ESIS TC 8 - Numerical Round Robin on Micro-Mechanical Models - Results of Phase II/Task B2 on Cleavage Toughness Prediction on CT Specimen

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ABSTRACT : This paper gives the results obtained for the phase II, Task B2 Round Robin organised by the CEA Saclay within the ESIS (European Structural Integrity Society), Technical Committee 8 on Numerical Methods. It is part of a larger project initiated in 1993 and organised in 3 phases. Phase I was focussed on the determination of local approach parameters for ductile tearing (Task A) and for cleavage (Task B) for a German pressure vessel steel. The objective of Phase II was to perform finite element simulation of crack growth CT for ductile tearing (Task A) and for cleavage (Task B). For this latter Task, the objective was to compute the toughness and the failure probability of a CT specimen on the lower shelf at –154°C for the 22 NiMoCr 3 7 German RPV steel. Eleven laboratories have contributed to this Round Robin and six different FE codes have been used.

INTRODUCTION

The ESIS (European Structural Integrity Society) Technical Committee 8 (TC8) is devoted to Numerical Methods in Fracture Mechanics. TC's activities can be subdivided in two main parts. The first part is the organisation of Round Robin, which are either numerical or experimental inter laboratories exercises. This forms the basis for discussions and comparison of methods, codes or apparatus. The second part is devoted to the writing of Technical Guidelines, which reflect the state of the art at the conclusion of the Round Robin. Eventually, these guidelines can be used as starting documents for normative committees such as EN or ISO. Within the framework of the TC 8, a Round Robin on finite element simulation of fracture mechanics specimens has been initiated by Professor W. BROCKS at GKSS (Germany). The overall project was organised in 3 distinct phases :

- Phase I : Determination of local approach parameters for ductile tearing (Task A) and for cleavage (Task B) for a German pressure vessel steel.
- Phase II : Finite element simulation of crack growth CT for ductile tearing (Task A) and for cleavage (Task B).

- Phase III : Finite element simulation in the brittle to ductile transition region.

Phase I was organised between 1993 and 1995. The material was the German 20 MnNiMo 5 5 RPV steel and the results are summarised in [1]. Then, Phase II - Task A on ductile tearing was organised and the results are summarised in [2]. The material was the German 22 NiMoCr 3 7 RPV steel. Phase II – Task B1 has been conducted and the results are summarised in [3]. The purpose of this Task was to identify cleavage material parameters. For the Phase II-Task B2 round robin, specifications have been issued by CEA in December 2000. This Round Robin is devoted to the use of a cleavage model for the prediction of toughness and corresponding failure probability for CT specimens in the cleavage range (-154°C). An outline of the specification is given in the following.

OUTLINE OF THE SPECIFICATIONS

Objectives of the Round Robin

Two types of computations were expected from each participant. The first one corresponded to the computation of a unit cell square subjected to external displacements. This exercise was merely viewed as a preliminary step, necessary however to be sure that the cleavage criterion implemented in each code is comparable. Although not reported in this paper, all the participants successfully reported results and only minor discrepancies between local stresses, strains or Weibull stresses were obtained. The second computation corresponded to the CT specimen calculations and the comparison with experimental results.

Material

The material investigated in this Round Robin corresponds to a low alloy ferritic steel (22 NiMoCr 3 7) extracted from a German PWR vessel. The corresponding material properties have been extracted from the database developed within the ESIS TC 1-4 sub-committee on "Fracture Mechanics Standards" [4]. For the purpose of this Round Robin, the tests results obtained at –154°C were considered for which 95 CT tests results are available. As for the Phase II-B1 round robin, the true stress-strain curve extrapolated for strain beyond ε=0.3 assuming an Hollomon formula as determined from tensile tests on smooth specimens at -150°C was used. The different material parameters are summarised in Table 1.

Beremin material characteristic values

The Beremin [5] material characteristic values (m=22, σ_u=2514MPa and V_0=100(μm)^3) corresponding to the mean value of the parameters determined in the Phase II-Task B1 ([3]) round robin were imposed to the participants.

However, participants were also encouraged to use other values of m, σ_u. and V_0 provided they were justified.

Table 1 : 22 NiMoCr 3 7 material characteristics at –150°C used for round robin (from [3]).

E (GPa)	ν (-)	K (MPa)	n (-)
213	0.3	1347.5	0.16824

CT specimen specification

For the CT specimen calculations, the 1T specimen (W=50 mm, B=25 mm and a_0=28.17 mm) was the mandatory geometry. The 1/2T and 2T geometries were made available for participants as an optional calculation. An example of a possible mesh was also given. Non-linear quadratic elements with reduced integration (QUA8R) were highly recommended together with plane strain conditions. At the crack tip, 50 microns square elements were to be used with a minimum of 4 elements on each side of the node corresponding to the crack tip. Loading was to be simulated as an imposed vertical displacement (0.25mm) applied to the CT pinhole centre. Participants were free to define the load steps to be used to solve the problem. The fracture toughness was to be calculated using K or J formulas as described in Fracture Mechanics Handbooks. It was also allowed to be numerically computed from the finite element analysis using a J-integral formulation.

RESULTS

Participants

Eleven contributions have been received to this Round Robin. Table 2 gives the name of the different organisations, country, the FE code and the version used for the computation. As general comments, it is worth mentioning that all participants used the Beremin model although it was possible to use any other model. Four organisations from France, three from Germany and one organisation from outside Europe have contributed to this round robin whilst six different FE codes have been used. Finally, in order to preserve the contributors, each organisation has been numbered so that the results can be described anonymously.

Table 2 : Round Robin participation.

ORGANISATION AND COUNTRY	FINITE ELEMENT CODE
Centre des matériaux Ecole des Mines de Paris, EMP, France	Zebulon 8.1
Electicité de France, EDF, France	Code_Aster 5
Commissariat A l'Energie Atomique, CEA, France, [YUR01]	CAST3M developent
Commissariat A l'Energie Atomique, CEA, France	CAST3M 1999
Bundesanstalt für Materialforschung und –prüfung, BAM, Germany	ABAQUS 5.8 and 6.1
Forschungszentrum Karlsruhe GmbH, Germany, FZK, [RIE01]	ABAQUS 5.08-08
GKSS Research Centre, Germany	ABAQUS STANDARD 5.8
Bhabha Atomic Research Centre, INDIA, [SAM01]	MADAM 9
University of Cassino, Italy, [BON01]	MSC/MARC 07:33
Ecole Polytechnique Fédérale de Lausanne, EPFL, Switzerland	Abaqus/Standard 5.8.14
University of Bristol, UOB, United Kingdom	ABAQUS CAE 5.8/6.1

1T CT Results with imposed BEREMIN model parameters

The results obtained for the 1T CT computation with the imposed BEREMIN model parameters are shown in Figures 1 to 3. An overall good correlation is obtained by all participants. However, it can be noted that 5 participants (#1, #2, #6, #7, #10) predict specimen stiffness in good agreement with the measured data. An analysis of the assumptions used by the participants shows that the best correlation is obtained when assuming that the pin behaves elastically with a Young's modulus identical to that of the specimen. All the participants that have attempted to model the pin with a higher Young's modulus, attempted to model the gap between the pin and the specimen or model crack tip blunting predict a stiffer specimen response than that observed experimentally.

In terms of failure probability and Weibull stress, similar results are obtained by those predicting a similar specimen response. The failure probability as a function of toughness is compared to that determined experimentally in Figure 3. In order to minimise possible discrepancies, the toughness reported on this figure has been determined using the ASTM E1820 standard and the load predicted by each participants. Similarly to the previous comments, participants #1, #2, #6, #7 and #10 predict similar failure probabilities. However, these are found to be slightly unconservative when compared to the experimental observations. Finally, although participants #8, #9 and #11 overestimate the specimen stiffness response, the imposed Beremin model parameters allow to predict failure probabilities versus toughness curves in good agreement with that observed experimentally.

1T CT Results with freely identified BEREMIN model parameters

A number of participants (participants #1, #8 and #9) have performed computations of the 1T CT specimen with Beremin model parameters identified from 7 notched tensile specimens of layer 4. As a general trend, these three participants obtain higher m and lower σ_u values than that imposed in the round robin (resulting from the mean values of the identified parameters for the notched tensile specimens from layer 4 in the preceding round robin). However, none of the participants obtained results that correlate well with the observations.

Four participants (participants #1, #3, #8 and #9) used the Beremin parameters resulting from the entire set of notched tensile specimens (32 specimens available). For this contribution, the stress-strain curve has not been updated to account for the variation of the material properties from one layer to another. As a result, much lower m values than resulting from the preceding case are obtained and the correlation between the experimental data and the computation is improved significantly. Participants #1 and #9 obtained very satisfactory results whilst participants #3 and #8 gave unconservative results.

One further contribution has been obtained by participant #1. In this analysis, the whole set of available specimens were used (32 specimens in 6 layers) to identify the Beremin model parameters but different material properties where used for specimens machined in layer 2 and 6 using a Brigman [6] correction factor to apply to the material true stress-strain curve used in the FE analyses. The results are shown in Figure 4 together with 5% lower bound and 95% upper bound predictions. The predictions are found to be in very good agreement with the experimental data with a set of Beremin model parameters commonly admitted in the open literature of this class of material (m=27.5 and σ_u=2288 MPa).

1/2T and 2T CT results

Six participants (#1, #2, #3, #5, #9 and #10) have analysed the 1/2T and 2T CT specimen geometries. The conclusions drawn from the predicted load versus load line displacement were found to be analogous to that obtained for the 1T CT (Figure 1). As an example, the failure probability versus toughness predicted obtained by participant #1 is given in Figure 5. When predicting the size effect, the trends observed experimentally are satisfactorily predicted by each participant although the size effect is not that pronounced at this temperature: the larger the specimen size, the greater the failure probability is. However, each participant predicts a shift of the failure probability with increasing specimen dimensions. This does not correspond to that observed experimentally since the slope of the failure probability is found to increase with specimen dimension. This implies that the Beremin model has to take into account this effect using a stress threshold.

However, in that case, the material parameter identification becomes more complex.

CONCLUSIONS & FUTURE WORK

This paper has summarised and commented the results obtained for the phase II, Task B2 Round Robin organised by the CEA Saclay within the ESIS (European Structural Integrity Society), Technical Committee 8 (Numerical Methods). The objective of this Round Robin was to compute the toughness and the failure probability of a CT specimen on the lower shelf at –154°C for the 22 NiMoCr 37 German RPV steel.

Eleven laboratories have contributed to this Round Robin and six different FE codes have been used. All the participants have used the Beremin model [BER83] for the determination of the failure probability. Unit cell computations with strictly imposed computing assumptions have been achieved and a very good correlation of the results between all the codes for this test case have been obtained which allowed to verify that the plasticity criterion and the Beremin routines are well implemented in each code.

For the 1T CT computation, it has been found that the assumption made to model the specimen (stiffness of the pin, contact between the pin and the specimen and crack tip blunting) affects significantly the results. The best correlation between the test result and the predictions was obtained when assuming an elastic pin with a Young's modulus identical to that of the specimen. Of course, this was found to significantly affect the failure probability predictions made using post processing Beremin, routines.

The imposed Beremin model parameters did not allow to obtain satisfactory predictions of the failure probabilities, 7 specimens being certainly an insufficient number of specimen in order to give meaningful results for the identification of parameters from notched tensile specimen data. Very good results were obtained by those using the entire parameters identified form the entire set of 32 notched tensile specimens available. This was improved by one participant using updated stress strain curves to account for a variation of the material properties in the block of material used to machined the notched tensile specimens. Finally, the influence of specimen dimensions was well reproduced by the participants although it was found to have a minor influence at this low temperature. A stress threshold behaviour is observed on the experimental results and is not described in the modelling with a two parameters Weibull approach.

This concludes the phase II, task B round robin on finite element simulations of cleavage for notched bars and CT specimens. As initially envisaged, it is now expected to carry on the round robin exercise with phase III in order to predict the brittle to ductile transition curve. This will be initiated by CEA in 2002.

REFERENCES

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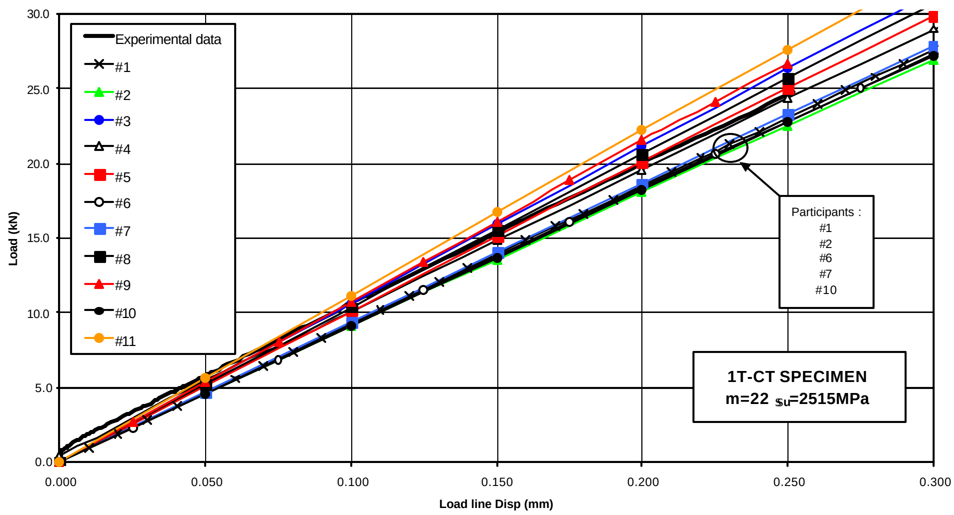
2 BERNAUER G. and BROCKS W., *"Numerical Round Robin on Micro-Mechanical Models - Phase II - Results of Task A"*, ESIS TC 8, August, (1999), Published as GKSS report 2000/15.

3 BERNAUER G. and BROCKS W., *'Numerical Round Robin on Micro-Mechanical Models - Phase II - Results of Task B1"*, ESIS TC 8, June, (2000), Published as GKSS Technical Note WMS/00/14.

4 HEERENS J., *"Fracture Toughness of Steel in the Ductile to Brittle Transition Regime"*, ESIS TC 1-4, GKSS Final Report, Contract MAT1-CT-940080, February 1999.

5 BEREMIN F.M., *"A Local Criterion for Cleavage Fracture of a Nuclear Pressure Vessel Steel"*, Metallurgical Transaction, vol. 14A, pp. 2277-2287, (1983).

6 BRIDGMAN. P.W., *"Studies in Large Plastic Flow and Fracture"*, Mc Graw-Hill, New York, (1952).



<u>Figure 1:</u> 1T CT computations – Load versus load line displacement

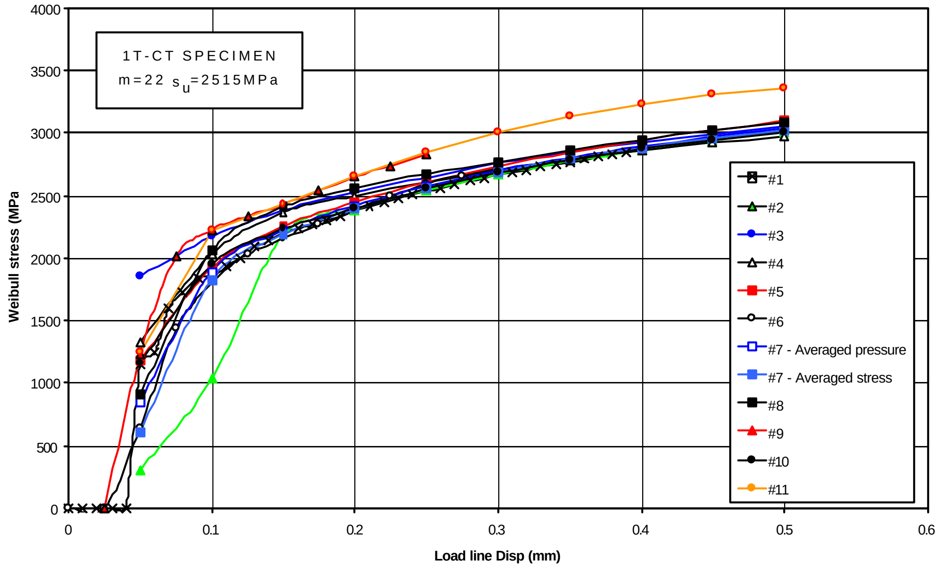


Figure 2: 1T CT computations with imposed m and s_u *(m=22,* s_u*=2515MPa) – Weibull stress versus load line displacement*

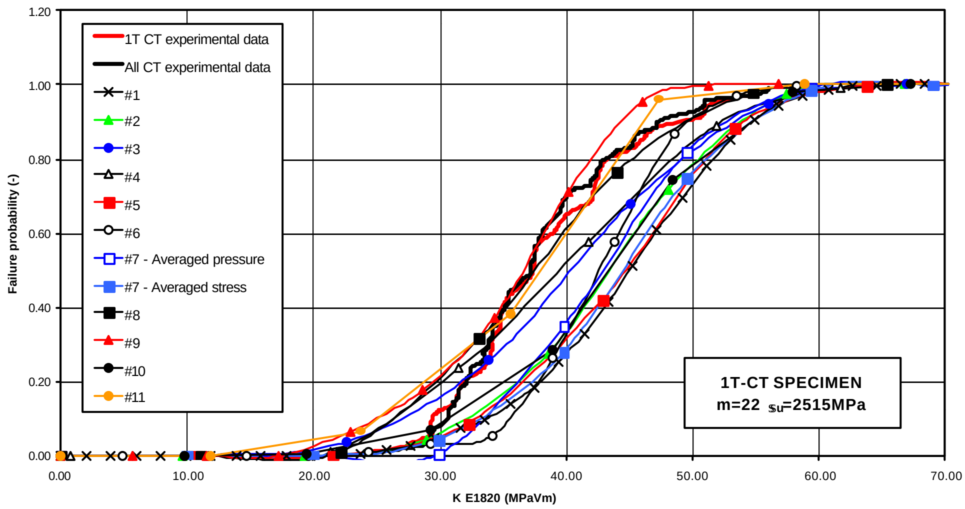


Figure 3: 1T CT computations with imposed m and s_u *(m=22,* s_u*=2515MPa) – Failure probability versus toughness*

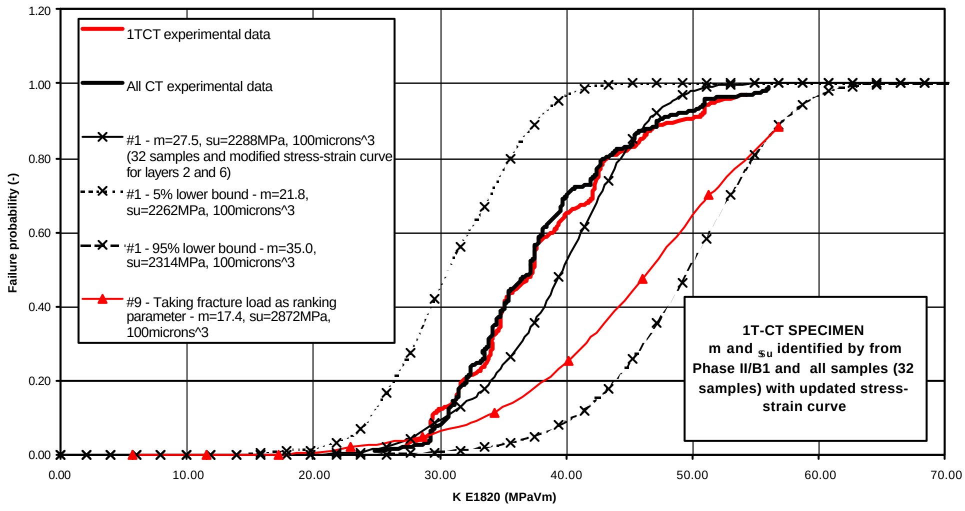


Figure 4: 1T CT computations with free m and s_u identified from phase II/B1 and all samples with an updated stress strain curve – Failure probability versus toughness

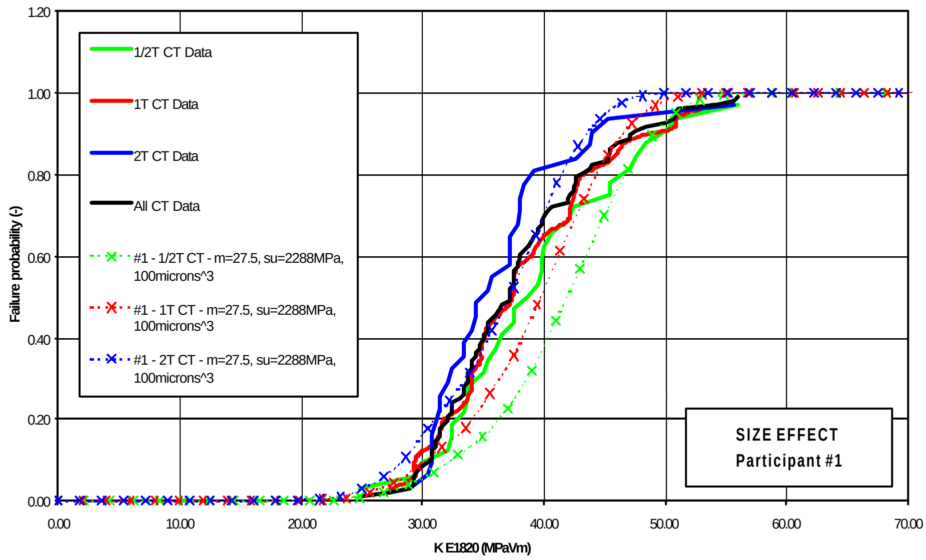


Figure 5: SIZE EFFECT – Failure probability versus toughness predicted by participant #1