing additional nodes and re-meshing the domain locally. An alternative approach is to introduce interface elements at element boundaries at the start of the analysis. In either case, advanced mesh-generators are generally required to model the changing topology (see Section 8.2).

8.2.2 Steel Reinforcement and Prestressing Tendons

Reinforcement in concrete has either been modelled in a distributed sense by adding directional stiffness to the concrete element or by linking discrete beam or bar elements to the concrete element nodes. In the former approach, some codes distribute the stiffness over the entire element, whereas others, more satisfactorily allow bars or membranes to be defined within the element. In either method, perfect bond between the steel and concrete is always implied

The discrete approach is more expensive to set-up, but it does enable bond-slip and dowel action effects [50] to be incorporated into the analysis. Simple uniaxial elasto-perfectly plastic (or linear work hardening plastic) models for the reinforcement are generally used. There have been few recent research developments in this area as effort has concentrated on capturing the fundamental fracture mechanisms in plain concrete, with the expectation that reinforcement interaction effects can be captured by local mesh refinement. However, an ‘up-scaling’ compromise must be taken when modelling full-scale engineering structures, as it is impractical (computationally) to model the local deformed bar profile using the current generation of computers.

8.3 Ageing Issues

Creep and shrinkage are two significant complex mechanisms associated with the ageing process in concrete. The principle of superposition has been assumed to apply under working loads and thus viscoelastic (Kelvin chain) material models are used to account for time-dependent deformations under variable load. Since creep is recognised as being profoundly influenced by the process of cement hydration, recent advances include the construction of solidification theories to account for these time-dependent effects [51]. Further advances will require the creep/shrinkage/swelling characteristics to take account of the specific moisture content and its rate of change. Here we note that the difference between the stress-induced thermal expansions under sealed or unsealed conditions can be very different due to pore pressure build-up under faster rates of heating.

Finite element analysis has been routinely used for diffusion studies in the field of geomechanical seepage analysis and heat transfer. The governing steady state quasi-harmonic equation is also encountered in many other fields, including the distribution of magnetic and electric flux. The processes of moisture loss during hydration, chloride migration and thermal conduction through concrete are governed by similar equations, although the mechanisms become rather more complex when different states and multiple phases are convected through a progressively fracturing, porous medium.

As a further example of the complex interaction between environmental conditions, consider the mechanism of chloride penetration that involves a diffusion process and the chemical binding of chloride ions with the hydration products of concrete. In order to estimate the rate of corrosion, an analysis must link the chloride concentration to the rate of oxygen diffusion to the cathode, the resistivity of the pore solution and the temperature of the substrate. The rate of corrosion should in turn be related to the mechanical loss of bond and spalling of cover concrete to finally allow realistic residual strength assessments to be made. Once cracks form, the boundary conditions change and hence the rate of chloride penetration will alter. This suggests a highly non-linear process where an FE mixed formulation is required to handle the different variables. The structural engineer needs to assess how sensitive the load-carrying capacity and deformation modes are to this potential local loss of bond. Equally importantly, the engineer needs to estimate the optimum time to carry out any repairs from the viewpoints of safety and economy. It is only during the past 5 years that researchers have begun to develop a reliability-based approach to tackle these questions through a probabilistic framework to account for the heterogeneity of the material and uncertainly of the environmental history.

The latest generation of 3D high-strain-rate viscoplastic models [52] have yet to appear in the main FE codes.

In order to undertake a detailed concrete durability study where long term processes dominate, each of the time-dependent phenomena (for example, creep, shrinkage, heat of hydration, stiffness evolution, thermal expansion, moisture transport, chemical alteration under thermal transients, progressive micro-cracking, chloride penetration, carbonation and corrosion of steel reinforcement) could be incorporated in a coupled, multi-physics analysis. In principle, much of this is already possible yet the application of FEA to this field is just emerging [53].

It is expected that the next 5-10 years will see significant advances in the combined modelling of these ageing processes. Much of this progress will depend on the availability of new test data from fundamental laboratory-based experimental programmes and back-analysis of the performance of full-scale insitu structures.

8.4 Stability of the FE Solution Algorithm

Three issues surface when striving for accuracy in simulating the complete non-linear behaviour of concrete containments and vessels.

i The level of realism that can be achieved by introducing a comprehensive range of physio-chemical mechanisms and phenomena.
ii The stability of the complete algorithm.
iii Computational efficiency.

The last ten years have seen a greater appreciation of these issues and the creation of more robust techniques [24].

The need for algorithmic reliability cannot be over-stated, with several areas to be avoided to ensure reliable results. These areas include the original problem/boundary conditions being ill-posed, incorrect choice of solution algorithm, loss of floating-point digits, solution bifurcation and time-stepping instability.

It is unlikely that a single, stable numerical non-linear solution approach will appear which is optimal for all problems faced by the structural engineer investigating concrete containments and vessels. Thus, while enormous progress has been made in making FE programmes easier to interact with (particularly in the areas of graphical pre- and post-processing), considerably more remains to be done before engineers can routinely and confidently perform complete non-linear analyses. As an example, no single incremental-iterative solution strategy can guarantee that a particular FE analysis will follow the true load-deformation path [26]. The full Newton-Raphson iterative strategy will only lead to the correct solution if the initial trial state lies with the local bowl of convergence. Some form of spherical or up-dated normal arc-length incremental method combined with a line-search procedure can assist in coping with snap-backs and speed-up the iteration loop, yet these methods are not fool-proof. Restricting minimisation of the residuals to just those degrees of freedom associated with local crack opening (rather than all degrees of freedom throughout the structure) has been shown to be successful in certain cases. Unfortunately, the commercial FE code developers generally offer little advice here, often because they themselves (as academic researchers) are unclear. More research is required to eliminate the causes that lead to a premature lack of convergence.

One area where some real success has been achieved recently is in the development of stable integration algorithms for rate-based inelastic constitutive models (often referred to as return-mapping algorithms in the field of plasticity) [27]. Many of the commercial FE codes now incorporate such routines at a simple level within constitutive models such as von Mises or Drucker-Prager plasticity. The research community has moved some way ahead to embrace more realistic constitutive formulations incorporating non-linear hardening and softening (see comments in the Material sub-section, Section 8.2).

9.0 PRIORITIES FOR FUTURE DEVELOPMENT

The tables given in this section summarise the areas where it is felt that the greatest benefits could be obtained from further development of the existing techniques. These have been split into six areas:

- Material data
- Ageing
- Pre- and post-processing
- Constitutive model
- Solver
- Validation

In each of these areas, the most significant needs have been listed, along with the benefits that would follow if these needs were met.

A qualitative indication (Low, Medium and High) is given of the relative scale of the costs which would be entailed in meeting these needs. Consideration of these costs in conjunction with the relative desirability of each need has assisted in the development of the list of recommendations given in Section 10.

MATERIAL DATA			
Need	**Benefits**	**Desirability**	**Cost**
International database of test data, along with a measure of the confidence level that can be attributed to the data.	Access by all to the best available information. Greater consistency of results.	**H**	**L**
Further experimental research into the effects of multi-axial confinement on material properties, under normal operating and fault conditions i.e. at ambient and elevated temperatures.	Increased understanding of the effects of multi axial confinement. Increased accuracy and reliability in FE modelling techniques.	**H**	**M**

AGEING			
Need	**Benefits**	**Desirability**	**Cost**
Link between crack damage (to containment structure) and effective permeability. To include simulation of these coupled processes. To consider multi-phase (steam and air) fluids.	Simulation of Integrated Leak Rate Tests. Prediction of consequences of cracking on containment safety case.	**H**	**H**
Gathering of material data especially related to ageing effects at elevated temperatures; e.g. concrete shrinkage and steel corrosion.	To support numerical simulation of ageing process.	**H**	**M**
Capture effects of pressurising cracks in vessel walls with hot reactor coolant gas.	Consequences of liner tears or ruptures can be assessed.	**H**	**M**
Development of coupled multi-physics analysis techniques.	To enable long term time dependent phenomena to be represented in a single ‘ageing’ analysis.	**H**	**H**

PRE and POST – PROCESSING			
Need	**Benefits**	**Desirability**	**Cost**
A means of automating the process of defining the layout of the rebars and tendons, including the definition of their geometry, section properties and material properties.	Current methods can be lengthy and error prone, due to the complexity of the layout of the rebars and tendons. Any means of automating this process would reduce analysis costs, and increase the number and complexity of analysis studies that could realistically be undertaken.	**M**	**H**
Improve means of post processing results, especially from complex 3D models and for crack visualisation.	Enables complex 3D models to be used with confidence. Results obtained can be visualised and more readily validated.	**M**	**H**

CONSTITUTIVE MODEL			
Need	**Benefits**	**Desirability**	**Cost**
Improved cracking predictions - elimination of strong mesh dependency	Improved confidence in results. Fewer analytical errors. Increased accessibility of techniques to new users.	**H**	**M**
Improved cracking predictions - better simulation of behaviour under general multi-axial stress states and post-fracture shear transfer	Better predictions of structural performance.	**H**	**M**
Improved cracking predictions - robust and entirely reliable algorithms based on sound physical principles	Reductions in analysis timescales and costs. Increased accessibility of techniques to new users.	**H**	**H**
Combination of smeared and discrete cracking, with automatic remeshing (or equivalent alternative).	Improved ease of use.	**M**	**M**
Better and simpler method of modelling concrete to steel bond.	Increased accuracy of results.	**M**	**M**

SOLVER			
Need	**Benefits**	**Desirability**	**Cost**
Non-linear solution algorithms that are more able to deal with severe softening (brittle material response) and bifurcation instabilities.	Prevent premature termination of simulation. This would have a major effect in reducing the overall time taken for an analysis project.	**H**	**H**
Widespread availability of efficient solution algorithms (e.g. sparse matrix solvers).	Reductions in solution times. Further opportunities for 3D analyses.	**H**	**L**
Widespread availability of parallel processing capability that is able to operate efficiently for brittle material behaviour.	Utilise power available in multi-processor machines to reduce solution times. Further opportunities for 3D analyses.	**H**	**M**
Distributed parallel processing.	Encompass the use of idle processors on computer networks.	**M**	**M**
Improved multi-physics solution capabilities.	Combined transient thermal and mechanical analyses. Coupled flow and mechanical analyses.	**M**	**M**
Ability to combine many non-linear phenomena (e.g. shrinkage, visco-elastic creep, transient thermal creep, plasticity, cracking etc.) in one analysis.	Overcome limitations present in some commercial codes, which currently make simplifying assumptions necessary.	**M**	**L**

VALIDATION			
Need	**Benefits**	**Desirability**	**Cost**
Further large-scale testing and comparison with analytical predictions.	Improved knowledge about confidence levels that can be associated with the various available techniques.	**H**	**H**
Database of existing benchmark problems and results.	Better comparison of current and new techniques with each other and with reality.	**H**	**L**

10.0 CONCLUSIONS

The application of advanced FEA techniques to the analysis of concrete nuclear structures offers substantial benefits for the prediction of performance under normal operating and fault conditions. FEA techniques are currently used extensively by almost all industries for the purposes of design calculations, validation of designs against functional objectives, and simulation of real performance.

In general, the civil and structural construction industries make some use of linear static FEA during the design process, but there is no widespread use of advanced non-linear techniques, as the perceived benefits are not seen to warrant the costs. Exceptions to this include:

- The design and qualification of high value structures operating in harsh environments with stringent safety requirements (e.g. offshore and nuclear industries, structures in regions with high seismic risk).
- Assessing the capabilities of existing structures to withstand new loading regimes (e.g. highway bridges under the action of increased traffic loads).
- Failure investigations.
- Design optimisation of precast concrete designs.
- Research into new methods of construction.

Currently, members of the nuclear industry are amongst the leading proponents of the use of advanced FEA for the analysis of concrete structures. The benefits gained from the use of these techniques is currently high, but their use is still hampered by some limitations, most notably:

- Issues of numerical stability.
- Long solution times, especially for 3D analyses.
- Limitations in methods to fully simulate ageing process.
- Lack of sufficient material data.
- Inability to simulate the link between cracking and leakage.
- Lack of collation of benchmark information for validation of techniques.

The areas of development which it is felt should be given the highest priority are summarised in Section 9.

10.1 Recommendations

The limitations listed above, and the areas for development tabulated in Section 9 should be resolved and progressed through the following;

- Further collaboration with representatives of other industries that stand to benefit from the advanced analysis of concrete.
- Formal liaison with commercial software developers, to communicate effectively the prioritised needs of industry for this type of analysis.
- Cooperation with other bodies with an interest in this area of work (e.g. ASRANet, NAFEMS and FENET).
- Develop database of materials information.
- Develop database of benchmark information.
- A joint meeting with the participants in the latest Sandia test.
- Review progress in approximately 3 years.

REFERENCES

1 OECD NEA/CSNI/R(95)19, OCDE/GD(96)31. Report of the Task Group Reviewing National and International Activities in the Area of Ageing of Nuclear Power Plant Concrete Structures.

2 OECD NEA/CSNI/R(97)9, OCDE/GD(97)225. Joint WANO/OECD-NEA Workshop, Prestress Loss in NPP Containments.

3 OECD NEA/CSNI/R(98)6. Development Priorities for Non-Destructive Examination of Concrete Structures in Nuclear Plant.

4 OECD NEA/CSNI/R(99)1. Finite Element Analysis of Degraded Concrete Structures. Workshop Proceedings, BNL, New York, United States, 29-30 October 1998.

5 OECD NEA/CSNI/R(99)11, NPP Containment Prestress Loss, Summary Statement.

6 FIB Bulletin No 13. Nuclear Containments, State of the Art Report, November 2001. ISBN 2-88394-053-3.

7 NAFEMS 1997. How to Model with Finite Elements.

8 NAFEMS 1986. A Finite Element Primer.

9 NAFEMS 1992. Introduction to Non-linear Finite Element Analysis.

10 ASME 1985. The ASME Boiler and Pressure Vessel Code. Division 2, Section III, Rules for Construction of Nuclear Plant Components.

11 BS 4975 1990. British Standard Specification for Prestressed Concrete Pressure Vessels for Nuclear Engineering.

12 RCCG Code RCC-G, Règles de conception et de construction du génie civil des ilots nucléaires REP, Editions AFCEN,France,1988

13 IAEA-TECDOC-1025, June 1998. Assessment and Management of Ageing of Major Nuclear Power Components Important to Safety: Concrete Containment Buildings.

14 NUREG/CR-6678 AND 00-1535. Pre-test Round Robin Analysis of a Prestressed Concrete Containment Vessel Model.

15 “Testing the One Tenth Scale Model of the Hinkley Point ‘B’ and Hunterston ‘B’ Power Station Prestressed Concrete Pressure Vessels” by D. McD. Eadie and D.J. Bell, Paper 14, Proc. Conf. On PCPV Model Techniques, British Nuclear Engineering Society, London, 1969.

16 NUREG/CR-5341, SAND 89-0349. Round-Robin Analysis of the Behaviour of a 1:6 Scale Reinforced Concrete Containment Model Pressurised to Failure: Post test Evaluations.

17 NUREG/CP-0095, SAND 88-1836. 3-D FEM Analysis of 1:6 Scale Reinforced Concrete Containment Under Static Overpressurisation and Local Analysis of the Liner Plate Tearing.

18 “Qualification of Composite Liners and Pressure Tests at the Mock-Up at Walldorf, Germany”, 16th SMIRT International Conference, 12-17 August 2001, Division H by R Danisch, C Stiepani and H Kolsch.

19 “Comparison of Pre-Test Analyses with the Sizewell ‘B’ 1:10 Scale Prestressed Concrete Containment Test”, 11th SMIRT International Conference, 18-23 August 1991, Paper H10/5, pages 271 to 276, by R.A. Dameron, Y.R. Rashid an M.B. Parks.

20 “What kind of predictions for leak rates for Nuclear Power Plant Containments in accidental conditions?” L Granger and F Fleury, 1998. (Presented as part of Reference [4])

21 “Ultimate Load Test of a 1/10th Scale Model Prestressed Concrete Containment”, 11th SMIRT International Conference, 18-23 August 1991, Paper H10/6, pages 277 to 282, by J. Palfrey and J.C.W Smith.

22 Anchor Bolts in Concrete Structures: Summary of Round Robin Tests and Analysis Arranged by RILEM TC 90-FMA Fracture Mechanics Applications by TC 90-FMA. Materials and Structures. The RILEM Scientific Journal. ISSN 1359-5997.

23 Tension of Reinforced Concrete Prisms. A RILEM Round Robin Investigation Arranged by TC 147-FMB. Fracture Mechanics to Anchorage and Bond. Materials and Structures. The RILEM Scientific Journal. ISSN 1359-5997.

24 For example, see Acton, F S, (1996), *Real computing made real*, Princeton Press, 259; Gershenfeld, N, (1999), *The nature of mathematical modelling*, Cambridge University Press, 344; Badii, R and Politi, A, (1997), *Complexity: Hierarchical structures and scaling in physics*, Cambridge University Press, 318.

25 Gambarova and Kakakoc, A new approach to the analysis of the confinement role in regularly cracking concrete elements. 7th SMIRT International Conference, Volume H, 1983.

26 de Borst, R, (1987), Computation of post bifurcation and post-failure behaviour of strain-softening solids, *Comput Struct*, 25, 211-224.

27 Simo, J C and Hughes, T J R, (1998), *Computational Inelasticity*, Springer-Verlag, 392.

28 Spector, D H M,(2000), *Building Linux clusters*, O’Reilly, 332.

29 Zienkiewicz, O C and Taylor, R L, (2000), *The Finite Element Method*, McGraw-Hill, 3 volumes; Crisfield, M A (1991 and 1997), *Non-Linear Finite Element Analysis of Solid and Structures*, Wiley, 2 volumes; Bathe, K-J, (1996), Finite Element Procedures, Prentice-Hall; Belytschko, T, Liu, W K and Moran, B, (2000), *Nonlinear Finite Elements for Continua and Structures*, Wiley.

30 Huerta, A and Casadei, F, (1994), New ALE applications in non-linear fast-transient solid dynamics, *Eng Computations*, 11, 317-345.

31 Belytschko, T and Tabbara, M, (1996), Dynamic fracture using element-free Galerkin methods, *Int J Num Meth Eng*, 39, 923-938.

32 Zienkiewicz, O C and Zhu, J Z, (1991), Adaptivity and mesh generation, *Int J Num Meth Eng*, 32, 783-810.

33 Ortiz, M, (1985), A constitutive theory for the inelastic behaviour of concrete, *Mech Mats*, 4, 67-93.

34 Marotti de Sciarra, G, (1997), General theory of damage elastoplastic models, *J Eng Mech*, ASCE, 123(10), 1003-1011.

35 Carol, I and Bazant, Z P, (1996), Damage and plasticity in the microplane model, *Int J Solids and Structures*, 29, 1173-1191.

36 Lee, J and Fenves, G L, (2001), A return-mapping algorithm for plastic-damage models: 3-D and plane stress formulation, *Int J Num Meth Eng*, 50, 487-506.

37 Pearce, C J, (1996), *Computational plasticity in concrete failure mechanics*, PhD Thesis University of Swansea; Tahar, B, (2000), *C_2 continuous hardening/softening elasto-plasticity model for concrete*, PhD Thesis University of Sheffield.

38 Ngo, D and Scordelis, A C, (1967), Finite element analysis of reinforced concrete beams, *J ACI*, 64, 152-163.

39 de Borst, R and Nauta, P, (1985), Non-orthogonal cracks in a smeared Finite Element model, *Eng Computations*, 2, 35-46.

40 Bazant, Z P and Belytschko, T B, Wave propagation in a strain softening bar: Exact solution, *J Eng Mech*, ASCE, 111, 381-389.

41 Oliver, J, (1989), A consistent characteristic length for smeared cracking models, *Int J Num Meth Eng*, 28, 461-474.

42 Bazant, Z P and Oh, B, (1983), Crack band theory for fracture of concrete, *Mat Struct*, RILEM, 16, 155-177.

43 Bazant, Z P and Pijaudier-Cabot, J, (1988), Nonlocal damage, localisation instability and convergence, *J Applied Mech*, 55, 287-293.

44 Muhlhaus, H B and Aifantis, E C, (1991), A variational principle for gradient plasticity, *Int J Solids and Structures*, 28, 845-857.

45 Ortiz, M, Leroy, Y and Needleman, A, (1987), A finite element method for localized failure analysis, *Comp Meth Appl Mech Eng*, 61, 189-214.

46 Askes, H, (2000), *Advanced spatial discretisation strategies for localised failure*, PhD Thesis University of Delft.

47 Rashid, Y R, Analysis of prestressed concrete pressure vessels, *Nucl Eng Design*, 7, 334-344.

48 Cope, R J, Rao, P V, Clarke, L A and Norris, P, (1980), Modelling of reinforced concrete behaviour for finite element analysis of bridge slabs, *Numerical Methods for Non-Linear Problems*, Pineridge Press, 457-470.

49 Bazant, Z P, Hauggarrd, A, B, Baweje, S and Ulm, F-J, (1997), Microprestress-solidification theory for concrete creep. II: Verification and Application, *J Eng Mech*, ASCE, 115(8), 1704-1725. Also see Isenberg, J (1993), *Finite Element Analysis of Concrete Structures II*, ASCE, 233-313.

50 Sercombe, J, Ulm, F-J and Toutlemonde, F, (1997), Viscous hardening plasticity for concrete under high rate dynamic loading, *J Eng Mech*, ASCE.

51 Stabler, J T, (2000), *Computational modelling of thermo-mechanical damage and plasticity in concrete*, PhD Thesis University of Queensland.

52 Groot, A K, de Kusters, GMA and Monnier, T, (1981), *Numerical modelling of bond slip behaviour*, Heron, 26, 1-90.

53 Cervera, M, Oliver, J and Prato, T, (1998), A thermo-chemo-mechanical model for the hydration and ageing of concrete, *Computational Modelling of Concrete Structures*, Balkema, 1, 513-522.

54 Dafalias, Y F, Bounding surface plasticity I: Mathematical foundation and hypoplasticity, ASCE, J Eng Mech, 112(9), (1986), 966-987.

55 Yazdani, S and Schreyer, H L, Combined plasticity and damage mechanics model for plain concrete, ASCE, J Eng Mech, 116 (1990), 1435-1450.

56 Desai, C S, Krempl, E, Kiousis, P D and Kundu, T (Eds.), Constitutive laws for engineering materials, 2nd Int Conf, Tucson, Arizona, Elsevier, (1987).

57 Reinhardt, H W, Joints, Fracture mechanics of concrete structures, (1989), 363-368.

58 Gawin, D, Majorana, C E and Schreflet, B A, Numerical analysis of hygro-thermic behaviour, stresses and damage of concrete at high temperature, Mech of Cohesive-Frictional Mats, 4, (1999), 37-76.

59 Krysl, P and Bittnar, Z, Parallel explicit finite element solid dynamics with domain decomposition and message passing: dual partitioning scalability, Computers and Structures, 79(3), (1999).

60 Bettess, P, Infinite elements, Penshaw, (1992).

61 Wolf, J P and Song, C, Finite-element modelling of unbounded media, Wiley, (1996).

62 Jefferson, A D, Plastic-damage model for interfaces in cementitious materials, ASCE, J Eng Mech, 124, (1998), 775-782.

63 Gutierrez de la Merved, M A, Objective simulation of failure in heterogeneous softening solids, PhD, University of Delft, (1999).

64 Etse, G and Willam, K, A fracture energy formulation for inelastic behaviour of plain concrete, ASCE, J Eng Mech, 120(9), (1994), 1983-2011.

65 Sluys, L J, Wave propagation, localization and dispersion in softening solids, PhD, University of Delft, (1992).

66 Crisfield, M A, Non-linear finite element analysis of solids and structures: Advanced topics, Wiley, (1997).

67 Wiggers, P and Simo, J C, A general procedure for direct computation of turning and bifurcation points, Int J Num Meth Eng, 30, (1990), 155-176.Lackner, R and Mang, H, Simulation of local failure of concrete plates on the basis of error control, 3rd Int Conf Fracture, Mechanics of Concrete and Concrete Structures, Gifu, Japan, Aedificatio, (1998).

68 Khennane, A, Mathematical model for the behaviour of concrete at elevated temperatures, PhD, University of Queensland, (1991).

69 Wells, G N, Discontinuous modelling of strain localisation and failure, PhD, University of Delft, (2001).

70 Mazars, J, Ramtani, S and Berthaud, Y, An experimental procedure to delocalize tensile failure and to identify the unilateral effect of distributed damage, Mazars and Bazant (Eds.) Cracking and Damage: Strain Localization and Size Effect, Elsevier, (1989), 55-64.

71 Fernandez-Vega, J, Tensile properties of heat damaged concrete, PhD, University of Sheffield, (2001).

72 CEB, RC elements under cyclic loading, SOTA report, Thomas Telford, (1996).

73 Isenberg, J (Ed.) , Finite Element Analysis of Concrete Structures II, ASCE, (1993).

74 Mesmar, S T On the use of Dyvaut-Lions viscosity as a regularisation technique for hardening/softening constitutive models, PhD, University of Sheffield, (2000).

75 Bazant, Z P, Current status and advances in the theory of creep and interaction with fracture, Creep and shrinkage of concrete, Bazant and Carol (Eds.), E F N Spon, (1993), 291-307.

76 Khoury, G A, Grainger, B N and Sullivan, P J E, Transient thermal strain of concrete: Literature review, conditions within specimen and behaviour of individual constituents, Mag Concrete Res, 37, (1985), 131-144. Karihaloo, B L and Santhikumar, S, Time-dependent behaviour of cracked and aged concrete, Mechanics of quasi-brittle material and structures, Pijaudier-Cabot, Bittnar and Gerard (Eds.), Hermes, (1999), 139-166.

77 Xi, Y, Suwito, A, Wen, X, Meyer, C and Jin, W, Testing and modeling alkali-silica reaction and the associated expansion of concrete, Mechanics of quasi-brittle material and structures, Pijaudier-Cabot, Bittnar and Gerard (Eds.), Hermes, (1999), 217-232.

78 Barrett, R, Berry, M, Chan, T F, Demmel, J, Donato, J, Dongara, J, Eijkhout, V, Pozo, R, Romine, C and van de Vorst, H, Templates for the solution of linear systems: Building blocks for iterative methods, SIAM, (1993).

FIGURES

1 Behaviour of Concrete in Compression

2 Overlapping Thicknesses at Joints of Shell Elements

3 Development of Secondary Cracks

4 Tensile Behaviour of Concrete

5 Representation of Unloading / Reloading

6 Reduction in Shear Modulus With Increasing Crack Strain

7 Spring and Damper Analogy For Representing Creep & Relaxation

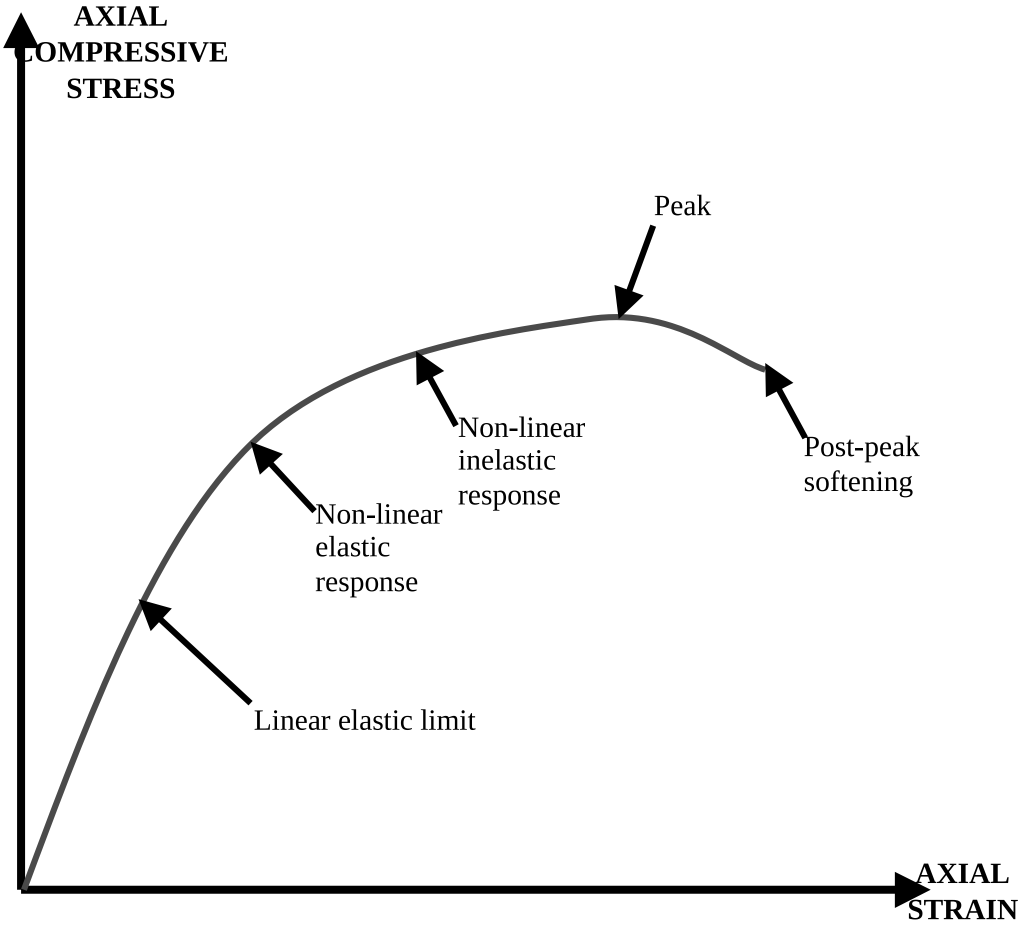


Figure 1 Behaviour of Concrete in Compression

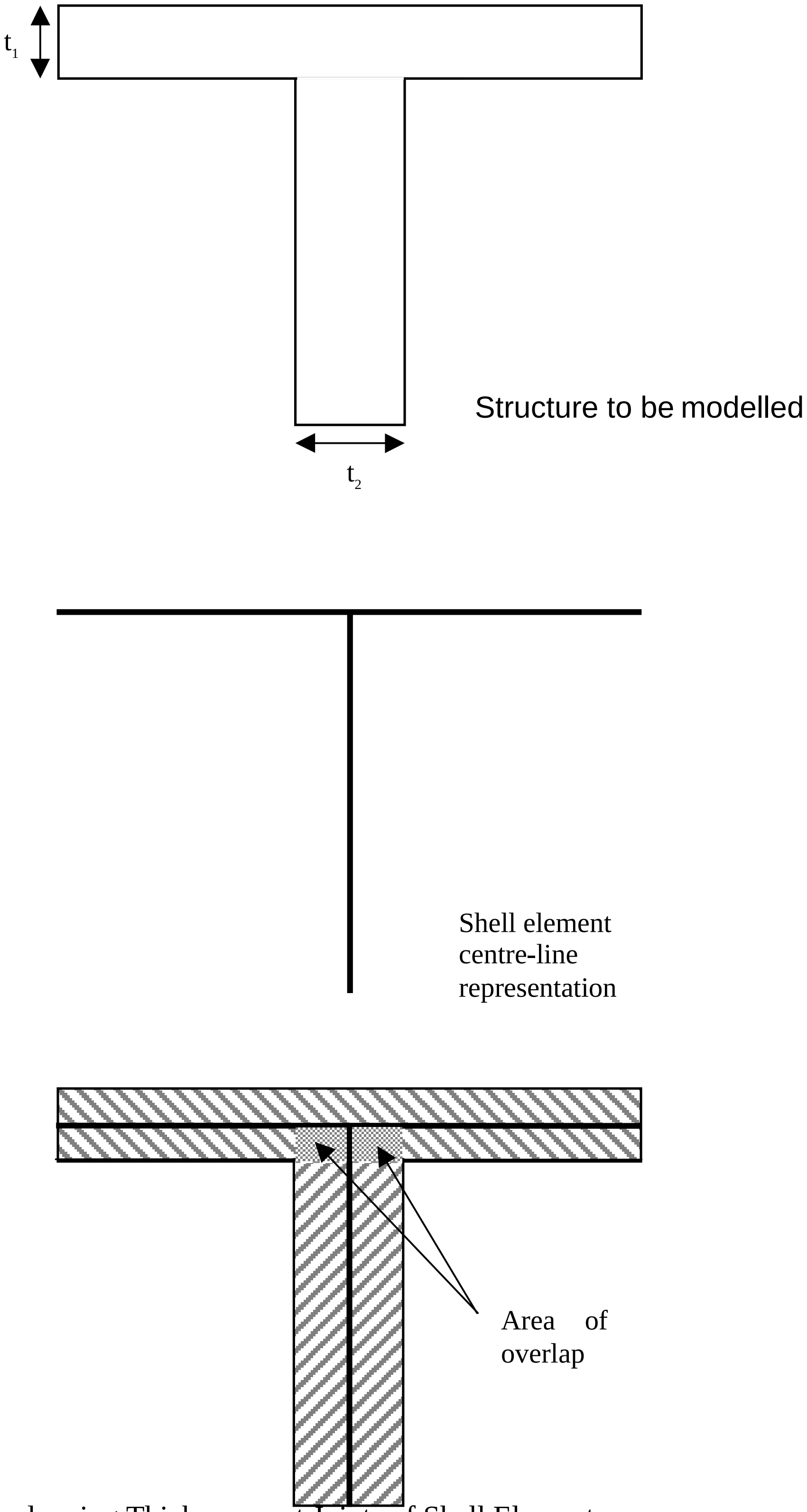
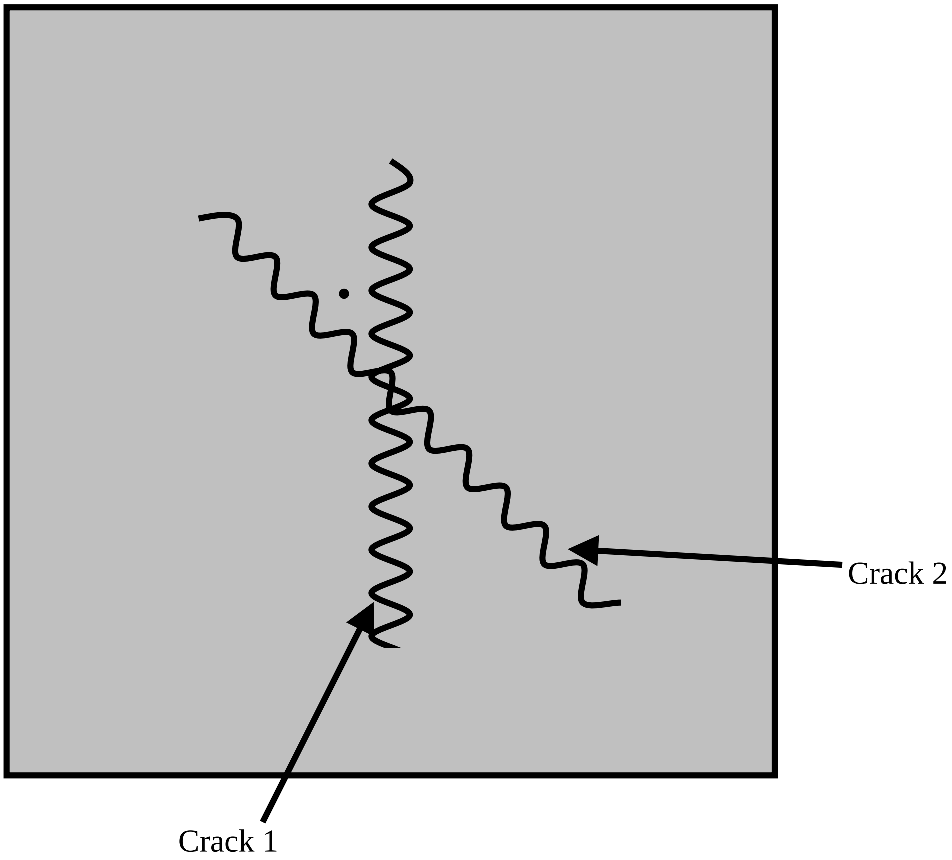


Figure 2 Overlapping Thicknesses at Joints of Shell Elements



- cannot be less than some threshold value (say 60°)

Figure 3 Development of Secondary Cracks

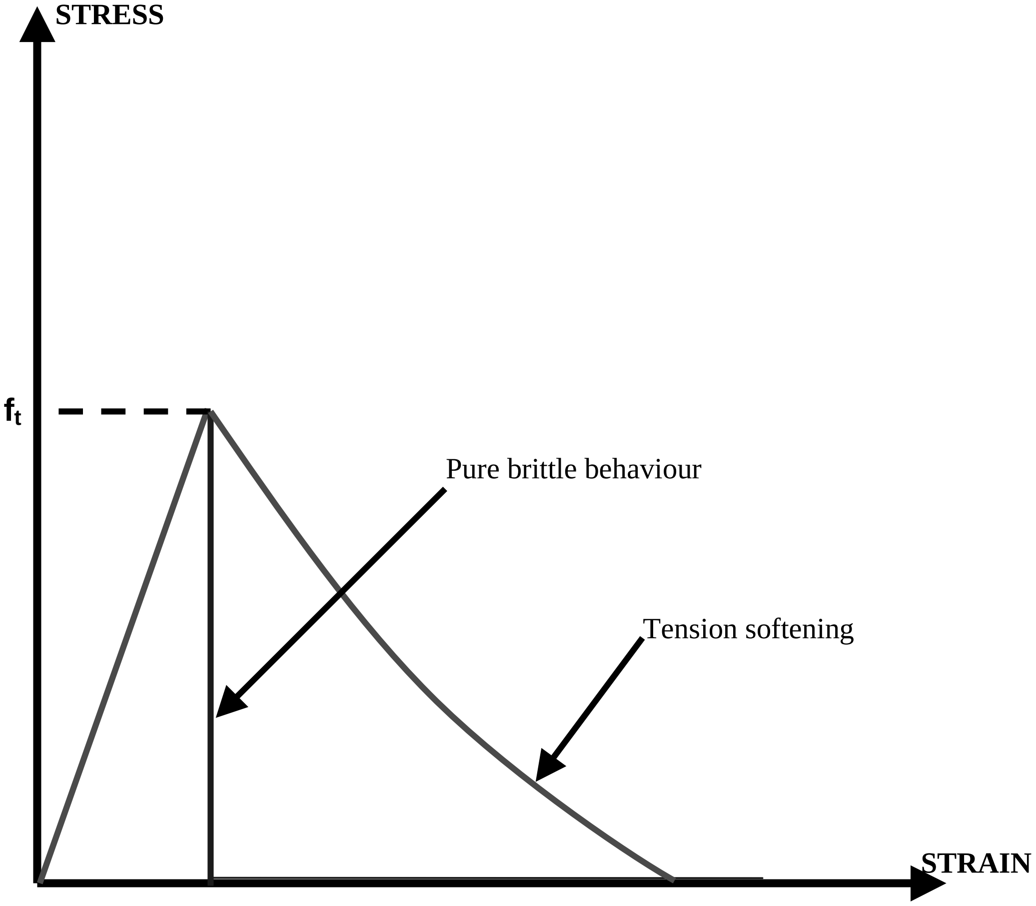


Figure 4 Tensile Behaviour of Concrete

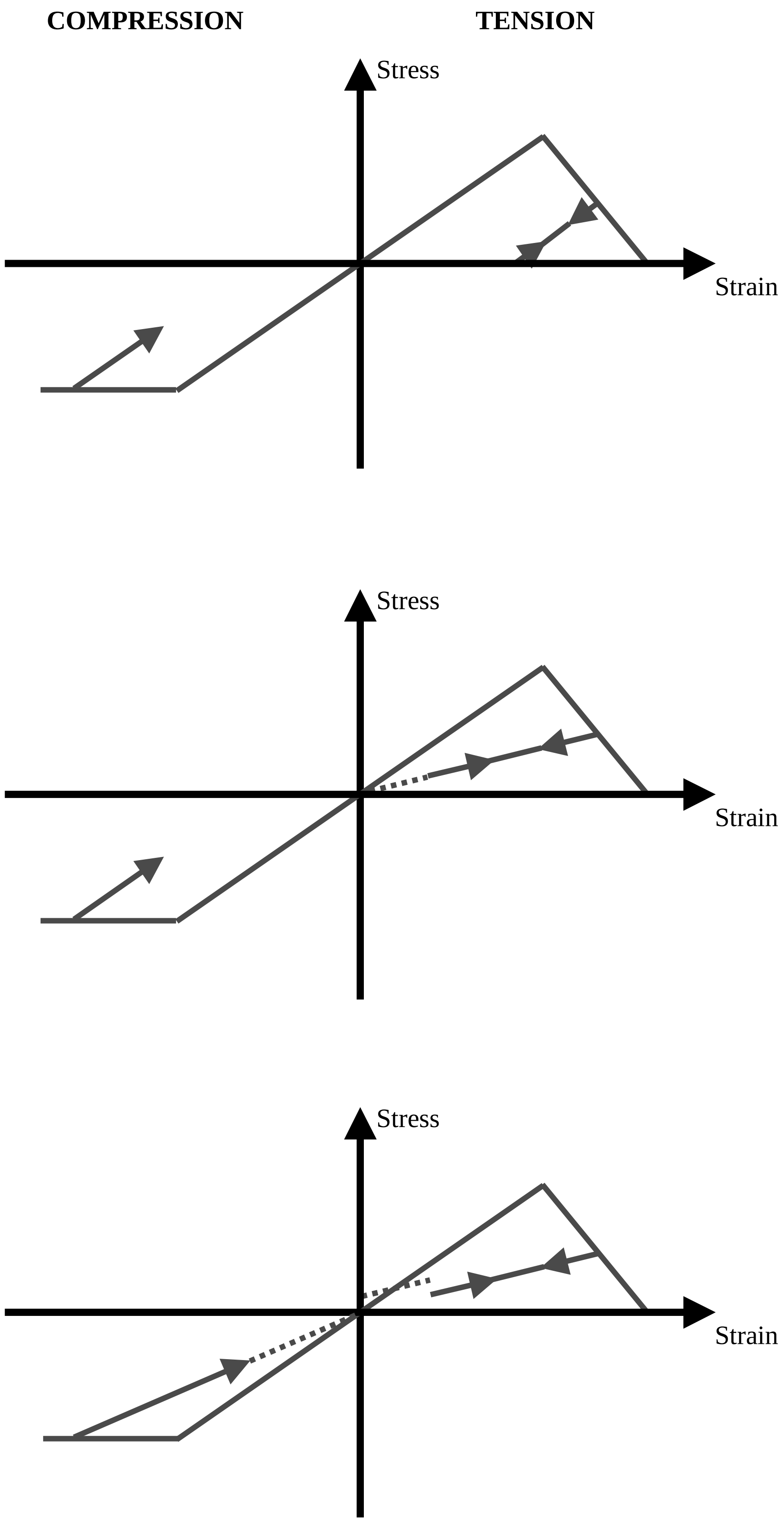


Figure 5 Representation of Unloading / Reloading

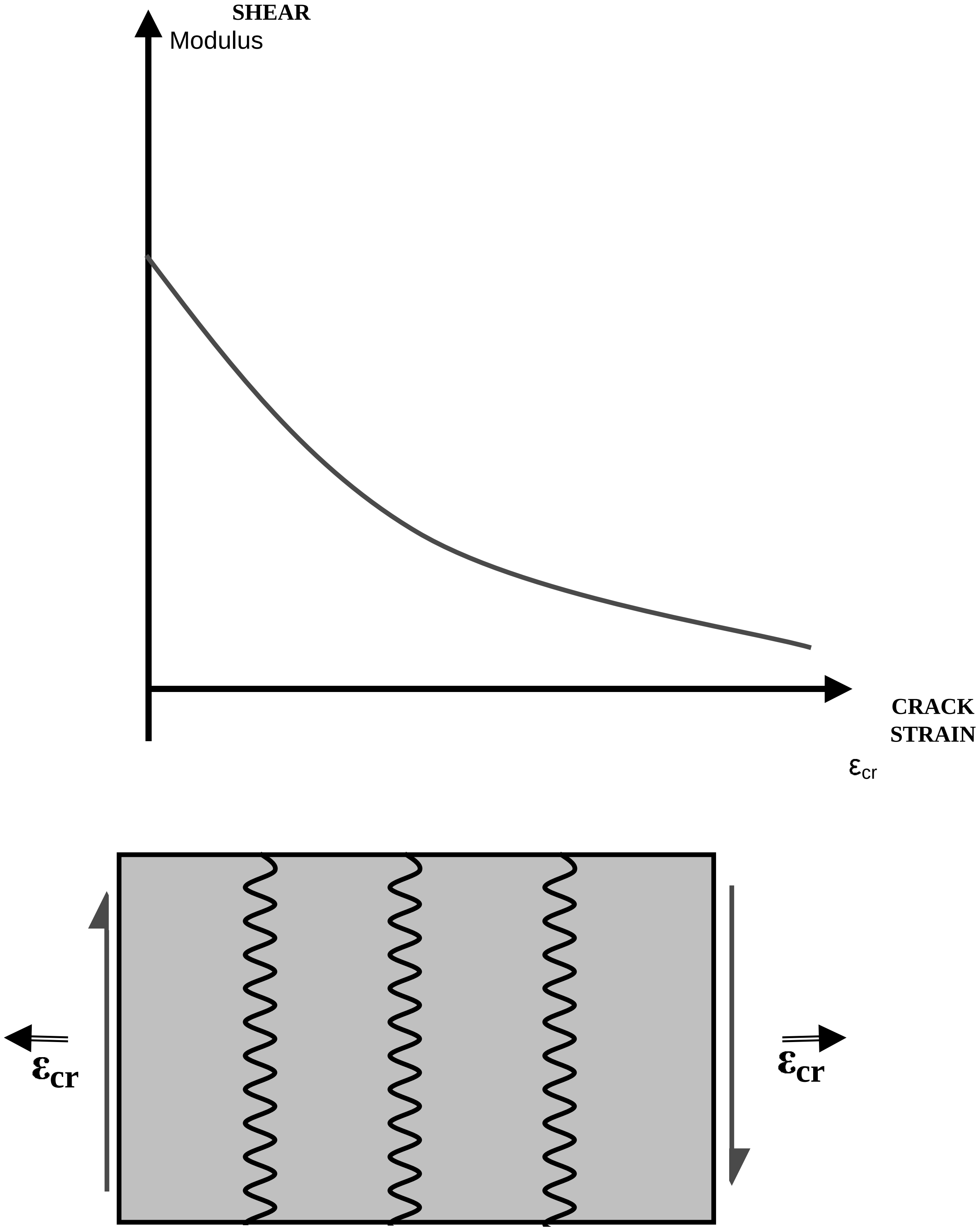
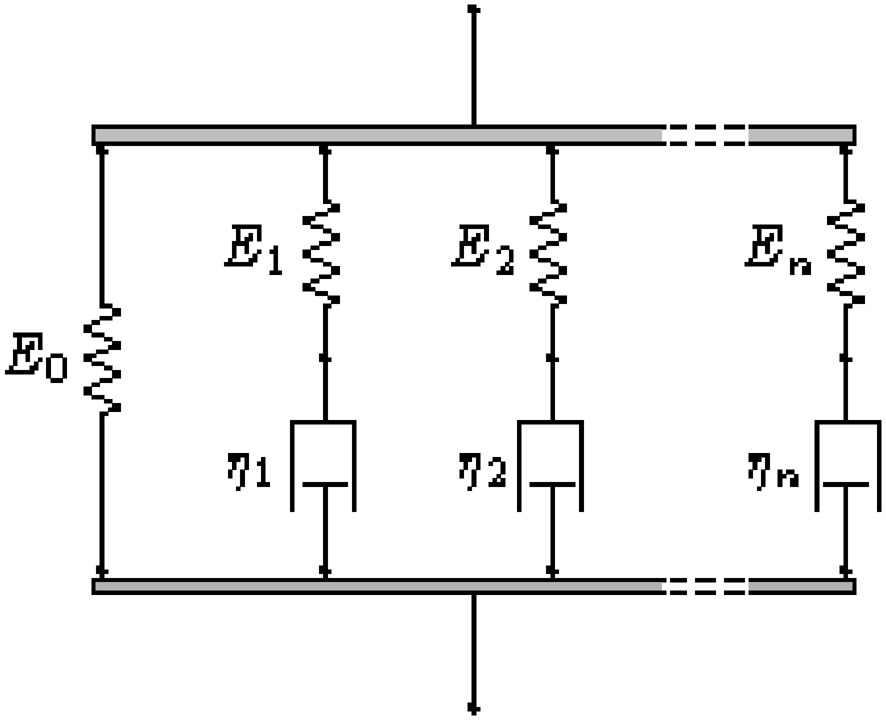
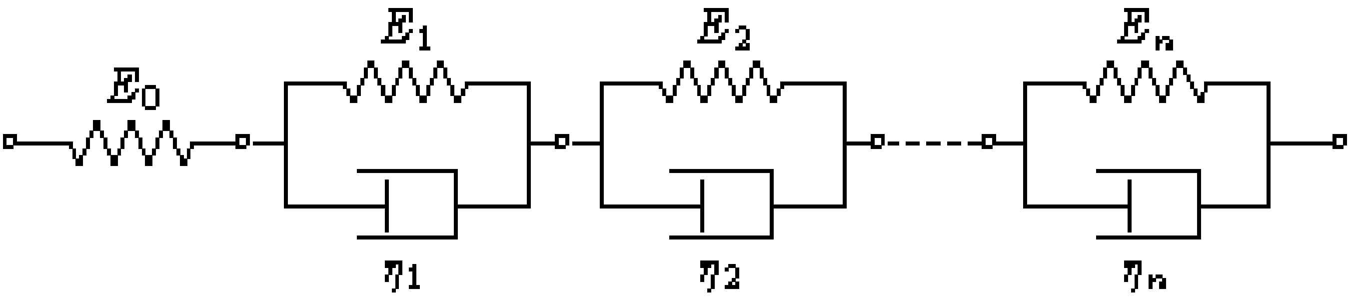


Figure 6 Reduction in Shear Modulus With Increasing Crack Strain



Maxwell Chain



Kelvin Chain

Figure 7 Spring And Damper Analogy For Representing Creep & Relaxation

Appendix A Details Of UK Stations

This Appendix A gives further description and information relating to UK containments and vessels to illustrate some areas of typical details.

Containments

The UK PCC for Sizewell B is double walled with a steel liner to the inner primary containment structure and can be characterised as thin walled. The text that follows describes the UK PCC in some detail with Figure A1 showing a typical cross section.

The inner structure has a 1.4m thick barrel, a 1.0m thick hemispherical dome and is supported on a substantial concrete base (minimum thickness 1.7m, typically 4m). The steel liner to the inner dome and barrel is continuous with a liner cast into the base. The dome and barrel are of prestressed concrete construction with the base being conventionally reinforced.

The prestressing is arranged to apply a state of vertical and circumferential pre-compression within the barrel walls and an equivalent state of the orthogonal pre-compression within the dome. Vertical tendons are provided within the barrel walls with the tendons extending and turned across the domed roof to form a rectangular double layer pattern across the dome. Individual vertical/dome tendons are stressed from both ends in galleries beneath the walls. Horizontal/circumferential tendons are provided within the barrel wall extending between and stressed at external buttresses 240° apart.

The secondary containment structure is of reinforced concrete construction. A secondary dome, 0.3m thick is supported by an annular cantilever from the top of the inner barrel wall. The remainder of the secondary containment, essentially to the barrel wall is provided by adjacent structures that surround the containment up to the cantilever level.

The steel liner is typically 10mm thick and is attached to the containment concrete by closely spaced shear studs. The liner is not considered (by design) to contribute to the containment strength.

There are several penetrations through the containment wall, with the equipment access hatch at 5.8m diameter, two personnel air locks and various service penetrations. These are all sealed to the containment wall/liner to maintain the pressure boundary. The larger penetrations have an influence on the wall design and local tendon layout.

The wall/base junction is an area of particular interest in the containment design. This area is a junction between the thin prestressed concrete walls and substantial reinforced concrete base with a complex distribution of applied (LOCA pressure and prestress) and associated internal forces.

The Sizewell containment is supported by a substantial reinforced concrete base which in turn is founded on mass concrete on the underlying dense sands of the Norwich Crag Deposits.

There are several voids and recesses within the concrete base with some substantial reinforced concrete walled structures built above the base. These are configured to suit plant layout and shielding requirements, concentrated local to the reactor pressure vessel. Such voids, recesses and walls can have an influence on the structural behaviour of the base.

Vessels

In the UK, there are nine power station sites with PCPV's with each site having two vessels. The 18 vessels can be considered as three generic types:

- i) short vertical cylinders with flat ends and cylindrical cavities (12 No.)
- ii) short vertical cylinders with flat ends and spherical cavities (2 No.)
- iii) short vertical cylinders with flat ends, cylindrical cavities and with podded boilers within the cylinder walls (4 No.)

Figure A2 shows a typical cross section for a type i) vessel.

The vessels can be characterised as thick walled (3.4 to 6.4m) with thick top and bottom slabs (3.4 to 7.5m). Prestressing tendons are distributed throughout the vessel walls to apply a state of vertical and circumferential pre-compression within the walls and a state of radial and circumferential pre-compression within the top and bottom slabs. The various prestressing systems that are used fall into the following generic layouts:

- i) alternate rows of helical tendons, running clockwise and anti-clockwise (Figure A3 shows such a typical tendon layout).
- ii) vertical tendons combined with external circumferentially wound tendons.
- iii) vertical tendons combined with circumferential tendons provided in discrete lengths within the vessel walls and slabs.

There are areas within the vessels where conventional steel reinforcement is provided. This is generally to distribute and minimise cracking, particularly at the outer surface. Such reinforcement is not considered to contribute to the overall vessel strength.

The inside surface of the PCPV's are lined with a mild steel membrane (12 to 38mm thick) which is attached to the vessel concrete by closely spaced shear studs. The liner is not considered (by design) to contribute to the vessel strength. Attached to the vessel face of the liner are a series of pipes carrying cooling water. The gas face of the liner is covered with thermal insulation. The cooling system and insulation act together to limit concrete temperatures, with typical operational vessel concrete temperatures at 50 to 70°C.

There are numerous penetrations through the vessel wall and slabs which permit the passage of services, equipment and personnel through the vessel boundary. The penetrations are essentially tubes through the vessel and are sealed to the liner at one end to maintain the pressure boundary. Substantial restraint structures are provided to resist the effects of the vessel pressure acting on the penetrations. The penetrations vary in size and spacing and in some areas have a significant influence on vessel behaviour.

The behaviour of the vessel at the junction between the wall and top and bottom slabs is of particular interest in the design of vessels.

The vessels are supported on substantial foundations. The vessels are either founded directly on the underlying strata via a circular raft or are supported directly by a reinforced concrete sub-structure via a system of annular bearings. The substructure is in turn supported by the underlying strata. The degree to which the vessel ‘interacts’ with the underlying strata is influenced by several factors with the least degree of interaction achieved where vessels are supported by a substantial substructure founded on competent bedrock.

Figure A1 Section Through Sizewell B Containment Building.

Figure A2 Section Through Heysham 2 and Dungeness B Vessels.

Figure A3 Typical Vessel Prestressing Tendon Layout.

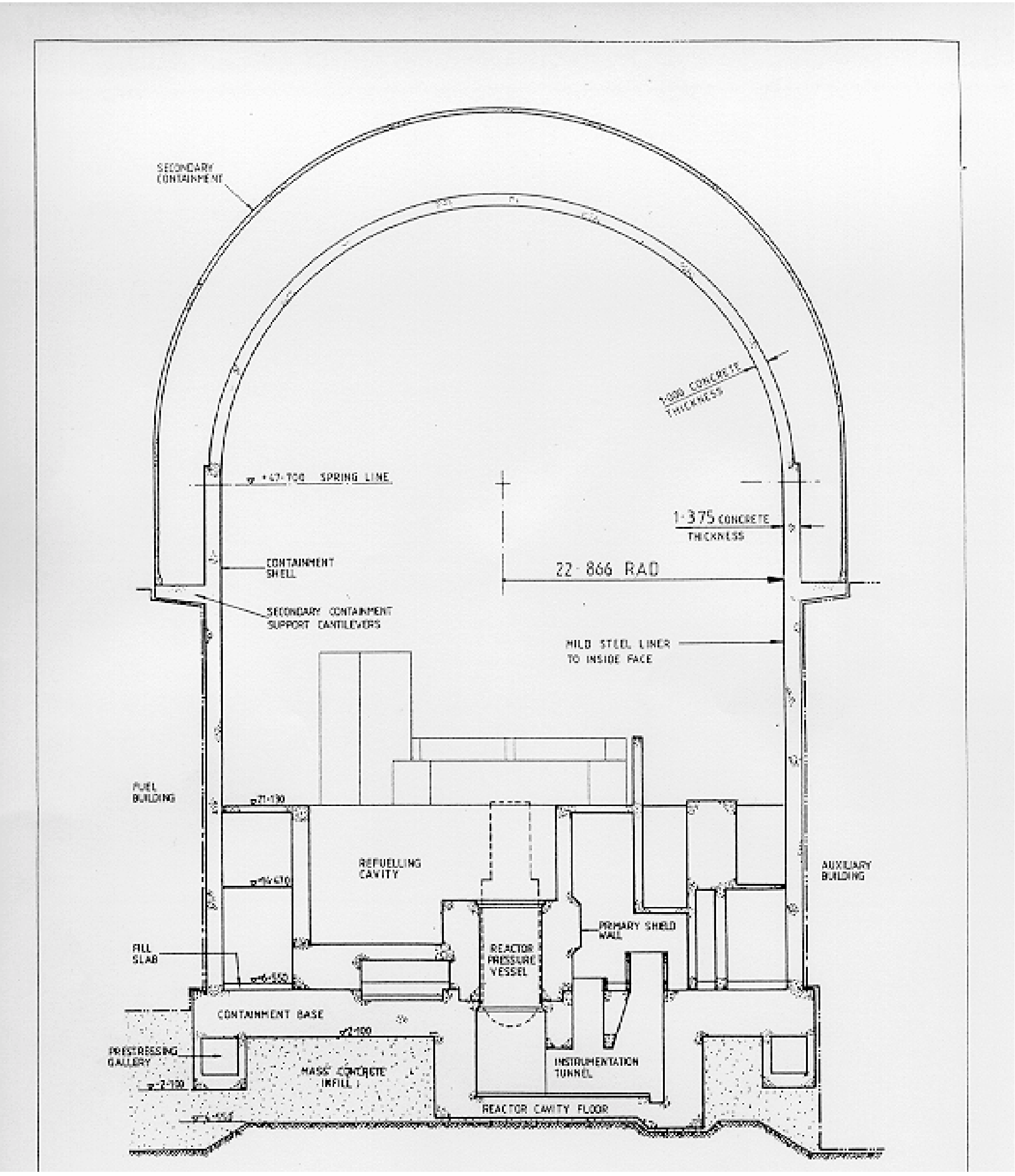


Figure A1 Section Through Sizewell B Containment Building

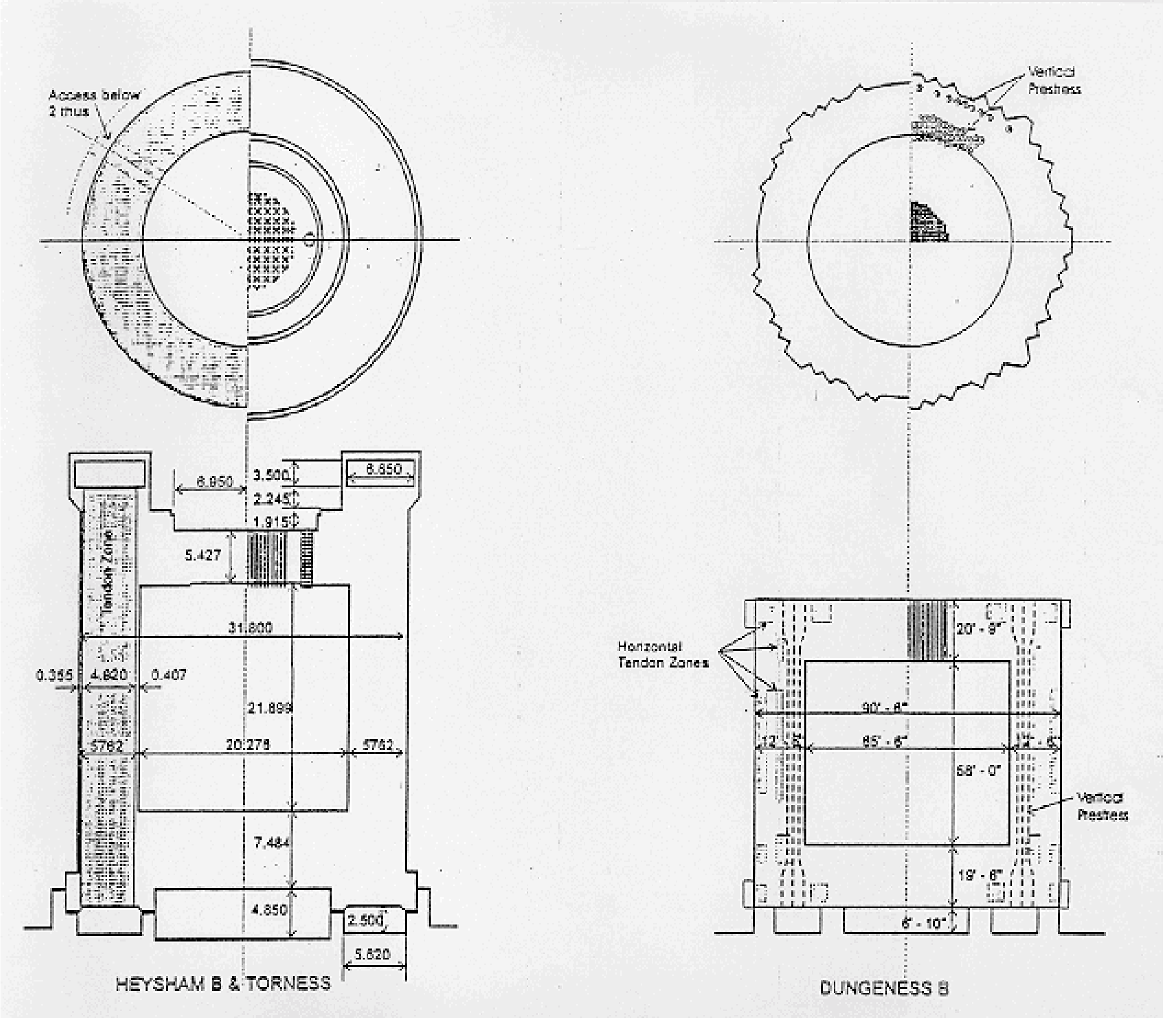


Figure A2 Section Through Heysham 2 and Dungeness B Vessels

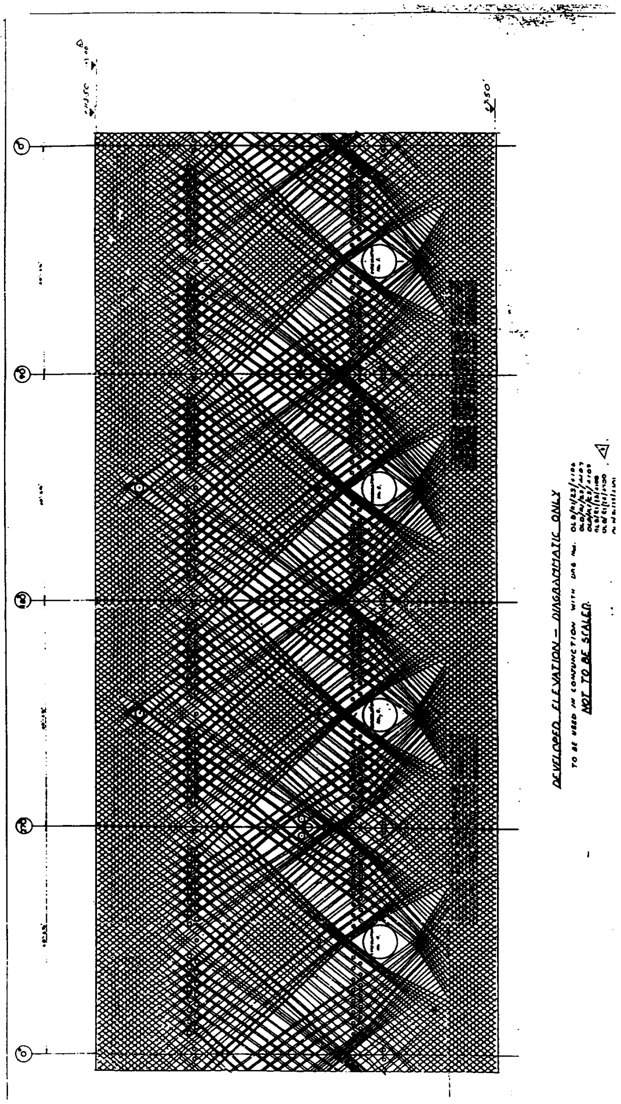


Figure A3 Typical Vessel Prestressing Tendon Layout