Structural Integrity Assessment Procedures

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ABSTRACT

This paper describes a family of structural integrity assessment procedures which are being developed in the UK. In addition to the well known R6 methodology, the procedures cover dynamic loads, pressure boundary failure, impact, seismic loading, and structures operating at high temperature. An expert system which is under development to assist the user is also described.

1 INTRODUCTION

Any change in the physical state or the operating regime of existing nuclear plant requires the Safety Case of the plant to be considered. It is therefore necessary to assess the structural integrity of plant, taking into account plant modifications, defects, ageing phenomena, and changes in operating regimes or regulatory environment. Although each assessment could be carried out in an ad hoc manner, the use of standardised procedures leads to greater efficiency, and improves the acceptability of the assessment to regulators.

This approach to assessment is well established in the UK for defective structures which could potentially fail by any combination of fast fracture and plastic collapse. The R6 procedure (Milne et al 1986) is used routinely as the basis for safety cases, and is also used widely in any other countries. R6 is written as a procedure, that is as a series of steps and logical decisions, which must be followed in a systematic manner. The outcome of an assessment using the procedure is the conclusion that the structure either has, or has not, been demonstrated to be safe.

The benefits which Nuclear Electric and its predecessor the Central Electricity Generating Board have derived from the R6 procedure are substantial, and the procedural approach to structural assessment is being extended to cover other potential failure modes. A family of procedures is being developed, which includes:

- R2 Response and integrity of structures to unsteady loads.
- R3 Assessment procedure for pressure boundary failure and impact.

- R4 Response and integrity of nuclear plant to seismic loading.
 R5 Assessment procedure for the high temperature response of structures.
 R6 Assessment of the integrity of structures containing defects.

The following sections describe the scope and the current status of each of the procedures. Fuller details of each procedure are being published separately. A final section describes an integrated software system under development, which combines an expert system implementation of the procedures themselves, with the BERSAFE engineering analysis system which carries out detailed calculations.

2 UNSTEADY LOADS - R2

Most nuclear plant components are subject to vibrational loads in normal operation. There is therefore a requirement to assess the life of components subject to vibrational loads, for the design of new plant, for the modification of existing plant, or for justifying continued operation when evidence of damage has been discovered from plant inspections. The scope of the assessment procedure is based on a framework proposed by Allen et al (1985) and aims to:

- ensure that all appropriate fluid dynamic and mechanical excitation mechanisms are considered and properly assessed
- provide a comprehensive and logically based assessment route from excitation mechanism through to damage quantification
- improve the efficiency with which assessments are made by structuring the route through initial simplified bounding calculations, leading to more detailed analysis only where required to meet target component life.

The procedure has been sub-divided into a number of 'stand-alone' volumes each of which deals with different aspects of the assessment. Some volumes are complete but awaiting peer review, and others are under development (see Table 1). Each volume draws on existing state-of-the-art knowledge and databases, and is independently verified by Peer Review. As an aid to improving efficiency and quality assurance of applying the procedures, the volumes are currently being computerised.

Table 1. Current Status of R2 Volumes

Vol. 1:	Overview	Under development
Vol. 2:	Fatigue Life of Defective Structures *	Completed (awaiting Peer Review)
Vol. 3:	Fatigue Life of Non-Defective Structures *	Completed (awaiting Peer Review)
Vol. 4:	Linear System Response *	Complete draft
Vol. 5:	Wear	Partially complete
Vol. 6:	Flow Induced Vibrations	Under development
* Note - computer modules undergoing or completed field trials		

3 IMPACT ASSESSMENT PROCEDURE - R3

The R3 Impact Assessment Procedure (Fullard et al 1991) brings together methods which are partly based on an accepted interpretation of experimental data and partly on theoretical and numerical studies. The modes of failure of plant or other sources explicitly considered in the first issue of R3 include pressure boundary failure giving rise to projectiles or jets and blast, hot gas or steam release giving rise to global pressure and temperature transients, producing thermal damage, rotating machinery failure giving rise to projectiles, wind borne projectiles and aircraft crash.

The modes of damage considered are:

- (1) whipping pipe impact leading to target pipe local damage or global collapse
- (2) steel or concrete target perforation or penetration into the impact face of a concrete target
- (3) concrete scabbing
- (4) impact resulting in a plug of concrete target being formed, and
- (5) global distortion of non-pipe targets by impact or over-pressure loading.

Correlations of experimental data have been used for characterising missiles generated by rupture of gas-pressurised vessels. Similarly, the procedures for impact on concrete targets have been derived from the results of extensive series of experiments and analyses carried out by organisations world-wide. For steel targets, perforation assessment employs high velocity empirical correlations which have been used in the nuclear industry for as much as three decades.

Missile generation from rotating machinery failure is treated theoretically. Wind borne projectiles are also treated theoretically. Much of the procedure for determining the characteristics of a whipping pipe is theoretically based. The approach makes use of simplifications which have been used in design against pipewhip in the UK and elsewhere, supplemented by the use of non-linear finite element methods.

4 SEISMIC LOADING - R4

The R4 procedure covers the response and integrity of nuclear plant to seismic loading. The fact that most nuclear plant in the UK was constructed before seismic design was required has led to an approach which distinguishes between design for new plant, design for modifications to plants which were not originally seismically designed, and assessment of existing plant. In the case of existing plant, the procedure is intended to exploit as fully as possible the known capability of many structures which have not undergone seismic design to withstand earthquakes larger than those expected in the UK. Within all of these categories, R4 will address all aspects of the assessment of response and failure criteria in earthquakes. It will not, however, cover the assessment of seismic hazard: a well-established methodology for this has already been established in the UK by the Seismic Hazard Working Party (1988) and applied to a number of sites designed for future PWR plants. The following parts of R4 have been planned:

- R4 Part 1 This covers modifications to existing plant. The guidelines to which Nuclear Electric currently works are in the process of being developed into a form suitable for the procedure.
- R4 Part 2 This covers assessments of existing plant and is currently

being written to reflect the safety reviews at present being carried out on Nuclear Electric plants and the procedures developed in the USA which make extensive use of walkdowns and experience data.

R4 Part 3 This will cover design of new plant and will be the last part to be completed. However, it is expected that the procedure will adhere closely to the methods and criteria used in the design of Sizewell 'B' plant (Carmichael and Heath, 1990).

5 STRUCTURES AT HIGH TEMPERATURE - R5

R5 is a procedure for assessing the integrity of structures operating at high temperatures. It has been developed to remove conservatisms in elastic analysis methods without necessarily requiring the complexity of full inelastic analysis. This has been achieved by the use of reference stress and shakedown concepts. In writing R5, the opportunity has been taken to extend the limited code treatments of welds and to address defect assessments. R5 has been produced in seven volumes as follows:

- Volume 1: Overview
- Volume 2: Analysis/Assessment Methods for Defect-Free Structures
- Volume 3: Creep-Fatigue Crack Initiation
- Volume 4: Assessment of Defects Under Steady Loading
- Volume 5: Creep-Fatigue Crack Growth
- Volume 6: Dissimilar Metal Welds
- Volume 7: Behaviour of Similar Welds

The first issue of R5 was produced in 1991 (Goodall et al, 1991) and includes volumes 1 - 6 above. Volume 7 will be added to the procedure in 1991.

The first issue was based on a number of documents which had been produced as internal reports and subject to Peer Review and trial applications within Nuclear Electric and the former Central Electricity Generating Board. The procedures have also been published externally in journals and at conferences. Further details of the R5 method, including examples illustrating its application to components, are contained in another paper at this Conference (Goodall and Ainsworth, 1991).

6 ASSESSMENT OF STRUCTURES CONTAINING DEFECTS - R6

The R6 Procedure for the Assessment of the Integrity of Structures Containing Defects considers the interaction between failure arising as a consequence of linear elastic fracture mechanics (LEFM), and by plastic collapse, and combines them via a Failure Assessment Diagram (FAD). The primary underlying philosophy behind R6 is the assessment of failure avoidance, NOT failure prediction. A number of assumptions are built into the procedure which make it inherently conservative. Three Options are available to the user with increasing levels of complexity, and reducing degrees of conservatism.

To use R6 requires knowledge of stress intensity factors, plastic yield loads and fracture toughness data. The Procedure does not make specific recommendations on what data to use, but advice is given and sources of information are referenced. The role of secondary stresses such as thermal or residual stresses are specifically addressed, as is mixed mode loading, and the advice on the treatment of both of these topics has recently been updated.

Although R6 was developed to assess failure avoidance, failure prediction is important in some areas such as Leak before Break (L-b-B). A new appendix has been added to R6 to cover such requirements. Other developments in fracture assessments include the use of probabilistics, and again new developments in this area have been incorporated.

Wherever possible R6 has been fully validated and data are included in the document. In those areas where it is necessary to make pessimistic judgements, this is identified. In some areas further work is in hand to reduce the degree of pessimism currently applied.

7 COMPUTER AIDED ENGINEERING ASSESSMENTS

The practical application of the Assessment Procedures is often a major task requiring a clear understanding of the rules implicit in the Procedures together with methods for idealising the structural loads, component mechanics and failure modes. The need for accuracy, correct interpretation of the Procedures and high Engineer productivity point to the need for computer tools to support application of the Procedures.

The approach adopted has been to develop a common User Interface which can be used to address the program modules which perform the calculations needed. The User Interface is written in the declarative language PROLOG and it incorporates extensive graphics facilities to enable problems and results to be displayed in the most convenient form. The suite includes a number of finite element programs for modelling both fluid and structural characteristics. The Nuclear Electric program, FEAT is used to model the complex turbulent flows found in many reactor applications and hence to derive pressure and temperature loads. Structural analysis is undertaken with BERSAFE. This program can be used to model both elastic and inelastic crack growth as well as to undertake the inelastic analysis, dynamic and other general stress analysis needed.

This approach is exemplified with a current project to automate R6 (the procedure for the assessment of defective structures) using the program FRACTURE as the computational base. FRACTURE2 contains a library of solutions for the calculation of plastic collapse loads and stress intensity factors, characterised by the parameters K_r and L_r .

Matching a particular problem to the appropriate library solution requires considerable judgement and experience. The FLEX* expert and system tool kit (implemented using Berkeley Prolog), is used to encapsulate these skills. The user progresses through several "themes" to identify loading conditions, material properties and appropriate geometries, the FLEX based decision aid guiding his choices (Figure 1). When the conditions have been adequately defined, data is passed automatically to FRACTURE2 for the computer intensive calculations, the results being returned for display on an R6 diagram. A similar approach to computerisation is being adopted for other assessment procedures.

8 CONCLUSIONS

This paper has outlined the structural integrity assessment procedures under development in the UK. Computer software is being developed to assist the user of these procedures.

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* Trademark of LPA (Logic Programming Associates)

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FIG. 1. THE COMPUTER-AIDED R6 SYSTEM