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OAK RIDGE NATIONAL LABORATORY

OPERATED BY MARTIN MARIETTA ENERGY SYSTEMS, INC.
POST OFFICE BOX X, OAK RIDGE, TENNESSEE 37831

ORNL

FOREIGN TRIP REPORT

ORNL/FTR-2526

DATE: April 28, 1987

SUBJECT: Report of Foreign Travel of B. R. Bass, Engineering Mechanics Section Head, Computing and Telecommunications Division (Work funded by Engineering Technology Division)

TO: Herman Postma

FROM: B. R. Bass

PURPOSE: To confer with Dr. H. K. Stamm and the staff at Kernforschungszentrum Karlsruhe (KFK), Federal Republic of Germany to accomplish several objectives that relate to the computational analysis of dynamic crack run-arrest phenomena in reactor pressure vessel steels; to present a seminar at KFK describing the fracture analysis of the wide-plate and pressurized-thermal-shock experiments being performed in the Heavy-Section Steel Technology Program.

Sites Visited:

3/30-4/3/87	KFK	Karlsruhe, FRG	Hermann Stamm

(For the week of 4/5-11/87 the traveler used **vacation** to attend the following conference in Barcelona, Spain. **All costs** of the week including registration, travel between Karlsruhe, FRG and Barcelona, Spain, lodging and per diem, were assumed by traveler.)

4/6-10/87	Technical University of Catalonia, Barcelona, Spain	International Conference on Plasticity	Prof. E. Onate
4/13-16/87	KFK	Karlsruhe, FRG	Hermann Stamm

Abstract:

The traveler visited Kernforschungszentrum Karlsruhe (KFK), Federal Republic of Germany (FRG) to confer with Dr. H. K. Stamm and other staff members to accomplish several objectives that relate to the computational analysis of dynamic crack run-arrest phenomena in reactor

pressure vessel steels. These objectives included: (a) obtain from KFK a computer implementation of the Robinson viscoplastic constitutive model that utilizes an implicit time-integration scheme; (b) provide KFK with a computer implementation of five candidate elastic and inelastic fracture parameters utilized in the ORNL ADINA/VPF computer program; (c) hold in-depth discussions with Dr. Stamm and the staff concerning implementation, application, and future development of the above viscoplastic computational techniques; and (d) present a seminar at KFK describing fracture analysis of HSST wide-plate and pressurized-thermal-shock experiments.

Access to the information in this report is limited to those indicated on the distribution list and to U. S. Government Agencies and their Contractors.

Introduction

The traveler's visit to Kernforschungszentrum Karlsruhe (KFK) was motivated by the objectives of the Heavy-Section Steel Technology (HSST) Program crack-arrest studies. A primary objective of these studies is to understand pressure vessel conditions that can initiate growth of an existing crack and conditions that can lead to arrest of a moving crack. In meeting this objective, the HSST program is generating crack-arrest data over an expanded temperature range through tests involving large cylinders, pressure vessels and wide-plate specimens. A subject of growing interest is the role of nonlinear rate-dependent effects in the interpretation of crack run-arrest events in these ductile materials. In concert with subcontracting groups, the HSST program is supporting research efforts to develop viscoplastic-dynamic finite-element analysis techniques and to validate their utility through the analysis of carefully performed crack-arrest experiments. These analysis capabilities are expected to give an improved basis for assessing the dynamic fracture behavior of the wide-plate crack-arrest specimens currently being tested by the HSST program.

In HSST studies at the Oak Ridge National Laboratory (ORNL), various viscoplastic constitutive models and several nonlinear fracture criteria are being installed in the ADINA general purpose finite-element computer program. The first two viscoplastic constitutive models selected for installation in ADINA were those due to Bodner-Partom and to Perzyna. Other models planned for installation in ADINA include those due to Robinson and to Hart (Milestones in the FY 1987 HSST Program Plan). To facilitate the ORNL studies of the Robinson model, an agreement was worked out with the Institut für Material-und Festkörperforschung (IMF) at KFK by which the traveler would obtain from Dr. Stamm a computer implementation of the Robinson model that could be installed in the ORNL version of ADINA. This computer

implementation is the product of approximately three years of KFK work in the area of unified constitutive theories for rate-dependent materials. In exchange, the traveler would discuss with KFK a computer implementation of five elastic and inelastic candidate fracture parameters utilized in the ORNL ADINA computer program for elasto-dynamic and viscoplastic-dynamic fracture analysis. An essential feature of this exchange would be in-depth discussions with the KFK staff concerning implementation, application, and future development of these computational techniques.

Discussions at KFK

Discussions at KFK were intended to accomplish several objectives that relate to the computational analysis of dynamic crack run-arrest events in rate-dependent inelastic materials. The primary objective was for the traveler to become familiar with the computer implementation of the Robinson model as developed by KFK and installed in the ABAQUS general purpose finite-element code. To this end, the traveler held several days of discussions with Mr. K. Hornberger of Dr. Stamm's staff concerning the detailed computer coding of the KFK-Robinson algorithm. The model employed by KFK utilizes evolutionary laws for both isotropic and kinematic state variables, including hardening and thermal-recovery terms in the kinematic variable (Refs. 1-2). The computational algorithm includes the option of either explicit or implicit (generalized-midpoint rule) time integration of the constitutive equations, used in combination with a time-step control strategy. A unique feature of the implicit algorithm is the application of a projection formalism to reduce the number of independent variables in the Newton-Raphson iteration loop to two and, thus, facilitate convergence.

The traveler also discussed with Mr. Hornberger the necessary changes to the KFK-Robinson computer implementation for installation in the ORNL version of the ADINA program. One area of potential difficulty is the time-step control strategy employed by KFK in the algorithm; the current version of the ADINA program does not permit a variable time step. At the end of this series of discussions, Mr. Hornberger supplied the traveler with an annotated hard-copy listing of the relevant KFK subroutines and a magnetic tape containing the subroutines and a sample validation problem. These materials will be used to install the Robinson model in the ORNL ADINA code according to HSST-milestone schedules.

The traveler also had discussions with Dr. Stamm and Ms. U. Spermann of KFK concerning the testing program underway at KFK to determine material constants for the Robinson model. This program is utilizing cyclic, creep, and relaxation tests of 316L stainless steel at elevated temperatures (~550°C). The data derived from the tests are being used in procedures described by Cescotto and Leckie (Ref. 3) to determine the relevant parameters in the flow law and evolutionary equations of the Robinson model. Additional details of the techniques

being used are described in a report by Stamm (Ref. 4). Current KFK viscoplastic analyses are based on the material parameters for 2-1/4 Cr-1 Mo steel summarized in the report by Robinson and Bartolotta (Ref. 5). These parameters were determined in part in previous ORNL studies by Robinson and Swindeman (Ref. 6).

The traveler provided KFK with the computer implementation procedures utilized in the ORNL ADINA program for five elastic and inelastic path/domain integrals which are used as candidate fracture parameters. These integrals are currently being evaluated by ORNL through applications to the series of wide-plate crack-arrest tests. The traveler discussed with Dr. Stamm and Mr. Hornberger the results of these ORNL applications, as well as the numerical techniques employed in the evaluation of the integrals in the ADINA program. Dr. Stamm is considering plans to install these integral formulations in a finite element post-processor program to be used in conjunction with the ABAQUS code. This approach will avoid difficulties associated with internal modifications of the KFK version of the ABAQUS code.

Short discussions with other staff members in the IMF at KFK were arranged by Dr. Stamm in order to provide the traveler with exposure to ongoing work. In the first of these discussions, Dr. C. Mattheck described the EASY computer program (Ref. 7) developed at KFK for simplified fracture-mechanics analysis. The EASY computer program uses a simple numerical integration scheme to calculate stress-intensity factors for a class of crack geometries subjected to arbitrary loading. The only requirement is that the weight function for the crack be part of the collection available in the EASY program. The EASY program is available from KFK for an unspecified fee.

In another discussion, Dr. A. Bruckner described ongoing work concerning crack extension in the ductile-brittle transition region of ferritic steels. Analytical and experimental studies have been performed on 20-MnMoNi-55-reactor steel to determine the effect of specimen size on fracture-toughness parameters. The analytical studies have utilized a weakest-link model which is based on the assumption that failure starts from a weak point near the crack front where the weak points are statistically distributed in the material (Ref. 8).

The traveler met briefly with the director of the IMF, Professor D. Munz, who is also on the faculty of the University of Karlsruhe. Professor Munz described the close working relationship between KFK and the University of Karlsruhe. In particular, he explained that graduate students from the University receive limited contracts through the IMF to perform research work at KFK. During their tenure at the Institute, the students evidently play an important role in conducting the research work directed by Professor Munz. At the completion of the

degree or the contract, the students are generally required either to leave the Institute or to obtain a permanent position at KFK.

Following this meeting, the traveler was escorted on a brief tour of some of the laboratory facilities in the IMF. One of the several small-scale experiments underway concerned fatigue-crack growth under cyclic thermal-shock loading. The experiments are carried out by using a water jet to cyclically cool a hot steel plate containing a small surface crack. Thus far, fatigue-crack growth has been performed using thermal loading only. However, preparations are underway to study combined thermo-mechanical loading by superimposing a four-point bend load on a small-beam specimen. It was the traveler's impression that much of the work involved in setting up and executing these small-scale experiments is performed by graduate students from the University.

Seminar on Fracture Analysis of HSST Crack-Arrest Experiments

During his visit to KFK, the traveler was invited to give a seminar to the KFK staff and other interested researchers. The seminar, entitled "Fracture Analysis of Large Crack-Arrest Experiments in the HSST Program," was presented on March 31, 1987, to a group of approximately 25 people comprised primarily of KFK staff and University personnel. Also in attendance was Dr. J. Sievers who had come down from GRS Cologne primarily to learn about results from the second HSST pressurized-thermal-shock experiment, PTSE-2. After an introduction by Professor Munz, the traveler made a one-hour presentation on recent fracture test and analysis results from HSST studies in two major areas that relate to assessing nuclear reactor pressure-vessel integrity under PTS conditions: crack run-arrest behavior in wide plates (WP-1 and -2); and fracture behavior of a thick-walled vessel under combined thermal and pressure loadings (PTSE-2). A summary of the test results and of posttest analyses conducted thus far were presented. Points of discussion following the presentation included the transition from ductile tearing to cleavage at Charpy upper-shelf temperatures in the wide-plate tests, the appropriate fracture parameters for inelastic dynamic fracture, and the availability of reports on the recent tests. The traveler suggested that requests for reports be forwarded to the HSST program manager.

International Conference on Computational Plasticity

In connection with the discussions of viscoplastic constitutive models at KFK, the traveler accompanied Dr. Stamm and members of his staff from KFK to the **Conference on Computational Plasticity** held at Barcelona, Spain, April 6-10, 1987. The primary purpose for attending the conference was to participate in the sessions devoted to creep, viscoplasticity and thermal problems. In one of these sessions, Dr. Stamm presented a paper in which he described the numerical implementation of the Robinson viscoplastic model in the KFK version of the

ABAQUS code (Ref. 1). Another paper of major interest was the keynote presentation by J. L. Chaboche which reviewed computational methods of cyclic plasticity and viscoplasticity. (The traveler used vacation leave to attend this conference and assumed **all** expenses for the trip, including travel between Karlsruhe and Barcelona, conference registration, hotel, and per diem).

REFERENCES

1. K. Hornberger, et al., "Numerical Integration and Implementation of Viscoplastic Models into Finite-Element Codes," **Proc. of International Conference on Computational Plasticity**, Barcelona, Spain, April 6-10, 1987.

2. K. Hornberger and H. Stamm, "Anwendung viskoplastischer Stoffgesetze in Finite-Element Programmen," Kernforschungszentrum Karlsruhe, KFK-4254, 1987. (in German).

3. S. Cescotto and F. Leckie, "Determination of Unified Constitutive Equations for Metals at High Temperature," **Proc. Int. Conf. on Constitutive Laws for Engineering Materials.**

4. H. Stamm, "Bestimmung der Material Konstanten das Robinson-Modells," Kernforschungszentrum Karlsruhe, GmbH (report in preparation in German).

5. D. N. Robinson and P. A. Bartolotta, "Viscoplastic Constitutive Relationships with Dependence on Thermomechanical History," NASA Contractor Report 174836, University of Akron, Akron, Ohio, March 1985.

6. D. N. Robinson and R. W. Swindeman, "Unified Creep-Plasticity Constitutive Equations for Structural Alloys at Elevated Temperature," **ORNL/TM-8444**, Oak Ridge Natl. Lab., Martin Marietta Energy Systems, Inc., Oak Ridge National Laboratory (Oct 1982).

7. C. Mattheck and D. Munz, "Effective Assessment of Cracks and Life Prediction with the EASY Computer Code," paper to be presented at the **Conf. on Fast Breeder Systems,** Richland, WA, (Sept 1987).

8. W. Ehl, D. Munz, and A. Bruckner," Scatter of Fracture Toughness in the Ductile-Brittle Transition Region," **Fracture Control of Engineering Structure,**" ECF6, Amsterdam, Netherlands (1986).

APPENDIX A

Itinerary

March 27, 28	Travel	Knoxville, TN to Karlsruhe, FRG
March 29,	Sunday	Weekend
March 30-April 3	Discussions and Seminar	Kernforschungszentrum, Karlsruhe, FRG
April 4-5	Travel	Karlsruhe, FRG to Barcelona, Spain
April 6-10 (Traveler on vacation)	Meeting	International Conference on Computational Plasticity, Barcelona, Spain
April 11-12	Travel	Barcelona, Spain to Karlsruhe, FRG
April 13-16	Discussions	Kernforschungszentrum, Karlsruhe, FRG
April 17	Travel	Karlsruhe, FRG to Knoxville, TN

APPENDIX B

Persons Contacted

Dr. H. K. Stamm	KFK
Mr. K. Hornberger	KFK
Dr. C. Mattheck	KFK
Professor D. Munz	KFK/University of Karlsruhe
Dr. A. Bruckner	KFK
Ms. U. Spermann	KFK
Dr. G. Zahn	KFK
Dr. B. Kneifel	KFK
Dr. J. Sievers	GRS Cologne
Professor E. Onate	Technical University of Catalonia

APPENDIX C

List of Research Material and Literature Acquired

One 9-track magnetic tape containing the following files:

1) FORTRAN-77 source program (31 subroutines) of the KFK computer implementation of the Robinson-viscoplastic model
2) Sample problem-perforated plate

Literature

1. K. Hornberger, et al., "Numerical Integration and Implementation of Viscoplastic Models into Finite-Element Codes," **Proc. of International Conference on Computational Plasticity,** Barcelona, Spain, April 6-10, 1987.

2. K. Hornberger and H. Stamm, "Anwendung viskoplastischer Stoffgesetze in Finite-Element Programmen," Kernforschungszentrum Karlsruhe, KFK-4254, 1987. (In German).

3. V. K. Arya, et al., "On the Numerical Integration of Viscoplastic Models," Kernforschungszentrum Karlsruhe, KFK-4082, May 1986.

4. S. Cescotto and F. Leckie, "Determination of Unified Constitutive Equations for Metals at High Temperature," **Proc. Int. Conf. on Constitutive Laws for Engineering Materials.**

5. H. Stamm, "Bestimmung der Material Konstanten das Robinson-Modells," Kernforschungszentrum Karlsruhe, GmbH (report in preparation in German).

6. D. N. Robinson and P. A. Bartolotta, "Viscoplastic Constitutive Relationships with Dependence on Thermomechanical History," NASA Contractor Report 174836, University of Akron, Akron, Ohio, March 1985.

7. C. Mattheck and D. Munz, "Effective Assessment of Cracks and Life Prediction with the EASY Computer Code," paper to be presented at the **Conf. on Fast Breeder Systems,** Richland, WA, (Sept 1987).

8. W. Ehl, D. Munz, and A. Bruckner," Scatter of Fracture Toughness in the Ductile-Brittle Transition Region," **Fracture Control of Engineering Structure,**" ECF6, Amsterdam, Netherlands (1986).

Literature (Continued)

9. **Computational Plasticity**, eds., D. R. J. Owen and E. Hinton, **Proc. of International Conference on Computational Plasticity**, April 6-10, 1987, Barcelona, Spain, Vols. I and II, Pineridge Press (1987).

Distribution

1-2. Assistant Secretary for International Affairs, DOE, Washington, DC 20545
3. G. A. Arlotto, Director, Division of Engineering, NRC, Washington, DC 20555
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8-9. Director, Division of International Security Affairs, DOE, Washington, DC 20545
10-11. C. Z. Serpan, Jr., Division of Engineering, NRC, Washington, DC 20555
12-13. M. Vagins, Division of Engineering, NRC, Washington, DC 20555
14. D. J. Cook, DOE/ORO
15. J. A. Lenhard, DOE/ORO
16. Herman Postma, Director, ORNL
17. J. R. Merriman, Associate Director, ORNL
18. W. L. Fourney, University of Maryland, College Park, MD 20742
19. M. F. Kanninen, Southwest Research Institute, 6220 Culebra Road, San Antonio, TX 78494
20. R. J. Fields, National Bureau of Standards, Gaithersburg, MD 20899
21. G. R. Irwin, University of Maryland, College Park, MD 20742
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