Application of the Beremin-model for predicting the Brittle Fracture Resistance of Steel for Spent Nuclear Fuel Containers

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ABSTRACT: *The aim of our work was to study the applicability of the Beremin-model for predicting the brittle fracture behaviour of ferritic cast steel used for spent nuclear fuel containers, and to study the sensitivity of the model for different material parameters. The model parameters were determined according the recommended ESIS procedure on the basis of experiments on notched tensile specimens performed at –160 °C. The fracture loads and fracture probabilities of V-notched Charpy-type specimens were determined and compared with experimental data. The effect of material parameters, i.e. yield stress and strain hardening exponent on the model parameters and the prediction results was also investigated. Also it was analysed how the applied numerical procedure affects the results. As it was found, the strain hardening exponent has small effect on the model parameters, the yield stress has stronger effect. The accuracy of the prediction mostly depends on the variation of the yield stress.*

INTRODUCTION

The brittle fracture resistance of the materials can be described by statistical methods. Nowadays the micromechanical modelling of the fracture behaviour is widely applied and studied, when size, geometry and temperature dependent material parameters can be determined. The Beremin-model [1] uses two parameters for describing the fracture process connecting the microscopic defects and the stress state with the fracture probability. The applicability conditions of this model are widely investigated. The aim of our work was to analyse the effect of different material parameters on the applicability of the Beremin-model for predicting the brittle fracture resistance of cast ferritic steel used for spent nuclear fuel containers.

DETERMINATION OF THE BEREMIN-MODEL'S PARAMETERS

The Weibull-parameters have been determined by applying a proposed standard procedure which was elaborated by the European Structural Integrity Society (ESIS) [2]. The MARC code has been used for the finite element calculations.

Tensile experiments of notched cylindrical specimens were performed at low temperature (T = -160 °C) at the Institute for Physics of Materials, Brno. In this study the results of the specimens with 1 mm notch radius were used. Elastic-plastic constitutive equation determined at –160 °C was first applied in the FEM calculations (Table 1). Then the constitutive equations were modified artificially, simulating the possible scatter of the material parameters, i.e. strain hardening exponent (n) and yield stress (σ_y). The measured and the modified stress-strain curves are shown in Figure 1. (The yield stress was changed with ±50 MPa, and the strain hardening exponent was varied between 0.2 and 0.3.)

At first the Weibull-parameters were determined applying the maximum likelihood method for fitting the Weibull-distribution function and considering the fracture strain as the basis of Weibull-stress calculation (Table 2.).

TABLE 1. Measured material parameters (T = -160 °C)

Measured material parameters (average of three experiments)		
ε	σ	Equation
0-0.002434	498±10	σ = 205 000*ε
0.002434-0.03981	524	σ = 695.6336*ε+496.3068
0.03981-0.18		σ =1151*ε^0.24361

The ESIS procedure allows also to use the average fracture stress as fracture parameter, and the fitting of Weibull-distribution function can be done by linear regression as well. So several calculations have been performed applying the combinations of these different possibilities and different constitutive equations, to study the effect of the applied calculation methods and material parameters. The results are summarised in Figure 2. and 3.

On the basis of these results it can be concluded that the strain hardening exponent has a small effect on the model parameters, the yield stress has a stronger effect, and the tendency is opposite when different fracture parameters are considered. The fitting method can cause larger differences.

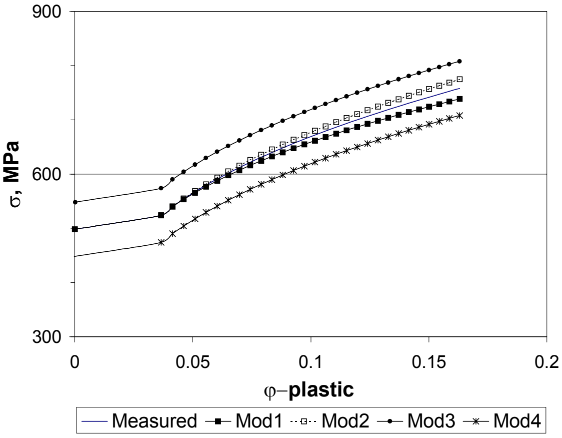


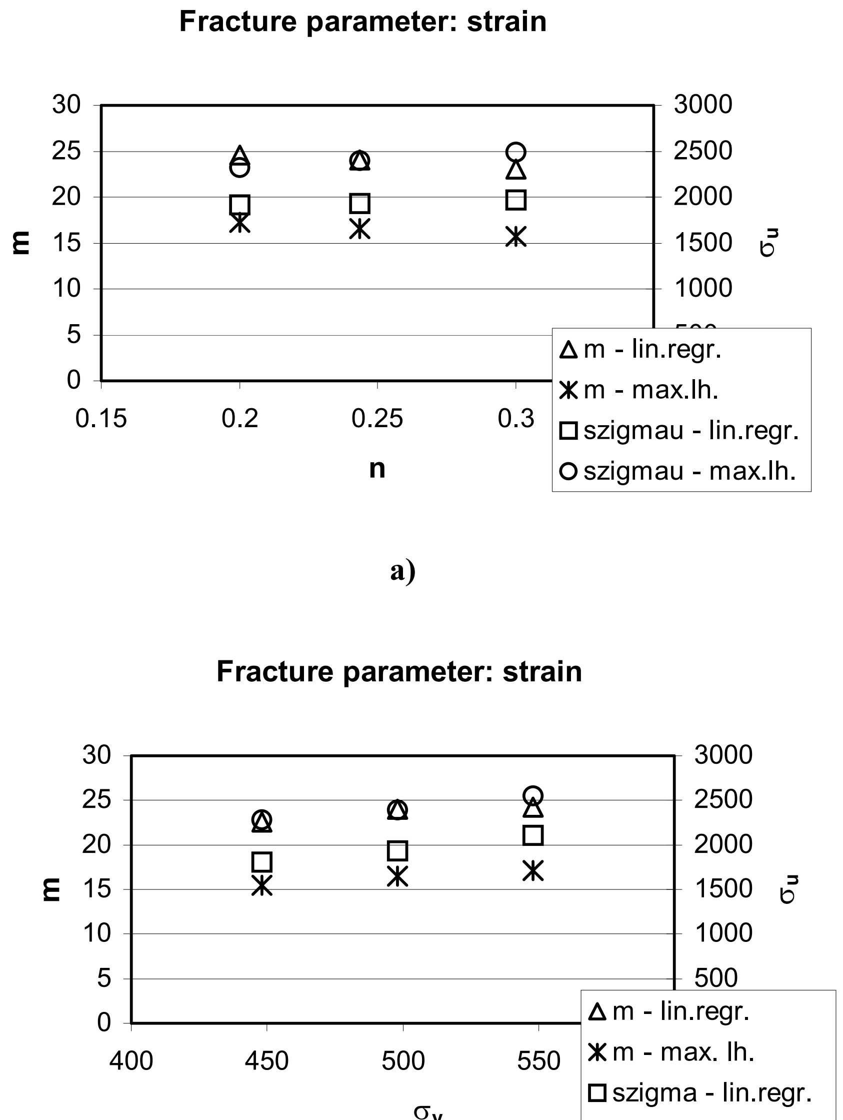
Figure 1: Stress-strain curves used in the finite element calculations

TABLE 2. Calculated Weibull-parameters with different material equations (fracture parameter is strain, maximum likelihood method is applied)

Constitutive equation	**m**	σ_u
Measured	16.53	2394.9
Modified1 (n=0.2)	17.29	2321
Modified2 (n=0.3)	15.72	2486
Modified3 (σ_y+50)	17.1	2553
Modified4 (σ_y –50)	15.5	2279

BRITTLE FRACTURE PREDICTION FOR V-NOTCHED CHARPY SPECIMENS

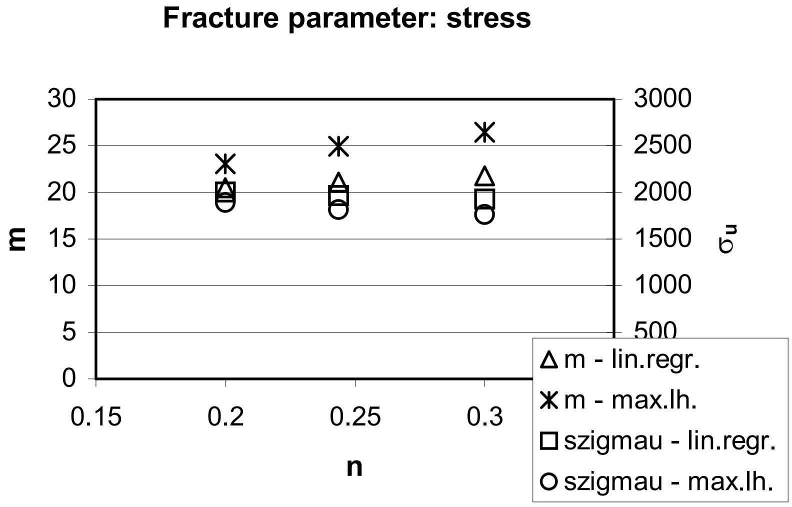
Since the determined Beremin-model's parameters are size and geometry independent, they can be used for predicting the fracture probability of specimens of other geometry. So the Beremin-model was used for analysing the brittle fracture behaviour of Charpy-V specimens under static loading conditions on the basis of 3D finite element calculation.



a)

b)

Figure 2: Effect of strain hardening exponent (a) and the yield stress (b) on the Beremin- model's parameters, applying the strain as fracture parameter



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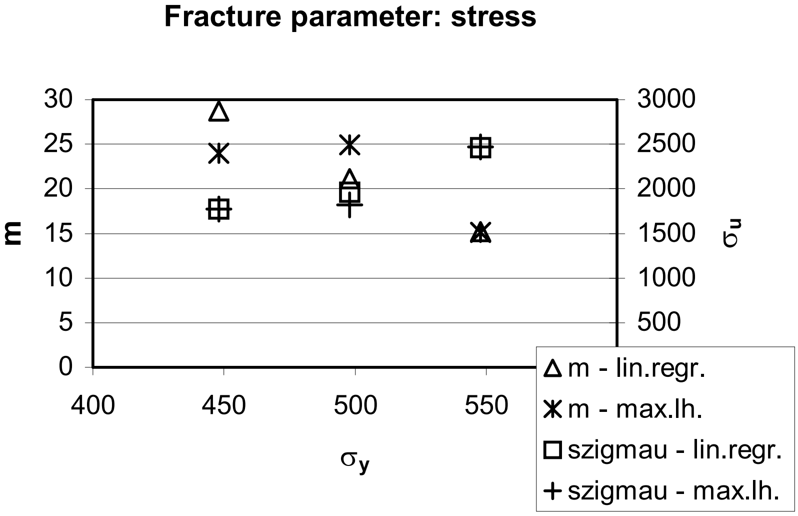

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Figure 3: Effect of strain hardening exponent (a) and the yield stress (b) on the Beremin- model's parameters, applying the stress as fracture parameter

Figure 4 and Figure 5 show the predicted fracture forces using different constitutive equations comparing with experimental data. It can be stated that there is usually good agreement between the predicted and the measured fracture forces, but the material parameters, the selection of the fracture parameter and the applied fitting method can have smaller or larger effect: e.g. when the fracture parameter was the strain with the maximum likelihood method the predicted force values shifted toward higher values as compared to the other obtained with linear regression. But when the fracture stress was used as fracture parameter, in both cases the averages of the predicted force values are almost the same. Only their intervals are different. This could be explained by the fact that the correlation of the Weibull-distribution function was much better when the stress was the fracture parameter.

The strain hardening exponent practically does not have effect on the prediction (cases 1-3 in Figure 4-5.), but the yield stress modifies the results significantly (cases 4-5 in Figure 4-5.): with higher yield stress the predicted fracture force could be 5-10 % higher.

SUMMARY AND CONCLUSIONS

Analyses on the effect of variation of different material properties, the selected fracture parameter and applied fitting procedure on the Beremin-model’s parameters has been performed.

On the basis of the obtained results the following can be concluded:

1. The strain hardening exponent has small effect on the model parameters, the yield stress has stronger effect. The model parameters also depends on which fracture parameter (strain or stress) is selected.
2. The fitting method can cause larger differences. The numerical values of the Weibull-parameters depends strongly on the scatter of the measured fracture probability values.
3. With the application of the Beremin-model it was possible to predict well the fracture force of Charpy-V specimens. The accuracy of the prediction mostly depends on the variation of the yield stress.

ACKNOWLEDGEMENT

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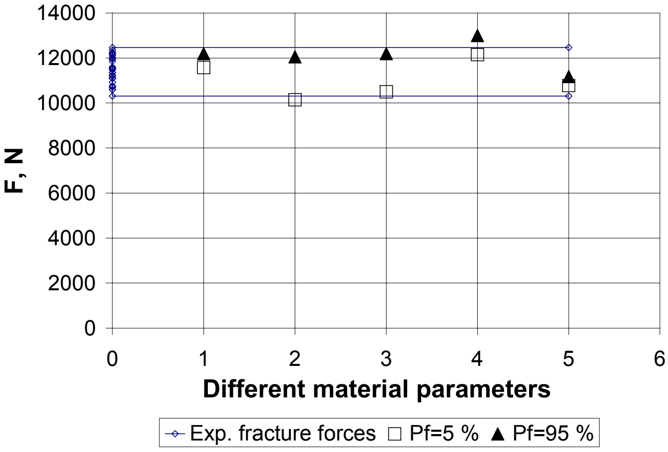

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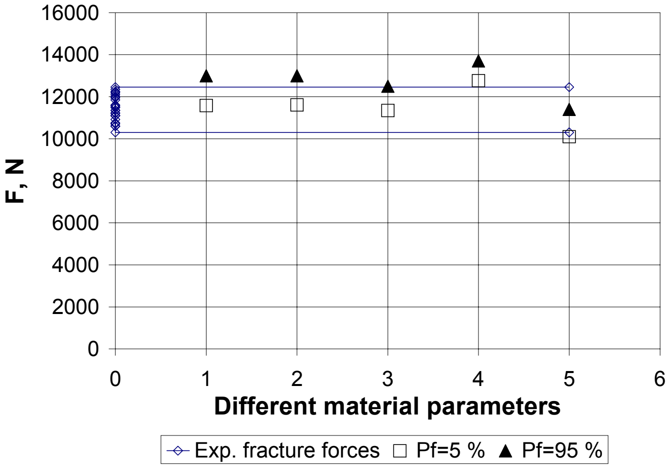
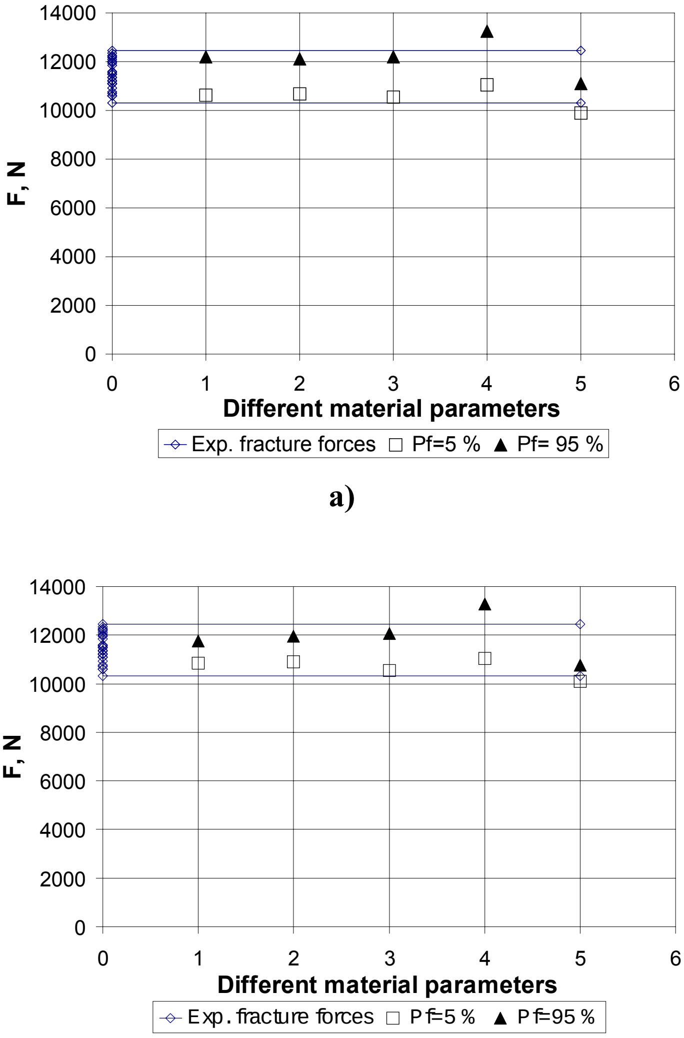


b)

Figure 4: Comparison of the measured and predicted fracture forces of Charpy-V specimens (at 5% and 95 % failure probability) for different constitutive equations, fracture parameter is strain: a) linear fitting ; b) maximum likelihood method



a)

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Figure 5: Comparison of the measured and predicted fracture forces of Charpy-V specimens (at 5% and 95 % failure probability) for different constitutive equations, fracture parameter is stress: a) linear fitting ; b) maximum likelihood method