EFFECT OF SHALLOW FLAWS AND BIAXIAL LOADING ON TRANSITION TEMPERATURES USING A WEIBULL STRESS MODEL

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ABSTRACT

The aim of the VOCALIST analytical work of the European Commission Project VOCALIST [1] is to analyze the different constraint conditions of tested specimens and to develop a method to describe and predict the constraint dependent shift of the transition temperature T_0 for the analyzed specimens. This document describes the analytical work performed within VOCALIST for the biaxial loaded cruciform bend specimens at Oak Ridge National Laboratory (ORNL) USA and FRAMATOME-ANP (FANP) Germany.

INTRODUCTION

The main purpose of the European Commission (EC) project VOCALIST (Validation of Constraint-Based Assessment Methodology in Structural Integrity) [1] is to understand and verify the constraint behavior of different structures loaded in the transition between brittle and ductile material behavior. The constraint-dependent differences are induced by geometry and/or loading, e.g., biaxial vs. uniaxial loading, deep and shallow cracks.

Within the VOCALIST test program, standard fracture mechanics three-point bend specimens with different sizes and crack depths have been tested. The selected specimen sizes and crack depths are representative of the variable constraint behavior of small fracture mechanics specimens. Large-scale tests were also performed (outside the framework of VOCALIST) to quantify the constraint shift between the laboratory specimens and real components. The large-scale tests used cruciform four-point bend specimens under biaxial loading with a 4T (100 mm) thickness and an *a/W* ratio of 0.1. The analytical work in VOCALIST is focused on developing a methodology to quantify the constraint states associated with different fracture-mechanics test specimens. The aim is to transfer fracture-mechanics properties between the analyzed structures taking the constraint state into account. The final outcome should be a methodology to perform safety assessments by using small-scale fracture mechanics specimens such as a sub-size pre-cracked Charpy V-Notch (PCCV) specimen.

MATERIALS

The material under investigation is a forged, quenched and tempered, large ring segment of the ferritic steel DIN 22NiMoCr37. This material corresponds to the requirements of ASTM A508 Grade 3, Class 1, and is denoted in VOCALIST as *Material A.* The properties of this steel are prototypic of an nuclear reactor pressure vessel (RPV) at the start of life.

EXPERIMENTS

The experimental results of the VOCALIST project are used to analyze the constraint shift between small three-point bend specimens with shallow and deep cracks and large-scale cruciform four-point bend specimens.

The transition temperature determined for the standard specimens with deep flaws and a 1T thickness of 25 mm is designated T_0 as per ASTM E 1921-02, *Standard Test Method for Determination of Reference Temperature,* T_0, *for Ferritic Steels in the Transition Range*. In this paper, the transition temperature calculated for non-standard specimens, e.g., shallow pre-cracked PCCVs, is designated T_0^*.

Four point bend cruciform specimen (BB) [2]

The cruciform bend specimens have a test section with the dimensions of 104mm x 104mm, as shown Fig. 1. All cruciform bend specimens have a 2-dimensional shallow crack with a crack-depth ratio of *a/W* = 0.1. The crack was located near the middle plane of the original plate. Load-diffusion control slots (LDCS) were machined into the specimen loading arms to create the boundary conditions required to achieve a uniform shear stress field in the central test section. Mechanical biaxial (8-point bending) is applied to the cruciform specimen using a large-scale test fixture in a 3.1 MN Instron servo-hydraulic testing machine located at ORNL. Fig. 2 shows the post-test state of one of the cruciform specimens. The results of the cruciform BB test series are summarized in Table 1.

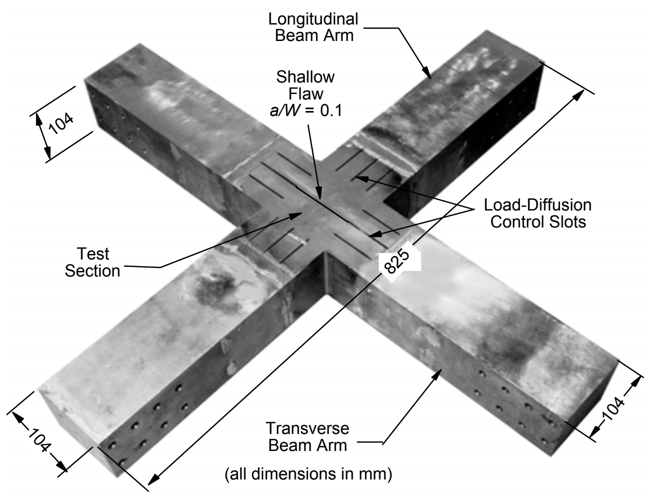

Fig. 1. Geometry of the cruciform shallow-flaw biaxial fracture toughness test specimen, thickness 104mm.

Four tests were performed at a temperature of -60°C, and two tests were performed at -50°C. All six of these tests had a biaxial transverse to longitudinal loading ratio of 1:1. One test, at -60 °C, had a biaxial ratio of 0.87 caused by problems with the test facility during the test. The provisional transition temperature T_0^* for the cruciform bend experiments was determined to be -118°C.

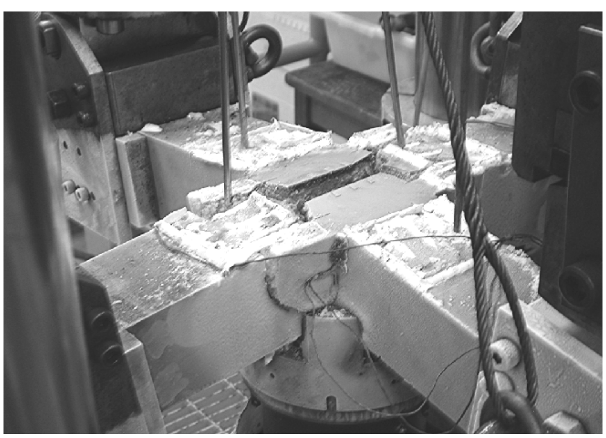

Fig. 2. Cracked cruciform specimen after test at -60°C

Table 1. Cruciform Bend Specimen Test Results

Test	Temp.	Moment	Biaxiality ratio	J
ID			(PT:PL)	
-	(°C)	(kN-m)	-	kJ/m2
BB7	-61.22	123.18	1.01	194.80
BB5	-60.89	124.43	1.01	236.80
BB1	-61.00	125.11	1.00	239.70
BB2	-49.39	125.74	1.04	254.30
BB3	-49.28	125.96	1.01	258.50
BB6	-61.00	131.89	1.01	308.50
BB4	-60.00	135.40	0.87	353.80

Pre-cracked Charpy 10 mm x 10 mm (PCCV)

Within the VOCALIST test program, 27 PCCV specimens with a cross-sectional area of 10 mm x 10 mm were tested. Ten specimens with a/W = 0.5 represent the high-constraint conditions. The remaining specimens were fabricated with $0.096 < a/W < 0.144$ and are considered low-constraint specimens. They were fabricated and tested at VTT in Finland and at SERCO in England [3]. The test temperature was approximately -110°C for all tests. Fig. 3 shows the failure probability vs. fracture toughness for all of the tested PCCVs.

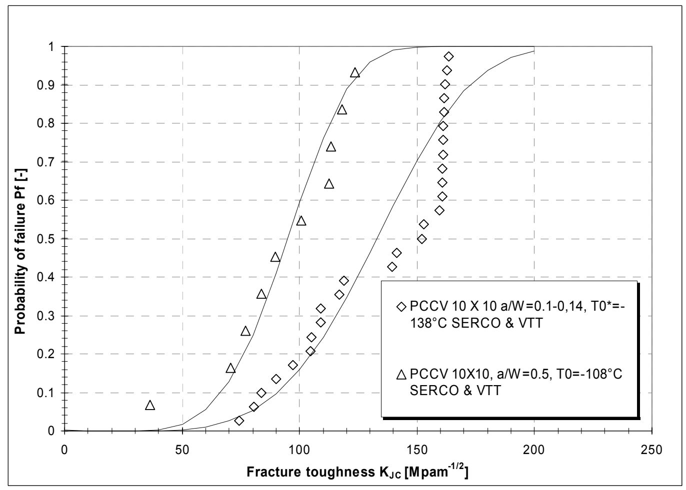

Fig. 3. Failure probability Pf vs. fracture toughness, K_{JC}, for deep-flaw and shallow-flaw PCCV specimens.

The provisional transition temperature T_0* results indicate a constraint-based temperature shift of 30 °C between the two crack configurations. The calculated T_0^* for the low-constraint, shallow-flaw specimens is -138 °C, and the high-constraint, deep-flaw tests produced a T_0* of -108°C, size corrected to 1T. All test results from the VOCALIST project are summarized in [4].

Standard 4T (100 mm) C(T) Specimens

The temperature dependency of the applied Weibull model was investigated using temperature-dependent fracture toughness data. The EC Master Curve testing program [5] provides fracture toughness data from 4T C(T) specimens with the same Material A used in VOCALIST. Four sets of 4T-data at temperatures of -91 °C , -20 °C , 0 °C, and 20 °C are available. Each dataset contains 16 ASTM E-1921 valid test results. Fig. 4 shows the cumulative failure probability vs. fracture toughness K_{IC} for the first three temperatures.

THREE PARAMETER WEIBULL STRESS MODEL

In the *local approach* to cleavage fracture, the probability distribution P_f for the fracture stress of a cracked solid at a global load level quantified by either K_J or J follows a two-parameter Weibull distribution [6] of the form

$$Pf(\sigma_W) = 1 - \exp\left[-\frac{1}{V_0}\int_V \left(\frac{\sigma_1}{\sigma_u}\right)^m dV\right] = 1 - \exp\left[-\left(\frac{\sigma_w}{\sigma_u}\right)^m\right] \qquad (1),$$

where V denotes the volume of the cleavage fracture process zone (usually defined as the region $\sigma_1 \geq \lambda\sigma_0$, where σ_1 is the maximum principal stress, σ_0 is the yield stress, and λ is a constant), inside the fracture process zone. The parameters m and σ_u denote the Weibull modulus and the scale parameter of the Weibull distribution. Following Beremin [6], the integral over the fracture process zone is denoted as σ_w, and is termed "Weibull stress",

$$\sigma_w = \left[\frac{1}{V_0}\int_V \sigma_1^m dV\right]^{\frac{1}{m}} \qquad (2).$$

Gao, Ruggieri, and Dodds [7] added a threshold parameter, the two-parameter Weibull description changes to the form of

$$P_f(\sigma_w) = 1 - \exp\left[-\left(\frac{\sigma_w - \sigma_{w-\min}}{\sigma_u - \sigma_{w,\min}}\right)^m\right] \qquad (3),$$

where $\sigma_{w\text{-min}}$ represents the minimum σ_w-value above which macroscopic cleavage fracture becomes possible.

Calibration of the applied Weibull model

In addition, Gao, Ruggieri, and Dodds [7] proposed a new calibration procedure based on Small Scale Yielding (SSY) and Large Scale Yielding (LSY) values for cleavage fracture toughness, measured in the Ductile to Brittle Transition (DBT) region. The procedure uses two datasets with different constraint states, e.g., shallow- and deep-flaw bend specimens. The LSY data are constraint-corrected by mapping all values back into the SSY stress space. The SSY solution is represented by a modified boundary layer model with a homogeneous crack tip field. Temperature and thickness should be the same as for the LSY data.

Applying an iterative process, that m value is sought that gives both SSY datasets (shallow and deep) the same statistical properties within the SSY stress space. Fig. 5 shows the correlation between LSY- and SSY- data for the 10 mm x 10 mm PCCV specimens, shallow and deep-flawed, used for the calibration of the Weibull model. All data points in Fig. 5 have been stochastically simulated with the same T_0, T_0^* as determined by the test data. The straight line represents a one-to-one correlation between LSY and SSY, where values along this line are not influenced by constraint.

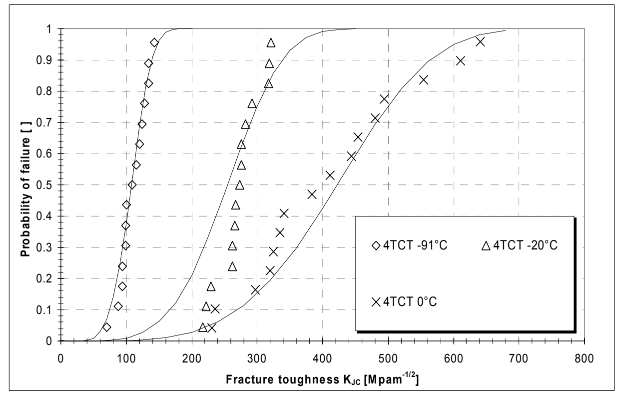

Fig. 4. Failure probability for 4T-C(T) specimens at -91 °C, -20 °C & 0 °C, size corrected to 1T.

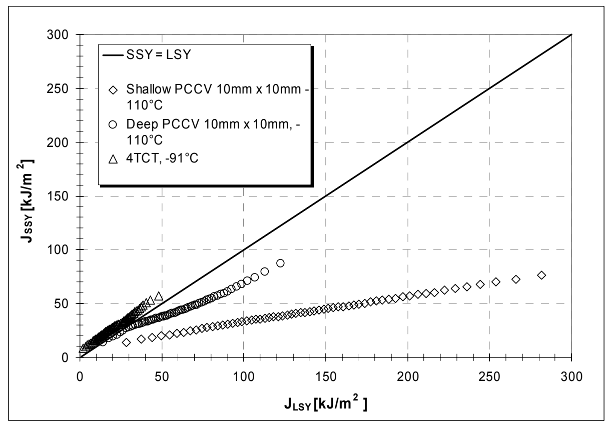

Fig. 5. $J_{LSY} \rightarrow J_{SSY}$ correction for deep and shallow PCCV specimens and CT specimens (stochastically-simulated data).

In the lower loading state, the deep-flawed PCCV specimens follow this line. After increasing loading (with increasing plastic deformation), the data deviates from this line and becomes constraint dependent. The low-constraint, shallow-flaw PCCV data show a large deviation from the one-to-one line for the full loading range. The triangles in Fig. 5 are data points for 4T-C(T) specimens, tested at -91°C. This dataset shows a higher constraint state than the reference line which is consistent with the observed positive T-stress values for the C(T) geometry. After successful calibration, all required parameters in Eq. (3) can be determined. The Weibull shape parameter m follows directly from the calibration; $\sigma_{w\text{-min}}$ is the Weibull stress at $K_J = K_{\min} = 20\text{MPa}\sqrt{\text{m}}$ (from ASTM E-1921); and σ_u represents the Weibull stress at a failure probability of 63%. For a detailed description of the procedure see [7]. The Weibull shape parameter m can now be used to calculate the Weibull stresses for other constraint states. Applying Equation (3), the failure probability history and the constraint-based shift in K_J or J between the analyzed structures can be determined. Finally, the constraint-corrected shift in the transition temperature T_0 can be calculated.

DEVELOPMENT OF A MODIFIED WEIBULL STRESS MODEL TO PREDICT CLEAVAGE FRACTURE OF SHALLOW-FLAW CRUCIFORM BEND SPECIMENS (ORNL CONTRIBUTION)

To analyze the biaxially loaded shallow-flaw specimens tested within VOCALIST, a modified Weibull stress model is being investigated. The aim of this analysis is the validation and prediction of the T_0^* shift governed by the biaxial loading, the size, and shallow flaw of the specimens. The goal is to take the temperature dependency of the statistical model into account.

FEM Analysis of the Cruciform Beams

Two finite-element models (FEM) of the cruciform bend specimen were prepared. One model with sharp crack tip is used to calculate the *J*-integral load path, and the second model, with a small finite crack-tip radius to calculate the nonlinear finite-strain and stress fields ahead of the crack tip for the Weibull stress determination. All elastic-plastic FEM calculations were conducted by using the ABAQUS code [8]. The required material-characterization data, e.g., stress-strain curves, Young's elastic modulus, *E*, and Poisson's ratio, ν, were experimentally determined within the VOCALIST project [1].

Fig. 6 shows the used FEM mesh of a quarter of the specimen. The model is loaded by imposing a pressure on both the longitudinal and the transverse moment arms and is supported at four points on the bottom, producing an 8-point bending load.

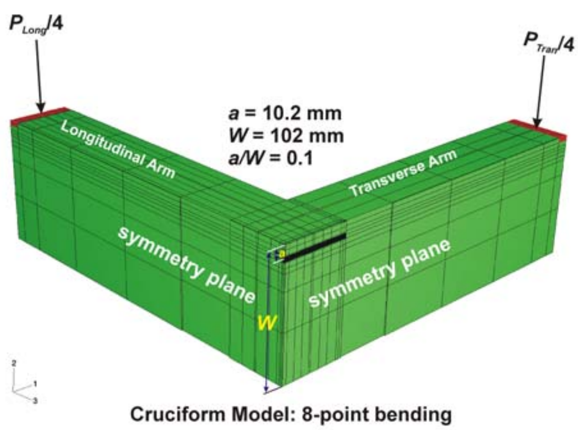

Fig. 6. Finite Element mesh of the cruciform beam

A comparison of the global behavior between the tests and the FEM calculations is given in Fig. 7 at -60 °C. The experiments are well described by the computation and lie only slightly below the FEM-solution.

Calibration of the Weibull Model

The calibration of the Weibull model is based on the transition temperature derived from the testing of shallow and deep cracked small size specimen, as described before.

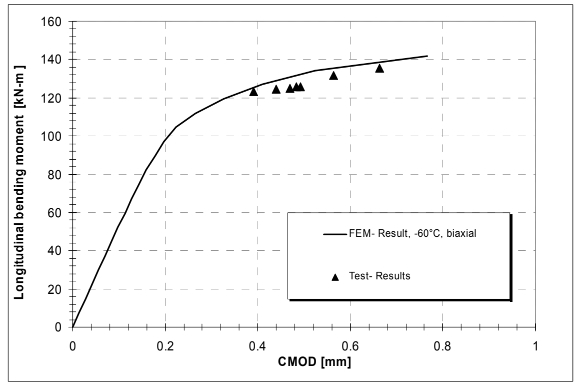

Fig. 7. Bending moment vs. CMOD: biaxial bend tests and FEM-solution

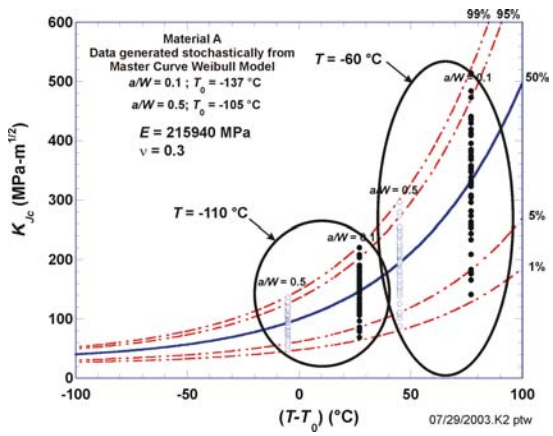

Fig. 8. Stochastically-generated fracture toughness data for shallow-flaw (a/W = 0.1) and deep-flaw (a/W = 0.5) SE(B) 1T specimens at two test temperatures, -110°C and -60°C

In the calibration procedure $T_{0\mathrm{deep}}$ = -105°C and $T_0^*{}_{\mathrm{shallow}}$ = -137 °C are used. To have experimental data to calibrate the Weibull model at -60 °C, the stochastically-generated data at -110 °C are shifted to the test temperature of the cruciform specimens by using the Master Curve. Both generated datasets contain about 60 simulated data points. Fig. 8 shows the simulated data at both temperatures. The FE-models used for calculating the Weibull stress history are plotted in Fig. 9. All three models have an initial root radius at the crack tip. The J-integral is calculated using sharp crack tip models. The modified 2D plane strain boundary layer model is loaded by a displacement field on the outer boundary of the layer [7], to produce a crack tip stress field with T-stress equal zero. In the ORNL approach, the calibration of the Weibull stress parameters is based on the hydrostatic stress to capture the constraint effects due to both a shallow-crack geometry and a biaxial loading state.

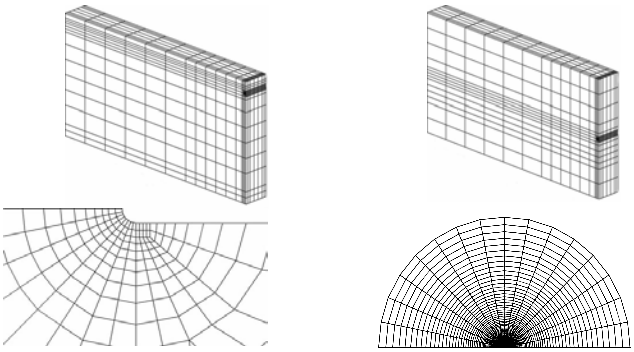

Fig. 9. Quarter-symmetry finite element models of SE(B) 1T specimens: shallow- and deep-cracked with crack tip detail and 2D plane strain layer

Inside the modified WSTRESS code [9], used for calculating the Weibull stress, the fracture process zone near the crack-tip is defined as the volume including all of the material elements satisfying the condition $\sigma_{eff} \geq \lambda\sigma_o$, where σ_o is the yield stress and σ_{eff} is the Mises effective stress. It is important to define a well-contained fracture process zone in the Weibull stress calculation because it was observed that the calibration is very sensitive to the selection of the cut parameter λ. To get a reasonable region, a cut parameter of $\lambda = 1.2$ was used here.

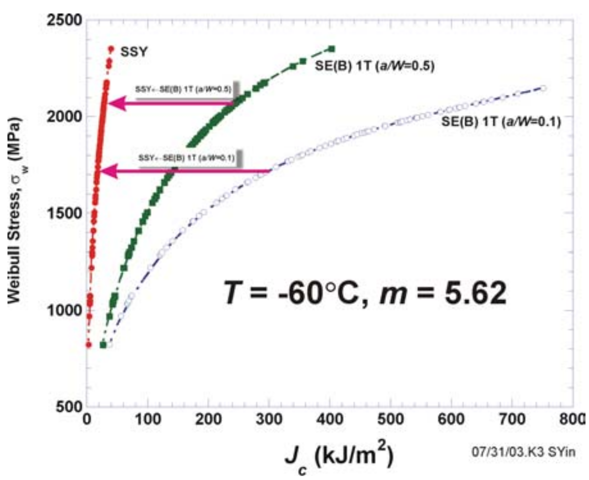

Fig. 10. Mapping the SSY toughness data to the uniaxial and biaxial loading Weibull spaces for m=5.62

Fig. 11 shows the Weibull stress history vs. J-integral value for the converged calibration, using m = 5.62. The Weibull stress vs. J history is then calculated for the 3D cruciform 4T model for different biaxial ratios: Equibiaxial loading (1:1) with the same loading on both arms, uniaxial (1:0) and biaxial (1:2).

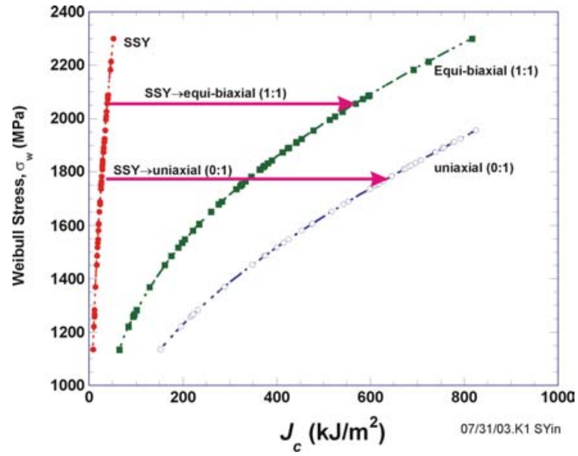

Fig. 11. Weibull stress as a function of J-integral for converged calibration: T = -60°C, m = 5.62

The generated SSY data are mapped into the LSY space and crossed with the σ_W vs. J line for the biaxial and uniaxial cruciform beam, Fig. 10 explains this procedure.

Prediction of the failure probability for biaxial and uniaxial loaded cruciform beams

The outcomes of the Weibull approach are datasets for the different loading situations, biaxial, uniaxial and equibiaxial. These failure values can be used to calculate the transition temperature T_0^*, by using the Master Curve approach [11]. The failure probability curve for the different loading ratios can be calculated by using

$$P_f = 1 - \exp\left\{-\left[\frac{\left(K_{Jc} - K_{\min}\right)}{\left(K_0 - K_{\min}\right)}\right]^4\right\}. \quad (4)$$

K_O and K_{min} in Equation (4) follows from the Master Curve approach and K_{JC} are the predicted failure points derived from the Weibull model.

Fig. 12 shows the calculated failure probabilities for all analyzed loading situations. The straight line is the failure probability for the SSY solution with T_0^* = -28°C. The uniaxial loaded cruciform beam (no test values available) shows a T_0^* of -138.8°C, equal to the shallow PCCVs. Then there is a constraint dependent shift between the uniaxial and equibiaxial loaded beam towards a lower T_0^* value, -119.5°C. A doubling of the transverse load produces a higher constraint state compared to the one to one loading. The T_0^* for the biaxial (2:1) case shows therefore the lowest transition temperature with -108°C (no test values available). The failure probability for the test results in Fig. 12 were calculated using the median rank probability

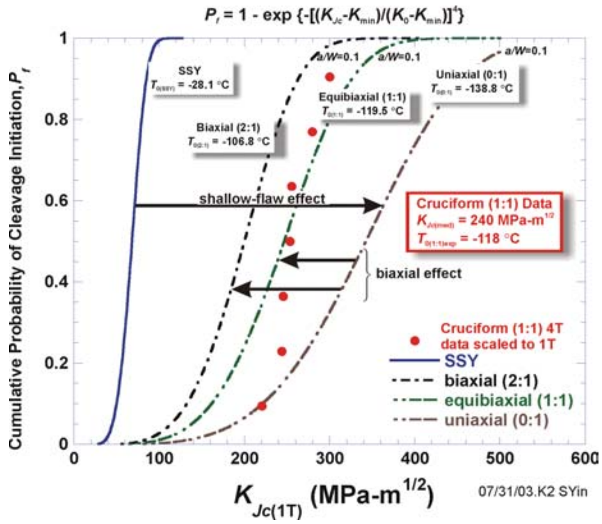

Fig. 12. Cumulative failure probability of SSY model and cruciform beams under biaxial and uniaxial loading, compared with cruciform (1:1) 1T(converted from 4T) experimental data, N = 7

$$P_{f(i)} = \frac{i - 0.3}{N_{\exp} + 0.4}, \qquad (5)$$

where N_{exp} is the number of test results. The cruciform (1:1) test data indicates a provisional estimate for T_0^* of $T_0^*{}_{(1:1)(exp)}$ = -118°C compared to the calculated $T_0^*{}_{(1:1)}$ = -119.5°C based on the simulated cruciform dataset using the calibrated Weibull stress model [10].

CONFIRMATION OF THE LACK OF TEMPERATURE DEPENDENCY OF THE WEIBULL SHAPE PARAMETER *m* AND CONSTRUCTION OF σ_U AND $\sigma_{w\text{-}min}$ AS A FUNCTION OF TEMPERATURE (FRAMATOME-ANP CONTRIBUTION)

One of the basic assumptions of the applied approach is the temperature independency of the Weibull shape parameter m. Furthermore it is expected that the Master Curve shape, derived by testing of small size specimens e.g. PCCV 10mm x 10mm, follows the same statistical assumptions as described in ASTM 1921 - 02 [11] by using standard specimens. Both of these assumptions are essential for generating datasets at different temperatures along the Master Curve, as implemented in the previous approach: Calibration with datasets at different test temperatures using small size specimens and prediction of benchmark tests at another test temperature.

To confirm these assumptions additional investigations were performed by FANP. The following approach is based on a calibration of the used Weibull model, described in [7], near the test temperatures of the used small size specimen. By using stochastically generated failure data for 4T-C(T) standard specimens a temperature dependent curve for the lacking parameters σ_u and $\sigma_{w\text{-}min}$, in Equation (3), will be created. The accuracy of this curve should then be validated with test results from 4T-C(T) specimens for the full temperature range of the constructed curve. Finally the model is applied to predict the failure probability and biaxial vs. uniaxial effects of the cruciform tests.

Calibration of the Weibull model

Very detailed Finite Element models of both, deep and shallow cracked specimens were idealized to create the Weibull stress vs. J history for the PCCV small size specimens, Fig. 13.

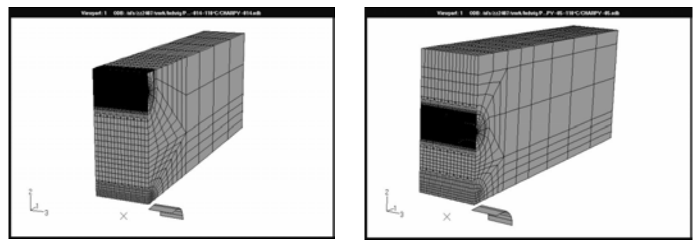

Fig. 13. Deep and shallow cracked PCCV specimens: B = 10mm, W = 10mm

Both crack tips consist of sharp collapsed elements, the nodes concentrated at the crack tip are free to move. Investigations of the influence of the crack tip radius on the Weibull stress show only a minor effect when a sharp crack tip is used, to save modeling time only one very detailed model with sharp crack tip is generated for each crack depth. In thickness direction of the model there are 256 elements with homogeneous length along the crack front. Also the ratio of, length / height of all elements around the crack tip is nearly one. The loading and supporting are modeled by applying contact interaction. The crack tip region of the required SSY modified boundary layer, (same geometry as in Fig. 9), is equal to the one of the specimen. The models were calculated by using the same material properties as described above.

To generate the input data for the calculation of the Weibull parameter m two datasets are generated using the experimentally obtained transition temperature for the deep and shallow cracked small size specimens: -137.6°C for the shallow crack and -108.1°C for the deep crack. Each dataset contains 62 data points. As described in [7] an *m* value is searched which matches both datasets to the same statistical properties within the SSY-space. In contradiction to the ORNL approach the Weibull stress, Equation (2), is calculated by using the maximum principal stress, as mentioned in [4]. This difference also influences the absolute values of the Weibull parameters between the two approaches.

Fig. 14 shows the generated failure points for both constraint configurations after converged calibration. The open symbols are the LSY-data, the filled ones show the mapped SSY-data. As shown in Fig. 5 the deep flaw data follows the SSY-solution and deviates after increasing plastification from the SSY line.

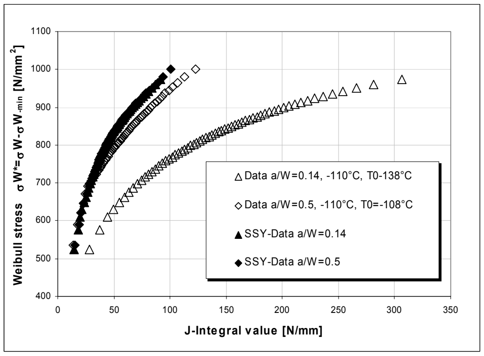

Fig. 14. Weibull stress vs. J for the converged calibration m = 14.83, *T* = -110°C

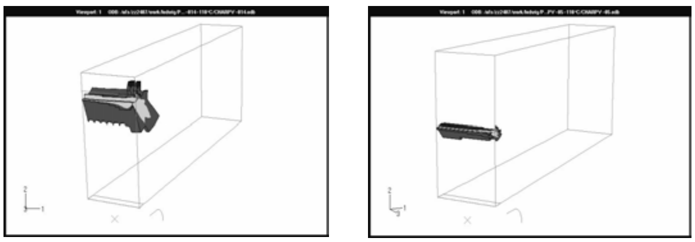

Fig. 15. Process zones of the shallow and deep cracked specimens at median fracture toughness, T = -110°C

The process zones, defined by including all integration points with higher stresses than 1.2 * $\sigma_{y,}$ are shown at K_{med} in Fig. 15. The high level of plastic deformation of the shallow cracked specimen, compared to the deep one is obvious. Fig. 16 summaries all data points used within the calibration. The open symbols, triangles and rhombuses show the test results from the VOCALIST testing program. The cruxes and bars show the generated data, replacing the experiments. The dashed lines follow from Equation (3) by using the Weibull parameters from the calibration. The good description of the experiments verifies the calibration procedure.

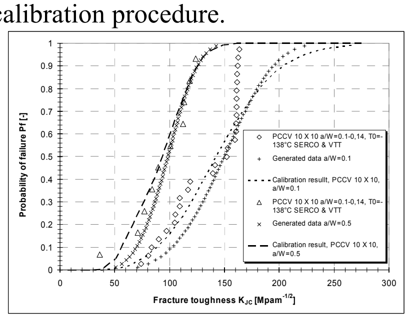

Fig. 16. Calibration results at -110°C, PCCV 10mm X 10mm (SERCO & VTT Data), $T_0{}^*{}_{(a/W=0.5\,)}$= -108°C, $T_0{}^*{}_{(a/W=0.1\text{-}0.14)}$ = -138°C, size corrected to 1T

Construction of σ_u, $\sigma_{w\text{-}min}$f(T)

To construct the temperature dependent curves of σ_u and $\sigma_{w\text{-}min}$ five temperatures (-150°C, -110°C, -90°C, -40°C and -20°C) were considered. For this reason detailed FE calculations of 4T-C(T) specimens were carried out. The 4T-C(T) specimens have been selected because they have the same thickness as the cruciform bend bars. In addition, datasets with 62 values were stochastically generated for each temperature in the same way as in the calibration.

The shape parameter *m* is assumed to be independent of temperature. Therefore the shape of the σ_W / J- history depends on the hardening and flow stress and not on m. After calculation of all σ_w/J-histories, using the calibrated m, a small scale yielding dataset can be calculated for all temperatures by mapping the generated LSY-data back onto the SSY curve. This allows the calculation of σ_u and $\sigma_{w\text{-}min}$ for each temperature using the same procedure as in the calibration of m. Fig. 17 shows both parameters versus temperature in a temperature range of -150°C to -20°C. $\sigma_{w\text{-}min}$, based on a K_{min} of 20MPa√m, shows no temperature dependent behavior. The scale parameter of the Weibull distribution, σ_u, is temperature dependent. The values at -150°C show a different behavior compared to the one at higher temperatures, this is caused by the relatively coarse mesh referring to the small degree of plastic deformation at this temperature, especially at low failure values. A more refined crack tip region is therefore required to build up the plasticity in the beginning of the loading.

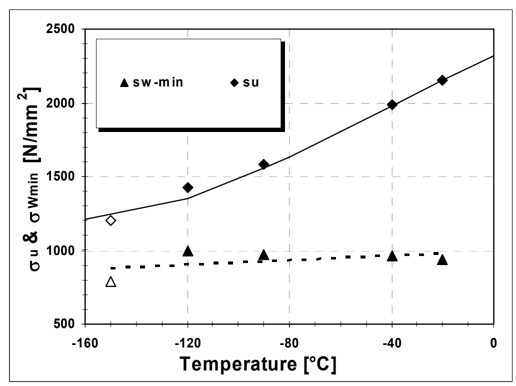

Fig. 17. Weibull parameters σ_u and $\sigma_{W\text{-}min}$ vs. temperature

Application of the temperature-dependent Weibull approach

The temperature dependent Weibull approach is verified by prediction of the failure probability for standard 4T-C(T) specimens, tested within [5]. Test results are available at -91°C, -20°C and 0°C. Finite Element models are considered, the same as used for the σ_u- $\sigma_{w\text{-}min}$f(T) calculation, to calculate the σ_w / J-history, using the calibrated m value. Fig. 18 shows the failure probabilities (dashed lines) for the analyzed 4T-C(T) specimens by using Equation (3), with σ_u and $\sigma_{w\text{-}min}$ from Fig. 17. The calculation of T_0 for all three temperatures at a failure probability of 50% gives the expected T_0 of -95°C for Material A.

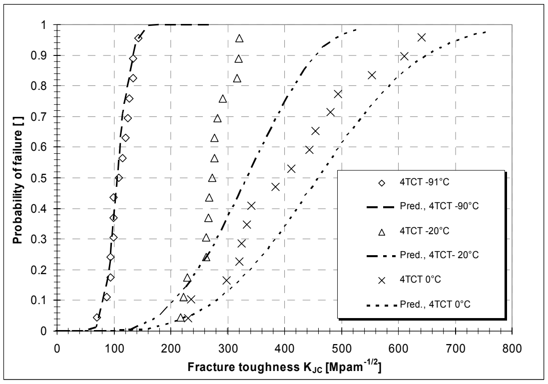

Fig. 18. Failure probability for 4T-C(T) specimens -91°C, -20°C & 0°C, size corrected to 1T

In the same way the Weibull stress history was calculated for the biaxial loaded beam, shown in Fig. 6, at -60°C. Additionally a Finite Element model was generated having the same geometry as the cruciform bend specimen but without the transverse loading arm to have a 4T uniaxial solution. The model is used to analyze the influence of biaxial vs. uniaxial loading on T_0^*.

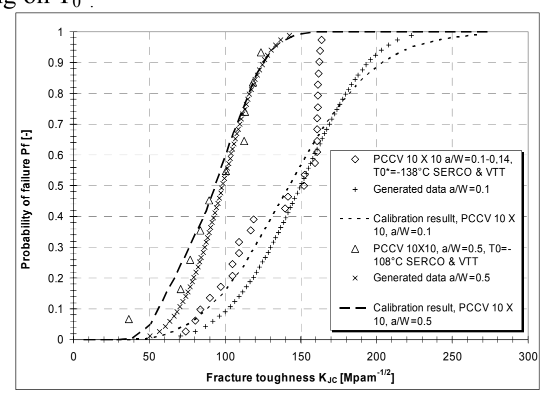

Fig. 19. Failure probability for 4T-C(T), -91°C, biaxial and uniaxial bend bar, -60°C , size corrected to 1T

Fig. 19 shows the predicted failure probability history vs. fracture toughness for both calculations, dashed lines. The circles in Fig. 19 are the test results of the cruciform beam tests. The results calculated for the 4T-C(T) specimen at -91°C are shown for comparison. The predicted T_0^* for the uniaxial case is -125°C and for the biaxial -112°C. This means there is a biaxial effect of 13°C.

SUMMARY

The Weibull statistical model has been applied to predict constraint effects on shallow cracked beams loaded by uniaxial and biaxial bending conditions. The applied Weibull model has been calibrated using deep and shallow cracked small bend specimens (PCCVs) at different test temperatures. The temperature dependence or independence of the Weibull parameter m and the sizes σ_u and $\sigma_{w\text{-}min}$ has been investigated by predicting the behavior and transition temperatures of 4T CT fracture toughness specimens at different temperatures.

It could be shown that the parameter m and $\sigma_{w\text{-}min}$ are temperature independent in the investigated temperature regime and that σ_u reveals a strong dependence with temperature.

Both of the applied statistical Weibull models which are based on [6] and [7] and which are modified to take the temperature dependency into account, show an effect on T_0^* concerning different loading ratios, uniaxial and biaxial. The calculated shift in T_0^* is 18°C in the ORNL calculation and 13°C in the FANP approach. The predicted T_0^* for the uniaxial beam shows the same value as tested on the shallow flaw PCCVs, about -138°C. An influence of the thickness, 10mm to 100mm, has not been observed. The predicted transition temperatures are in good agreement with the measured ones.

The application of the Weibull model by using stochastically generated data, tested on small size specimens confirmed the shape of the Master curve.

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REFERENCES

[1] Lidbury D., et al: "Validation of Constraint Based Methodology in Structural Integrity – VOCALIST: Overview" Contribution to ASME PVP, 2002

[2] B. R. Bass, et al., *Vocalist & NESC-IV Projects*, "Biaxial Bend Fracture Tests on a Forged Ferritic Steel," Test Report, November 2002.

[3] Sherry A, Brikett P., "Material A: Results from miniature-scale SE(B) tests", Serco Assurance, 2003

[4] Eisele U., "Additional test data", Deliverable D4, EC-Project VOCALIST, Contract No. FIKS CT-2000-00090

[5] Heerens J., Hellmann D.: "Fracture Toughness of steel in the Ductile to Brittle Transition Regime", EC Contract MAT1-CT-940080, GKSS Forschungszentrum Geesthacht, 1999

[6] Beremin F. M., "A local criterion for cleavage fracture of a nuclear pressure vessel steel", Metallurgical Transactions 114A, 2277-2287, 1983

[7] Gao X., Ruggieri C., and Dodds, R. H., "Calibration of Weibull Stress Parameters using Fracture Toughness Data," International Journal of Fracture 92, (1998) 175-200.

[8] ABAQUS Theory Manual, Version 6.3, 2002 Hibbitt, Karlsson and Sorensen

[9] Ruggieri, C. and Dodds, Jr., R. H., "Numerical Evaluation of Probabilistic Fracture Parameters with WSTRESS," Engineering and Computers, Vol. 15, No. 1, 1998, pp. 49-73.

[10] B. R. Bass, *Monthly Letter Status Report* for NRC Project JCN Y6533, Oak Ridge National Laboratory, Oak Ridge, TN, September 22, 2003, pp. 3-14.

[11] ASTM E 1921-02, "Standard Test Method for Determination of Reference Temperature, T_0, for Ferritic Steels in the Transition Range".