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NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

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FINITE ELEMENT ANALYSIS OF DEGRADED CONCRETE STRUCTURES

Workshop Proceedings

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ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

Pursuant to Article I 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) and the Republic of Korea (12th December 1996). 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 all OECD Member countries except New Zealand and Poland. The Commission of the European Communities takes part in the work of the Agency.

The primary objective of the NEA is to promote co-operation among the governments of its participating countries in furthering the development of nuclear power as a safe, environmentally acceptable and economic energy source.

This is achieved by:

- *encouraging harmonization of national regulatory policies and practices, with particular reference to the safety of nuclear installations, protection of man against ionising radiation and preservation of the environment, radioactive waste management, and nuclear third party liability and insurance;*
- *assessing the contribution of nuclear power to the overall energy supply by keeping under review the technical and economic aspects of nuclear power growth and forecasting demand and supply for the different phases of the nuclear fuel cycle;*
- *developing exchanges of scientific and technical information particularly through participation in common services;*
- *setting up international research and development programmes and joint undertakings.*

In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has concluded 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

Principal Working Group 3 of the CSNI 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 structures was prepared during 1995 by a task group to initiate activities in this field under PWG3. This recommended that workshops be held on the following topics:

- First priority
  - Loss of pre-stressing force in tendons of post-tensioned concrete structures (workshop held at Civaux, August 1997)
  - In-Service Inspection techniques for reinforced concrete structures having thick sections and areas not directly accessible for inspection (workshop held at Risley, UK, November 1997)
- Second priority
  - Response of degraded structures, including Finite Element analysis techniques (subject of this workshop)
  - Viability of development of performance-based database (it has been decided not to pursue this)
- Third priority
  - Instrumentation and monitoring (workshop will be held in Brussels in March 2000)
  - Repair methods (to be addressed later)
  - Criteria for condition assessment (to be addressed later).

A status report on the seismic behaviour of structures was prepared during 1996 in a similar fashion, which proposed the following topics in this area:

- Re-evaluation of existing facilities and assessment beyond design basis (a report on re-evaluation has been issued)
- Validation of analysis methods
  - A seismic shear wall benchmark exercise has been carried out, and two more are planned to start in 2000, on piping and structure-structure interaction
  - This workshop jointly held with the concrete sub group also addresses this issue
- Engineering characterisation of seismic input (workshop to held in the USA in November 1999)
- Ageing effects (a short summary statement is being prepared by the group)
- Piping analysis and design (it has been decided that this is now of less interest).

This workshop addresses both static analysis (mainly of interest to the sub group on the ageing of concrete structures) and dynamic analysis (mainly of interest to the sub group on the seismic behaviour of structures).

The complete list of CSNI reports, and the text of reports from 1991 on, is available on http://www.nea.fr/html/nsd/docs/

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SESSION No. 1

USE OF FINITE ELEMENT ANALYSIS IN SAFETY ASSESSMENTS

Purpose:

A keynote address was prepared to provide an overview of the historical development of finite element methods applied to concrete structures, from the 1960's to present.

Additional papers were prepared to provide a regulatory perspective on the use of finite element analysis in safety assessments. The authors were requested to discuss how regulatory bodies ensure the validity of finite element analyses conducted to meet licensing-basis safety criteria.

Summary:

Over the past forty (40) years, advances in the state-of-the-art for finite element modeling and analysis has been partly driven by the need to predict the complex behavior of concrete structures, not only for design but also for safety evaluation of accident-challenged and degraded concrete structures.

The paper by Y. R. Rashid, R.A. Dameron and R.S. Dunham provided an overview of the historical development of finite element methods applied to concrete structures and served as an appropriate starting point for this workshop. It provided an analytical perspective on degradation and discussed the evolution of material-behavior modeling and structural analysis. It also presented two example analyses of damaged structures.

Following the keynote address, four papers were presented which provided some regulatory perspectives on the use of finite element analysis in safety assessments.

The paper by Peter Zwicky and Daniel Kluge discussed the experience with finite element methods for safety assessments in Switzerland. Typical problems and discussions were presented, as well as representative review practice examples. The Swiss guidelines do not regulate the procedure for finite element analysis. The review approach depends on the main review concern and typically includes independent analysis, use of simpler models for sensitivity analysis or use of more sophisticated models to investigate special features.

The paper by G. Dundalis, E. Narvydas and E. Uspuras presented the structural analysis results of the RBMK-1500 Accident Confinement System (ACS) for the Ignalina Nuclear Power Plant. The ACS compartments were analyzed by employing the ALGOR and NEPTUNE finite element computer codes. The ALGOR code was used for linear analysis. For some of the compartments, the analysis results indicated that maximum principal stresses in the rebars were above the yield strength. For these compartments, additional analyses were performed using the NEPTUNE code. This non-linear code was specifically developed to model reinforced concrete structures stressed to their material limits. The analysis demonstrated that the structural integrity of the compartments will be maintained under the Design Basis Accident (DBA).

The paper by J.M. Rambach, G. Nahas, G. Grillon, and N. Chretien presented some tools developed using the CASTEM 2000 finite element code to better understand the behavior of degraded concrete structures. The concrete behavior is represented by the Ottosen crack model and the liner, tendon, and rebar behavior is represented by elasto-plastic laws. The report demonstrated the feasibility of using the code to understand the behavior of prestressed concrete containments under severe accident loading. It was noted that the Ottosen model cannot predict the exact location of cracks nor the distance between successive cracks. However, this aspect will soon be developed in the CASTEM 2000 code. The paper by I.V. Kaliberda, S.S. Nefedov and T.Z. Yugai discussed the application of finite element analysis for the design and support of operation of nuclear power plant containments in Russia. For design analysis domestic program packages and licensed Western codes are used. For support of operations special FEM codes have been developed to take into account structural degradation. The most significant aging factor was reported to be relaxation of prestressing. Finite element models have been developed to include the concrete and individual tendons. The tension in each tendon can be individually adjusted to match the actual prestressing pattern or simulate rupture. The paper identified some problems with using finite element analysis for aged structures and the importance of regulatory activities in verifying and certifying FEM codes.

While the finite element method provides a very powerful analytical tool to solve complex structural problems, its proper technical application is still primarily a function of the knowledge and experience of the structural analyst. Beyond the definition of broad guidelines, its application is not codified even for relatively straightforward design analyses.

Application of finite element methods to highly nonlinear behavior of concrete structures is the realm of only a small number of researchers and expert analysts. Given this situation, regulators are tasked with ensuring the technical validity of finite element analyses on a case-by-case basis. To effectively accomplish this, regulatory bodies must either possess their own experts or have access to the necessary expertise. Codification and standardization of finite element modeling and analysis methods, to the extent practical, would have significant benefit for regulators.

Key Observations:

Finite Element Methods are widely used to meet regulatory requirements for assurance of structural safety.

The computer programs selected, the assumptions made, the model refinements, and the accuracy of numerical results are the responsibility of the structural analyst.

In general, regulatory bodies provide very little formal guidance for the use of Finite Element Methods. The burden of ensuring adequacy resides with the licensee.

Regulatory review is on a case-by-case basis.

The level of review varies from cursory assessment of the analysis documentation to independent confirmatory analysis, depending on the perceived level of uncertainty in the accuracy of the results and the safety significance of the analysis conclusions.

SESSION No. 2

CONCRETE CONTAINMENT STRUCTURES UNDER ACCIDENT LOADS

Purpose:

Many containments have shown some degradation during plant lifetimes, either in the concrete itself or in the steel reinforcement or liner. Whether capacity is affected depends on both the location of degradation and the amount of degradation. In some locations, there could conceivably be a significant amount of degradation before any loss of capacity. In other locations, those near the location of the dominant failure mode of the as-built containment, a small amount of degradation may affect capacity.

An ability to distinguish between these situations is needed in order to develop a risk informed perspective on the seriousness of observed degradation. Finite element models have the potential to address this question. The objective was to present and discuss papers which describe applications of this type. The authors were requested to discuss the models, analysis methods, difficulties encountered, and results. Of particular interest were the authors' assessments of the robustness of the calculational procedure as shown by comparison to experimental results and recommendations they have for future improvement.

Summary:

A total of seven papers were submitted and presented in this session.

The paper by Jan-Anders Larsson and Jochev Jeschke described two application examples of concrete containment structures under accident load conditions. The first example consisted of a non-linear dynamic analysis of a reinforced concrete culvert subjected to internal overpressure loading and impact loads from a pipe break. The ABAQUS computer code was utilized with three-dimensional solid elements and steel reinforcement (REBAR) elements. A special material model was used by superimposing the REBAR elements on the concrete mesh which permitted handling steel and concrete behavior separately. This material model used a linear elastic model for the concrete in compression and a smeared cracking assumption in tension.

The second example consisted of a non-linear thermal stress analysis around a steel penetration. A three-dimensional finite element model (90 degree segment) of the containment structure was generated. A postfailure stress-strain relation of the concrete was implemented in the analysis. Reinforcement was modeled using one-dimensional strain theory rod elements embedded in the concrete elements. To simulate load transfer across cracks through the rebar, tension stiffening was utilized.

The paper by Laurent Granger and Francois Fleury described studies being performed by EDF on leaktightness of concrete containments. Two programs were described: (1) a study of a high performance concrete (HPC) cylinder subjected to temperature, humidity, and pressure and (2) a scale model of a containment (MAEVA mock-up) subjected to temperature and pressure. The paper also described the predictive calculations on the scale model of containment using finite element methods. The main achievements were presented and the use of FE calculations for this difficult problem was discussed. The results of the predictive calculations performed by eight participants of the European Community on the MAEVA mock-up were presented. Comparisons of the results from the different participants were shown and possible reasons for some of the variation in results were explained

The paper by G. Heinfling, J.M. Reynouard, & C. Duval evaluated the capability of different numerical models to accurately predict the behavior of a NPP reinforced concrete foundation and core-catcher subjected to a core melt down accident. These structures are subjected to extremely high temperatures which induce strong chemical and physical changes that alter the mechanical behavior of concrete. The paper analyzed the consequences of using different hypotheses to determine the behavior of this particular structure. The study was performed by comparing the results obtained using a simplified model and a thermo-elastic-plastic model specially developed to describe the nonlinear and cracking behavior of concrete at elevated temperatures. Including thermomechanical interaction in the thermo-elastic-plastic model was important to avoid overestimating thermal cracking of this structure.

The paper by R.S. Crouch and M. Petkovski described some of the difficulties associated with performing ultimate limit state predictions using NLFEA on existing and degrading PCPV and PC structures. The paper examined recent advances in the constitutive modeling of concrete, nonlinear finite element solution strategies, and experimental testing of concrete at elevated temperatures. Some of the topics related to constitutive modeling of concrete included hardening and softening yield surfaces, development of accurate return strategy, return paths, and the microplane model. The development of a multi-axis test facility for testing concrete under compression at elevated temperatures was also described.

The paper by J.A. Smith and J.L. Cherry evaluated the effects of liner corrosion on the capacity of a degraded containment. This was investigated by performing finite element analyses of a typical PWR reinforced concrete containment with liner corrosion. The ABAQUS finite element code with the ANACAP-U nonlinear concrete constitutive model was used to analyze the containment under a loss of coolant accident consisting of pressure and temperature. A strain-based failure criterion was used to evaluate the different scenarios of degradation location and varying degrees of liner degradation. The locations of degradation were picked at regions of highest stress, where corrosion damage has been observed in existing containments, and in regions that are likely to experience corrosion. The pressure capacity of the containment for the different degraded conditions was compared to the non-degraded containment.

The paper by Valek Ivo which was presented by J. Maly described the system for monitoring the state of stress and deformation of the Temelin NPP containment structure. This has been achieved by using 1) tensometers/string strain gauges installed in the containment wall, dome, and on the reinforcement during construction, 2) magnetoelastic sensors mounted on the tubes of prestressing cables, and 3) resistance tensometers placed on anchor bolts of the prestressing system.

The paper by Z. Bittnar and P. Rericha described the nonlinear finite element analysis effort for a degraded reinforced concrete cooling tower due to atmospheric and industrial effects. The degradation consisted of a loss of the outer layer of concrete and exposure of the reinforcement to air in a local region of the tower. Both geometric and material nonlinearities were utilized. Two improvements were introduced into the analysis. The first enhancement consists of coupled shear-bending failure of reinforced concrete cross-sections. The second is a material model for cracking reinforced concrete which utilizes a concept based on position dependent tension softening in concrete.

Key Observations:

A number of non-linear FE modeling techniques have been presented which can be used to predict the response of concrete containment structures under accident loads.

Some scatter and uncertainty in the results have been identified which should be improved. With few exceptions, analysis of initially degraded concrete containments has not been adequately investigated.

There is very limited experimental data on degraded concrete structures to permit confirmation/benchmarking of the non-linear FE analytical methods.

SESSION No. 3

CONCRETE STRUCTURES UNDER EXTREME ENVIRONMENTAL LOAD

<u>Purpose:</u>

Reassessments have been performed of concrete structures at nuclear power plants, most often in connection with concerns that the plant might see an earthquake larger than that considered for design. Typically, significant margins have been found for the as-built plant structures. Local degradation has the potential to change the response of a plant structure by both the introduction of inelastic behavior and the reduction of structural capacity. Either of these effects, if large enough, can be risk significant. Papers were solicited that document the application of finite element analysis to estimate the consequences of degradation on concrete structures. Authors were asked to emphasize difficulties encountered, evidence of robustness, and recommendations for improvement.

<u>Summary</u>:

A total of five papers and two additional presentations were submitted in this session. One of these papers was about reassessment analysis efforts of an existing NPP using commercially available FEM codes. The other four papers addressed the effects of degradation on concrete structures primarily under severe seismic loads.

The paper by A.Habasaki et al. described the shear transfer mechanism of cracked concrete by performing large-scale RC panel tests subject to both constant axial stress and cyclic shear stresses. Several existing shear transfer models were compared with the test results for the purpose of improving the nonlinear FEM code.

The paper by S.Tinic was about reassessment of an old NPP under seismic load. The soil-structure interaction analysis was performed using the SASSI code, and a detailed 3-D building model was also constructed using the ANSYS code. The seismic responses were computed based on the response spectra approach.

The paper by Ile & Reynouard presented the results of simulation analyses of the CAMUS test, which was a shaking table test of a lightly reinforced 5-story RC building. Nonlinear FE analyses were performed to simulate the highly nonlinear dynamic responses under severe earthquake motions. The unique nonlinearities due to bond-slippage of main rebars, as well as the discrete cracks at construction joints, were considered for a better correlation.

The paper by Y.J.Park presented an overview of current knowledge on the effects of age-related degradation on the seismic performance of RC structures. Key findings regarding the seismic responses of degraded concrete structures were summarized based on past experiments. Attempts were made to apply nonlinear FE analysis to degraded RC components in order to single out the areas for improvements.

The paper by F. Stangenberg described the framework of the probabilistic evaluation of concrete structures under various loads expected during the life span of a structure. The use of nonlinear FE analysis was suggested to account for the effects of degradation. The results of Monte Carlo simulation were presented, which considered the variabilities in both demand and capacity.

Two additional presentations were provided by O.Mayboroda and V.Kritsky. Both described the current practice on the use of FEM codes for WWER NPP's in Ukraine.

Key Observations:

The modeling of unique nonlinearities of concrete structures and the application/ improvement of nonlinear FE analysis to degraded RC structures were the main themes of this session.

The use of discrete crack models was emphasized in two papers to properly account for the degraded condition of concrete structures. The test results for the shear transfer in cracked RC panels, presented by A. Habasaki, are very useful to develop/refine such crack models for degraded structures.

The application of nonlinear FE analysis to degraded concrete structures is considered to be a relatively new research subject. Several new ideas were presented in the papers in this area, including the modeling of bond-slippage relationships, use of discrete crack models, and modeling of degradation conditions in terms of nonlinear hysteresis rules.

Overall, the papers reflected some recent advances in the state-of-the-art of the nonlinear FE analysis on degraded concrete structures.

Conclusions and Recommendations

Degradation refers to changes in the material with time and operation, and covers the concrete, steel and liner. Both functional and structural aspects are considered here.

Conclusions

1. Finite Element methods are widely used to meet regulatory requirements for assurance of structural safety.

2. For most analyses of concrete structures, simplified methods or linear elastic analyses are adequate but for realistic response predictions non-linear analyses are often needed, especially for high temperature applications or predictions of local failures.

3. The application of non-linear FE analysis to degraded concrete structures is considered to be a relatively new research subject. There is limited information available on non-linear behaviour of concrete. A valid non-linear analysis depends on a constitutive model that can adequately represent the behaviour of concrete beyond its linear range, and appropriate materials data

4. Other industries are currently pursuing FE analysis of degraded structures

5. Some scatter and uncertainty in the results have been identified.

6. Three dimensional FE calculations for reinforced concrete require a good understanding of the behaviour of concrete structures, and experience to judge the validity of the results.

7. Degraded structures have special features of material behaviour and structural modelling that need to be considered.

8. With few exceptions, analysis of initially degraded concrete containment structures has not been adequately investigated.

9. There are very limited experimental data on degraded concrete structures to permit validation of the non-linear FE analytical method

Recommendations

1. Consideration should be given to future benchmarks/ISPs to improve the validation of the methods.

2. Some improvement is needed in the analyses where thermal and mechanical processes must be coupled to permit specific applications to degraded structures.

3. Test results for the shear transfer in cracked reinforced concrete panels would be useful to develop/refine models for degraded structures .

4. The use of probabilistic methods, including stochastic FE methods, should be pursued.

5. The use of instrumentation on real structures to validate FE codes is a topic that it would be useful to pursue in the proposed PWG3 workshop on instrumentation of concrete structures.

6. There is a need to do further work to better determine material property data and constitutive models.

7. Consideration should be given to the development of indicators of local and global ageing.

OECD-NEA Workshop on FE Analysis of Degraded Concrete Structures

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